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PERSPECTIVES ON INTEGRATED METHANE MONITORING SYSTEMS

Sandia National Laboratories

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Controlled by:

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U.S. DEPARTMENT OF ENERGY

NNSA

CURRENT CAPABILITIES

Satellites platforms:

- **Pros:** can resolve plumes from large sources (>100 kg h^{-1})
- **Cons:** intermittent measurements (once every 1 to 16 days); can't detect smaller sources.

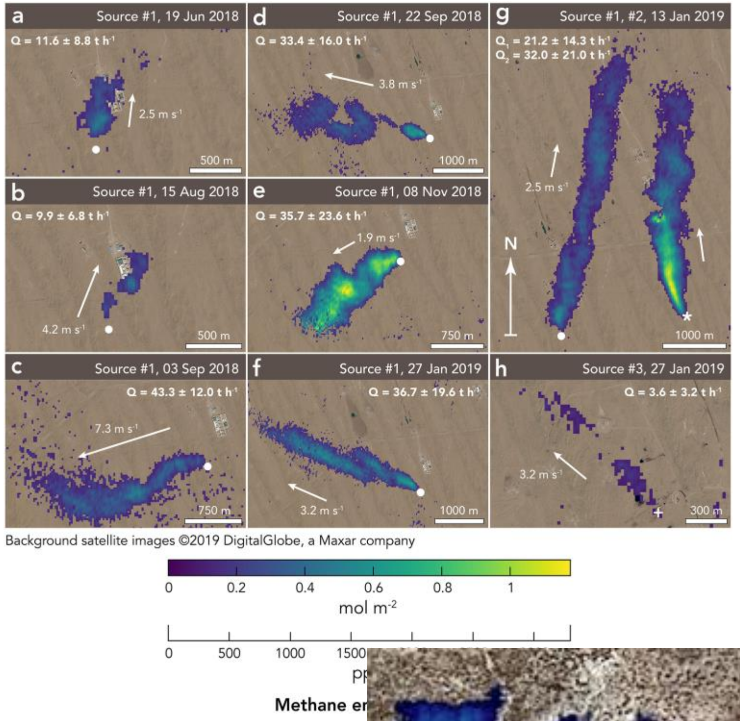
Drone-based sensors:

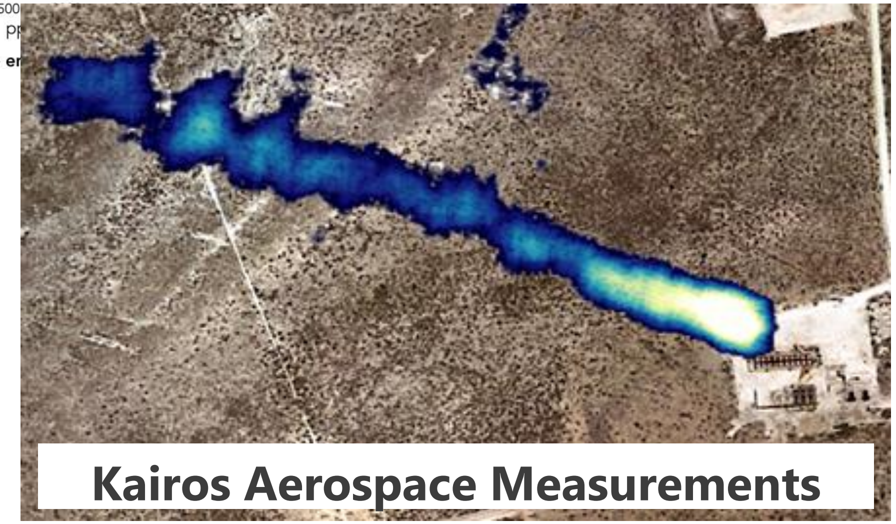
- **Pros:** greater sensitivity and accuracy
- **Cons:** expensive and labor intensive, and therefore, intermittent.

Ground-based sensors:

- **Pros:** Mostly autonomous and continuous
- **Cons:** Only measure one point or a subset of points; Cost vs. performance tradeoffs

GHGSat Data





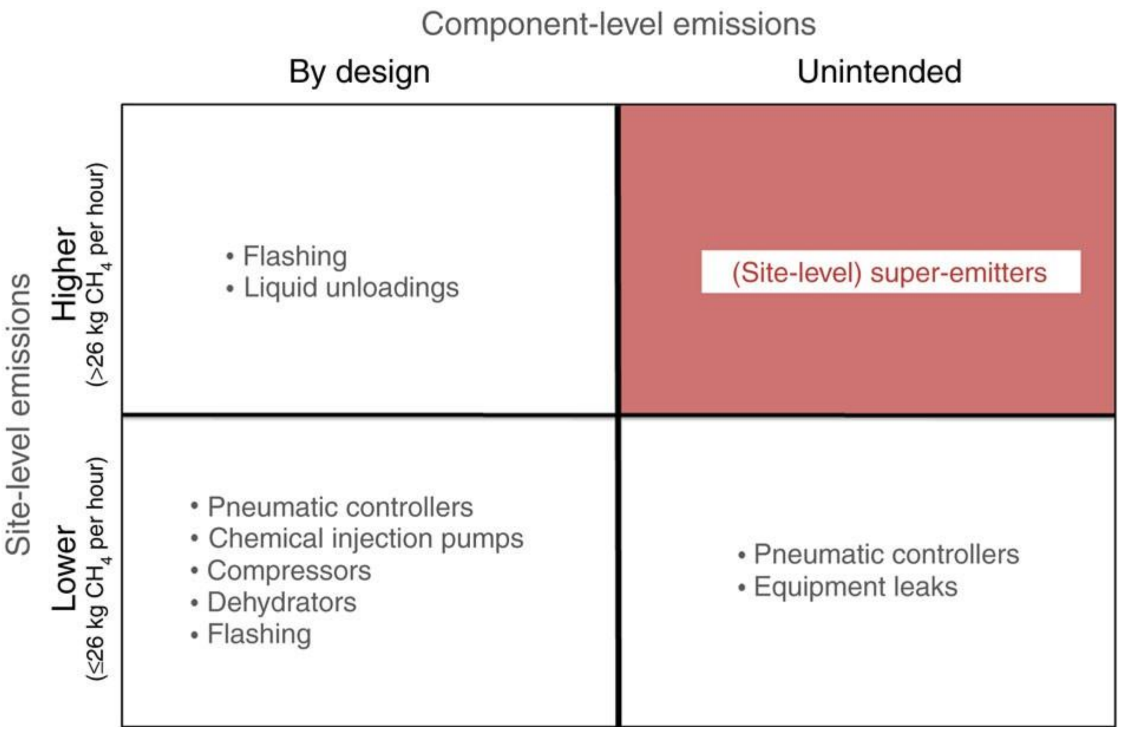
1. Varon, Daniel J., et al. "Satellite discovery of anomalously large methane point sources from oil/gas production." *Geophysical Research Letters* 46.22 (2019): 13507-13516.
2. Kairos Aerospace

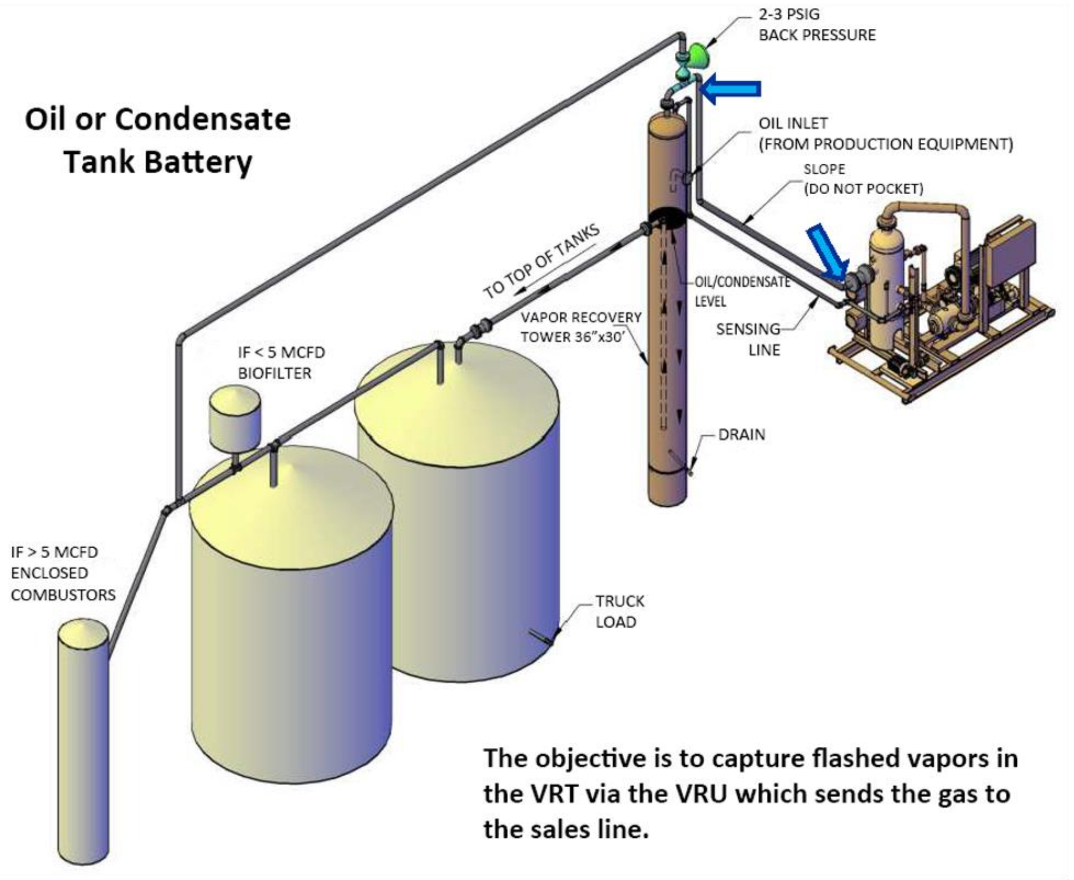
METHANE EMISSIONS FROM OIL & GAS INDUSTRY

Frequently, these are **persistent** and **small emissions**…

…but **short-duration, high emission** events are important.

Both can be difficult to detect.





Zavala-Araiza, Daniel, et al. "Super-emitters in natural gas infrastructure are caused by abnormal process conditions." *Nature communications* 8.1 (2017): 14012.

RELEVANT EXPERTISE AND PAST WORK AT SANDIA

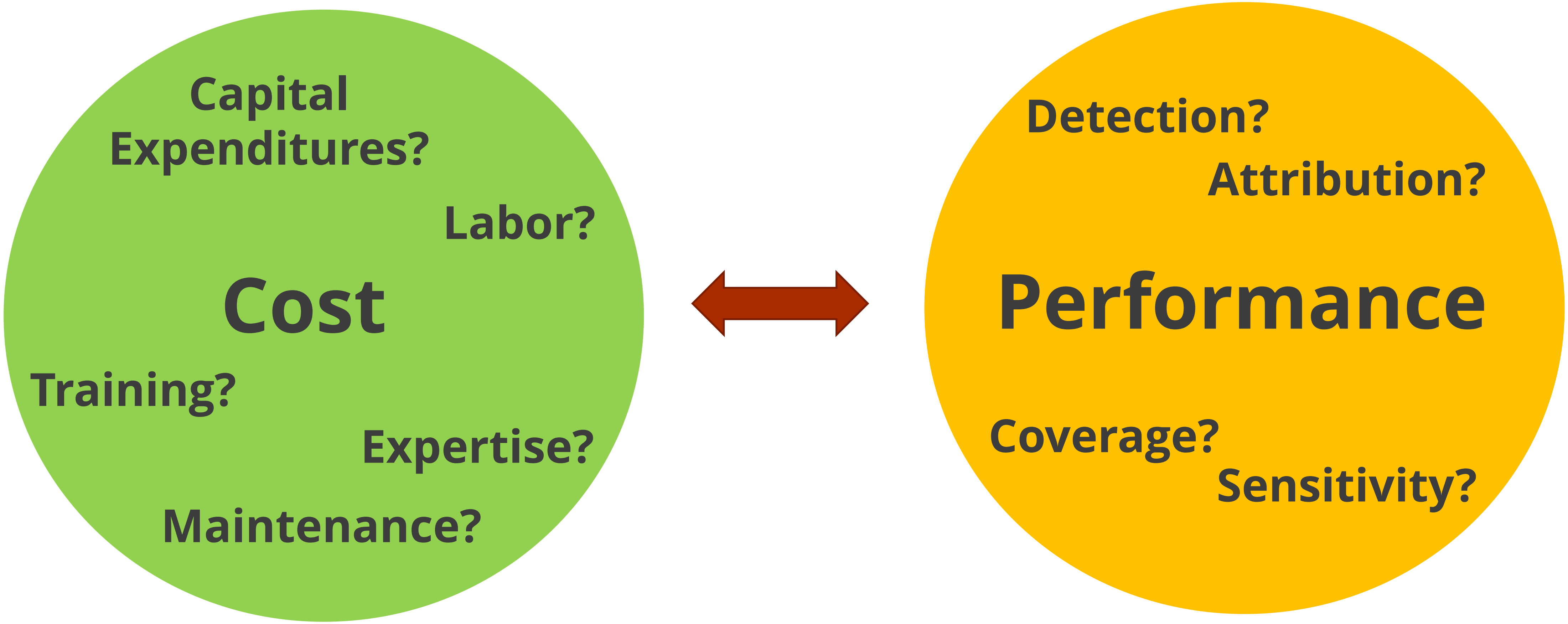
- Sensor Network Optimization - Chama
- Sensor Development
- Satellite Expertise
- GIS Programming & Visualizations
- Statistical Data Fusion
- O&G Environmental Compliance & Permitting

Chama

SENSOR PLACEMENT OPTIMIZATION

CONCEPTUALIZING A SOLUTION

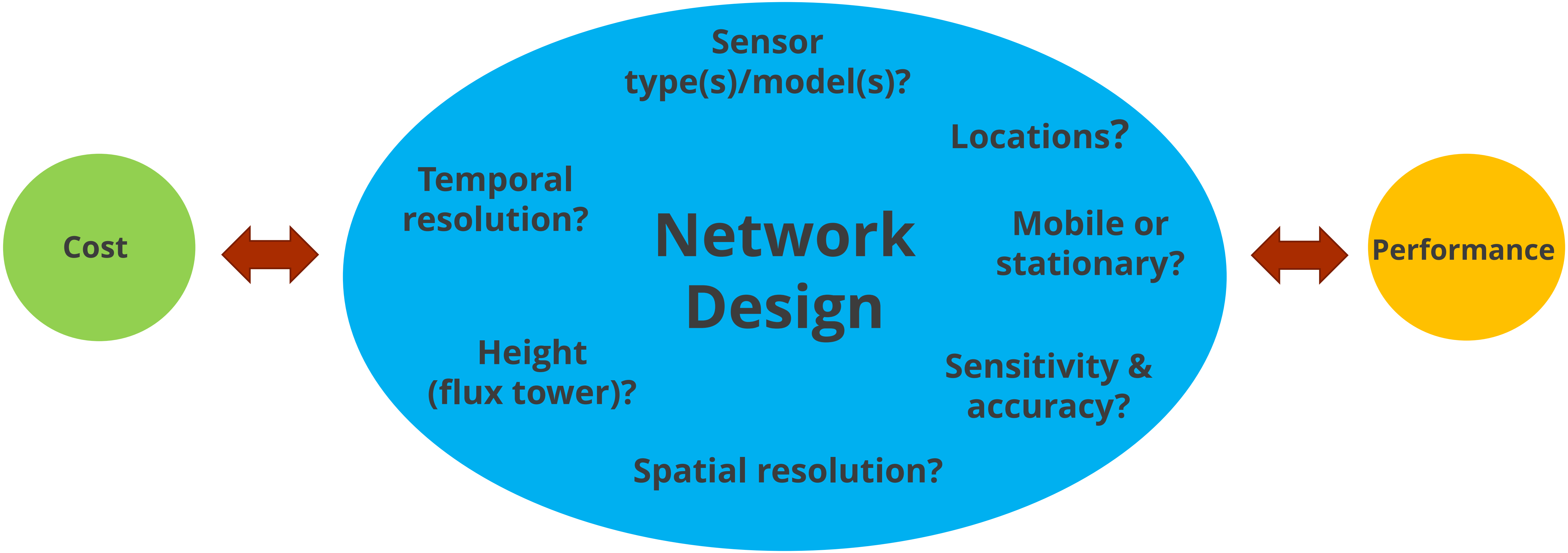
Depends on who you ask?



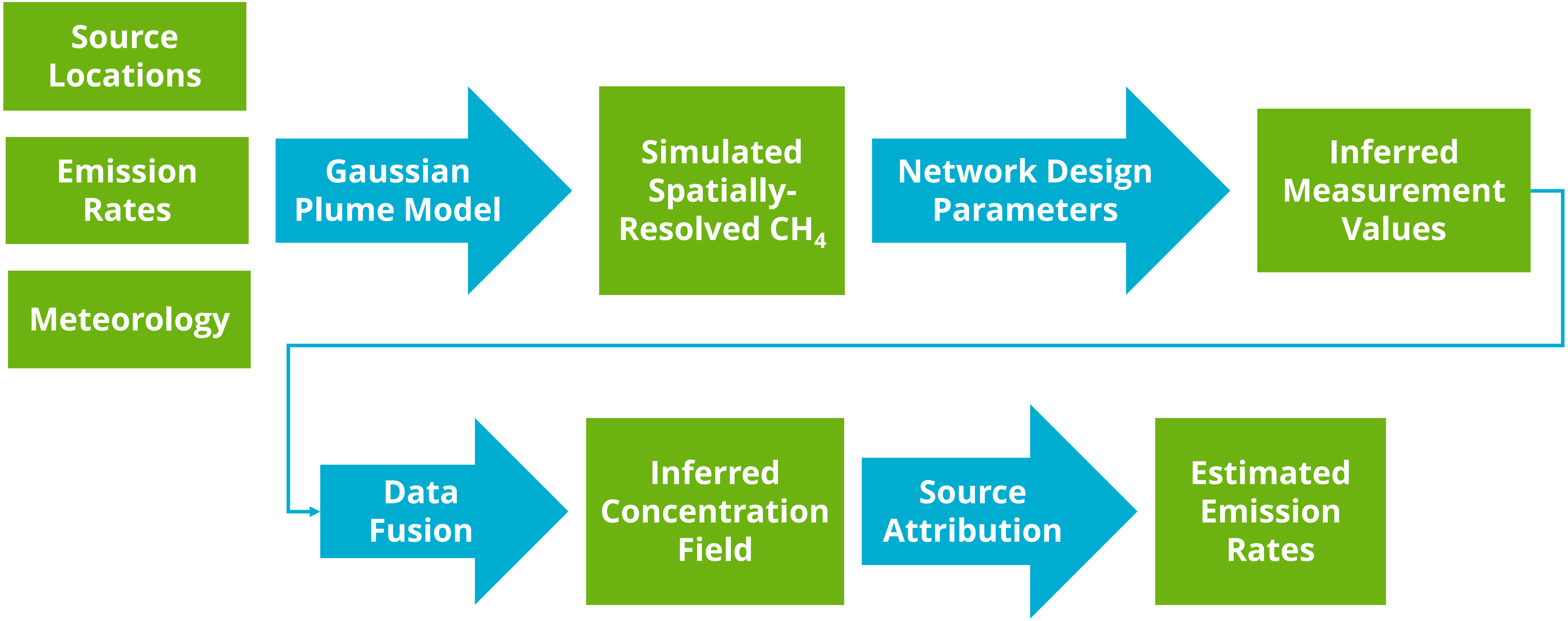
Need a design tool with agile optimization parameters

CONCEPTUALIZING A SOLUTION CONT.

Infinite possibilities → some design constraints are required.

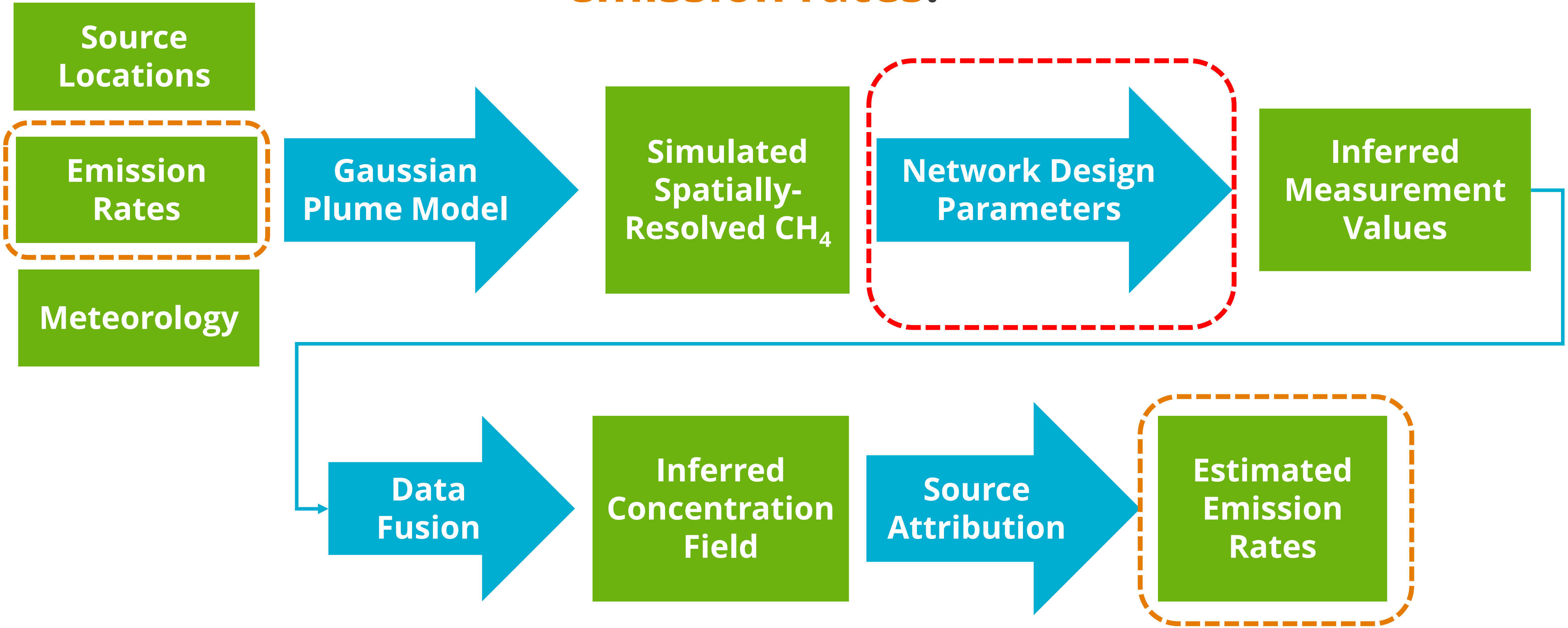


How do we evaluate network performance without measurements or known emission rates?



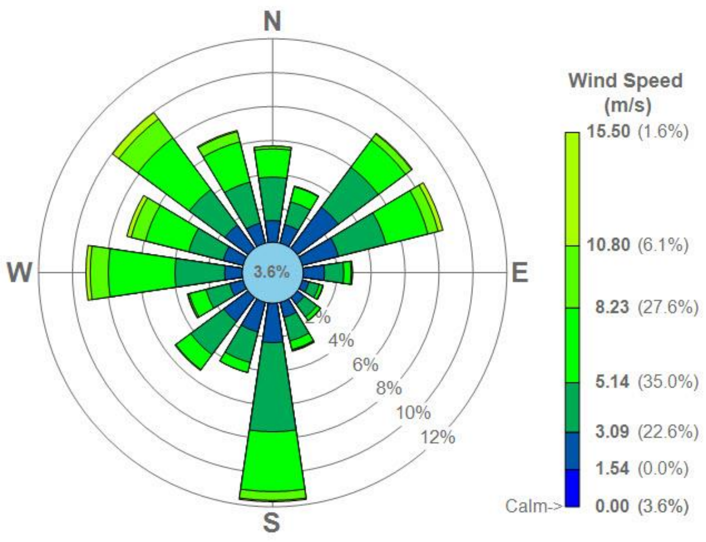
OVERVIEW OF TECHNICAL APPROACH

Goal: Optimize unconstrained design parameters by minimizing the difference between actual and estimated emission rates.

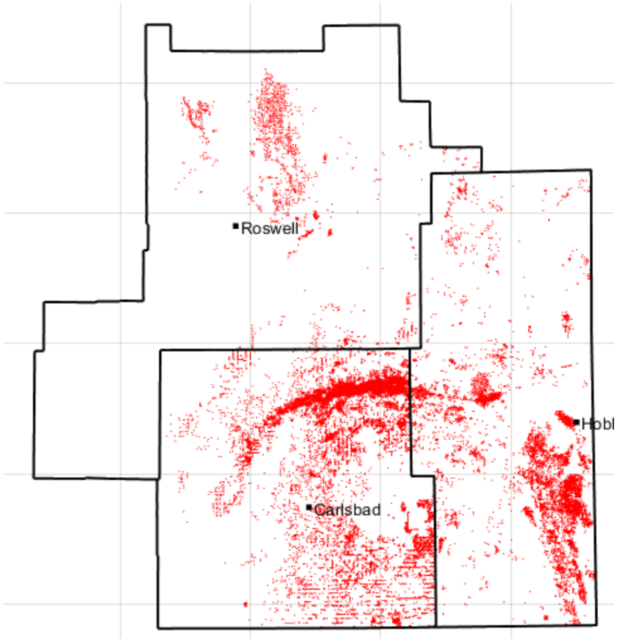


TECHNICAL APPROACH: EMISSION INVENTORY, SOURCES, & METEOROLOGICAL DATA

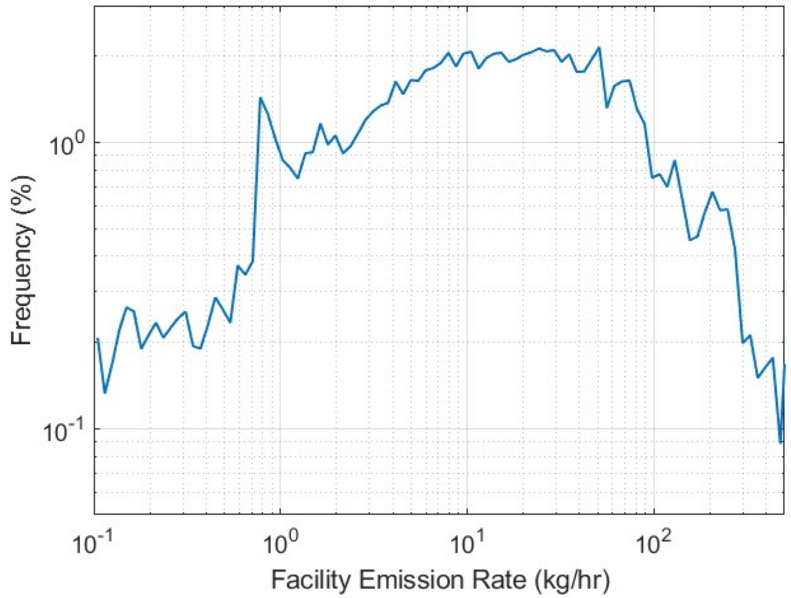
Local Meteorological Data



Facility Locations

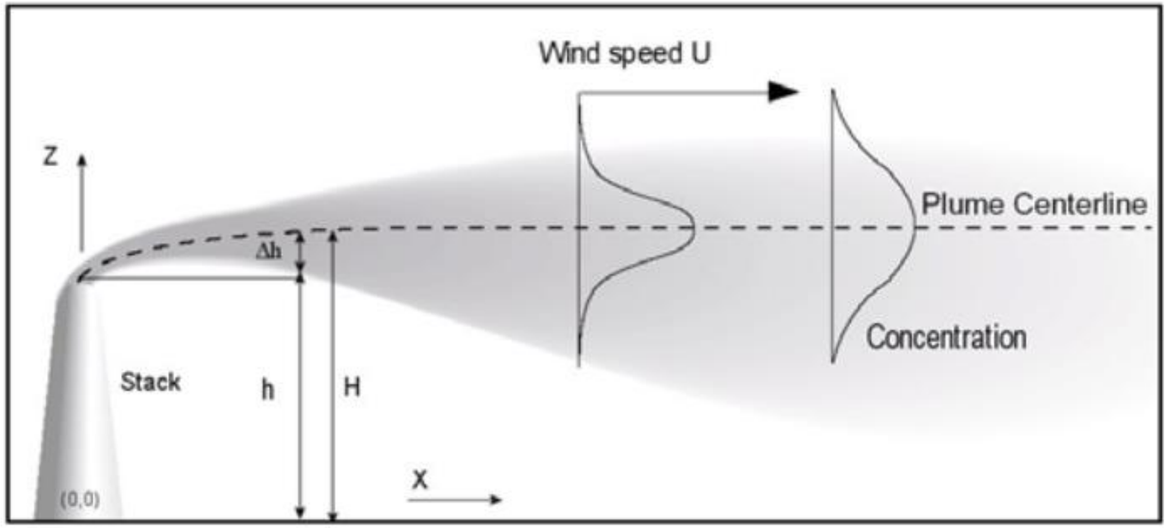


Emission Factors (Rutherford et al., 2021)

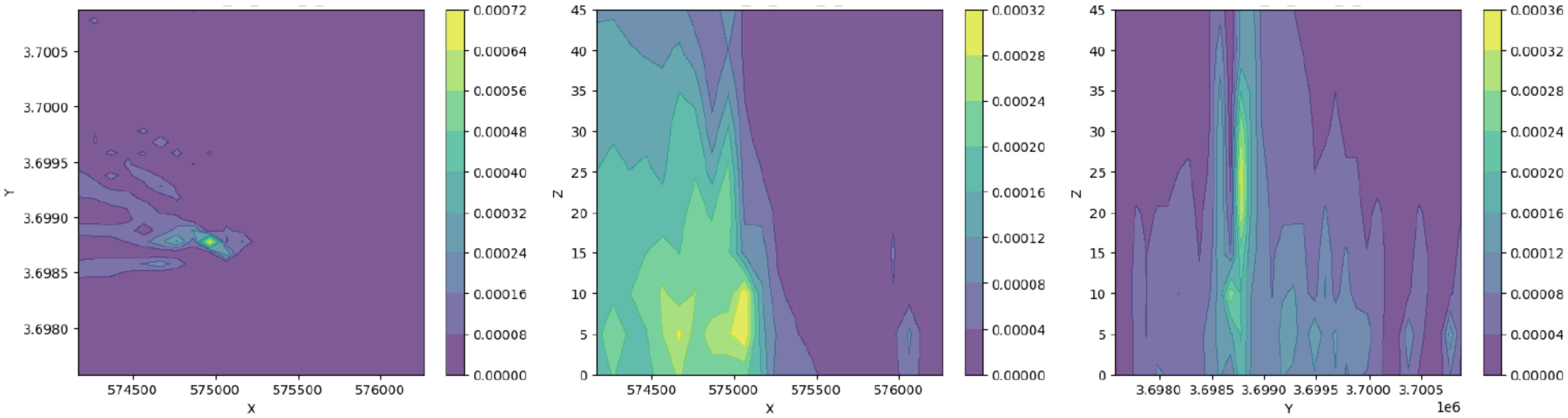


TECHNICAL APPROACH: SIMULATED METHANE CONCENTRATION

Steady-State Gaussian Plume Model



Exemplar Concentration Field



TECHNICAL APPROACH: INFERRING & FUSING MEASUREMENT DATA

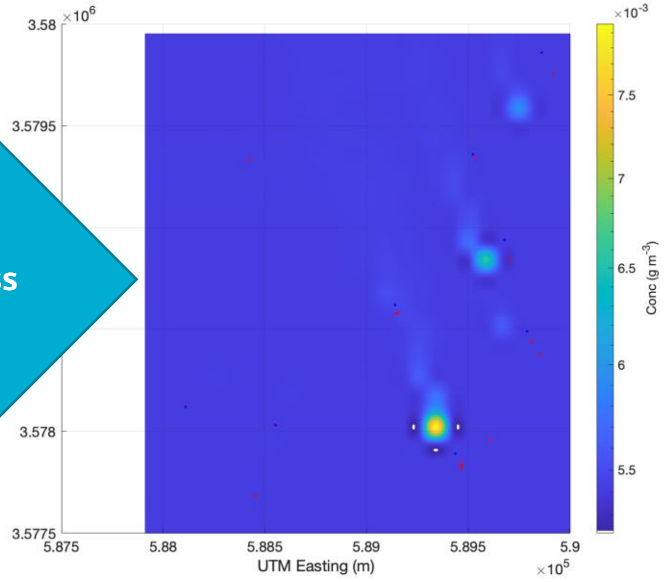
Point Measurements

Modeled concertation at sensor location

Add stochastic uncertainty for sensor

Inferred Point Measurement

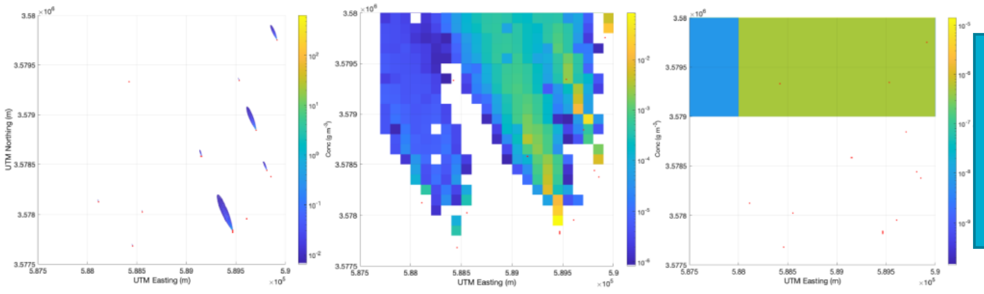
Inferred Conc. Field



Data Fusion: Gaussian Process Regression

OR

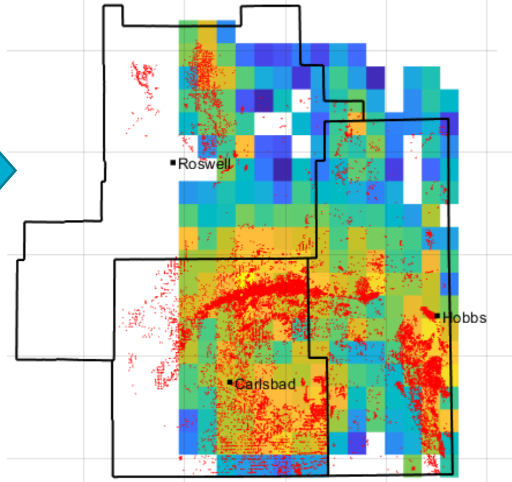
Spatially-Resolved Measurements



High Res → Low Res

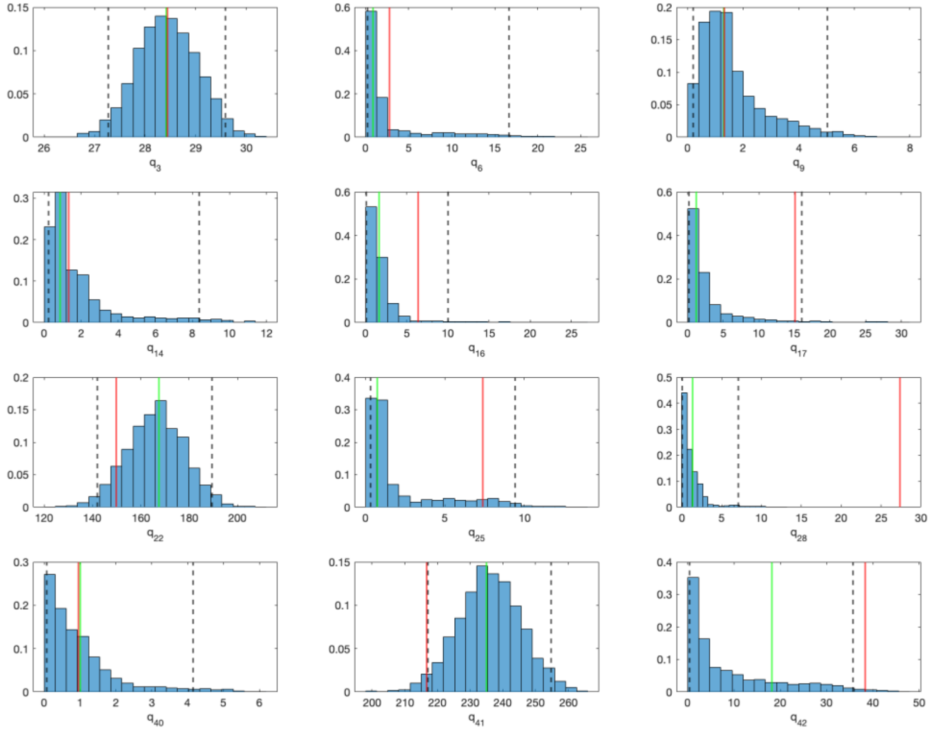
Transform to full column & add stochastic uncertainty

Inferred TROPOMI Data



Two Methods

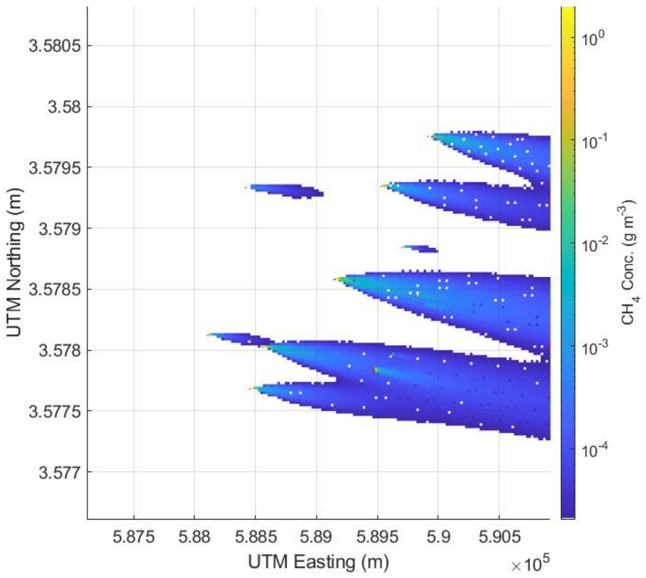
Bayesian Model



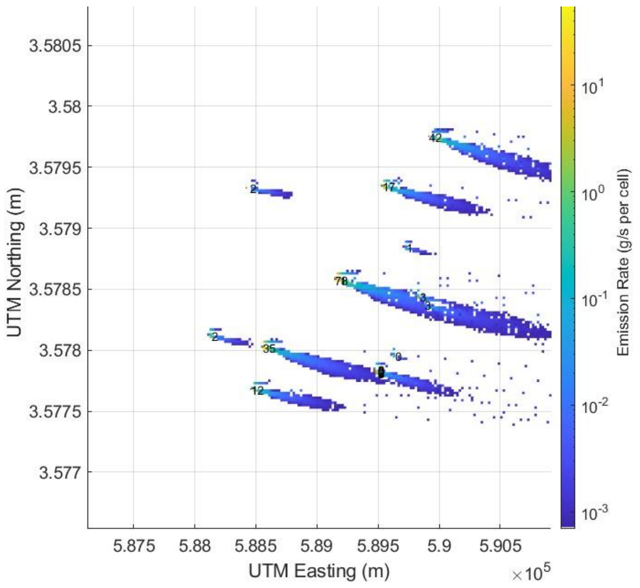
Quantify uncertainty directly using known uncertainties

Inverse Plume Model

Inferred Conc. Field



Estimated Emission Rates

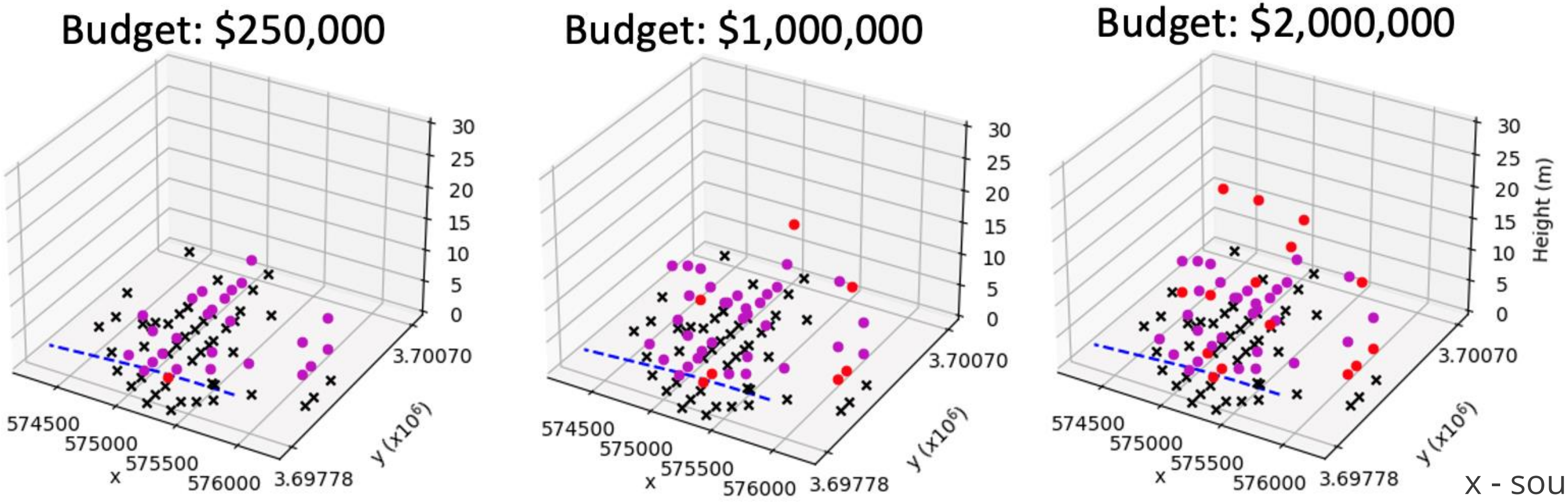


Quantify uncertainty by calculating the difference between actual and estimated emission rate and iterating over many scenarios (Monte Carlo approach)

TECHNICAL APPROACH: OPTIMAL SENSOR PLACEMENT

Optimizing ground-sensor placement with Chama

- Open source sensor network optimization tool developed by Sandia.
- Define optimization metrics (e.g. cost and time to detection) → Optimally placed sensors
- Performed here with mixed sensor types and different budgets



x - source
• - ground-level sensor ($)
• - flux tower sensor ($$$)

RESULTS: GROUND-BASED NETWORK PERFORMANCE TRENDS

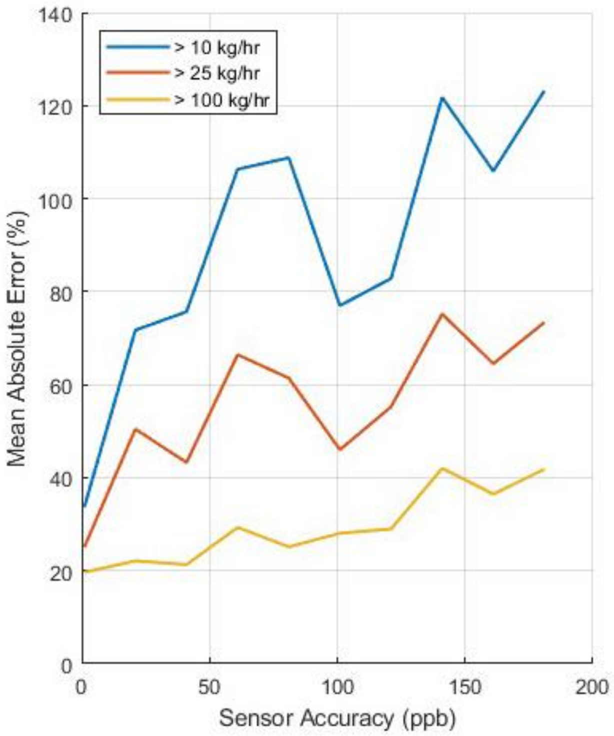
Impact of Sensor Accuracy

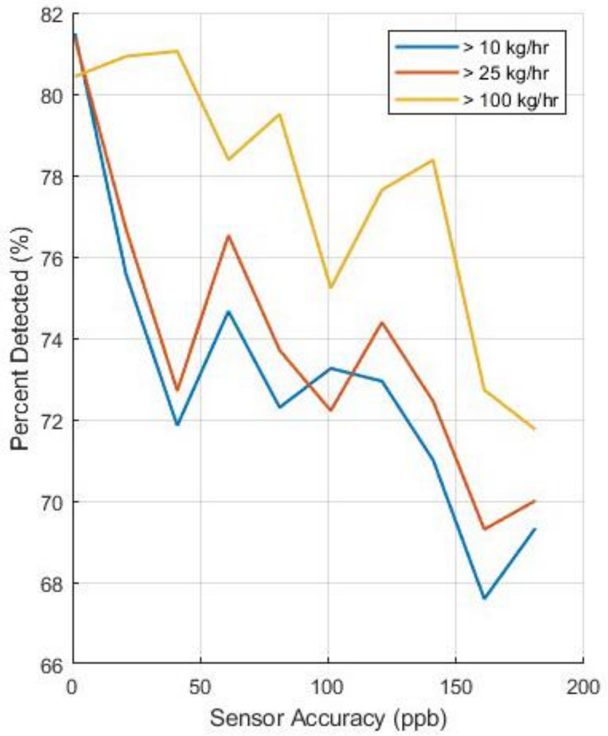
Constraints

- Design
  - Ground-based sensors only
  - Located 100 m from each facility at 90° intervals
  - Type/performance unconstrained
- Performance Definitions – “Mean absolute error” or “percent detected”
- Cost – Unconstrained

Output

- Estimated emission rate error and detection rate vs. sensor accuracy.





RESULTS: GROUND-BASED NETWORK PERFORMANCE TRENDS

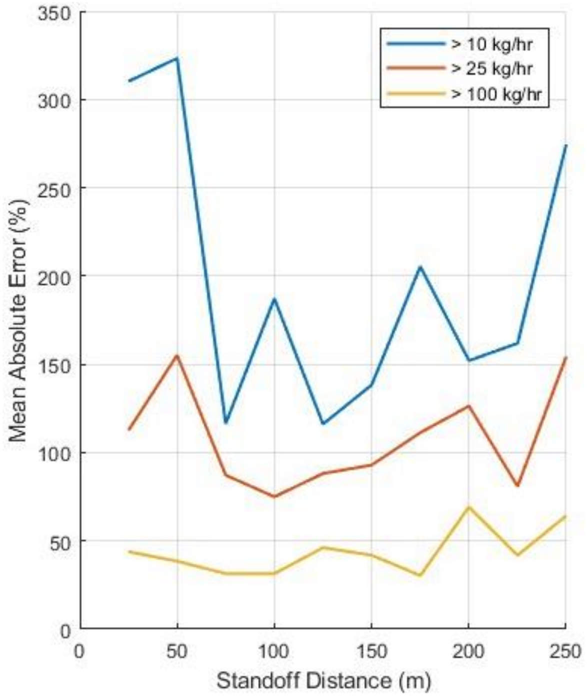
Impact of Standoff Distance

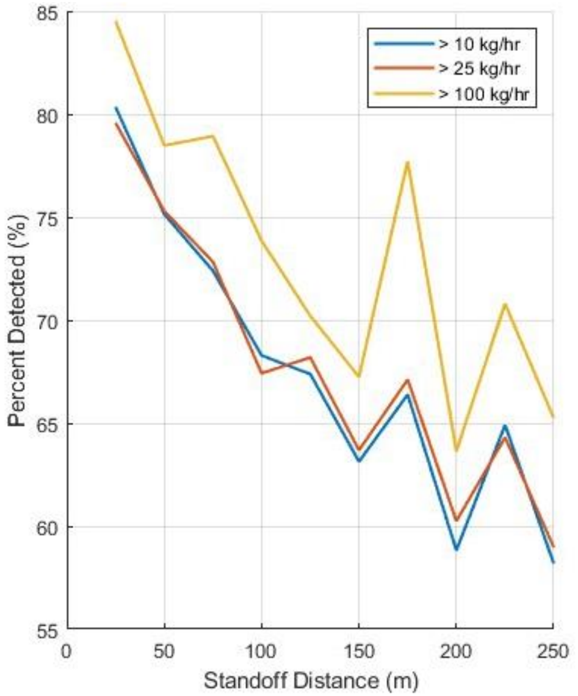
Constraints

- Design
  - Ground-based sensors only
  - Located at each facility at 90° intervals at an unconstrained distance
  - Sensor accuracy of 0.22 ppb
- Performance Definitions – “Mean absolute error” or “percent detected”
- Cost – Unconstrained

Output

- Estimated emission rate error and detection rate vs. standoff distance.





RESULTS: GROUND-BASED NETWORK PERFORMANCE TRENDS

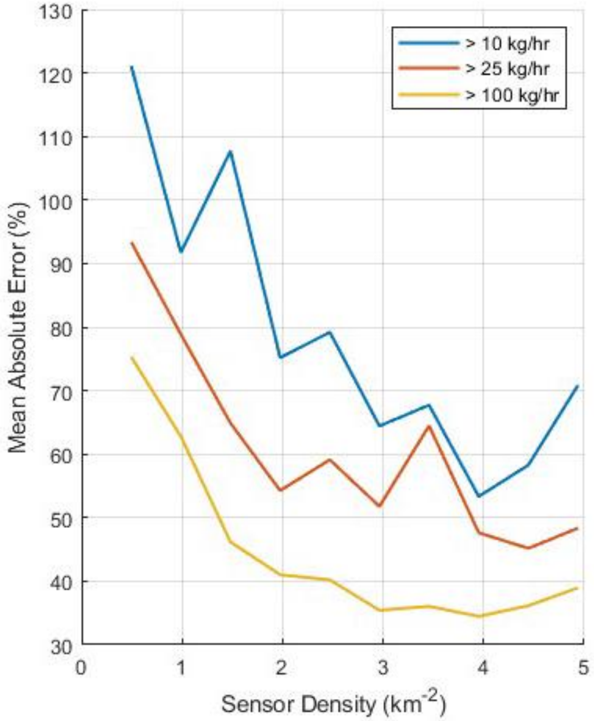
Impact of Sensor Density

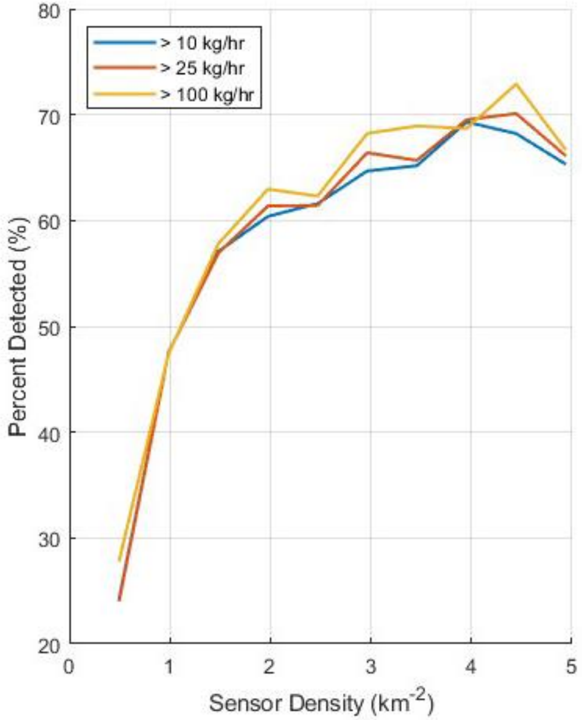
Constraints

- Design
  - Ground-based sensors only
  - Location is unconstrained (random)
  - Sensor accuracy of 0.22 ppb
- Performance Definitions – “Mean absolute Error” or “percent detected”
- Cost – Unconstrained

Output

- Estimated emission rate error and detection rate vs. sensor spatial density





RESULTS: PERFORMANCE OF MULTI-TIERED NETWORK

Impact of Different Tiers:

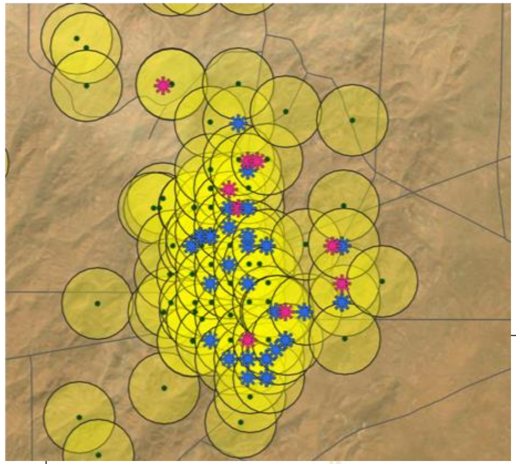
Using Chama and Inverse Bayesian Model

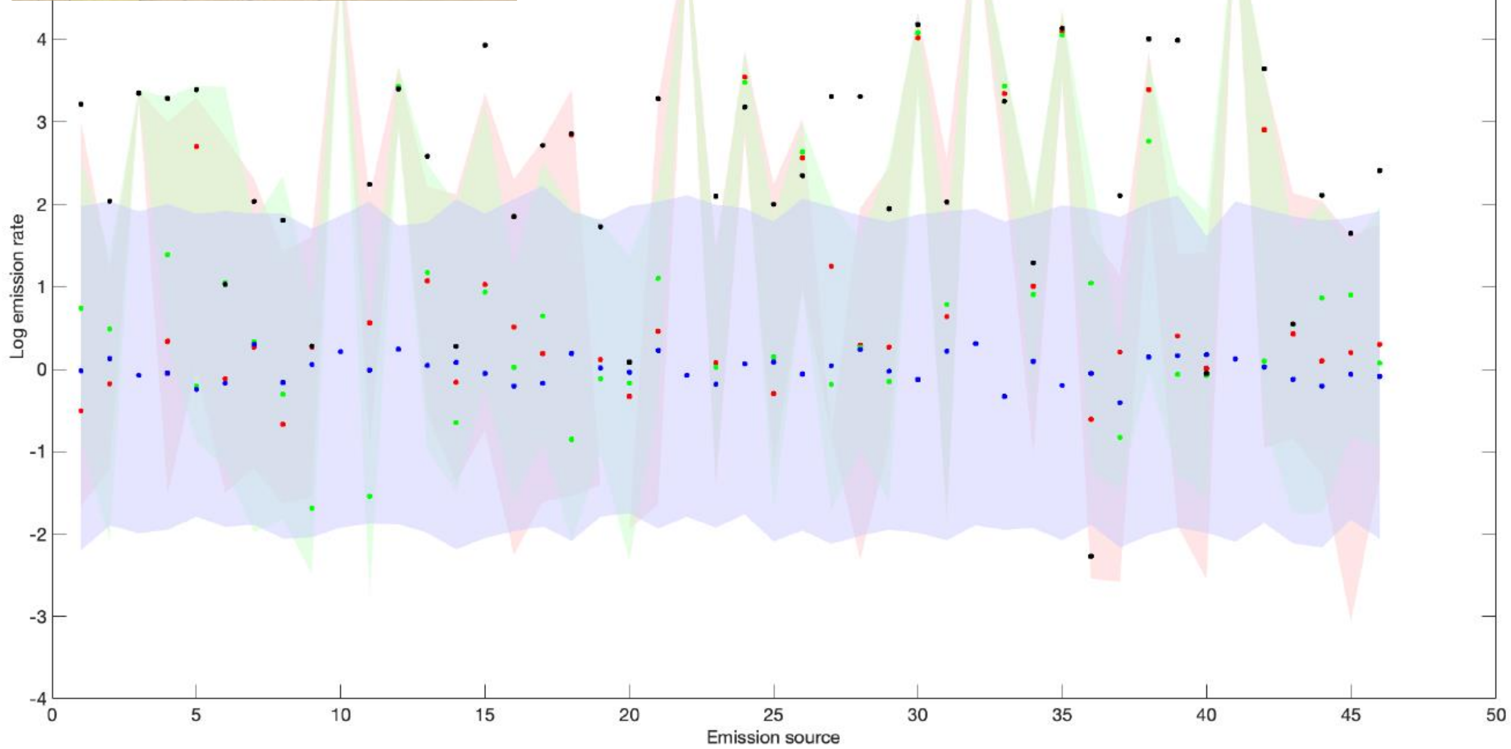
Constraints

- Design
  - Evaluate different combinations of Tiers:
    1. all tiers
    2. ground & airborne
    3. ground only
  - Options for high and low cost sensors
  - Sensor quantities and locations are constrained by cost and optimized by chama.
- Performance – Defined as “time to detection” or “Coverage of Scenarios”
- Cost – Unconstrained

Output

- Estimated emission rate and uncertainty for each source with different tier combos.





RESULTS SUMMARY

- Team investigated a wide variety of sensors from different tiers (ground-based, drones and satellites)
- Developed a framework that can be used to evaluate different designs of a tiered system
- Due to temporal/spatial resolution limits and increasing costs of sensors at different tiers, it is important to optimize performance from the ground up
- Deployment of optimally placed Tier 3 (ground) sensors can be achieved with Chama to enhance performance of tiered sensor networks, due to higher fidelity and ease of control
- Provided initial insights on approximate costs vs. performance of ground-based sensors
- Deploying an optimal Tier 3 (ground) sensor network (before addition of drones/satellites) over the Permian Basin would range between $4.2-13.5 billion
- With a fully integrated sensor network, we demonstrate improved rate quantification with (much) lower uncertainties from a Bayesian inverse model (as opposed to Tiers 2-3 or 3)
- **Monetary cost of including Tiers 1-2 sensors (drones/towers/satellites) is minimized by maximizing performance of Tier 3 (ground) sensor network**

FUTURE DEVELOPMENT

In this project:

- Identify solutions additional stakeholder requirements
- Impact/value of other Satellite data than TROPOMI and tier 2 measurements

After this project:

- Enhance the evaluation framework to address new requirements
- Continue to improve the technical basis of the framework (e.g. more accurate modeling tools, more comprehensive sources and sinks, additional instrumentation, etc.)
- Develop a user-friendly beta version of this software and conduct iterative testing
- Pilot study field demonstration for verification and validation.