Progress Toward the Potential for Continuous Leak Detection and Quantification

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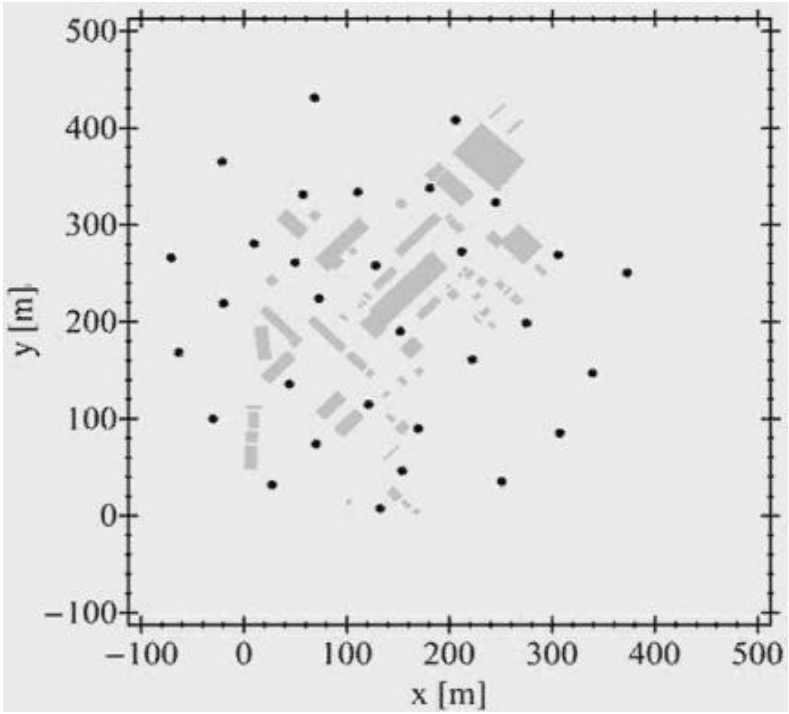
Fugitive Emissions: Motivation

- Fugitive emissions are significant sources:
  - UNFCCC 2011 estimates:
    - 576 Mt CO_2 eq.
    - 3.8% of reported GHG emissions
- Fugitive emissions are often economic to mitigate based on value of gas alone
- Advances in IR camera technology and operation protocols have improved detection ability
  - Quantification remains a challenge
- Could leaks be detected and *quantified* on a quasi-continuous basis?

Fugitive Emissions: Inverse / Sensor Oriented Analysis

Is there another approach?

- Starting from measureable sensor data, what source(s) would reproduce observations?
  - Sensor data contains information about upwind concentrations
- Similar approaches used on continental scale since 1980s
- Project considers two classes of methods:
  - Statistical (trajectory based)
  - Adjoint (gradient optimization based)



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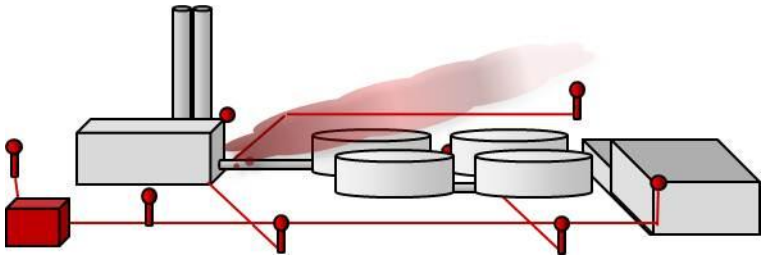
What is the concept?

- Semi-permanent concentration sensor network combined with wind direction and speed
  - Quasi-continuous operation
  - Directed maintenance to new leaks as they appear
  - Reduced costs and reduced emissions



- Current research focus:
  1. Novel detection system design
  2. Numerical testing and development of statistical source location algorithms
  3. Simulation and development of advanced, gradient adjoint based, quantification algorithms

Tuneable Diode Laser Based Detector Network Design & Testing

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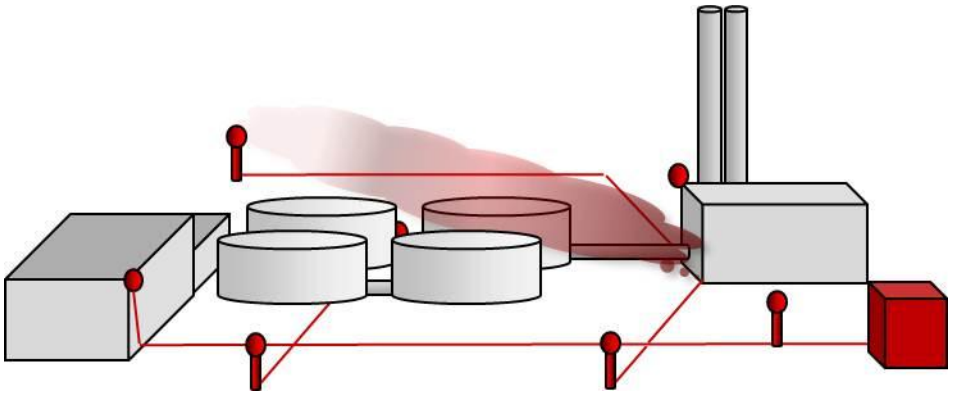
Fugitive Emission Sensing System

- Sensor system required attributes:
  - Fast
    - Many gas measurements over an array of sensors every minute
  - Selective
    - Low interference from other constituents (CO_2, H_2O)
  - Accurate
  - Sensitive
    - Must measure small changes (0.25 ppm) in ambient methane concentration (~2.0 ppm)
  - Robust
    - Operate in a harsh outdoor environment year-round
    - Function over a wide range of temperatures



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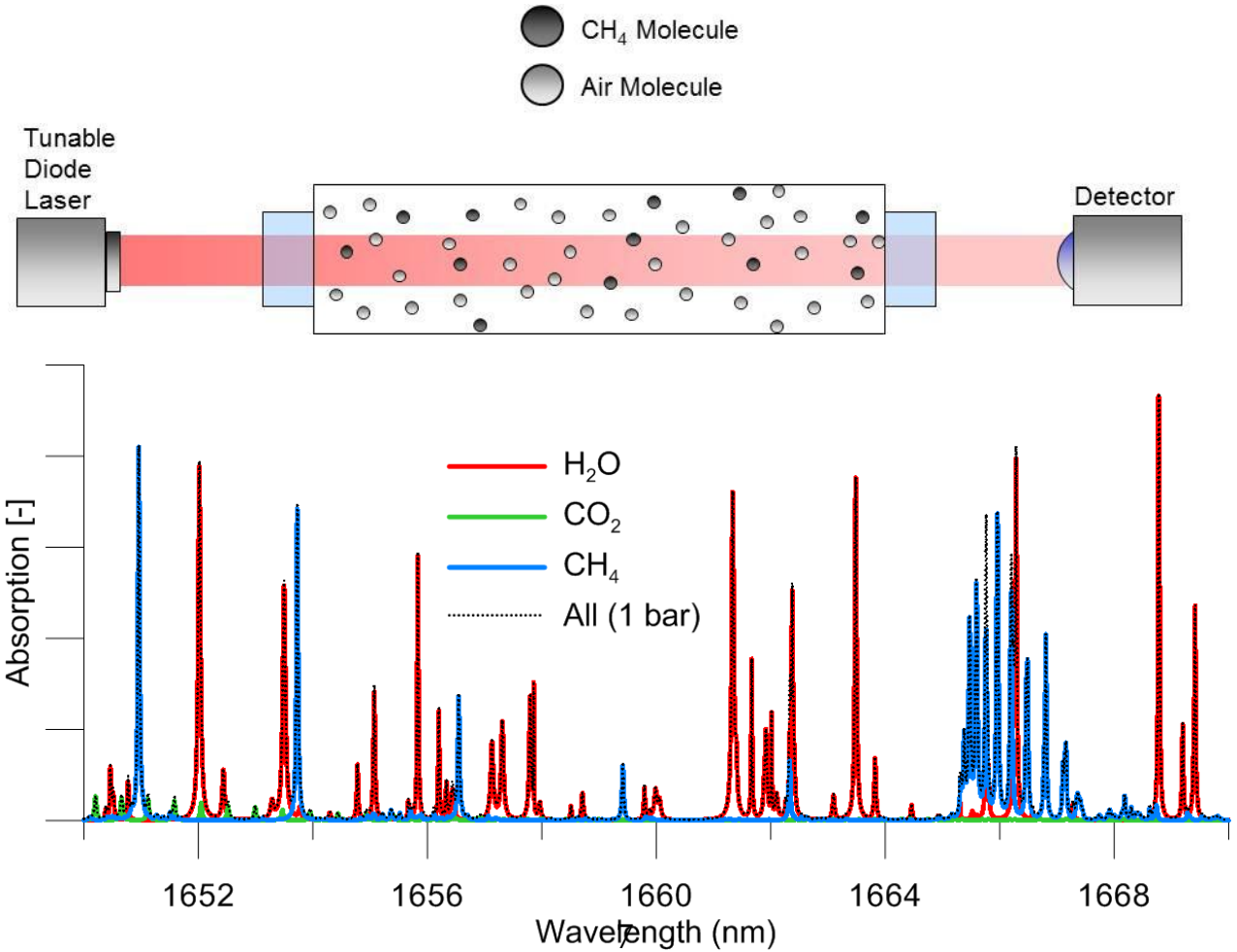
A Novel Fibre-optic-based TDLAS System

- How does it work?



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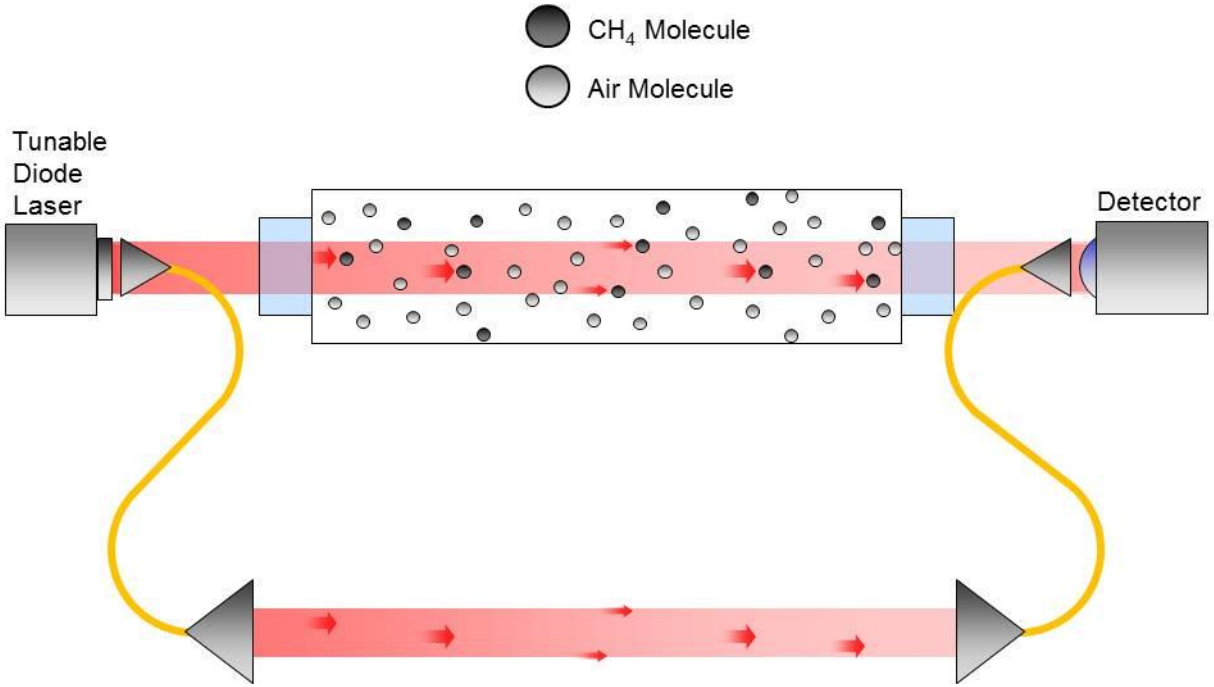

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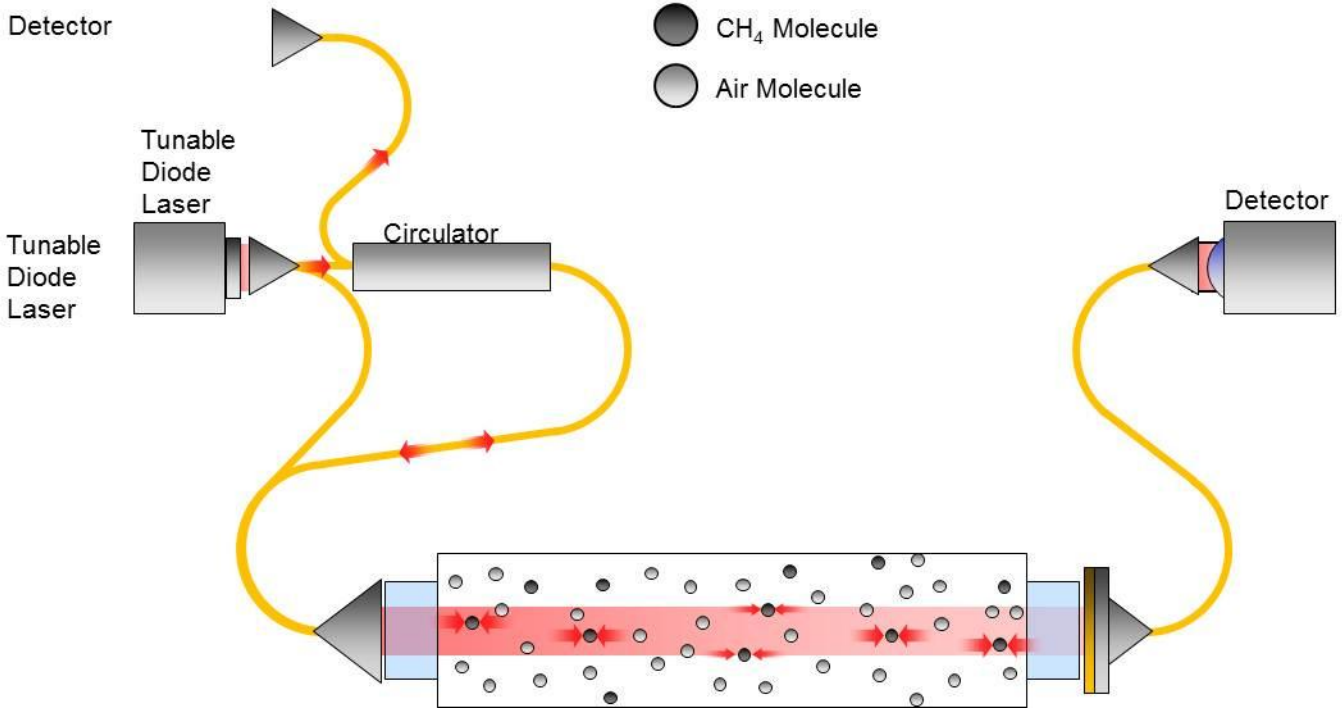

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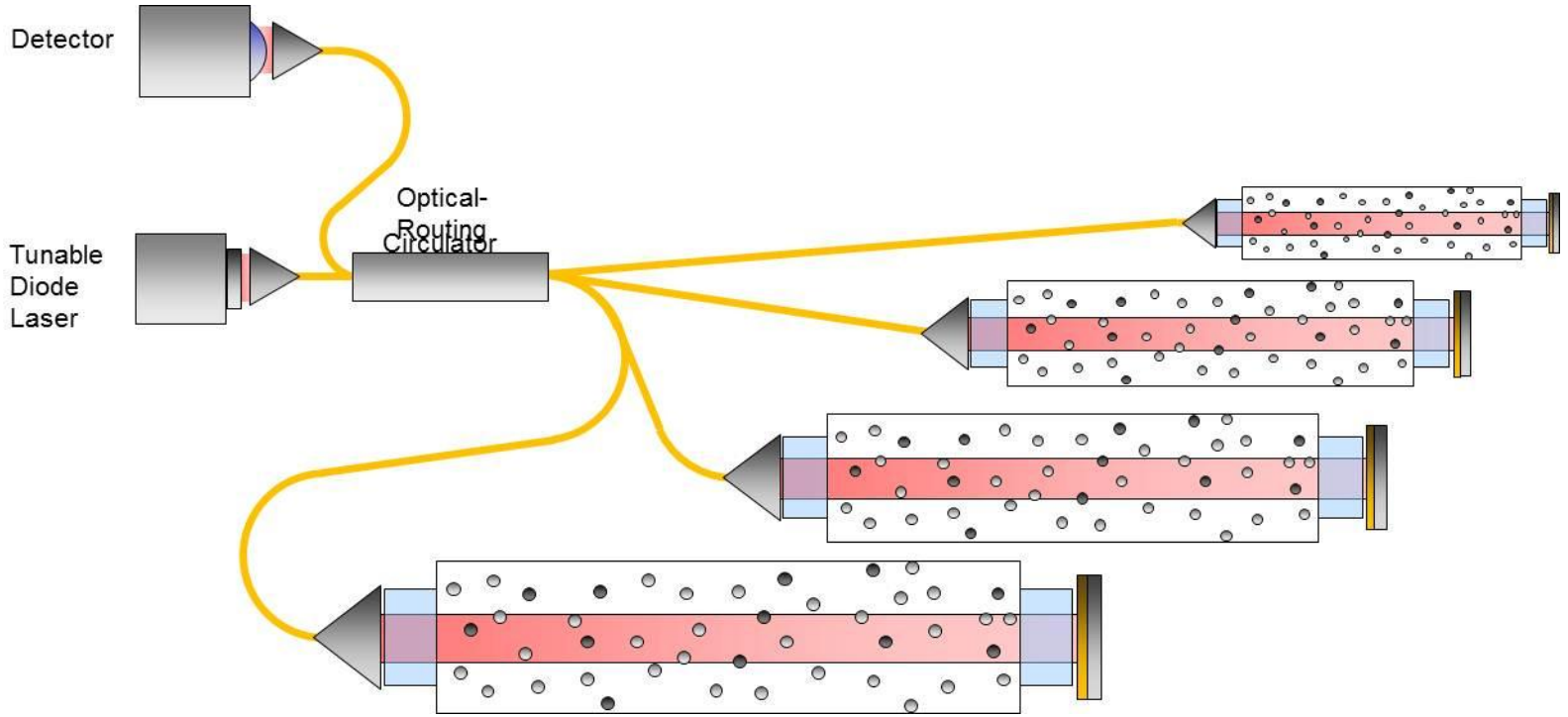

S. B. Schoonbaert, . R. Tyner, J. Albert & M. R. Johnson (2014) Ambient Gas Quantification Using Multipoint Optical Detection, Air & Waste Management Association 107th Annual Conference, Long Beach, CA, June 24-27, 2014.

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SOURCE LOCATION & QUANTIFICATION ALGORITHMS

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Tests on a Simplified Gas Plant Geometry

- Basic gas plant layout meshed for numerical testing
- Detailed wind modelling and simulated fugitive emissions releases
- Simulation based development using both in-house and commercial codes

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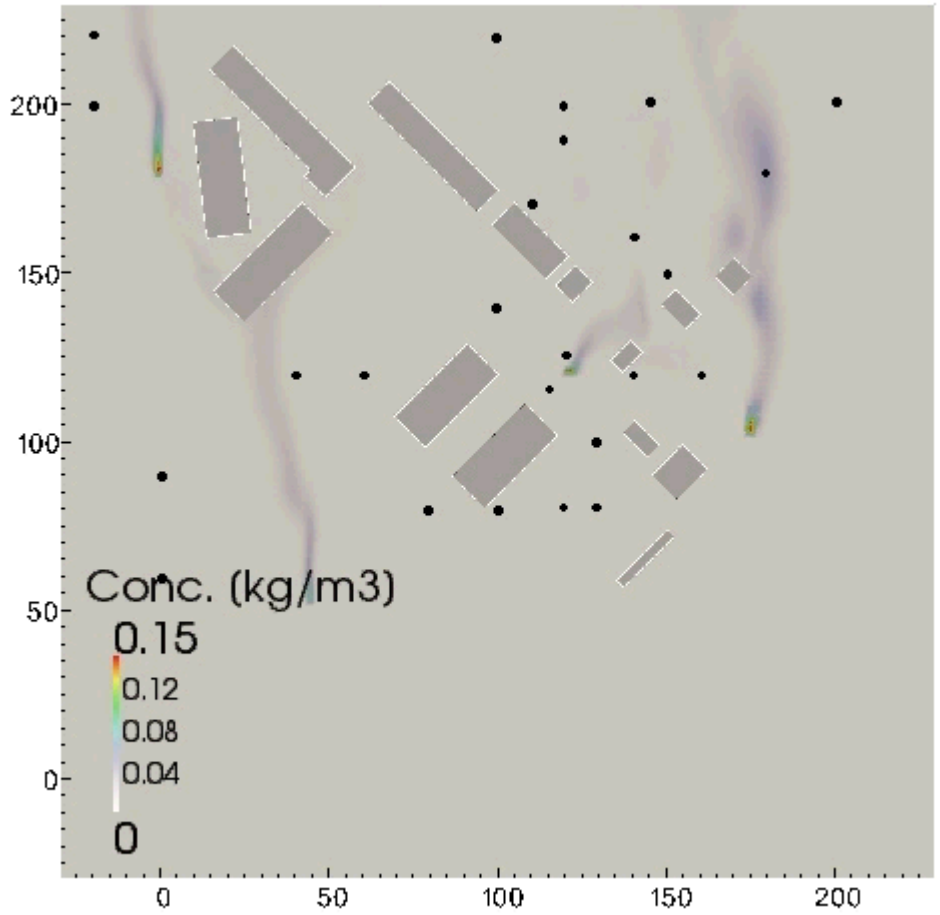
CFD Simulations

- Video shows plume in a realistic transient wind flow
  - Inflow velocity profile from actual tower data
  - Highly dynamic, complex flow behavior and entrapment of gas in building wakes



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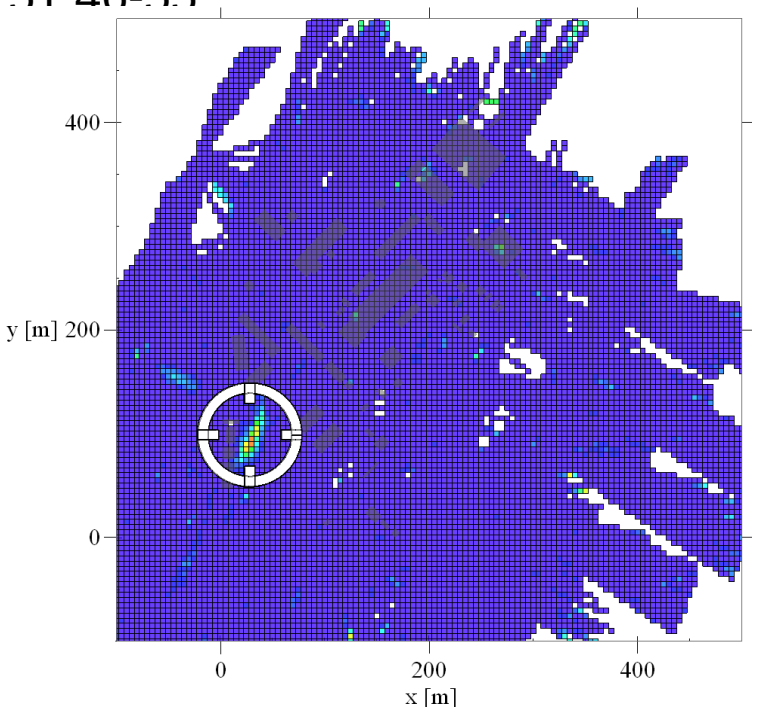
2. Statistical Source Location: *Summary*

- Trajectory-based algorithms show very good potential for leak location in complex environments
  - C.A. Brereton, M.R. Johnson (2012) **Identifying Sources of Fugitive Emissions in Industrial Facilities using Trajectory Statistical Methods**, *Atmospheric Environment*, 51:46-55
- Success in using algorithms with pre-computed, simplified wind profiles raises possibility of quasi-continuous source detection
- However methods shown up to now are only good for source location…



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3. Advanced Algorithms: Adjoint Methods

- Early-phase investigation of adjoint-based optimization to locate and quantify stationary fugitive emissions
  - Advanced mathematical approach to solving ill-posed inverse problems
  - Similar techniques have been implemented in a variety of fields
- Current research focus is on development and practical implementation of algorithms

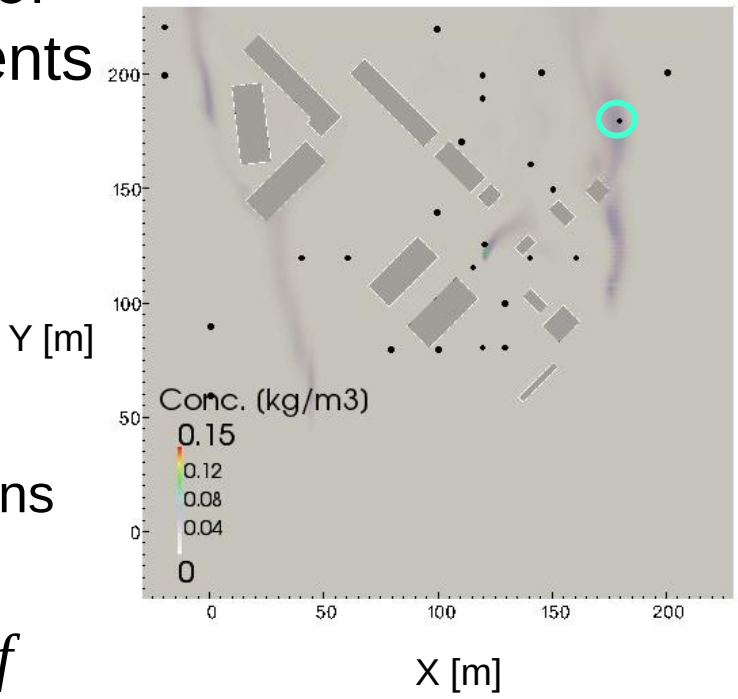
How Does it Work?

- Want source(s) to reproduce observations
  - "Objective Function": measure of mismatch between measurements & model prediction

$$f = \frac{1}{2} \sum_{receptors} (c - c^*)^2$$

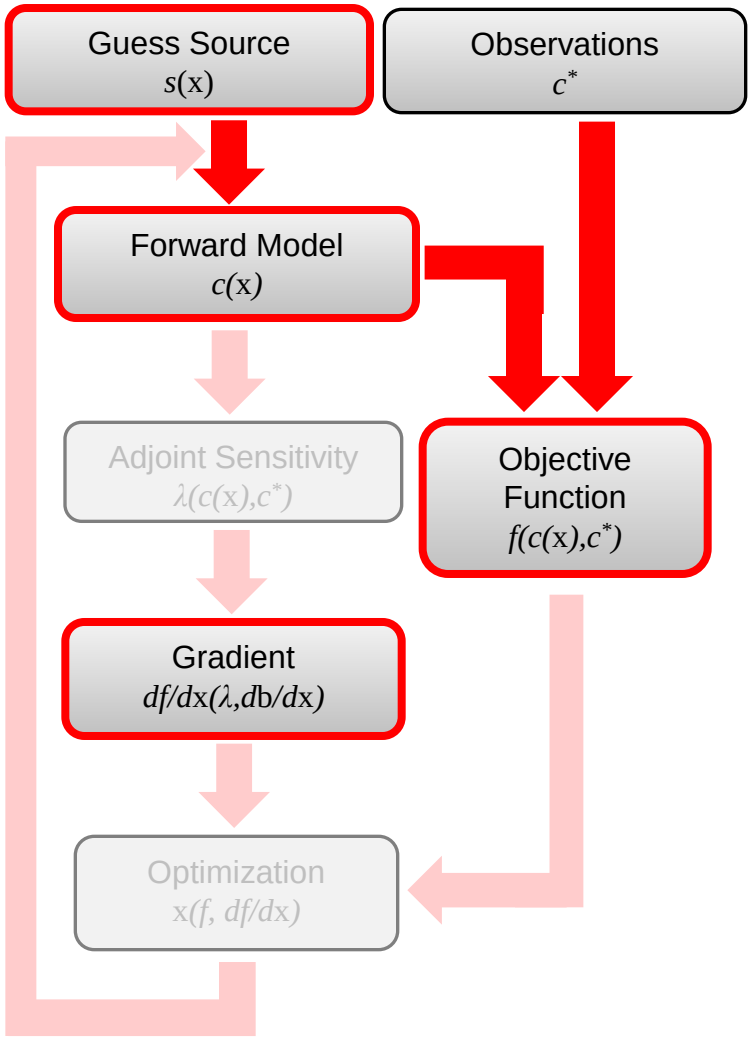
$c \equiv$ receptor measurements

$c^* \equiv$ predicted receptor concentrations



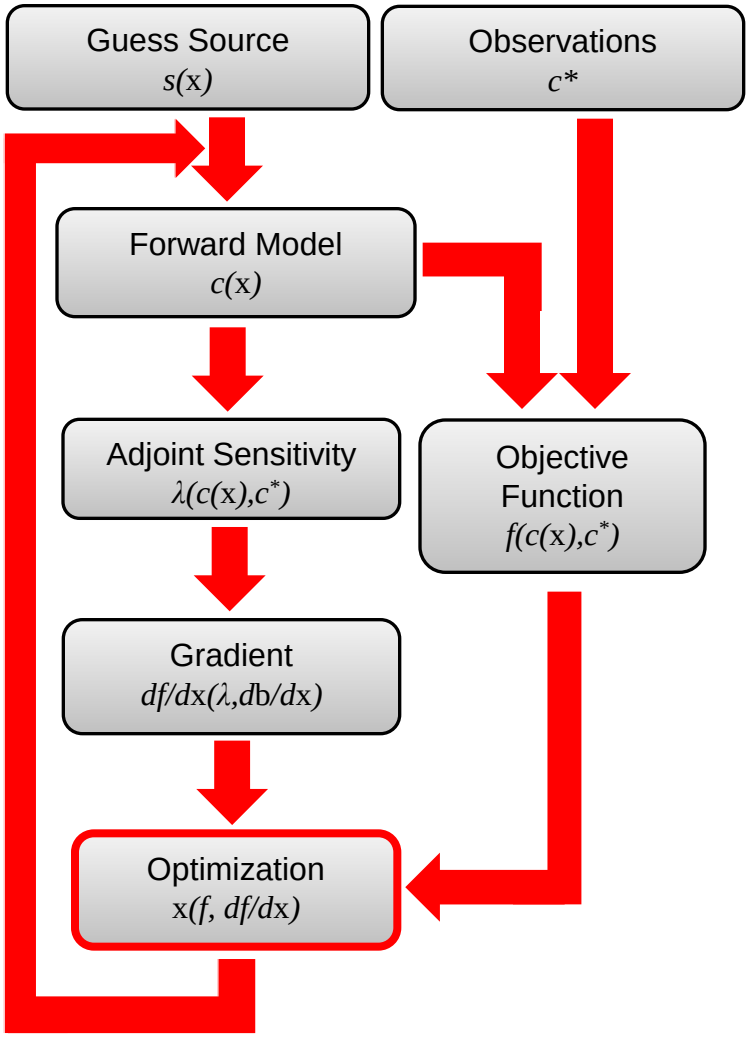
- Find the source(s) that minimizes f

Objective Function, f



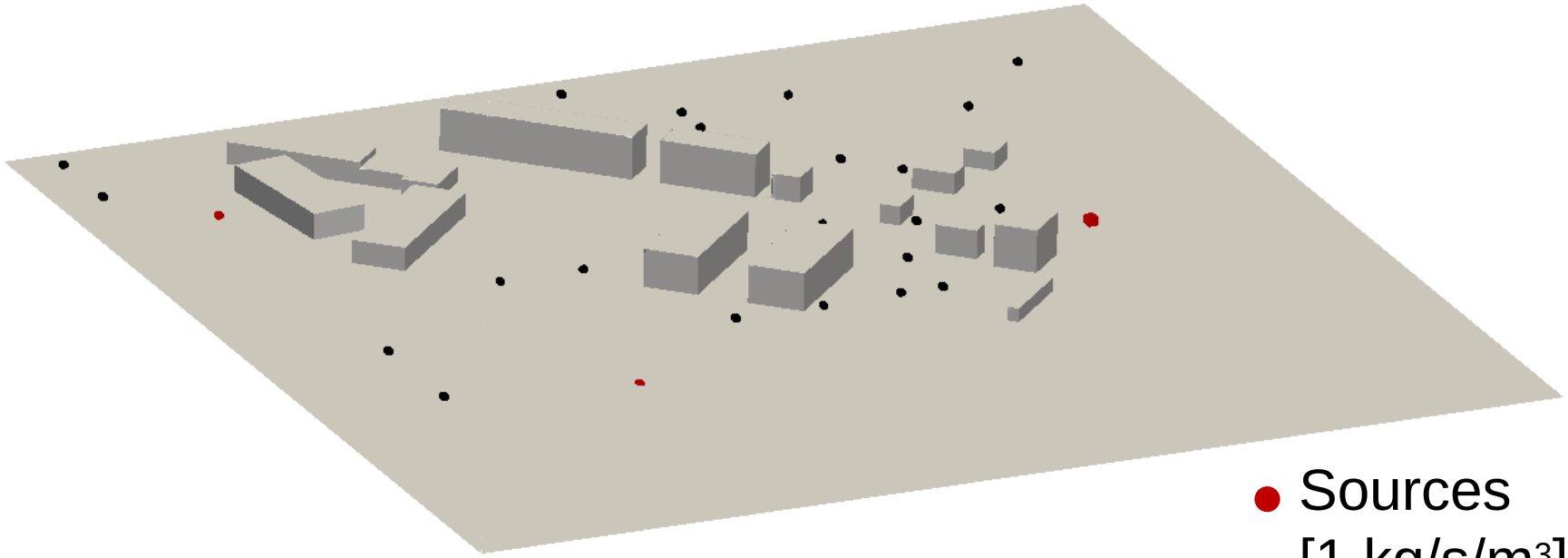
- Find the source parameters $\boldsymbol{s(x)}$ that minimize $\boldsymbol{f}$
- Need to know the *gradient* of $\boldsymbol{f}$ (how $\boldsymbol{f}$ changes with model inputs)

Optimization



- Find the source parameters $\boldsymbol{s(x)}$ that minimize $\boldsymbol{f}$
- Need to know the *gradient* of $\boldsymbol{f}$ (how $\boldsymbol{f}$ changes with model inputs)
  - Find it using the adjoint sensitivity method
- Standard gradient-based optimization algorithm
  - L-BFGS-B
  - Get a better source guess $s(x)$ to minimize $f(x)$

Sample Results: 3D – 4 Source Case



- Sources [1 kg/s/m^3]
- Sensors

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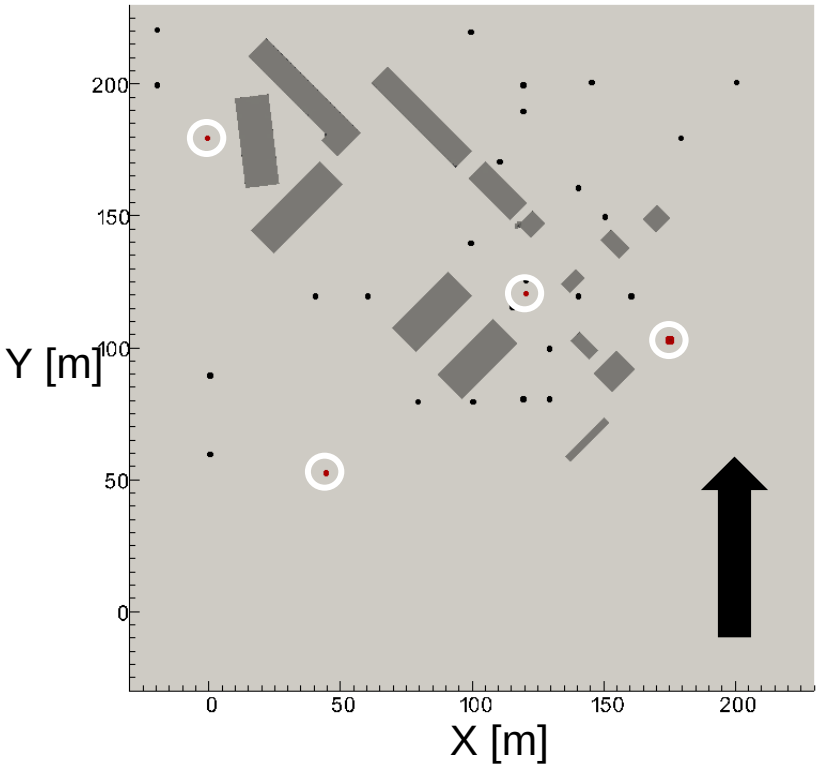
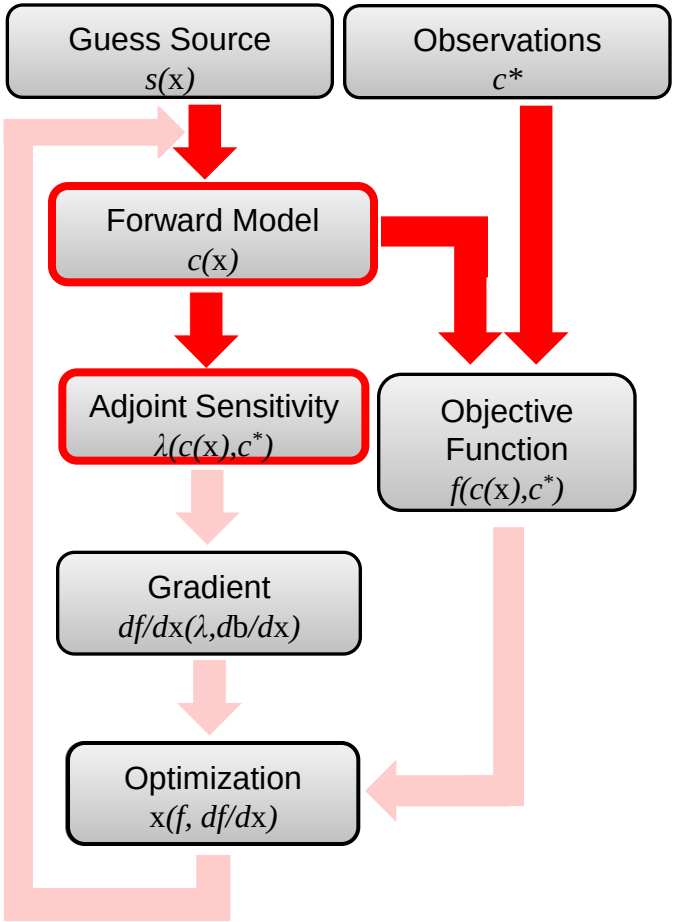
Sample Results: Adjoint Transport



- Sources [1 kg/s/m^3]
- Sensors

Wind primarily from South



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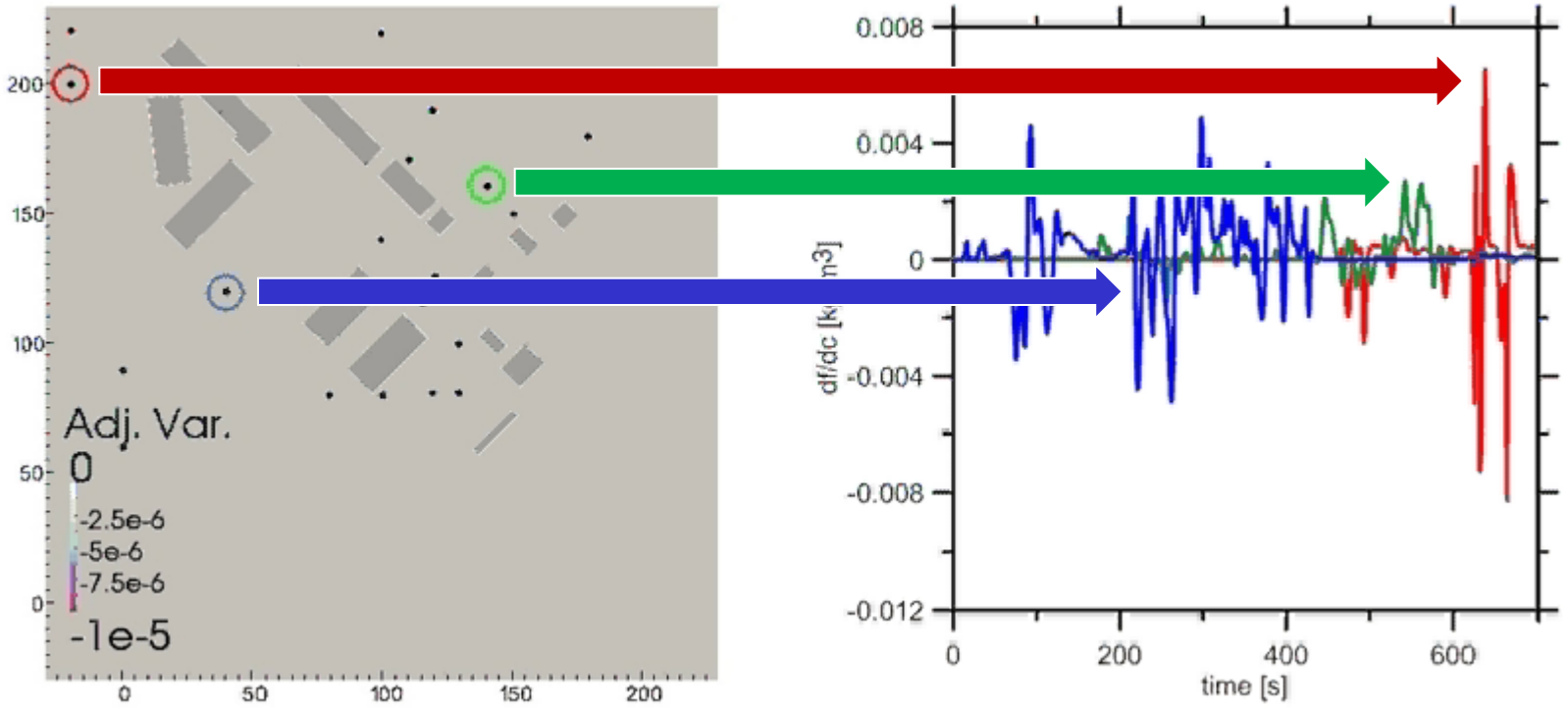

Adjoint Variable [kg s/m³]

Transport backwards from sensors to determine sensitivity

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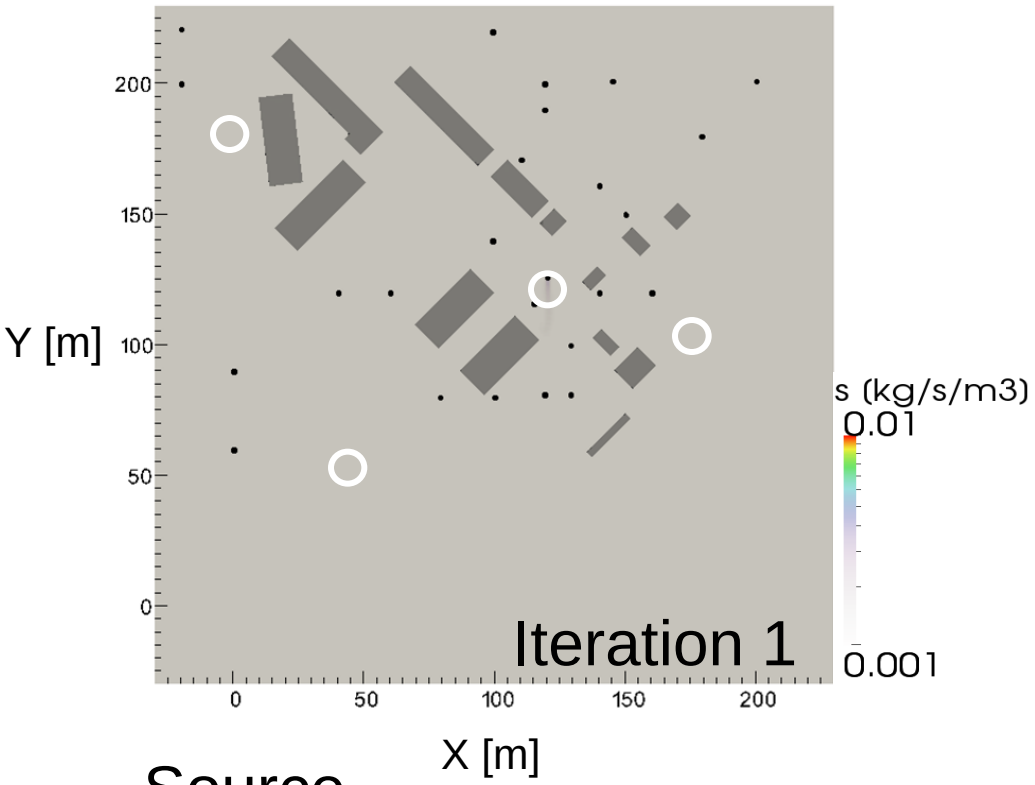
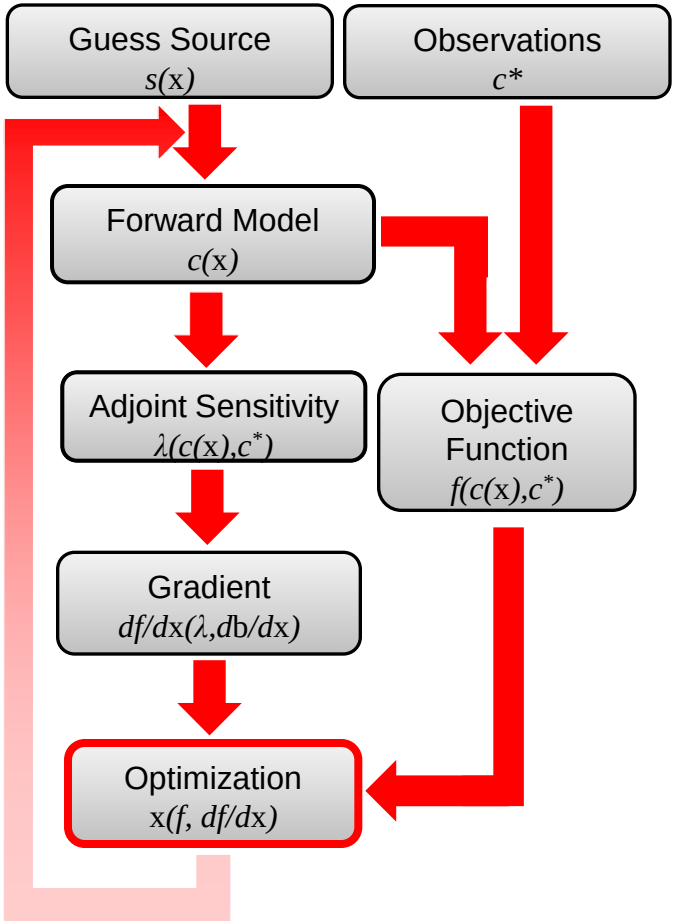


Source Prediction



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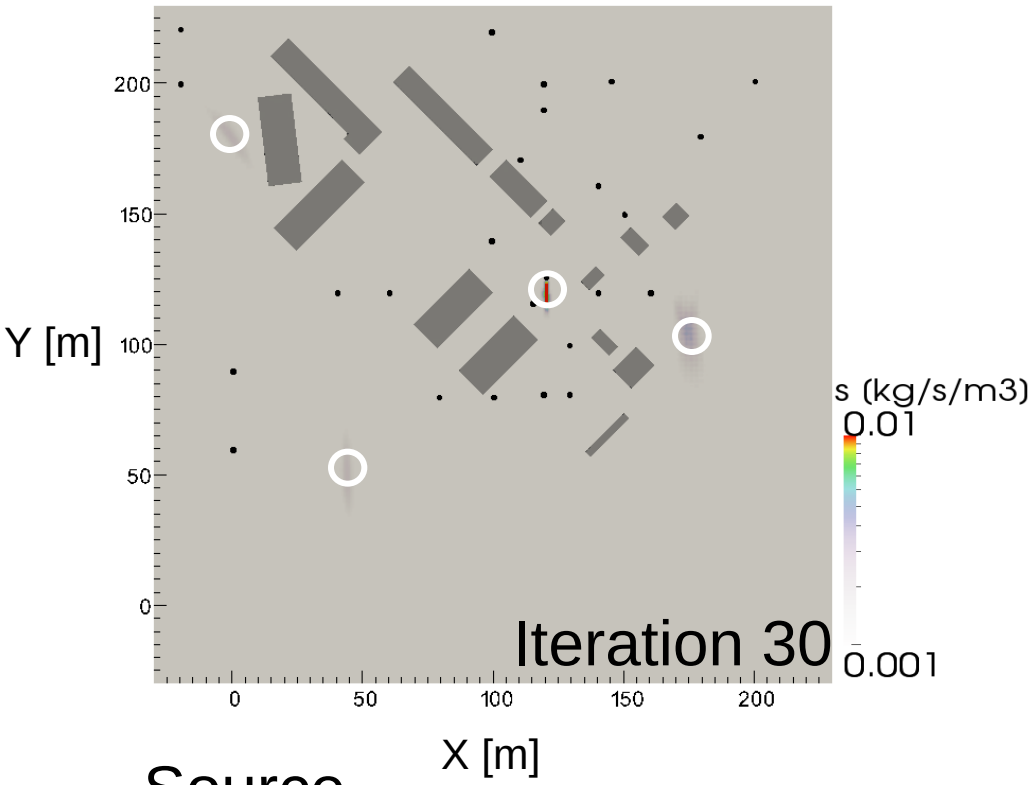

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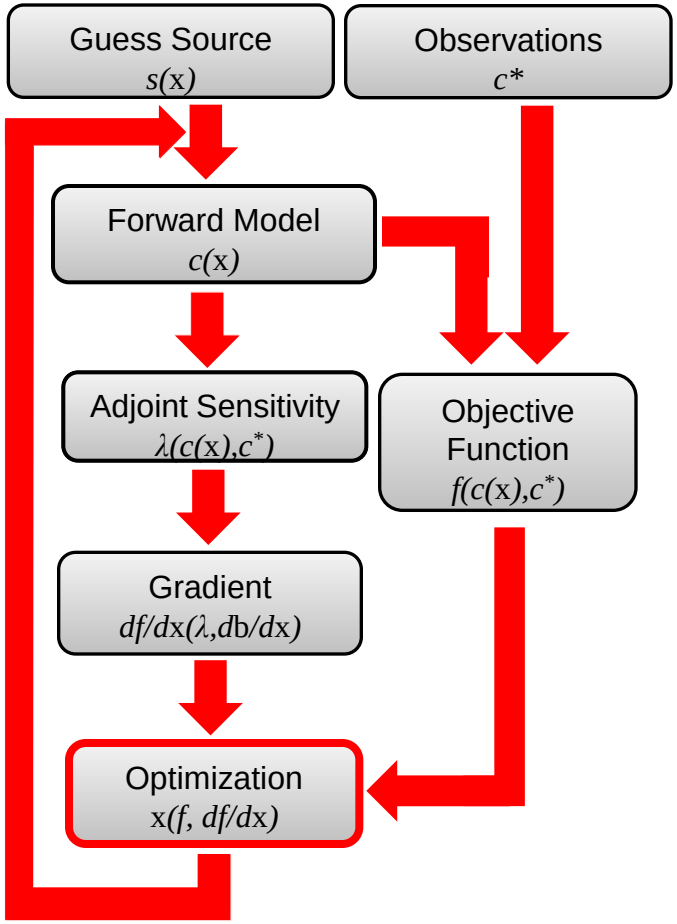

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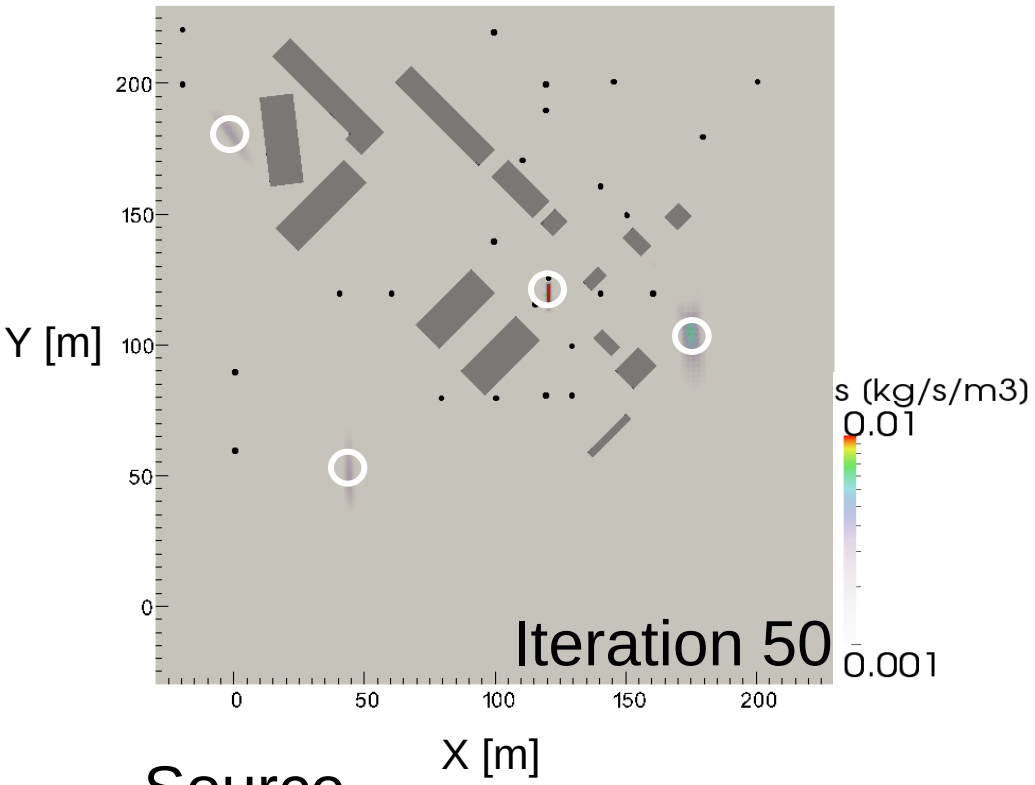

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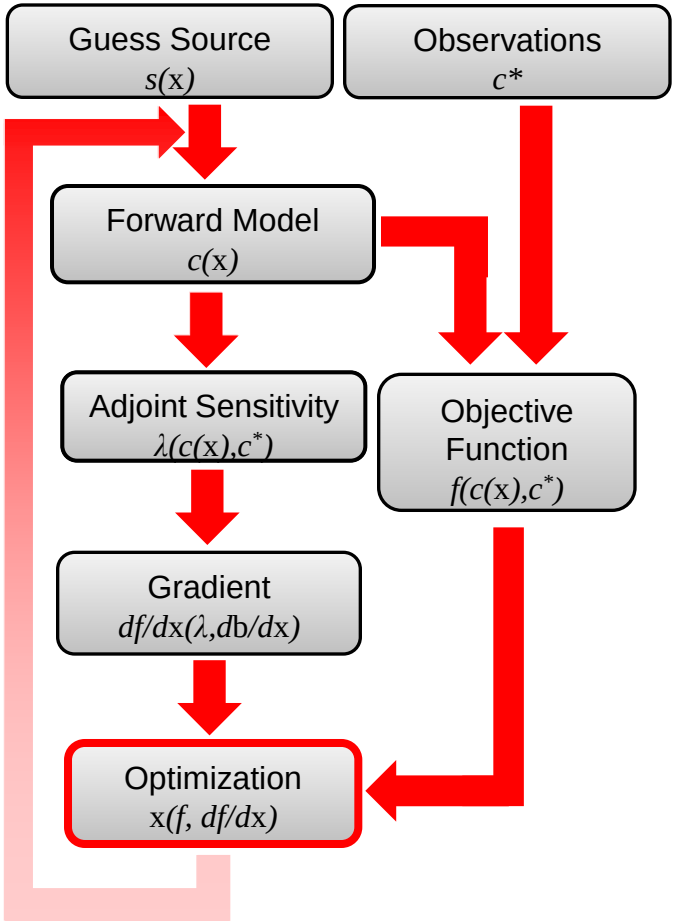

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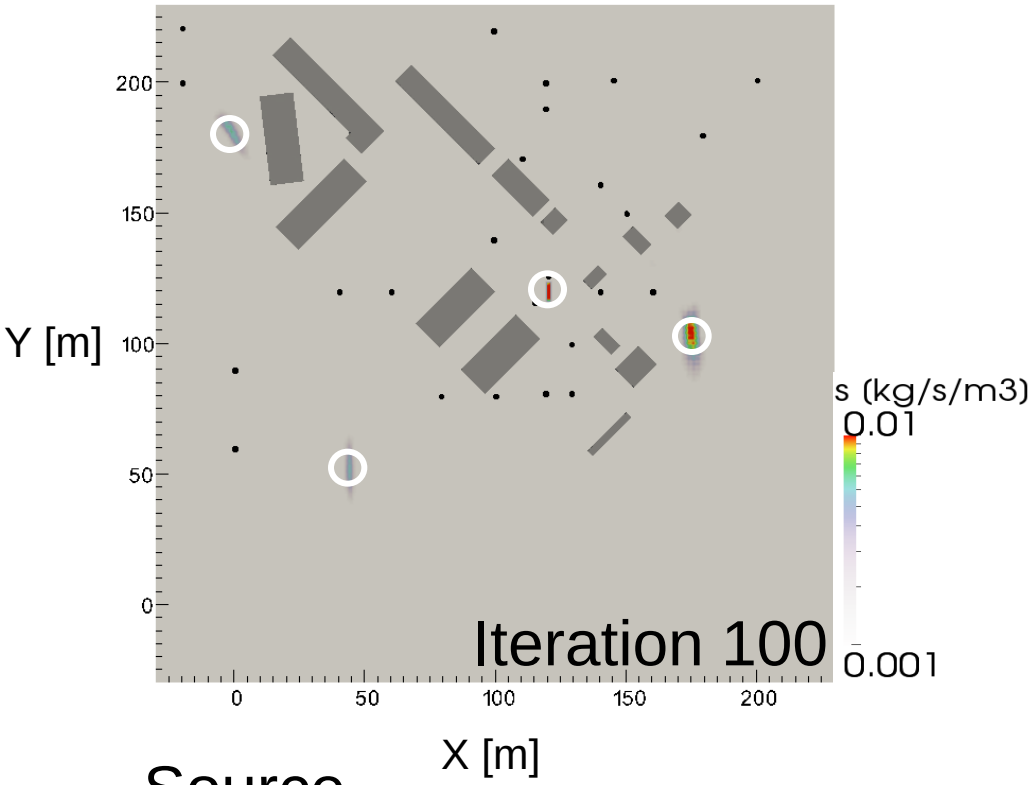

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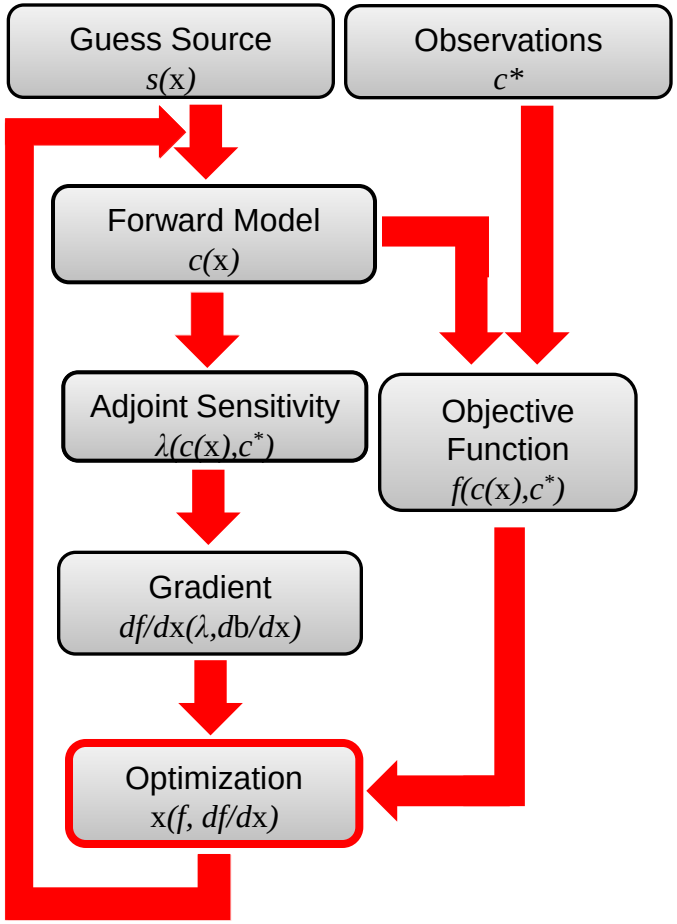

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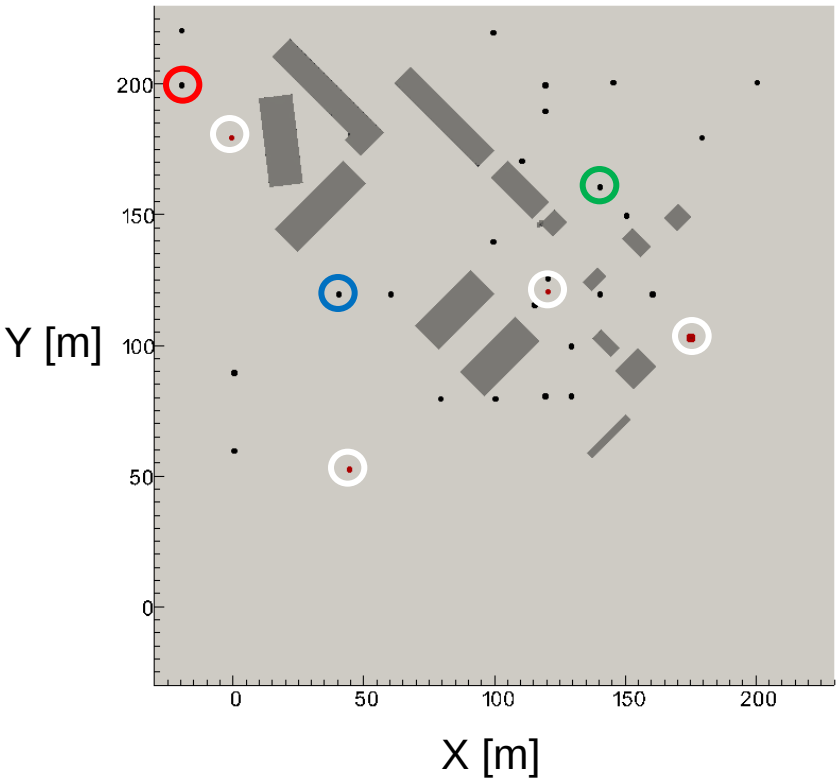

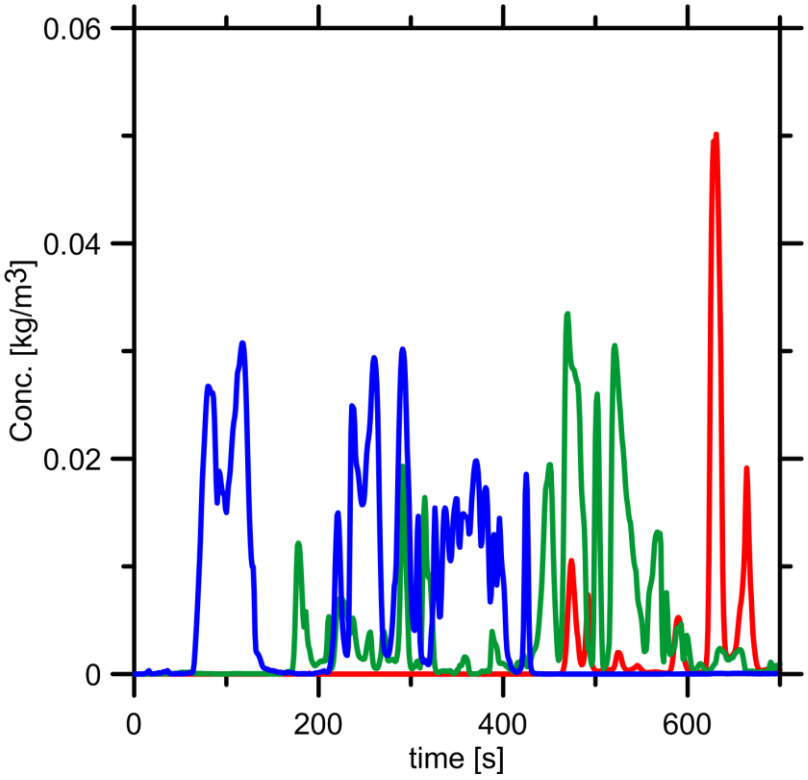

Synthetic Data Set

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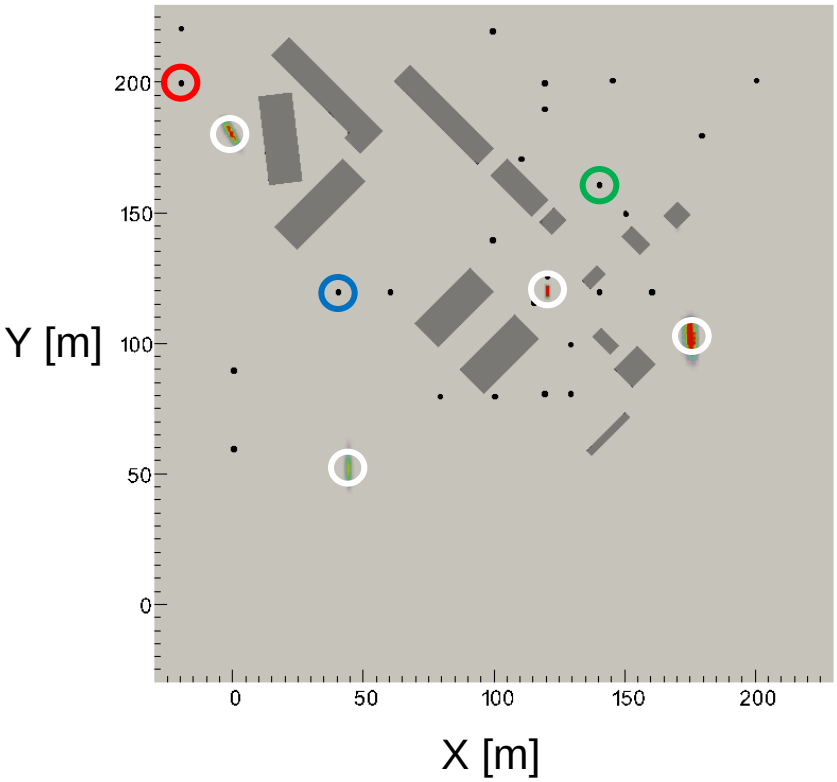
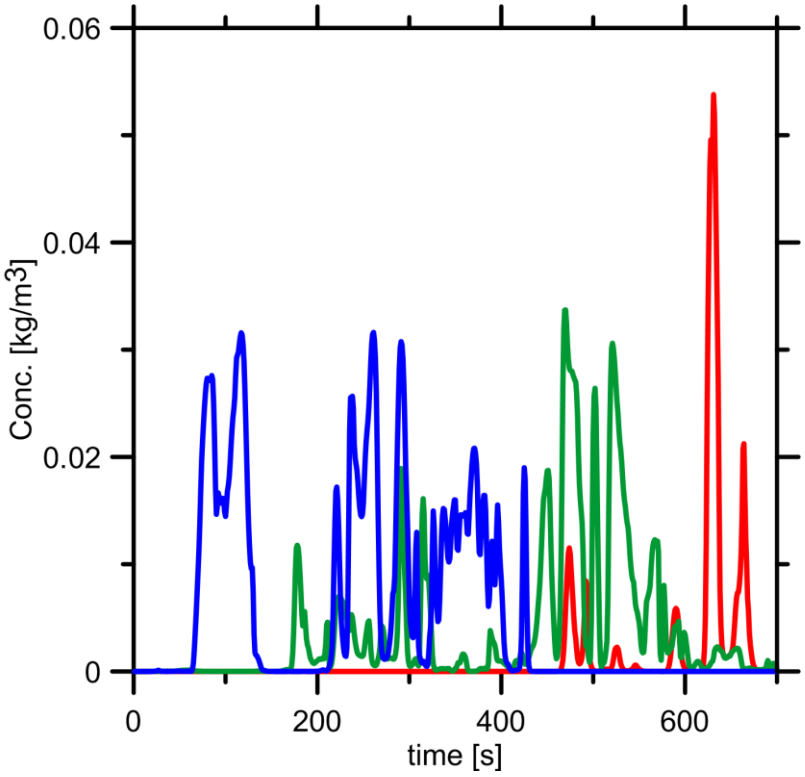
Sample Results: 3D – 4 Source Case





Reconstructed

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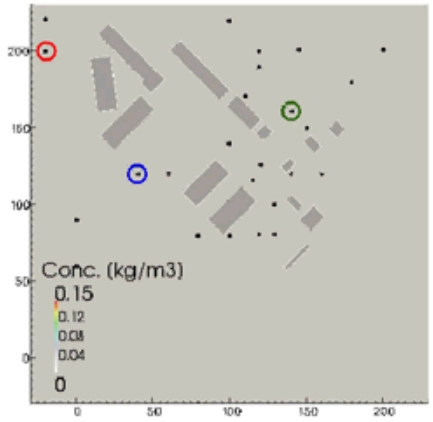
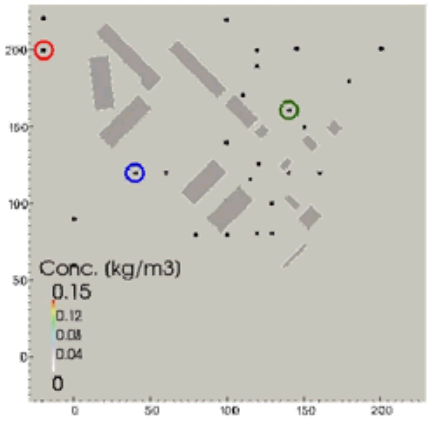
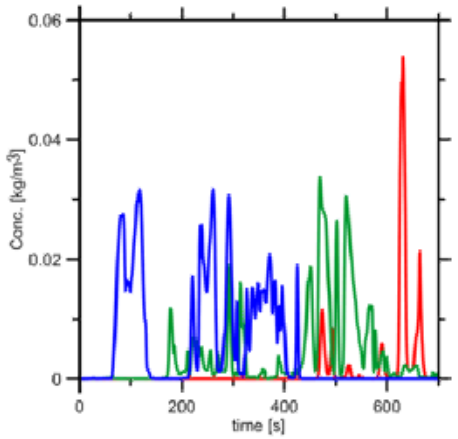
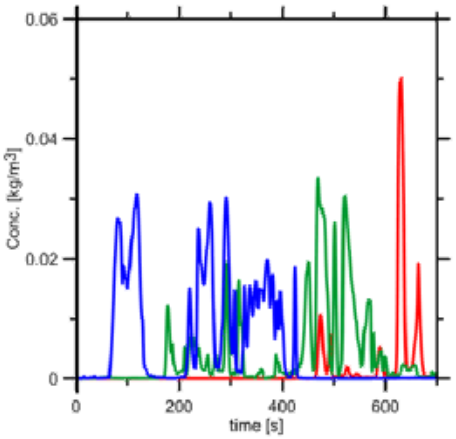
Sample Results: 3D – 4 Source Case

Synthetic Data Set Observations









Reconstructed Observations

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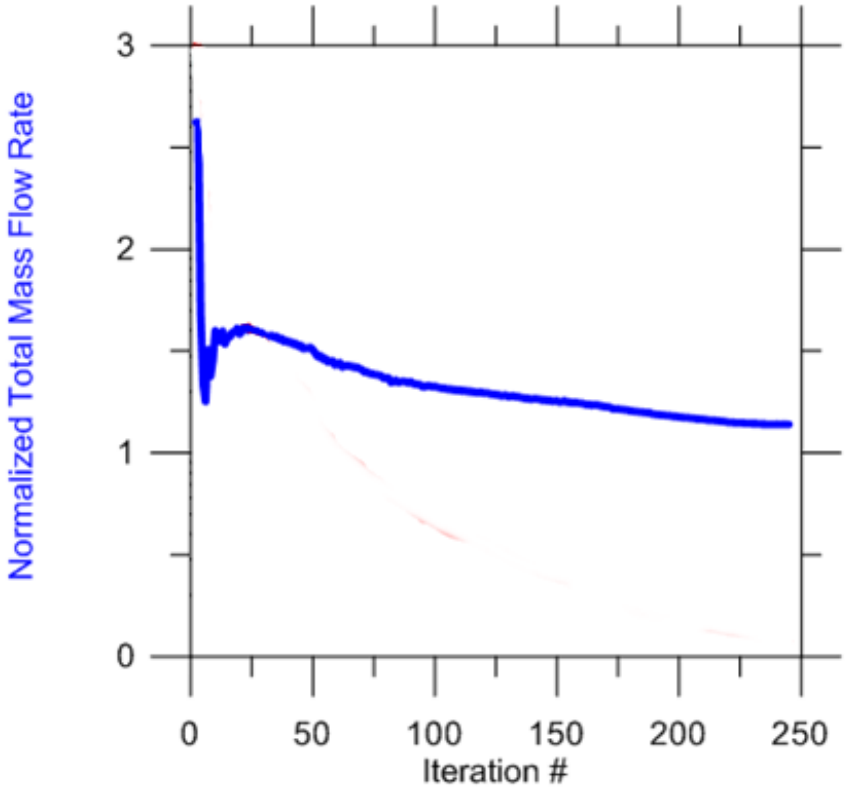
Sample Results: Quantification

Proof-of-concept results:

- ~16% overestimation in total mass flow rate in simplified test case with 4 sources
- Uncertainty in wind field will affect results
  - Ongoing work focussed on simpler wind modelling approaches



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Conclusions

- Fugitive emissions: *is there another approach?*
  - Quite possibly…
- Innovative fibre-optic sensor approach could have a number of applications related to fugitive type sources
- Proof of concept simulations reveal trajectory methods as a promising approach for quasi-continuous source location monitoring
- Preliminary adjoint-based simulations suggest emissions quantification could be possible but practical implementation will require innovative approaches for using pre-computed wind fields

Future Directions

- Development of a full working prototype gas detection network
  - Investigate related applications for direct flux measurements (e.g. vent stack emissions from liquid storage tanks)
- Continued research and development of advanced source quantification and location algorithms
  - Currently reconstructing field experiment releases
  - Investigate possible ways to reduce computational requirements to make the method more tractable

Acknowledgements

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