Emission Inventories from Natural Gas Storage Facilities using Regional Frequency Comb Laser Monitoring and Aircraft Flyovers

Project Number DE-FE0029168

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U.S. Department of Energy

National Energy Technology Laboratory

Addressing the Nation's Energy Needs Through Technology Innovation – 2019 Carbon Capture, Utilization, Storage, and Oil and Gas Technologies Integrated Review Meeting

August 26-30, 2019

Key Contributors & Collaborators

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Field & Comb Data

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Algorithm Devel.

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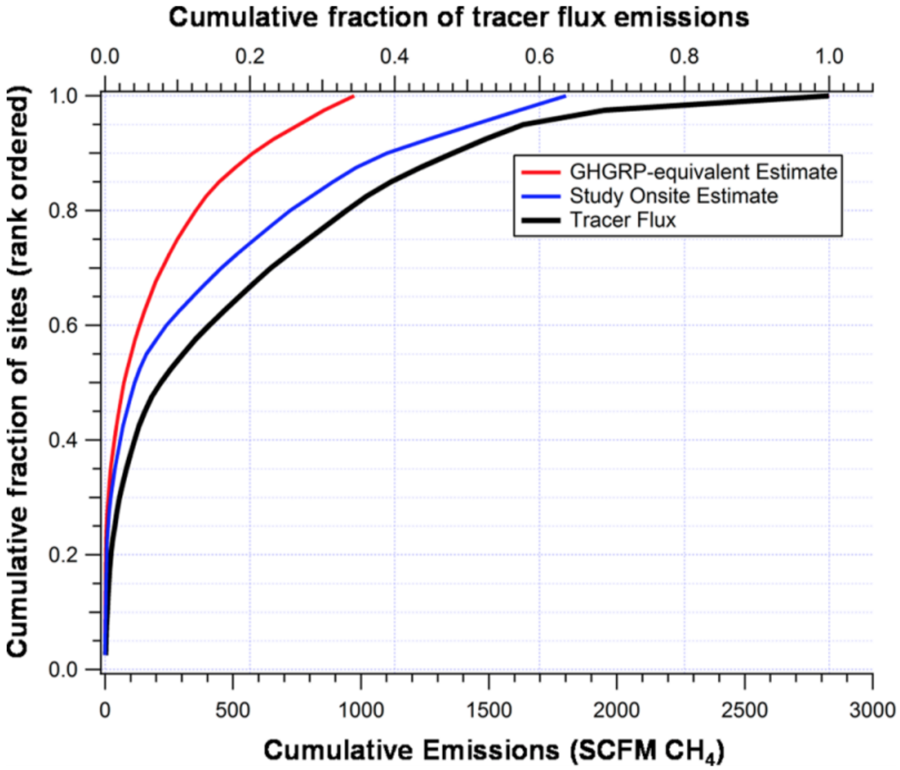
Flight Interp.

Robbie Wright
Comb Engineer

Need for Gas Storage Emissions Characterization

- Methane emissions from storage not well-known
- Limited studies suggest emissions estimates are incorrect, not accounted for in EPA Greenhouse Gas Reporting Program (GHGRP)
- **Critical need for information on temporal variability of emissions**
- New regulations → new technology needs for monitoring



Subramanian et al., 2015

Current Methods to Estimate Emissions from Natural Gas Storage Facilities

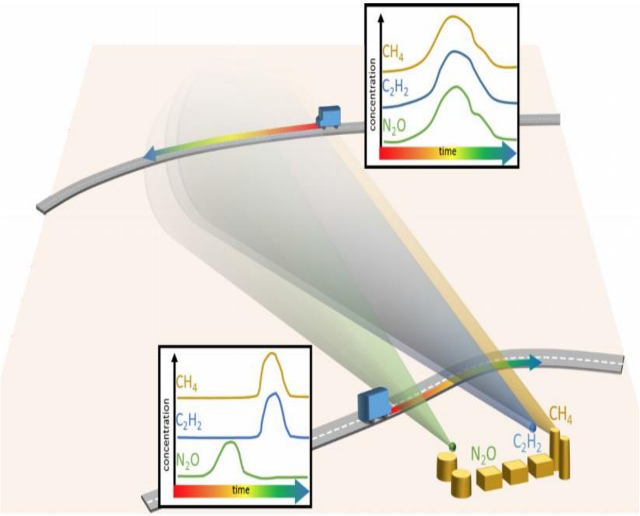
- Aircraft mass balance surveys
- Direct (bottom-up) methods: Infrared imaging, Hi-Flow samplers, calibrated bags
- Mobile point sensors: Downwind Tracer flux estimates, road-based surveys
  - * Strong focus on compressors
  - * Focus on isolated/catastrophic emissions events

Aircraft Mass Balance

OGI Camera

olssonassociates.com

Downwind Tracer Flux

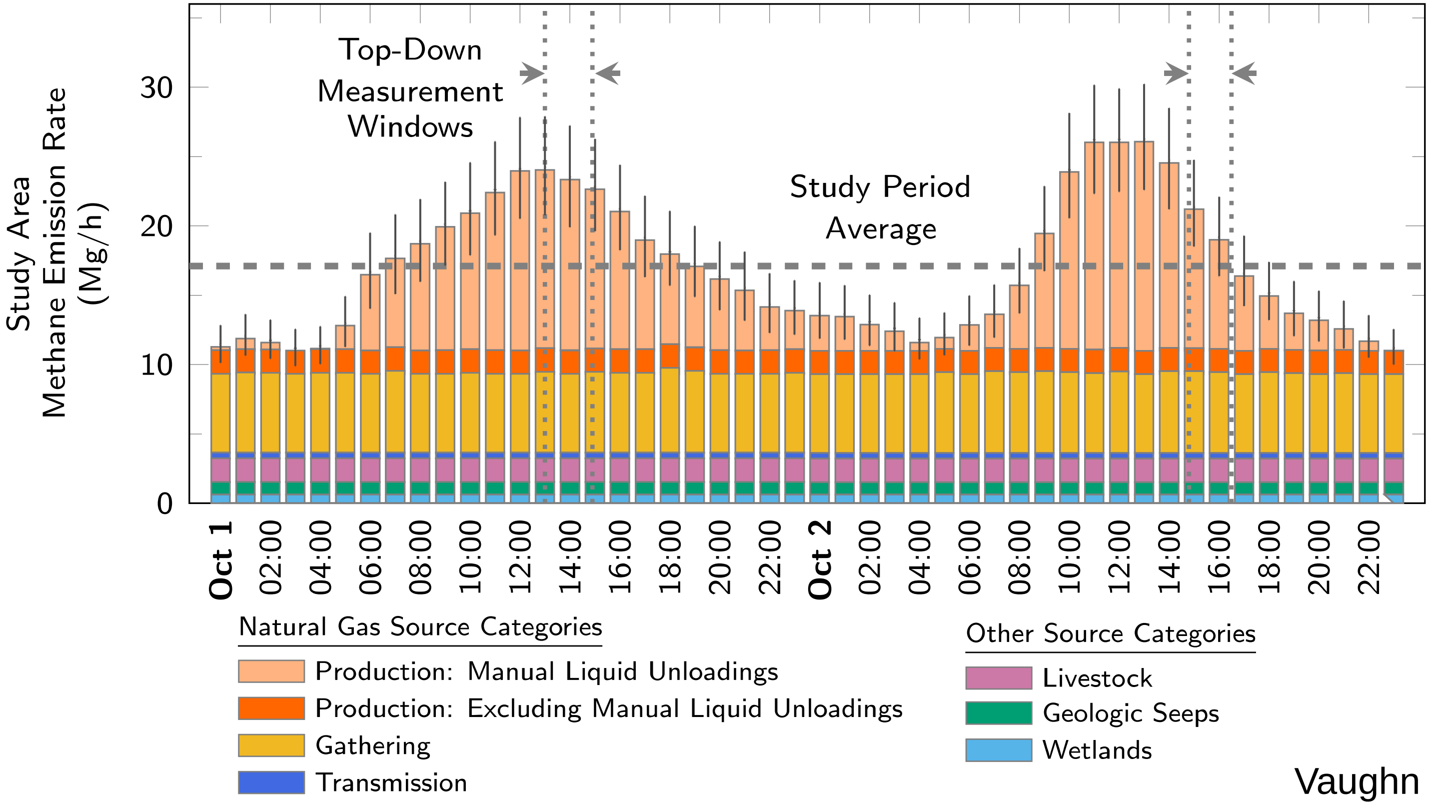


Roscioli et al., 2015 (AMT)

→ All ‘snapshot-in-time’ measurements

Underground Natural Gas Storage Emissions: Temporal Variability may be Major Factor

- Limited repeat aircraft mass balance flights at underground natural gas storage sites suggest possibility of **high variability in emissions**
- Growing awareness that temporal variability in emissions can contribute to uncertainties in emissions estimates in other parts of Natural Gas supply chain



Vaughn et al., *PNAS* 2018

What is the Ideal Emissions Measurement?

Broad coverage of all potential sources

Quantification of emissions

Continuous monitoring (“snapshots” can bias intermittent sources)

Lowest possible cost (ideal)

Project Objectives

Quantify average methane emissions at underground storage sites

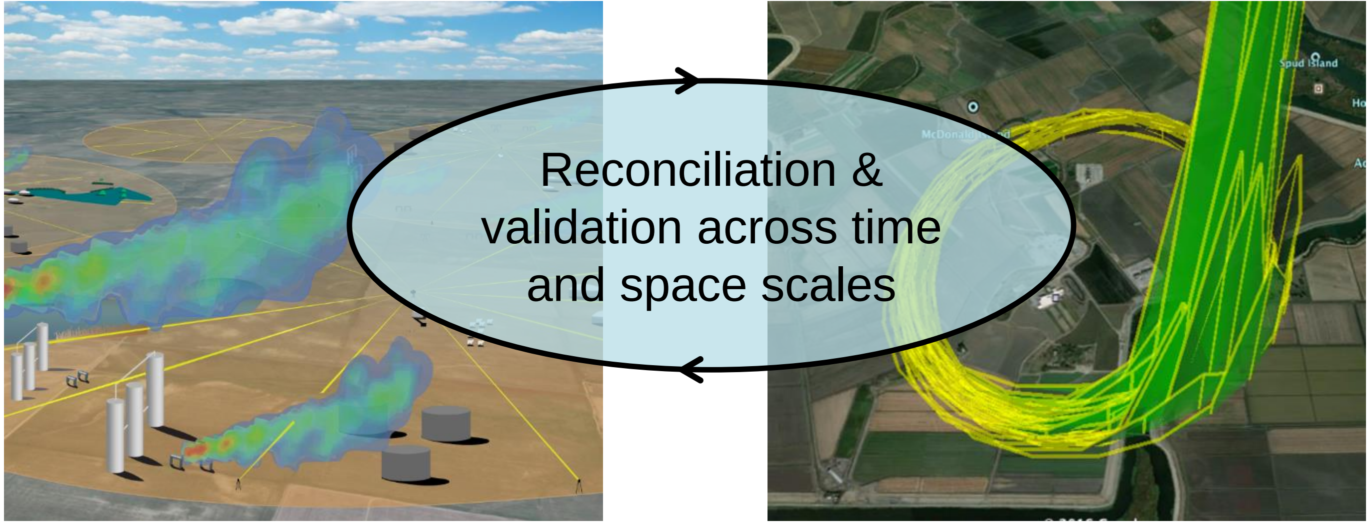
Quantify time variability of methane emissions at underground storage sites

Integrate ground- and aircraft-based observations at co-located sites

Develop a methane emission inventory: facility-wide quantification of average emissions and seasonal variability of emissions

Continuous frequency comb laser monitoring

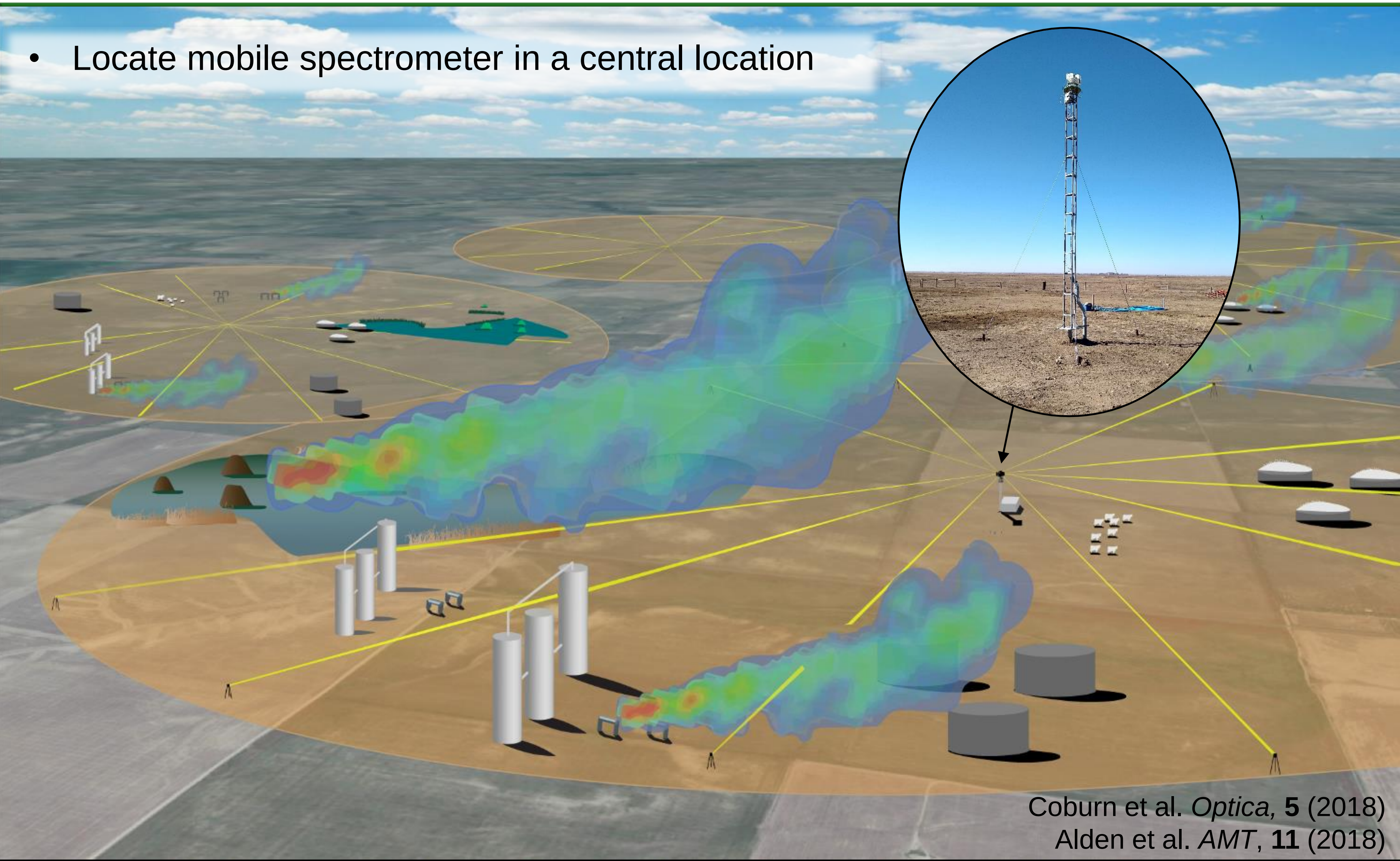
Regular aircraft mass balance flights



Reconciliation & validation across time and space scales

Continuous frequency comb laser monitoring

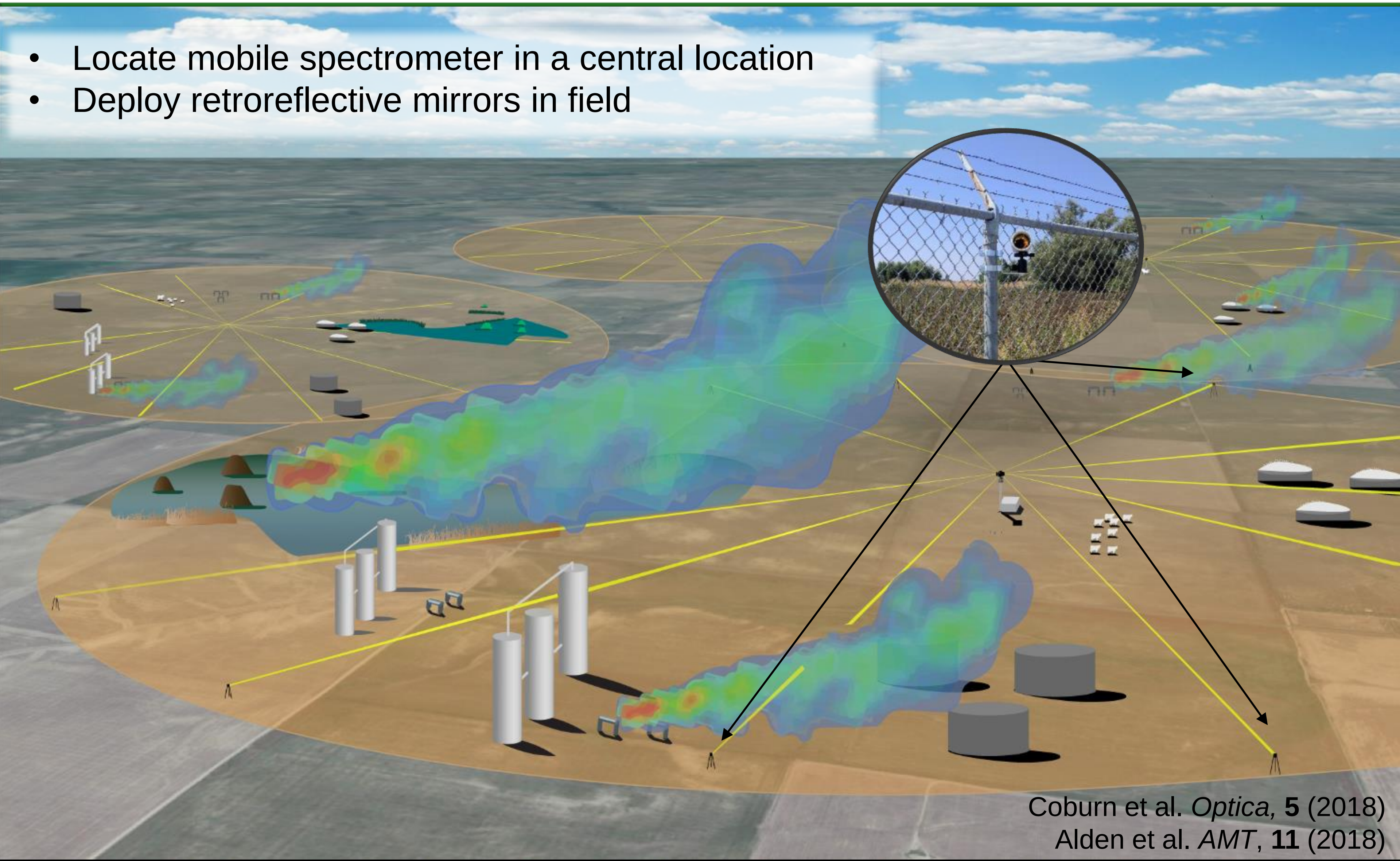
- Locate mobile spectrometer in a central location



Coburn et al. *Optica*, **5** (2018)
Alden et al. *AMT*, **11** (2018)

Continuous frequency comb laser monitoring

- Locate mobile spectrometer in a central location
- Deploy retroreflective mirrors in field



Coburn et al. *Optica*, **5** (2018)
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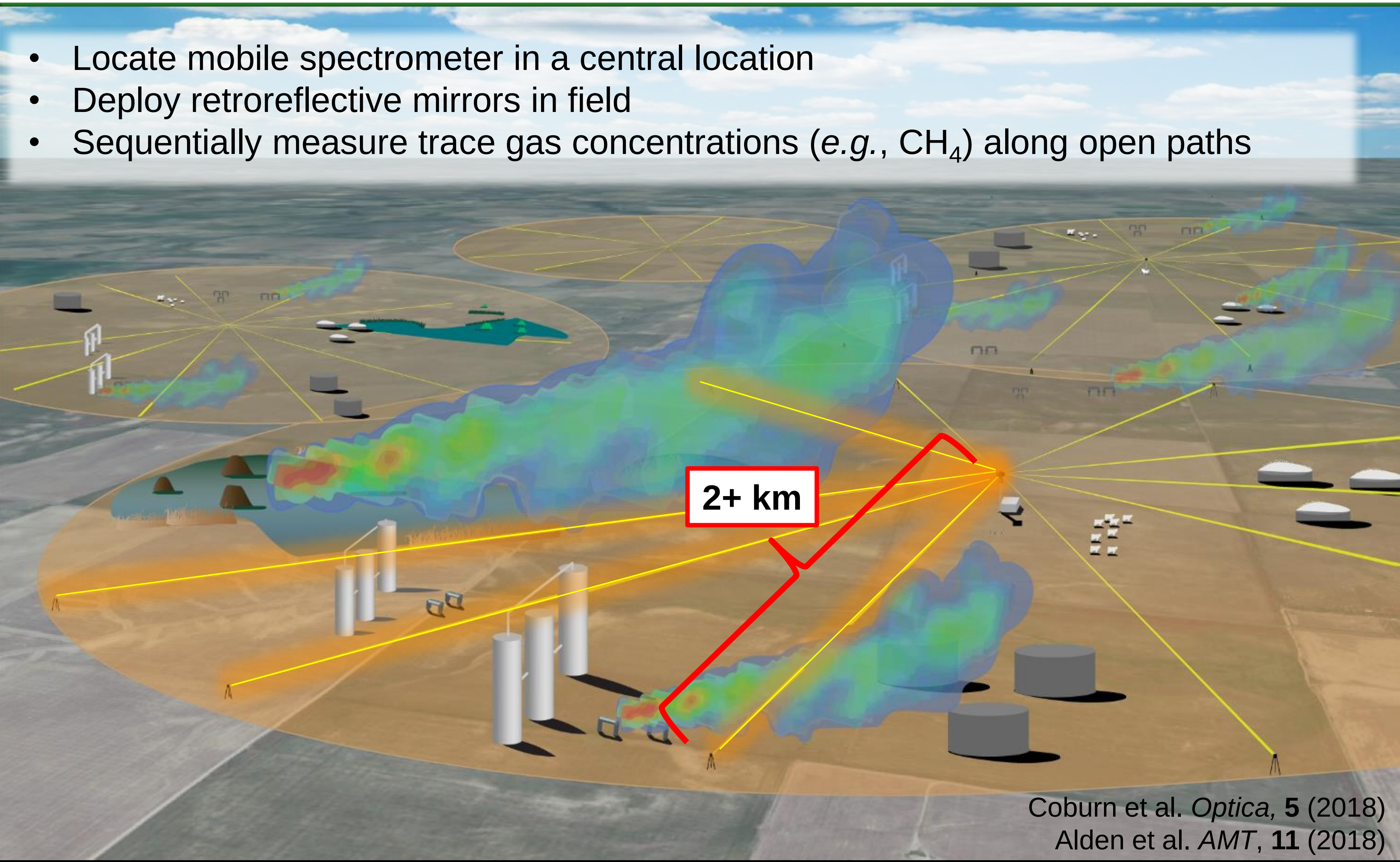
Continuous frequency comb laser monitoring

- Locate mobile spectrometer in a central location
- Deploy retroreflective mirrors in field
- Sequentially measure trace gas concentrations (*e.g.*, CH_4) along open paths



Coburn et al. *Optica*, **5** (2018)
Alden et al. *AMT*, **11** (2018)

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SCIENTIFIC AVIATION

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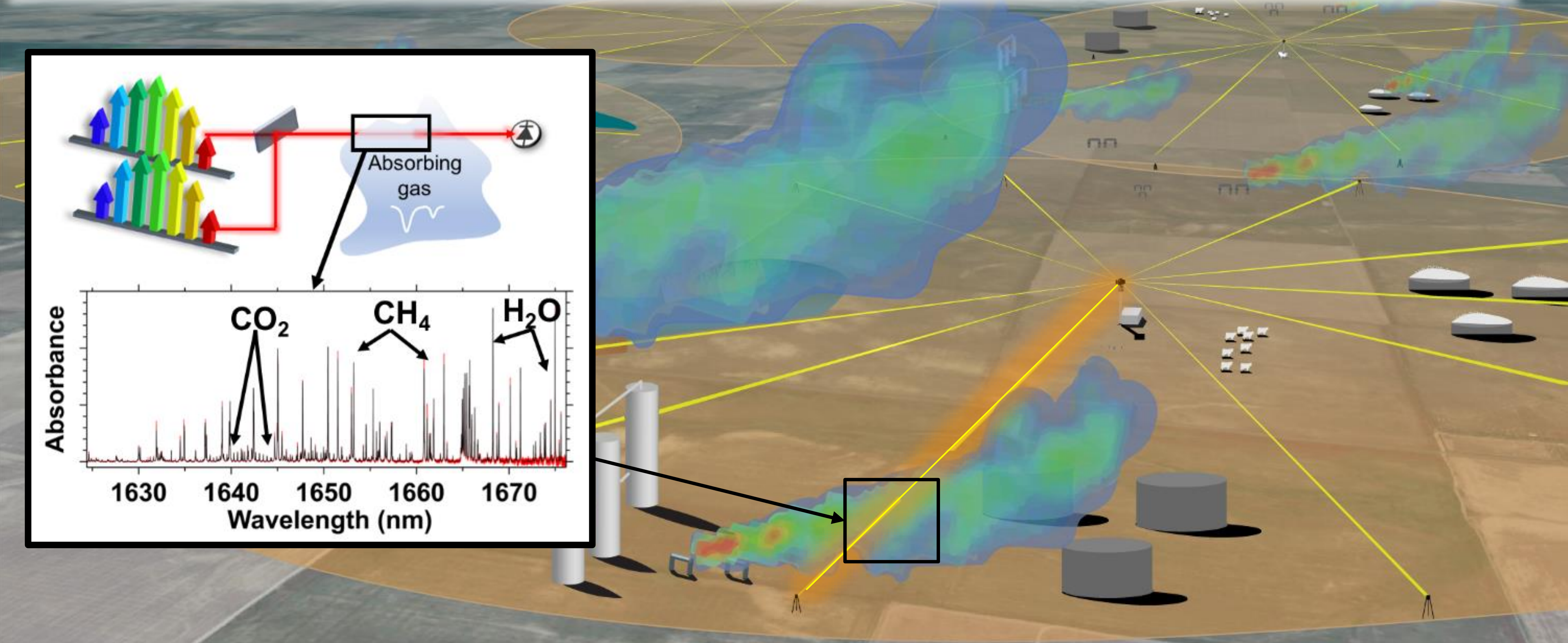
Continuous frequency comb laser monitoring

- Locate mobile spectrometer in a central location
- Deploy retroreflective mirrors in field
- Sequentially measure trace gas concentrations (*e.g.*, CH_4) along open paths
- Determine species concentration

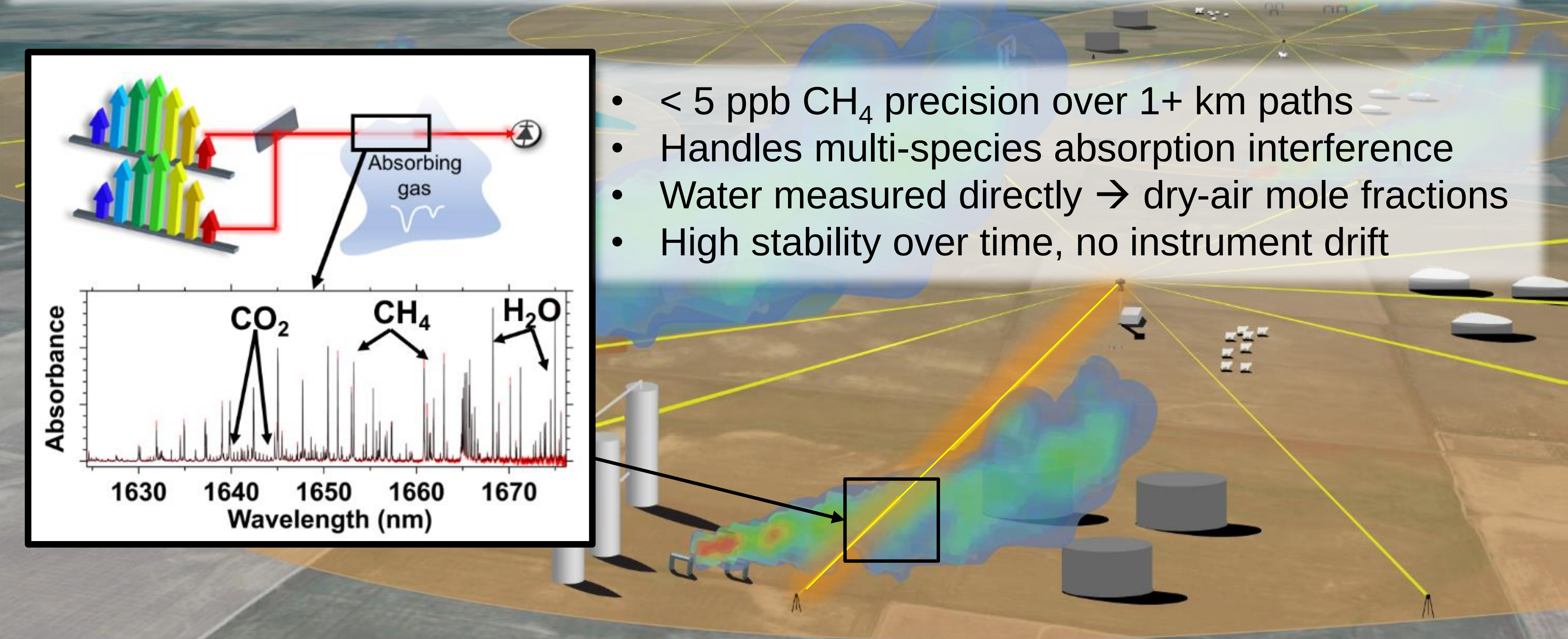


Coburn et al. *Optica,* **5** (2018)
Alden et al. *AMT*, **11** (2018)

Continuous frequency comb laser monitoring

- Locate mobile spectrometer in a central location
- Deploy retroreflective mirrors in field
- Sequentially measure trace gas concentrations (*e.g.*, CH_4) along open paths
- Determine species concentration

- < 5 ppb CH_4 precision over 1+ km paths
- Handles multi-species absorption interference
- Water measured directly → dry-air mole fractions
- High stability over time, no instrument drift



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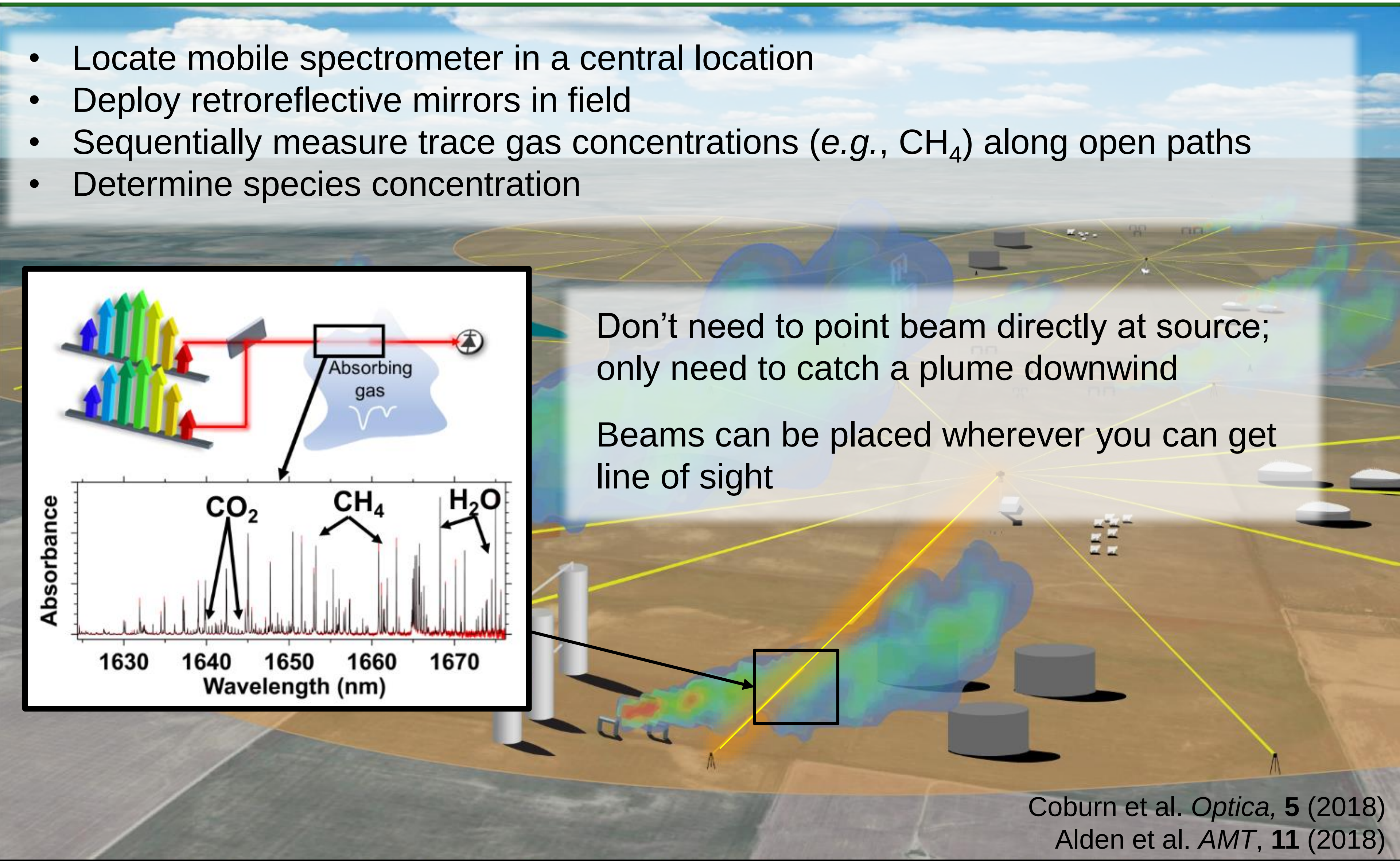

Don’t need to point beam directly at source; only need to catch a plume downwind

Beams can be placed wherever you can get line of sight

Coburn et al. *Optica,* **5** (2018)
Alden et al. *AMT*, **11** (2018)

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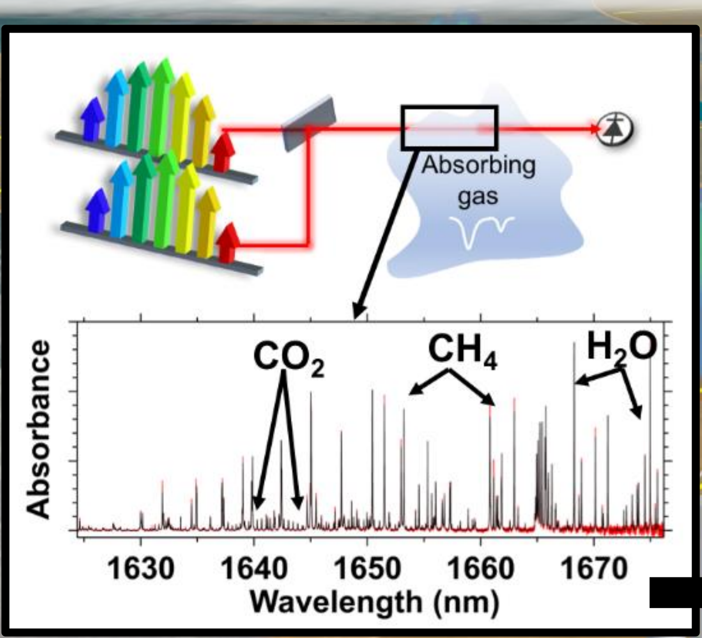
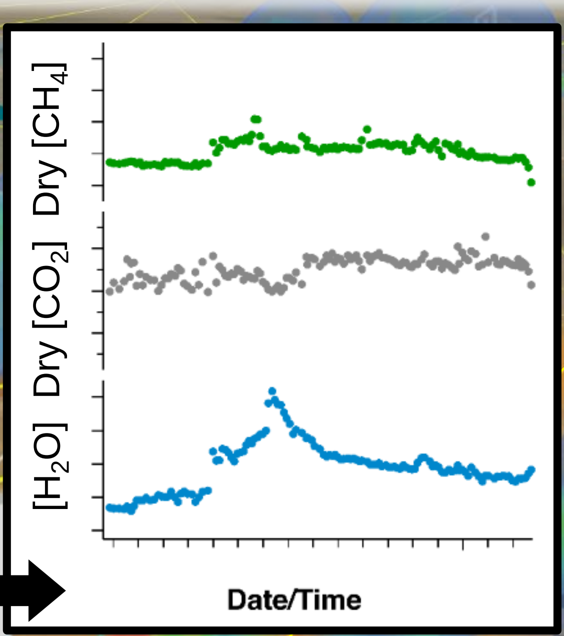
Continuous frequency comb laser monitoring

- Locate mobile spectrometer in a central location
- Deploy retroreflective mirrors in field
- Sequentially measure trace gas concentrations (*e.g.*, CH_4) along open paths
- Determine species concentration, track variability through time

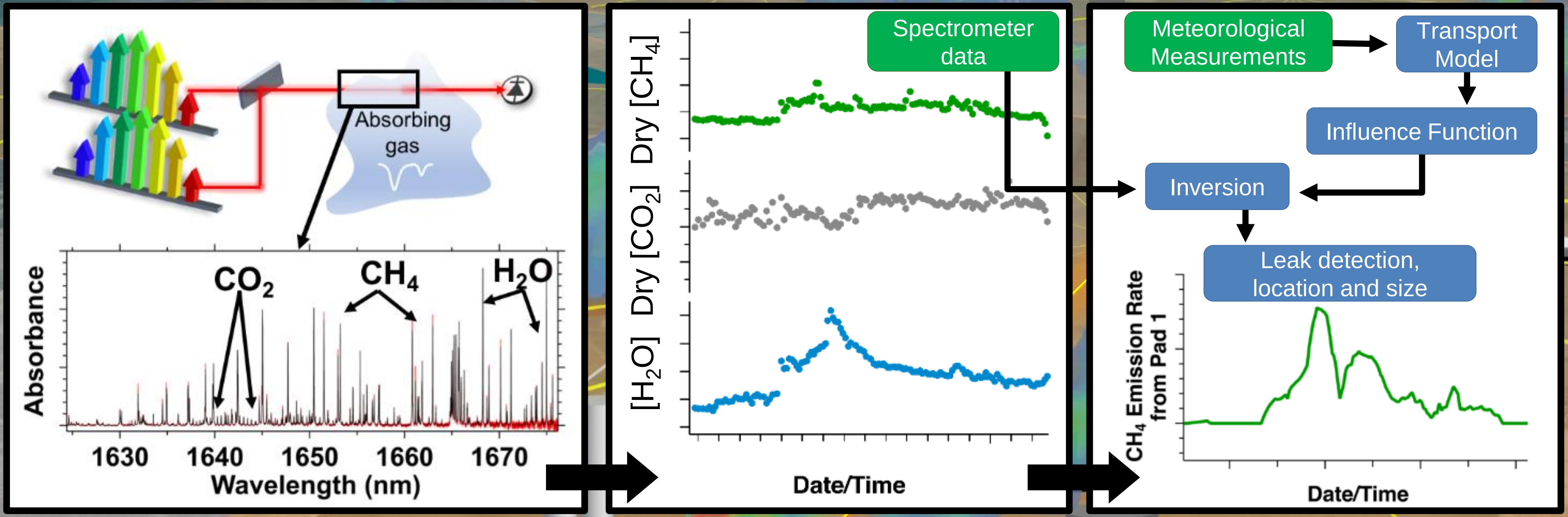




Coburn et al. *Optica*, **5** (2018)
Alden et al. *AMT*, **11** (2018)

Continuous frequency comb laser monitoring

- Locate mobile spectrometer in a central location
- Deploy retroreflective mirrors in field
- Sequentially measure trace gas concentrations (*e.g.*, CH_4) along open paths
- Determine species concentration, track variability through time, couple with atmospheric modeling and inversions

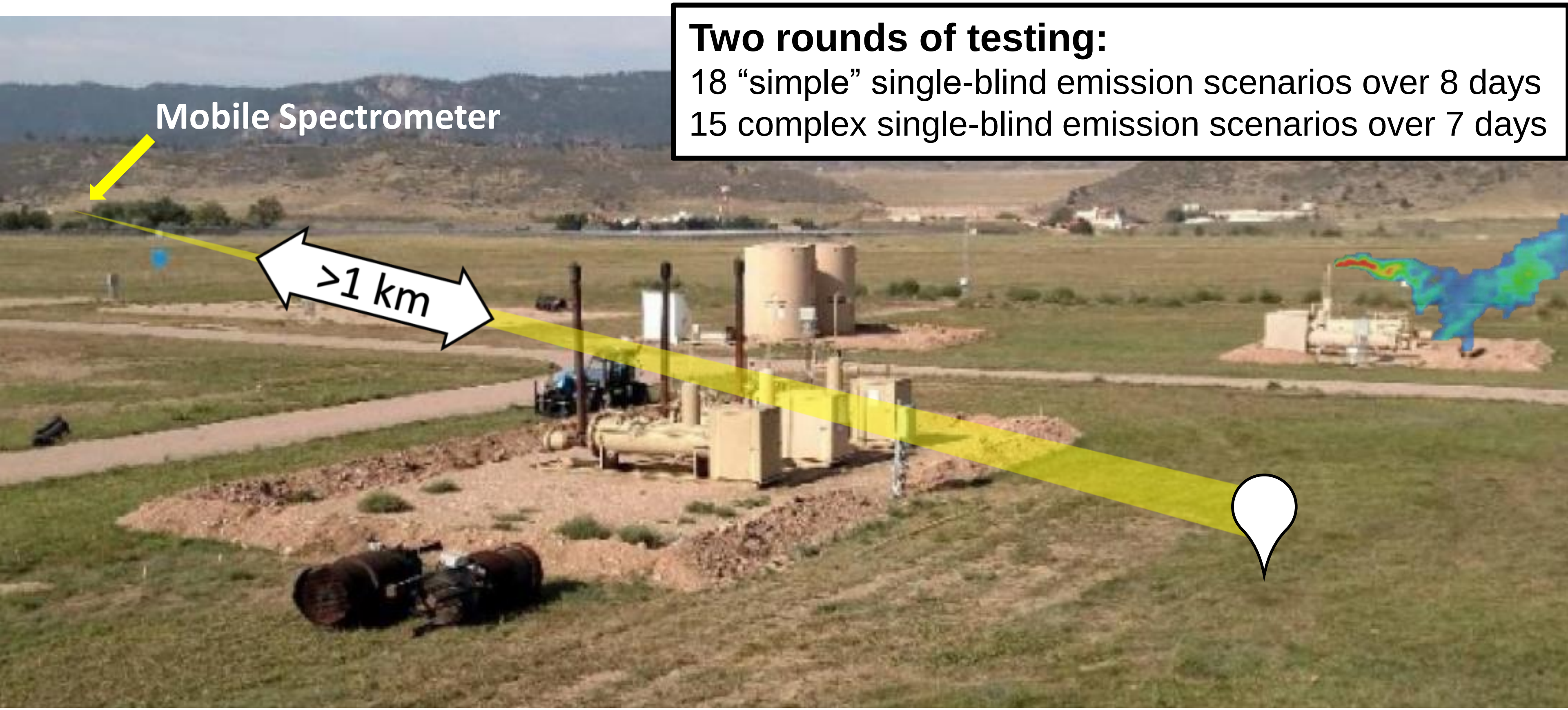


Coburn et al. *Optica*, **5** (2018)
Alden et al. *AMT*, **11** (2018)

Blinded Demonstration of Capabilities

ARPA-E Methane Emissions Technology Evaluation Center

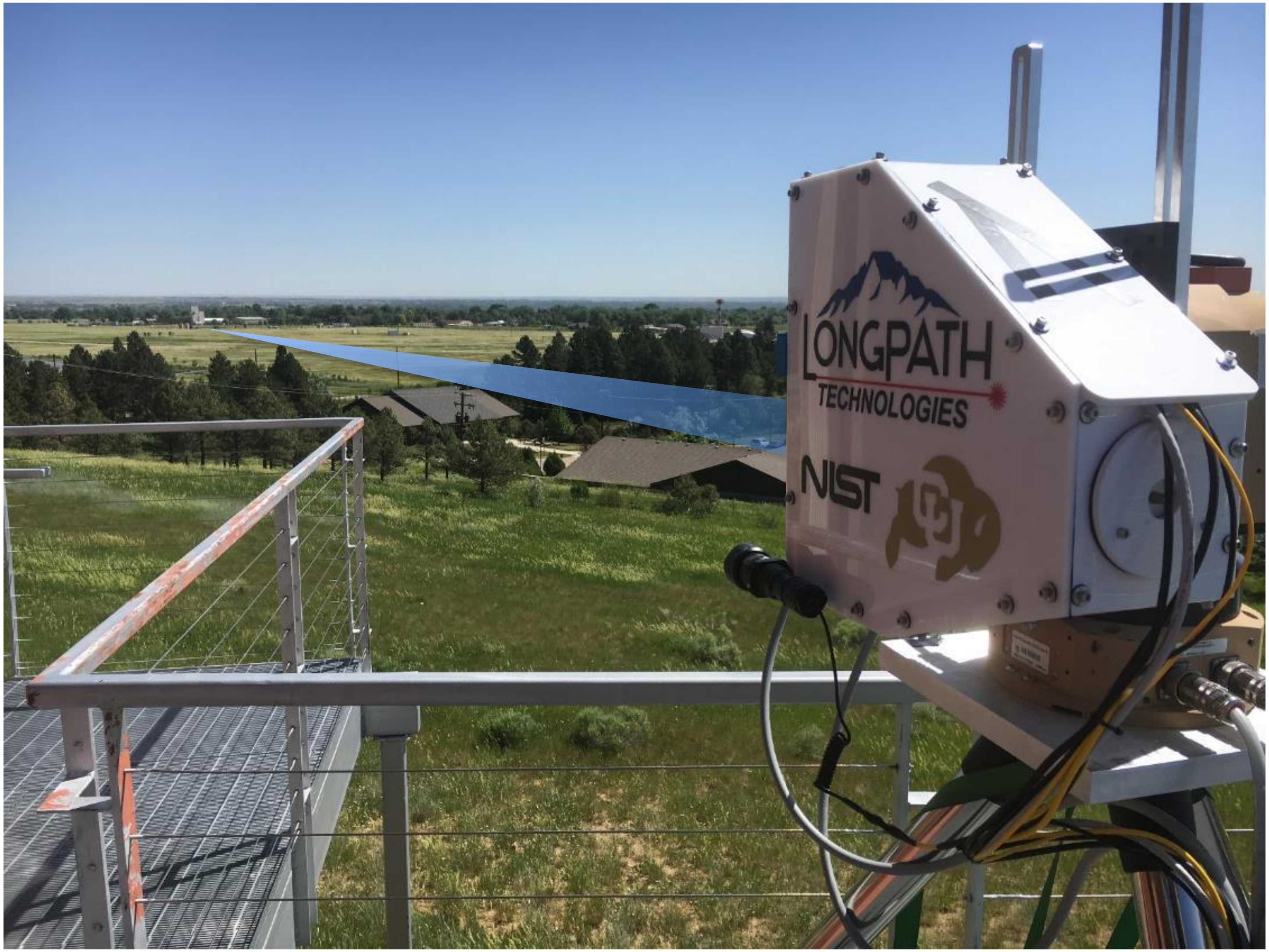
“Hollywood” production pads



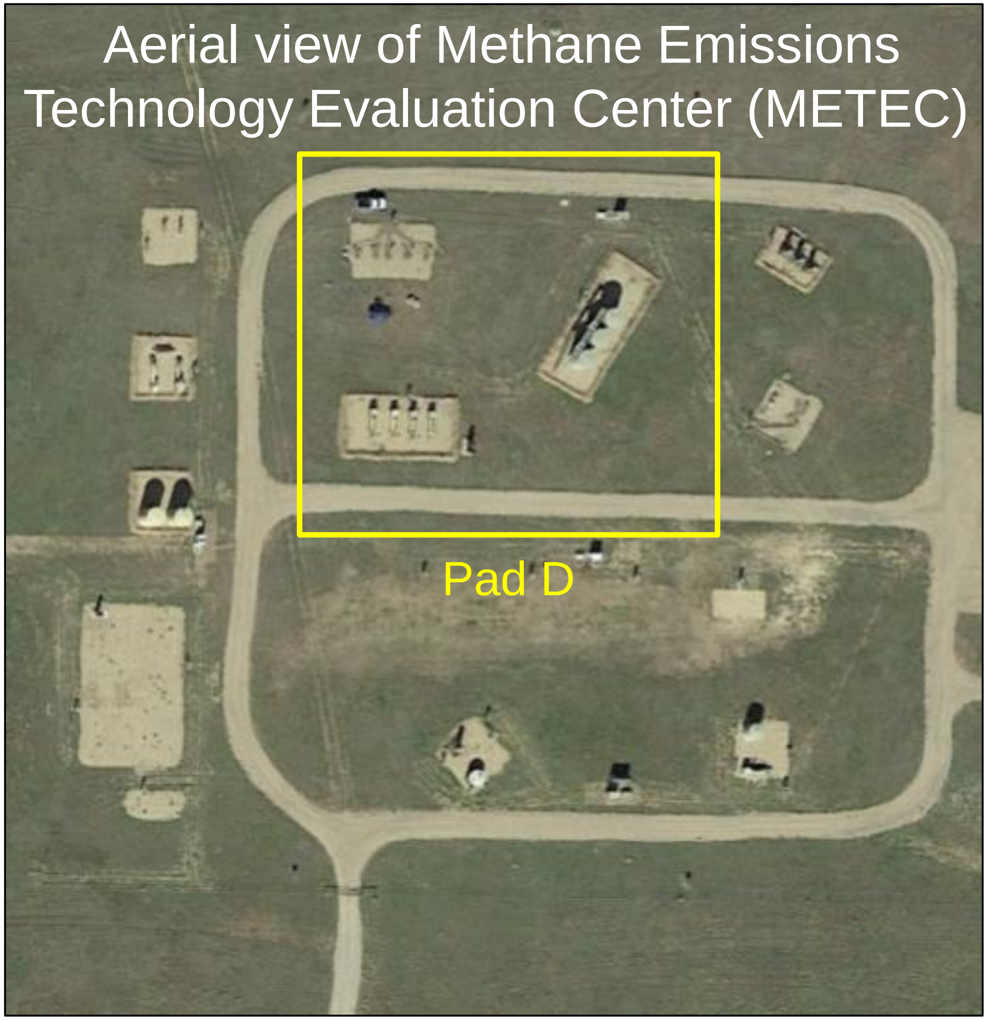
Two rounds of testing:
18 “simple” single-blind emission scenarios over 8 days
15 complex single-blind emission scenarios over 7 days

Coburn, et al., *in prep*
Alden, et al., *Env. Sci. & Technol. (2019)*

View from Laser System



Single-Blind Complex Emissions Tests (R2)



Test method: Continuous Monitoring
Single steady emission
Multiple steady emissions
Operational emissions

Detection: is there a leak?

- Detected 90% of all leaks
- Detected 100% of leaks > 2.4 m^3/day
- 6 false positives < 3.4 m^3/day

Attribution: where is the leak?

- 100% for groups of equipment
- 82% for correct or neighboring equipment

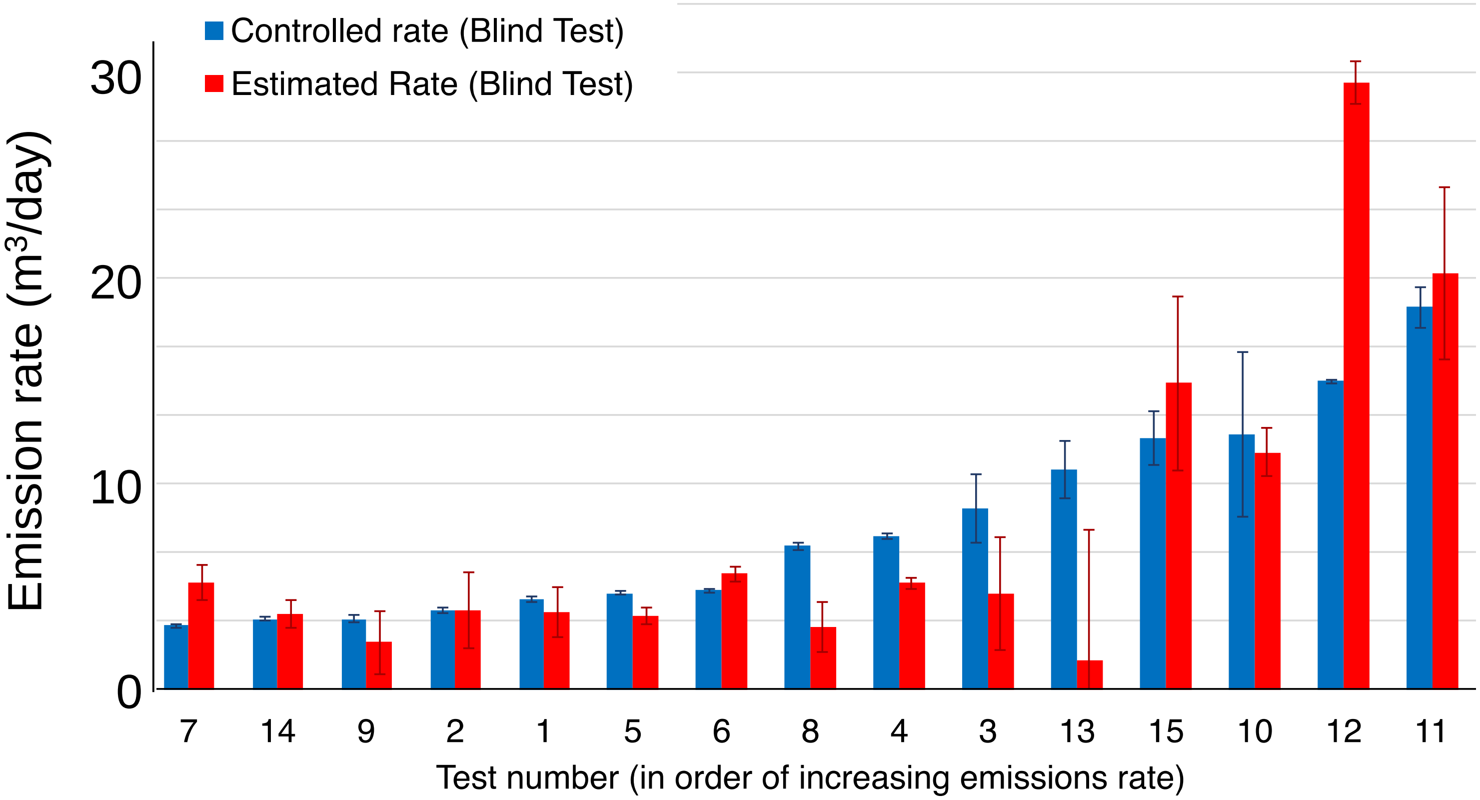
Quantification: how big is the leak?

- Battery-scale controlled leaks 3 - 19 m^3/day

Coburn, et al., *in prep*

Round 2 Single-Blind Test: Quantification

87% of all battery-level leaks estimated to within < 4 m^3/day



Coburn, et al., *in prep*

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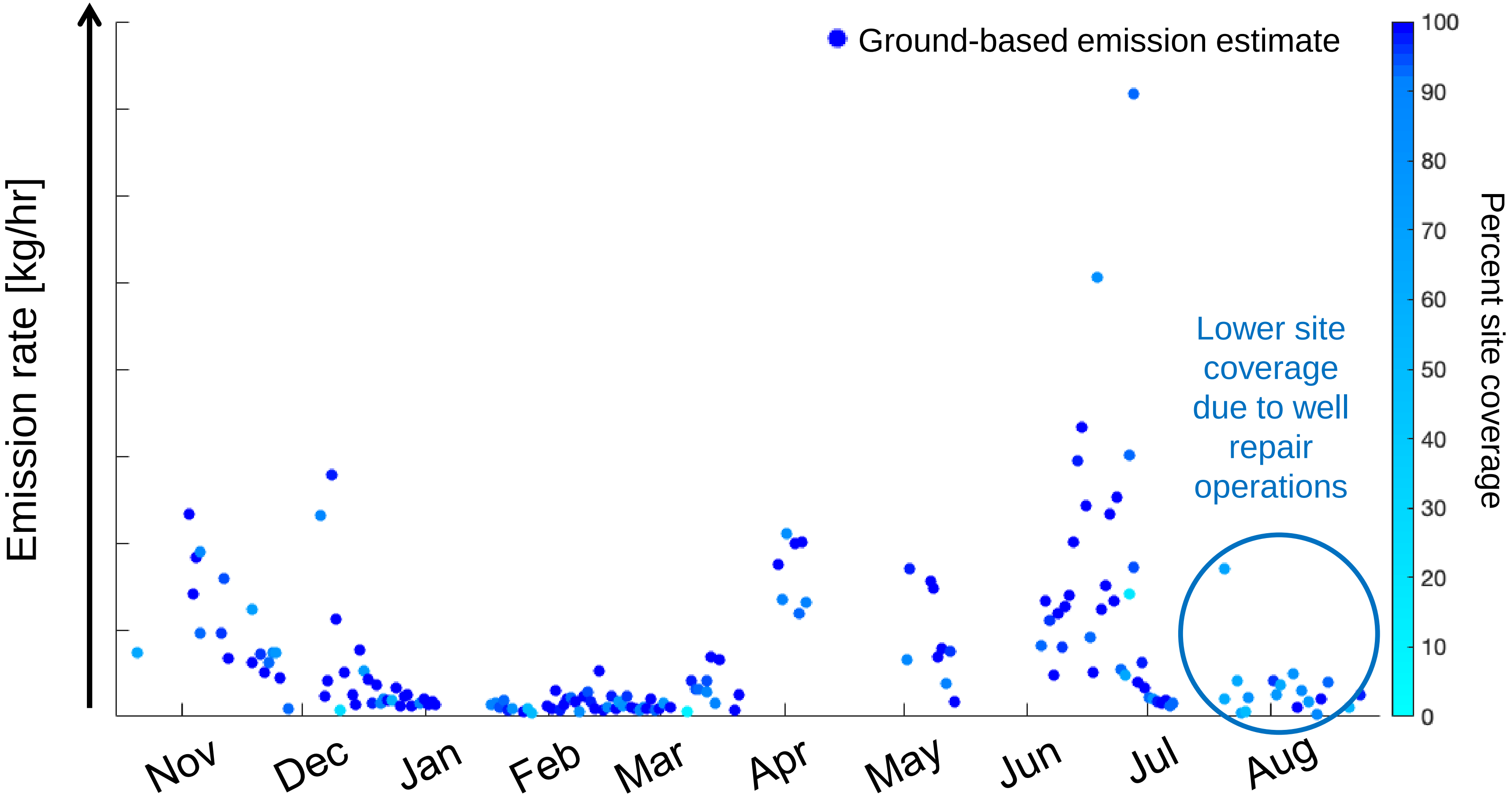
Continuous frequency comb laser monitoring

Two installations at Western US methane storage facilities

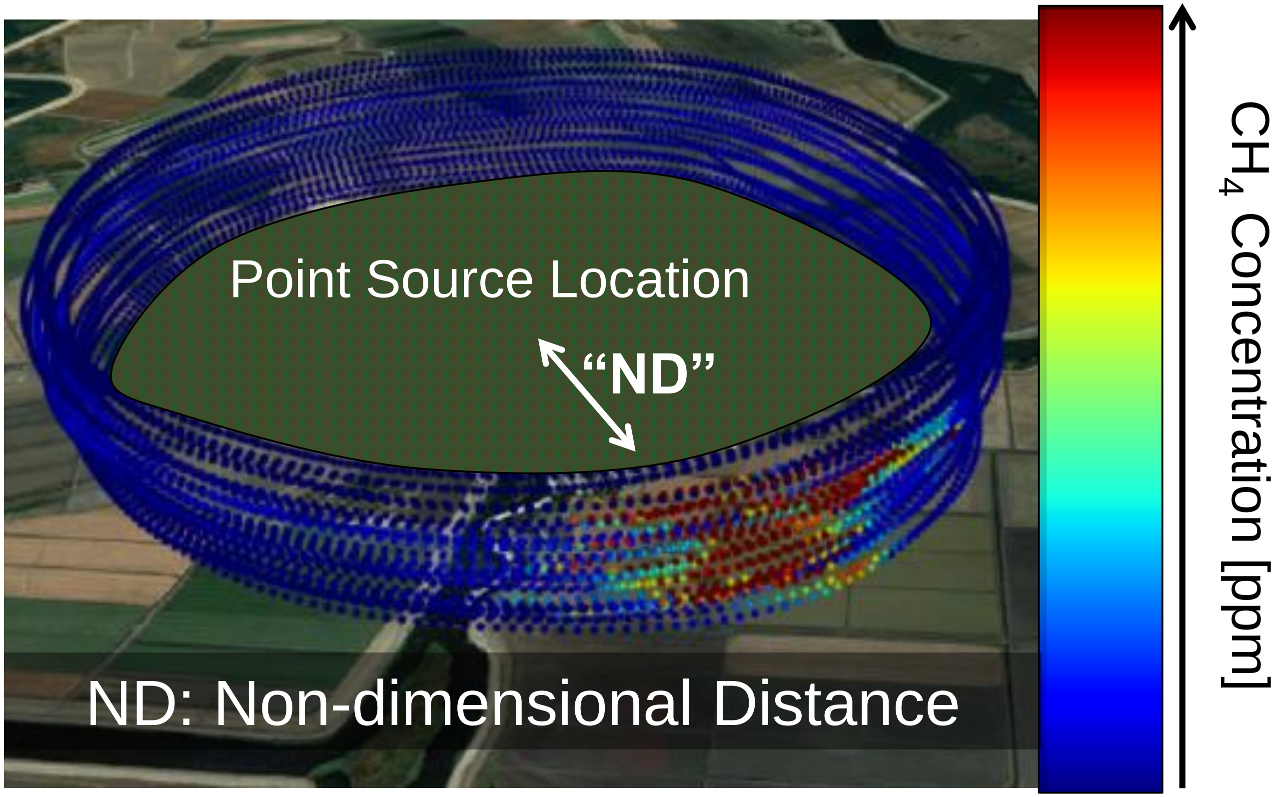
Observed Emissions Variability

Obtained one full year of data at one site…
More to come, plus other site



Aircraft-based emission estimation & innovations

- "Cylinder" flown around point source; rings of 100-200 m altitude increments
- Concentration enhancements quantified on downwind pass
- Total emission rate estimated with Gauss' theorem within closed flight path

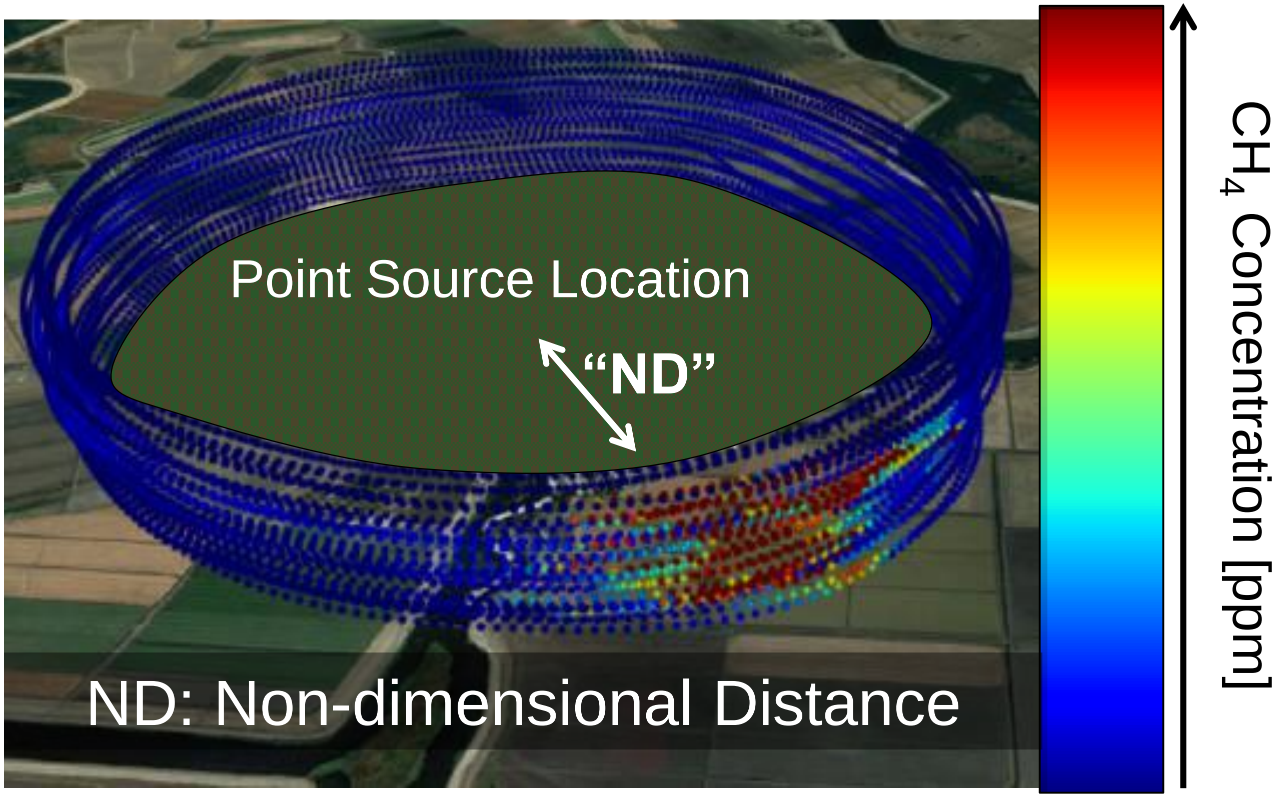


Example flight path

Aircraft-based emission estimation & innovations

Non-dimensional distance from the emission source is ratio of advection time (d/U) to eddy-turnover time (z_i/w_*)

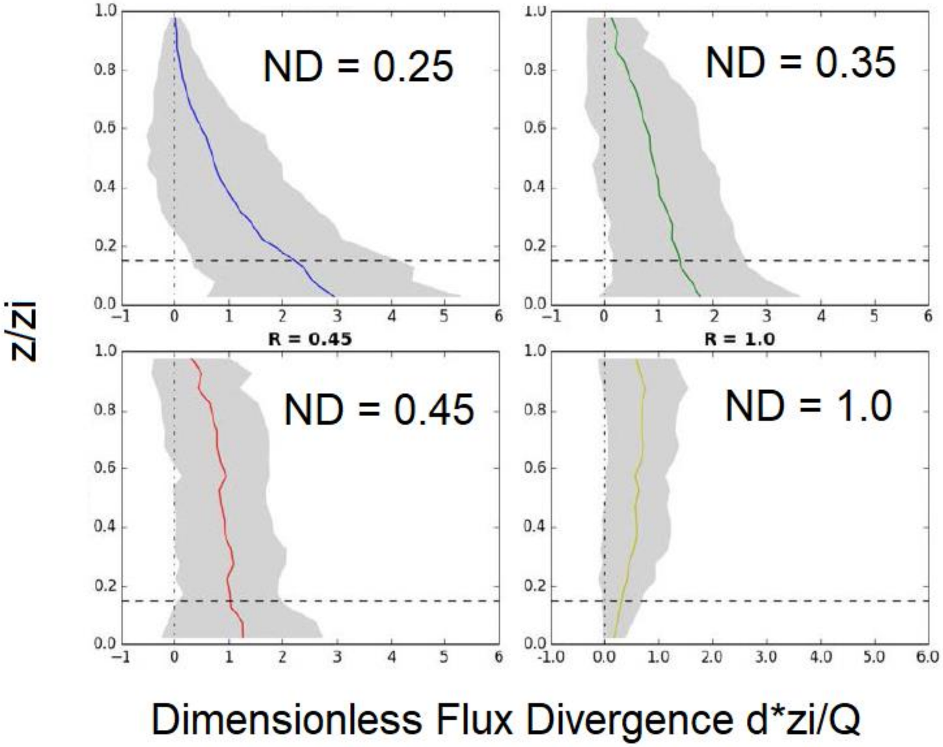
$$ND = \frac{d\, w_*}{U\, z_i}$$



Example flight path

Aircraft-based emission estimation & innovations

- Optimal Non-dimensional Distance (ND): **0.4**
- At this distance the horizontal flux divergence is ~constant from lowest flight leg to ground (from LES simulations)
- Measuring convective velocity scale (w_*) is critical, but *requires many assumptions without direct measurements of turbulence*



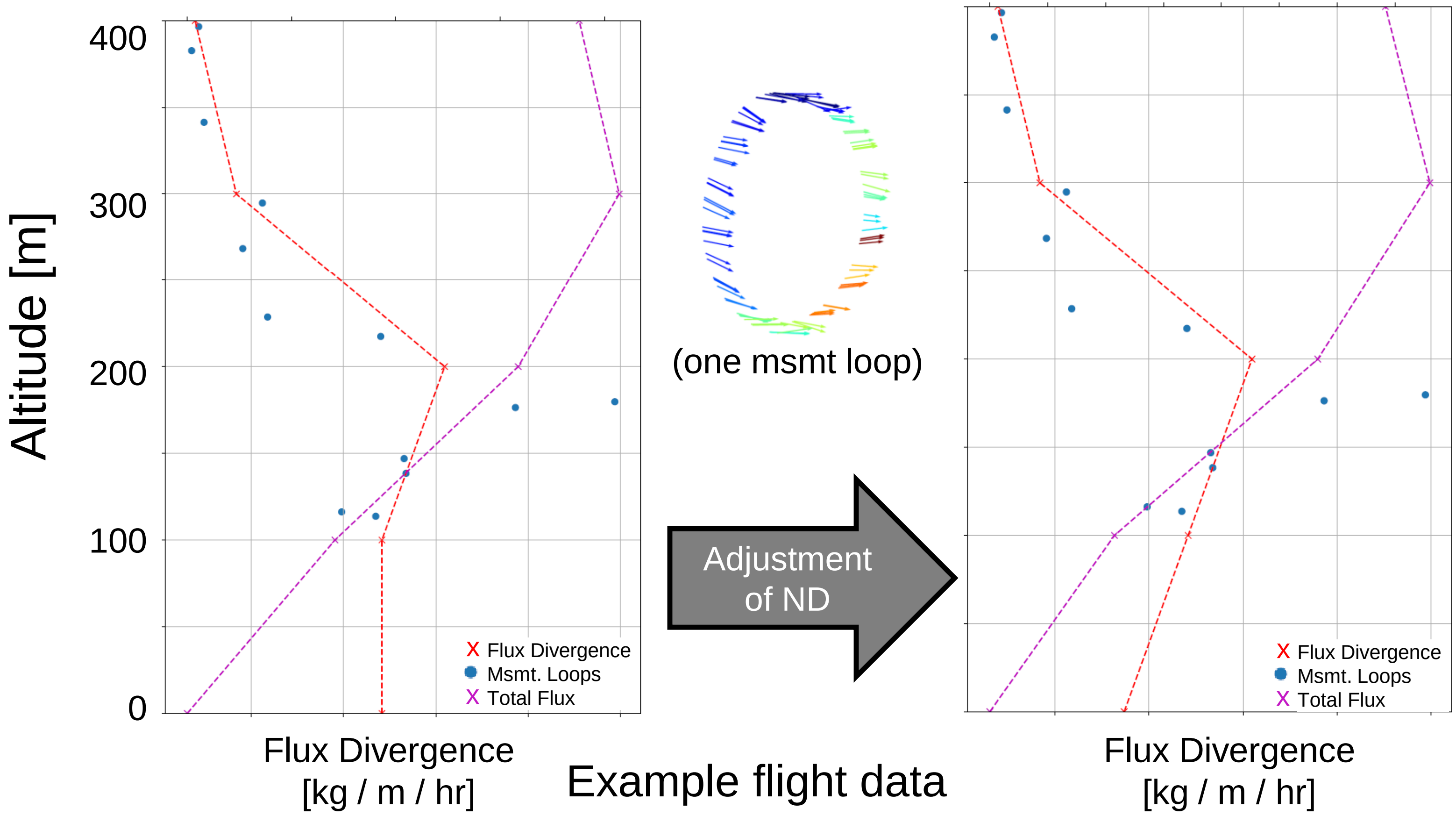
← Lowest flight leg

← Lowest flight leg

Aircraft-based emission estimation & innovations

By estimating and adjusting for non-dimensional distance, emission estimation can be improved

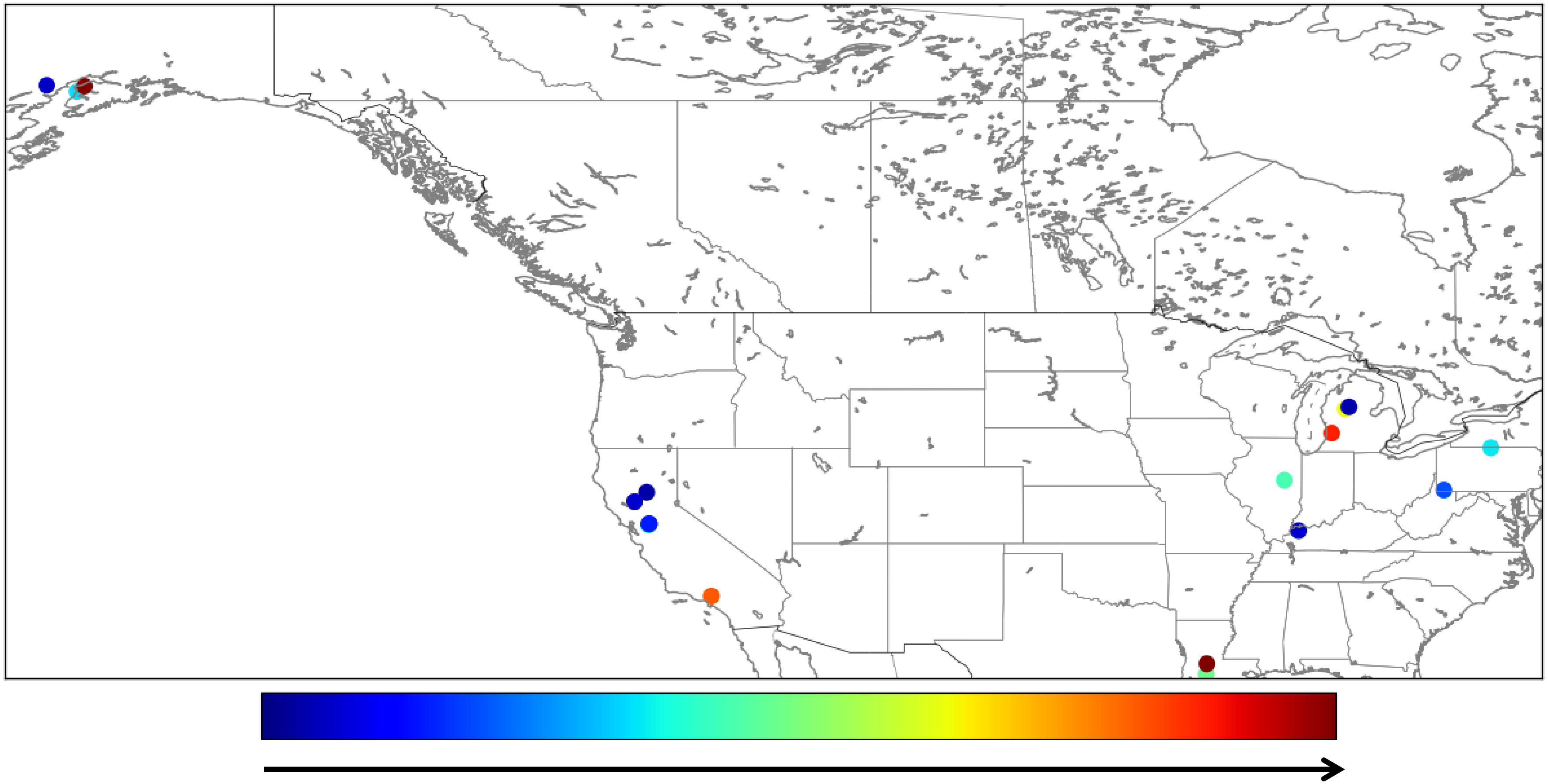
Can result in improvements up to 40%



Example flight data

Aircraft-based emission estimation & innovations

- Natural Gas storage facility sites flown to date

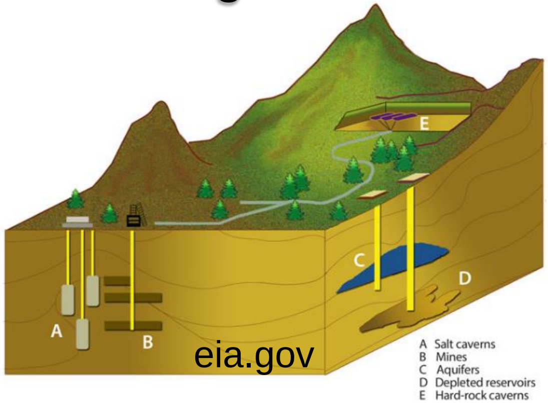


Average discernible emission rate (kg / hour)

Cross-scale Emissions Estimates at Storage Sites

MIDSTREAM

Mountain Region NG Storage



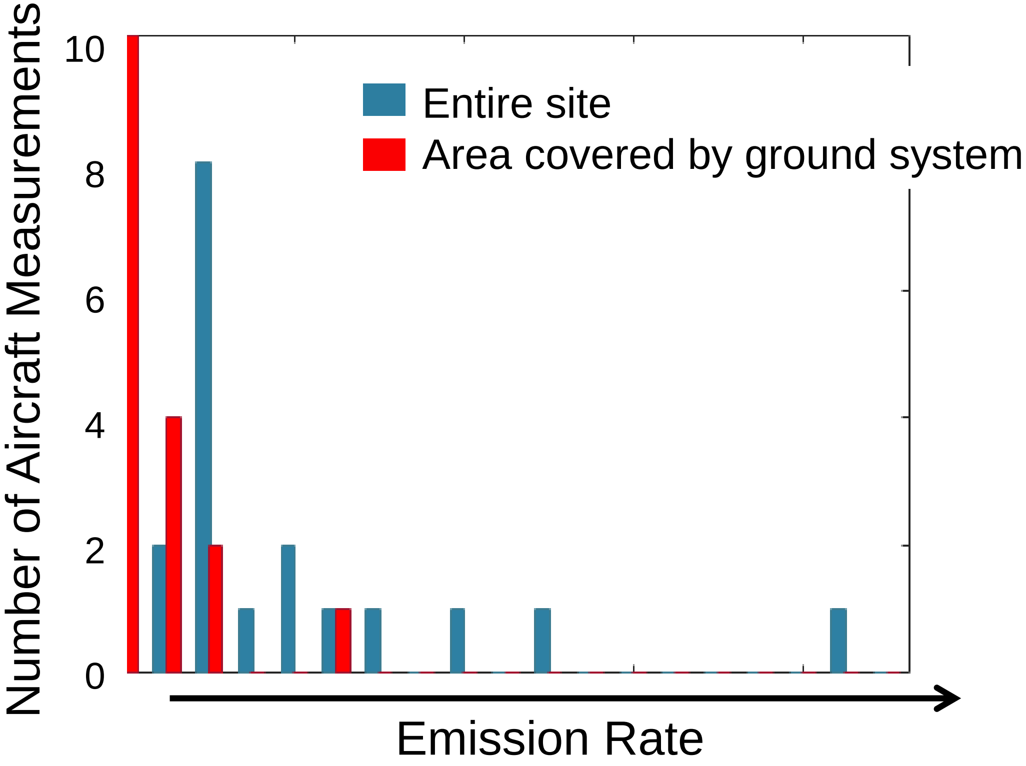
eia.gov

Pacific Region NG Storage

bloomberg.com

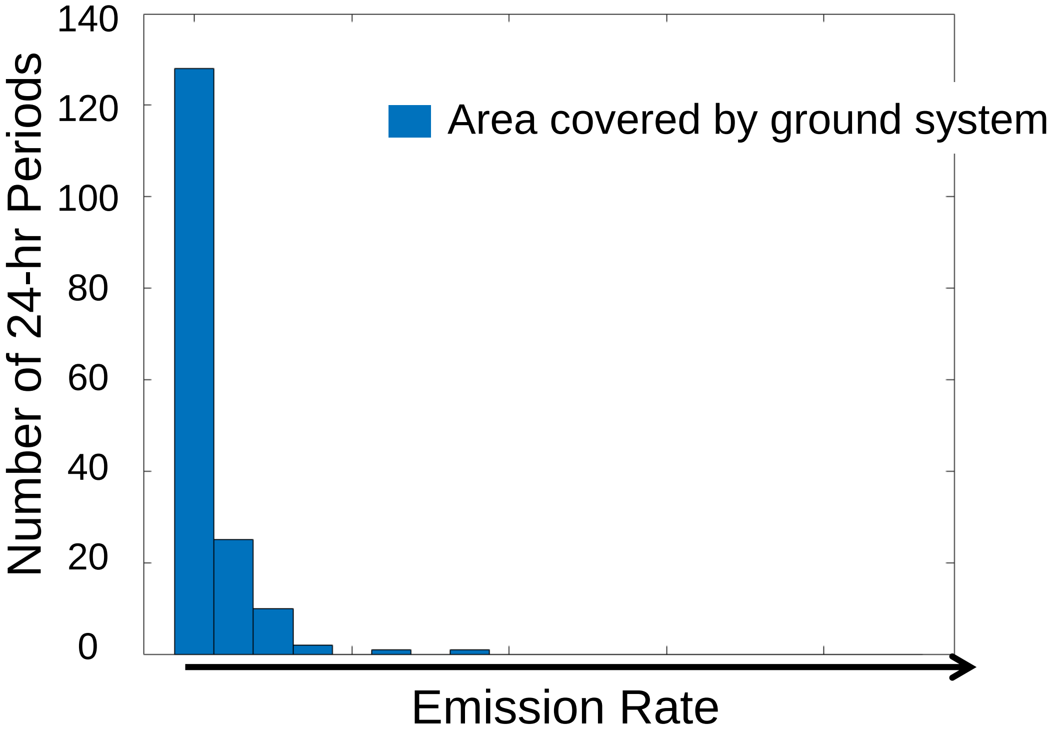
Observed Emissions Variability: Aircraft Mass Balance

- **One Facility:** standard deviation of emissions from repeat aircraft mass balance is 90% of mean emissions
- **Portion of facility covered by the regional laser comb system:** standard deviation is 150% of mean emissions



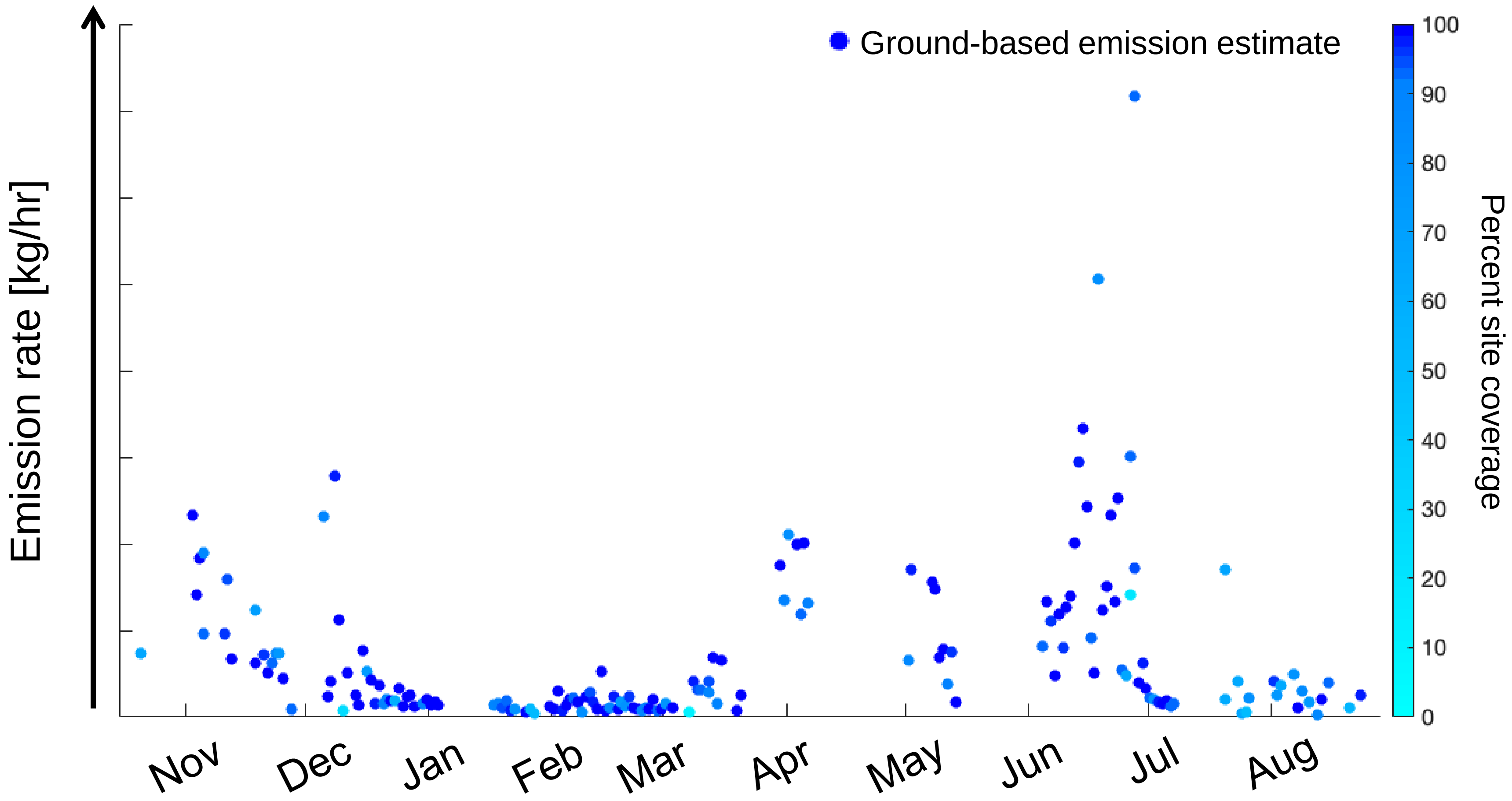
Observed Emissions Variability: Continuous Dual Comb

- Daily mean emissions demonstrate standard deviation of 133% of mean emissions



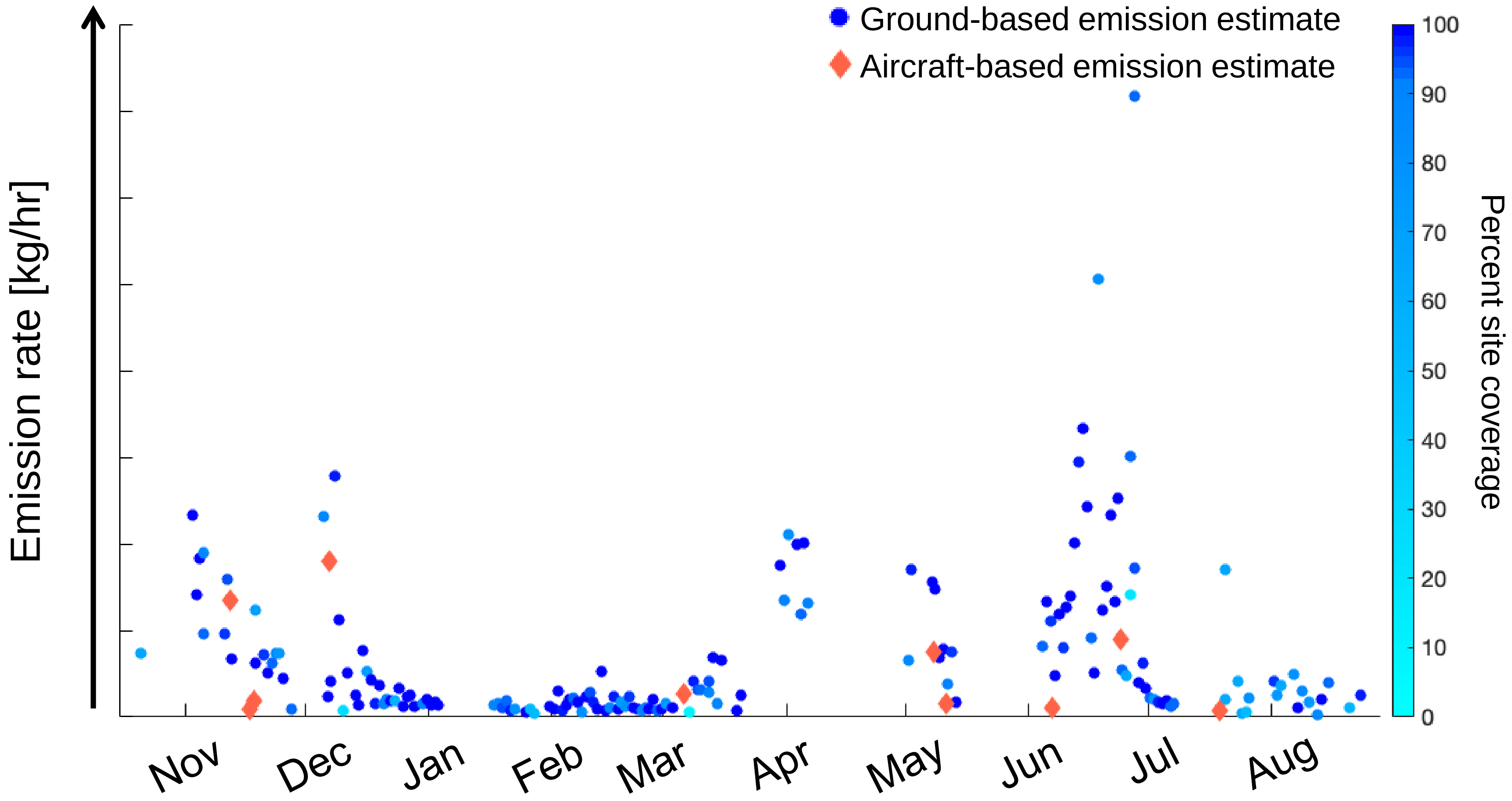
Observed Emissions Variability: Seasonal Variability

One year of data reveals potential seasonal cycle



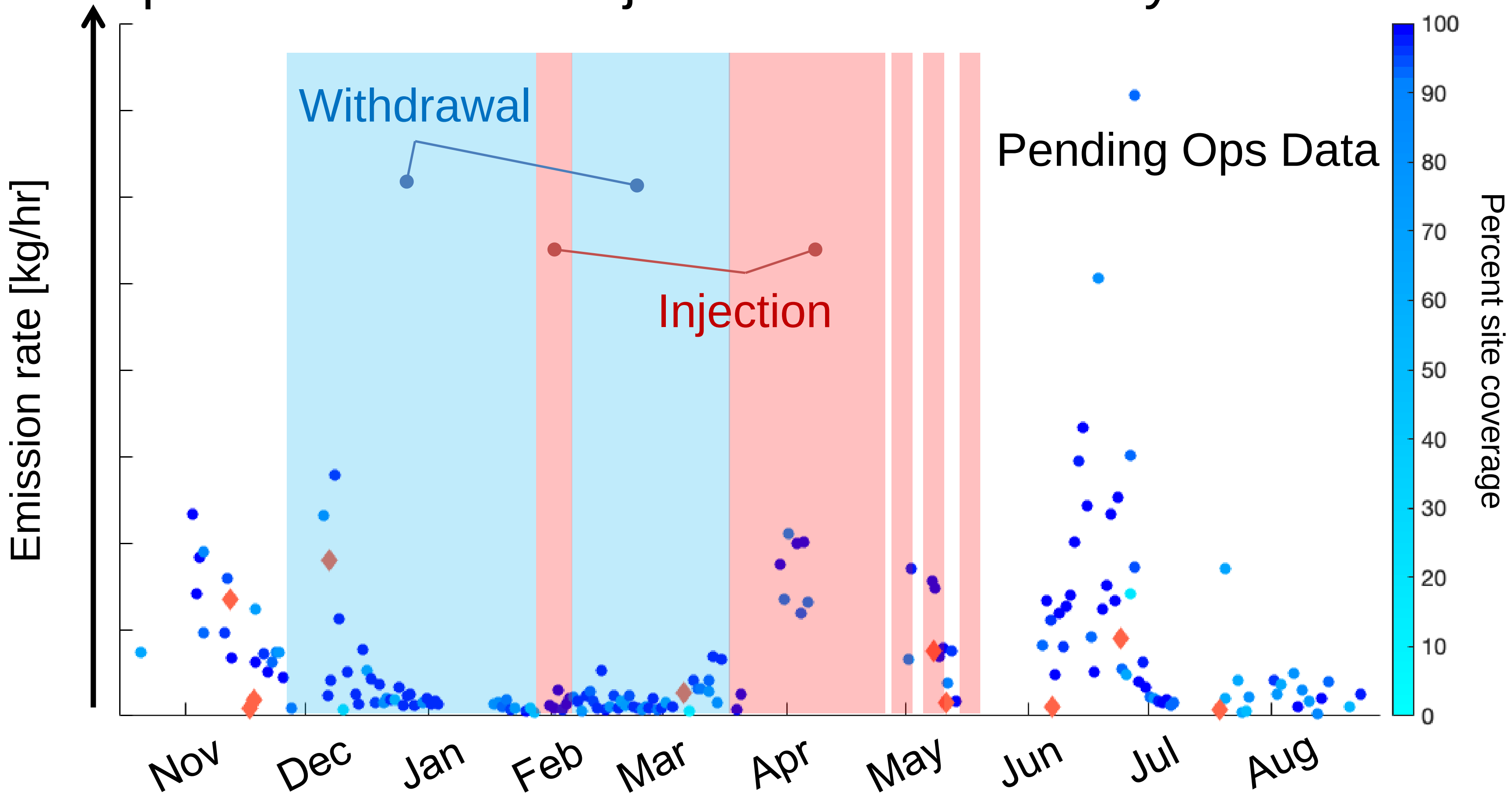
Observed Emissions Variability: Seasonal Variability

Aircraft data corroborate flux magnitudes and variability



Observed Emissions Variability: Seasonal Variability

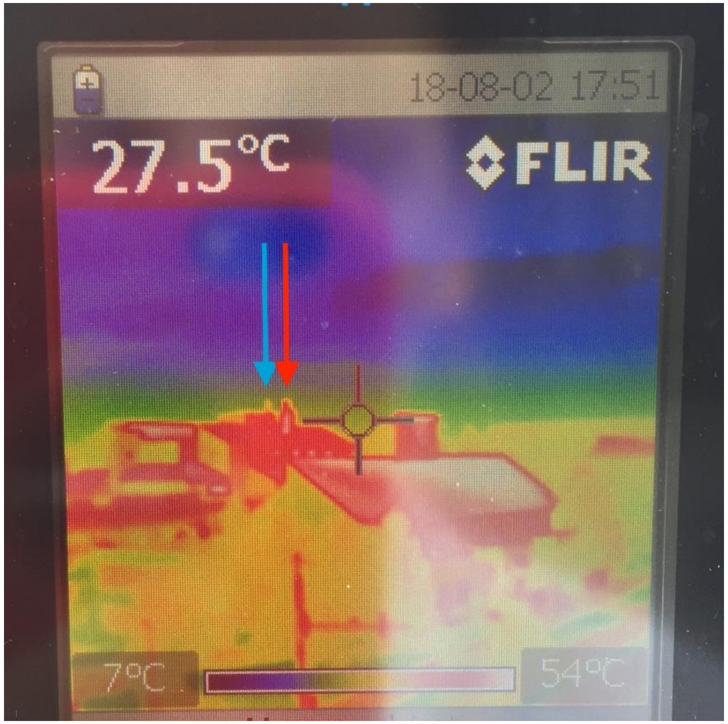
Overlap with available operations data suggests possible link with injection / withdrawal cycles?



Toward an Updated Emissions Inventory

The devil is in the details…determining what the data tells us is complex

Added infrared imaging to aircraft to determine compressor status



Obtaining operations data to correlate with continuous data

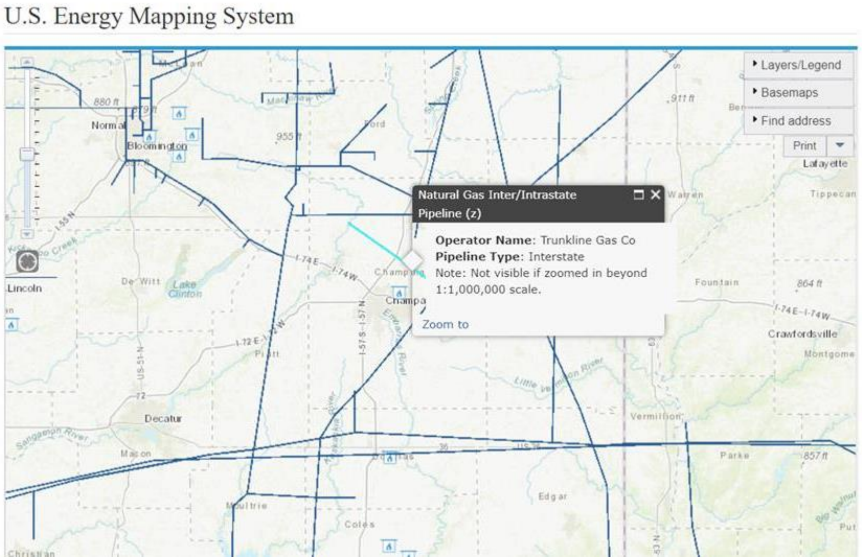
Toward an Updated Emissions Inventory

From an inventory perspective, this is not going to be a one size fits all situation

We are searching for a correlation with ‘obtainable’ data about a site that we can use to extrapolate to other facilities

Nominations as proxy for injections / withdrawals

- New data added to EIA website gives us pipeline locations
- Combine with our new maps of storage site locations
- Track down nominations data for sites we have measured



U.S. Energy Mapping System

Natural Gas Inter/Intrastate Pipeline (z)

Operator Name: Trunkline Gas Co
Pipeline Type: Interstate
Note: Not visible if zoomed in beyond 1:1,000,000 scale.

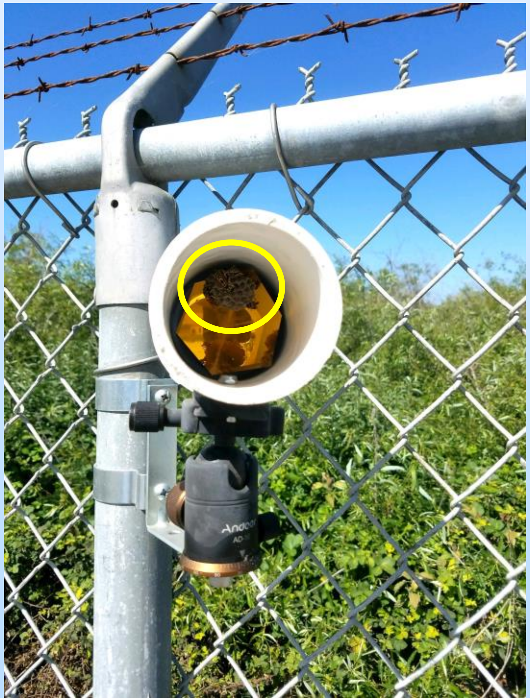
Zoom to

Accomplishments to Date

- First field deployed regional dual-comb monitoring system
- First daily time-resolved emissions data from methane storage facilities
- To our knowledge, first repeated comparisons of simultaneous ground and aircraft measurements
- To our knowledge, largest number of aircraft flyovers and repeat flyovers of methane storage facilities
- Significant improvements to aircraft emissions rate calculations
- Significant progress toward more complete picture of methane storage facility emissions

Lessons Learned

- Getting permission and siting for ground-based systems takes significant time
- Finding the location and physical boundaries of underground storage facilities is difficult
- Wasps and birds seem strangely attracted to electronics and optics enclosures



Synergy Opportunities

- **Clear synergy exists between our technology and the two mobile approaches presented here today**
  - The technologies give snapshots in time, but can presumably cover more facilities with greater detail than our current flyovers
  - The combination of the time-resolved ground system and the extension to more facilities would generate the most complete picture of emissions

Project Summary

- **Take Home Message:** Emissions from underground natural gas storage facilities demonstrate substantial temporal variability.
- Emissions variability is evident at scales from day-to-day to seasonal, and likely even hour-to-hour (Next Steps will confirm this finding).
- Repeat aircraft mass balance measurements corroborate the mean emissions rates and the presence and magnitude of seasonal variability in emissions at underground natural gas storage sites.
- New methods for aircraft mass balance improve analysis.
- Analysis of similarities and differences in mean emissions and emissions variability will provide input to the GHGI.
- **Next steps include:**
  - Completing final measurements for remainder of program and under a no-cost extension
  - Completing analysis of spatiotemporal variability in emissions
  - Completing interface with EPA GHGI for inclusion of updated mean and variability numbers into the inventory

Appendix

Benefit to the Program

Technology or approach being developed or studied:

- Dual frequency comb spectrometer and aircraft measurements deployed with regular frequency and at numerous underground natural gas storage sites to provide time-resolved measurements of emissions from underground natural gas storage sites

Summary of how the project supports one of more of the programmatic goals

- See following slide

Benefit to the Program

- Program Goals Addressed
  - Improve data for methane emission quantification to support the EPA GHGI; specifically, to better quantify methane emissions from the natural gas value chain
  - Develop time series of leak frequency from natural gas storage wells in order to develop an understanding of the relatively large leaks that have occurred
  - Collect measurements to quantify the frequency of leaks at storage wells to improve the quantification of this source in the GHGI
- Project Benefits Statement
  - The research project is deploying continuous measurements with dual frequency comb spectroscopy based estimation of emissions, and repeat aircraft mass balance estimation of emissions. These measurements provide new understanding of the spatiotemporal nature of methane emissions from the underground storage sector of the natural gas value chain. This work contributes to the Midstream Program's goals of better quantifying methane emissions from the natural gas value chain.

Project Overview

Goals and Objectives

- To achieve a comprehensive quantification of methane emissions from storage facilities through ground-based and aircraft-based measurements.
- Data analysis of similarities between storage wells and fields will be used for assessing emissions at different types of facilities so that a comprehensive understanding of the storage sector can be gained.
- Integrate all data gathered during ground- and aircraft-based measurement campaigns into a comprehensive and detailed inventory of methane emissions from underground natural gas storage wells and fields, providing temporal detail of emissions from the natural gas storage sector.
- **Each of the above project goals directly support the stated Midstream Program goals and objectives**

Success Criteria

Objective 1: quantify average emissions at a variety of sites

- BP1: co-deployment of ground and aircraft instrumentation
- BP2: have data for cross-comparison and cross-validation of the two techniques
- BP3: complete emissions quantification

Objective 2: quantify time variability of emissions

- BP1: Quantify instrument “up-time” and continuity of autonomous data collection possible
- BP2: establish timeframe needed for detailed characterization of a storage site
- BP2-3: establish time variability of emissions

Objective 3: develop and publish methane emissions inventory

- BP1: advances toward this objective not expected in BP1
- BP2: perform aircraft and ground-based data cross-comparisons to establish uncertainties and identify relationships between emissions at different storage sites
- BP3: complete data comparison and inventories with complete dataset

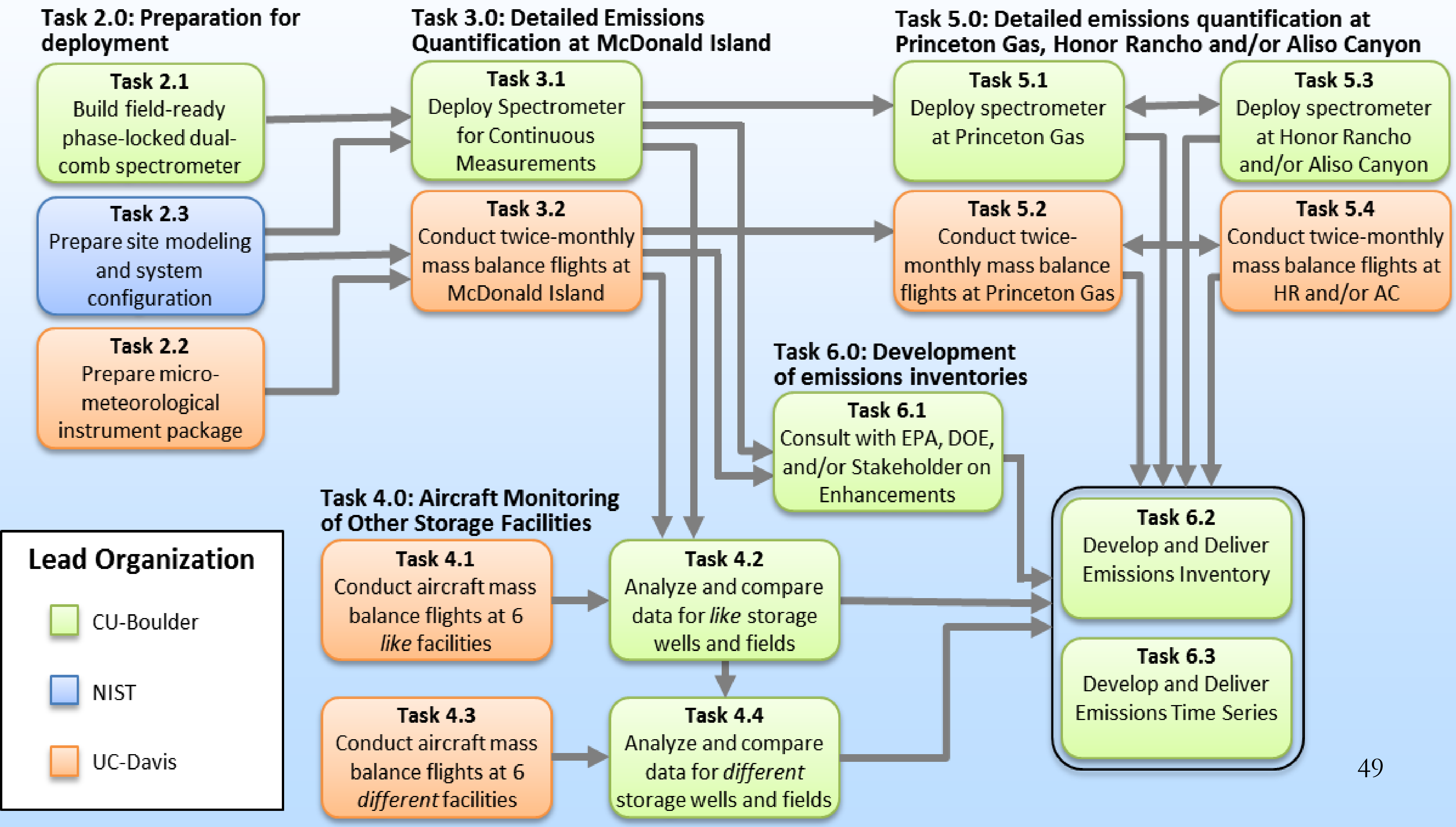
Objective 4: collect new micrometeorological measurements and improve atmospheric transport models

- BP1: LES model validation and/or confirmation with aircraft-based observations
- BP2: apply improved models and micrometeorological observations to emissions estimates
- BP3: apply improved models and micrometeorological observations to emissions estimates

Objective 5: integrate ground- and aircraft-based observations at co-located measurement sites

- BP1: begin data collection at co-located measurement site
- BP2: demonstrate model ability to incorporate data from one or all data platforms into a single inversion and determine posterior uncertainties and comparisons with data withheld from the inversion
- BP3: use integrated data approaches to perform analysis and complete emissions inventory

Organization Chart



Task 2.0: Preparation for deployment

Task 2.1
Build field-ready phase-locked dual-comb spectrometer

Task 2.3
Prepare site modeling and system configuration

Task 2.2
Prepare micro-meteorological instrument package

Task 3.0: Detailed Emissions Quantification at McDonald Island

Task 3.1
Deploy Spectrometer for Continuous Measurements

Task 3.2
Conduct twice-monthly mass balance flights at McDonald Island

Task 5.0: Detailed emissions quantification at Princeton Gas, Honor Rancho and/or Aliso Canyon

Task 5.1
Deploy spectrometer at Princeton Gas

Task 5.3
Deploy spectrometer at Honor Rancho and/or Aliso Canyon

Task 5.2
Conduct twice-monthly mass balance flights at Princeton Gas

Task 5.4
Conduct twice-monthly mass balance flights at HR and/or AC

Task 6.0: Development of emissions inventories

Task 6.1
Consult with EPA, DOE, and/or Stakeholder on Enhancements

Task 6.2
Develop and Deliver Emissions Inventory

Task 6.3
Develop and Deliver Emissions Time Series

Task 4.0: Aircraft Monitoring of Other Storage Facilities

Task 4.1
Conduct aircraft mass balance flights at 6 *like* facilities

Task 4.2
Analyze and compare data for *like* storage wells and fields

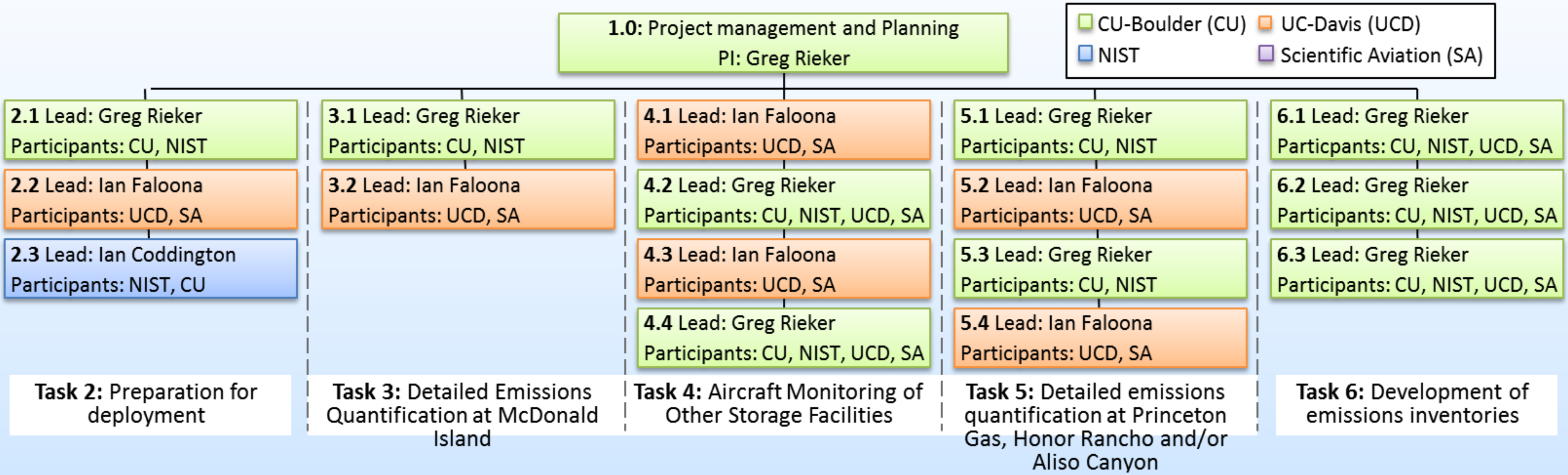
Task 4.3
Conduct aircraft mass balance flights at 6 *different* facilities

Task 4.4
Analyze and compare data for *different* storage wells and fields

Lead Organization

- 🟩 CU-Boulder
- 🟦 NIST
- 🟧 UC-Davis

Organization Chart



1.0: Project management and Planning
PI: Greg Rieker

🟩 CU-Boulder (CU) 🟧 UC-Davis (UCD)
🟦 NIST 🟪 Scientific Aviation (SA)

2.1 Lead: Greg Rieker
Participants: CU, NIST

2.2 Lead: Ian Faloona
Participants: UCD, SA

2.3 Lead: Ian Coddington
Participants: NIST, CU

Task 2: Preparation for deployment

3.1 Lead: Greg Rieker
Participants: CU, NIST

3.2 Lead: Ian Faloona
Participants: UCD, SA

Task 3: Detailed Emissions Quantification at McDonald Island

4.1 Lead: Ian Faloona
Participants: UCD, SA

4.2 Lead: Greg Rieker
Participants: CU, NIST, UCD, SA

4.3 Lead: Ian Faloona
Participants: UCD, SA

4.4 Lead: Greg Rieker
Participants: CU, NIST, UCD, SA

Task 4: Aircraft Monitoring of Other Storage Facilities

5.1 Lead: Greg Rieker
Participants: CU, NIST

5.2 Lead: Ian Faloona
Participants: UCD, SA

5.3 Lead: Greg Rieker
Participants: CU, NIST

5.4 Lead: Ian Faloona
Participants: UCD, SA

Task 5: Detailed emissions quantification at Princeton Gas, Honor Rancho and/or Aliso Canyon

6.1 Lead: Greg Rieker
Particpants: CU, NIST, UCD, SA

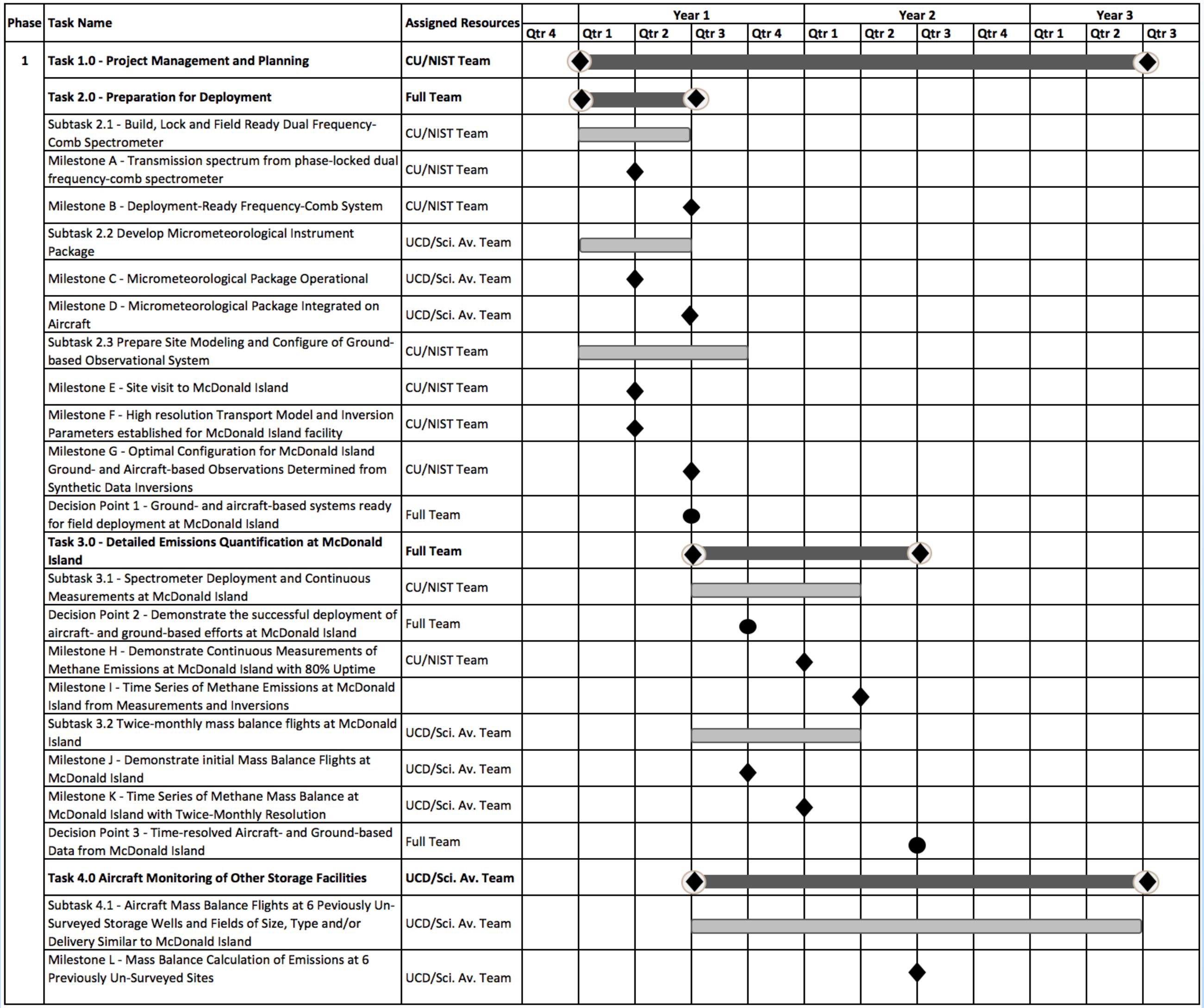
6.2 Lead: Greg Rieker
Participants: CU, NIST, UCD, SA

6.3 Lead: Greg Rieker
Participants: CU, NIST, UCD, SA

Task 6: Development of emissions inventories

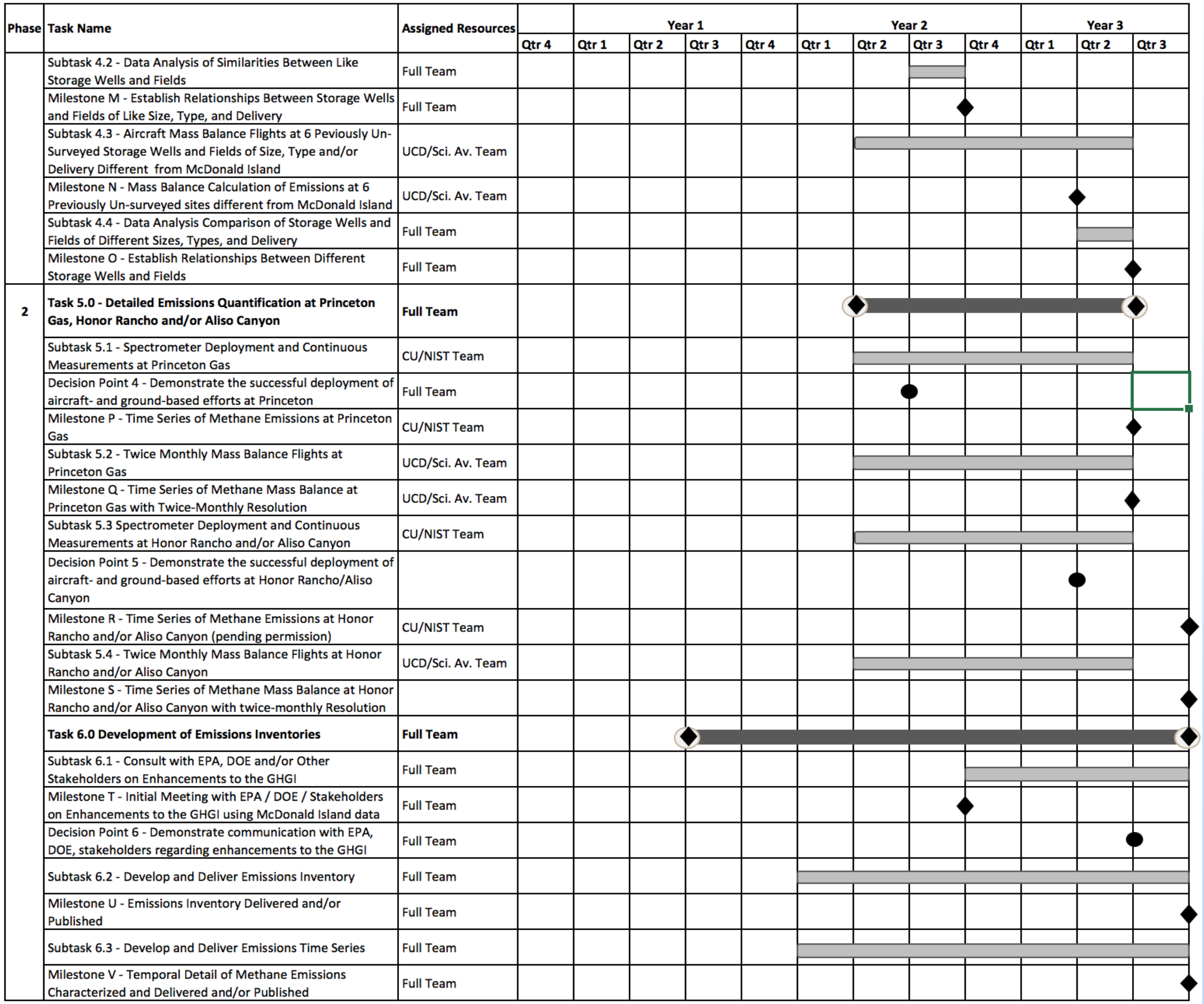
Roles of Participants Chart: task-by-task identification of lead and participating organization for proposed project. Tasks are shaded by organization of technical and management lead participant.

Gantt Chart (zoom to view)



Phase	Task Name	Assigned Resources
1	**Task 1.0 - Project Management and Planning**	**CU/NIST Team**
	Task 2.0 - Preparation for Deployment	**Full Team**
	Subtask 2.1 - Build, Lock and Field Ready Dual Frequency-Comb Spectrometer	CU/NIST Team
	Milestone A - Transmission spectrum from phase-locked dual frequency-comb spectrometer	CU/NIST Team
	Milestone B - Deployment-Ready Frequency-Comb System	CU/NIST Team
	Subtask 2.2 Develop Micrometeorological Instrument Package	UCD/Sci. Av. Team
	Milestone C - Micrometeorological Package Operational	UCD/Sci. Av. Team
	Milestone D - Micrometeorological Package Integrated on Aircraft	UCD/Sci. Av. Team
	Subtask 2.3 Prepare Site Modeling and Configure of Ground-based Observational System	CU/NIST Team
	Milestone E - Site visit to McDonald Island	CU/NIST Team
	Milestone F - High resolution Transport Model and Inversion Parameters established for McDonald Island facility	CU/NIST Team
	Milestone G - Optimal Configuration for McDonald Island Ground- and Aircraft-based Observations Determined from Synthetic Data Inversions	CU/NIST Team
	Decision Point 1 - Ground- and aircraft-based systems ready for field deployment at McDonald Island	Full Team
	Task 3.0 - Detailed Emissions Quantification at McDonald Island	**Full Team**
	Subtask 3.1 - Spectrometer Deployment and Continuous Measurements at McDonald Island	CU/NIST Team
	Decision Point 2 - Demonstrate the successful deployment of aircraft- and ground-based efforts at McDonald Island	Full Team
	Milestone H - Demonstrate Continuous Measurements of Methane Emissions at McDonald Island with 80% Uptime	CU/NIST Team
	Milestone I - Time Series of Methane Emissions at McDonald Island from Measurements and Inversions	
	Subtask 3.2 Twice-monthly mass balance flights at McDonald Island	UCD/Sci. Av. Team
	Milestone J - Demonstrate initial Mass Balance Flights at McDonald Island	UCD/Sci. Av. Team
	Milestone K - Time Series of Methane Mass Balance at McDonald Island with Twice-Monthly Resolution	UCD/Sci. Av. Team
	Decision Point 3 - Time-resolved Aircraft- and Ground-based Data from McDonald Island	Full Team
	Task 4.0 Aircraft Monitoring of Other Storage Facilities	**UCD/Sci. Av. Team**
	Subtask 4.1 - Aircraft Mass Balance Flights at 6 Peviously Un-Surveyed Storage Wells and Fields of Size, Type and/or Delivery Similar to McDonald Island	UCD/Sci. Av. Team
	Milestone L - Mass Balance Calculation of Emissions at 6 Previously Un-Surveyed Sites	UCD/Sci. Av. Team

Gantt Chart (zoom to view)



Phase	Task Name	Assigned Resources		Year 1				Year 2				Year 3		
			Qtr 4	Qtr 1	Qtr 2	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
	Subtask 4.2 - Data Analysis of Similarities Between Like Storage Wells and Fields	Full Team								▬				
	Milestone M - Establish Relationships Between Storage Wells and Fields of Like Size, Type, and Delivery	Full Team								◆				
	Subtask 4.3 - Aircraft Mass Balance Flights at 6 Peviously Un-Surveyed Storage Wells and Fields of Size, Type and/or Delivery Different from McDonald Island	UCD/Sci. Av. Team							▬	▬	▬	▬	▬	
	Milestone N - Mass Balance Calculation of Emissions at 6 Previously Un-surveyed sites different from McDonald Island	UCD/Sci. Av. Team										◆		
	Subtask 4.4 - Data Analysis Comparison of Storage Wells and Fields of Different Sizes, Types, and Delivery	Full Team											▬	
	Milestone O - Establish Relationships Between Different Storage Wells and Fields	Full Team											◆	
2	**Task 5.0 - Detailed Emissions Quantification at Princeton Gas, Honor Rancho and/or Aliso Canyon**	**Full Team**							◆▬	▬	▬	▬	▬◆	
	Subtask 5.1 - Spectrometer Deployment and Continuous Measurements at Princeton Gas	CU/NIST Team							▬	▬	▬	▬	▬	
	Decision Point 4 - Demonstrate the successful deployment of aircraft- and ground-based efforts at Princeton	Full Team							●					
	Milestone P - Time Series of Methane Emissions at Princeton Gas	CU/NIST Team											◆	
	Subtask 5.2 - Twice Monthly Mass Balance Flights at Princeton Gas	UCD/Sci. Av. Team							▬	▬	▬	▬	▬	
	Milestone Q - Time Series of Methane Mass Balance at Princeton Gas with Twice-Monthly Resolution	UCD/Sci. Av. Team											◆	
	Subtask 5.3 Spectrometer Deployment and Continuous Measurements at Honor Rancho and/or Aliso Canyon	CU/NIST Team							▬	▬	▬	▬	▬	
	Decision Point 5 - Demonstrate the successful deployment of aircraft- and ground-based efforts at Honor Rancho/Aliso Canyon											●		
	Milestone R - Time Series of Methane Emissions at Honor Rancho and/or Aliso Canyon (pending permission)	CU/NIST Team												◆
	Subtask 5.4 - Twice Monthly Mass Balance Flights at Honor Rancho and/or Aliso Canyon	UCD/Sci. Av. Team							▬	▬	▬	▬	▬	
	Milestone S - Time Series of Methane Mass Balance at Honor Rancho and/or Aliso Canyon with twice-monthly Resolution													◆
	Task 6.0 Development of Emissions Inventories	**Full Team**				◆▬	▬	▬	▬	▬	▬	▬	▬	▬◆
	Subtask 6.1 - Consult with EPA, DOE and/or Other Stakeholders on Enhancements to the GHGI	Full Team									▬	▬	▬	▬
	Milestone T - Initial Meeting with EPA / DOE / Stakeholders on Enhancements to the GHGI using McDonald Island data	Full Team								◆				
	Decision Point 6 - Demonstrate communication with EPA, DOE, stakeholders regarding enhancements to the GHGI	Full Team											●	
	Subtask 6.2 - Develop and Deliver Emissions Inventory	Full Team						▬	▬	▬	▬	▬	▬	▬
	Milestone U - Emissions Inventory Delivered and/or Published	Full Team												◆
	Subtask 6.3 - Develop and Deliver Emissions Time Series	Full Team						▬	▬	▬	▬	▬	▬	▬
	Milestone V - Temporal Detail of Methane Emissions Characterized and Delivered and/or Published	Full Team												◆

Gantt Chart Summary

Budget Period 1
Oct 2016 – Sep 2017

Budget Period 2
Oct 2017 – Sep 2018

Budget Period 3
Oct 2018 – Sep 2019

- Build dual-comb spectrometer
- Develop micrometeorological package for aircraft
- Begin ground-based emissions quantification at storage site 1
- Begin aircraft-based emissions quantification at storage site 1 and other storage facilities

- Continue detailed emissions quantification at storage site 1
- Begin ground- and air-based emissions quantification at storage site 2
- Continue aircraft-based emissions quantification at other storage facilities
- Consult EPA/DOE/other stakeholders to develop inventory and time series

- Complete detailed emissions quantification at all storage sites
- Complete aircraft-based emissions quantification at other storage facilities
- Finalize and publish inventory and emissions time series in consultation with EPA/DOE/stakeholders and deliver

Bibliography

- Alden, C. B., S. Coburn, S. Wright, R., Baumann, E., Cossel, K., Perez, E., Hoenig, E., Prasad, K., Coddington, I. Rieker, G., 2019, Single-blind quantification of natural gas leaks from 1 km distance using frequency combs. Environmental Science & Technology, available at: 10.1021/acs.est.8b06259.
- Alden, C. B., Ghosh, S., Coburn, S., Sweeney, C., Karion, A., Wright, R., Coddington, I., Prasad, K., Rieker, G., 2018, Bootstrap inversion technique for atmospheric trace gas source detection and quantification using long open-path laser measurements, Atmospheric Measurement Techniques, available at: 10.5194/amt-11-1565-2018.
- Coburn, S., Alden, C. B. Wright, R., Cossel, K., Baumann, E., Truong, G.-W., Giorgetta, F., Sweeney, C., Newbury, N., Prasad, K., Coddington, I., Rieker, G. B., Regional trace-gas source attribution using a field-deployed dual frequency comb spectrometer, Optica, available at: 10.1364/OPTICA.5.000320.