Sicherheit in Technik und Chemie

18.01.2023

MOBILE APPLICATIONS WITH DRONES/ROBOTS

Aerial- and Ground-based Gas Tomography

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DAY 3

Outline

- **Introduction**
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  - » Research **@BAM**
- **Gas Sensing: in-situ vs. open-path**
  - » Working Principles
  - » Advantages & Disadvantages
- **Tomography**
  - » Computed Tomography
  - » Our Vision
  - » Computed Tomography of Gases
    - ○ Working Principle
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    - ○ Reconstruction Algorithm
    - ○ Path Planning
- **Aerial Robot(s)**
  - » Sensor Integration
- **Gas Dispersion Simulation**
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  - » First 2D Plume Reconstructions
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  - » Drone-to-Drone Gas Sensing
- **Conclusion and Outlook**

Introduction

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Introduction
General Motivation

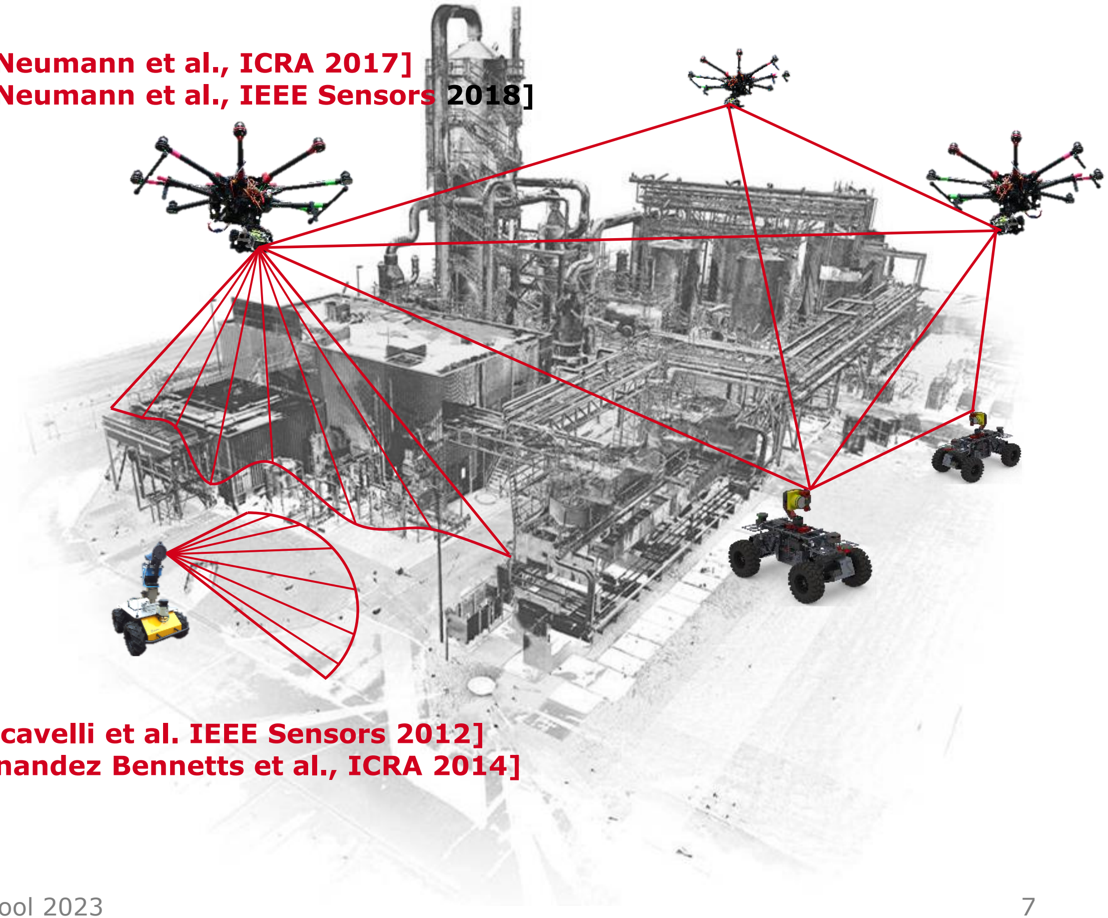




Disaster **Safety** **Environment**

Our Vision: Aerial- and Ground-based Gas Tomography

- … combines ground and aerial robots into a heterogeneous robot swarm
- … equips robots with gas sensors (in-situ/open-path) and/or reflectors as payload
- … reconstructs potential gas plumes/ clouds in 3D
- … identifies potential gas leaks based on reconstructed tomographic images



[Neumann et al., ICRA 2017]
[Neumann et al., IEEE Sensors 2018]

[Trincavelli et al. IEEE Sensors 2012]
[Hernandez Bennetts et al., ICRA 2014]

Research @BAM

Mobile and Aerial Robot Olfaction

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Timeline – The Past

2008

In-Situ Sensing

- AirRobot AR100-B
- Gas transport
- 2D sensorless wind vector estimation

Timeline – The Past

2008

In-Situ Sensing

Timeline – The Past

2008

In-Situ Sensing

2015

- DJI Spreading Wings S1000
- Simulation environment and TDLAS sensor model
- Gas tomography

Remote Sensing

Timeline – The Past

2008 **In-Situ Sensing**

2015 **Remote Sensing**

Timeline – The Past

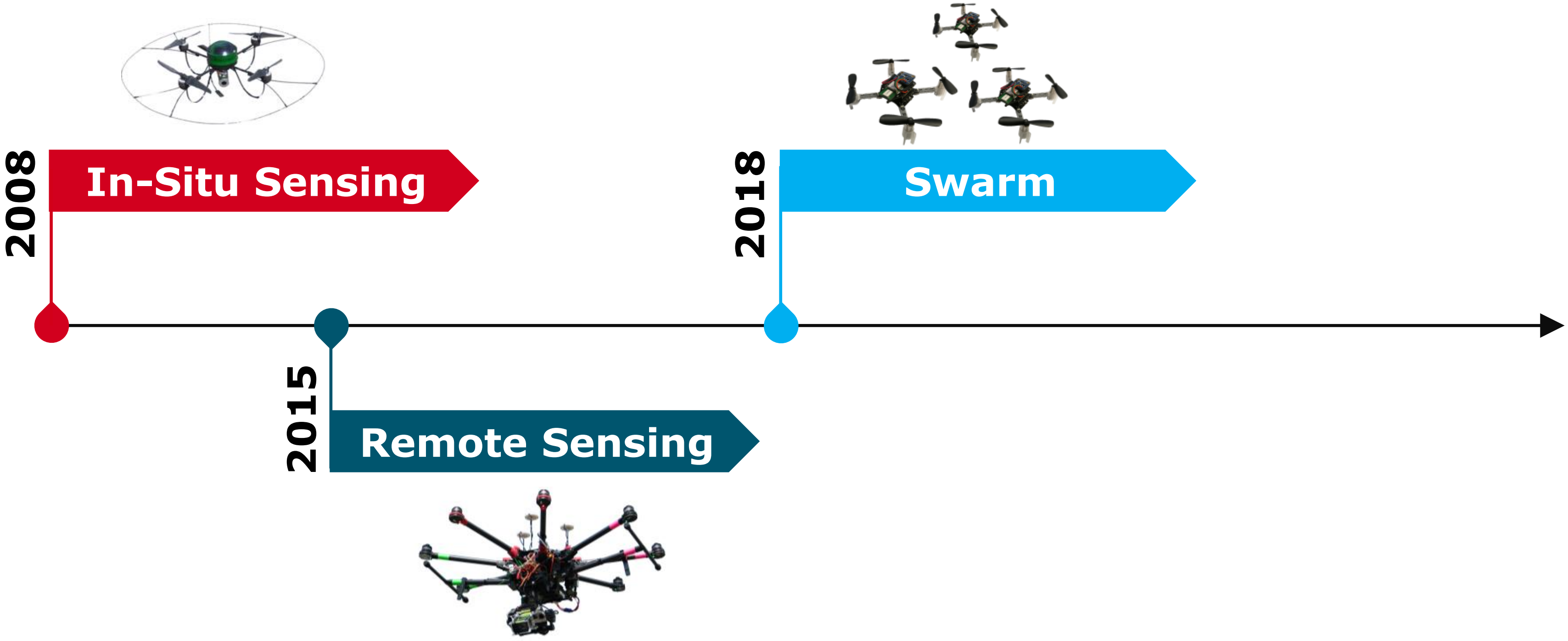
2008 In-Situ Sensing

2015 Remote Sensing

2018 Swarm

- Bitcraze Crazyflie 2.0
- Indoor air quality gas sensors
- Trail following
- Bout Potential Field

Timeline – The Past



Timeline – The Past

2008 In-Situ Sensing

2018 Swarm

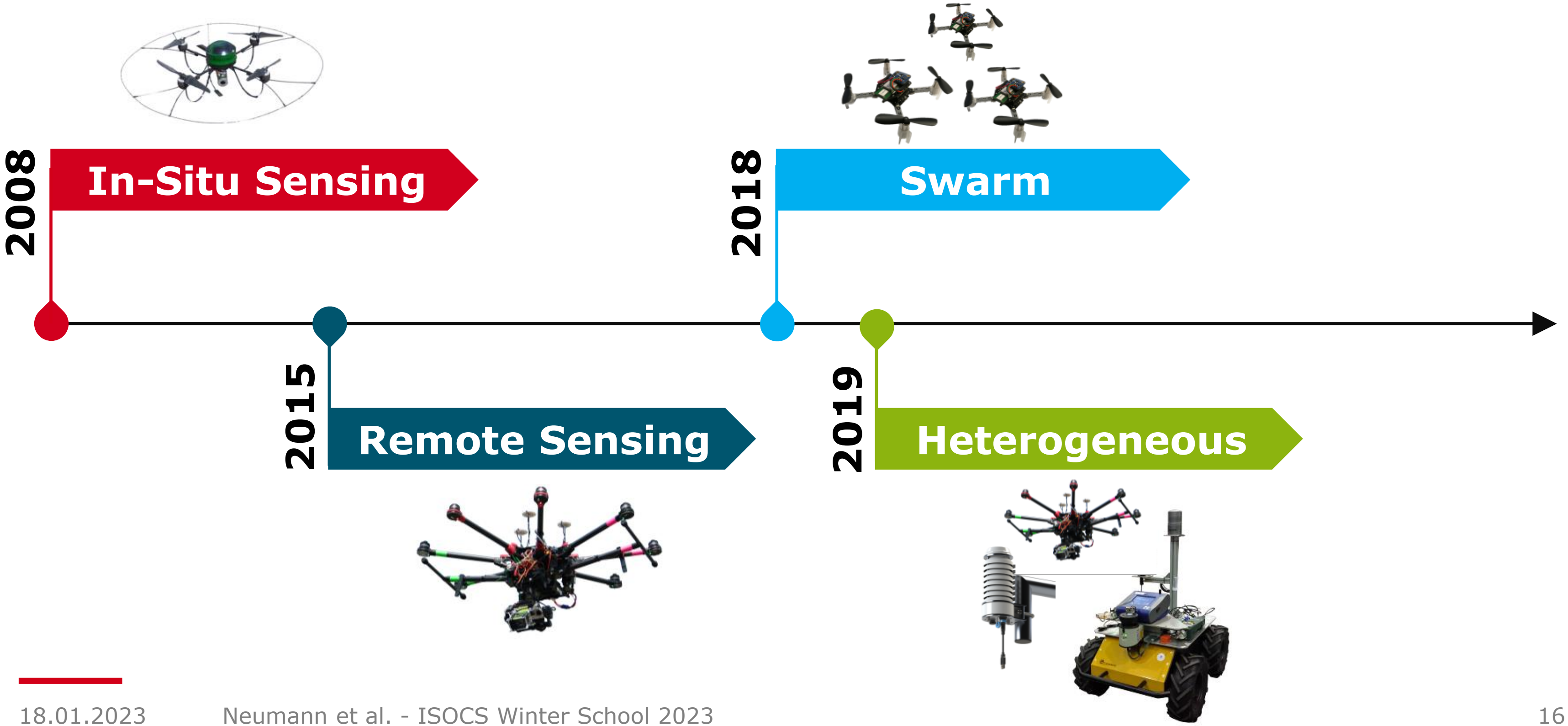
2015 Remote Sensing

2019

- » Sensor networks combined with robots & drones
- » Measurements (dust and gas) with varying quality and spatial resolution
- » Super-resolution for GDM

Heterogeneous

Timeline – The Past



Gas Sensing Technologies

In-Situ vs. Open-Path

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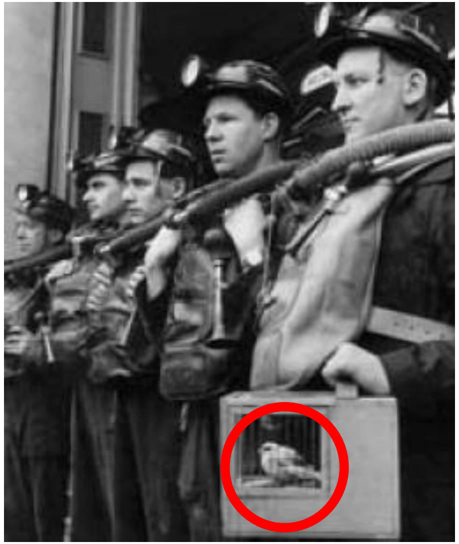
Gas Sensor Technology:
A Quick Overview

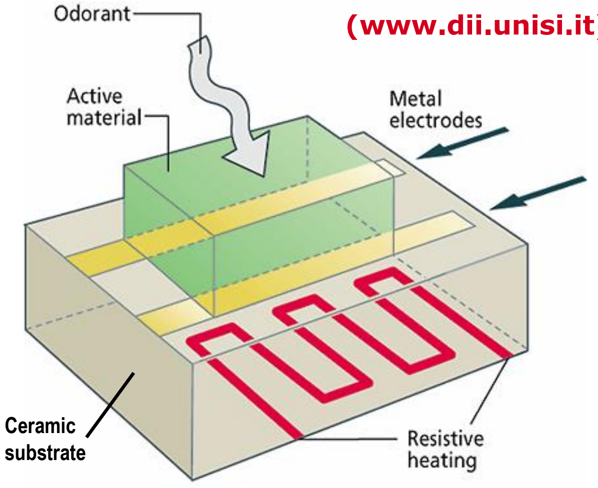
- **Canaries** were once regularly used in coal mining as an early warning system (from 1911 until **1986**)
  - » stopped singing and eventually die in the presence of gas
- **State-of-the-art** gas sensors technology
  - » catalytic
  - » electrochemical cell
  - » quartz crystal microbalances (QCM)
  - » *metal oxide (MOX) semiconductor*
  - » conductive polymer
  - » infrared (point / open path)
- **Analytical equipment**
  - » IR spectroscopy, gas chromatography, and mass spectrometry
    - o too heavy, large, and expensive



[Dräger 2008]

In-Situ Sensing of Gases:
Functional Principle of MOX Gas Sensors

- **Operating temperatures** lie between 300°C and 550°C
- **Working principle:** adsorption of gases modifies conductivity (→ resistance) of a sensing membrane (active material)
  - » presence of reductive gases causes a drop in the resistance of the semiconductor
  - » resistance increases, if the concentration of the target gas is reduced
- **Selectivity** of these sensors is enhanced by
  - » doping the surface of the sensing membrane with different additives
  - » setting different operating temperatures (temperature modulation)
    - ○ oscillation of heater voltage
    - ○ kinetics of adsorption and reaction are altered



(www.dii.unisi.it)

In-Situ Sensing of Gases:
Pros and Cons of MOX Gas Sensors

- **The most widely used gas sensing technology in artificial/mobile robot olfaction**
  - » **advantages** / disadvantages
    - commercially available
    - relatively quick response
    - highly sensitive
    - inexpensive
    - simple electronic interface required
    - usable life-span of three to five years

Figaro 2620 – alcohol sensor

In-Situ Sensing of Gases:
Pros and Cons of MOX Gas Sensors

- **The most widely used gas sensing technology in artificial/mobile robot olfaction**
  - » advantages / **disadvantages**
    - ○ point measurement (not only MOX)
      - → sensor surface is very small (≈ 1 cm^2)
    - ○ calibration is difficult
      - → cross-sensitive to changing environmental conditions
      - → variation between individual sensors
      - → long-term drift
    - ○ poor selectivity
      - → combustion process is not strongly selective to the target gas
    - ○ comparatively high power consumption
      - → due to high operating temperatures
    - ○ sensors have to be heated before operation
    - ○ slow sensor recovery

Figaro 2620 – alcohol sensor

Challenges with Drones

- **Problem:** rotor movement of UAV induce disturbances
  - » dilution and dispersion of the surrounding gas-air mixture
  - » problematic for punctual gas sources creating small plumes

- **Approach:**
  - → replace in-situ sensors with open-path gas sensors
  - → reconstruction of gas distribution using integral measurements

Remote Sensing of Gases:
Optical Sensor Systems

- **General working principle:** modulation of light properties is measured
  - » e.g., absorption in a specific frequency range

Helicopter-based Differential Absorption LIDAR (DIAL, Adlares GmbH)

Remote Methane Leak Detector (RMLD, Sewerin)

Differential Optical Absorption Spectroscopy (DOAS, Crowcon SafEye 700)

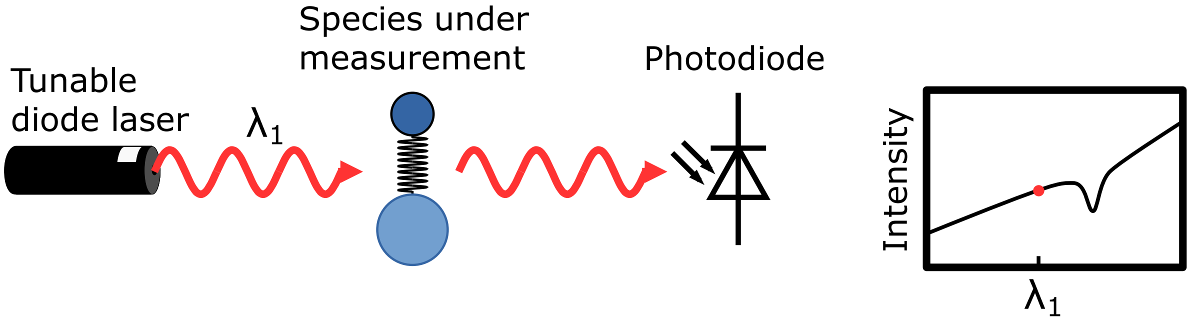
Remote Sensing of Gases:
TGE LaserMethane mini-G (SA3C50A)

- **Exclusively developed for detecting methane gas**
  → no cross-sensitivity to other hydrocarbons*

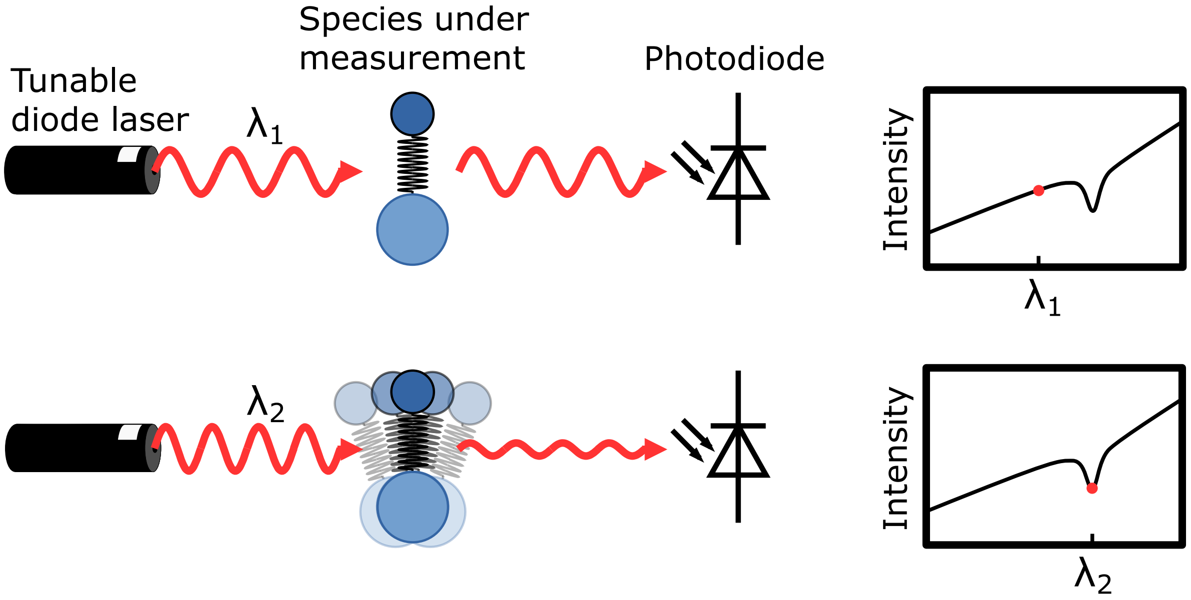
- **Measurement principle**
  » Based on Tunable Diode Laser Absorption Spectroscopy **(TDLAS)**

- **Technical details**
  » Weight ca. 530 g (incl. battery)
  » Measurable Distance: 0 to 30 m (without reflectors)
  » Measurement range: 1 to 50,000 ppm·m
  » Measuring speed: 0.1 s
  » Measurable accuracy: ±10%

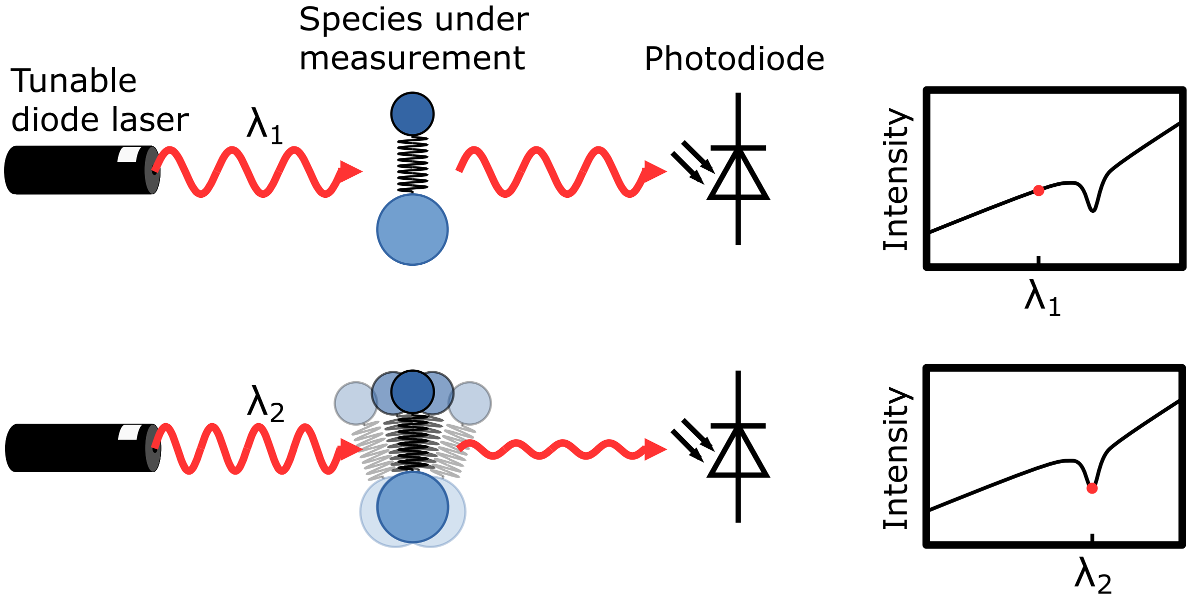
Remote Sensing of Gases:
Measurement Principle of the LMm-G



Remote Sensing of Gases:
Measurement Principle of the LMm-G



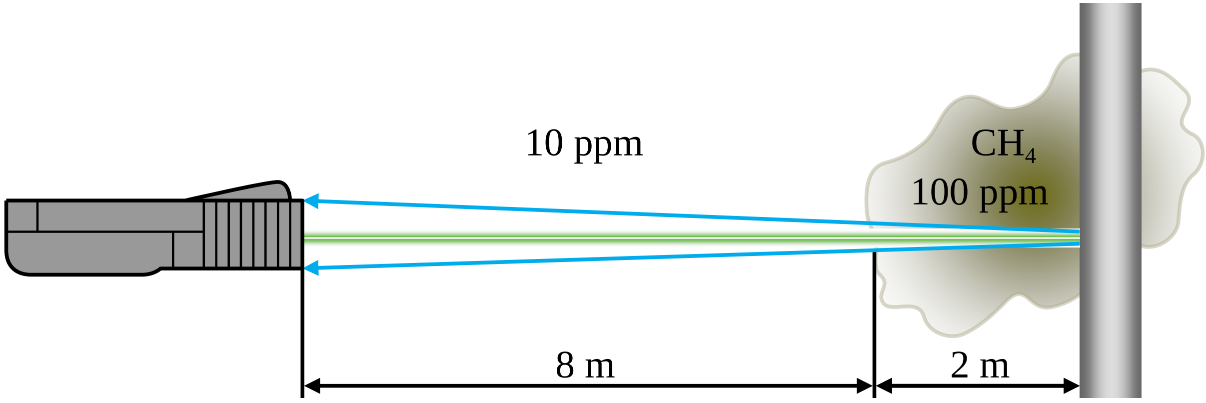
Remote Sensing of Gases:
Measurement Principle of the LMm-G



→ Methane concentration is determined using the difference from emitted and received laser beam (**Lambert-Beer** law)

Remote Sensing of Gases:
Measurement Specifications of the LMm-G

- **TDLAS** gives integral measurements:



Measurement: 280 ppm·m

Remote Sensing of Gases:
Measurement Specifications of the LMm-G

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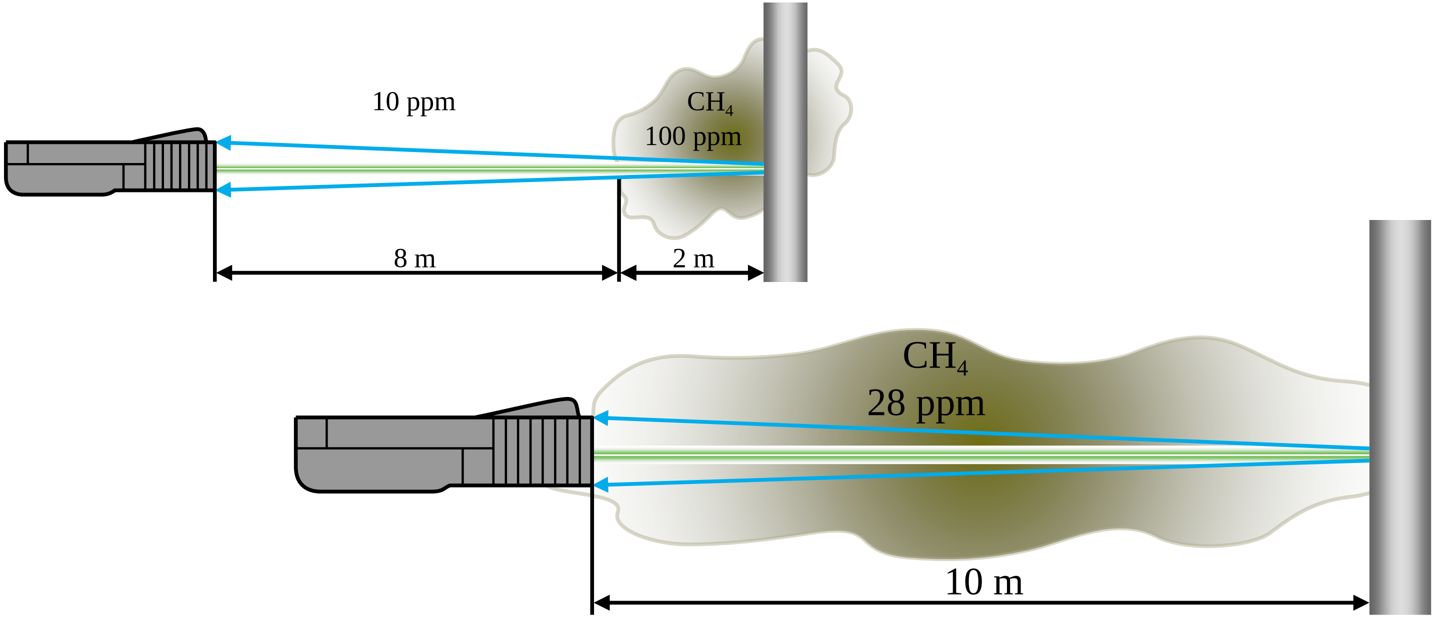
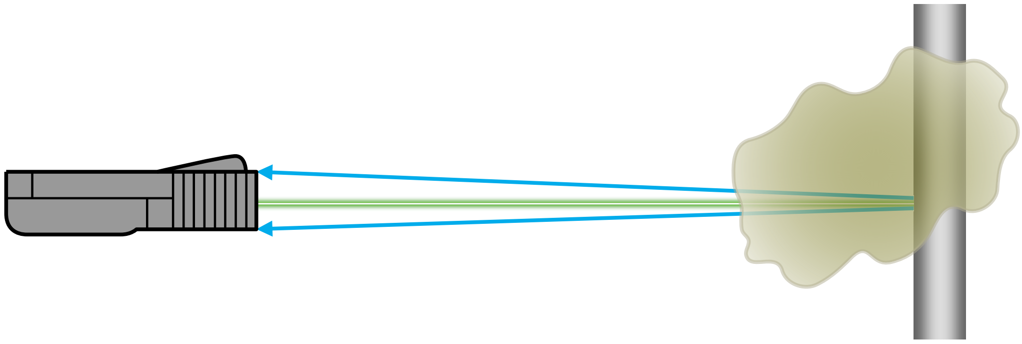


Measurement: 280 ppm·m

Remote Sensing of Gases:
Measurement Specifications of the LMm-G

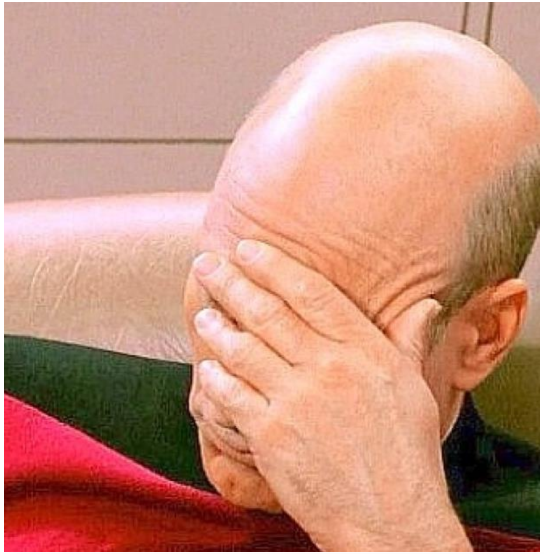
- **Measurement laser**
  - class 1 laser (no eye protection required)
  - wavelength: 1653 nm
  - "beam extension": ≤ 8.5 mrad **(measured 6 mrad)**
  - conical beam, theoretical spot diameter:
    - at 10 m distance: 19 cm
    - at 30 m distance: 56 cm



Remote Sensing of Gases:
Laser Specifications of the LMm-G

- **Measurement laser**
  - class 1 laser (no eye protection required)
  - wavelength: 1653 nm
  - "beam extension": ≤ 8.5 mrad
  - conical beam, theoretical spot diameter:
    - at 10 m distance: 19 cm
    - at 30 m distance: 56 cm

- **Guide laser**
  - class 3R laser **(eye injury hazard)**
  - wavelength: 532 nm
  - "beam extension": ≤ 1.5 mrad



Remote Sensing of Gases:
Pros and Cons of TDLAS Gas Sensors

- **Advantages**
  - » direct physical measurement
    - → real spectroscopy
  - » fast response, instantaneous measurements (0.1 s)
  - » high selectivity and no cross-sensitivity due to
    - → narrow band, tunable laser source
    - → selection of optimal absorption lines
  - » highly sensitive
  - » theoretically no calibration (gas) needed
    - → built-in standard gas cell allows auto-calibration and self-check
    - → can be repeated during operation in case of wavelength stability errors

Remote Sensing of Gases:
Pros and Cons of TDLAS Gas Sensors

- **Disadvantages**
  - » integral measurement
    - → increased complexity for estimating gas distribution maps
  - » conical beam
    - → always a volume is measured
    - → relatively large spot diameter
  - » no range information available
  - » performance and accuracy of the sensor is limited
    - → especially in the case of small absorption and
    - → by reflections and scattering effects
  - » very expensive (~15 k€)

Background

Computed Tomography of Gases

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Medical imaging:
Computed Tomography (CT)

- **Medical imaging technique** focuses on visualizing internal (body) structures hidden by skin and bones

- **CT** was developed in the 1970s and has proven to be a versatile imaging technique for
  - medical diagnosis to detect diseases
  - non-destructive testing to detect structures and defects in specimens

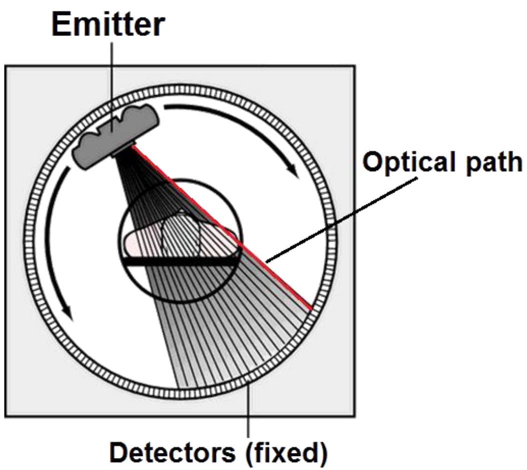
Modern CT scanner

Computed Tomography (CT):
CT Scanners

… **consist of**
- » a rotating X-ray tube (emitter) and
- » a row of (fixed) detectors

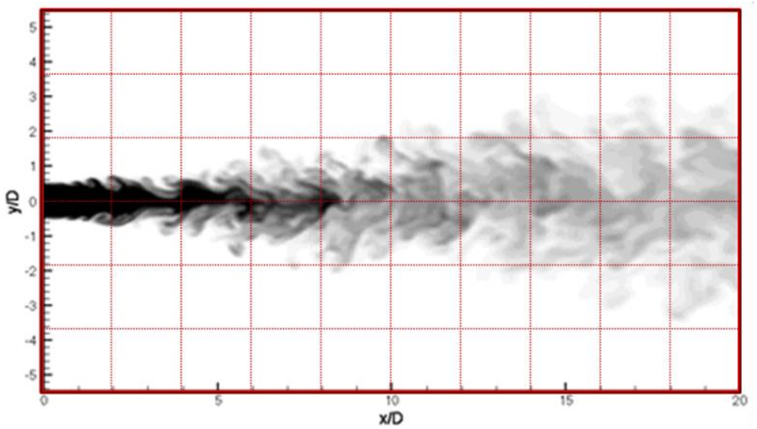
… **measure the attenuation of X-rays by various tissues in the (static) body**
- » pre-defined positions of emitter and detectors
- » up to 10,000 optical paths

- **Multiple X-ray measurements taken from different angles are then processed by**
  - » tomographic reconstruction algorithms
    to produce tomographic (cross-sectional) images (virtual "slices") of a body



Computed Tomography of Gases (CTG)

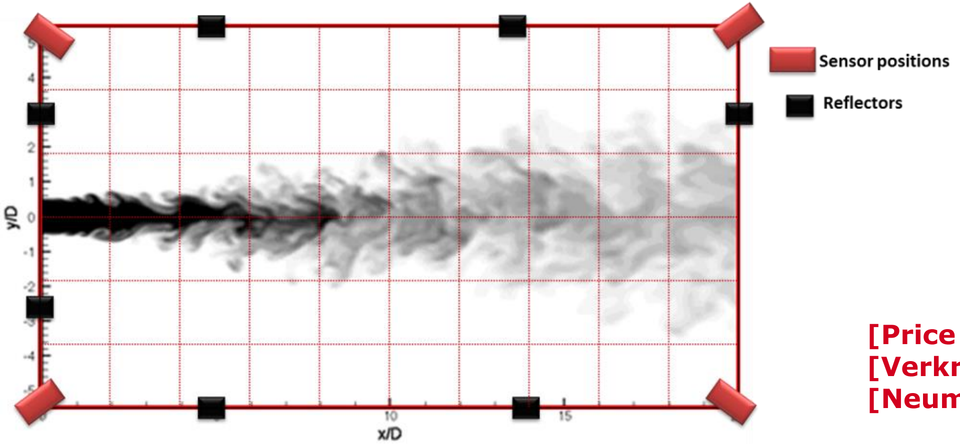
- **Goal:** reconstruction of a **very dynamic** phenomenon from integral concentration measurements
- Exploration area is discretized in a lattice of n cells
  - » **assumption:** each cell has a constant concentration value



[Price et al., Atmospheric Environment 2001]
[Verkruysse and Todd, Environ. Sci. Technol. 2005]
[Neumann et al., IEEE Sensors Journal 2016]

Computed Tomography of Gases (CTG)
Early Work

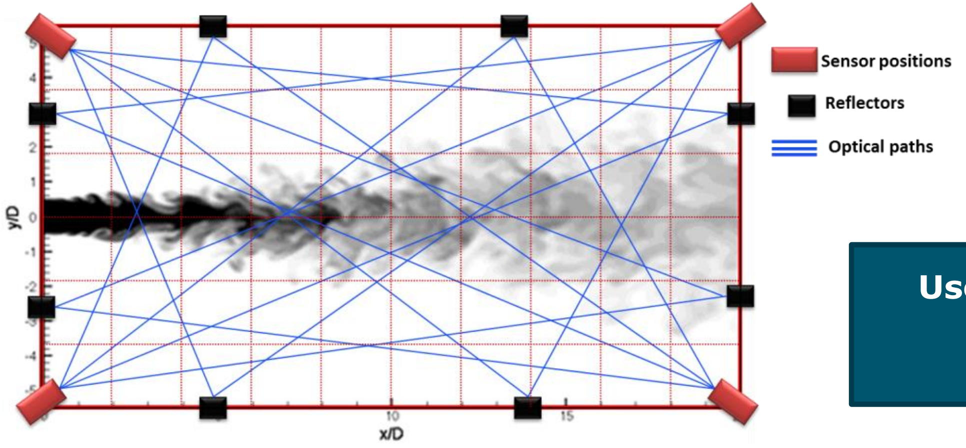
- **Goal:** reconstruction of a **very dynamic** phenomenon from integral concentration measurements
- Sensors are placed in a **pre-defined, fixed** measurement geometry / configuration



[Price et al., Atmospheric Environment 2001]
[Verkruysse and Todd, Environ. Sci. Technol. 2005]
[Neumann et al., IEEE Sensors Journal 2016]

Computed Tomography of Gases (CTG)
Early Work

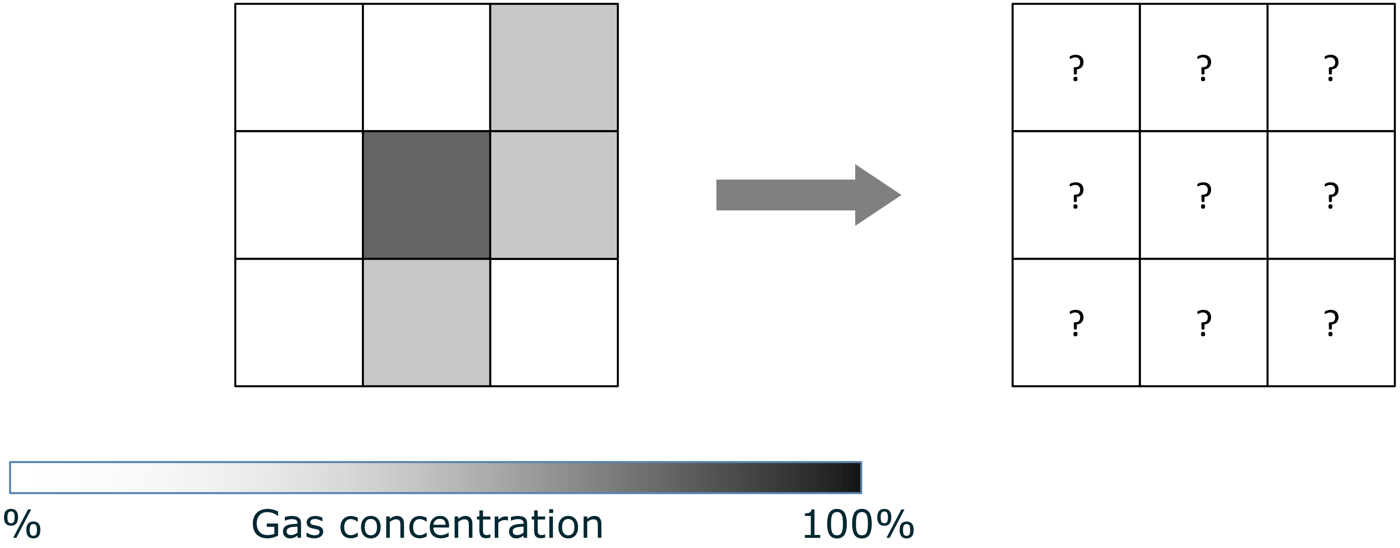
- **Goal:** reconstruction of a **very dynamic** phenomenon from integral concentration measurements
- Sensors are placed in a **pre-defined, fixed** measurement geometry → **number of optical paths rarely exceeds 100**



Use acquired integral measurements to determine concentration values at each cell

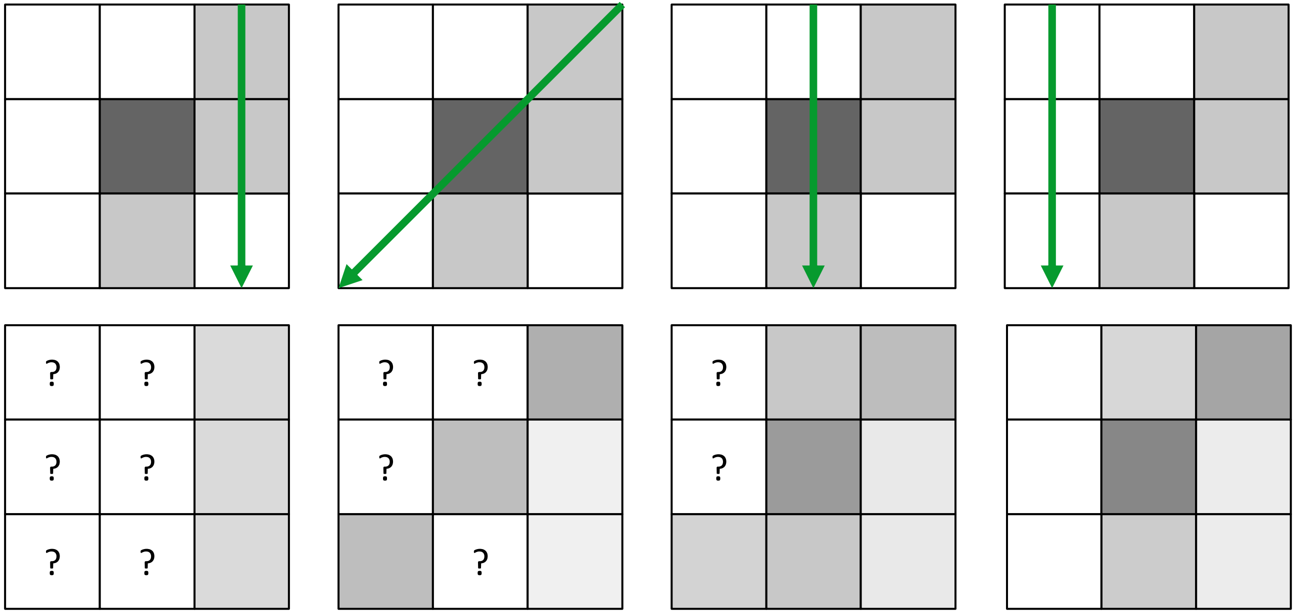
Computed Tomography of Gases (CTG):
General Working Principle

- Reconstruction of a gas plume intersection:



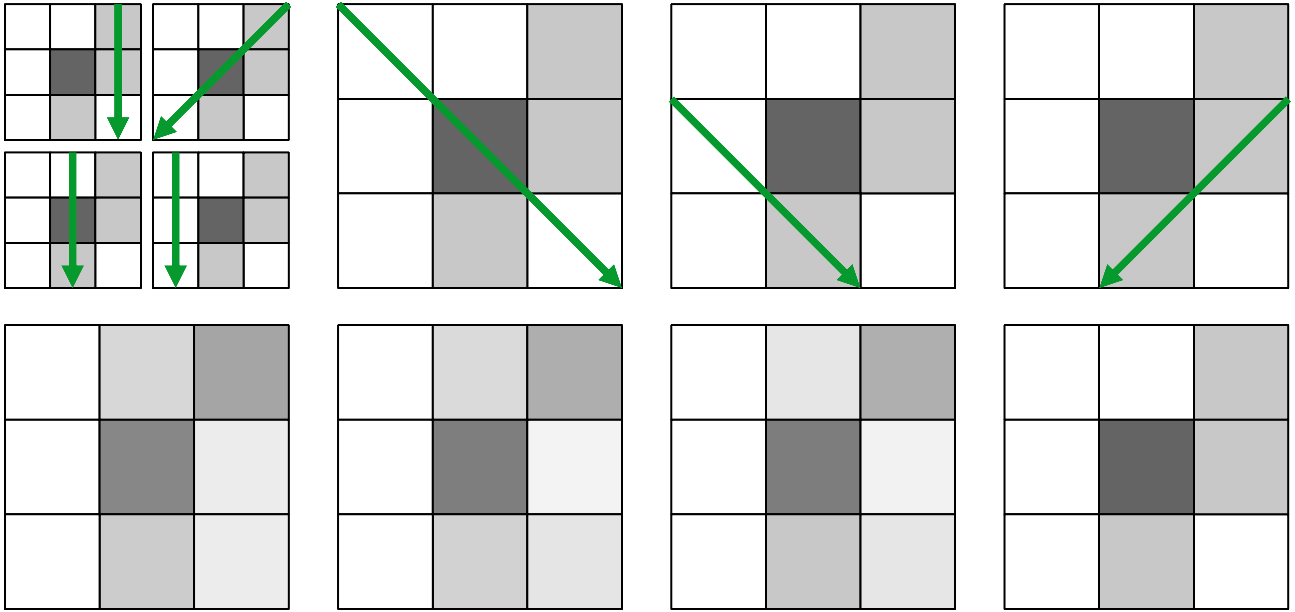
Computed Tomography of Gases (CTG):
General Working Principle

- Reconstruction of a gas plume intersection:



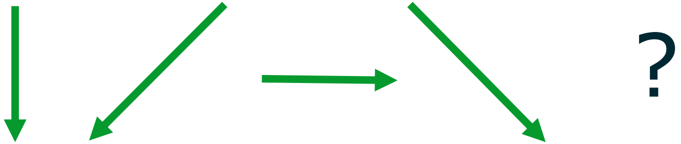
Computed Tomography of Gases (CTG):
General Working Principle

- Reconstruction of a gas plume intersection:



Computed Tomography of Gases (CTG):
General Working Principle

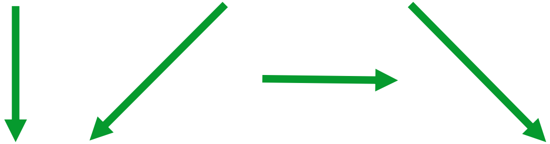
- How to place the measurement rays?



- How good is the result of the reconstruction?

Computed Tomography of Gases (CTG):
General Working Principle

- How to place the measurement rays?



?

- How good is the result of the reconstruction?

Robot Assisted Gas Tomography (RAGT)

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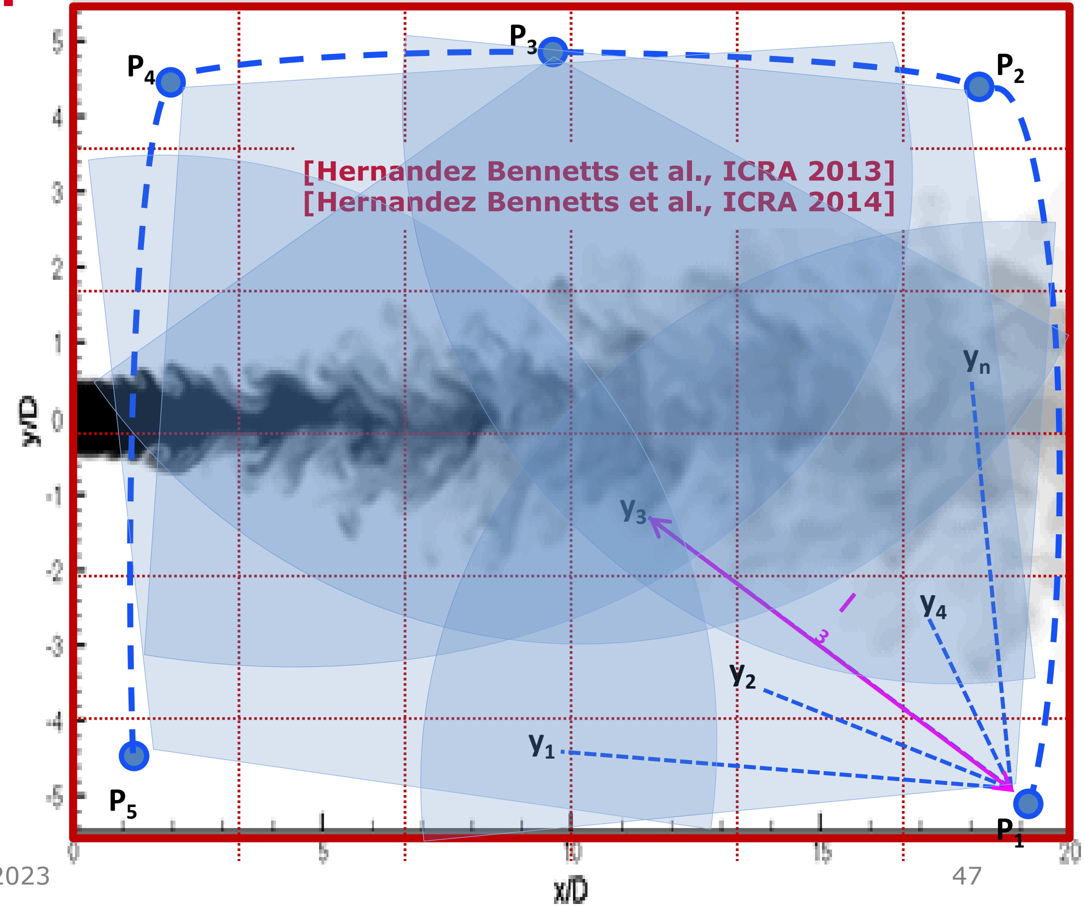
Robot Assisted Gas Tomography
Reconstruction Algorithm

Goal: Reconstruct a very dynamic phenomenon from integral concentration measurements

Task

- move robot to different locations and repeat scanning
- perform reconstruction and estimate
  - gas source location(s)
  - emission rates
  - …



Robot Assisted Gas Tomography
Reconstruction Algorithm

- Reconstruction of local concentrations

[Hernandez Bennetts et al., ICRA 2013]
[Hernandez Bennetts et al., ICRA 2014]

Robot Assisted Gas Tomography
Reconstruction Algorithm

- **Reconstruction of local concentrations**
  - » discretize area
  - » assume constant concentration at each cell

[Hernandez Bennetts et al., ICRA 2013]
[Hernandez Bennetts et al., ICRA 2014]

Robot Assisted Gas Tomography
Reconstruction Algorithm

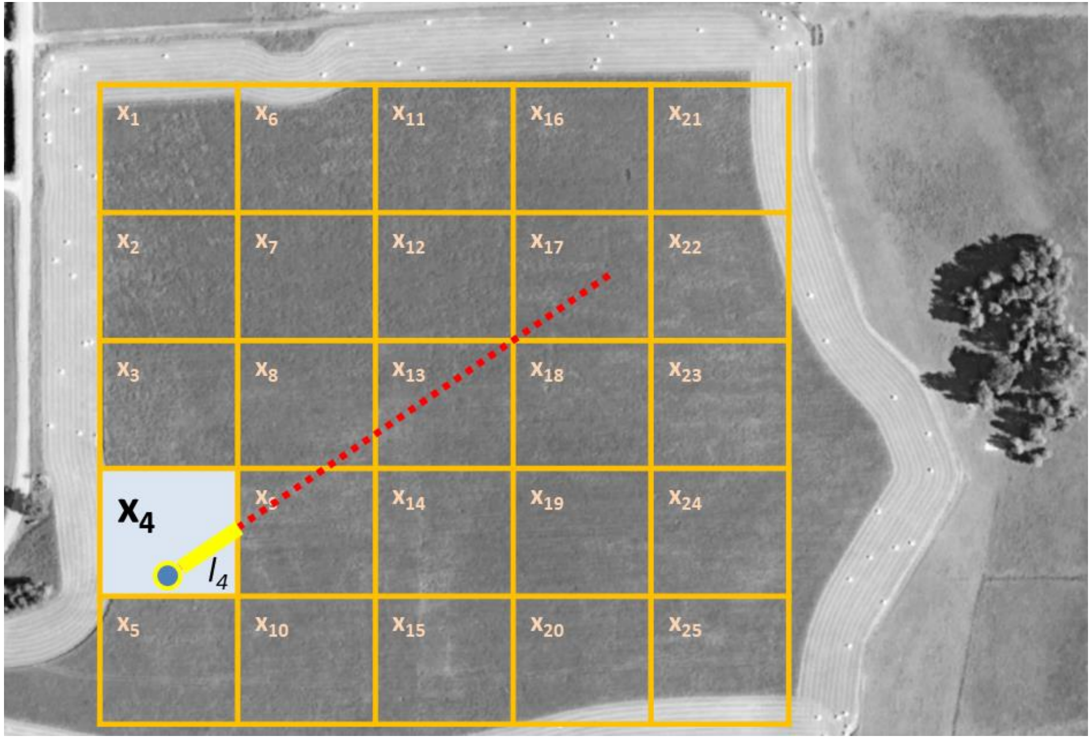
- **Reconstruction of local concentrations**
  - » line model of integral measurements

[Hernandez Bennetts et al., ICRA 2013]
[Hernandez Bennetts et al., ICRA 2014]

Robot Assisted Gas Tomography
Reconstruction Algorithm

- **Reconstruction of local concentrations**
  - line model of integral measurements

$y = x_4 l_4$

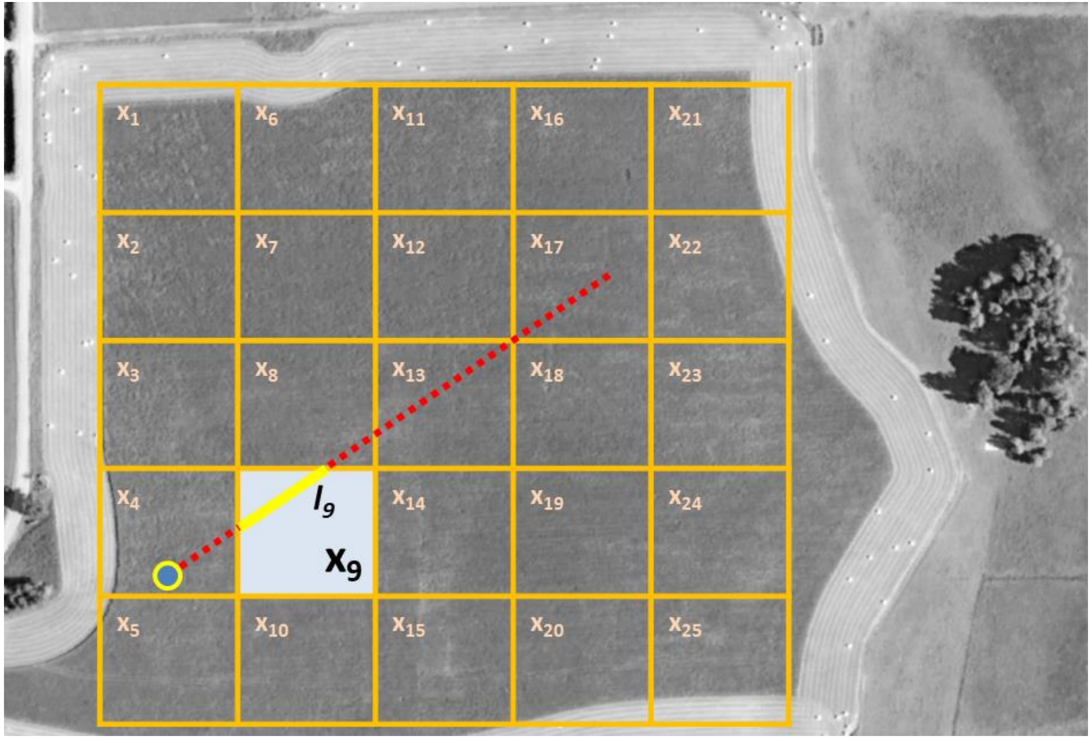


[Hernandez Bennetts et al., ICRA 2013]
[Hernandez Bennetts et al., ICRA 2014]

Robot Assisted Gas Tomography
Reconstruction Algorithm

- **Reconstruction of local concentrations**
  - » line model of integral measurements

$$y = x_4 l_4 + \boldsymbol{x_9 l_9}$$

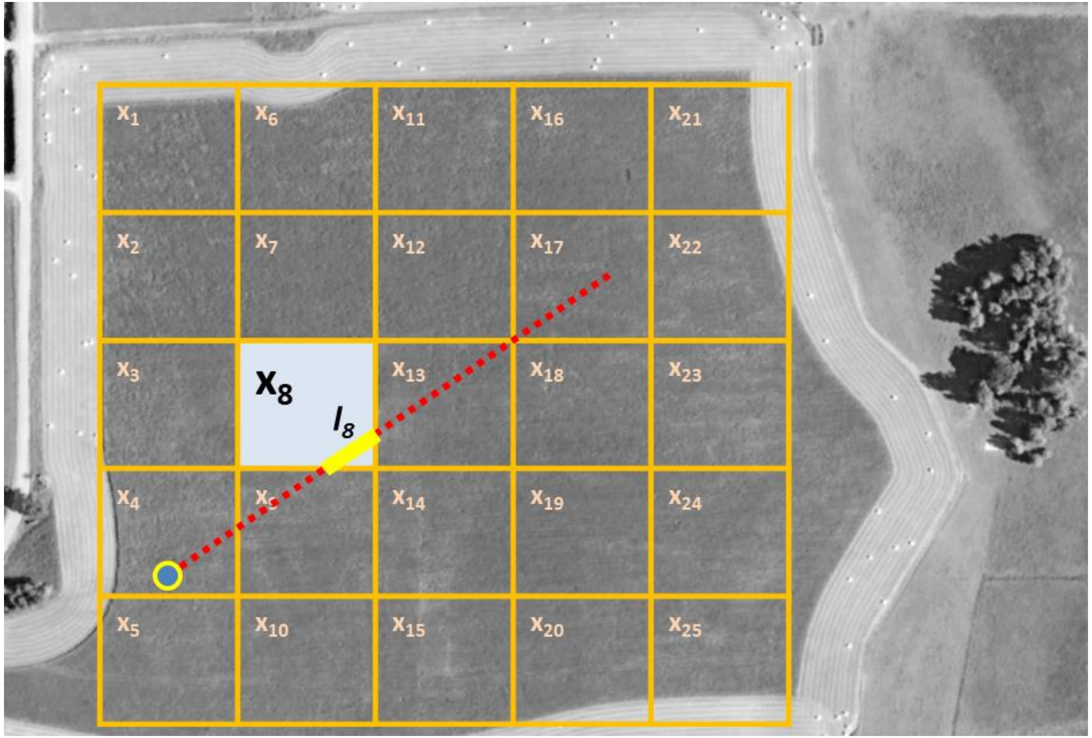


[Hernandez Bennetts et al., ICRA 2013]
[Hernandez Bennetts et al., ICRA 2014]

Robot Assisted Gas Tomography
Reconstruction Algorithm

- **Reconstruction of local concentrations**
  - » line model of integral measurements

$$y = x_4 l_4 + x_9 l_9 + \boldsymbol{x_8 l_8}$$

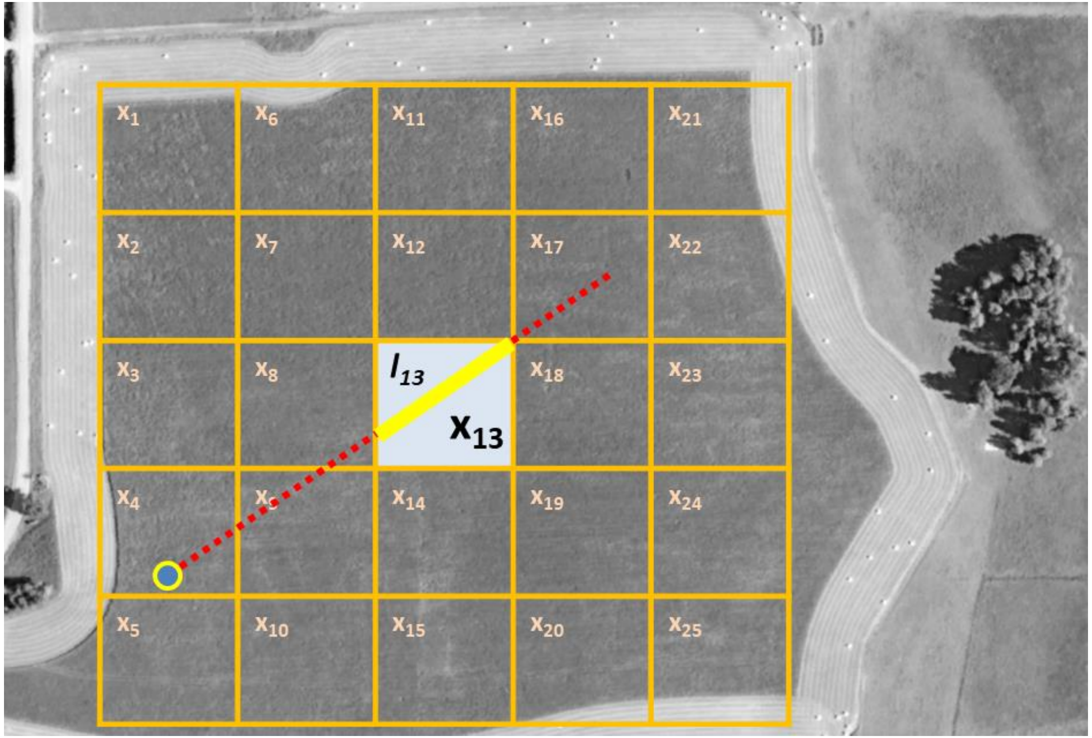


[Hernandez Bennetts et al., ICRA 2013]
[Hernandez Bennetts et al., ICRA 2014]

Robot Assisted Gas Tomography
Reconstruction Algorithm

- **Reconstruction of local concentrations**
  - » line model of integral measurements

$$y = x_4 l_4 + x_9 l_9 + x_8 l_8 + \mathbf{x_{13} l_{13}}$$

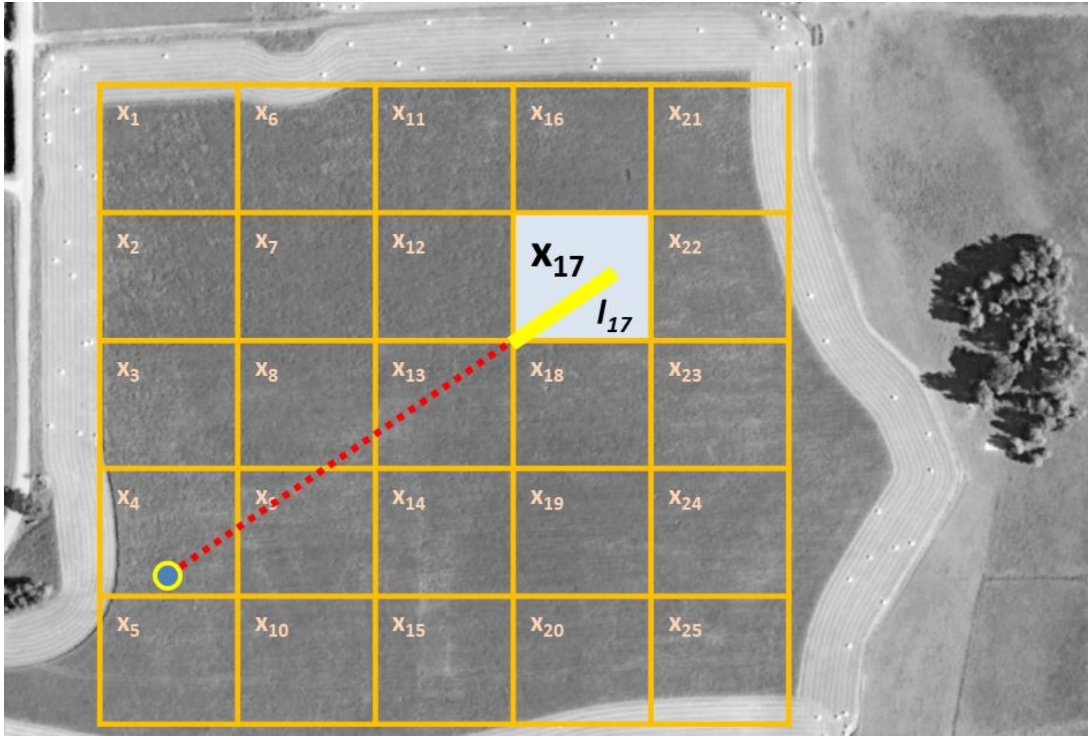


[Hernandez Bennetts et al., ICRA 2013]
[Hernandez Bennetts et al., ICRA 2014]

Robot Assisted Gas Tomography
Reconstruction Algorithm

- **Reconstruction of local concentrations**
  - » line model of integral measurements

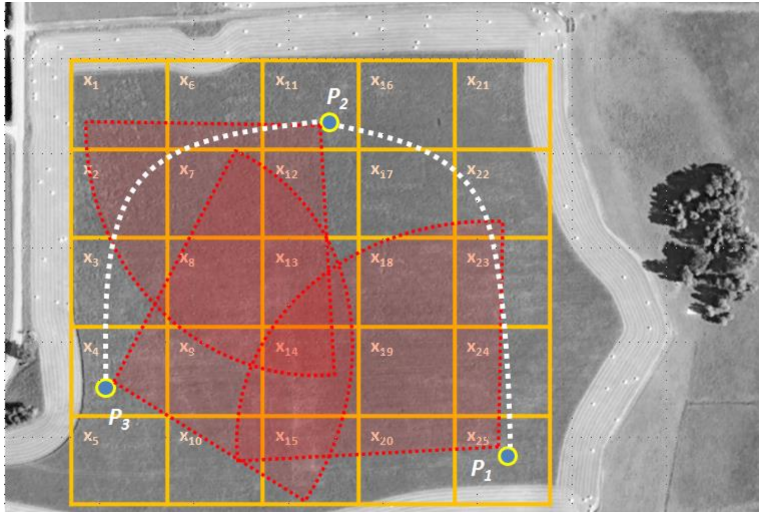
$$y = x_4 l_4 + x_9 l_9 + x_8 l_8 + x_{13} l_{13} + \boldsymbol{x_{17} l_{17}} + \varepsilon$$



[Hernandez Bennetts et al., ICRA 2013]
[Hernandez Bennetts et al., ICRA 2014]

Robot Assisted Gas Tomography
Reconstruction Algorithm

- **Approach: least squares formulation**
  - » give best explanation x for the given integral measurements y
  - » tend to be 0, if no information is available



measurements

path segments

Dataset → $\boldsymbol{y} = \boldsymbol{L}\boldsymbol{x} + \epsilon \mathbf{1}$

local concentrations

Likelihood of N measurements (assuming Gaussian noise):

$$p(\boldsymbol{y}|\boldsymbol{x}, \boldsymbol{L}, \beta) = \prod_{n=1}^{N} \mathcal{N}(y_n|\boldsymbol{L}\boldsymbol{x}, \sigma)$$

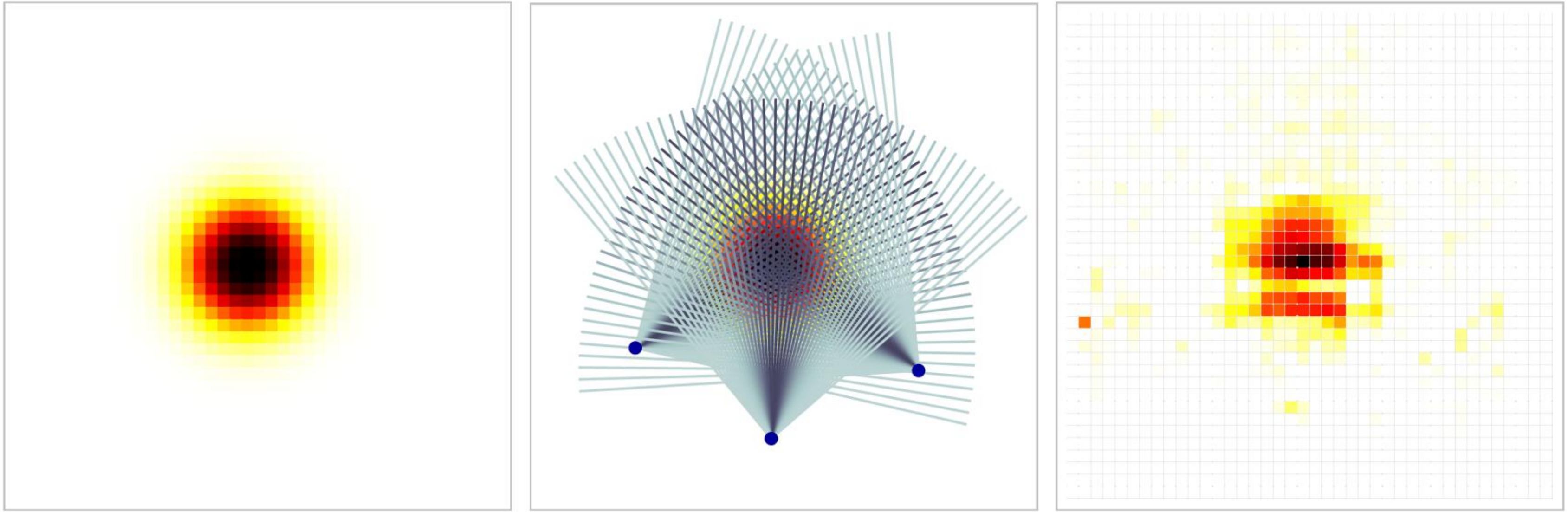
By log-likelihood maximization

$$\begin{aligned} \underset{\boldsymbol{x}}{\text{minimize}} \quad & \|\boldsymbol{L}\boldsymbol{x} - \boldsymbol{y}\|_2^2 + \lambda \|\boldsymbol{x}\|_2^2 \\ \text{subject to} \quad & \boldsymbol{x} \succeq \mathbf{0} \end{aligned}$$

[Hernandez Bennetts et al., ICRA 2013]
[Hernandez Bennetts et al., ICRA 2014]

Robot Assisted Gas Tomography
Example

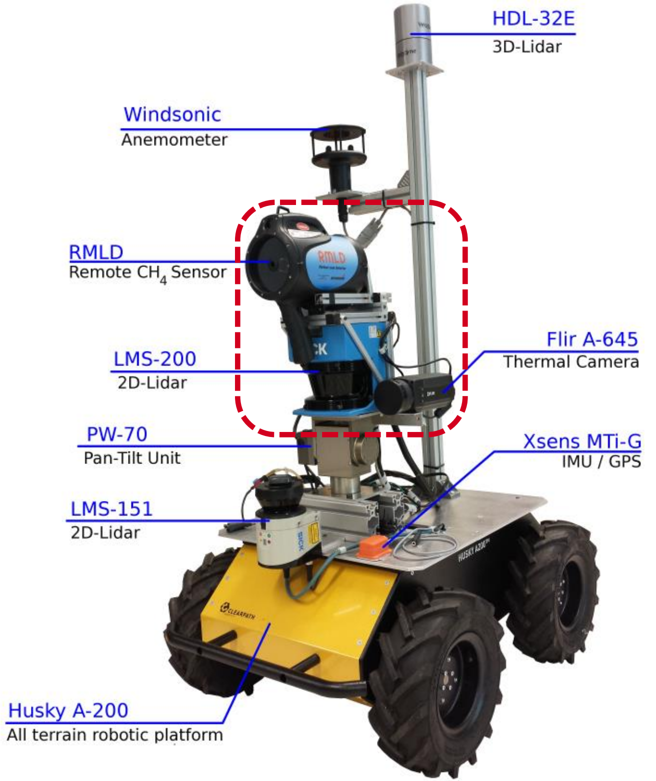
- **Reconstruction of local concentrations**
  - » simulated results from integral measurements taken at 3 measurement locations



[Hernandez Bennetts et al., ICRA 2013]
[Hernandez Bennetts et al., ICRA 2014]

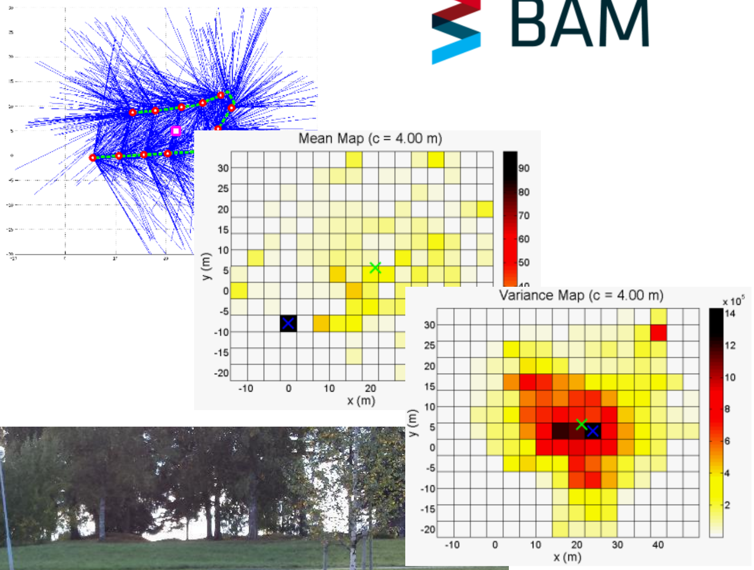
Gasbot from Örebro University
Husky A-200

- **Technical details**
  - » weight: max. 75 kg (incl. payload)
  - » dimensions: 990 x 670 x 390 mm³
  - » max speed: 1 m/s
  - » run time: 3 h
  - » sensors: 2D and 3D lidar, IMU/GPS, anemometer
- **Payload**
  - » pan-tilt unit for orienting the payload
  - » open-path gas detector based on Tunable Diode Laser Absorption Spectroscopy (TDLAS)
  - » 2D lidar for distance measurements
  - » thermal camera

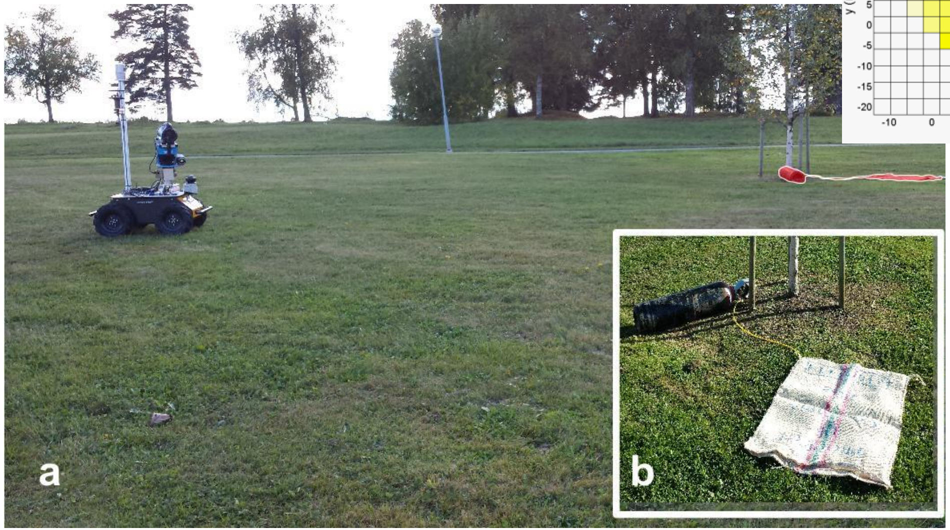


[Hernandez Bennetts et al., IROS 2012]

Robot Assisted Gas Tomography
Experimental (Outdoor) Validation



- **Two different trials**
  - » 154 m^2, 6 positions, 2450 optical paths
  - » 432 m^2, 12 positions, 4514 optical paths
- **Leak simulated with tube ring under permeable mat**
- **How to decide where to sample next?**
  → **Decision support is needed!**



Robot Assisted Gas Tomography

Summary

- **RAGT** can be used to detect CH_4 leaks in realistic environments
- Dynamic, adaptively dense measurement geometries can be generated using RAGT, compared to conventional CTG
- Variance Maximum Estimator (VME) in RAGT reconstructions seems highly correlated with the actual gas source location
- Improvement of the mean maps is needed
- Efficient, informative exploration trajectories need to be determined **(sensor planning)**

BAM

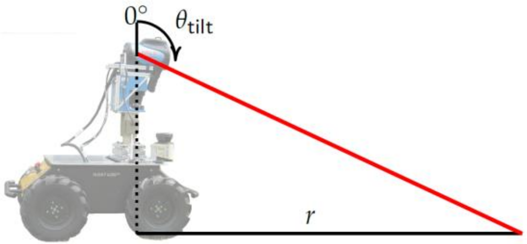
Sensor Planning

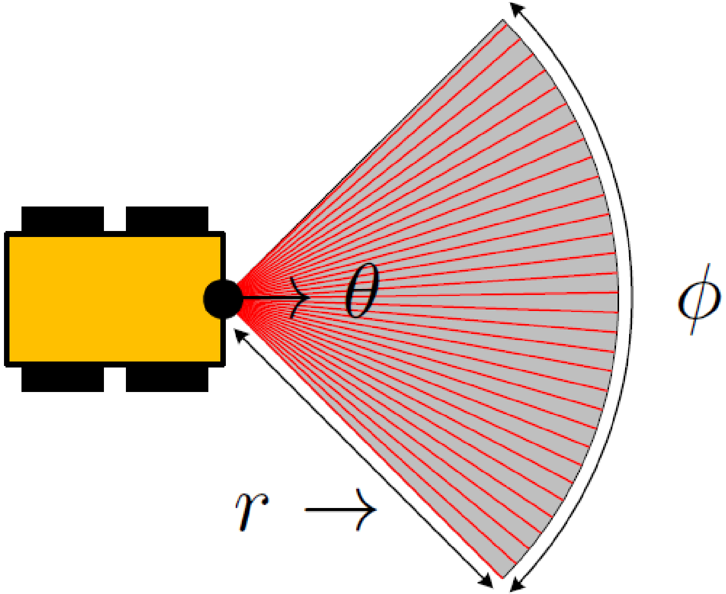
for Robot Assisted Gas Tomography (RAGT)

www.bam.de

Sensor Planning for RAGT

- **Under-sampling** is generally prevalent in environmental monitoring
- **Currently:** sampling often along predefined paths (or plume tracking)
- **Sensor planning:** adaptive sampling with high density is required





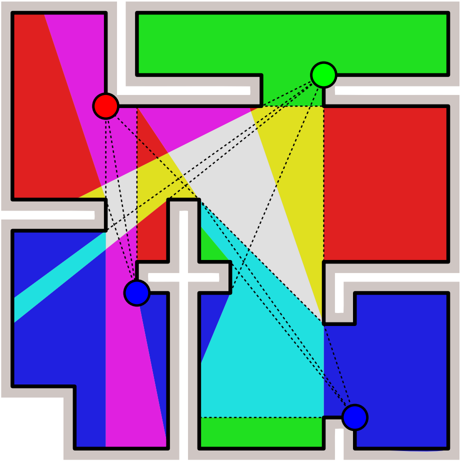
[Arain et al., ICRA 2015]
[Arain et al., Sensors 2015]

Sensor Planning for RAGT

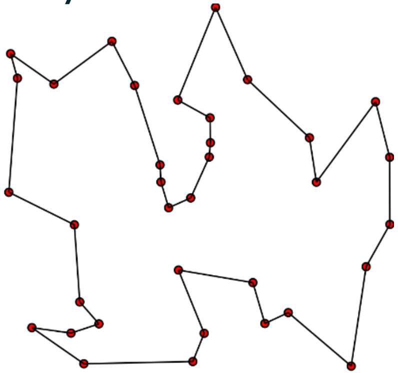
- **Hard to define target function**
  - » sensing coverage + desired cross angles
- Find optimal measurement plan with minimal operational cost → combination of two **NP-hard** problems:
  - » **Art Gallery Problem** for minimal sensing cost
  - » **Travelling Salesman Problem** for minimal traveling path

Quick Summary: Art Gallery Problem and Travelling Salesman Problem

- **Art Gallery Problem:**
  - » "In an art gallery, what is the minimum number of guards who together can observe the whole gallery?"



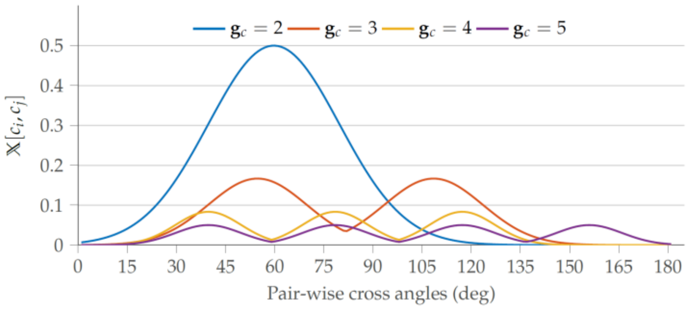
- **Travelling Salesman Problem:**
  - » "Given a list of cities and the distances between each pair of cities, what is the shortest possible route that visits each city exactly once and returns to the origin city?"



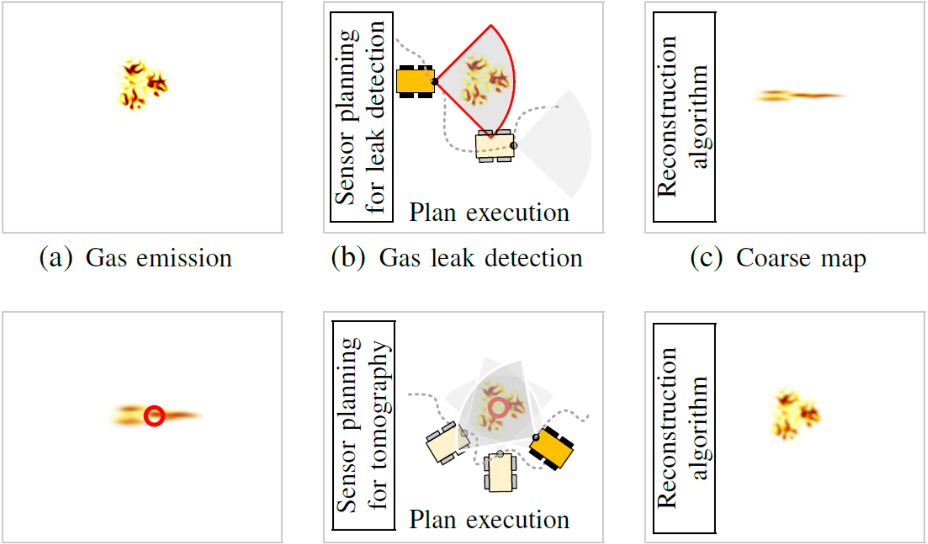
Sensor Planning for RAGT

- **Hard to define target function**
  - sensing coverage + desired cross angles
- Find optimal measurement plan with minimal operational cost → combination of two **NP-hard** problems:
  - **Art Gallery Problem** for minimal sensing cost
  - **Travelling Salesman Problem** for minimal traveling path
- **Near-optimal solution approximated**
  1. find a minimal set of configurations for desired sensing coverage
  2. find the shortest traveling path among selected configurations

Sensor Planning for RAGT
Basic Principle



Sensing geometry	$\mathcal{Q}_{max}$	Optimized pairwise cross angles
$g_c = 2$	0.63	{58.75° }
$g_c = 3$	0.78	{53.75°,107.50° }
$g_c = 4$	0.85	{38.75°,77.50°,116.25° }
$g_c = 5$	0.90	{38.75°,77.50°,116.25°,155.00° }

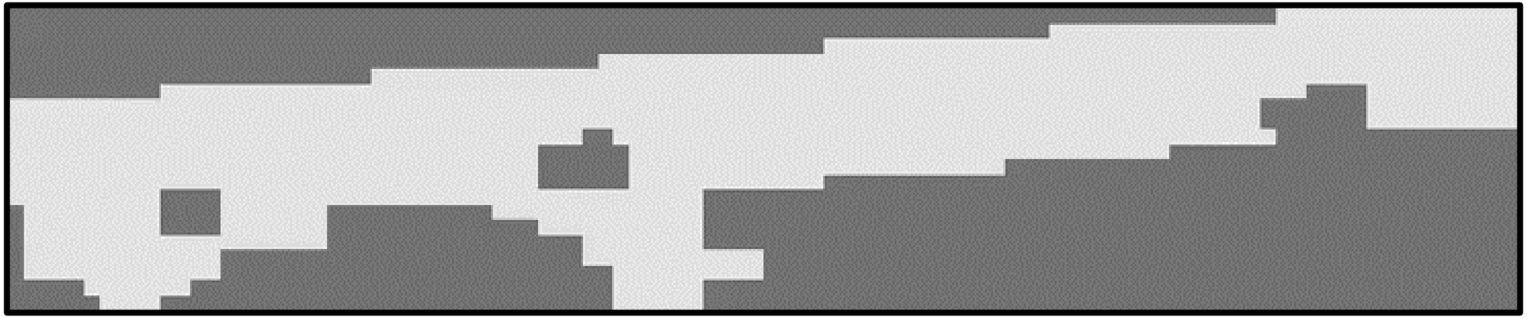


(a) Gas emission
(b) Gas leak detection
(c) Coarse map
(d) Hotspot
(e) Measurements for gas tomography
(f) Reconstruction of the emission

[Arain et al., ICRA 2016]
[Arain et al., ISOEN 2017]

Sensor Planning for RAGT
2t-ARMEx Example (Simulation)

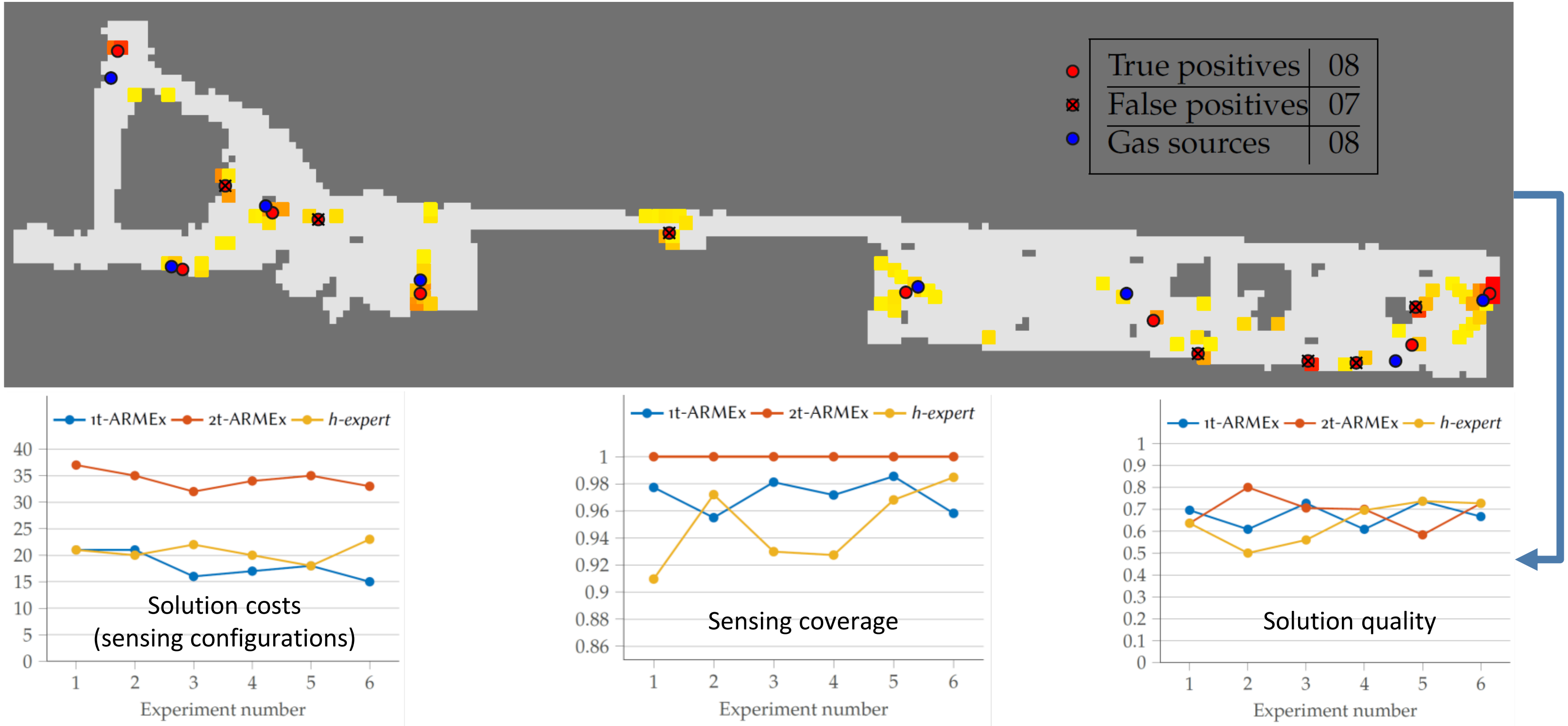
- **One-tour mission strategy of the Autonomous Remote Methane Explorer (1t-ARMEx)**
  - » 1t-ARMEx addresses gas detection and gas distribution mapping in one tour



[Arain et al., ICRA 2016]
[Arain et al., ISOEN 2017]
[Arain et al., IJRR 2021]

Sensor Planning for RAGT

Comparison to Human Expert: Real World Results



[Arain et al., IJRR 2021]

Robotic Platforms

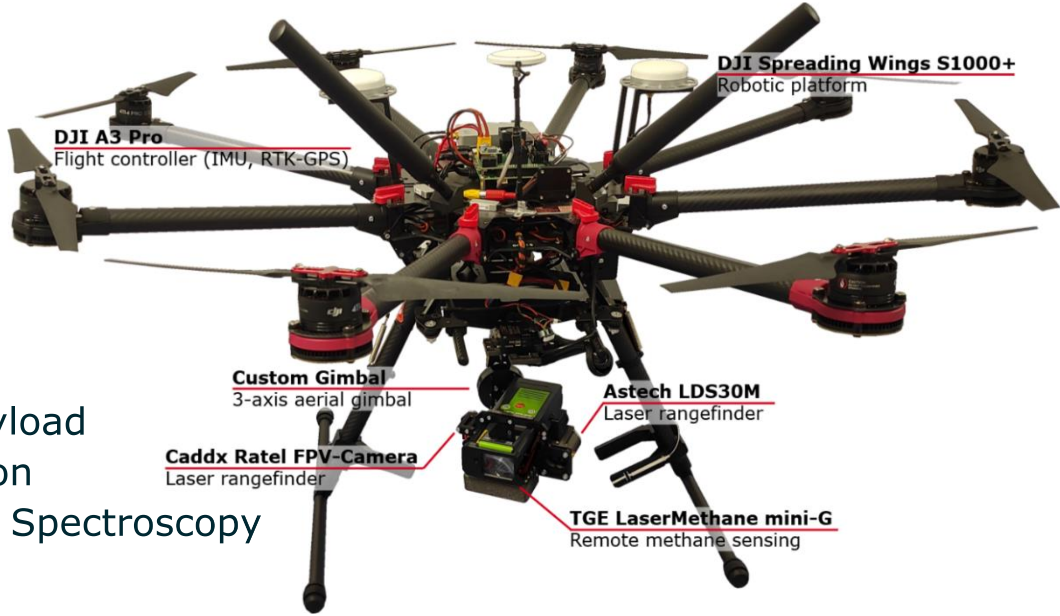
Ground and Aerial Robots

www.bam.de

Flying Remote Sensor
DJI Spreading Wings S1000

- **Technical details**
  - » Takeoff weight: max. 11 kg
  - » Diameter: approx. 1.4 m
  - » Max power consumption: 4 kW
  - » Max flight speed: 15-20 m/s
  - » Flight time: ≤ 15 min

- **Payload**
  - » Custom 3-axis aerial gimbal for stabilizing and orienting the payload
  - » Open-path gas detector based on Tunable Diode Laser Absorption Spectroscopy
  - » Laser range finder
  - » Wide angle camera



[Neumann et al., ICRA 2017]
[Neumann et al., IEEE Sensors 2018]

Flying Remote Sensor
Sensor Integration

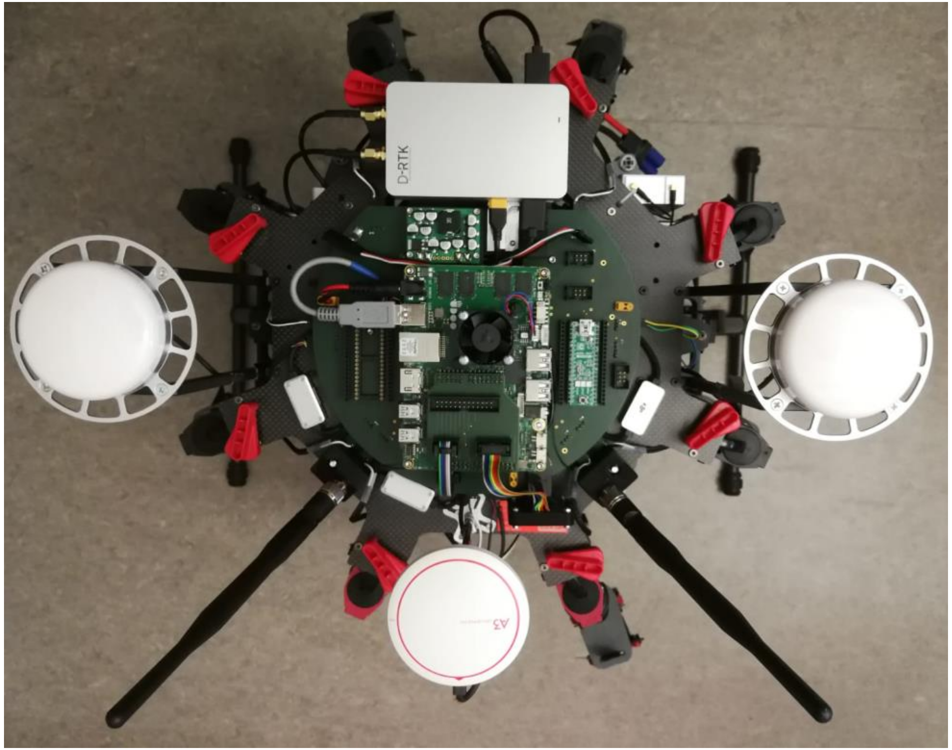
V1.1

V2.0

- Gimbal
- Inertial Measurement Unit (IMU)
- Laser Rangefinder
- Open-Path Gas Detector
- FPV Camera

Flying Remote Sensor
DJI Spreading Wings S1000

- **More hardware**
  - » **DJI D-RTK GNSS** incl. failsafe GPS
  - » **UDOO X86 II ULTRA** maker board incl. an Arduino™ Leonardo-compatible platform
    - ○ M.2 WIFI/BT
    - ○ M.2 SSD



Flying Reflector
DJI Matrice 100

- **Technical details**
  - Takeoff weight: max. 3.4 kg
  - Diameter: approx. 0.7 m
  - Max flight speed: 17-22 m/s
  - Flight time: 20-40 min

- **Payload**
  - DJI Zenmuse X3 camera gimbal
  - DIN A4 cardboard alias the "Reflector"

[Neumann et al., ISOEN 2022]

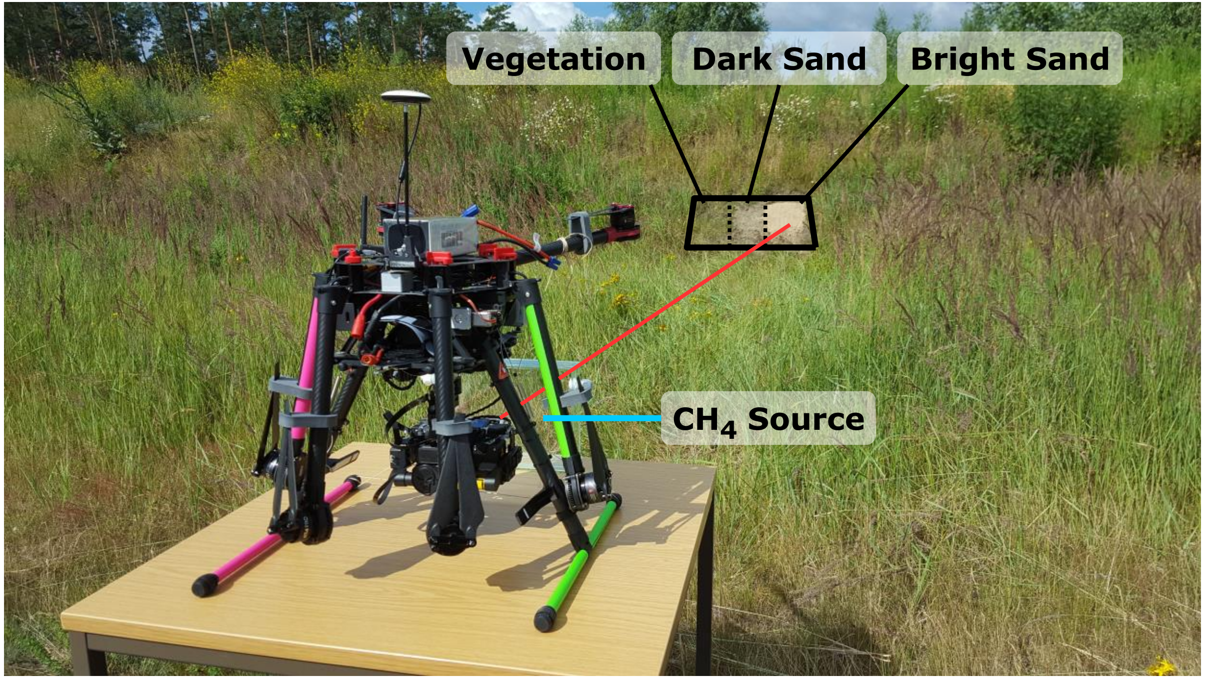
Robotic Platform
Ground Control Station

Field Experiments with Aerial RAGT

Experimental Setup and Results

www.bam.de

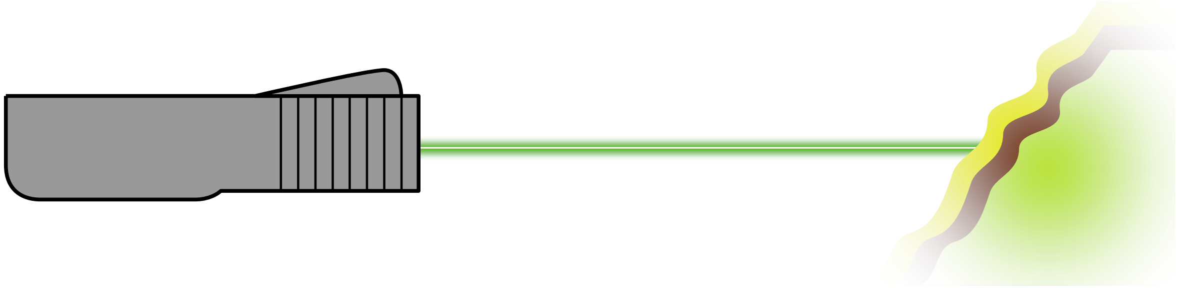
Field Experiment 1:
Gas Sensor Validation



[Neumann et al., ICRA 2017]

Field Experiment 1: Gas Sensor Validation

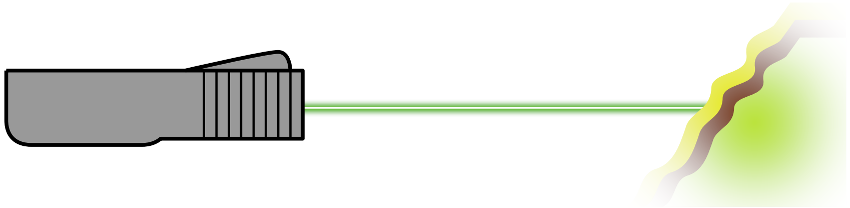
- **Background concentration**

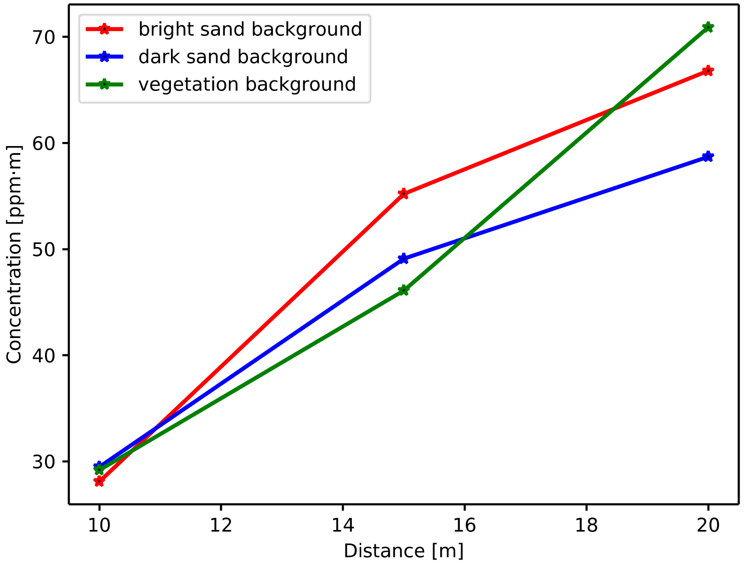


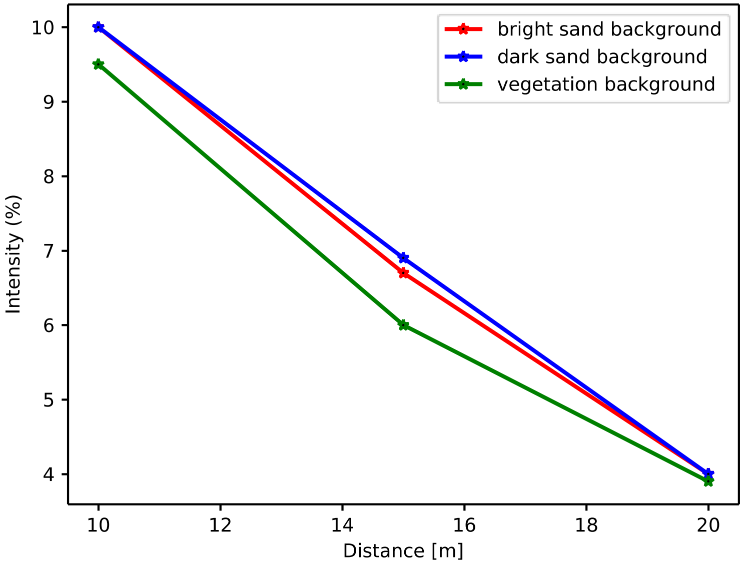
[Neumann et al., ICRA 2017]

Field Experiment 1:
Gas Sensor Validation

- **Background concentration**



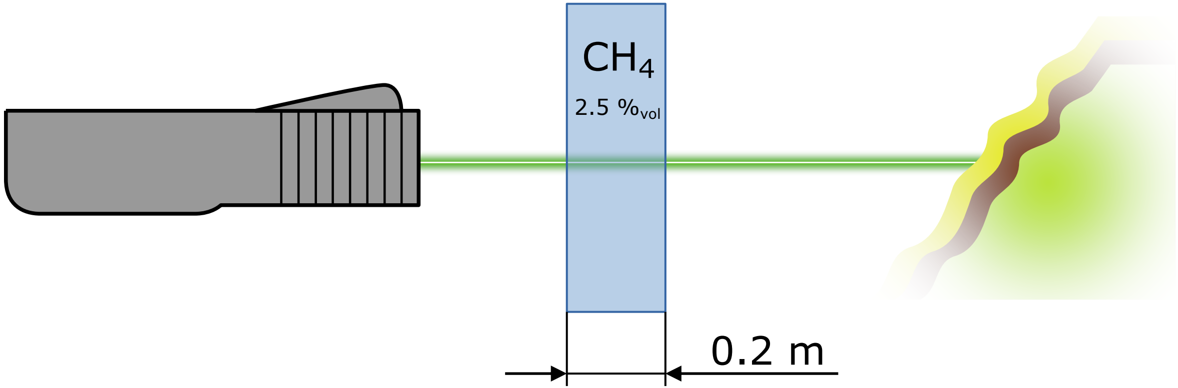




[Neumann et al., ICRA 2017]

Field Experiment 1:
Gas Sensor Validation

- **Gas concentration**

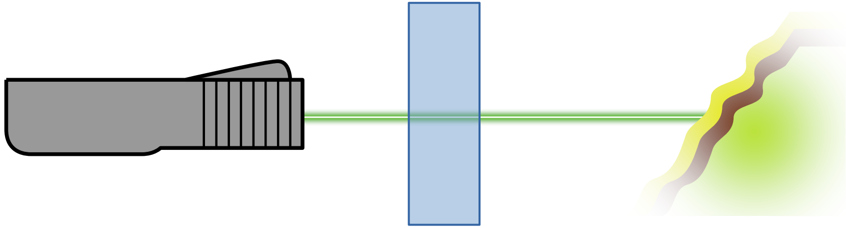


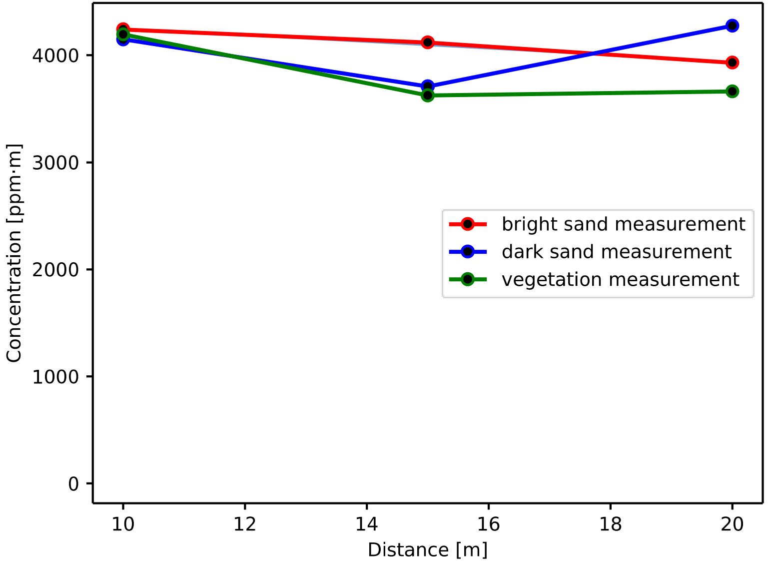
Expected concentration: 5000 ppm·m

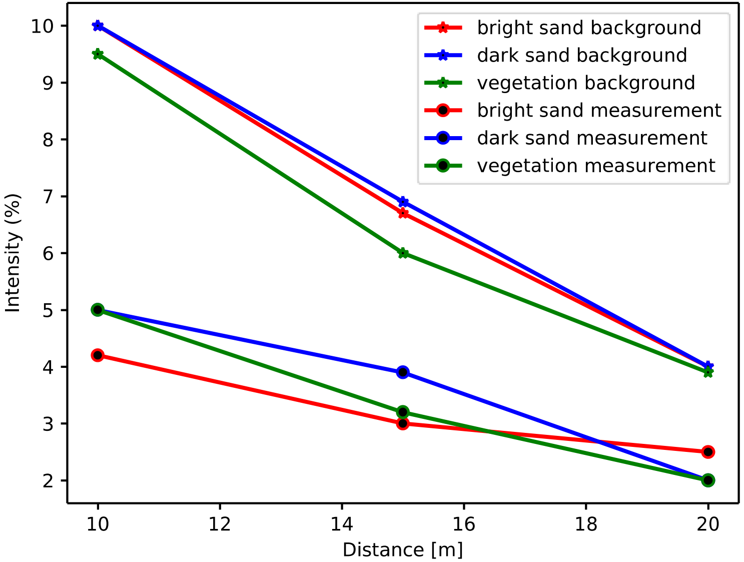
[Neumann et al., ICRA 2017]

Field Experiment 1:
Gas Sensor Validation

- **Gas concentration**



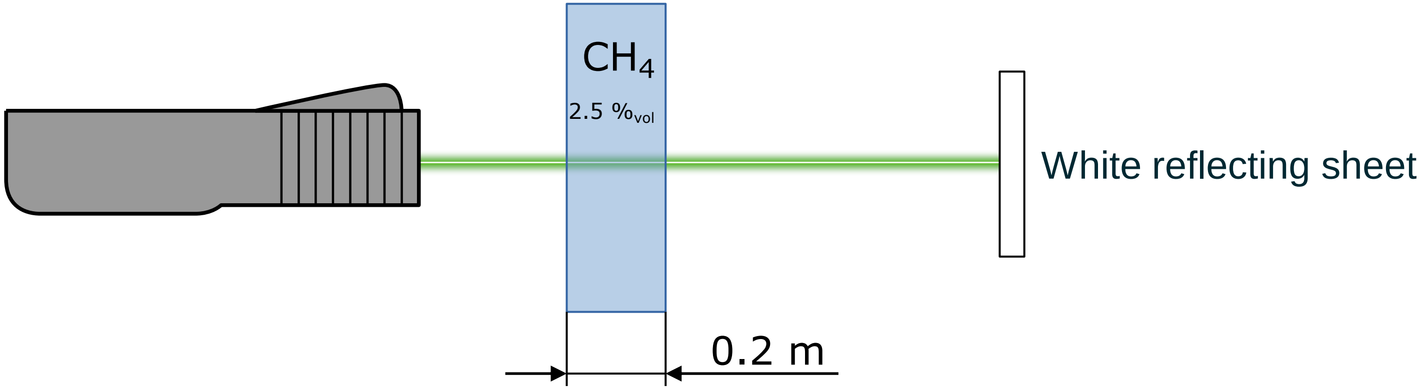




[Neumann et al., ICRA 2017]

Field Experiment 1:
Gas Sensor Validation

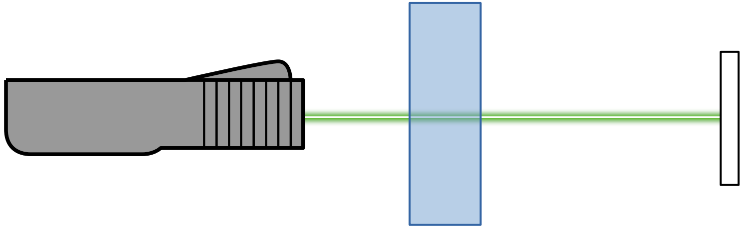
- **Reference measurement**

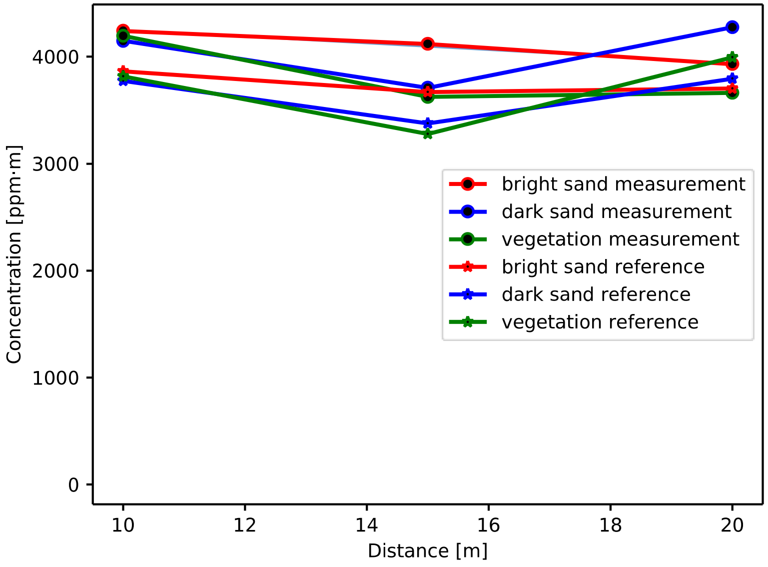


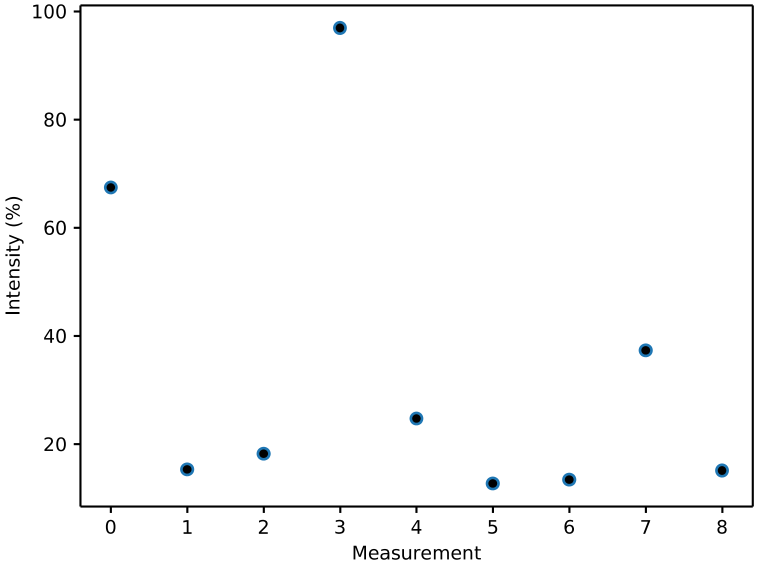
Expected concentration: 5000 ppm·m

Field Experiment 1:
Gas Sensor Validation

- **Reference measurement**

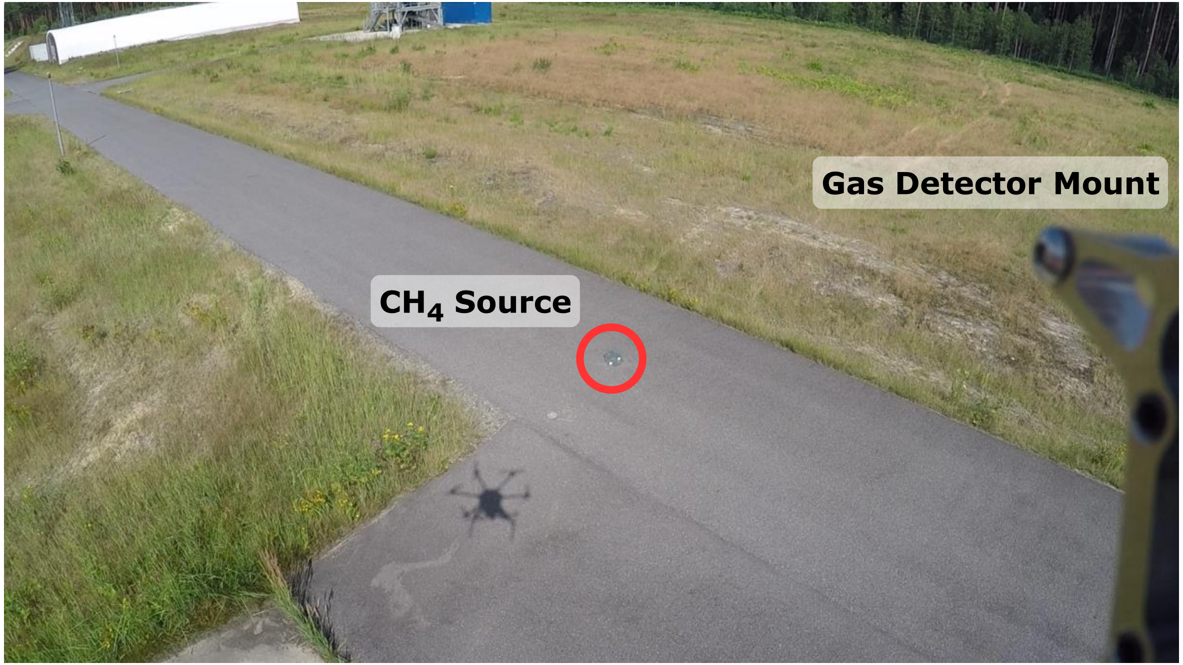






[Neumann et al., ICRA 2017]

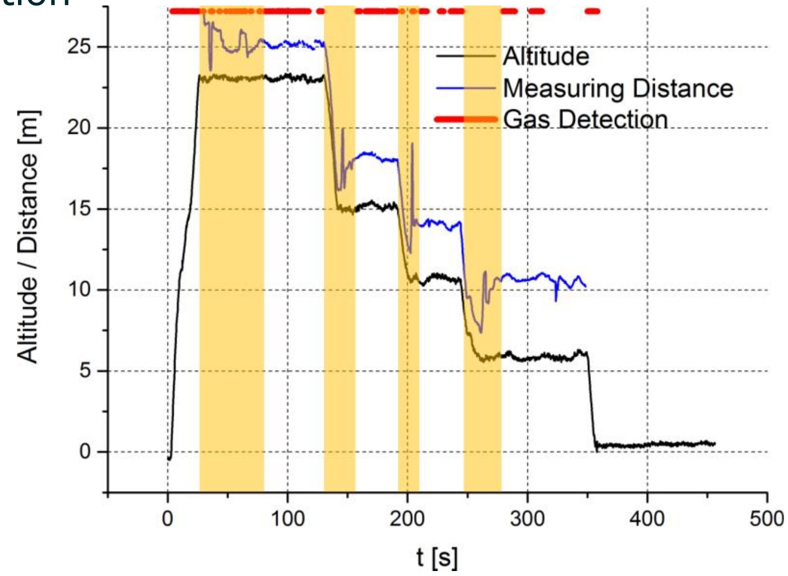
Field Experiment 2:
Manual Gimbal Aiming



[Neumann et al., ICRA 2017]

Field Experiment 2:
Manual Gimbal Aiming

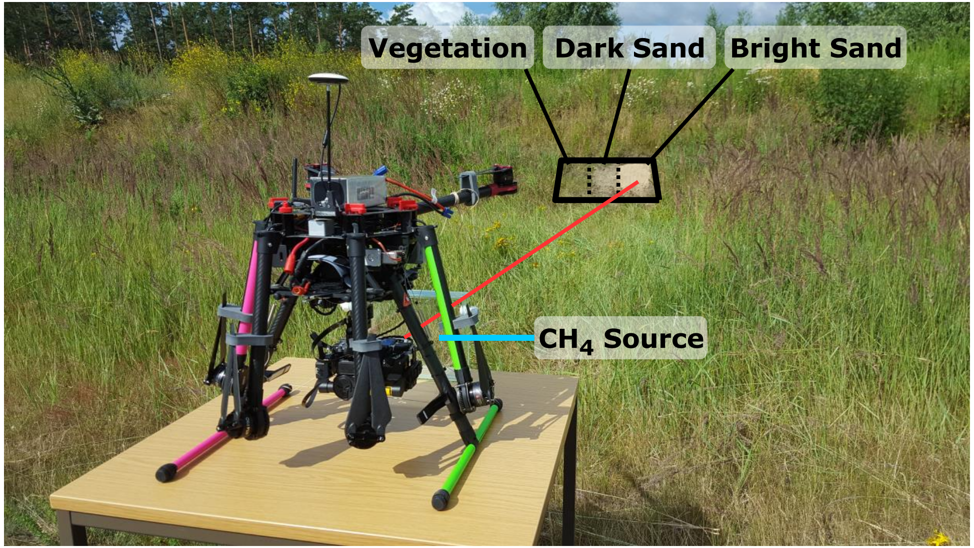
- **Gas detection**
  - » approx. 30.2 % of the time, a concentration above a threshold of 200 ppm·m were detected
    - → much higher than the measured CH_4 background concentrations (at similar distances)



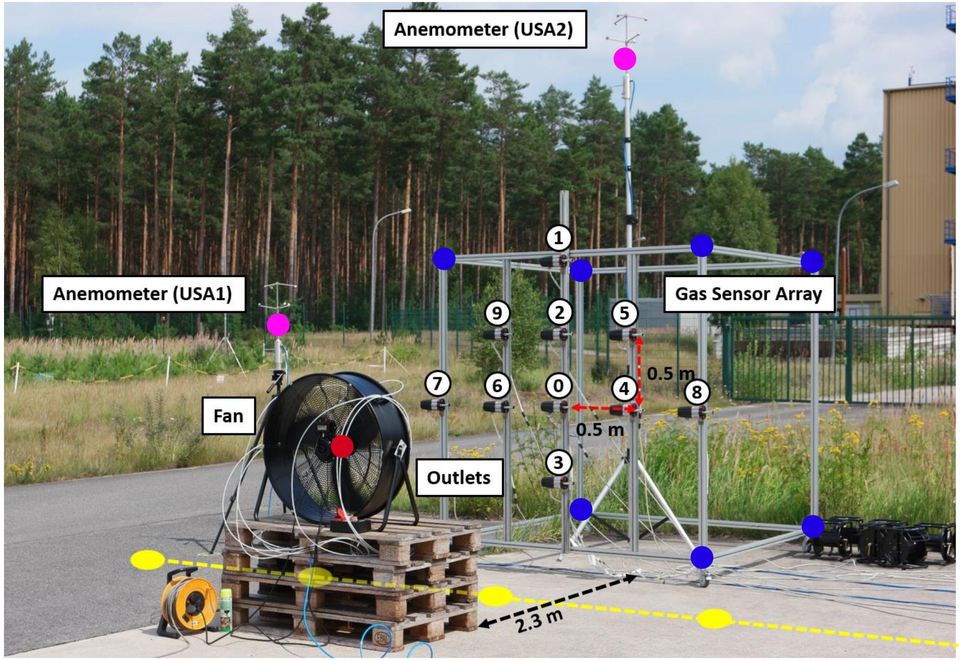
[Neumann et al., ICRA 2017]

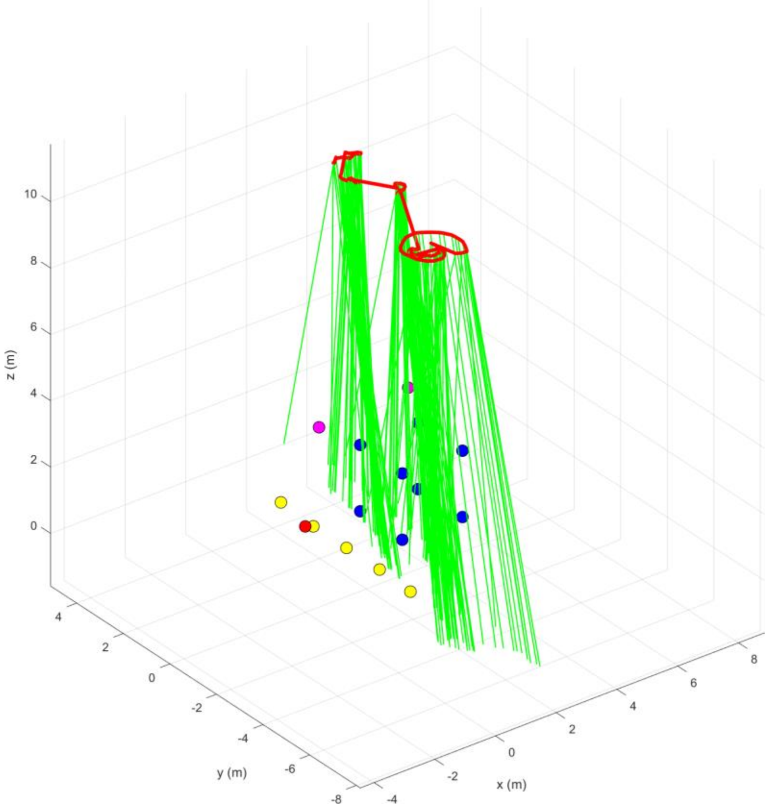
Field Experiment 1 and 2:
Summary

- **Gas sensor:**
  - works with relevant backgrounds
  - measurement distance of 30 m is achievable
  - accuracy is within the specified range (±10%)



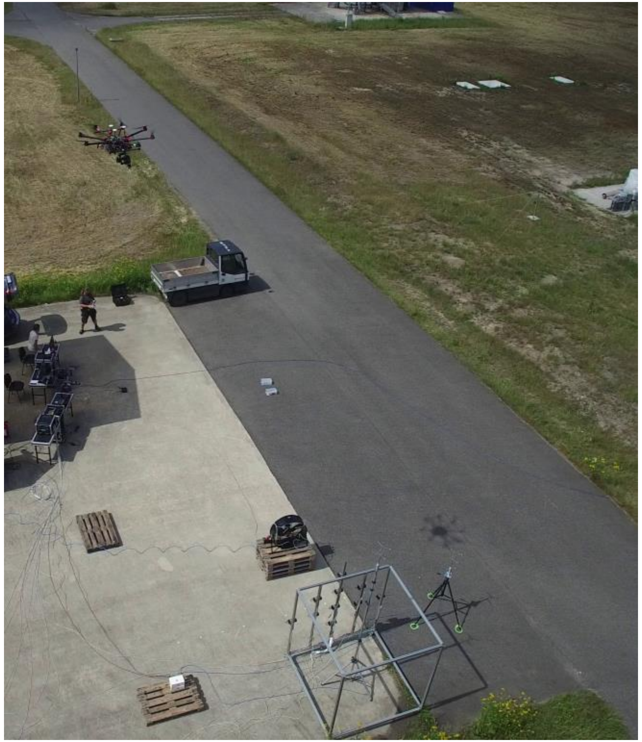
Field Experiment 3:
2D Plume Tomography





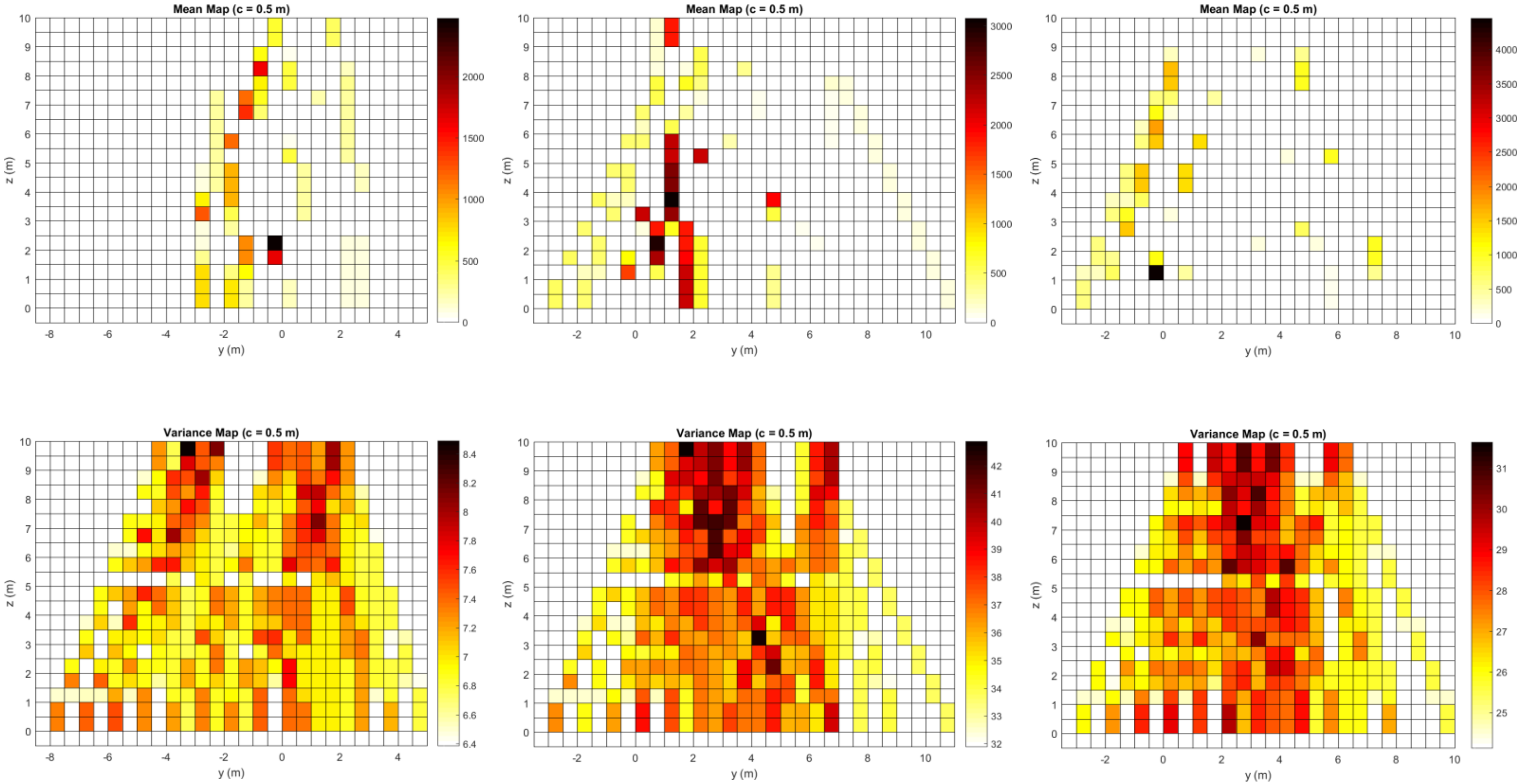
[Neumann et al., IEEE Sensors 2018]
[Neumann et al., Eur. J. Remote Sens.2019]

Field Experiment 3:
UAV on Mission



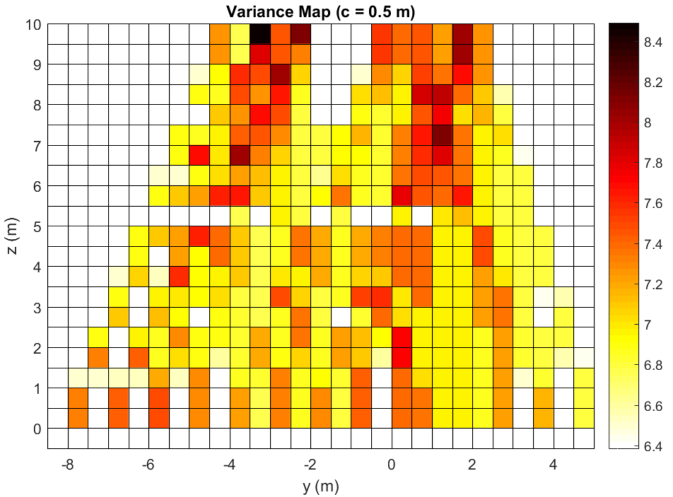
[Neumann et al., IEEE Sensors 2018]
[Neumann et al., Eur. J. Remote Sens.2019]

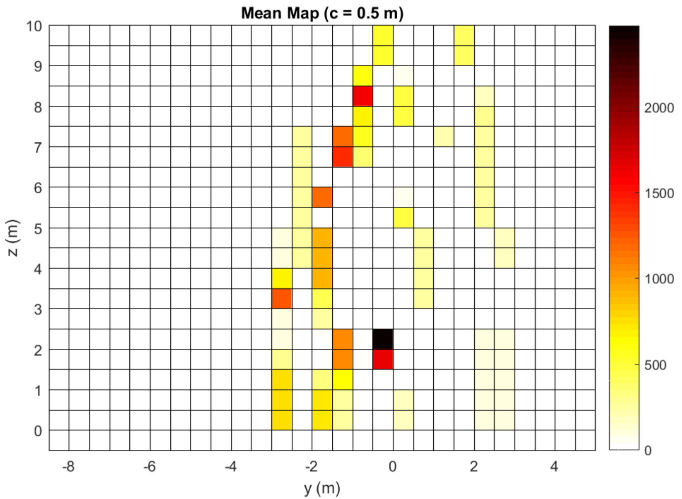
Field Experiment 3:
2D Plume Tomography



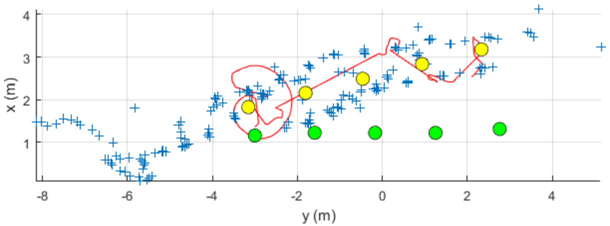
[Neumann et al., IEEE Sensors 2018]
[Neumann et al., Eur. J. Remote Sens.2019]

Field Experiment 3:
2D Plume Tomography





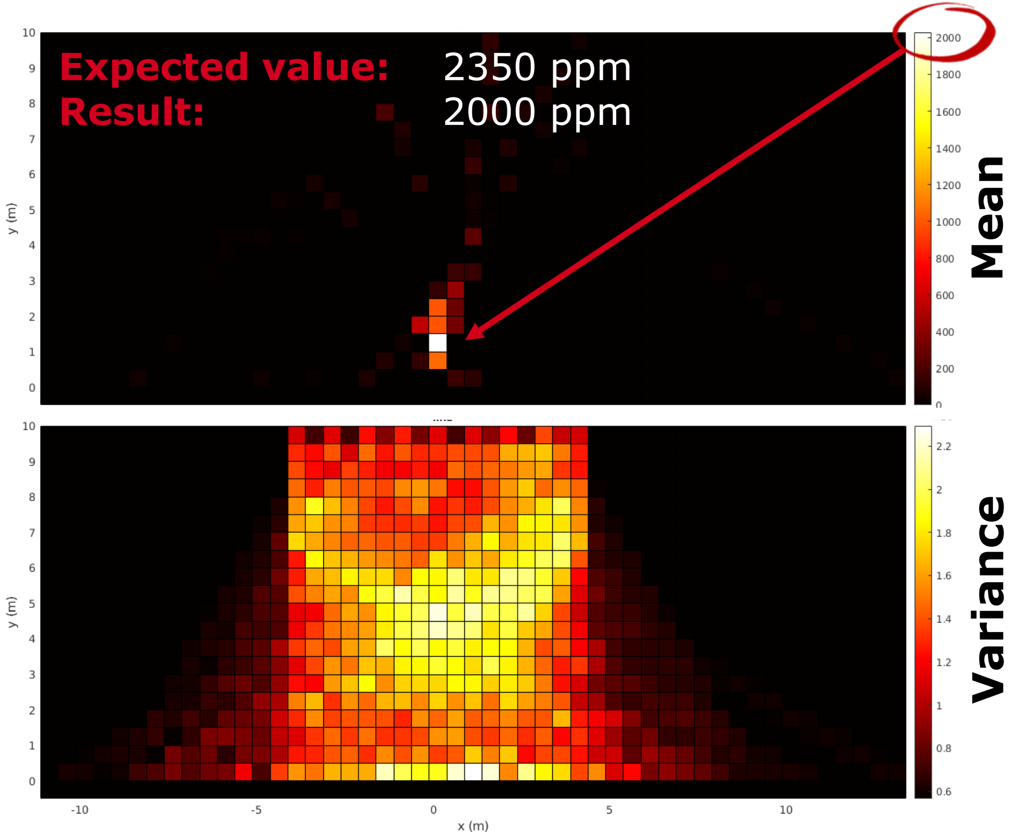
- **Problem:** standard GPS not accurate enough and standard DJI waypoint navigation too imprecise
  - → **RTK GPS** offering centimeter-level positioning (up to 1 cm + 1 ppm)



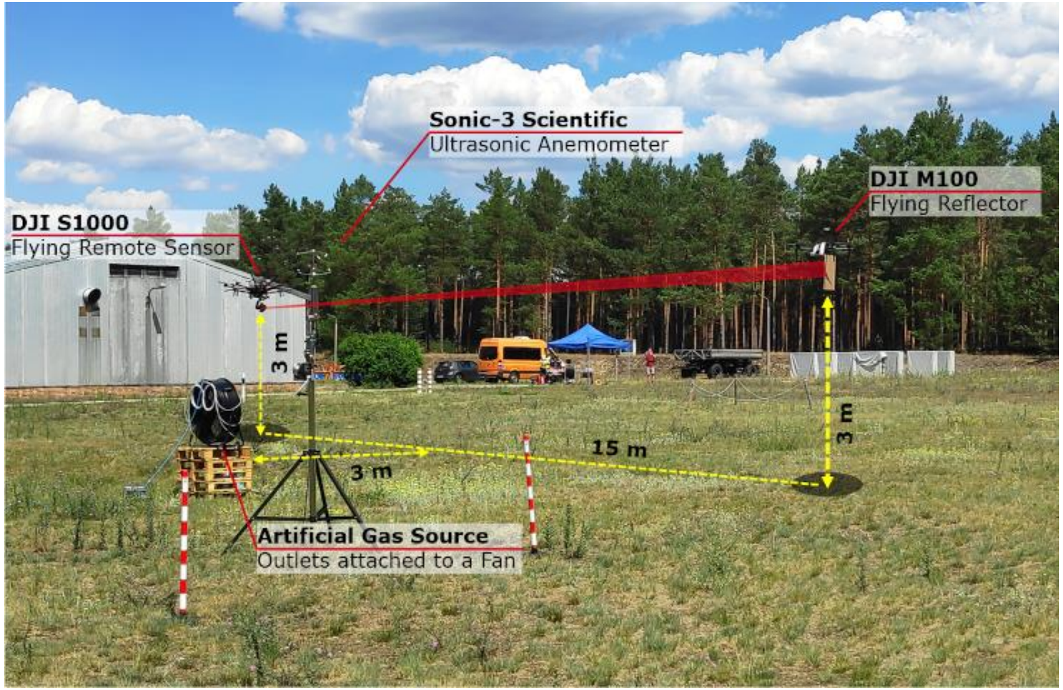
[Neumann et al., IEEE Sensors 2018]
[Neumann et al., Eur. J. Remote Sens.2019]

Field Experiment 3:
2D Plume Tomography of Static Gas Plumes

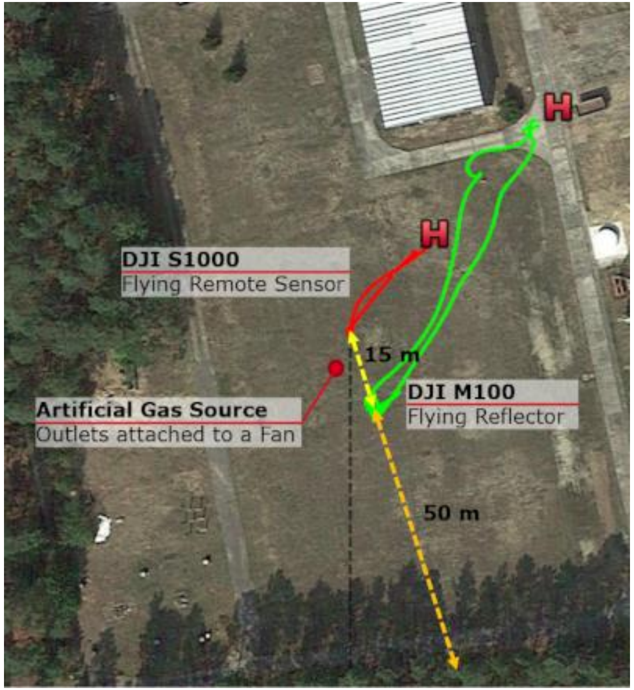
Field Experiment 3:
2D Plume Tomography of Static Gas Plumes



Field Experiment 4:
Remote Drone-to-Drone Gas Sensing



a) Side View



b) Top View

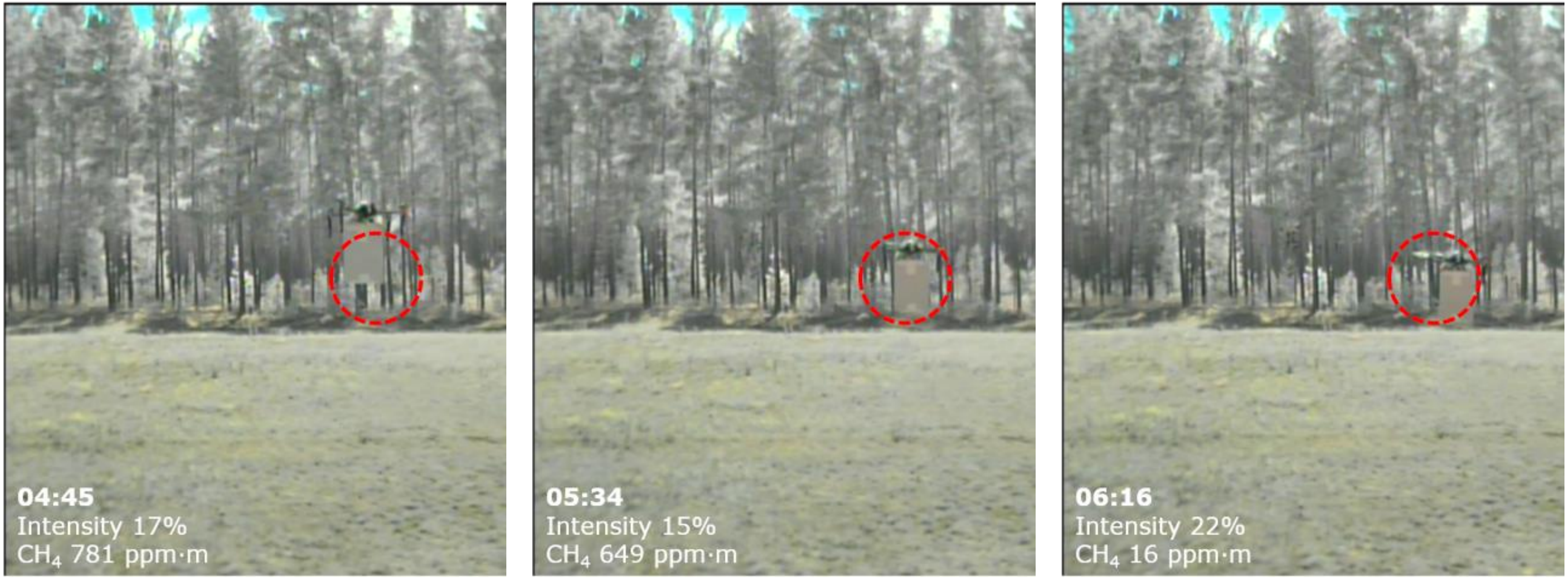
[Neumann et al., ISOEN 2022]

Field Experiment 4: Experimental Results – in Numbers #1

- **26.5%** **successful** measurements
  - » **21%** of measurements (#69): reflection intensity of **≥10%**
    - → enough for the sensor to give trustworthy readings
    - → indicate that flying reflector was hit
  - » **79%** of measurements: reflection intensity **<10%**
    - → indicate that forest was hit (or fractions of the drone) **(intensity typically between 2 to 5%)**
- **73.5%** of data were labeled **invalid**
  - » insufficient reflection
  - » error code

[Neumann et al., ISOEN 2022]

Field Experiment 4:
Experimental Results – in Pictures



[Neumann et al., ISOEN 2022]

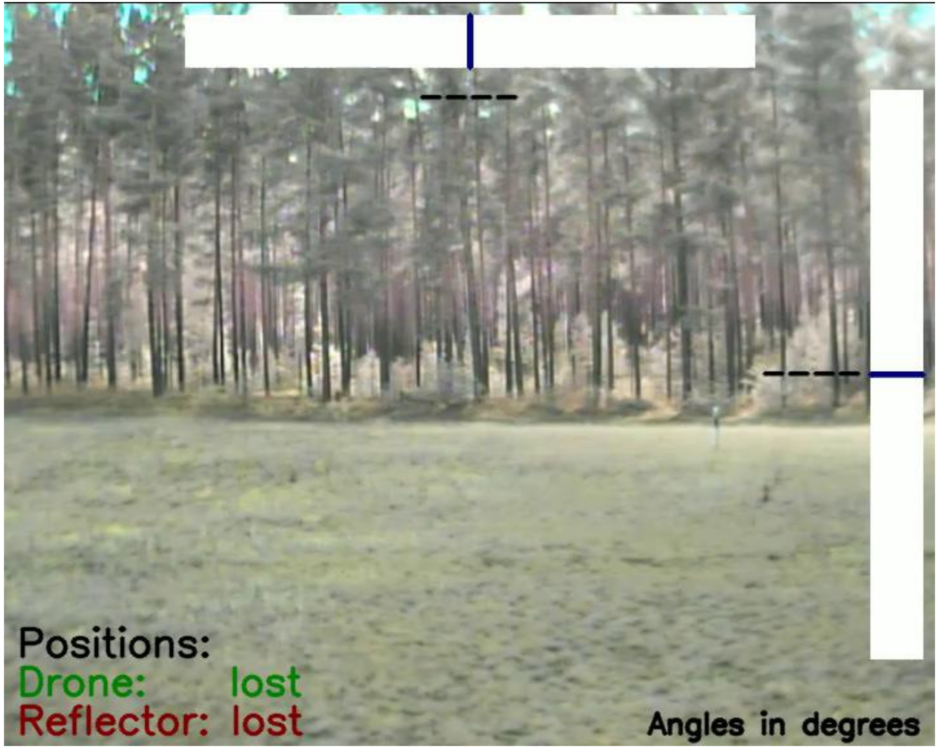
Field Experiment 4:
Experimental Results – in Numbers #2

- Max. integral **concentration** measured:
  - » **concentration:** 1,363 ppm·m
  - » **reflection intensity:** 12%
- Max. measured **reflection** intensity:
  - » **concentration:** 16 ppm·m
  - » **reflection intensity:** 22%
- Longest period of consecutive measurements: 4 s
- **Main cause of failure:**

  → misalignment between robots – due to the manual control of reflector drone and wind conditions

[Neumann et al., ISOEN 2022]

Field Experiment 4:
Experimental Results – in Video



[Neumann et al., ISOEN 2022]

Conclusions and Outlook

Challenges for the Next Year(s) :)

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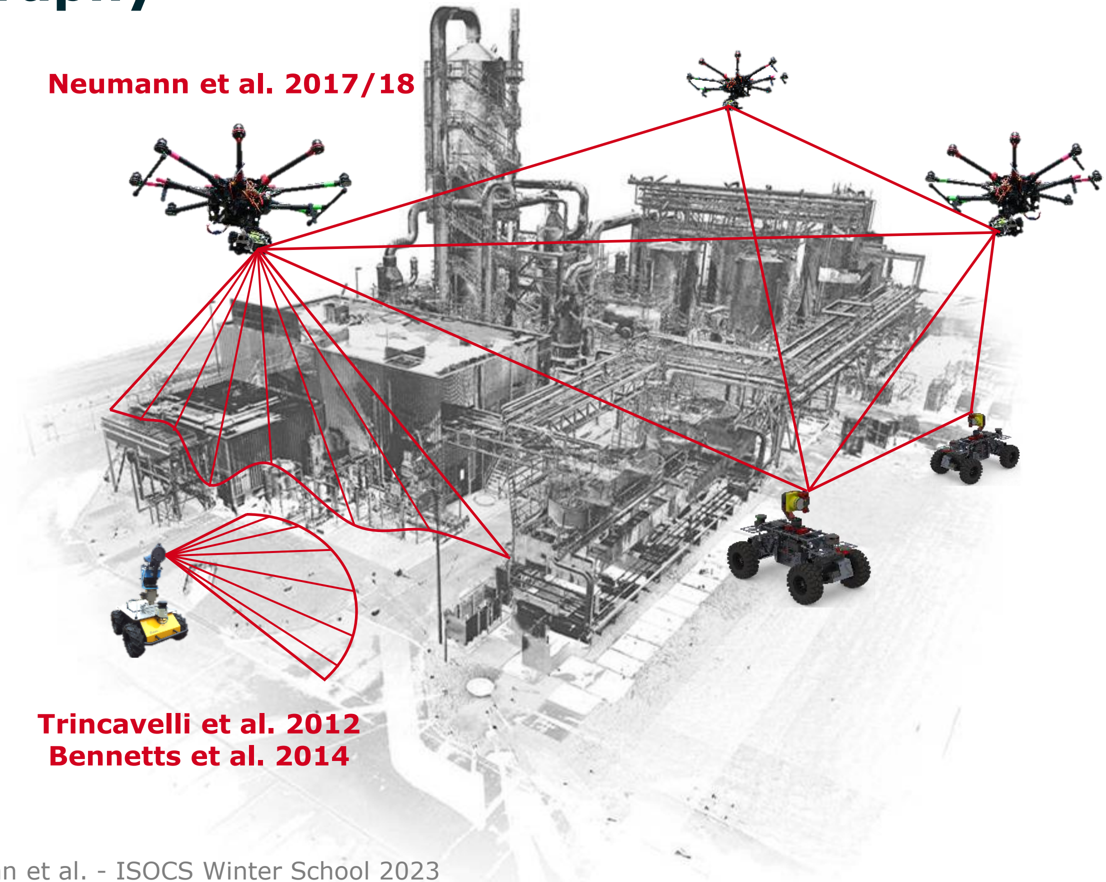
Reminder: Aerial- and Ground-based Gas Tomography



Conclusion

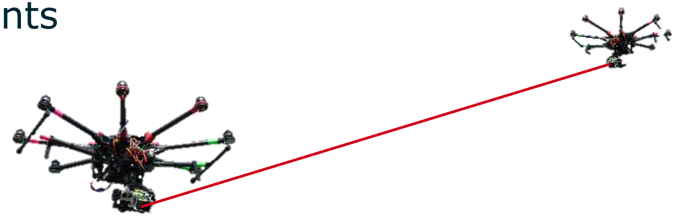
Exciting topic with...

...plenty of challenges ahead!

Challenges – Scenario

- **Dynamic scenario**
  - » no fixed setup, freely moving robots
  - » establish TDLAS measurement paths between flying UAVs by enhancing gimbals with visual object tracking functionality

- **Design of suitable reflectors that have**
  - » a negligibly small impact on the UAV’s flight performance,
  - » while increasing the measuring distance of the TDLAS sensor by using, e.g., retroreflector elements



Challenges – Algorithms

- Development of (near-)optimal sensor and path planning algorithms for the UAVs is an important aspect as flight times are limited

- Development of **tomographic reconstruction algorithms** that are able to cope with/include
  - highly **dynamic** nature of gas dispersion
  - **sparsity** of the measurements
  - measurement **geometry**
  - additional data (from, e.g., in-situ gas sensors)

- Estimation of a model of the gas distribution (plume/cloud) that capture its statistical properties only

Thank you for your attention.

Contact:

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8.1 Sensors, Measurement and Testing Methods

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Email: patrick.neumann@bam.de

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References

…in order of appearance – more or less ;)

www.bam.de

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Appendix

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Timeline

2008

In-Situ Sensing

- AirRobot AR100-B
- Gas transport
- 2D sensorless wind vector estimation

2015

Remote Sensing

- DJI Spreading Wings S1000
- 3D sensorless wind vector estimation
- Simulation environment and TDLAS sensor model

2018

Swarm

- Bitcraze Crazyflie 2.0
- Indoor air quality gas sensors

2019

Heterogeneous

- Sensor networks combined with robots & drones
- Measurements (dust and gas) with varying quality and spatial resolution

BAM Ground Robot

BAM

Specifications

- Length: ~800 mm
- Width: ~500 mm

Payload:

- Pixhawk 2.1 standard flight controller
- Here+ V2 RTK GNSS kit
  (centimeter-level GNSS positioning)
- *UDOO x86 computing unit*
- Distance sensors
- 360° Lidar & ultrasonic
- *Optical flow sensor & cameras*

<2.5 k€

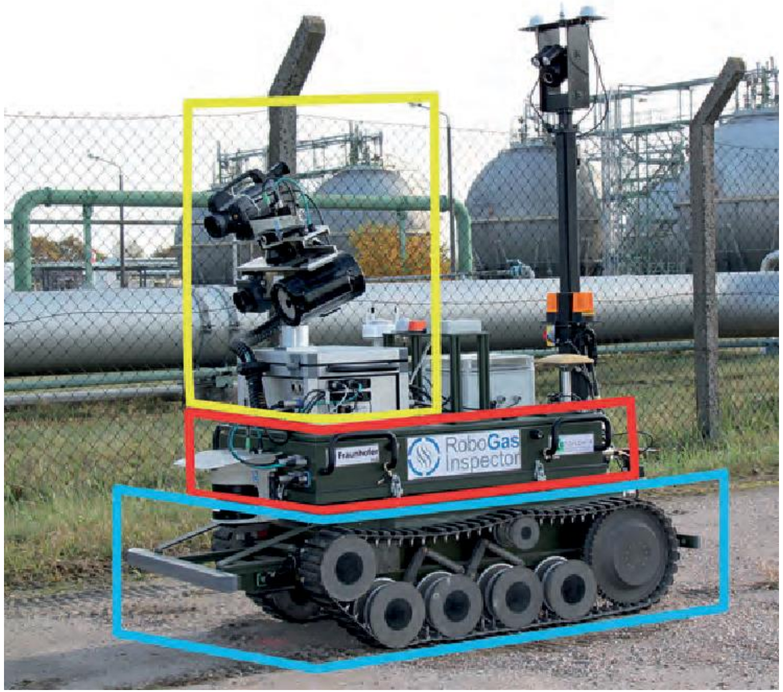
RoboGasInspector
Kassel University, Germany

Specifications

- …

Payload (yellow):

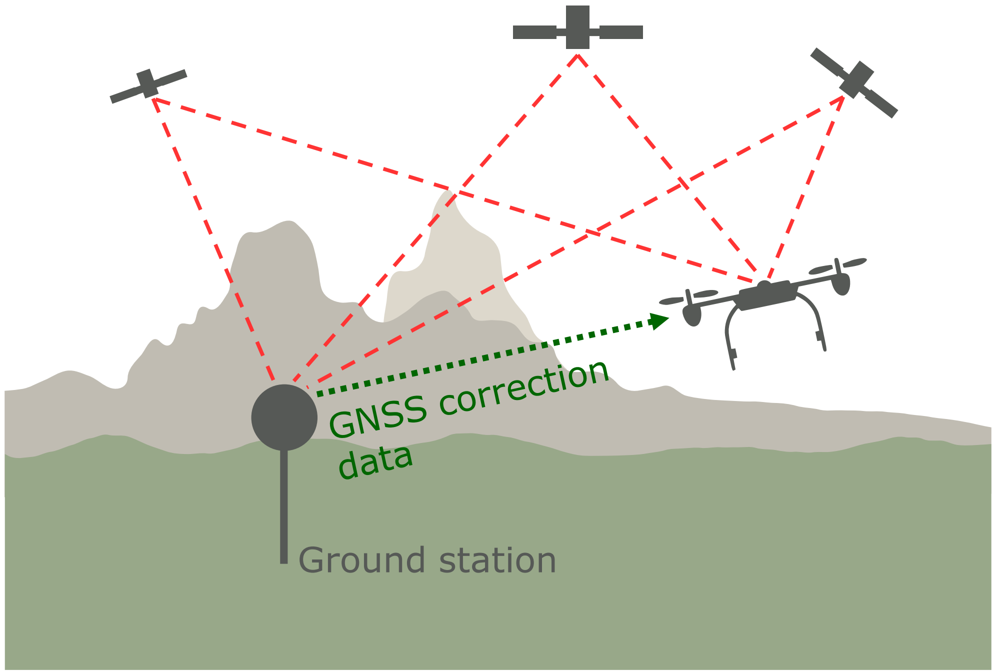
- pan-tilt unit for orienting the payload
- 2D lidar for distance measurements
- IR thermal camera
- TDLAS-based open-path gas detector
- FLIR GF320 thermal camera for gas visualization



[Soldan et al., IFAC 2012]
[Bonow and Kroll, ICRA 2013]

Lesson learnt: GNSS

- “Simple GNSS” → differential GNSS



Gas Dispersion Simulation

Simulator, TDLAS Sensor Model, Validation

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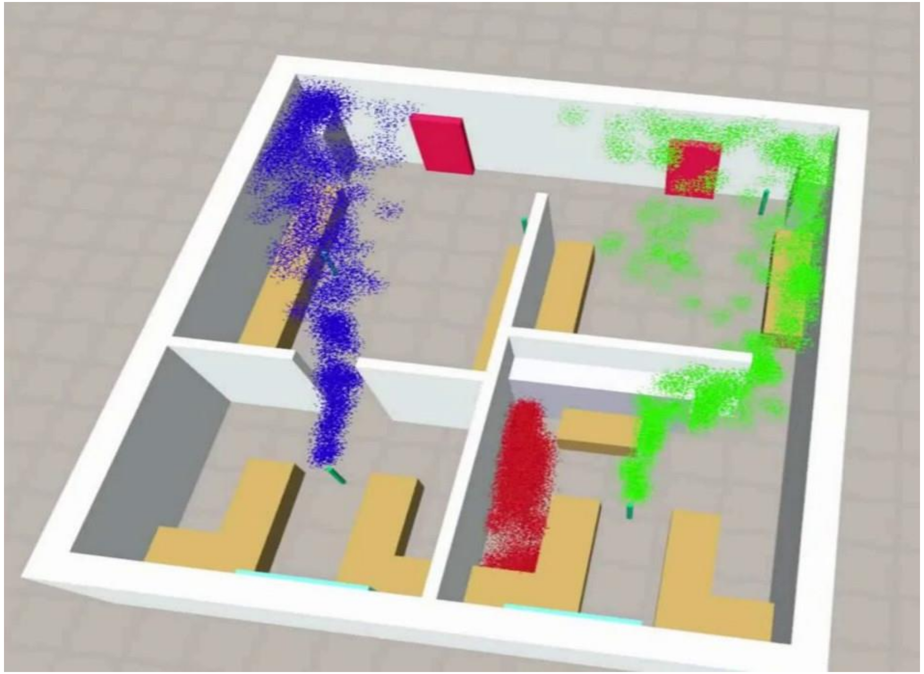
Gas Dispersion Simulation

- **Typical approach:** CFD simulation software such as Ansys CFX or OpenFOAM
  - computationally expensive
  - large (outdoor scale) scenarios limited to coarse grids
  - difficult to realize an interaction of the robot with the environment
- We need a simplified plume simulation which is computationally cheap!

Gas Dispersion Simulation
GADEN

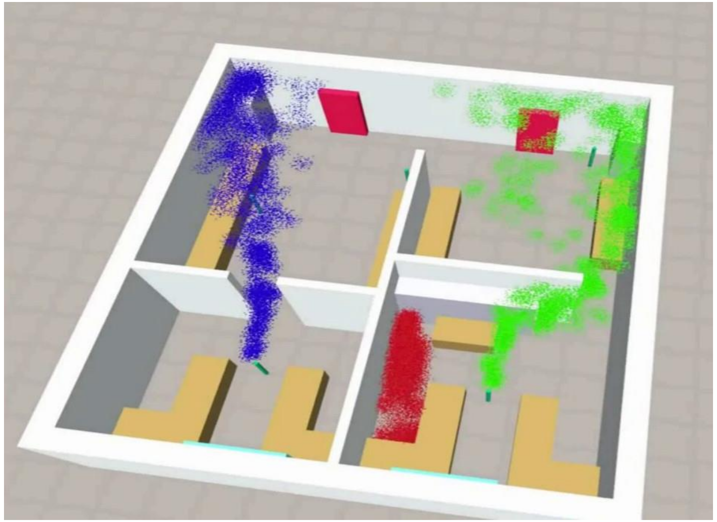


[Monroy et al., Sensors 2017]

Gas Dispersion Simulation
GADEN

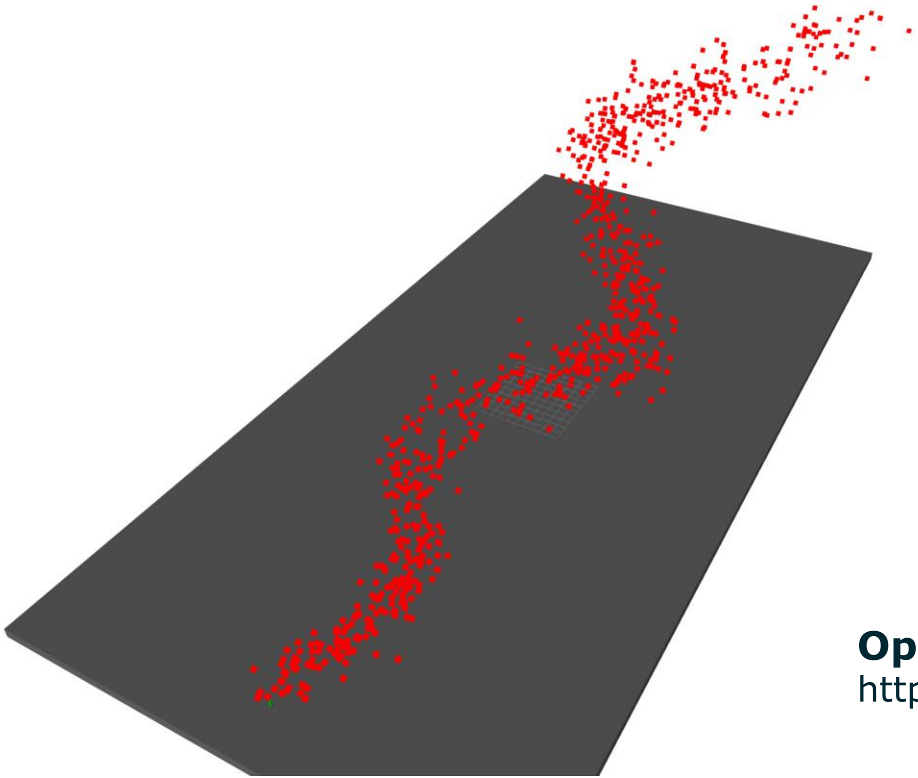
- Simulator is grid based
- Simulator output:
  - » concentration in cell i: c_i
- Sensor model:
  - » measurement: $c = f_{\text{Model}}(c_i)$

Open source software:
https://github.com/MAPIRlab/gaden



[Monroy et al., Sensors 2017]

Gas Dispersion Simulation



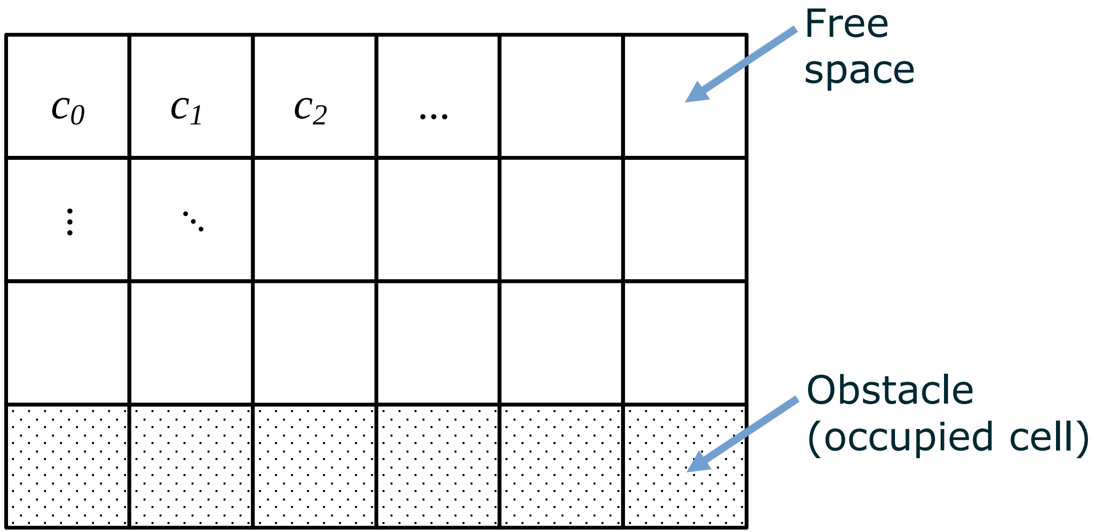
- **Optimize code to allow simulations of outdoor environments**
- **Implement a cone model of the TDLAS sensor**

Open source software:
https://github.com/BAMresearch/gaden2

[Hüllmann et al., ISOEN 2019]
[Hüllmann et al., IEEE Sensors 2019]

TDLAS Line Sensor Model

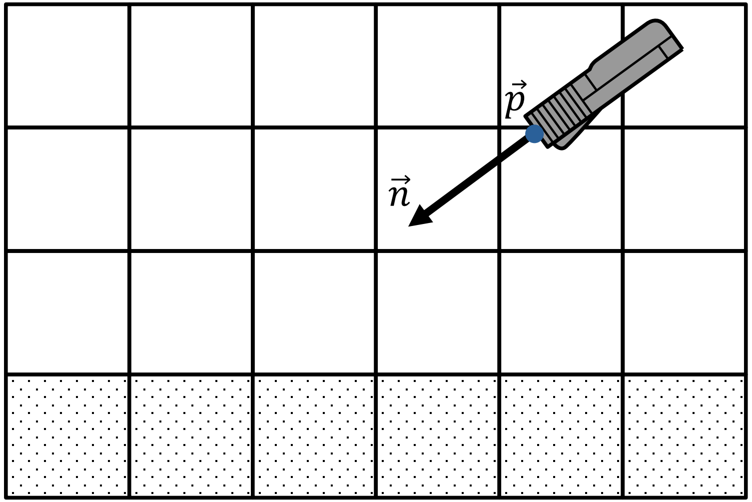
c_i Concentration in cell i



[Hüllmann et al., ISOEN 2019]
[Hüllmann et al., IEEE Sensors 2019]

TDLAS Line Sensor Model

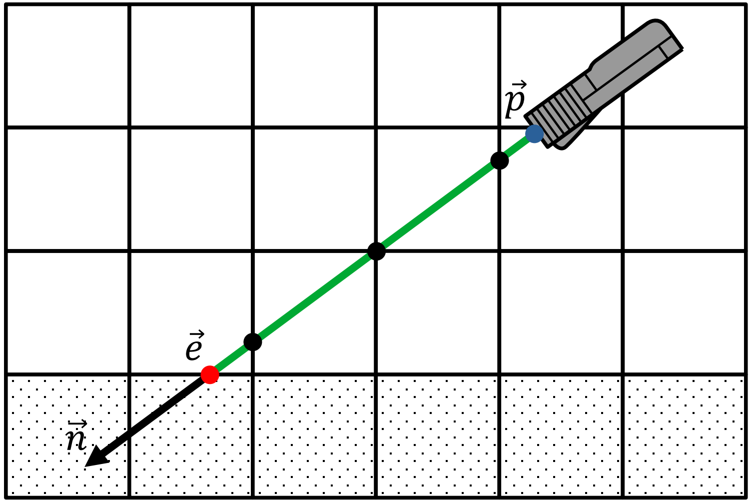
- $\vec{p}$ Position of the sensor
- $\vec{n}$ Measurement direction



[Hüllmann et al., ISOEN 2019]
[Hüllmann et al., IEEE Sensors 2019]

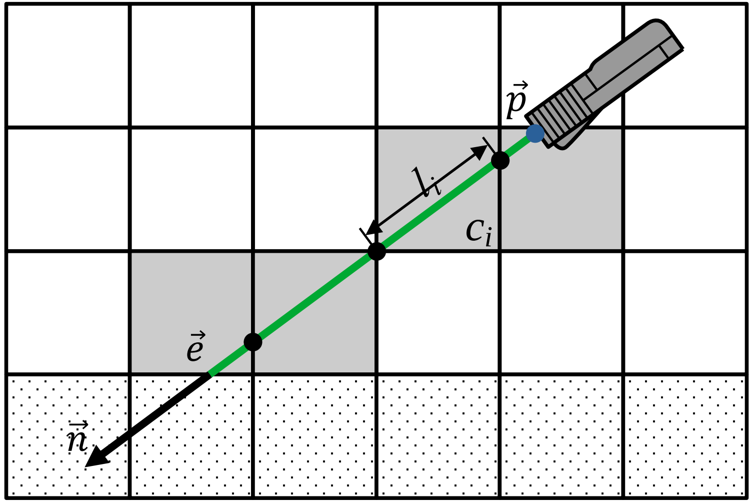
TDLAS Line Sensor Model

$\vec{e}$ End point of the measurement ray



[Hüllmann et al., ISOEN 2019]
[Hüllmann et al., IEEE Sensors 2019]

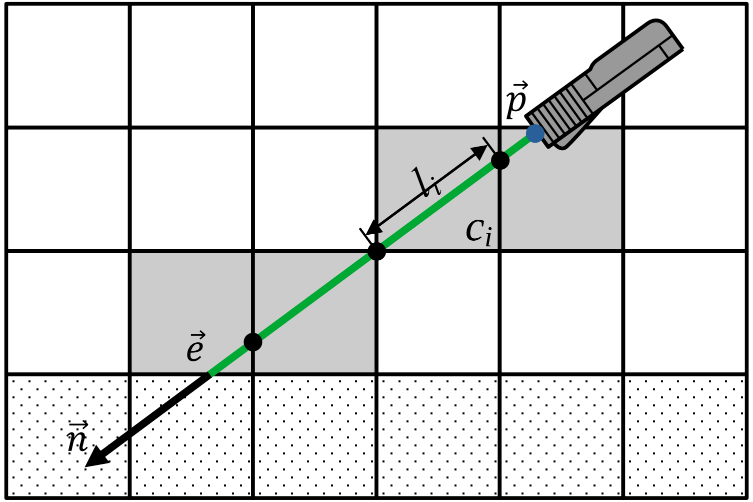
TDLAS Line Sensor Model



[Hüllmann et al., ISOEN 2019]
[Hüllmann et al., IEEE Sensors 2019]

TDLAS Line Sensor Model

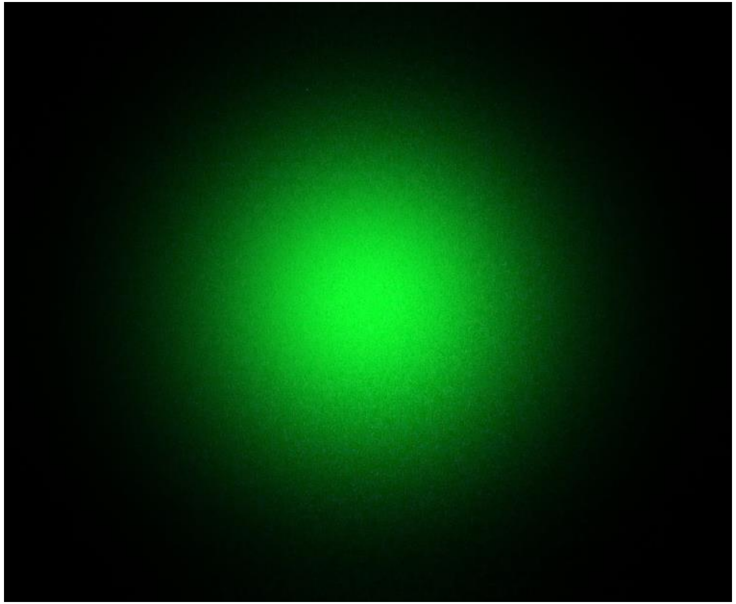
Measured concentration: $C = \sum_i c_i \; l_i + \varepsilon$ ε Noise term



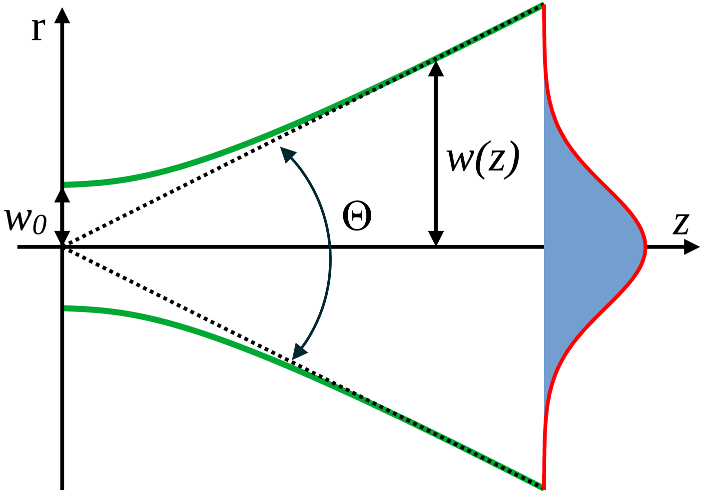
[Hüllmann et al., ISOEN 2019]
[Hüllmann et al., IEEE Sensors 2019]

TDLAS Sensor Model

- **A laser beam is not a line!**



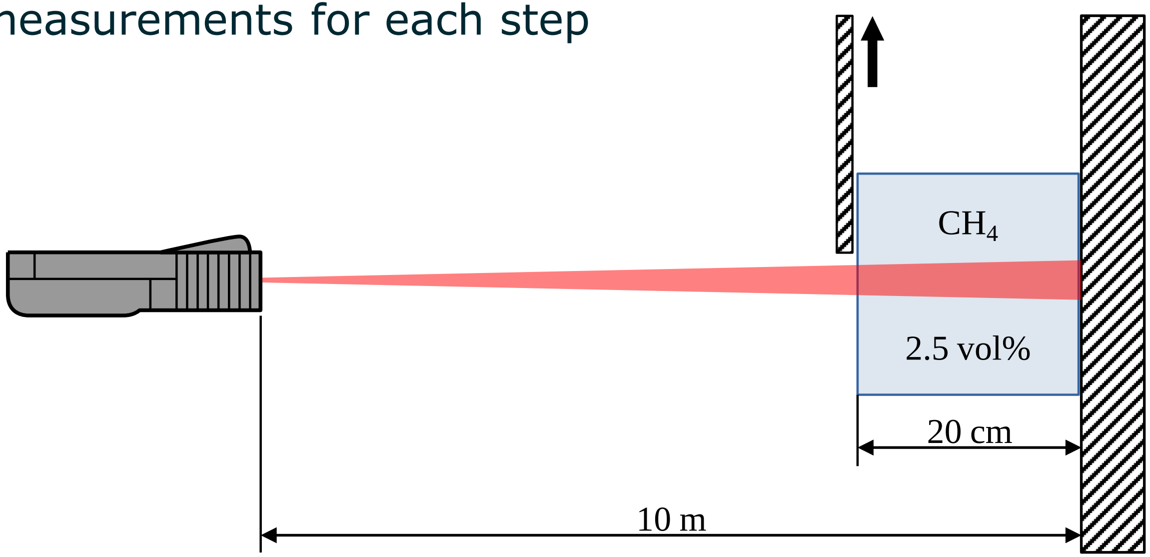
Gaussian beam profile of a laser pointer



[Hüllmann et al., ISOEN 2019]
[Hüllmann et al., IEEE Sensors 2019]

Measuring the Beam:
Experiment 1

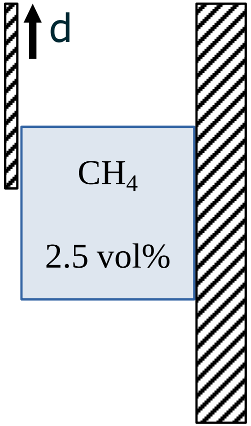
- **Moving an obstacle through the beam:**
  - » 5 mm steps
  - » 400 measurements for each step

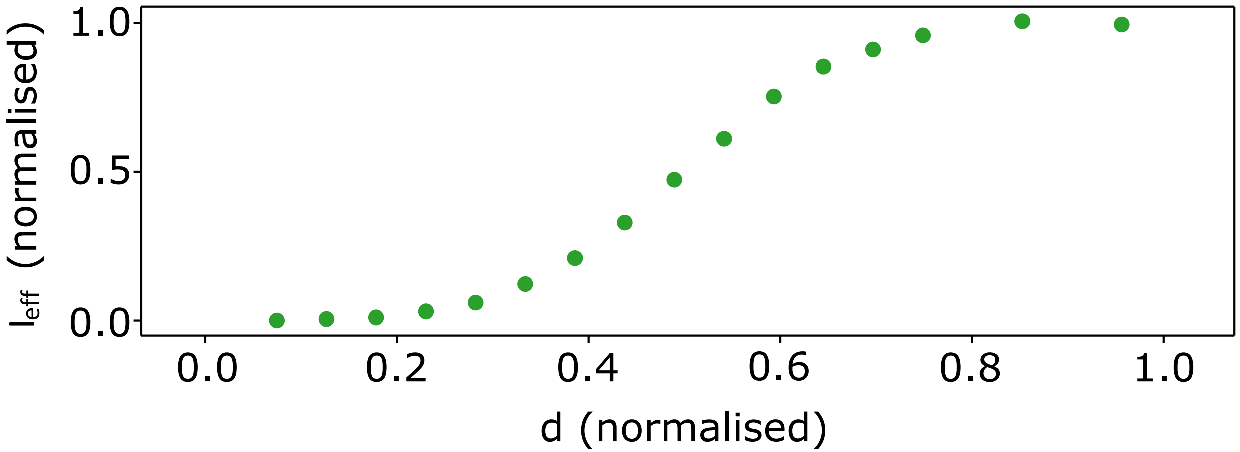


[Hüllmann et al., ISOEN 2019]
[Hüllmann et al., IEEE Sensors 2019]

Measuring the Beam:
Result 1

- **Spot diameter at 10 m distance: approx. 60 mm**
  → total angular spread of the beam: 6 mrad

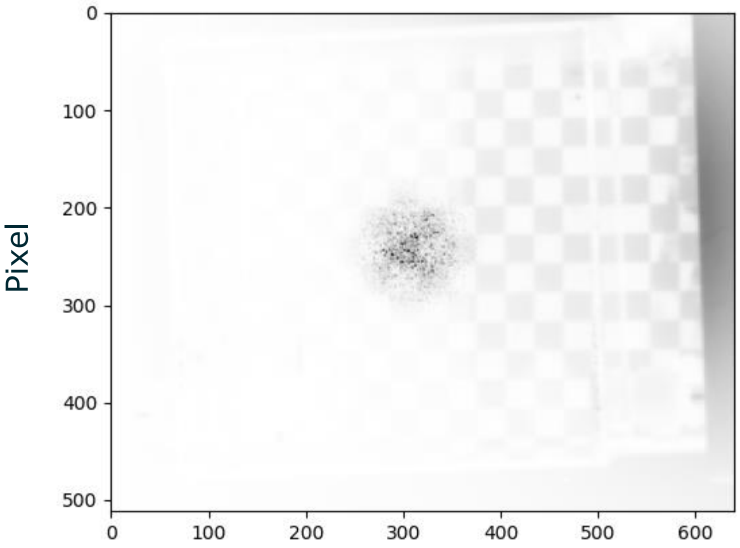




[Hüllmann et al., ISOEN 2019]
[Hüllmann et al., IEEE Sensors 2019]

Measuring the Beam:
Experiment 2

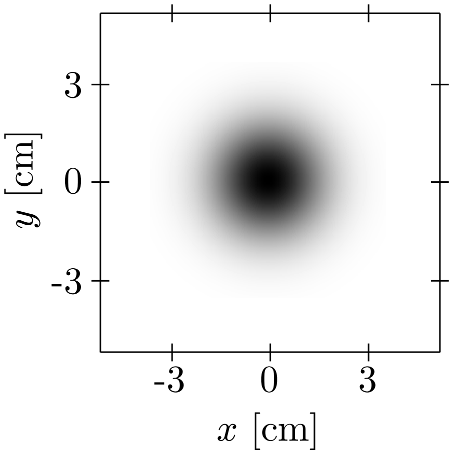
- **Short-wave infrared (SWIR) camera Allied Vision Goldeye**
  - » Spectral range: 900 nm to 1700 nm

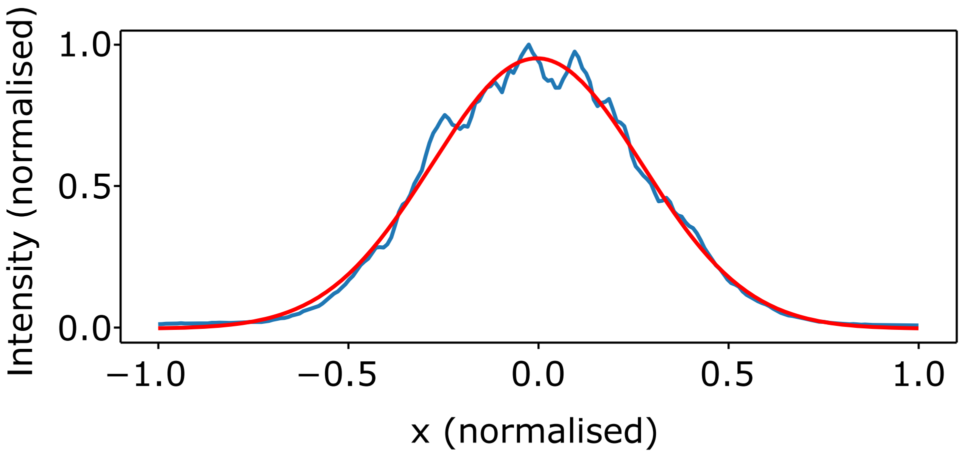


[Hüllmann et al., ISOEN 2019]
[Hüllmann et al., IEEE Sensors 2019]

Measuring the Beam:
Result 2

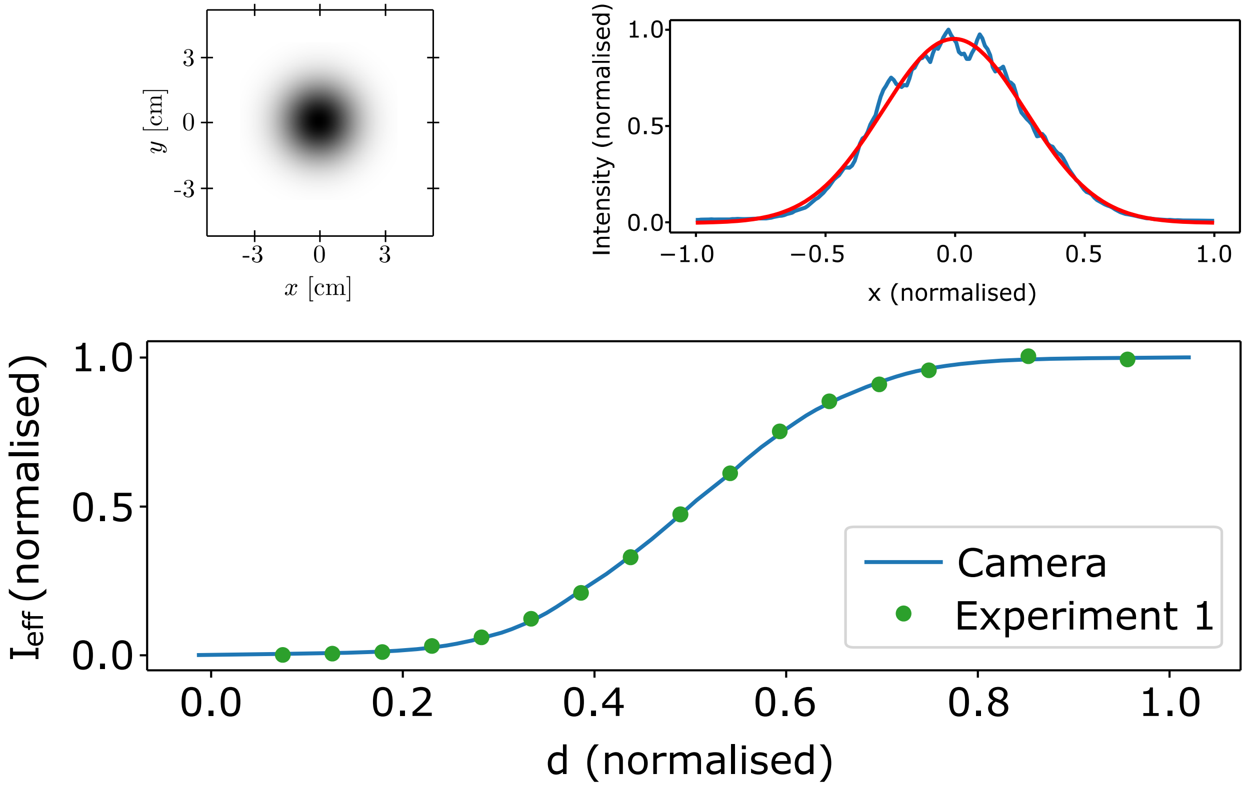
- **Mean value of 200 video frames:**





[Hüllmann et al., ISOEN 2019]
[Hüllmann et al., IEEE Sensors 2019]

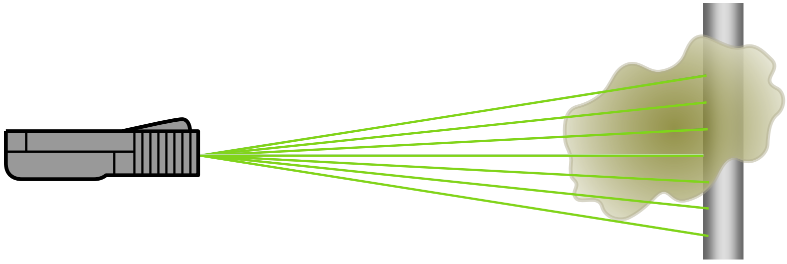
Measuring the Beam:
Result 2

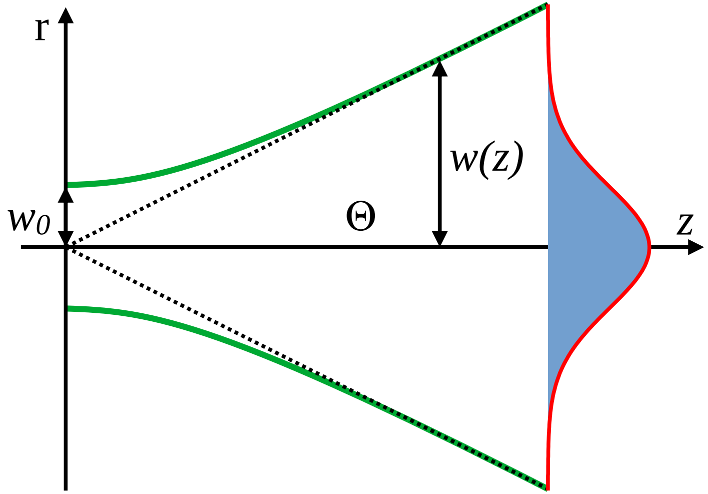


[Hüllmann et al., ISOEN 2019]
[Hüllmann et al., IEEE Sensors 2019]

TDLAS Cone Sensor Model

- Sample multiple rays
- Weight rays according to Gaussian intensity distribution



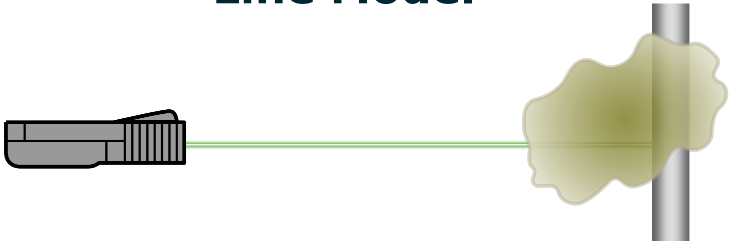


Waist radius: $w_0 \approx 56\ \mu m$

[Hüllmann et al., ISOEN 2019]
[Hüllmann et al., IEEE Sensors 2019]

TDLAS Sensor Models

Line Model



$$c_{Line} = \sum_i c_i \; l_i + \varepsilon$$

Cone Model

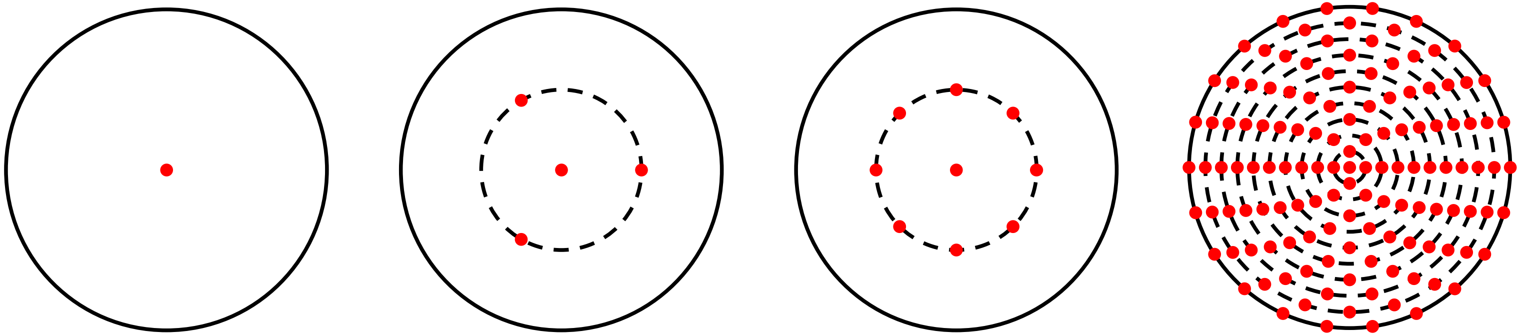
$$c_{Cone} = \frac{1}{\sum_j \; I_j} \sum_j I_j \; c_{Line,j}$$

I_j Integrated intensity of ray j

[Hüllmann et al., ISOEN 2019]
[Hüllmann et al., IEEE Sensors 2019]

TDLAS Sensor Model Comparison

- **Sensor configurations:**



1 ray
(line model)

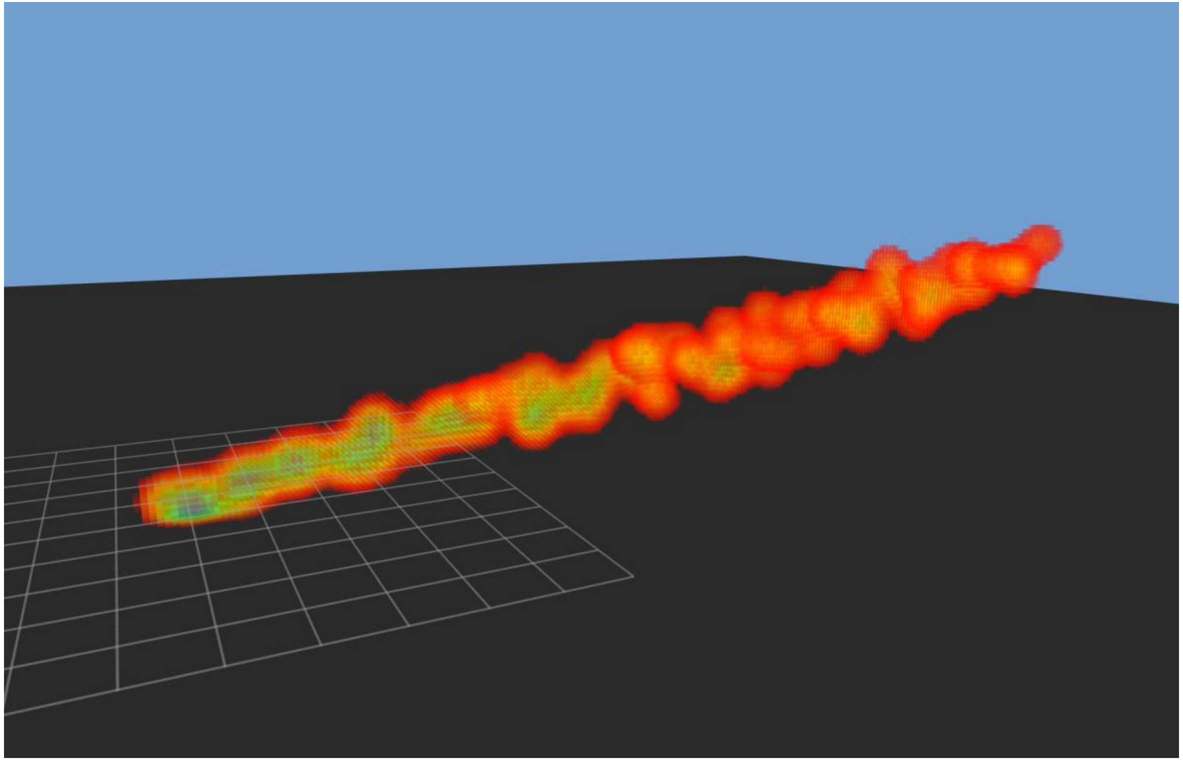
4 rays

9 rays

131 rays

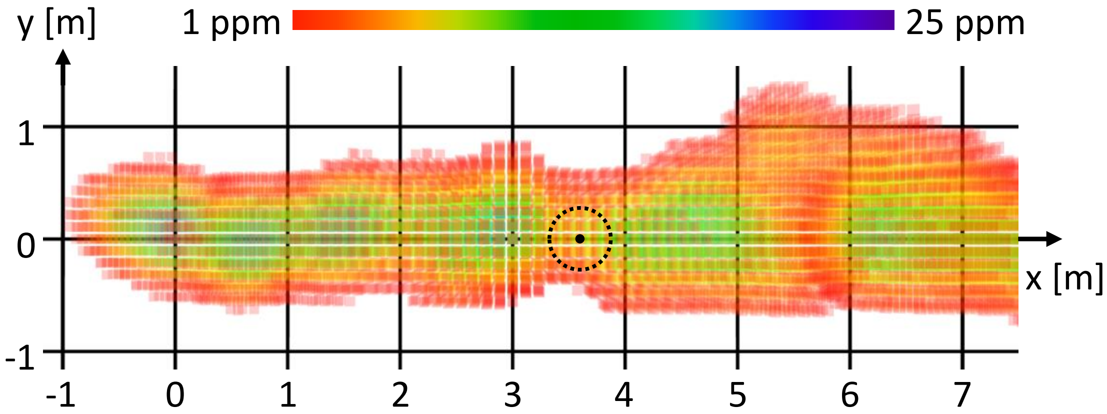
[Hüllmann et al., ISOEN 2019]
[Hüllmann et al., IEEE Sensors 2019]

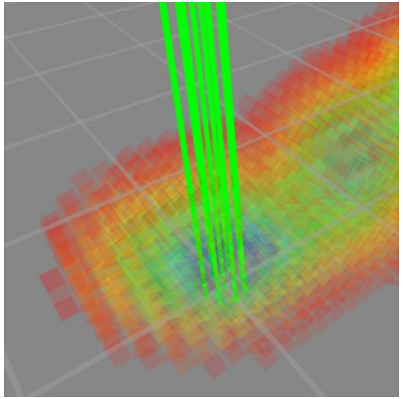
TDLAS Sensor Model Comparison



[Hüllmann et al., ISOEN 2019]
[Hüllmann et al., IEEE Sensors 2019]

TDLAS Sensor Model Comparison

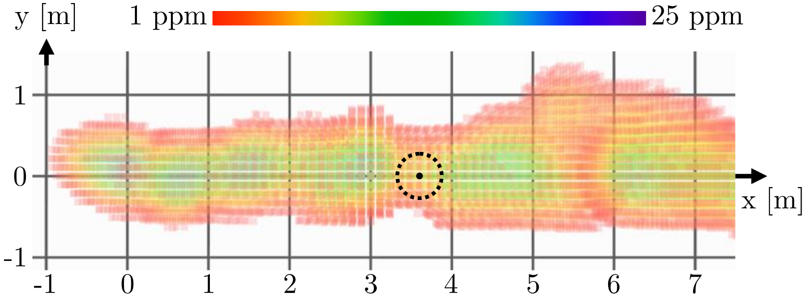


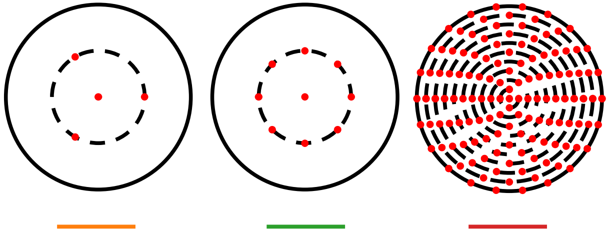


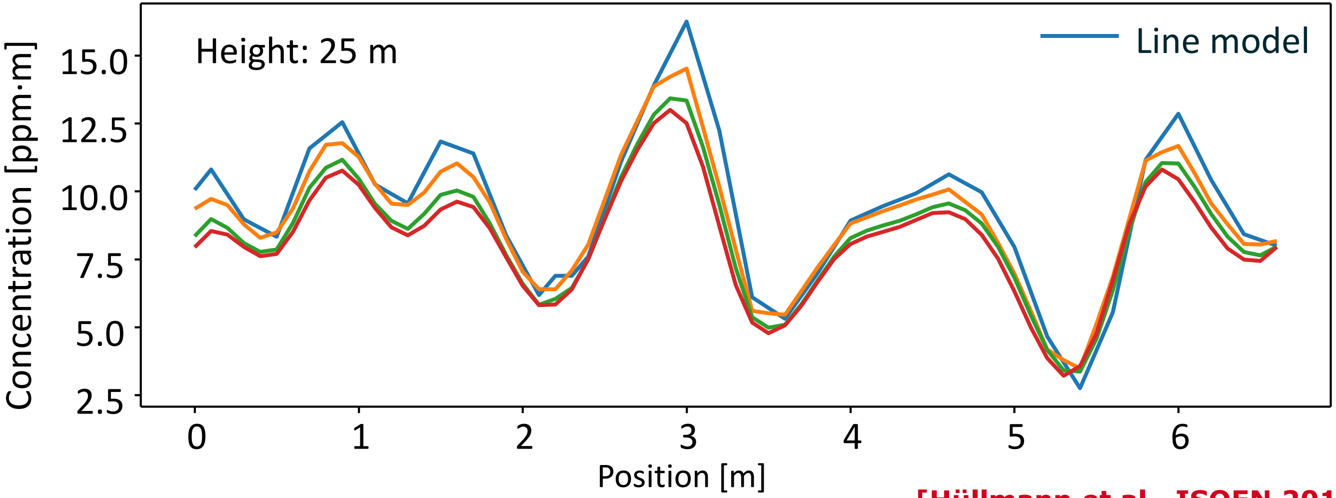
Sensor distance: 25 m

[Hüllmann et al., ISOEN 2019]
[Hüllmann et al., IEEE Sensors 2019]

TDLAS Sensor Model:
Comparison Results

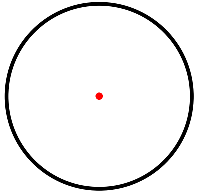
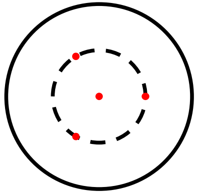
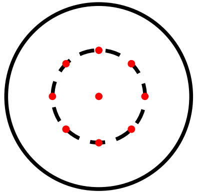
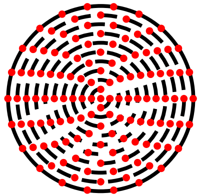






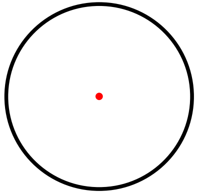
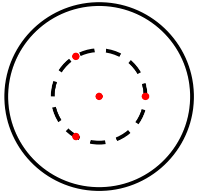
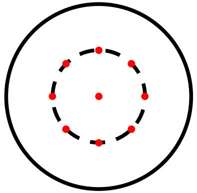
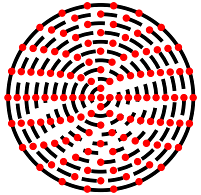
[Hüllmann et al., ISOEN 2019]
[Hüllmann et al., IEEE Sensors 2019]

TDLAS Sensor Model:
Comparison Results

Ray configuration				
Height [m]	5 / 25	5 / 25	5 / 25	5 / 25
Relative error [%]	12.9 / 18.1	7.0 / 11.0	2.7 / 4.1	0 / 0
Computing time [%]	0.2 / 0.9	0.8 / 3.1	1.6 / 7.0	23.2 / 100.0

[Hüllmann et al., ISOEN 2019]
[Hüllmann et al., IEEE Sensors 2019]

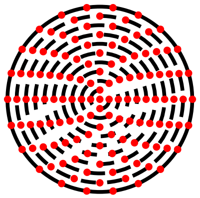
TDLAS Sensor Model: Comparison Results

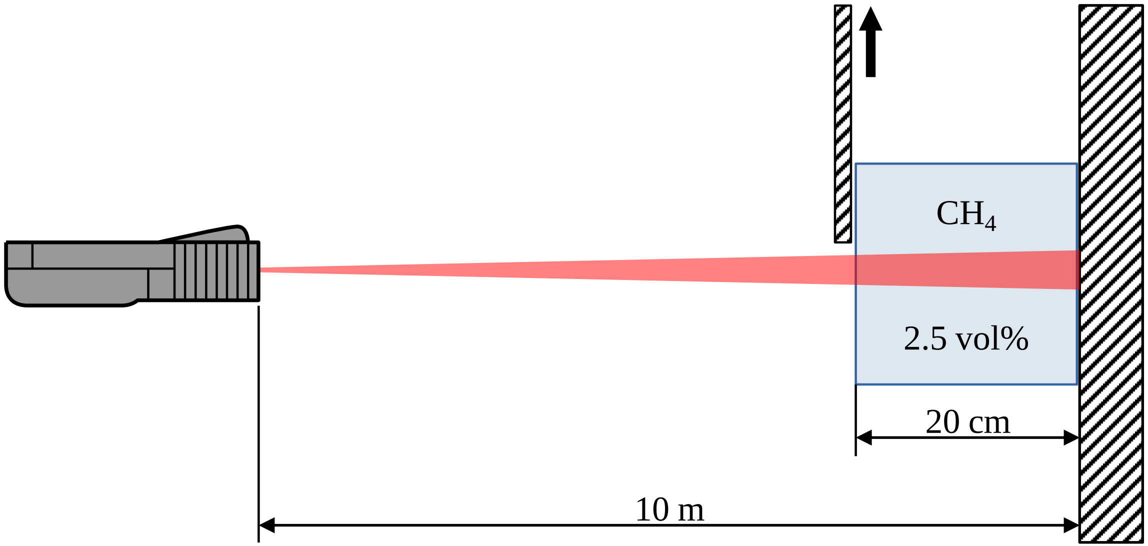
Ray configuration				
Height [m]	5 / 25	5 / 25	5 / 25	5 / 25
Relative error [%]	12.9 / 18.1	7.0 / 11.0	2.7 / 4.1	0 / 0
Computing time [%]	0.2 / 0.9	0.8 / 3.1	1.6 / 7.0	23.2 / 100.0

[Hüllmann et al., ISOEN 2019]
[Hüllmann et al., IEEE Sensors 2019]

Simulating the Experiment

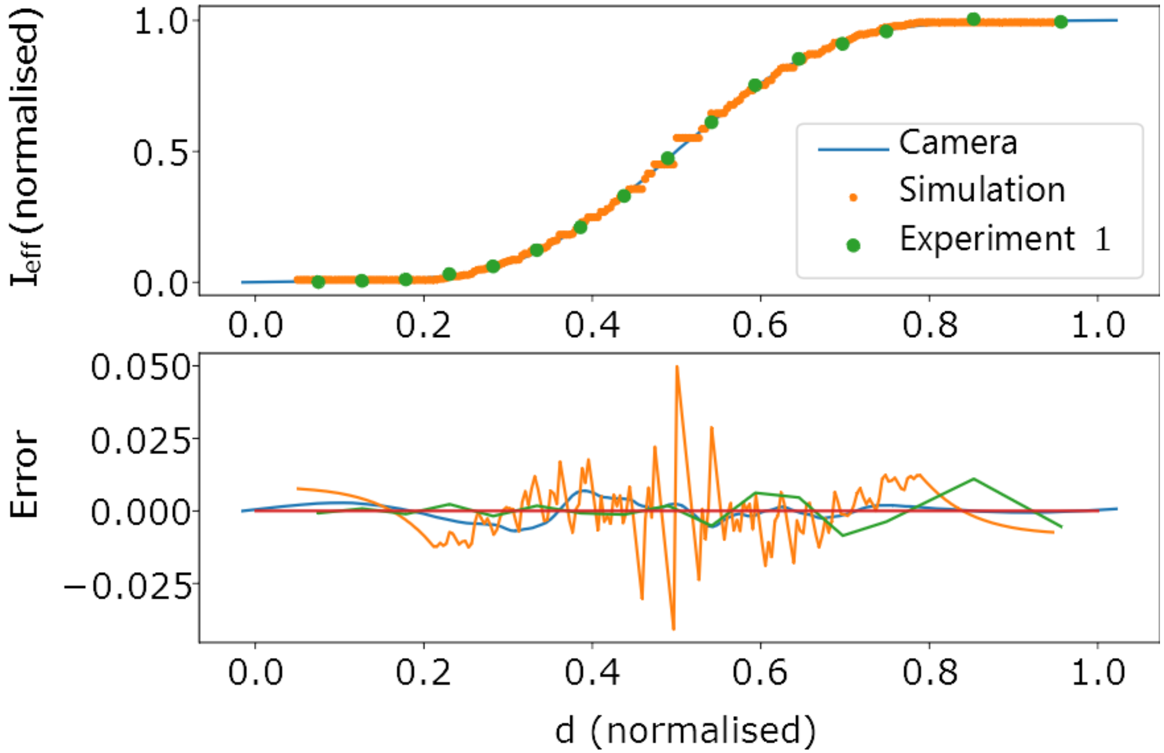
- Moving an obstacle through the beam
- Cone model with 131 rays





[Hüllmann et al., ISOEN 2019]
[Hüllmann et al., IEEE Sensors 2019]

TDLAS Sensor Model:
Validation



[Hüllmann et al., ISOEN 2019]
[Hüllmann et al., IEEE Sensors 2019]

Model in the Loop Simulation