Loughborough University

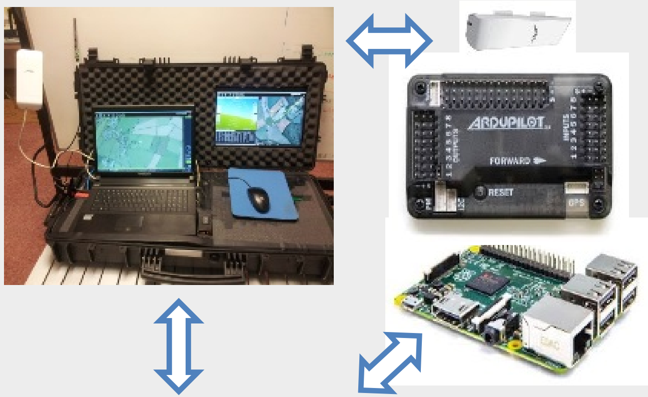
Source term estimation using unmanned autonomous vehicles

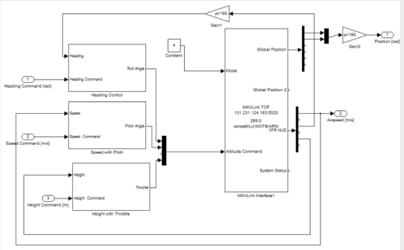
Michael Hutchinson, Dr Cunjia Liu, Prof. Wen-Hua Chen

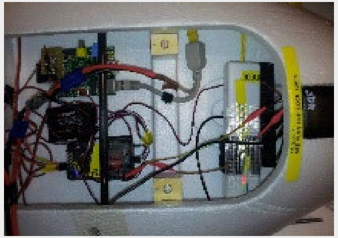
OUR LAB

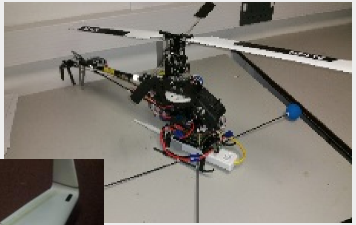
Autonomous systems laboratory

Autonomous systems laboratory









Ladosz, Pawel, Matthew Coombes, Jean Smith, and Michael Hutchinson.

"A Generic ROS Based System for Rapid Development and Testing of Algorithms for Autonomous Ground and Aerial Vehicles."

In *Robot Operating System (ROS)*, pp. 113-153. Springer, Cham, 2019.

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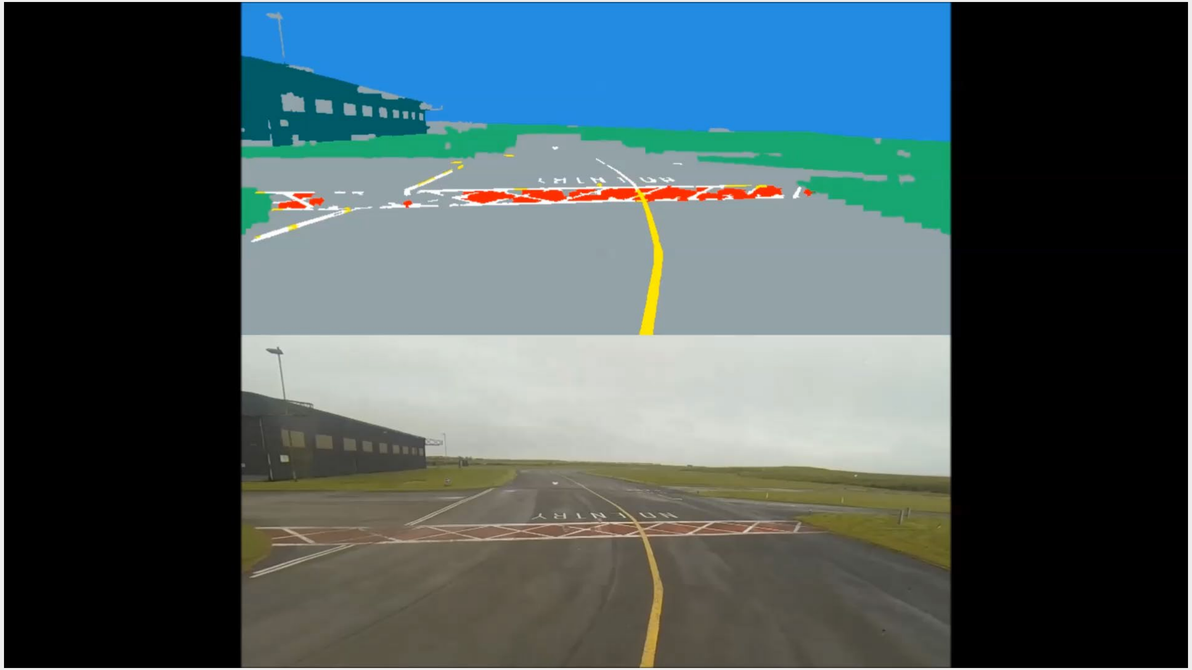
Control of small helicopters in wind.

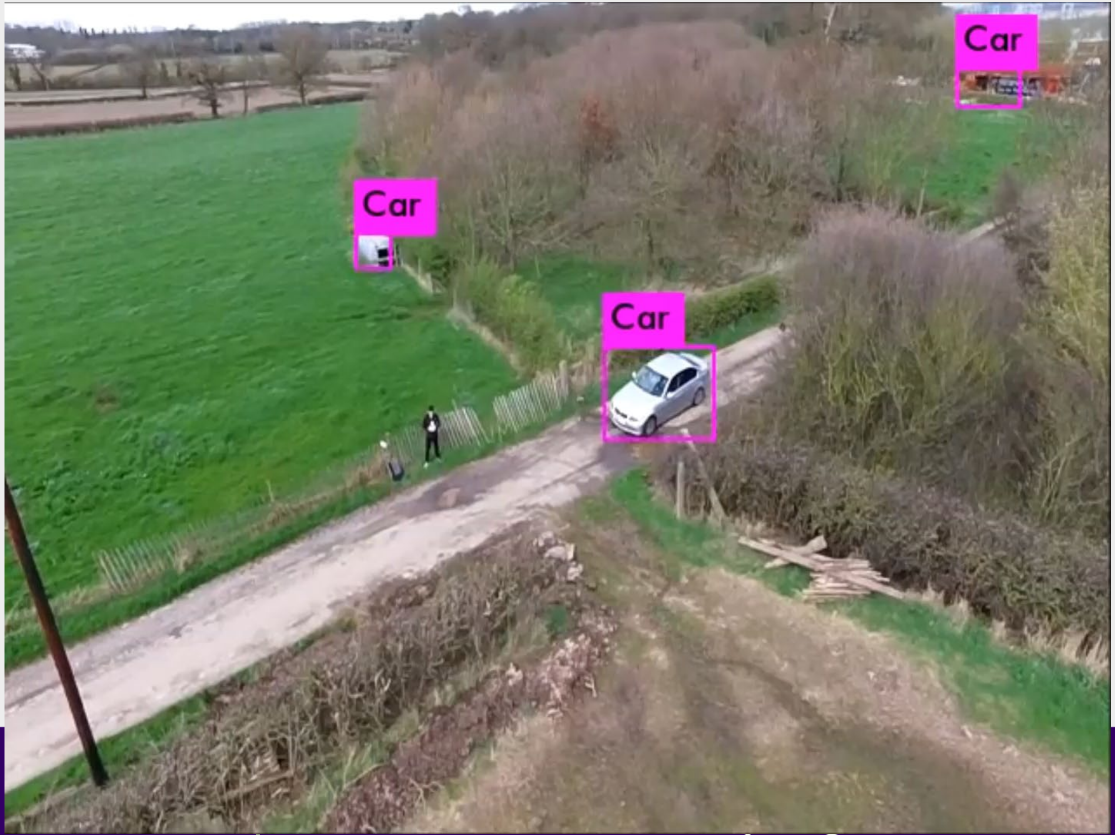
Autonomous systems laboratory

Towards autonomous terminal area operations for UAVs.

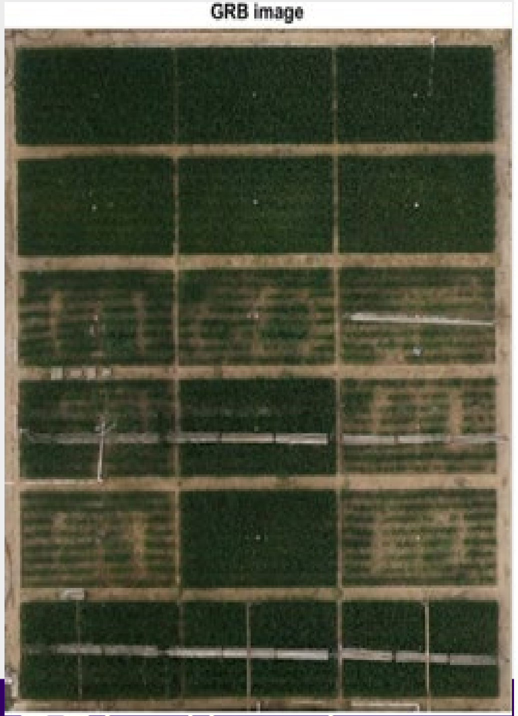


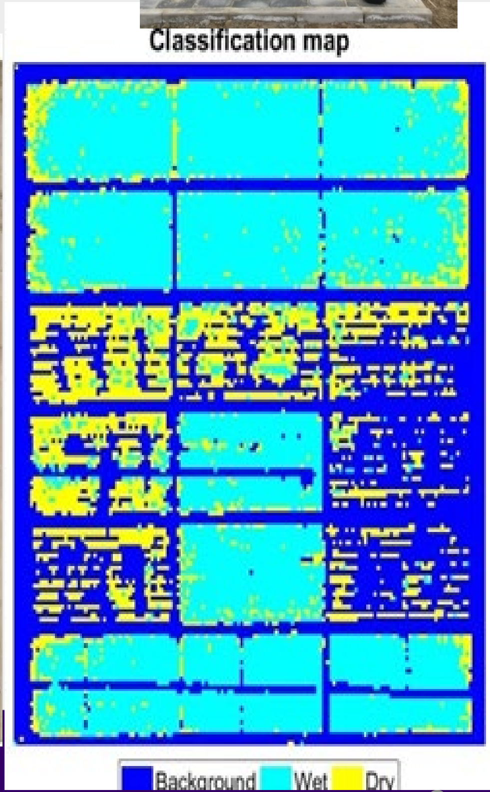
Autonomous systems laboratory

Ground target tracking and computer vision.



Agriculture





Wind – Sensing and handling

Surveying in wind.

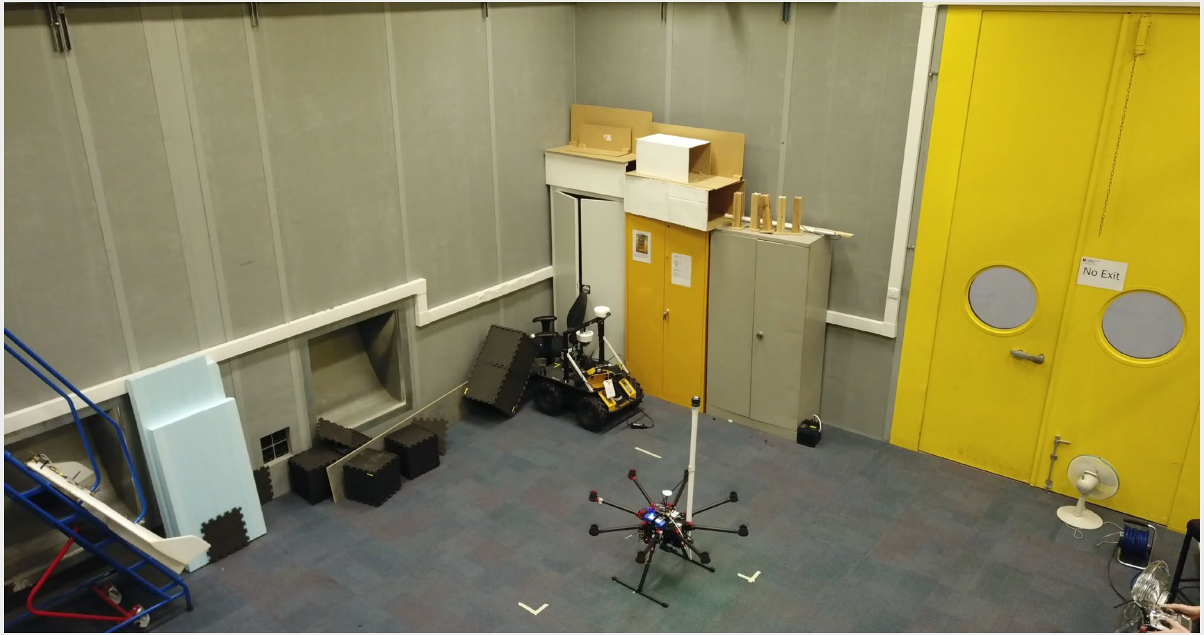
Survey of the wind.

Wind – Sensing and handling

Ultrasonic anemometer mounted on UAV.

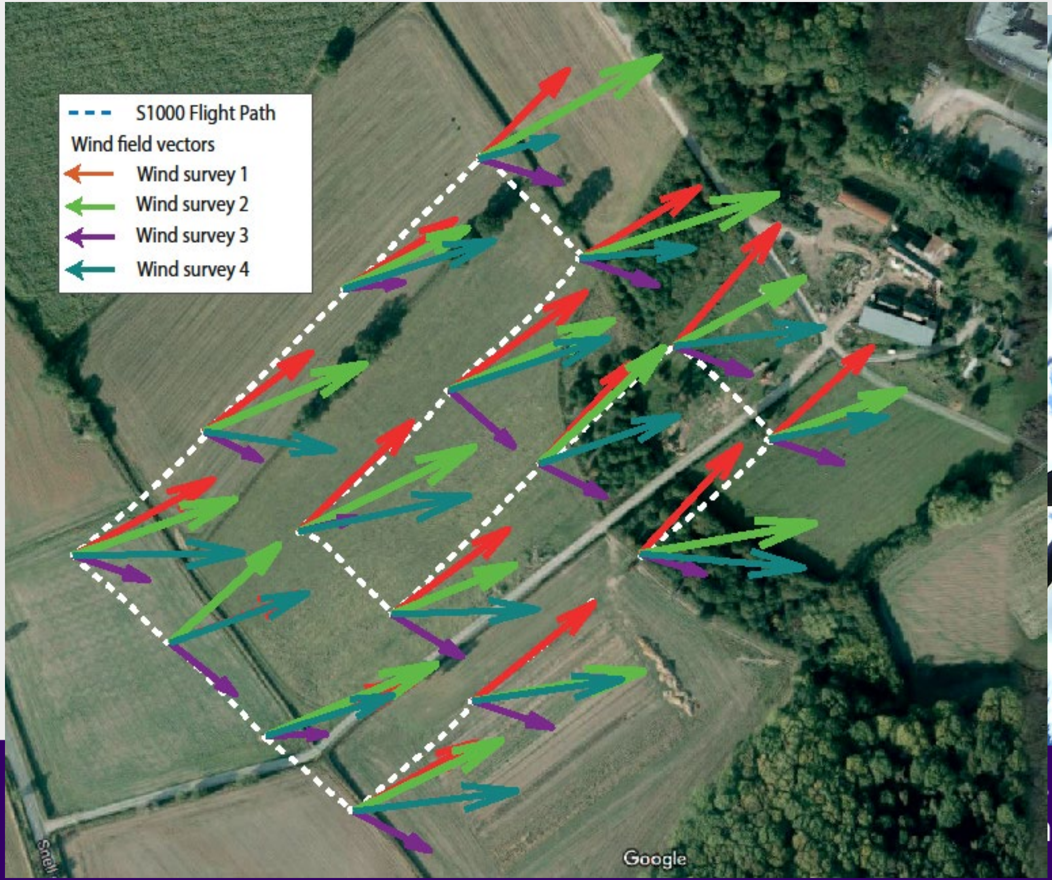
Stability test.

Effects on wind sensing?



Wind – Sensing and handling

Experiments measuring the wind field.



SOURCE TERM ESTIMATION USING A UAV

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Drones and robots to be used in Salisbury-style attacks to keep emergency services safe

share   Save

The drones and robots were tested last Wednesday in Gloucestershire CREDIT: DSTL/MOD/CROWN COPYRIGHT/PA

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Ministry of Defence

MoD to use drones and robots to investigate chemical attacks

Measure follows novichok poisonings in Salisbury and aims to avoid exposing emergency services to risk

Jessica Elgot
@jessicaelgot
Mon 17 Sep 2018 00.01 BST

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▲ One of the MoD's drones designed to test for chemical agents, provide 3D mapping and ide
Photograph: Dstl/MoD/Crown copyright/PA

Teams of officers in hazmat suits could be replaced by fleets of robots to investigate any future chemical attacks such as the n poisonings in Salisbury, the Ministry of Defence has announce

Defence chiefs are to trial using drones to examine sites for che and biological threats in order to avoid exposing emergency se personnel to risk.

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News story

UK tests life-saving chemical detection robots and drones

A new fleet of robots and drones designed to test for chemical agents, provide 3D mapping and identify casualties have been put through their paces by troops, police officers and scientists for the first time.

Published 17 September 2018
From: Home Office, Ministry of Defence, Defence Science and Technology Laboratory, and The Rt Hon Ben Wallace MP

Project Minerva tests cutting-edge robots and drones at DSTL, Porton Down. Crown copyright.

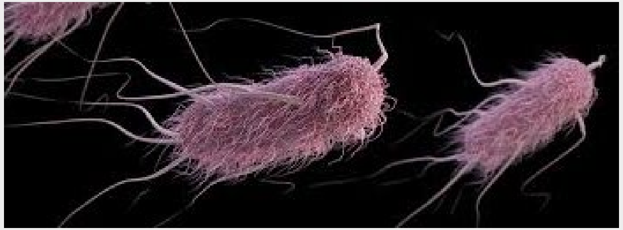
INTRODUCTION AND MOTIVATION

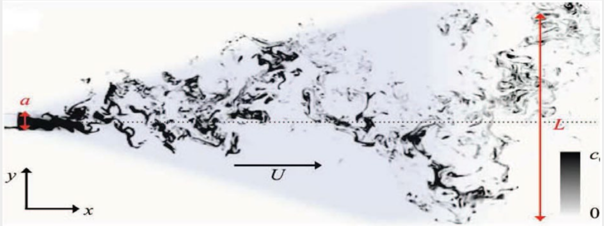
Introduction

- Emergency HAZMAT event.
- Where is the HAZMAT coming from?
- Where has it spread?
- The <u>Source term</u>
  - <u>Source location (x, y, z)</u>
  - <u>Emission rate (Q [grams/s])</u>

Background

- Finding an emitting source is not as easy as climbing concentration gradients!





- Sensor observations are noisy and sporadic, with more non-detections of hazard concentration then detections. – This is made worse with short sampling periods!

- A robust method is required to handle such poor sensing characteristics.

Estimation
And Planning

Simple algorithm overview

ALGORITHM DETAILS

Conceptual solution - Estimation

- Bayes probability theory is used to update probability densities of the source term θ in response to new sensor data d.
- Source term Parameters include Meteorological uncertainty:

$$P(\theta|d,I) = \frac{P(\theta|d)P(d|\theta)}{P(d)}$$

$$\theta = [X_0\ Y_0\ A_0\ U_0\ \phi_0\ D_0\ \tau_0]^T$$

Algorithm inputs (prior information):

X,Y location

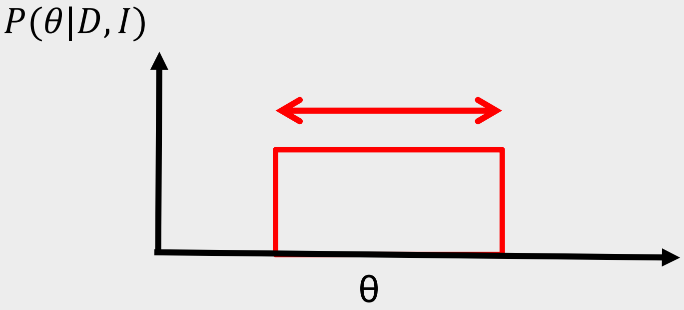
Emission rate

Wind speed

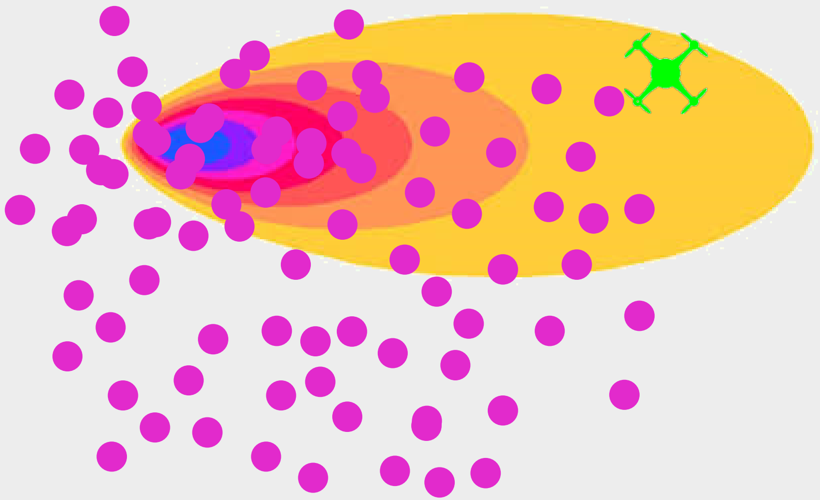
Wind direction

Diffusivity

Lifetime



Conceptual solution - Estimation



- Bayesian estimation is performed using a sequential Monte Carlo algorithm.
- Random samples (Pink dots) with low weights are resampled around highly weighted ones.
- One of the great challenges from experiments is in sensor modelling.

Modelling

Plume model

$$\mathcal{M}\left(\mathbf{p}_k, \Theta_k\right) = \frac{q_s}{4\pi\zeta_{s1}||\mathbf{p}_k - \mathbf{p}_s||} \exp\left[\frac{-||\mathbf{p}_k - \mathbf{p}_s||}{\lambda}\right] \times \exp\left[\frac{-(x_k - x_s)u_s \cos\phi_s}{2\zeta_{s1}}\right] \exp\left[\frac{-(y_k - y_s)u_s \sin\phi_s}{2\zeta_{s1}}\right]$$

Sensor model split

Detections

Non detections

$$p(z_k|\Theta_k) = \begin{cases} p(\overline{z}_k|\Theta_k) & \text{if } z_k > z_{thr} \\ p(\underline{z}_k|\Theta_k) & \text{if } z_k \leq z_{thr} \end{cases}$$

Probability of detection

Probability of non detection

$$p(\overline{z}_k|\Theta_k) = \frac{1}{\sigma_k\sqrt{2\pi}} \exp\left[-\frac{(z_k - \mathcal{M}(\mathbf{p}_k, \Theta_k))^2}{2\sigma_k^2}\right],$$

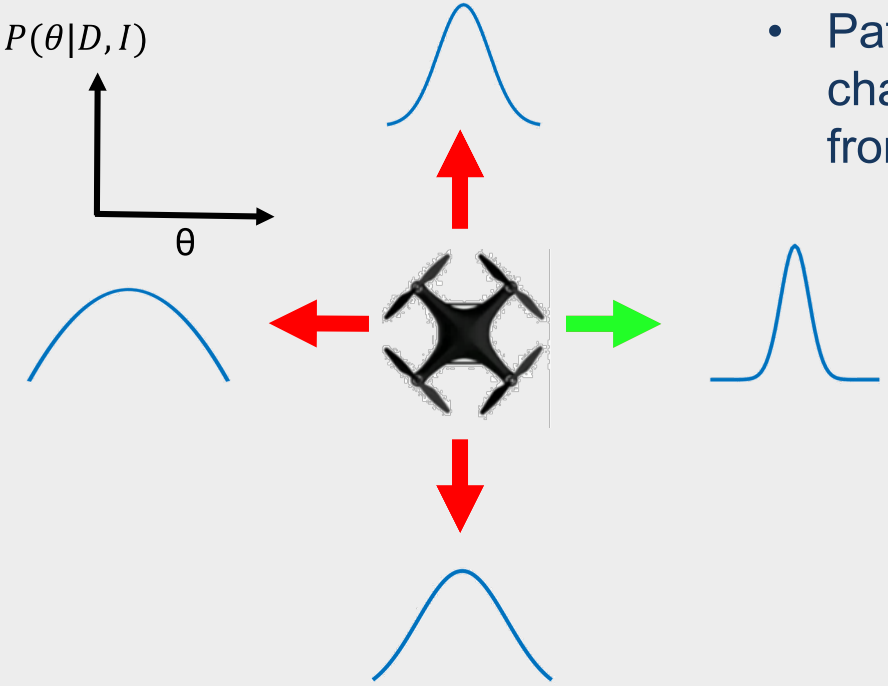
$$p(\underline{z}_k|\Theta_k) = \left(P_b \times \frac{1}{2}\left[1 + \text{erf}\left(\frac{z_{thr} - \mu_b}{\sigma_b\sqrt{2}}\right)\right] + P_m + P_s \times \frac{1}{2}\left[1 + \text{erf}\left(\frac{z_{thr} - (\mu_b + \mathcal{M}(\mathbf{p}_k, \Theta_k))}{\sigma_k\sqrt{2}}\right)\right]\right)$$

Background noise

Intermittency or missed detection

Below sensor threshold

Conceptual solution - Planning



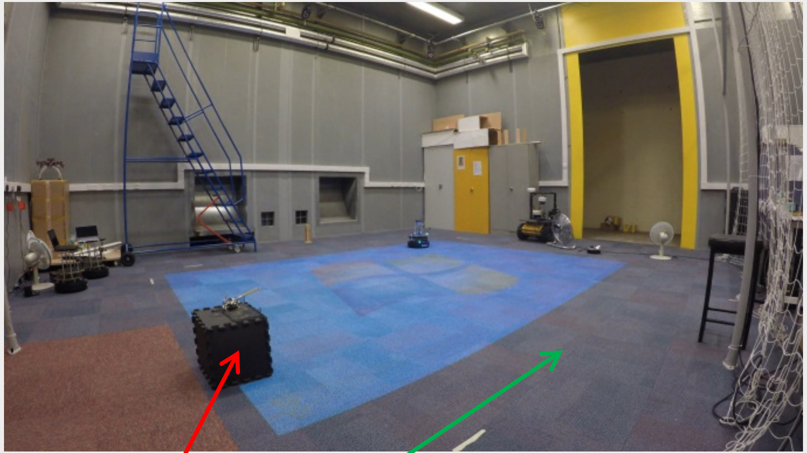
- Path planning is based on the expected change in what we know about the source from a manoeuvre.

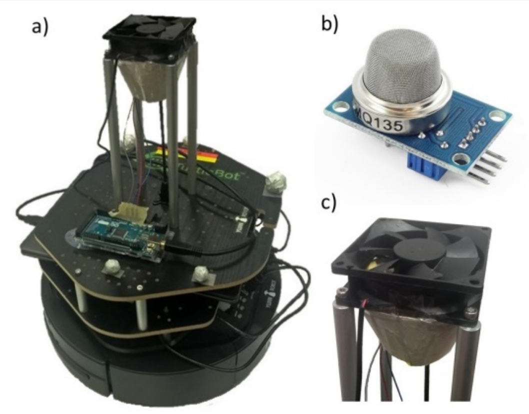
- Consider new locations to take a measurement from
- At each position:
  - Given what we know
  - Estimate what we expect to see
  - Approximate what I expect to learn (KL divergence)
- Move to most informative choice

Indoor experiments with a ground robot

EXPERIMENTS

Indoor experiment





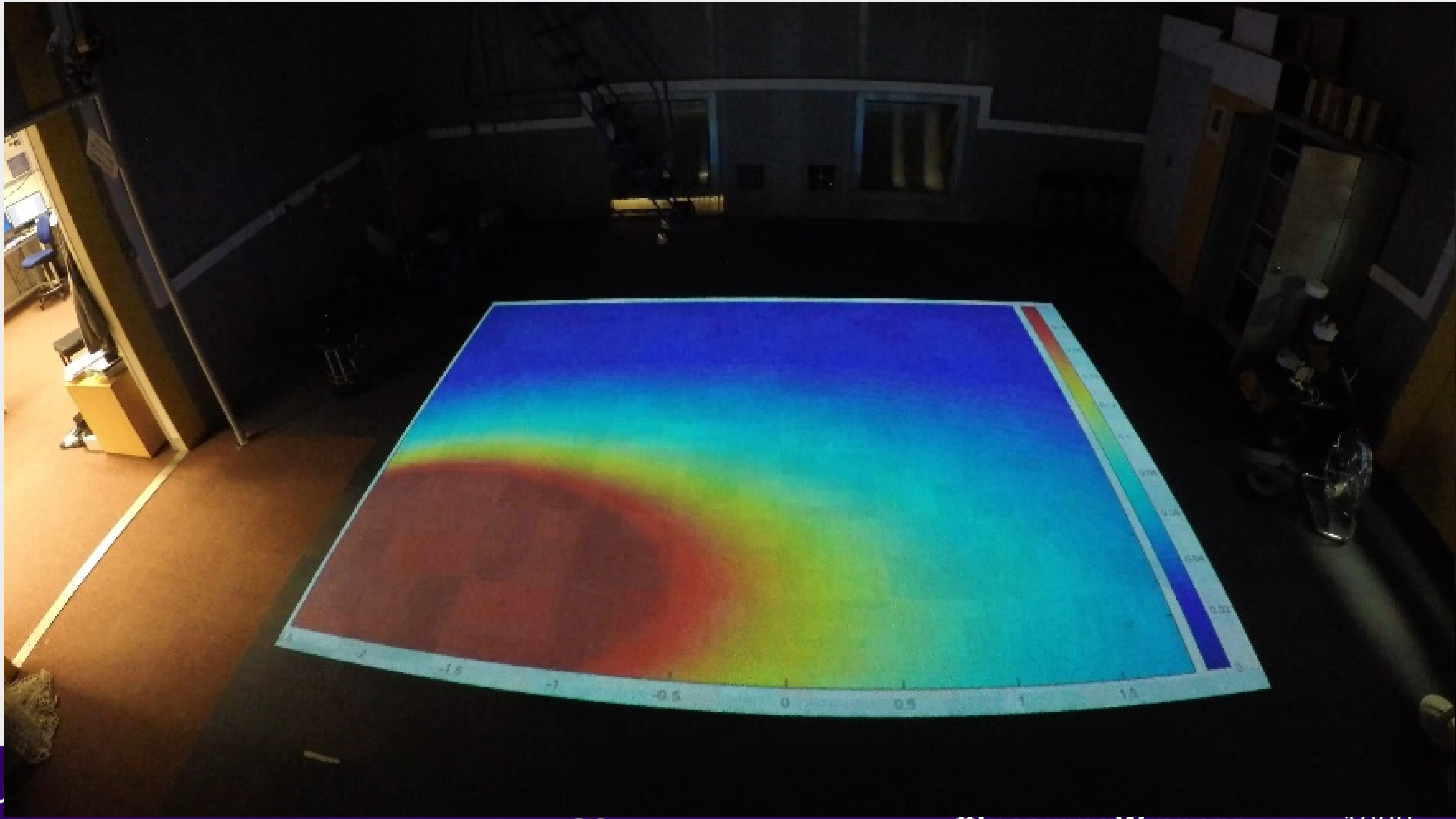
Wind direction

Smoke source

Indoor experiment

Result

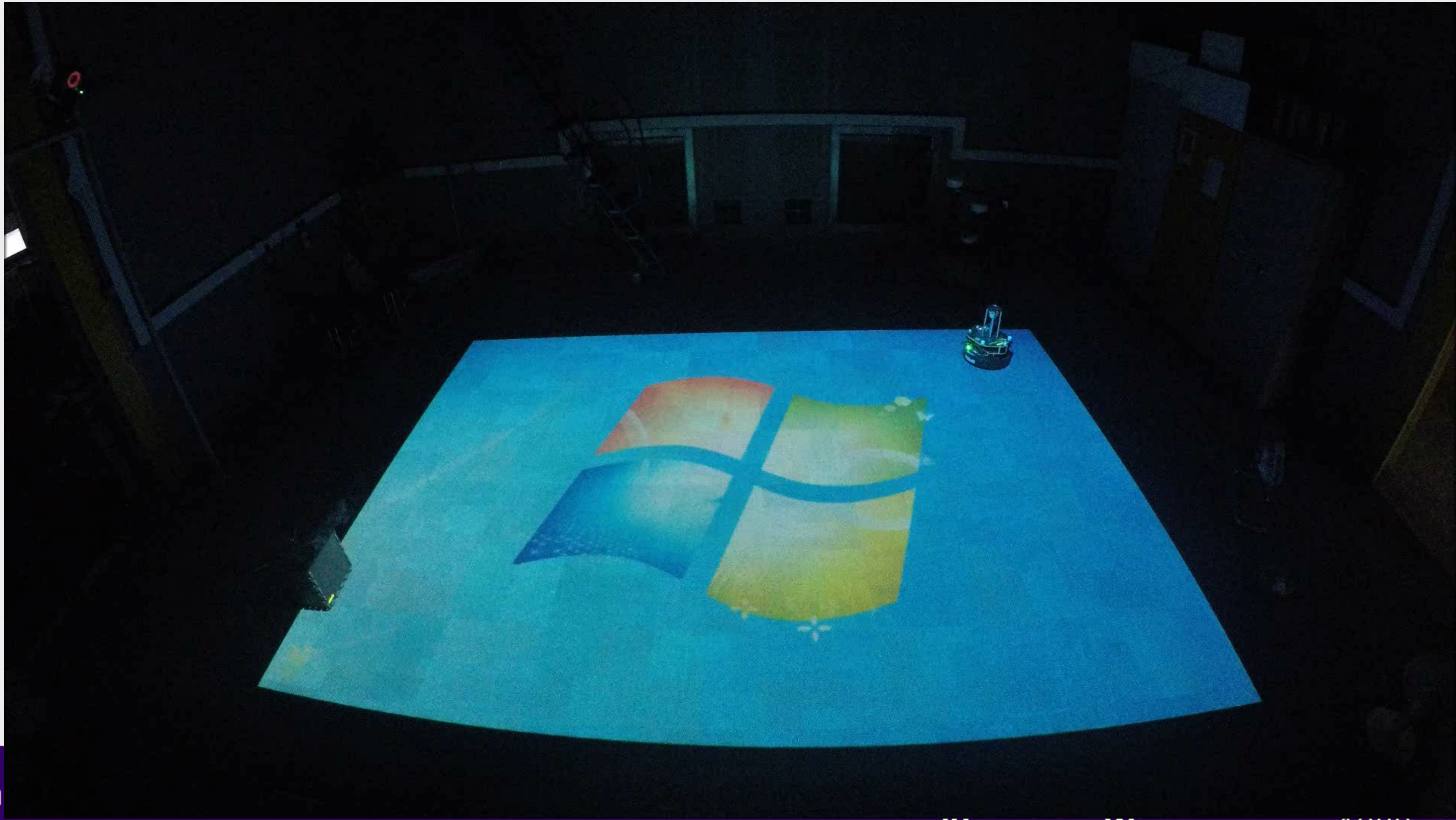
Example run with 2 burning incense sticks



Result

Example run with 6 burning incense sticks.

Search is much more effective, towards the source.



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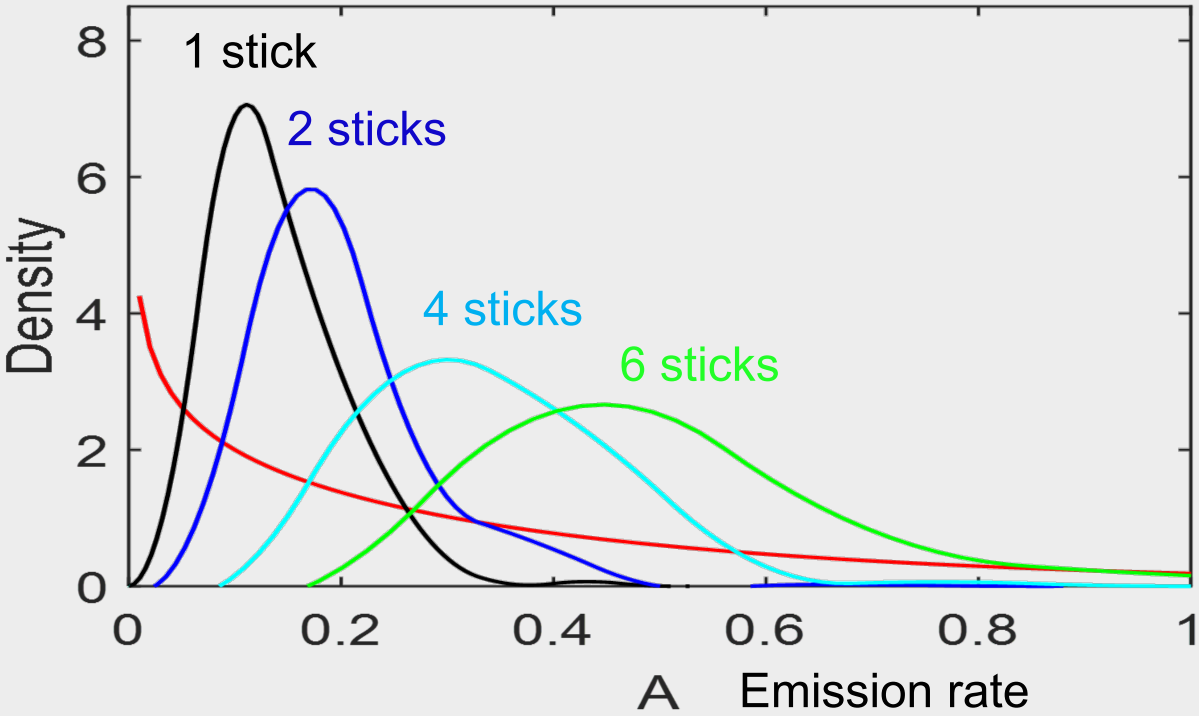
#InspiringWinners since 1909

Result – Emission rate estimates



Summary – Indoor experiments with a ground robot

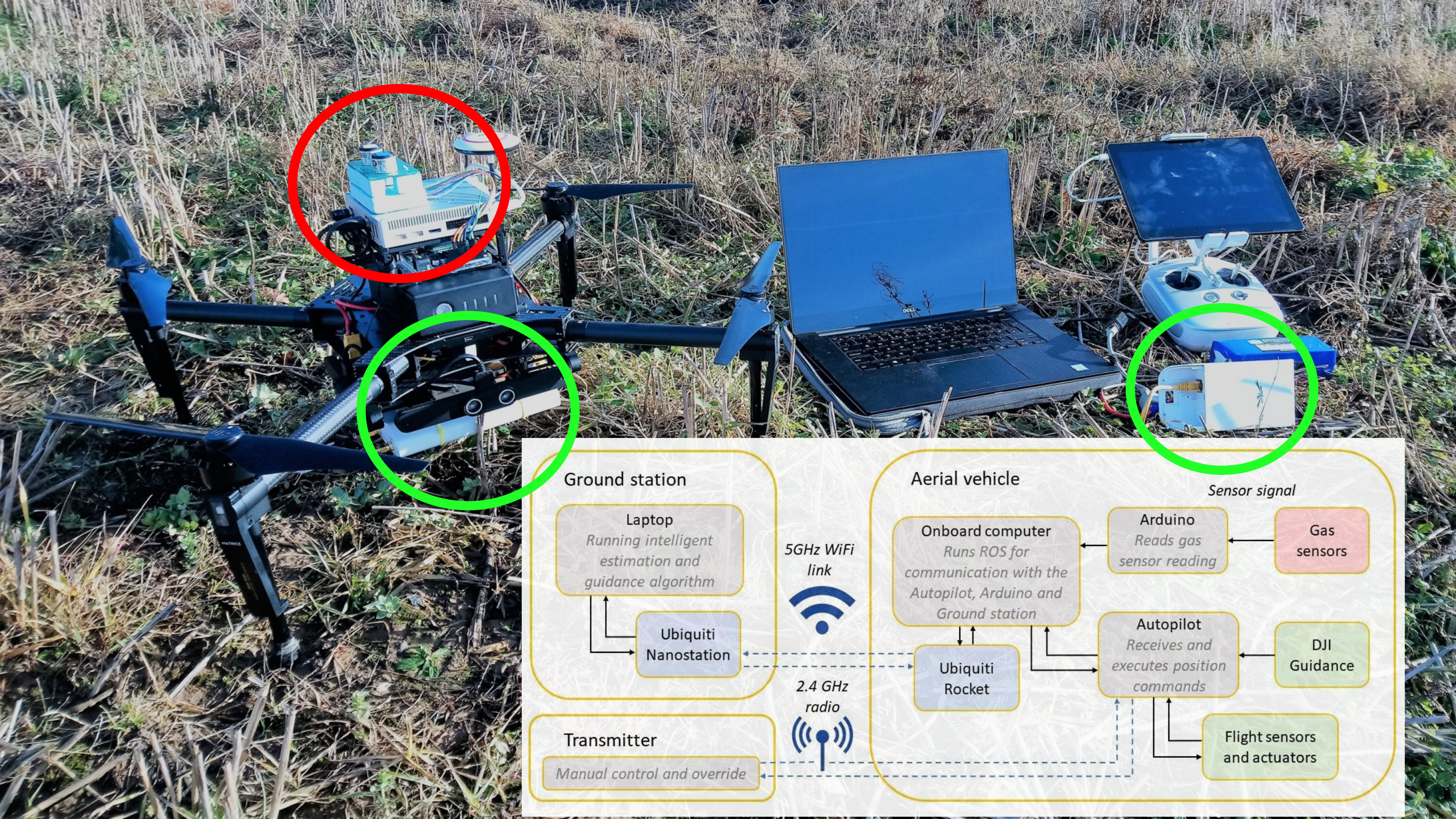
- First STE experiments performed using an autonomous robot with an information based planning algorithm.
- The system was very robust and accurate.
- Next step was to extend and test the system in an outdoor environment using a UAV.

Experiments with a UAV

EXPERIMENTS - SYSTEM

System overview

	PID-A12	PID-AH2
Power (max)	85mW	85mW
Weight	<8g	<8g
Min conc (isobutylene)	50ppb	1ppb
Conc range	6000ppm	50ppm
Material detected	Anything ionised by a 10.6eV UV lamp (see next slide)	



Ground station
Laptop
Running intelligent estimation and guidance algorithm
Ubiquiti Nanostation
5GHz WiFi link
2.4 GHz radio
Transmitter
Manual control and override
Aerial vehicle
Sensor signal
Onboard computer
Runs ROS for communication with the Autopilot, Arduino and Ground station
Arduino
Reads gas sensor reading
Gas sensors
Ubiquiti Rocket
Autopilot
Receives and executes position commands
DJI Guidance
Flight sensors and actuators

Outdoor experiments with a UAV

EXPERIMENTS - SETUP

Experiment setup

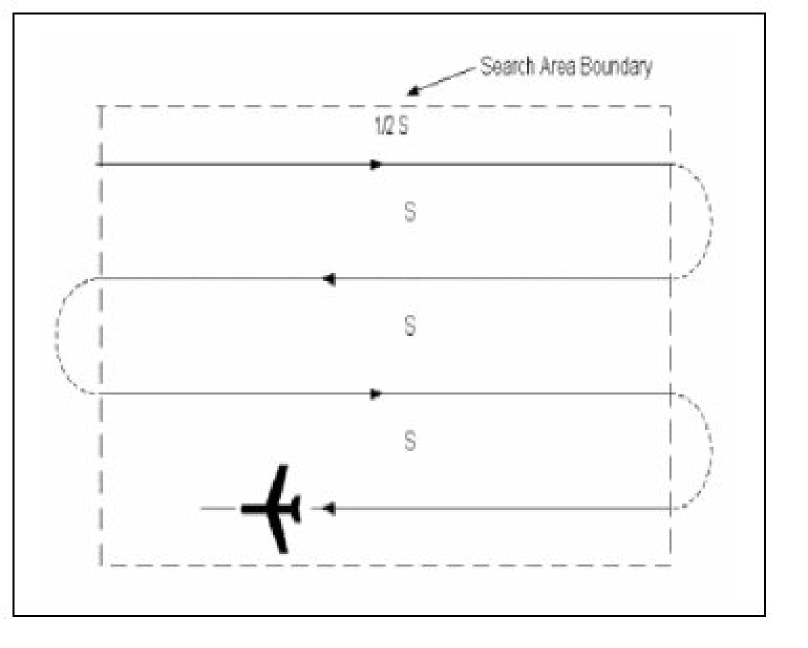
Acetone source, release roughly 1.5grams/s

Search area, starting position, source position and wind direction

Outdoor experiments with a UAV

EXPERIMENTS – UNIFORM FLIGHT PATTERN

Experiments – Uniform flight pattern



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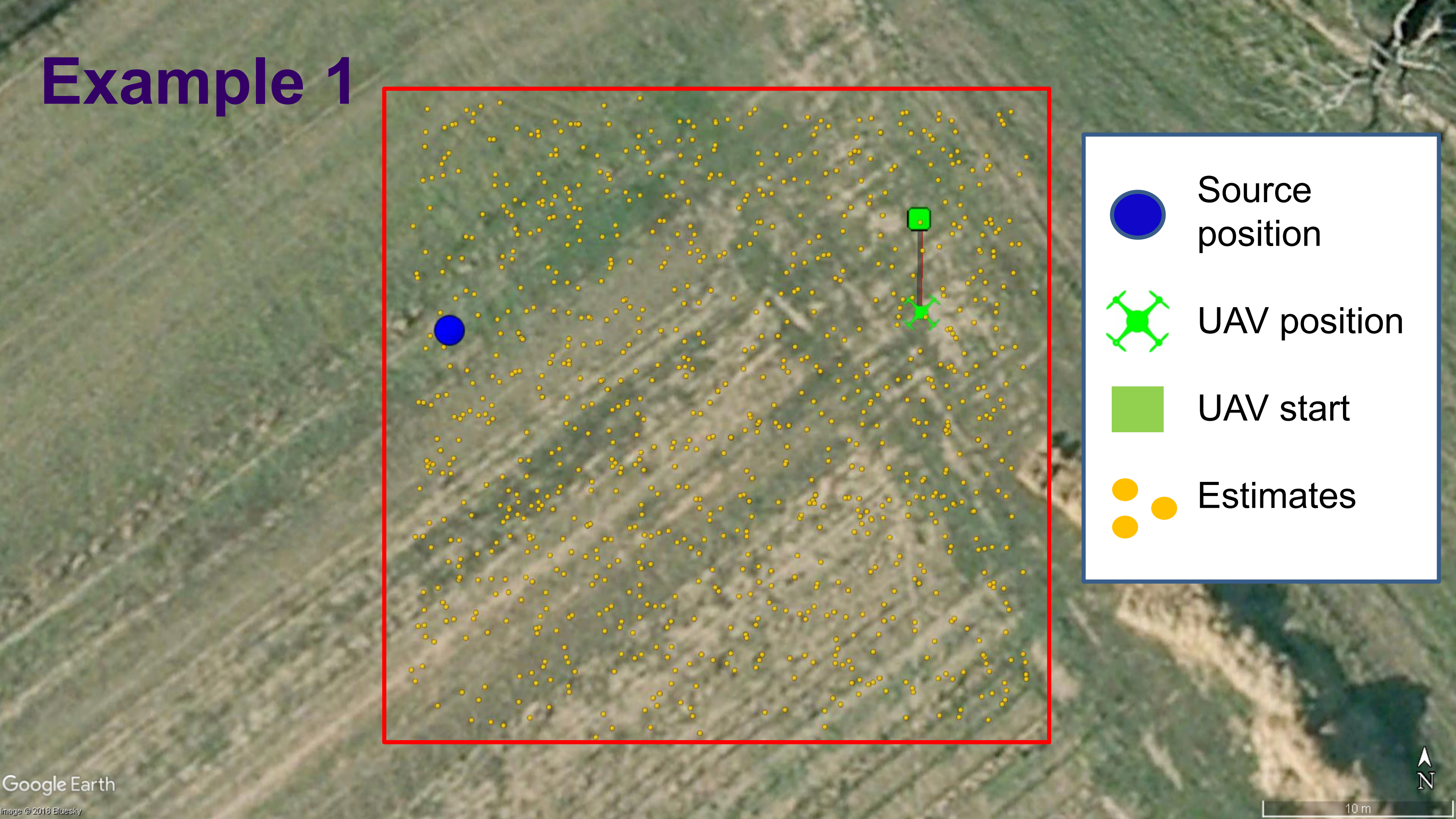
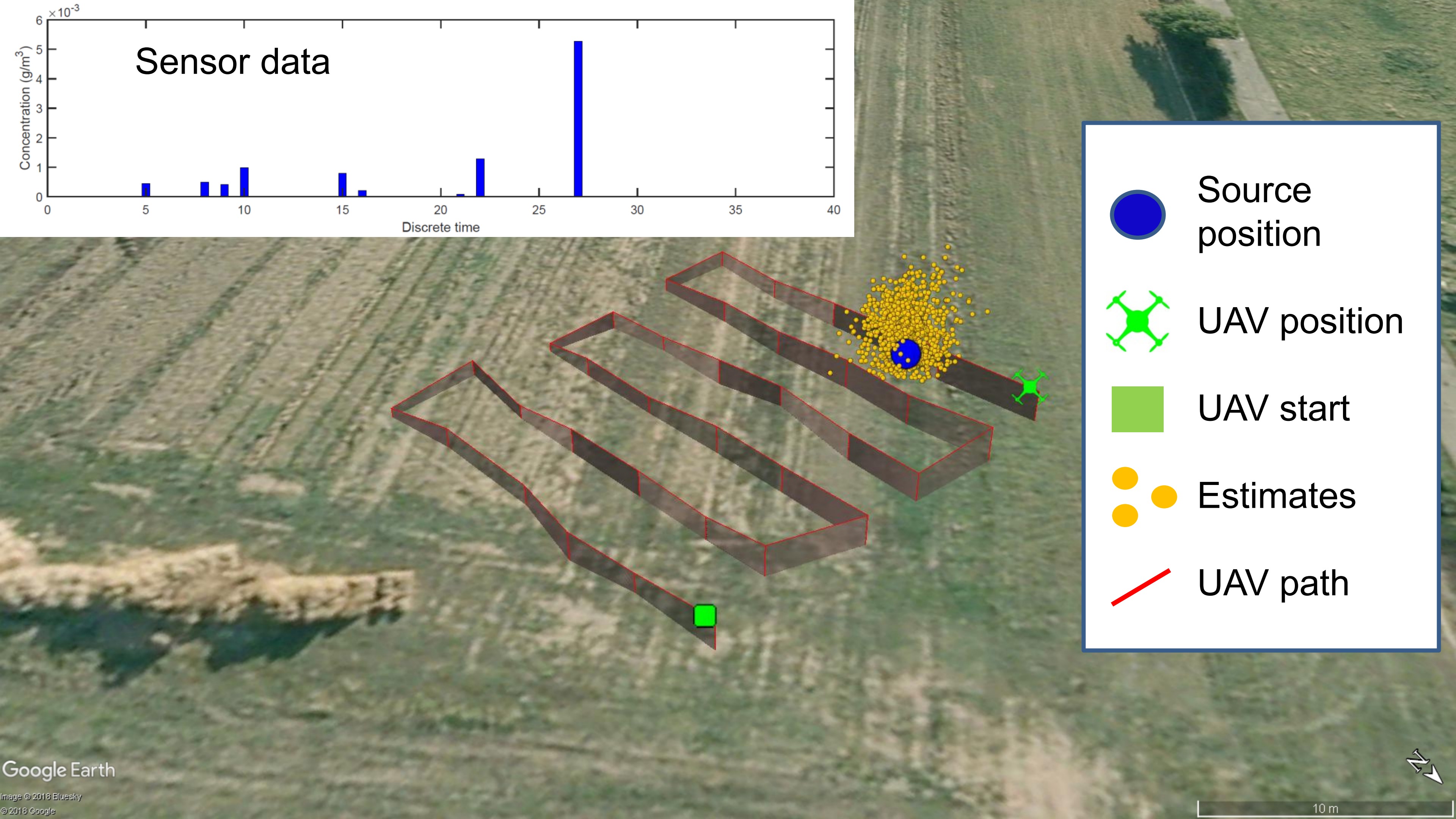
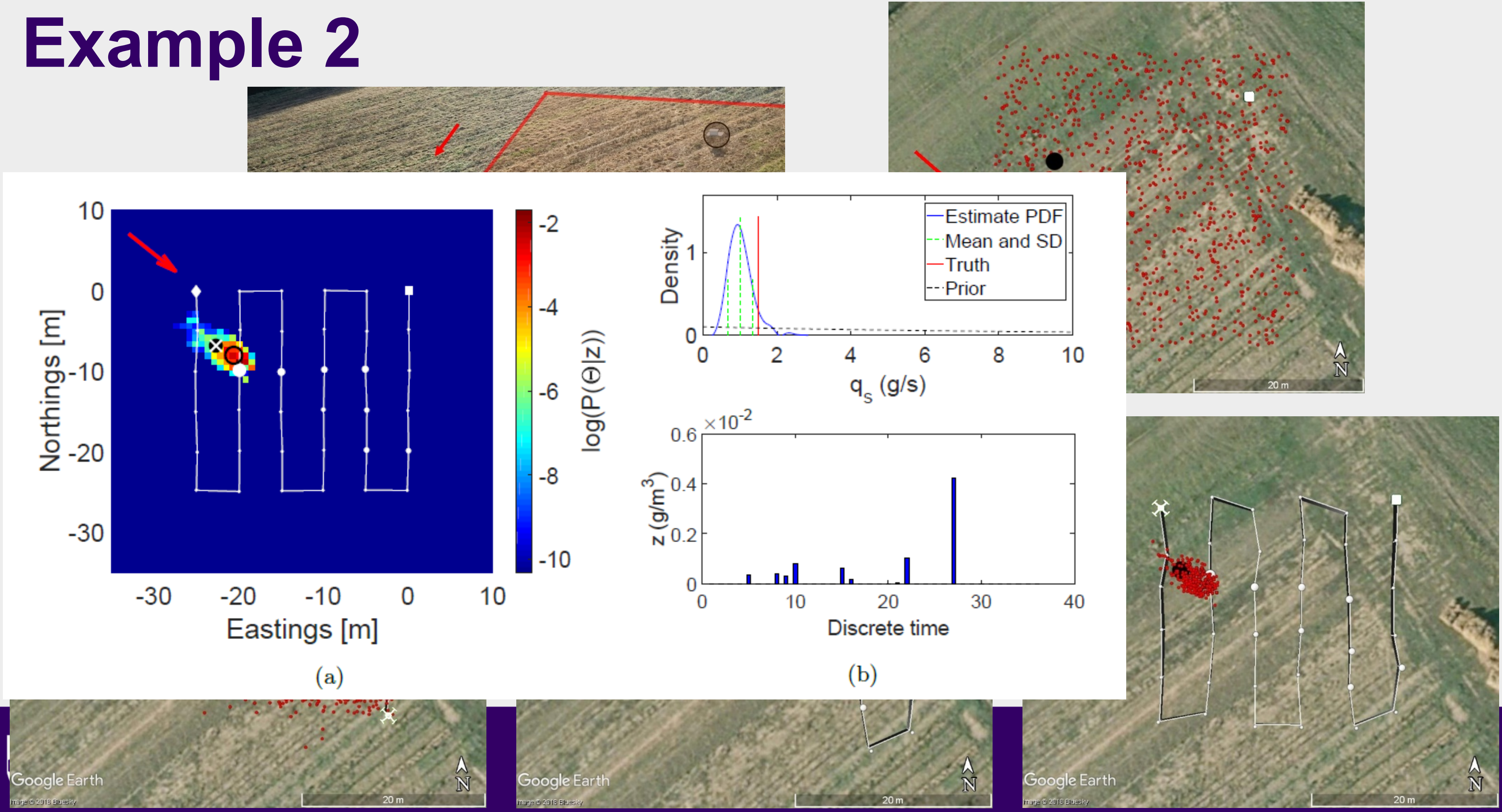
Example 1


Source position
UAV position
UAV start
Estimates
Google Earth
Image © 2018 Bluesky
N
10 m



Sensor data
Concentration (g/m³)
×10⁻³
Discrete time
Source position
UAV position
UAV start
Estimates
UAV path
Google Earth
Image © 2018 Bluesky
© 2018 Google
10 m

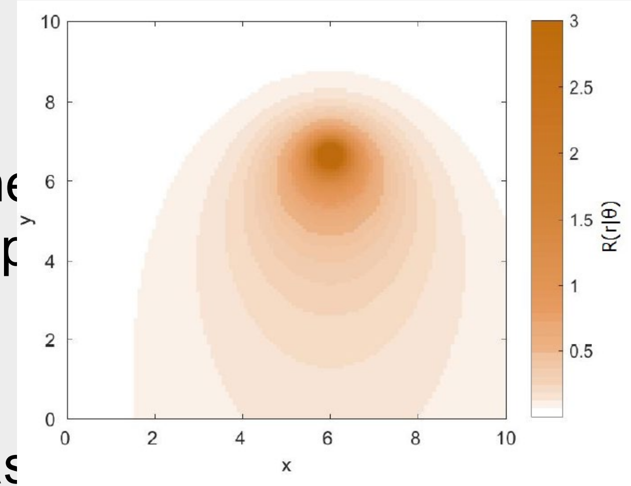
Example 2

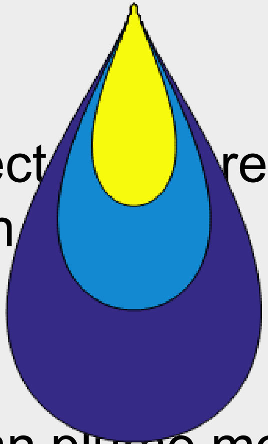


Northings [m]
Eastings [m]
log(P(Θ|z))
(a)
Density
Estimate PDF
Mean and SD
Truth
Prior
q_s (g/s)
$\times 10^{-2}$
z (g/m^3)
Discrete time
(b)
Google Earth
20 m
N

Results

- We performed 27 STE experiments using a uniform sweep flight pattern





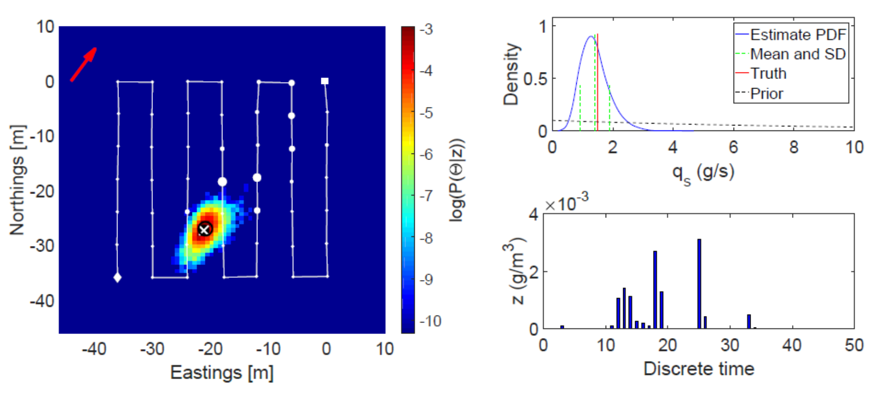
- The performance of the ubject rent flying altitudes, wind sp veen measurements.

- The STE accuracy was ssian plume model and the Isotropic plume model.

Results – Different altitudes

Altitude = 1.75m

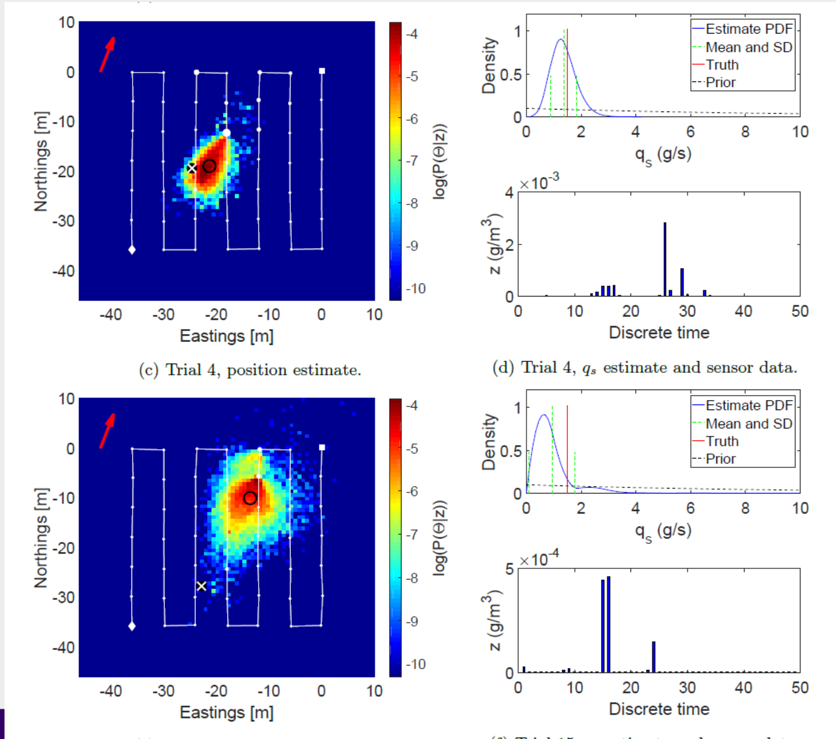
Altitude = 1.2m



(a) Trial 14, position estimate.

(b) Trial 14, q_s estimate and sensor data.

Altitude = 1.4m



(c) Trial 4, position estimate.

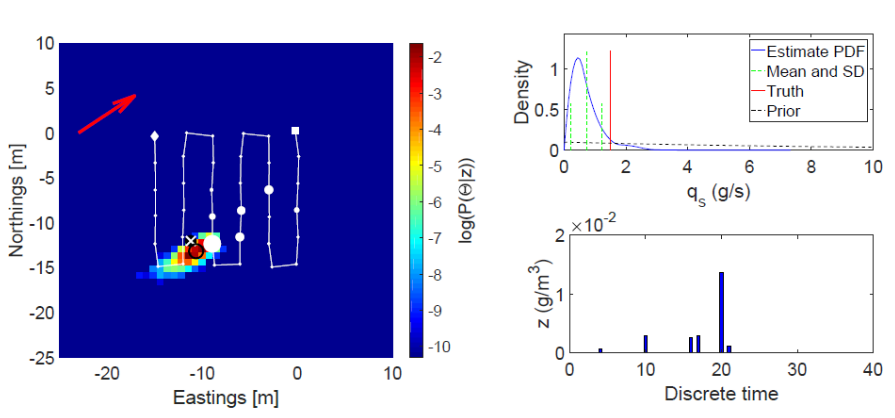
(d) Trial 4, q_s estimate and sensor data.

(e) Trial 15, position estimate.

(f) Trial 15, q_s estimate and sensor data.

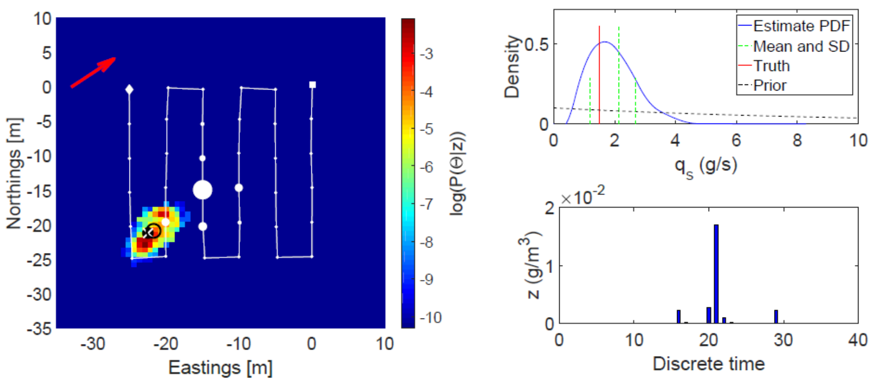
Results – Different step sizes during flight

Altitude = 3m



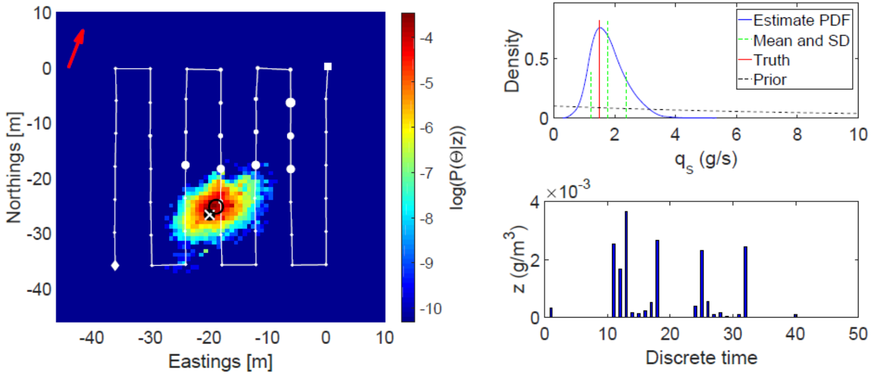
(a) Trial 22, position estimate. (b) Trial 22, q_s estimate and sensor data.

Altitude = 5m



(c) Trial 16, position estimate. (d) Trial 16, q_s estimate and sensor data.

Altitude = 6m



(e) Trial 12, position estimate. (f) Trial 12, q_s estimate and sensor data.

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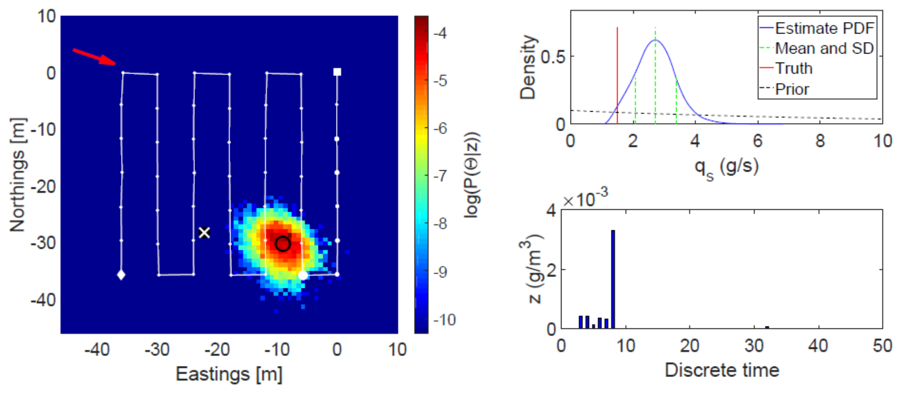
Results – Different wind speeds

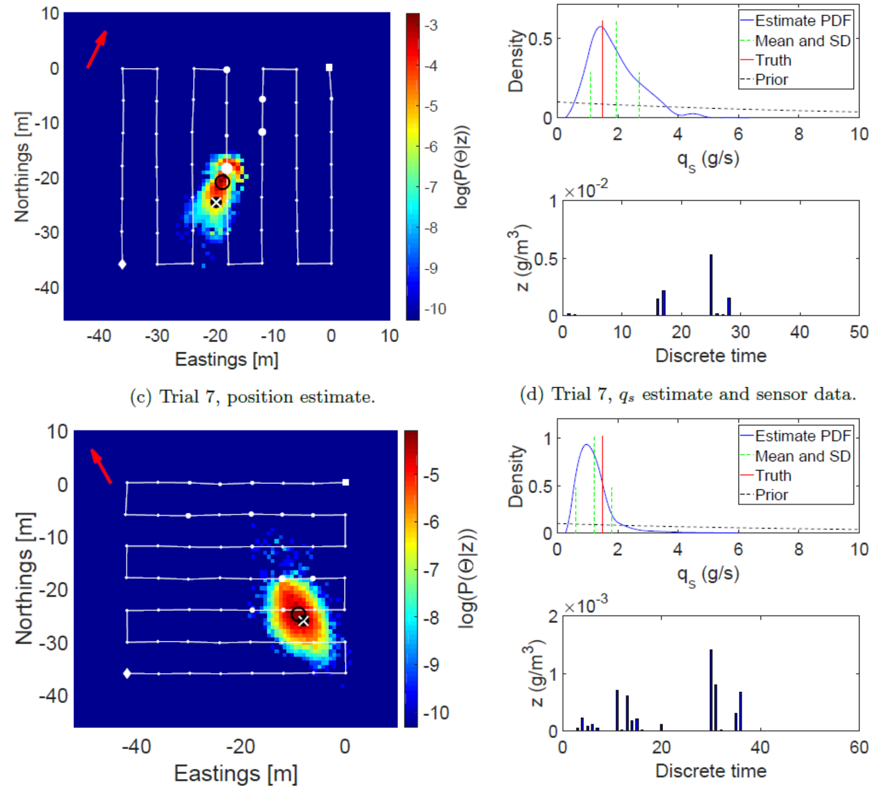
Wind speed = 3m/s



(a) Trial 9, position estimate. (b) Trial 9, q_s estimate and sensor data.

Wind speed = 5m/s

Wind speed = 7m/s



(c) Trial 7, position estimate. (d) Trial 7, q_s estimate and sensor data.

(e) Trial 24, position estimate. (f) Trial 24, q_s estimate and sensor data.

Results – Gaussian plume vs Isotropic plume model

Table 2: RMSE in the position and emission rate estimates using the GP and IP dispersion models.

Data subset	Position RMSE [m] GP model	Position RMSE [m] IP model	Emission RMSE [g/s] GP model	Emission RMSE [g/s] IP model
All data	4.75	3.35	0.75	0.65
Step size = 6m	5.37	4.08	0.77	0.63
Step size = 5m	3.38	2.69	0.61	0.73
Step size = 3m	3.55	1.72	0.70	0.66
Height ⩾1.5m	5.22	3.33	0.95	0.66
Height <1.5m	3.88	2.45	0.67	0.69
Wind speed ⩽3m/s	6.45	4.65	0.85	0.62
Wind speed >3m/s	3.86	2.63	0.69	0.66

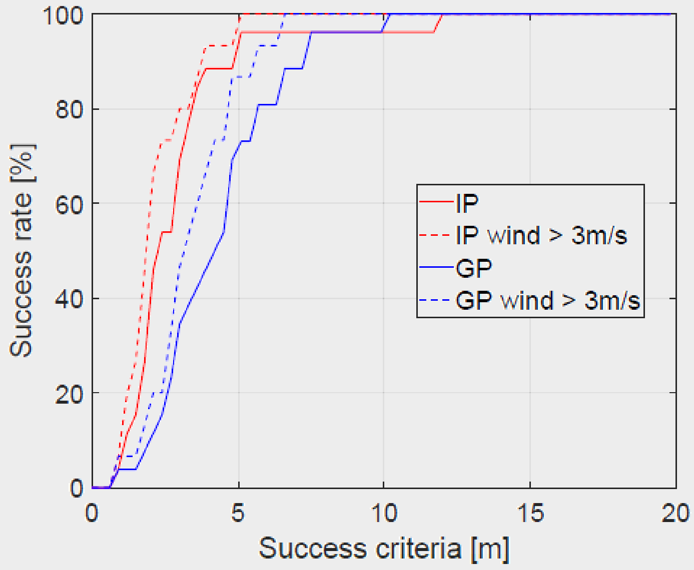


Figure 13: Success rates of the system.

Summary – Uniform sweep STE

- Our first successful STE experiments performed in outdoor conditions using a UAV.
- The system performed best flying at lower altitudes in higher wind speeds (further inside the plume in a more stable atmosphere).
- Next step was to test the information based planning algorithm.

Outdoor experiments with a UAV

EXPERIMENTS – INFORMATIVE SEARCH ALGORITHM

Video

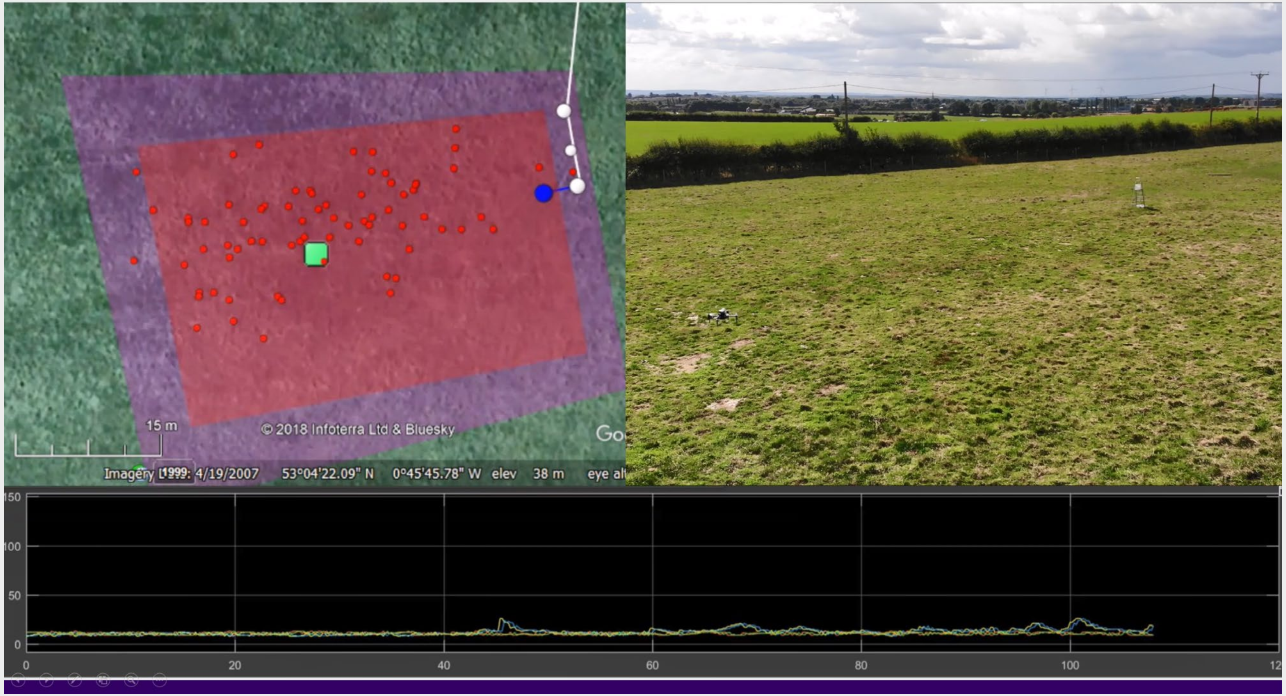
UAV position

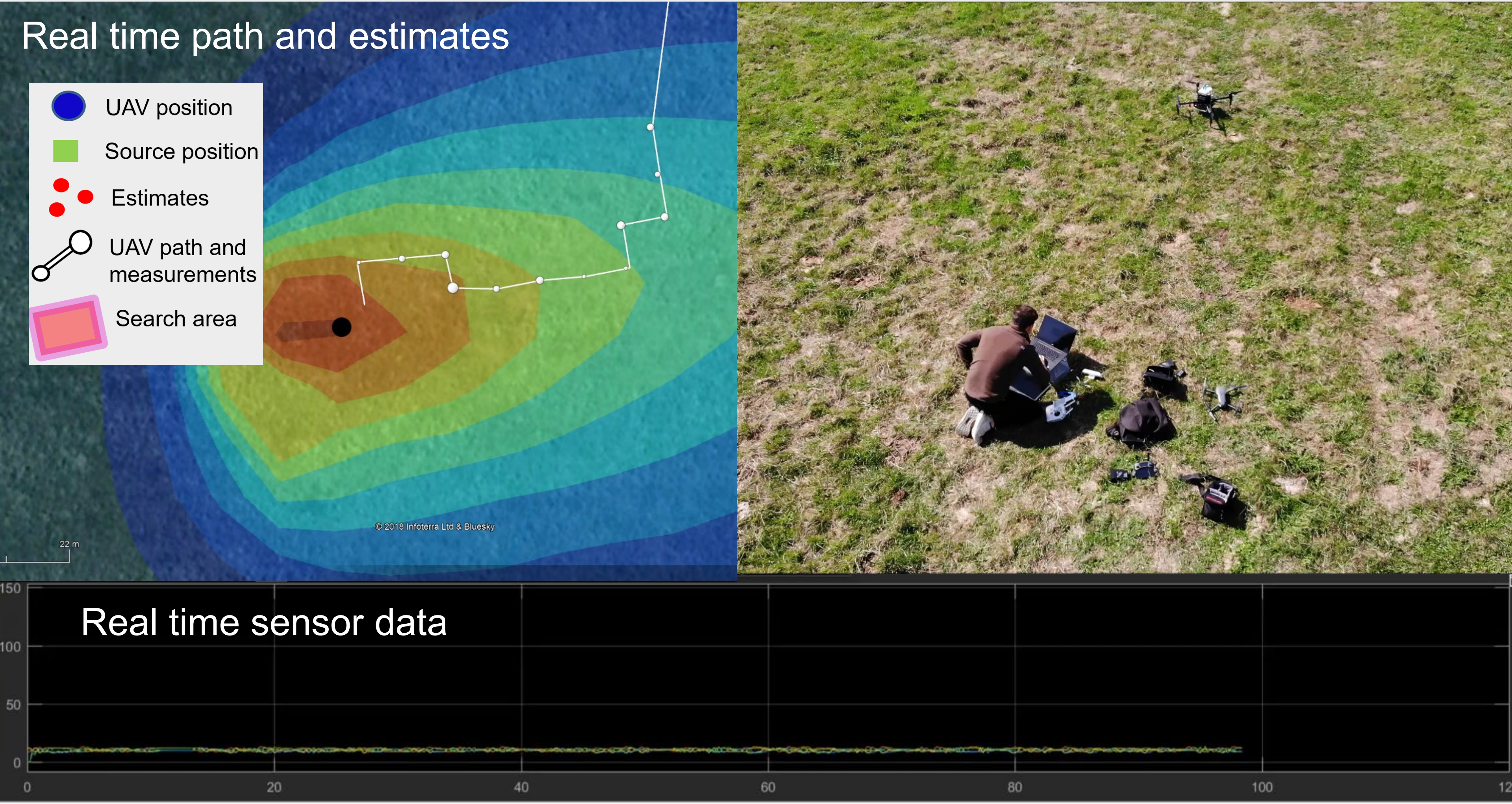
Source position

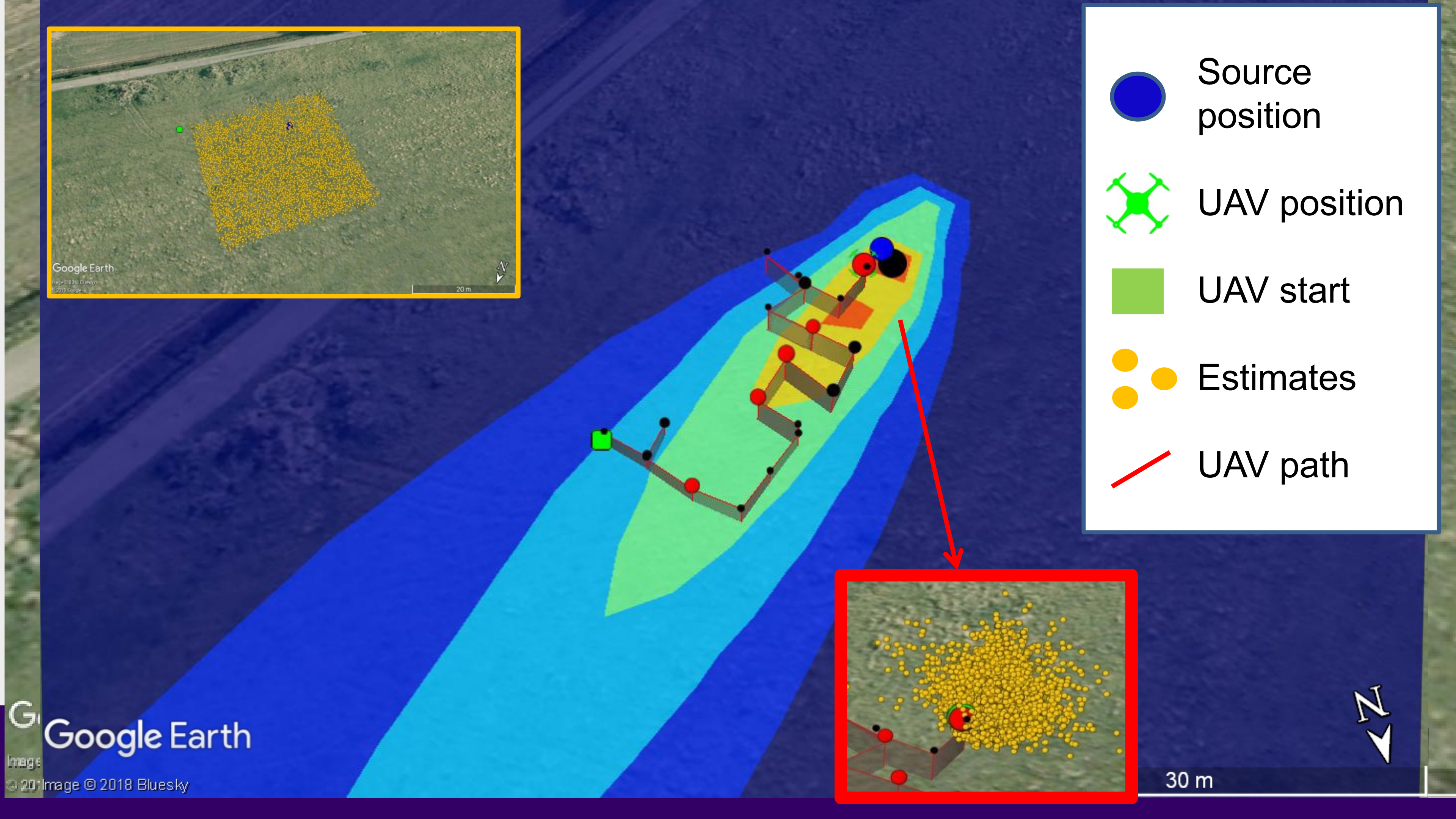
Estimates

UAV path and measurements

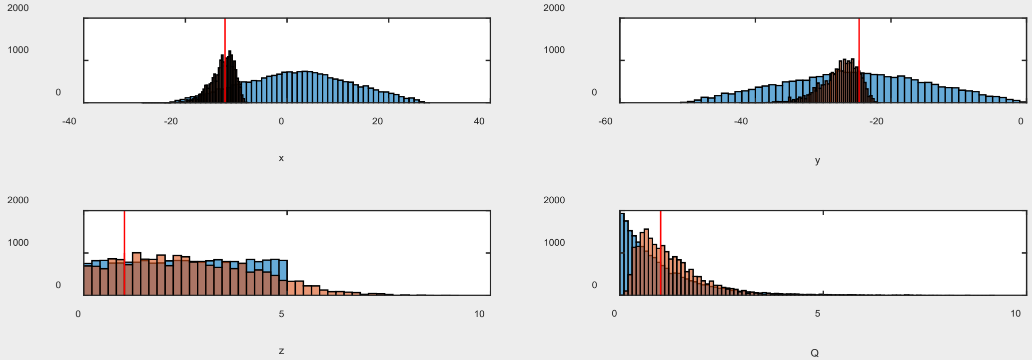
Search area




Real time path and estimates
UAV position
Source position
Estimates
UAV path and measurements
Search area
© 2018 Infoterra Ltd & Bluesky
22 m
Real time sensor data
150
100
50
0
0
20
40
60
80
100
12


Google Earth
20 m
N
Source position
UAV position
UAV start
Estimates
UAV path
Google Earth
Image © 2018 Bluesky
30 m
N


Google Earth
20 m


2000
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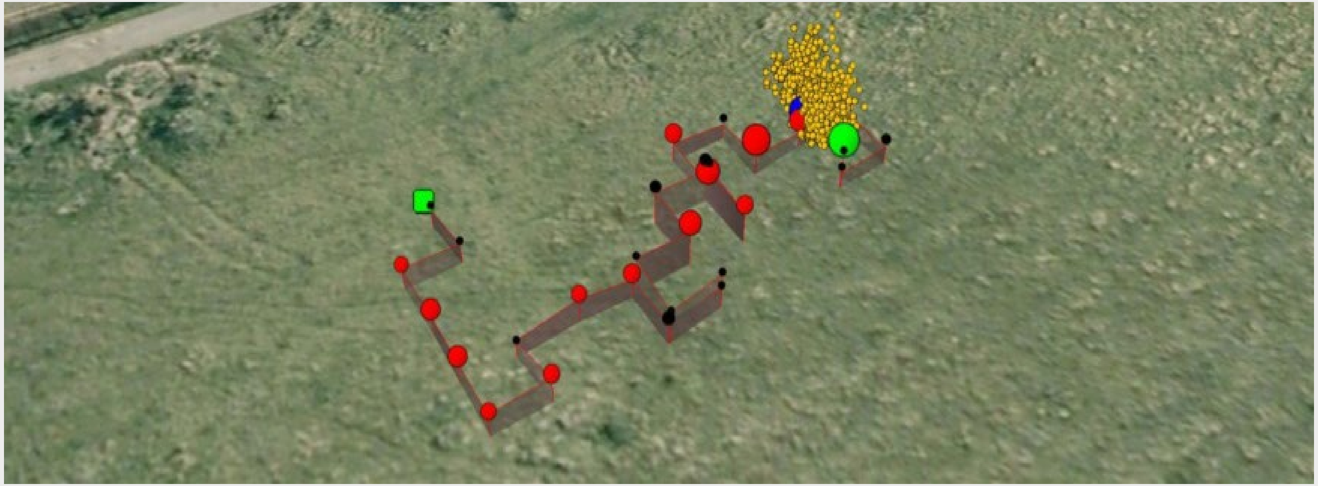
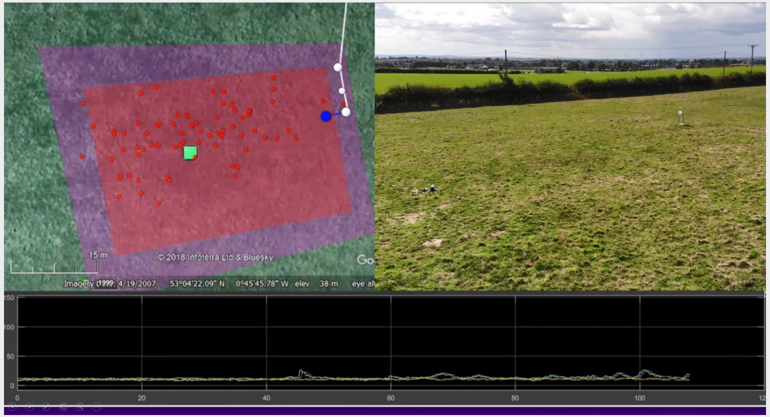


Informative Search Results

- Similarly to the sweep, accuracy is relative to the step size between measurements.



- Estimates the source term in less than half the time of the sweep (on average).

- Struggles in changing wind conditions due to model assumptions.

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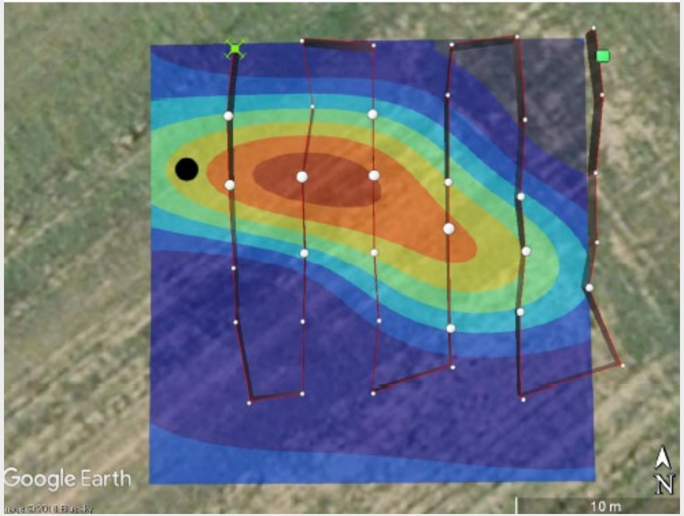
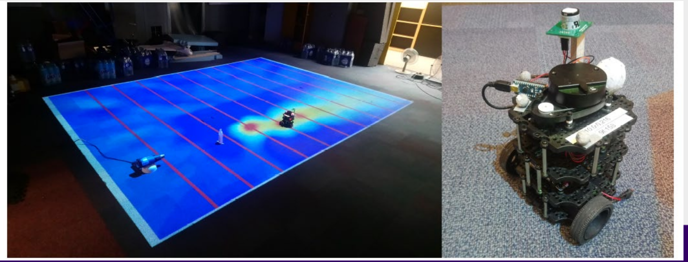
Summary

- Source term estimation using mobile sensors has been taken from purely theoretical work to real world experiments.
- We have shown that it is a viable method of response to HAZMAT incidents.
- Next steps will continue to extend the system to work in different environments and improve its performance.

Next steps

- Extend to handle changing wind conditions.
- Handle cluttered or urban environments (plan informative paths around obstacles)
- Plan more informative paths considering measurements in the future and whilst moving.
- Multiple vehicle coordination for STE and large area reconnaissance and survey for HAZMAT.
- Multiple source STE using UAV.
- Mapping using multiple UAVs
  - Include physics and account for non-detections





Questions?