High Accuracy Mobile Emissions Laboratory

Final Report

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Disclaimer

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Abstract

Los Gatos Research (LGR) applied its patented laser-based instruments, which are based on the use of high-finesse optical cavities as measurement cells, for real-time measurements of important greenhouse gases and pollutants in ambient air. LGR's technology provides optical path lengths of tens of kilometers to allow gas concentration measurements over a wide range of concentrations with unprecedented sensitivity, accuracy and precision in a compact package. LGR incorporated several instruments, along with global positioning, ambient temperature, air velocity and pressure and relative humidity monitors, into a vehicle that was used to record real-time measurements of several critical atmospheric gases at urban and rural locations, including Caldecott Tunnel, wetlands in the Sacramento-San Joaquin Delta (Sherman Island, Twitchell Island), Zero Emissions Research Technology site, and the Altamont Landfill site. This 'Mobile Emissions Laboratory' enables detailed measurements and long-term monitoring of mobile and fixed-location emissions and pollutant sources with unprecedented accuracy, precision and sensitivity. In addition, the on-board instrumentation is autonomous, easy to use, and automatically store and report data to a central station. The Mobile Emissions Laboratory enables untrained users to record accurate measurements of all important greenhouse gases and several pollutants with high sensitivity and over a very wide range of concentrations at the source in real time. These measurements provide regulatory agencies, monitoring stations, scientists and researchers with temporally and spatially resolved data (measurements of important greenhouse gases and pollutants) necessary for compliance monitoring, as well as cap and trade, at any location.

Introduction

This report is the final element of the Innovative Clean Air Technologies grant 07-2 to help develop, test and deploy a custom Mobile Emissions Laboratory for real-time measurements of multiple greenhouse gases and pollutants. To date, accurate gas emissions measurements at industrial sites, agricultural sites, or landfills have required expensive sampling methods by experts in the field. These measurements, while somewhat effective at times, are not conducive for mobile or long-term extensive detailed studies. The Mobile Emissions Lab will facilitate continuous measurements at remote locations with unsurpassed time resolution and thus provide a means for compliance monitoring, for cap and trade applications, carbon sequestration, and for quantitatively monitoring the sources and sinks of important greenhouse gases throughout California and elsewhere.

Innovative Technology

The Mobile Emissions Laboratory consists of Los Gatos Research's novel gas analyzers, which are based on narrow bandwidth tunable lasers (diode and quantum cascade) and use of high-finesse optical cavities as measurement cells, for real-time measurements of important greenhouse gases and pollutants in ambient air. LGR's patented technology provides optical path lengths of tens of kilometers to allow gas concentration measurements with unsurpassed sensitivity, accuracy and precision in a compact package. LGR incorporated several laser-based instruments, along with monitors for global positioning, ambient temperature, gas velocity, gas pressure and relative humidity, into a vehicle (trailer) that was used to record real-time measurements of critical atmospheric gases at several urban and rural locations throughout California. This 'Mobile Emissions Lab' enabled detailed measurements and long-term monitoring of mobile (i.e. while moving) and fixed-location emissions and pollutant sources with unprecedented accuracy, precision and sensitivity. In contrast to older technology, all of the on-board instrumentation on the Mobile Emissions Lab is autonomous, easy to use, and requires low maintenance and low power. In addition, the Mobile Emissions Lab includes deep-cycle lead-acid rechargeable batteries on-board that allows long-term measurements at locations without access to external electrical power. Finally, the Mobile Emissions Lab was demonstrated successfully at several locations for real-time continuous measurements of methane (CH_4), carbon dioxide ($^{12}CO_2$, $^{13}CO_2$), nitrous oxide (N_2O), carbon monoxide (CO), acetylene (C_2H_2), water vapor (H_2O), and water vapor isotopes (H_2O, H^2HO, $H_2{}^{18}O$) in the field.

The project enabled untrained personnel to record accurate measurements of important greenhouse gases and pollutants with unprecedented sensitivity at the source in real time. The new capabilities will provide regulatory agencies, monitoring stations, scientists and researchers temporally and spatially resolved data (measurements of important greenhouse gases and pollutants) necessary for compliance monitoring, as well as cap and trade, at any location.

ICAT Project

The purpose of the project is to demonstrate field-ready state-of-the-air gas analyzers for autonomous measurements of critical greenhouse gases and pollutants with high accuracy and sensitivity in a mobile vehicle. The vehicle containing the analyzers serves as a mobile laboratory (Mobile Emissions Lab) and allows automated measurements at any site without extensive operator training or access to external power. Measurements may be recorded within minutes of arriving at a new measurement site. In this project, LGR demonstrated and quantified the ability of the Mobile Lab to record and report measurements in real time with high accuracy. In addition, LGR worked with California Air Resources Board research personnel to deploy the Mobile Laboratory at urban, rural and landfill locations including Caldecott Tunnel, wetlands in the Sacramento-San Joaquin Delta (Sherman Island, Twitchell Island), Zero Emissions Research Technology site, and Altamont Landfill. The project tasks and associated results are described in detail below. The successful demonstrations illustrate how the Mobile Lab may be used to monitor hot spots, for compliance monitoring, cap and trade, and for pollutant credits accounting.

Build gas analyzers; purchase metrology instruments & vehicle

LGR built several gas analyzers to be incorporated into the Mobile Emissions Laboratory Trailer, including a model 907-0010 Fast Greenhouse Gas Analyzer (simultaneous CH_4, CO_2, H_2O), model 908-0003 Carbon Dioxide Isotope Analyzer (CO_2, $\delta^{13}C$), model 908-0004 Water Vapor Isotope Analyzer ($\delta^{18}O$, δ_2H, H_2O), and a model 908-0014 N_2O/CO Analyzer (N_2O and CO). LGR also bought the trailer (shown below), and assorted metrology instruments for measuring wind speed and direction, ambient pressure, and GPS coordinates. Although all data files recorded by each Analyzer within the Mobile Emissions Lab were recorded in real time on internal hard drives within each instrument, a separate data logger was purchased to store all data in a centralized location inside the Mobile Emissions Lab.

Figure 1. Trailer (Cargo Wagon; 7' wide) - contains several LGR Gas Analyzers and assorted metrology equipment to serve as the Mobile Emissions Laboratory.

LGR purchased a “Cargo Wagon”, a 7’ wide trailer (see Figure 1) to serve as the Mobile Emissions Lab. The trailer has the following features:

- Torflex® Rubber Torsion Axles (4” Drop)
- Electric Brakes with Breakaway Battery
- 5-Bolt Silver Spoke Wheels (E-Coated)
- Rear Door: Double
- Seamless Aluminum Roof
- Galvanealed Steel Fenderettes (powder-coated)
- .030 Prefinished Aluminum Exterior
- Anodized Aluminum Roof Cove & Bottom Trim
- 1/4” Plywood Interior Sidewall
- 3/4” Exterior Grade Plywood Floor
- Jack Ram Hoist with Sand Pad
- LED Exterior Lighting

LED Stop/Tail/Turn

Trailer includes LED lights which are brighter, more durable requiring less maintenance, and consume 90% less power reducing the load on the tow vehicle's electrical system as compared to traditional incandescent or bulb-style lights.

Wet Cell Battery

This battery is an essential part of a breakaway system.
It applies full braking capacity for a minimum of 15 minutes meeting D.O.T. requirements and includes a low-voltage indicator light.

Ramp Doors & Corner Post Jacks

Full-width hinge with free floating 3/4” steel pin. Welded perimeter door frame with gussets at major stress points. Full-length reinforcements prevent bowing. Spring assist cable(s) for safety. Rear-corner post stabilizer jacks with steel tube posts are coated in Zincdychromate for rust resistance.

12-Volt Electrical System

All circuitry distributed from an easily accessible interior junction box. Primary connections made with wire nuts. All wiring is SAE truck/trailer color-coded wire.

Side Doors (Aluminum Hinges)

All door openings are welded with formed steel channel headers and gusseted for rigid anchoring.

Anodized Roof Cove

Extruded aluminum roof cove provides extra body support and solid anchoring for roof and pre-finished aluminum skin.

All Aluminum Anti-Rack Cam Lock

Cast aluminum Cam Lock and stainless steel hasp provide no-rust finish. Anti-Rack design forms a structural link between door header and footer reducing door movement, frame torque, and road vibration.

Bottom Trim

Extruded aluminum Bottom Trim provides extra body support and solid anchoring for refinished aluminum skin. Special anodizing process minimizes maintenance.

Figure 2 shows the internal layout of the Mobile Emissions Laboratory. LGR's Mobile Emissions Laboratory has the capability of simultaneously including nine different LGR gas analyzers, a centralized data logging system, a dry scroll vacuum pump (for eddy covariance flux measurements), a sonic anemometer (mounted outside of the Laboratory), a fuel-powered electrical power generator and deep-cycle batteries under the floor (for long term operation off-grid and for applications without AC mains power), multiple reference gas cylinders, and a tool box. In addition, LGR incorporated RU-13 insulation throughout the walls of the Mobile Emissions Laboratory to facilitate operation in extreme environments.

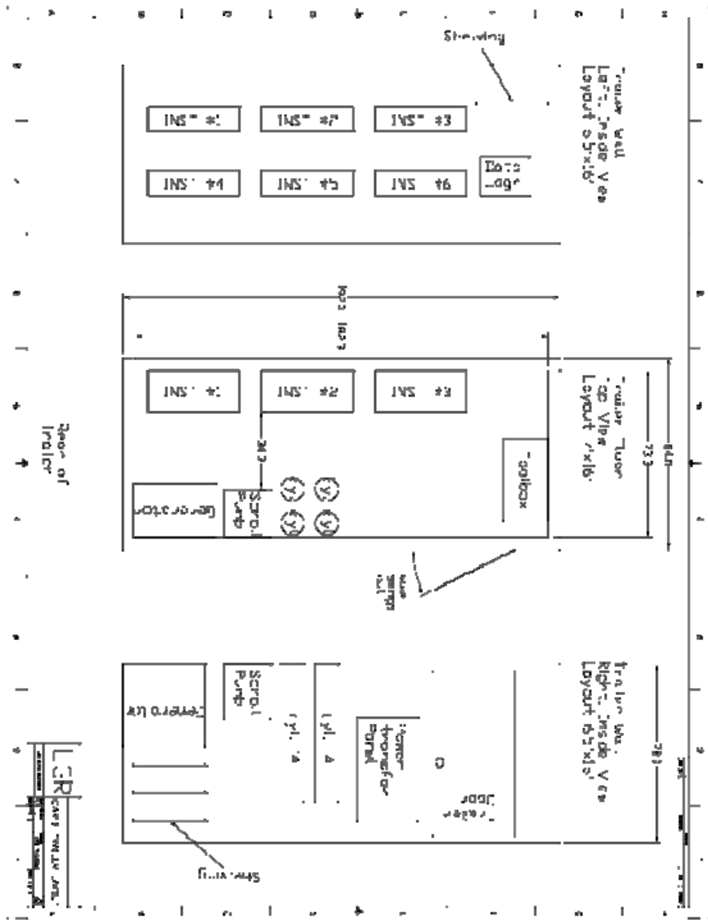


Figure 2. Layout of the inside of the Mobile Emissions Laboratory.

Figure 3. During construction of the Mobile Emissions Laboratory, insulation (RU-13) was added inside all walls to allow for long- term operation in extreme environments. Deep cycle marine batteries mounted under the floor provide DC power for applications where AC power is limited.

Datasheets for the model 907-0010 Fast Greenhouse Gas Analyzer (simultaneous CH_4, CO_2, H_2O), a model 908-0014 N_2O/CO Analyzer (N_2O and CO), model 908-0003 Carbon Dioxide Isotope Analyzer (CO_2, $\delta^{13}C$), and model 908-0004 Water Vapor Isotope Analyzer ($\delta^{18}O$, δ_2H,

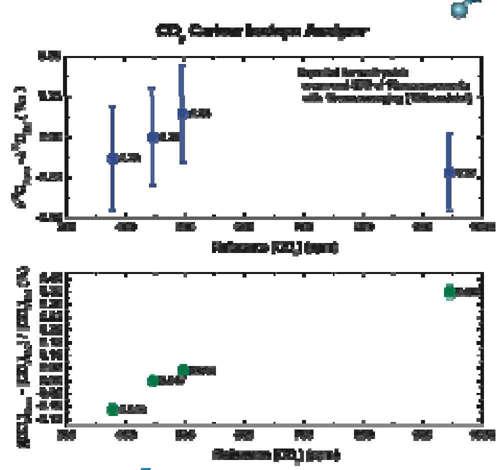
H_2O) are shown below. All instruments exceed the performance specifications described in the datasheets.

CO_2 ISOTOPE ANALYZER

HIGHEST PRECISION • FASTEST • LOWEST POWER

The CO_2 Isotope Analyzer is an autonomous instrument capable of measuring the $^{13}C/^{12}C$ ratio in ambient carbon dioxide over an extremely wide range of concentrations with better than 0.2‰ repeatability (for an integration time of 60 seconds) and without the need for costly consumables. This is possible because the instrument is built around conventional telecommunications-grade diode lasers that operate in the near-infrared spectral region. The Analyzer automatically removes water vapor from the sample using an included Nafion® dryer to eliminate dilution and line broadening effects due to humidity. In addition, since the measurement strategy is based on high-resolution direct-absorption spectroscopy (see www.LGRinc.com, Theory Section), the instrument is not affected by other atmospheric gases or by changes in ambient atmospheric pressure. Thus the need for regular calibration with expensive reference gases is also significantly reduced compared with traditional analytical instruments.

The instrument includes an internal computer that can store data practically indefinitely on its hard drive (for applications requiring unattended long-term standalone operation), and send real-time data to a data logger through its analog, digital (RS232), and Ethernet outputs.



Measurements of $\delta^{13}C$ and [CO_2] over a range of concentrations. In all illustrate the high precision of our CO_2 Isotope Analyzer even with a measurement time of only 20 seconds (longer averaging times and higher concentrations will yield higher precision, as expected).

Performance Specifications

Concentration Range
360–1000 ppmv

Operational Range
280–4000 ppmv

Data Rate
up to 1 Hz

Repeatability/Precision (60 seconds)
$^{13}C/^{12}C$: 0.25‰ (at 400 ppmv)
$^{13}C/^{12}C$: 0.15‰ (at 800 ppmv)
CO_2: 0.05% (over entire range)

Outputs
Digital (RS232), Ethernet

Data Storage
Internal Hard Drive

Display
12.1" Color TFT

Sample Temperature
0–50 °C

Operating Temperature
10–35 °C

Ambient Humidity
<98% RH Non-Condensing

Warm-Up Time
30 minutes

Inlet/Outlet Fittings
1/4", 1/4" Swagelok®

Power Requirements
160 W; 115/230 VAC; 50/60 Hz

Dimensions
10" H × 35" W × 14" D

Weight
Less than 55 pounds (27 kg) including vacuum pump, embedded video monitor, keyboard, and mouse

Ordering Information

Benchtop Package
Model Number: 908-0020

Option - Manual Injection Capability

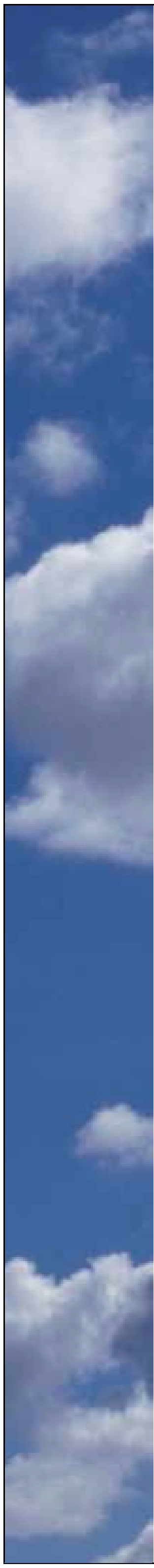
Model	Name
custom	Injection of samples via syringe

Option - Multiplexed Input Unit

Model	Name
custom	Multiport Input Unit (allows automated measurements at up to 16 locations)

Measuring the uptake of CO_2 in the field has never been easier. Get your results without having to take samples back to your lab.

www.lgrinc.com



WATER-VAPOR ISOTOPE ANALYZER

UNPRECENDENTED PRECISION ▪ NO SAMPLE PREP ▪ FAST ▪ LOW POWER

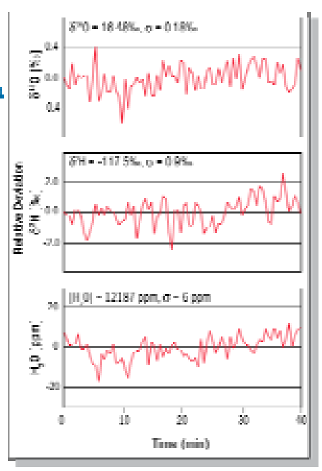
Now you can accurately measure the $^{18}O/^{16}O$ and D/H ratios in ambient water vapor rapidly with high precision (better than 0.5‰ and 2.0‰, respectively, in a measurement time of 1 second). Our Water-Vapor Isotope Analyzer does not require sample preparation or user intervention, which enables long-term studies of water-vapor isotopes with unmatched performance. In addition, the Water-Vapor Isotope Analyzer provides simultaneous measurements of water vapor mixing ratio $[H_2O]$ with ppm-level precision. The rugged, field-portable packaging (includes an embedded video monitor, keyboard and mouse) makes this instrument ideally suited for a myriad of hydrological, atmospheric science, medical, and industrial monitoring applications.

The instrument includes an internal computer that can store data practically indefinitely on its internal hard drive (for applications requiring unattended long-term operation) and send real-time data to a data logger through its digital output. In addition, an Ethernet connection allows remote access to data files stored on the instrument's hard drive. With the optional Water Vapor Isotope Standard Source, measurements of reference vapor flows (known D/H, $^{18}O/^{16}O$ and H_2O values) may be recorded routinely for automatic calibration of the Analyzer. Together, the WVIA and WVISS provide accurate, drift-free isotopic measurements of water vapor.

There is no easier way to measure D/H and $^{18}O/^{16}O$ in atmospheric water vapor.

Practice

Measurements of D/H, $^{18}O/^{16}O$ and $[H_2O]$ (water vapor mixing ratio) in ambient air recorded at 2 Hz illustrate the high measurement precision and fast response of our Water-Vapor Isotope Analyzer.



Performance Specifications

Concentration Range
1000 ppmv – near saturation (standard)

Measurement rate
up to 2 Hz

Precision (1-σ, 1 sec)
$^{18}O/^{16}O$: 0.5‰
D/H: 2.0‰
total $[H_2O]$: 40 ppmv

Precision (1-σ, 20 sec)
$^{18}O/^{16}O$: 0.1‰
D/H: 0.5‰
total $[H_2O]$: 10 ppmv

Outputs
Digital (RS232), Ethernet

Data Storage
Internal Hard Drive

Display
12.1" Color TFT

Sample Temperature
0–50 °C

Operating Temperature
10–40 °C

Warm-Up Time
2 minutes

Inlet/Outlet Fittings
1/4", 3/8" Swagelok®

Power Requirements
140 W; 115/230 VAC, 50/60 Hz (including external vacuum pump)

Dimensions
30" H × 28" W × 14" D

Weight
55 pounds (27 kg); includes video monitor, keyboard, mouse

Ordering Information

Benchtop Package
Model Number: 908-0004

Included in Package

Analyzer, external vacuum pump, keyboard, video monitor, mouse

Option - Water Vapor Isotope Standard Source

Model	Name
-0001	Water Vapor Isotope Standard Source

The Water Vapor Isotope Standard Source provides controlled humidified air flows with known D/H and $^{18}O/^{16}O$ and H_2O values automatically.

www.lgrinc.com

N_2O / CO ANALYZER

HIGHEST PRECISION • FASTEST • LOWEST POWER

The N_2O/CO Analyzer is designed for many demanding applications including eddy-correlation flux measurements, chamber flux measurements, combustion diagnostics, and trace-gas monitoring. These Analyzers have been applied successfully on-board NASA DC-8 aircraft for measurements in the upper troposphere / lower stratosphere. In fact, the N_2O / CO Analyzer is ideal for simultaneously measuring nitrous oxide and carbon monoxide in ambient air with data rates of up to 20 Hz, less than 1% uncertainty (without calibration; much higher accuracy may be obtained with calibration), and better than 0.3 ppbv precision in a 1 second measurement time. The Analyzer is unaffected by other atmospheric gases or changes in atmospheric pressure.

As described in the Theory Section, the measurement strategy is based on high-resolution direct-absorption spectroscopy. The instrument includes an internal computer that can store data practically indefinitely on its internal hard drive (for applications requiring unattended long-term operation), and send real-time data to a data logger through its analog and digital (RS232) outputs. In addition, an Ethernet connection allows remote access to data files stored on the instrument's hard drive.

The instrument includes a non-cryogenic, room-temperature quantum cascade laser and photodetector for easy long-term operation in the field as well as an internal computer that can store data practically indefinitely on its hard drive (for applications requiring unattended long-term standalone operation). The Analyzer can send real-time data to a data logger through its analog, digital (RS232), and Ethernet outputs.

Performance Specifications

Concentration Ranges
- N_2O: 1 – 4000 ppbv
- CO: 10 - 2000 ppbv

Response Time (flow time through cell)
- 10 seconds (standard internal pump)
- 0.1 seconds (optional external pump)

Accuracy
- Total uncertainty <1% of reading (w/o calibration)

Repeatability/Precision (1-sigma, ambient levels)
- 0.3 ppbv (1 second)

Outputs
- Digital (RS232), Analog, Ethernet

Data Storage
- Internal Hard Drive

Data Rate
- 0.01-20 Hz

Embedded Display
- 12.1" Color TFT

Sample Temperature
- 0 - 50 °C

Operating Temperature
- 10 - 30 °C

Ambient Humidity
- <100% Non-Condensing (ambient temperature)

Inlet/Outlet Fittings
- 3/8", 1/4" Swagelok®
- (slow flow, internal pump)

Inlet/Outlet Fittings
- 3/8", 1/2" Swagelok®
- (fast flow, optional external pump)

Power Requirements
- 150 W (excluding external pump)
- 115/230 VAC; 50/60 Hz

Dimensions
- *17" H × 38" W × 14" D*

Weight
- 90 pounds (40 kg)
- Including internal vacuum pump, embedded video monitor, keyboard, and mouse

Ordering Information

Desktop Package
- Model Number: 908-0014

Option - Dry-Scroll Vacuum Pump (DSVP)

Model	Name
-9001	Dry-Scroll Vacuum Pump (DSVP)
-9002	DSVP Maintenance Kit
-9003	DSVP Connection Kit
-9004	DSVP Exhaust Silencer
-9005	24 VDC to 110 VAC Pure Sine Inverter
-9006	24 VDC to 220 VAC Pure Sine Inverter

Accurately measuring the uptake of N_2O and CO in the field has never been easier. Get your results without having to take samples back to your lab.

www.lgrinc.com

Figure 4. Datasheets (as of March 2010) for the Fast Greenhouse Gas Analyzer, CO_2 Isotope Analyzer, Water Vapor Isotope Analyzer, and N_2O/CO Analyzer

Incorporate and test instrumentation in vehicle

LGR configured and tested the instruments in the Mobile Emissions Laboratory. The input gas sample lines and manifold (roof-mounted) were tested by directing known gas mixtures through the lines. Gas sample flow time response through all of the gas analyzers was equalized by adjusting sample line length to ensure reliability of correlations between the various instruments. As described later, inlet lines and internal power supplies to the instruments enable measurements of emissions while the Mobile Emissions Laboratory is moving or stationary.

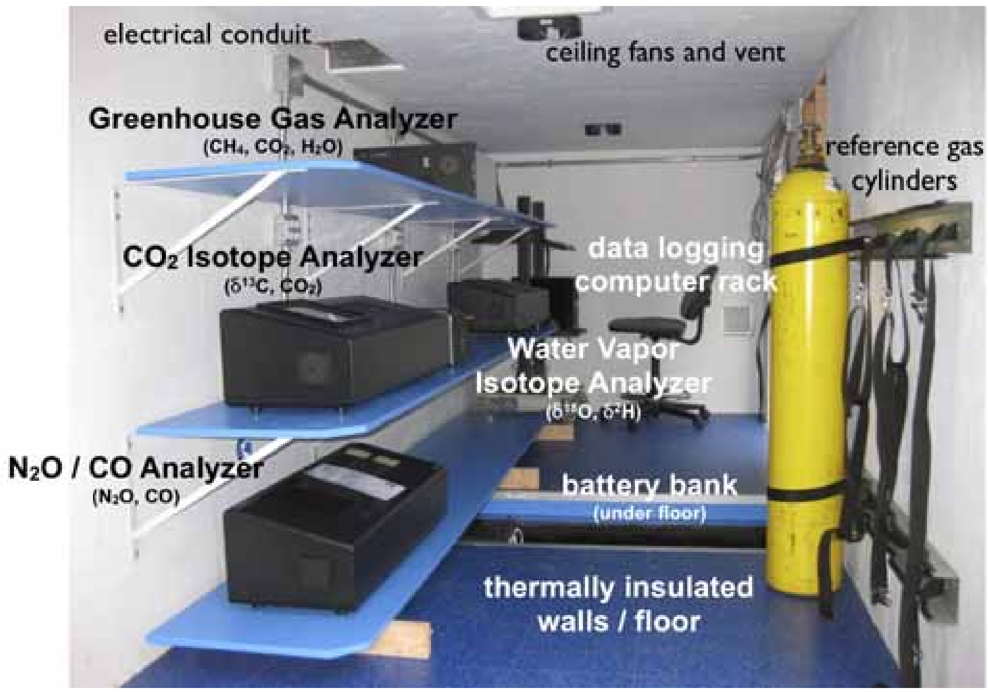


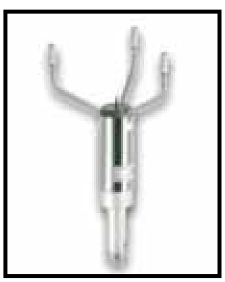
Figure 5. Inside the Mobile Emissions Lab equipped to measure several gas species in the field.

Figure 6. LGR's Multiport Inlet Unit (MIU) combined with long-length inlet lines (left) allow for measurements at multiple locations and at various distances (50 meters or longer) from the trailer.

Internal battery supplies located below the floor (right) allow long-term operation of several instruments in the field.

LGR's Multiport Input Units (MIU) were incorporated into the Mobile Emissions Laboratory. The MIU includes 16 programmable valves for automatic calibration and monitoring of several locations so that the user simply connects the input (calibration or sample) gas lines (using 1/4" OD tubing) to the MIU. Using control software included in an Analyzer, the user programs the sequencing of individual ports in the MIU to enable automatic sampling of multiple sources at user-selected intervals. Thus, the MIU enables monitoring of several locations outside the Mobile Emissions Laboratory automatically.

Figure 7. LGR's Multiport Input Unit (MIU) provides capability for 16 gas inputs to the Analyzer.



A sonic anemometer (Vaisala Wind Sensor WS425) measures wind speed and direction, and provides analog and RS-232 serial output to the data logger in the Mobile Emissions Laboratory. The sonic anemometer mounts on the front trailer hitch and extends above the LGR Mobile Emissions Laboratory. The sonic anemometer provides measurements of wind velocity and, combined with concentration measurements, allows the determination of eddy covariance fluxes using standard micrometeorological techniques.

Figure 8. Sonic anemometer mounted on top of the Mobile Emissions Laboratory for measurements of wind direction and velocity.

Before incorporating the instruments into the Mobile Emissions Laboratory, LGR performed standard accuracy, precision, linearity and stability tests using calibrated mixtures on every instrument to validate performance under all environmental conditions likely to be encountered in the field.

Accuracy/Precision

The accuracy of each unit was verified by measuring calibrated reference gas mixtures in air repeatedly over several hours. The target accuracy and precision are listed in each datasheet (see 0). To ensure reliability and data integrity during long-term operation in the field, the Mobile Emissions Laboratory includes appropriate gas cylinders containing suitable reference gases. These reference gases may be used to periodically check the calibration of each instrument in the field if necessary.

Dynamic Range and Linearity

The dynamic range and linear response of the analyzers was demonstrated by obtaining mixtures with elevated concentrations and using the highly accurate gas dilution system to create mixtures that vary over wide ranges likely to be encountered in the field (e.g., CO_2 between 300 – 10,000 ppmv) in urban and rural locations. LGR instruments deliver performance that requires a single calibration over the range denoted “measurement range” in the respective data sheet. For almost all cases encountered in the field, measurements will be recorded within the “measurement range” of the instrument. However, for measurements over an even wider range (denoted “operating range” on the data sheet), multiple calibration cylinders may be desired to provide a “standard curve” to accurately describe instrument response over the denoted range.

Thermal Stability

Field instruments must be able to provide accurate concentrations despite variations in ambient temperature. In order to establish the ability to record measurements in the Mobile Emissions Laboratory during operation, LGR validates all instruments while operating over the entire range from 5 °C – 45 °C in an Environmental Chamber at LGR to ensure that they meet their performance specifications, as described in their respective datasheets.

Figure 9. External power input/output connections to the Mobile Emissions Laboratory (left), breaker panels for AC input and internal power distribution (center), and inverter/charger for converting AC power to DC battery power (right).

Autonomous software for data logging & reporting

All data files recorded by each gas analyzer within the Mobile Emissions Lab were recorded in real time on internal hard-drives within each instrument. In addition, all Analyzers could be connected to an external data logger (CR1000-ST-SW-NC Campbell Scientific) inside the Mobile Emissions Lab capable of storing all data in a centralized location. Time stamps recorded by the analyzers and GPS data recorded by the GPS locator (Garmin or mobile phone technology) provide temporal and spatial tracking of all reported measurements.

Figure 10. Data logger (CR1000-ST-SW-NC Campbell Scientific) provides centralized data collection of all monitored parameters inside the Mobile Emissions Laboratory.

Multiple User Interfaces

All LGR Analyzers include multiple user interfaces to enable the user to monitor the numeric output (Numeric Mode), raw data transmission and absorption spectra (Spectra Mode) and real time data traces (Time Chart Mode). For example, software includes the display screens shown in Figures below. In "Numeric" mode, the software displays the concentration and isotope ratio both with and without sequential data averaging. In "Time Chart" mode, the measurements are displayed as a function of time to allow for temporal trends to be clearly visible. Finally, in "Spectra" mode, the user can view the cavity-enhanced transmission and absorption spectra, the data fit, and the fit residual in real time.

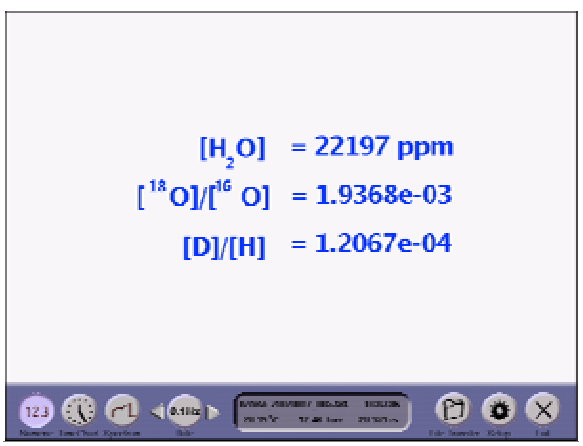


Figure 11. Example of Analyzer User Interface in Numeric Mode

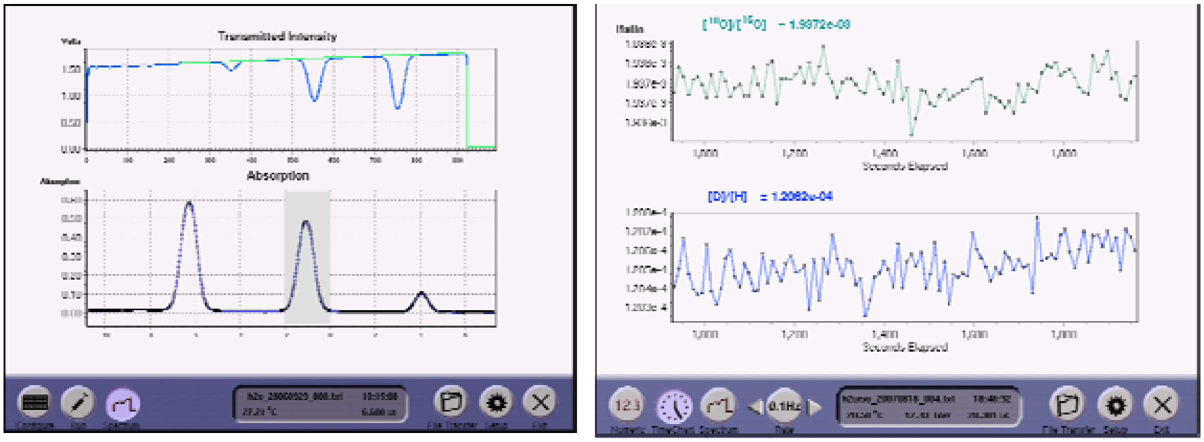


Figure 12. Examples of Analyzer User Interface in Spectra Mode (left) and Time Chart Mode (right)

Multiport Input Units (MIU)

In addition to the capability of monitoring concentrations of multiple gases while traveling, the Mobile Emissions Laboratory includes LGR's Multiport Input Units (MIU) that allow measurements at several different locations. In brief, LGR's MIU provides capability for 16 gas inputs to a particular Analyzer. The MIU includes 16 fully programmable valves for automatic calibration and monitoring several locations so that the User simply connects the input gas lines (e.g., 1/4" OD tubing) to the MIU. Using control software included in the Analyzer, the User can program the sequencing of the different individual ports in the MIU to enable automatic measurements and sampling at user-selected intervals.

Figure 13. Multiport Input Unit

Deploy Mobile Emissions Lab for measurements in urban environments

Deployment at Urban Sites

LGR demonstrated the ability to record measurements of several greenhouse gases while the Mobile Laboratory was driven from Mountain View to Oakland, CA and while deployed at the Caldecott Tunnel during commute hours on 2 March 2010. The Mobile Emissions Laboratory was parking near the top of the middle bore of the Caldecott Tunnel (Old Tunnel Road and Fish Ranch Road). Separate inlet tubes were used to sample air from the middle bore of the tunnel (denoted "Tunnel Air") and from an adjacent location 25 meters away from the tunnel (denoted "Ambient air" in the plots below. Measurements of N_2O, CO, CH_4, CO_2, H_2O vapor, and carbon isotope ratios ($\delta^{13}C$) were recorded in the Tunnel during several hours of the afternoon commute. In addition, measurements were recorded along the highway while the Mobile Emissions Laboratory was traveling to and from the Tunnel. Data recorded from this deployment is presented below.

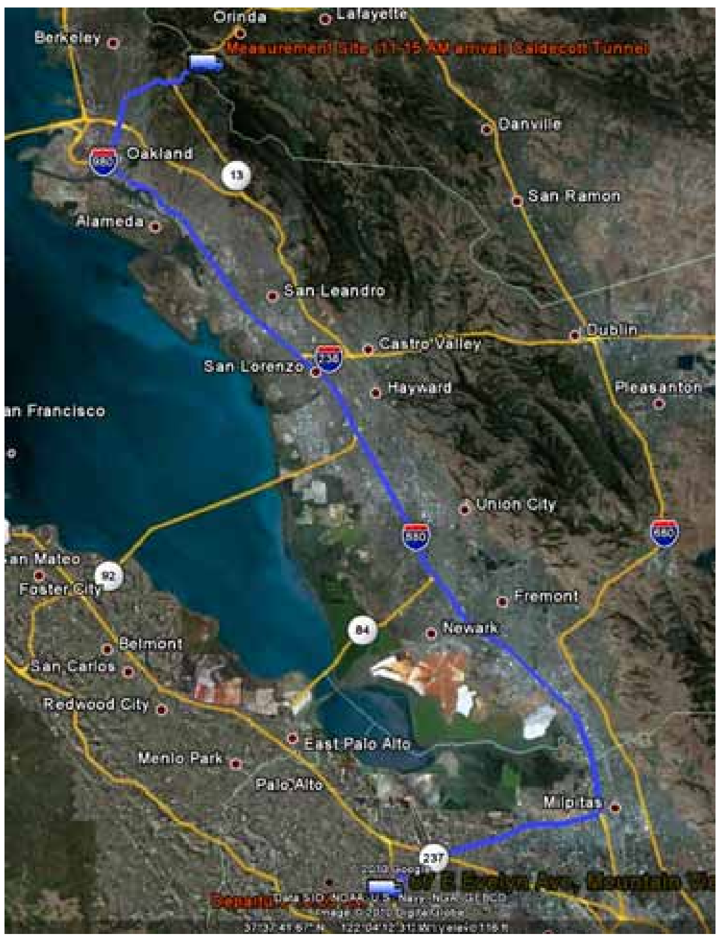


Figure 14. GPS coordinates of Mobile Emissions Laboratory during the journey from Los Gatos Research (at 10:05 a.m.) to the Caldecott Tunnel (arrival 11:15 a.m.) plotted in Google Maps.

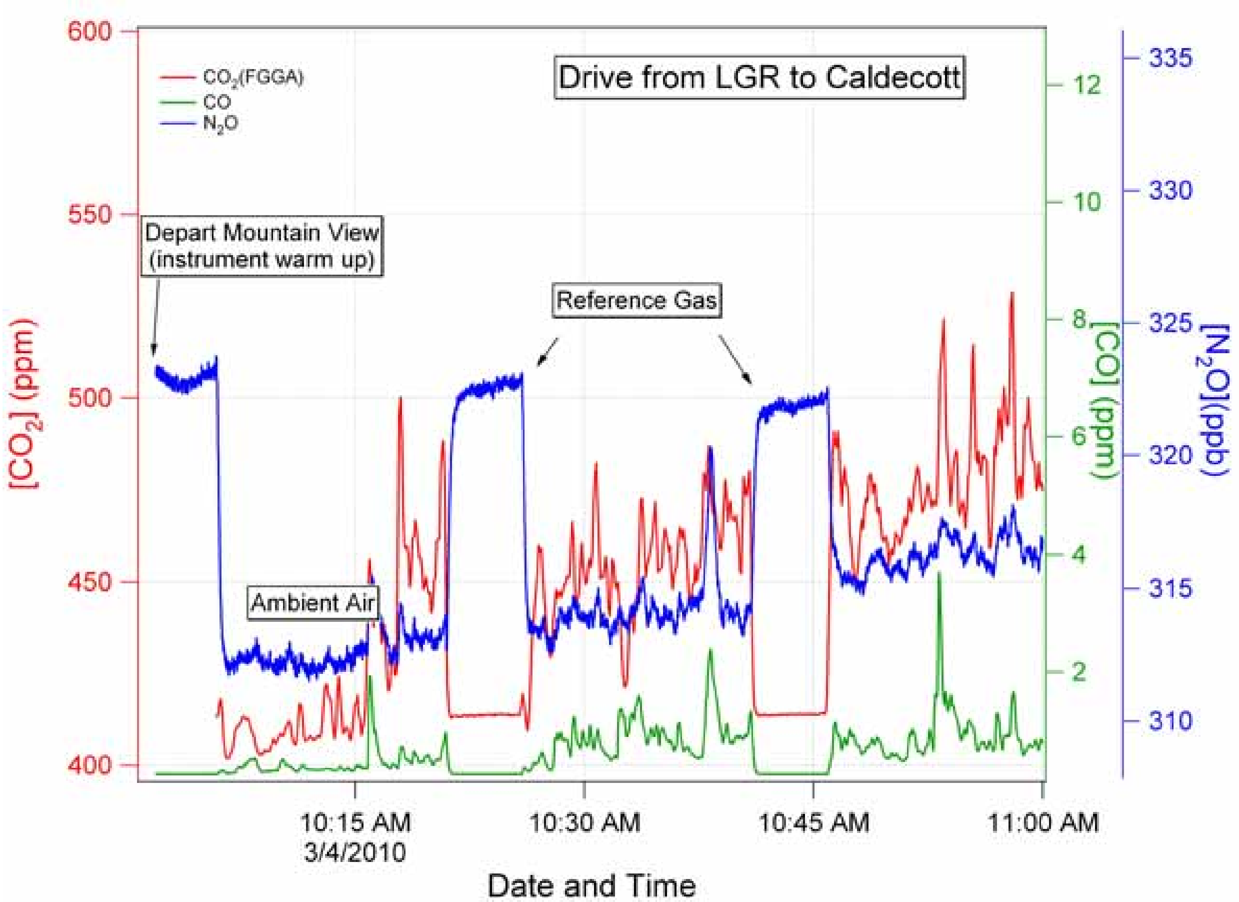


Figure 15. Measurements of CO_2, CO, and N_2O recorded by the Mobile Emissions Laboratory during the journey from LGR to the Caldecott Tunnel. Reference Gas cylinders in the Mobile Emissions Laboratory were sampled periodically as validation checks of the instruments during the journey.

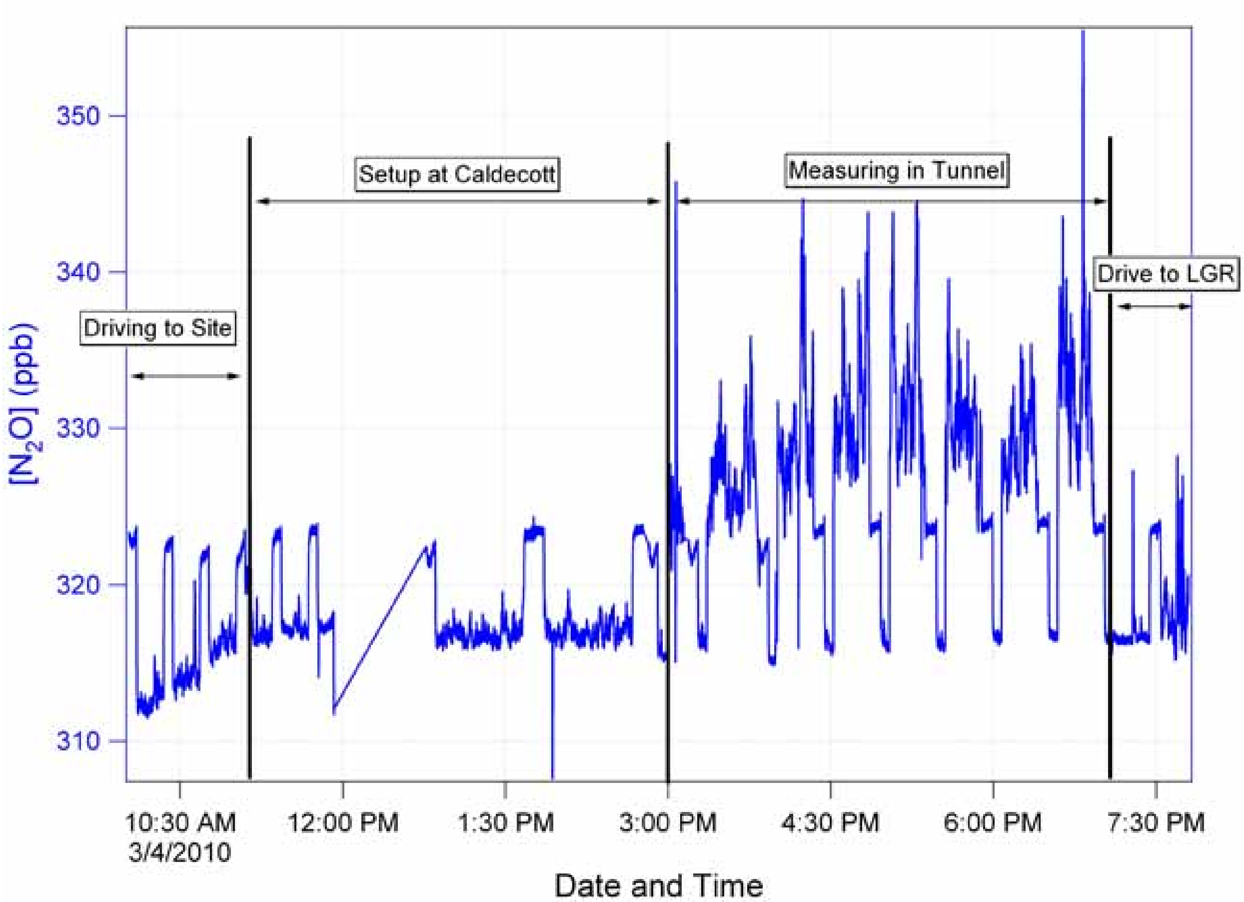


Figure 16. **N_2O measurements recorded by the N_2O/CO Analyzer in the Mobile Emissions Laboratory during the journey to the Caldecott Tunnel from Los Gatos Research ("Driving to Site"), setup ("Setup at Caldecott") and deployment ("Measuring in Tunnel") at the Caldecott Tunnel and return drive to Los Gatos Research ("Drive to LGR"). The interval "Measuring in Tunnel" includes measurements of ambient air near the tunnel and of reference gas cylinder.**

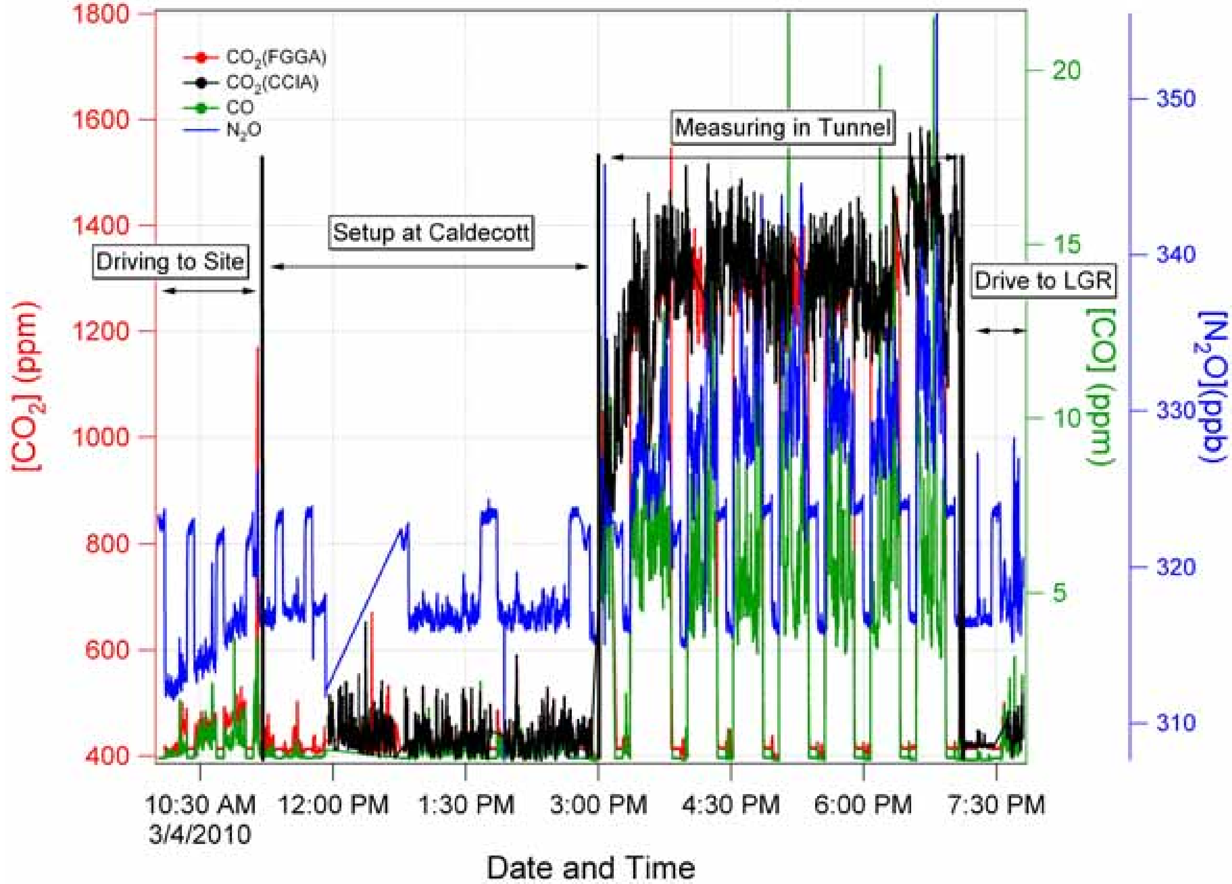


Figure 17. Measurements of CO_2, CO, and N_2O recorded by the Mobile Emissions Laboratory during the journey to the Caldecott Tunnel from Los Gatos Research ("Driving to Site"), setup ("Setup at Caldecott") and deployment ("Measuring in Tunnel") at the Caldecott Tunnel and return drive to Los Gatos Research ("Drive to LGR"). The interval "Measuring in Tunnel" includes measurements of ambient air near the tunnel and of reference gas cylinder.

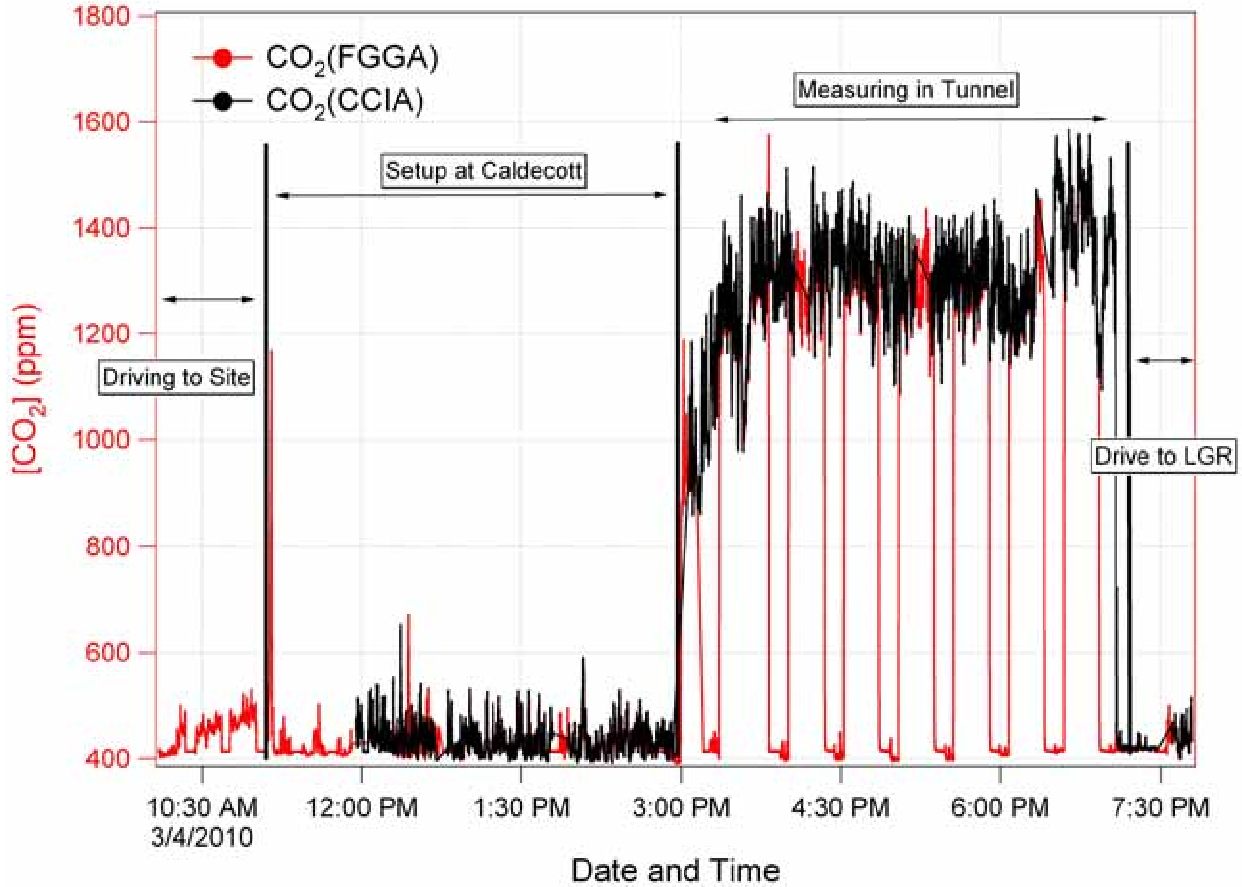


Figure 18. Measurements of CO_2 recorded by the Carbon Dioxide Isotope Analyzer (CCIA) and the Fast Greenhouse Gas Analyzer (FGGA) inside the Mobile Emissions Laboratory during the journey to the Caldecott Tunnel from Los Gatos Research ("Driving to Site"), setup ("Setup at Caldecott") and deployment ("Measuring in Tunnel") at the Caldecott Tunnel and return drive to Los Gatos Research ("Drive to LGR"). The interval "Measuring in Tunnel" includes measurements of ambient air near the tunnel and of reference gas cylinder.

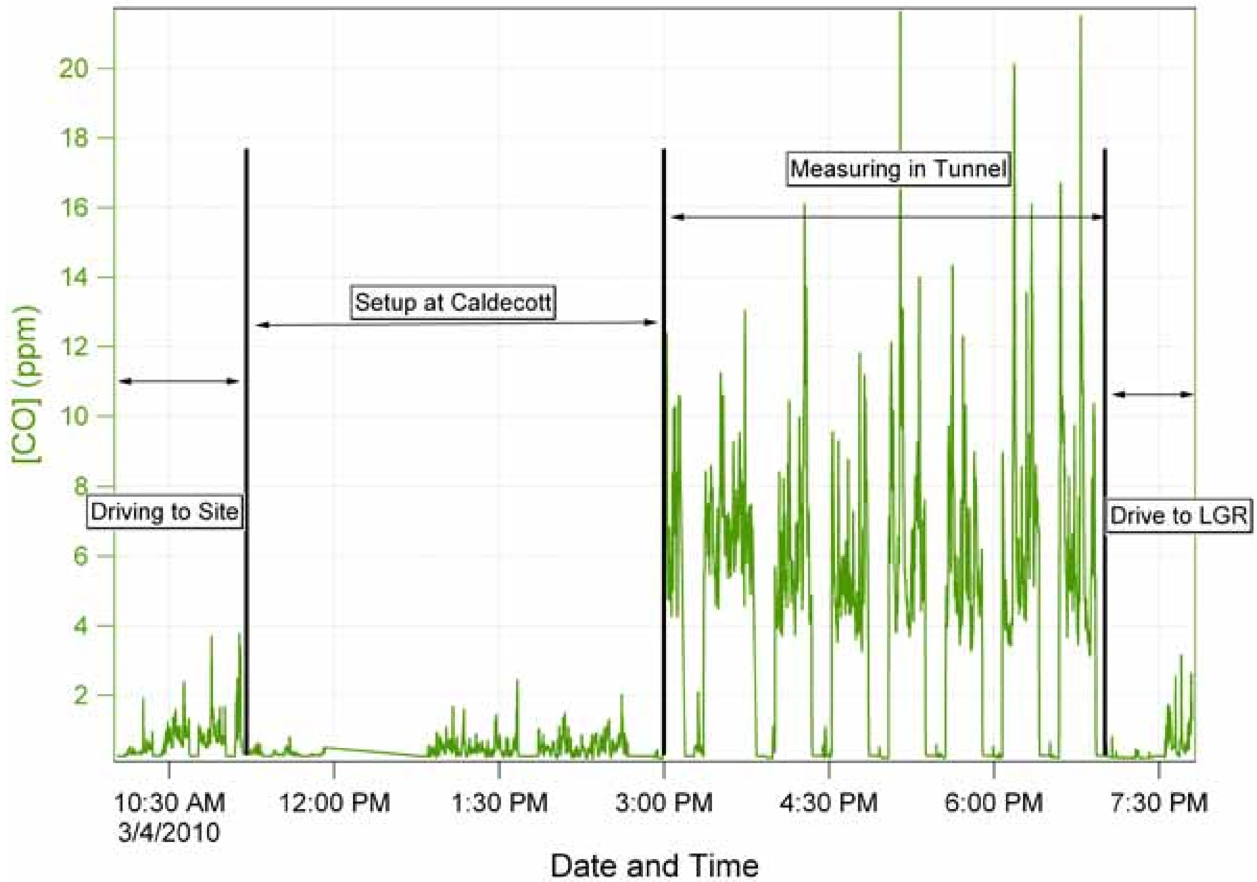


Figure 19. Measurements of CO recorded by the N_2O/CO Analyzer inside the Mobile Emissions Laboratory during the journey to the Caldecott Tunnel from Los Gatos Research ("Driving to Site"), setup ("Setup at Caldecott") and deployment ("Measuring in Tunnel") at the Caldecott Tunnel and return drive to Los Gatos Research ("Drive to LGR"). The interval "Measuring in Tunnel" includes measurements of ambient air near the tunnel and of reference gas cylinder.

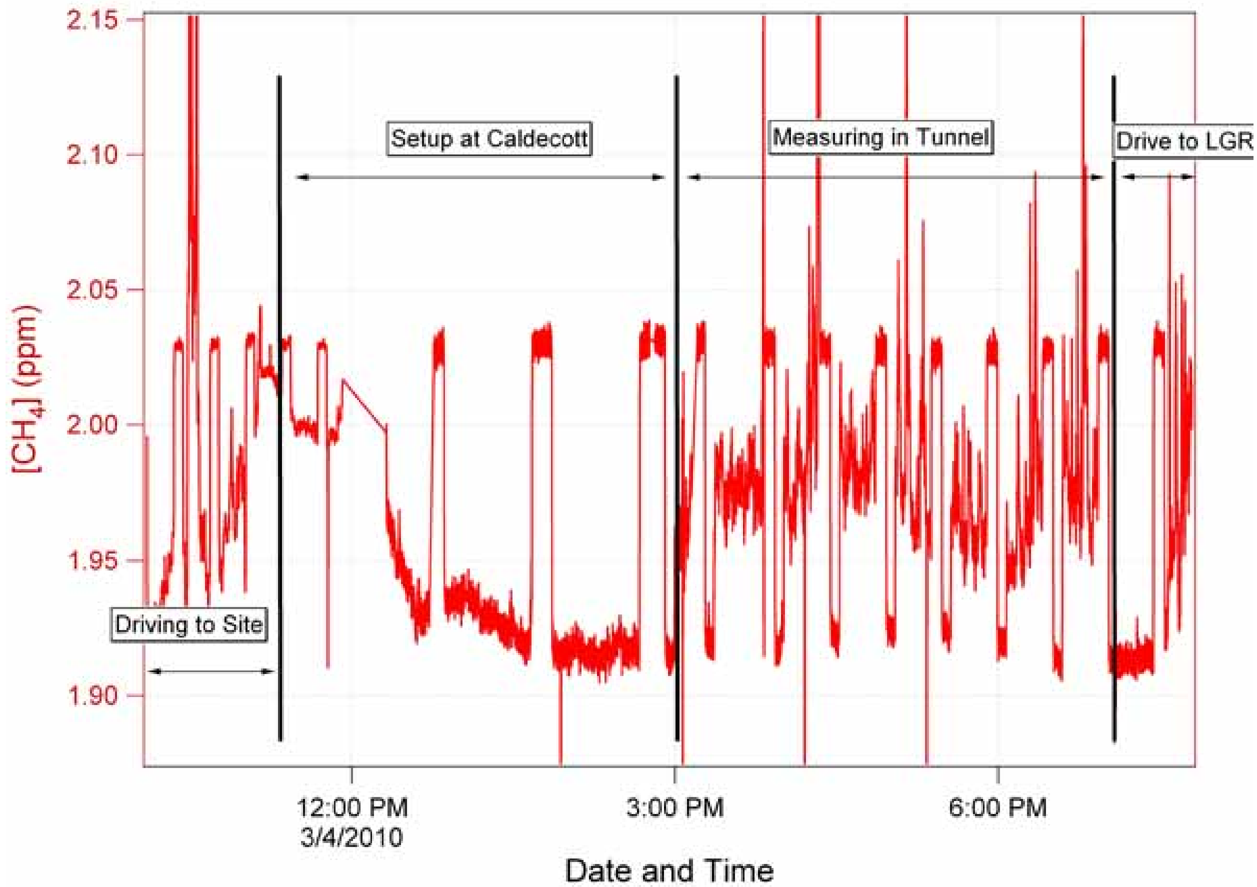


Figure 20. Measurements of CH_4 recorded by the Fast Greenhouse Gas Analyzer (FGGA) inside the Mobile Emissions Laboratory during the journey to the Caldecott Tunnel from Los Gatos Research ("Driving to Site"), setup ("Setup at Caldecott") and deployment ("Measuring in Tunnel") at the Caldecott Tunnel and return drive to Los Gatos Research ("Drive to LGR"). The interval "Measuring in Tunnel" includes measurements of ambient air near the tunnel and of a reference gas cylinder.

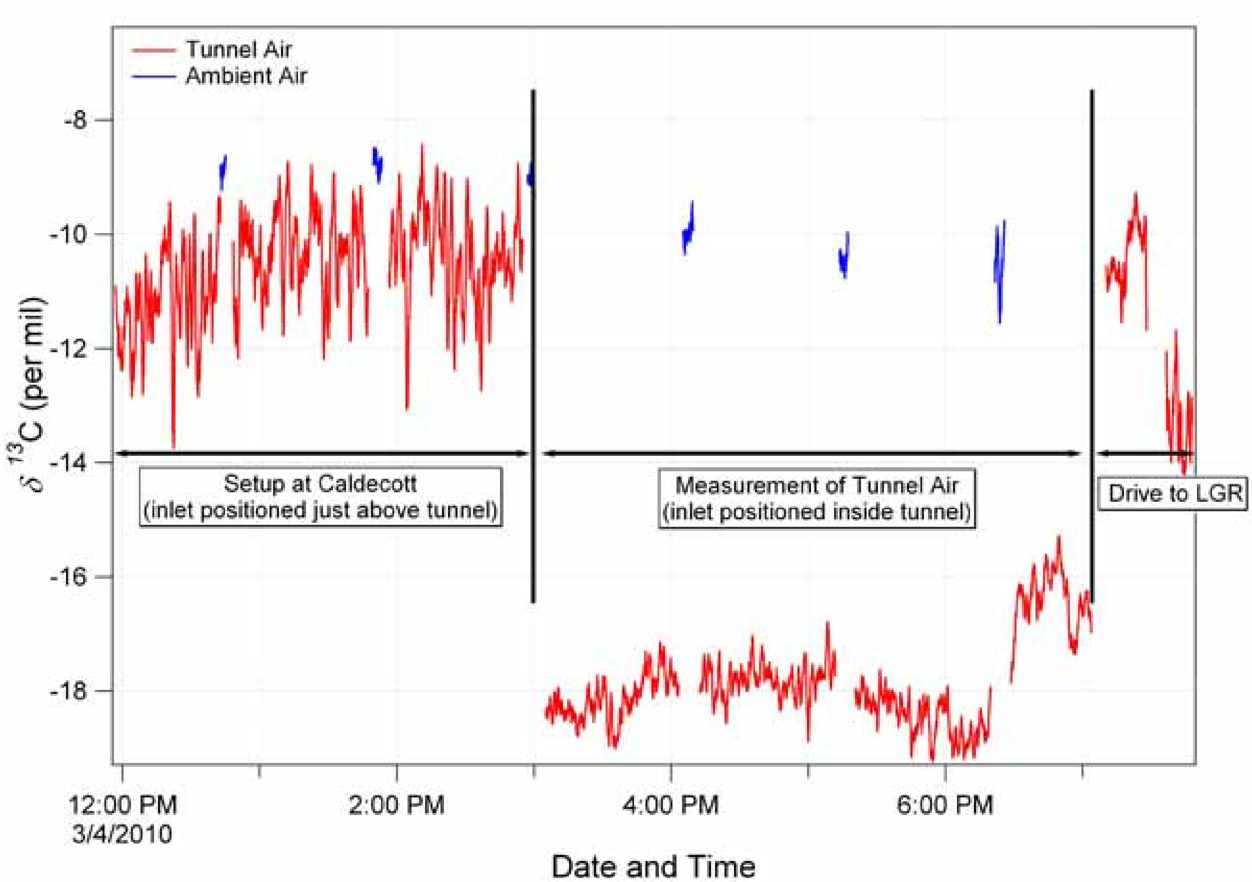


Figure 21. Measurements of $\delta^{13}CO_2$ and CO_2 recorded by the Carbon Dioxide Isotope Analyzer inside the Mobile Emissions Laboratory during the setup ("Setup at Caldecott") with the inlet positioned 10 cm above the tunnel middle bore and inside the tunnel ("Measurement of Tunnel Air") at the Caldecott Tunnel and during the return drive to Los Gatos Research ("Drive to LGR"). The ("Ambient Air") data denoted in blue represents data recorded in ambient air, 25 meters away form the Tunnel (middle bore) inlet.

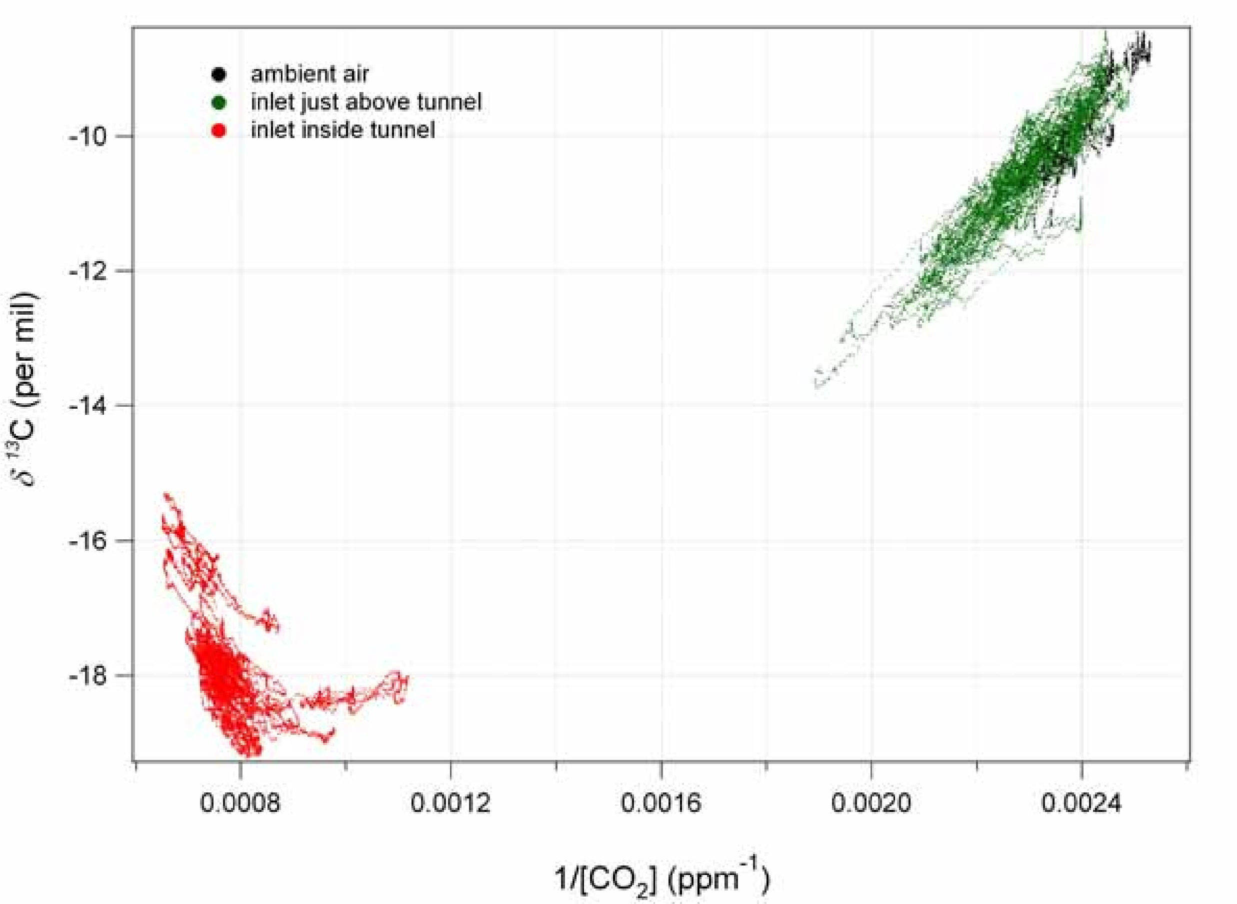


Figure 22. Measurements of CO_2 and $\delta^{13}CO_2$ in ambient air (Keeling plot ($\delta^{13}CO_2$ vs. 1/[CO_2]) 25 meters away from the tunnel (black), in air near the tunnel inlet (green) and in tunnel air (red) recorded by the Carbon Dioxide Isotope Analyzer (CCIA) using the data shown in the previous plot.

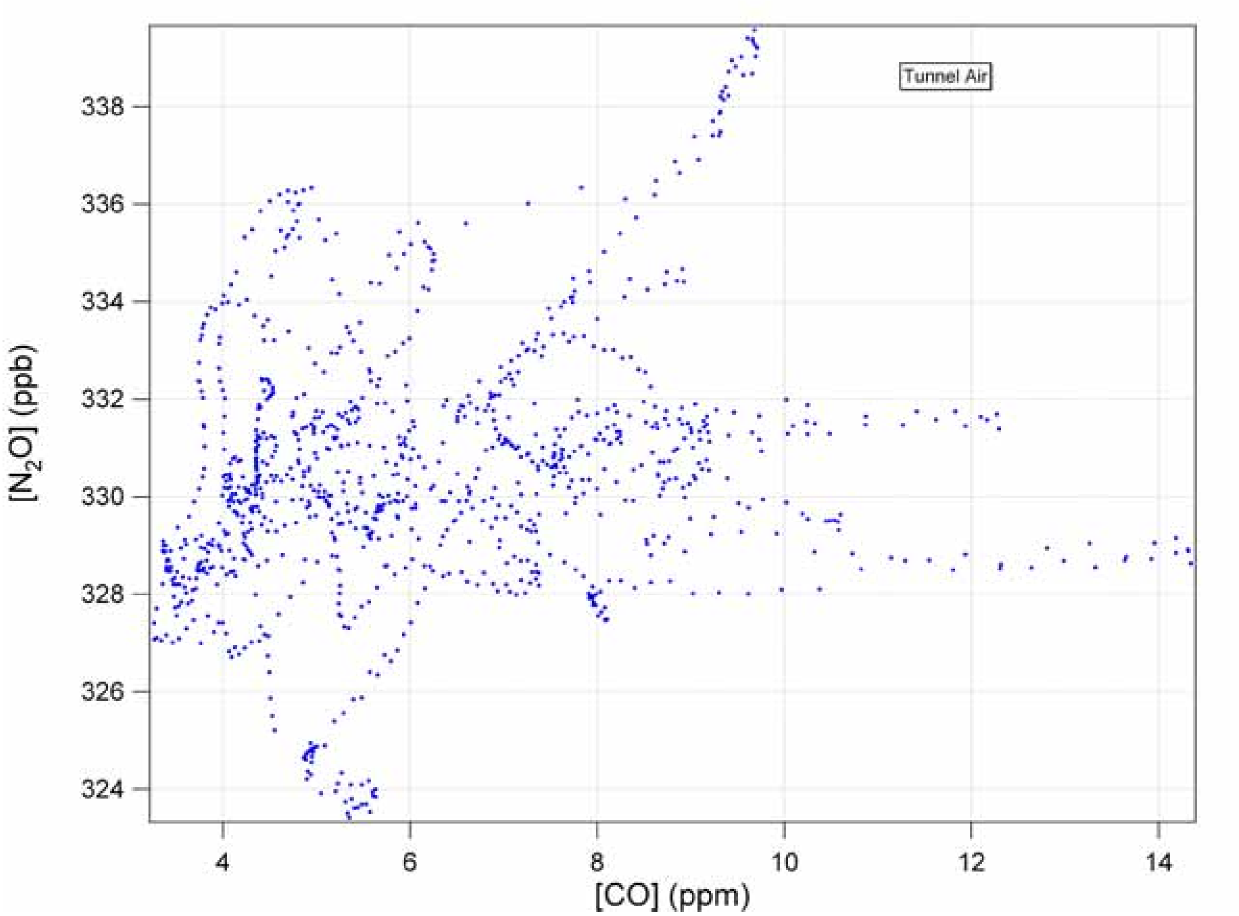


Figure 23. Measurements of N_2O and CO in tunnel air recorded by the N_2O/CO Analyzer in real time.

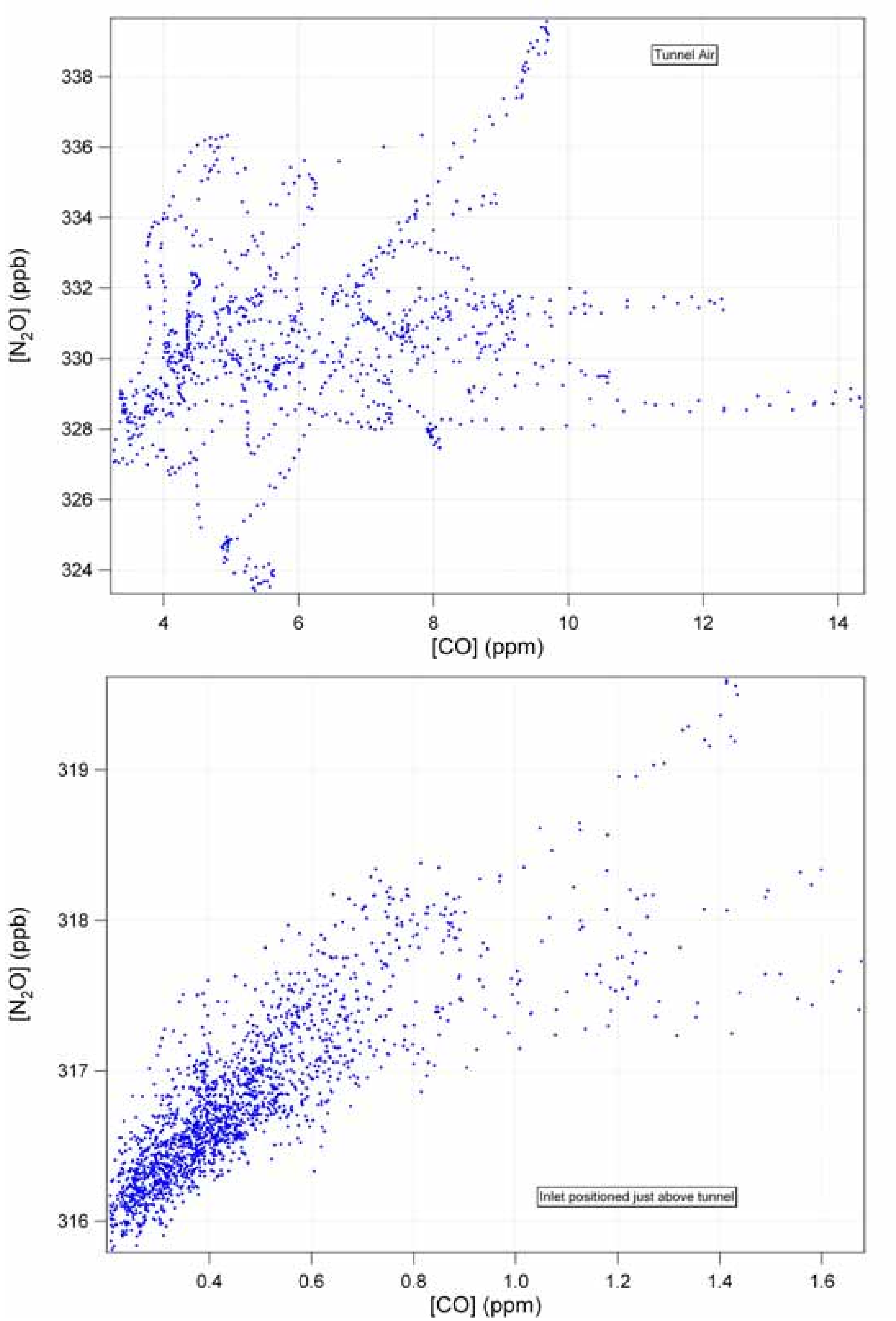


Figure 24. Correlations of N_2O and CO inside the tunnel ("Tunnel Air") and 10 cm above tunnel inlet.

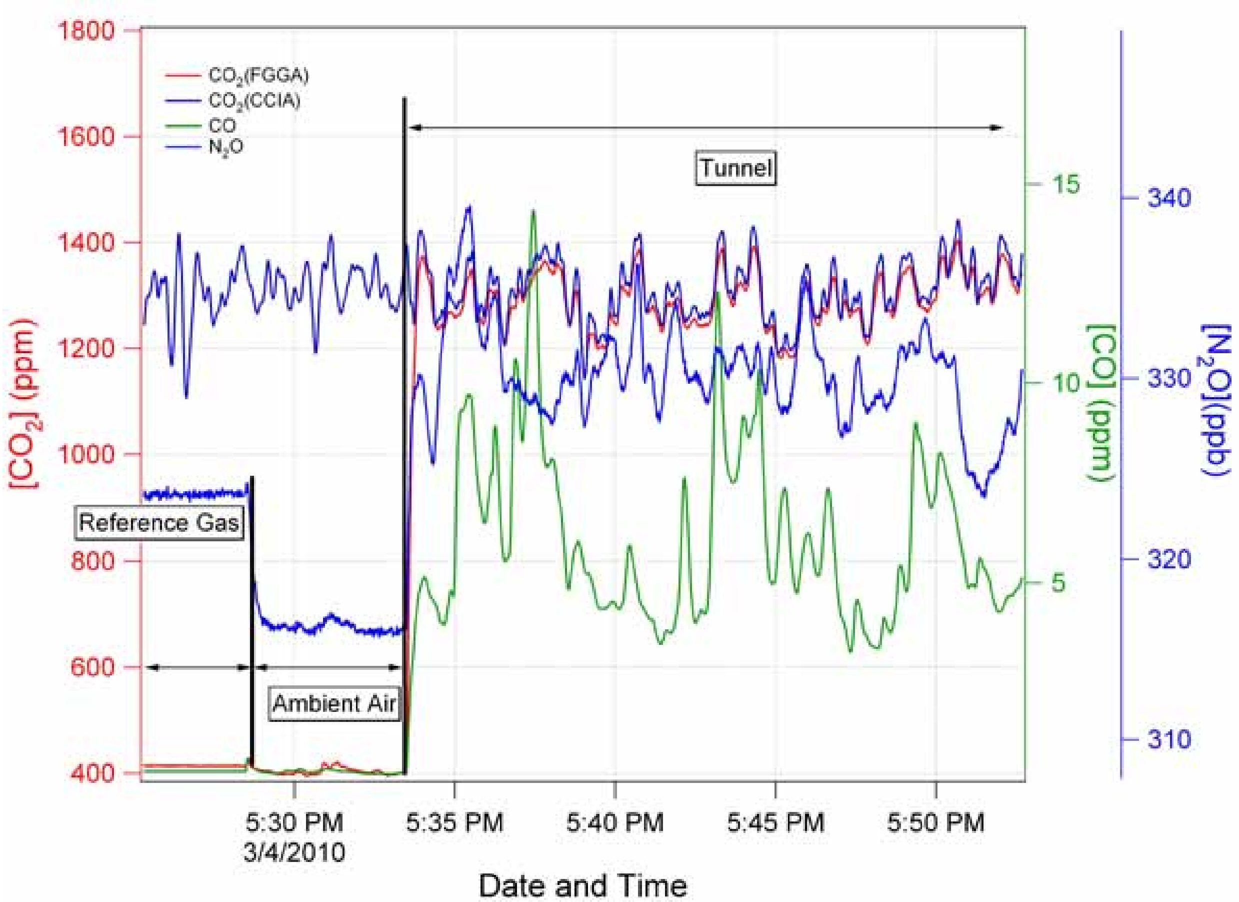


Figure 25. Measurements of CO_2, CO and N_2O during commute hour of reference gas cylinder, ambient air (25 meters from the tunnel) and inside the tunnel ("Tunnel").

Deploy Mobile Emissions Lab for measurements at rural sites

Deployment at Rural Sites - Sacramento-San Joaquin Delta - #1

LGR deployed the Mobile Emissions Laboratory at rural sites (Sacramento-San Joaquin Delta) to characterize the magnitude and variations of methane, carbon dioxide over several diurnal cycles. Measurements at various locations at the agricultural site were investigated to determine the spatial and temporal variability of the target gases. These measurements demonstrate the ability to record measurements over a wide dynamic range in real time. These measurements were reported in a presentation #A51N-07 ("Methane, Carbon and Water Fluxes in a Composite Landscape in the Sacramento-San Joaquin Delta") at the AGU Fall meeting (December 2009).

An abstract for the presentation is presented below.

Methane, Carbon and Water Fluxes in Composite Landscape in Sacramento-San Joaquin Delta

Matteo Detto, D. D. Baldocchi, F. E. Anderson, A. H. Goldstein, A. Guha , J. Hatala, M. Kelly, B. Runkle, O. Sonnentag, W. L. Silver, Y. Teh, J. Verfaillie, D. Baer

University of California Berkeley

Much of the Sacramento-San Joaquin Delta region post the Gold Rush era was reclaimed and drained for agriculture by building a network of 'islands' surrounded by levees. The exposure of organic peat soil to air has caused the peat soil to oxidize and soil to subside. Today, a combination of oxidation, subsidence, erosion, and compaction has caused many 'islands' to be 10 m below sea level. The continued oxidation/subsidence of the Delta peatlands is threatening long-term agricultural use of these lands by pushing the soil level further and further below sea-level. In an attempt to protect the Delta, State and Federal governmental institutions (e.g. CalFed) and local water districts are converting some of these agricultural lands back to wetlands. This is being accomplished by breaching levees, with the intent of sequestering carbon and building up the soils, by introducing flooded crops, like rice, or carbon farming by converting farm land to native tules and cattails. Knowing what the environmental trade-offs of such land conversion are on coupled carbon and water exchange is critical for proper environmental management, as there can be many unintended consequences such as the emission of greenhouse gases that promote global warming. Large greenhouse gas fluxes specially those of methane are expected from wetlands in the Sacramento-San Joaquin Delta for a variety of reasons.

This campaign aimed at measuring the methane fluxes over the complex and fragmented landscapes of the Delta where a piece of land can vary from being a slight sink of methane to a vast source depending upon land use, land cover and

degree of saturation of soil. Los Gatos Research (LGR) designed and fabricated a mobile trailer which housed their latest closed-path infrared laser based absorption spectrometers for fast response in-situ measurements of methane at a frequency which permits eddy covariance technique to be applied to measure flux. The trailer was taken to selected landscapes across the Delta which were expected to be hotspots for production of methane. These included a drained peatland at Sherman Islands, wet irrigated pastures, rice paddy fields at Twitchell Islands, marshy, tidal floodplains, and flooded water fowl habitat. In this way, methane fluxes were measured across a spectrum of time and space scales in the Delta.

The measurements address how fluxes of methane vary diurnally, seasonally, and annually over Delta peatlands. We focus on how methane fluxes vary with space in the vertical and horizontal and how this is affected by land use (e.g. agriculture, restored and native wetlands) and water management (e.g. water table and flooding)? Our findings address the issue of whether management decisions to sequester carbon, by flooding and ecological restoration, will be offset by enhanced emissions of methane.

Figure 26. LGR Mobile Emissions Lab deployed with (UC Berkeley) Professors Goldstein and Baldocchi for simultaneous methane, carbon dioxide and water vapor flux measurements at Twitchell Island.

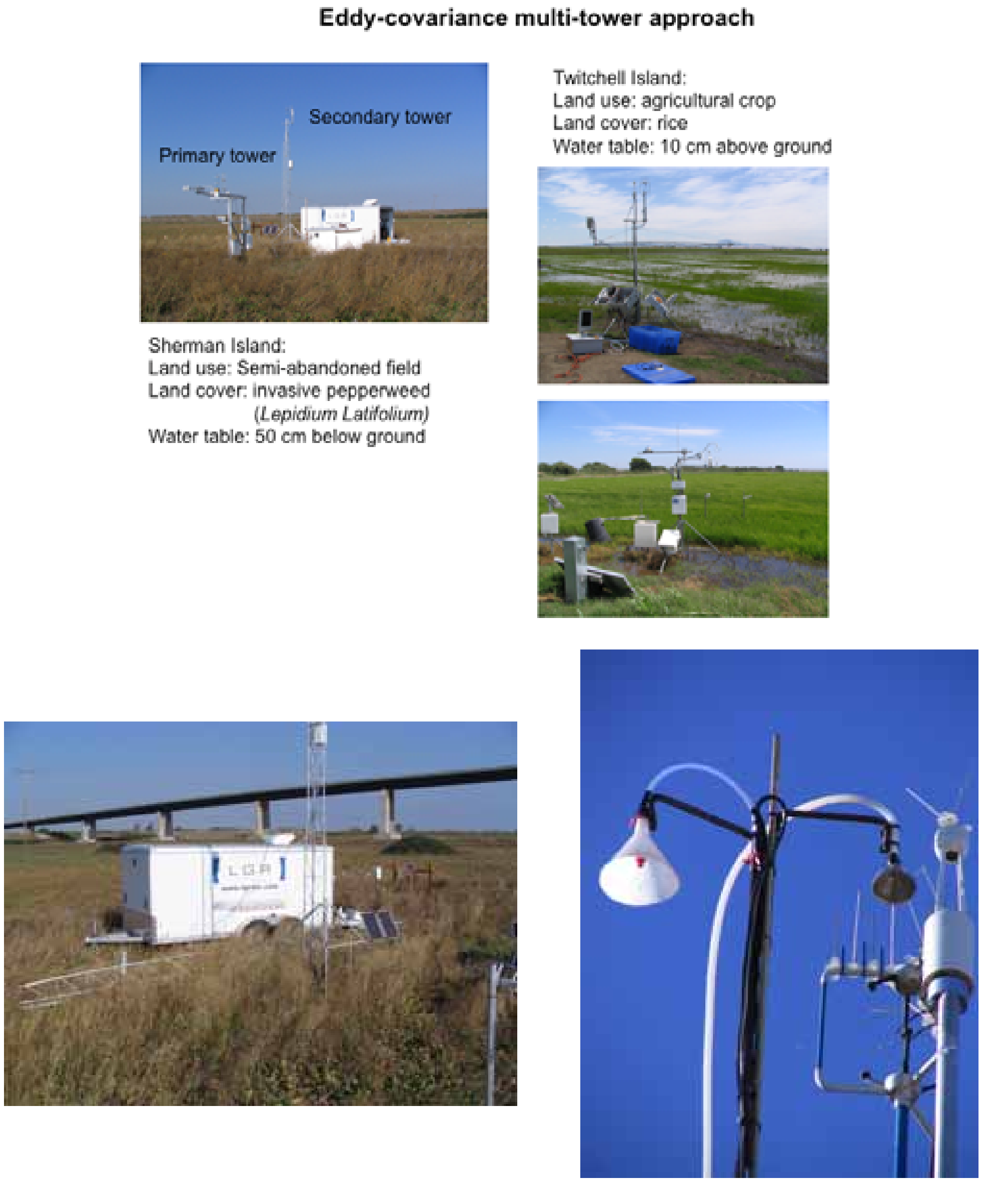
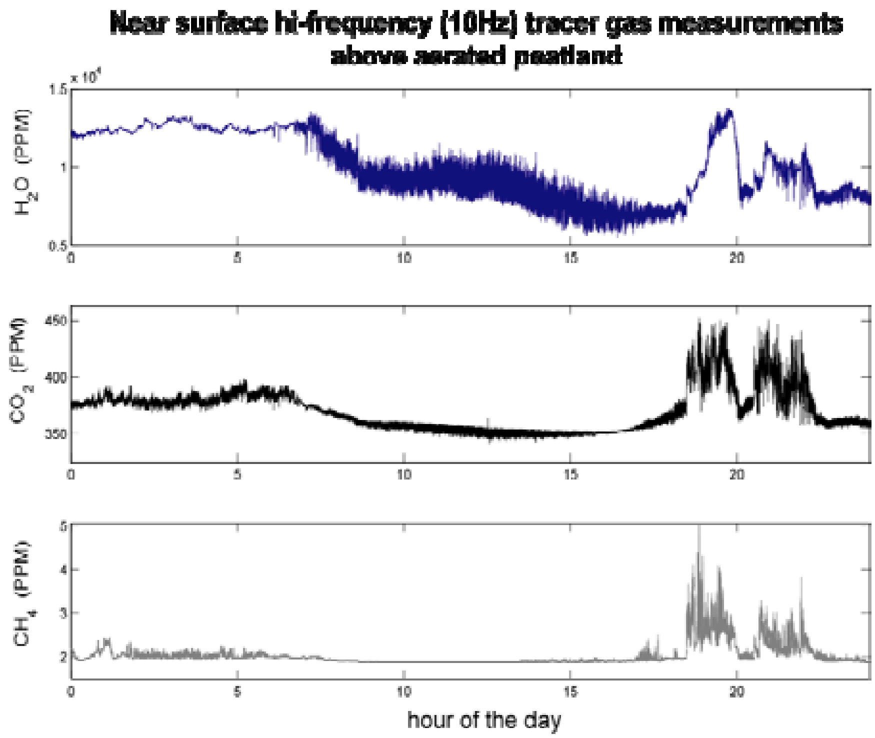


Figure 27. Setup for measurements of methane, carbon dioxide and water vapor at multiple sites (Twitchell Island and Sherman Island) in the Sacramento-San Joaquin Delta recorded with the Mobile Emissions Laboratory (Fast Greenhouse Gas Analyzer, Dry Scroll Vacuum Pump, sonic anemometers). Note that for these measurements, the dual flux tower setup was supplied by UC Berkeley. The site at Twitchell Island was selected to investigate fluxes near rice paddies whereas the site near Sherman Island was a semi-abandoned field near invasive pepperweed.



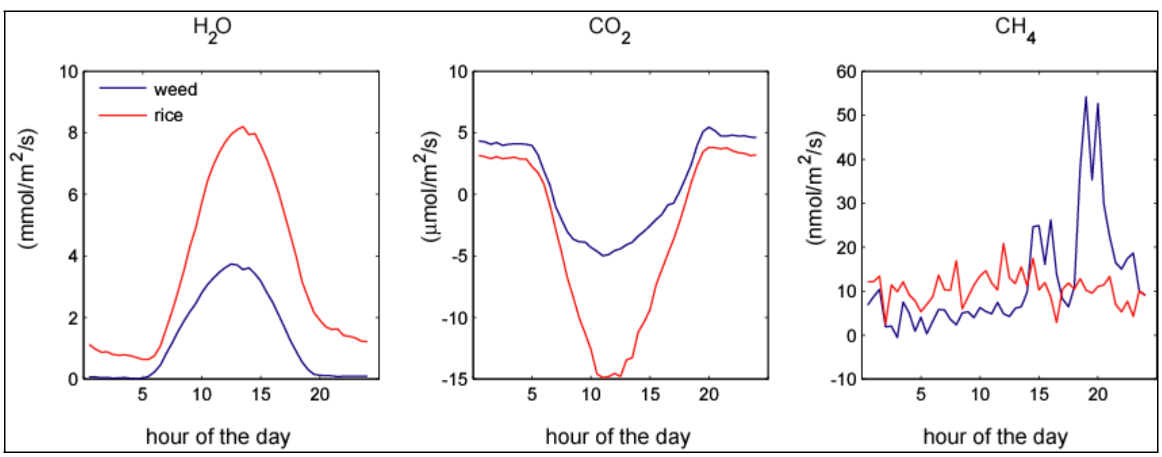


Figure 28. (top) Near surface 10-Hz measurements (methane, carbon dioxide, water) above aerated peatland.

Figure 29. (bottom) Measurements of methane, carbon dioxide and water vapor fluxes showing mean diurnal variation near rice and pepperweed.

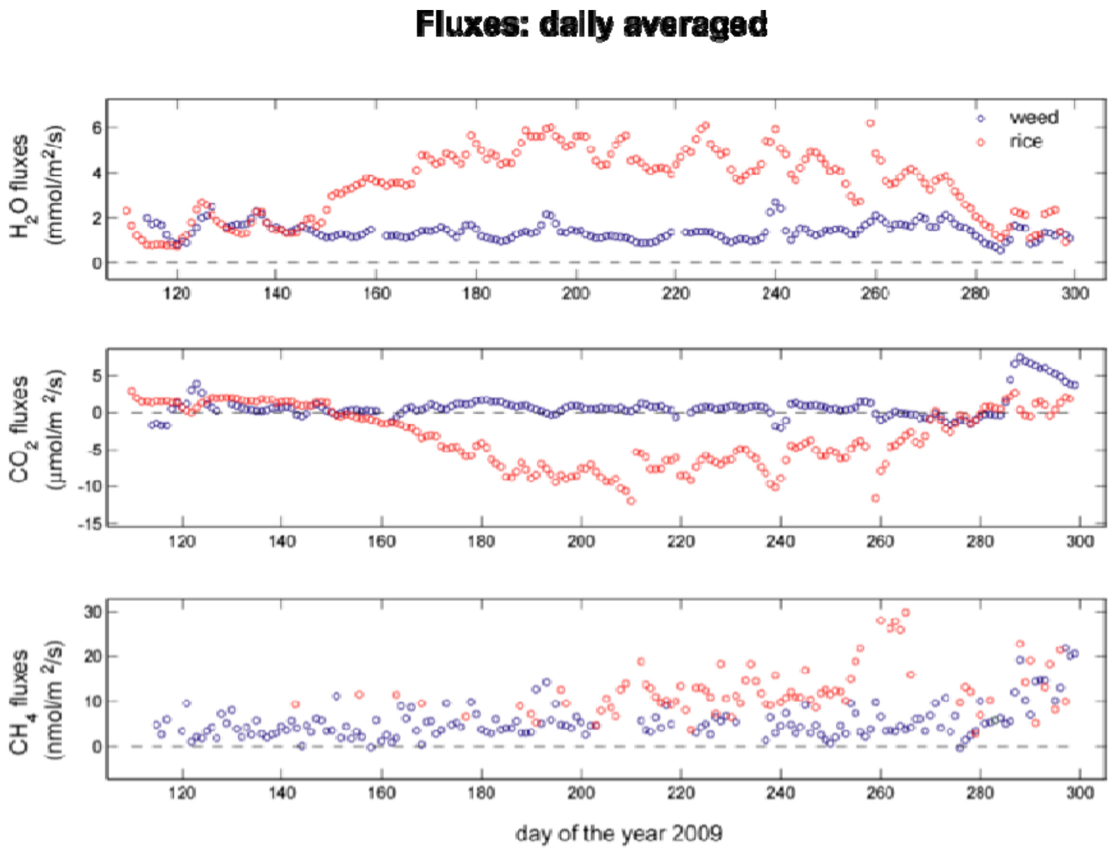


Figure 30. Measurements of methane, carbon dioxide and water vapor fluxes showing daily averaged fluxes variation near rice and pepperweed.

These results, which quantify the magnitude of multiple species (water, carbon dioxide and methane fluxes) fluxes near different land-use sites, demonstrate the potential for the Mobile Emissions Laboratory to provide measurements that support decisions of land managers and policy-makers in the Sacramento-San Joaquin Delta. In this initial study, UC Berkeley researchers concluded that the rice crop, at a cost of more water usage, was able to sequester greater quantities of CO_2 with minimum losses, in terms of ecosystem respiration and methane emissions, compared to an semi-abandoned field. Methane emissions from the rice were twice as high from the aerated peat soil, but still relatively low compared to CO_2 fluxes (less than 5% in term of GWP_{100}).

Deployment at Rural Sites - Sacramento-San Joaquin Delta - #2

LGR also deployed the Mobile Emissions Laboratory at Sherman Island (Sacramento-San Joaquin Delta) to characterize the magnitude and variations of water vapor isotopes over several diurnal cycles. These measurements were reported in a presentation #H41E-0947 ("*Development, Deployment and Validation of an Isotopic Water Analyzer for High Frequency Measurements in Water Vapor and Continuous Measurements in Liquid Water*") at the AGU Fall meeting in December 2009 in San Francisco.

Reliable in-situ measurements of δ^2H and $\delta^{18}O$ in water contained in liquids, vapor, fog and clouds are important in modeling the vapor dynamics and determining potential feedbacks on future climate change. In addition, fast, high-frequency isotopic water measurements provide detailed time-resolved information on the eco-physiological performance of plants and enable improved understanding of water fluxes at ecosystem scales. The Mobile Emissions Lab allowed us to demonstrate in the field LGR's Water Vapor Isotope Analyzer (WVIA), which is capable of real-time continuous measurements of δ^2H and $\delta^{18}O$ in water vapor at a measurement and system response rate of 5 Hz. In addition, LGR's new Water Vapor Isotopic Standard Source (WVISS) was combined with the WVIA to provide continuous isotopic measurements of liquid water samples (at the unprecedented rate of 240 samples per day). The availability of these new field instruments provides new opportunities for detailed continuous measurements of the hydrological cycle and ecological systems.

Figure 31. Water Vapor Isotope Analyzer and Water Vapor Isotope Standard Source deployed at Sherman Island, California, for continuous, unattended, automatic measurements of water isotopes.

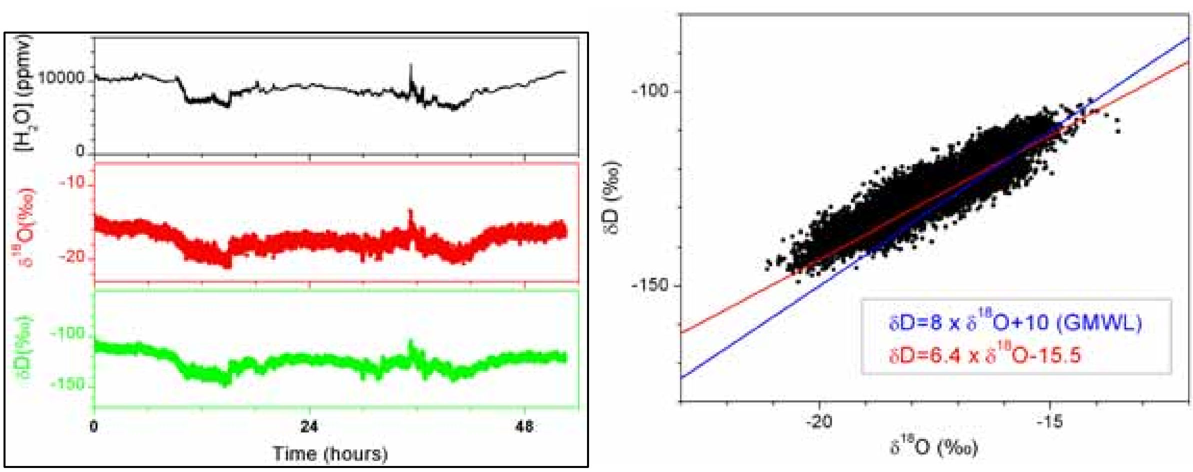


Figure 32. (left) Fast, continuous measurements (at 2-Hz data rate) of δ^2H, $\delta^{18}O$ and H_2O in air (right) Local $\delta^{18}O$ and δ^2H measurements (red line) compared with Global Meteoric Water Line (blue line).

These measurements demonstrated the ability of the Water Vapor Isotope Analyzer to rapidly (>2 Hz) quantify δ^2H and $\delta^{18}O$ in air, resolve dynamic changes in δ quickly (<0.5 sec) and thus enable studies of ecohydrological processes and atmospheric mixing dynamics.

Deployment at Rural Sites - #3

LGR deployed the Carbon Dioxide Isotope Analyzer at Zero Emissions Research and Technology site, a rural site (Bozeman, Montana) to characterize the magnitude and variations of carbon dioxide and $\delta^{13}C$ over several diurnal cycles. Measurements at various locations at the site were investigated using the Multiport Input Unit to determine the spatial and temporal variability of CO_2. These measurements demonstrate the ability to record measurements over a wide dynamic range (to 2000 ppmv and greater) in real time. These measurements were reported in the following two oral presentations at the AGU Fall meeting (December 2009):

"Real-time continuous measurements of CO_2 and $\delta^{13}C$ at multiple locations using cavity enhanced laser absorption," W. I. McAlexander, G. H. Rau, L. Dobeck, L. Spangler, American Geophysical Union meeting, (oral presentation) U12B-04, December 2009.

"Grassland Soil and Fossil CO_2 Fluxes Monitored Using Continuous CELS Measurements of CO_2 and $\delta^{13}C$," G. H. Rau, W. I. McAlexander, L. Dobeck, L. Spangler, American Geophysical Union Fall meeting, B52B-05, December 2009.

The Carbon Dioxide Isotope Analyzer was deployed in July 2009 at the ZERT carbon release site (Bozeman, MT) for real-time measurement of above-ground CO_2 concentration and isotope ratio ($\delta^{13}C$). An automated switching system sampled 13 different locations in the field, as well as two known references, over an 8-day period. Real-time Keeling plots were constructed showing distinct signatures of soil (-27.0 ‰) and fossil (-56.0 ‰) sources compared to background air (-8.2 ‰). Instrument performance gave 0.2 ‰ precision with only 100 seconds of averaging per inlet. Sequential sampling of the various inlets gave a temporal and physical mapping of the CO_2 release plume that is difficult to obtain using more conventional techniques. The figures show the nature and quality of the data from one of the locations.

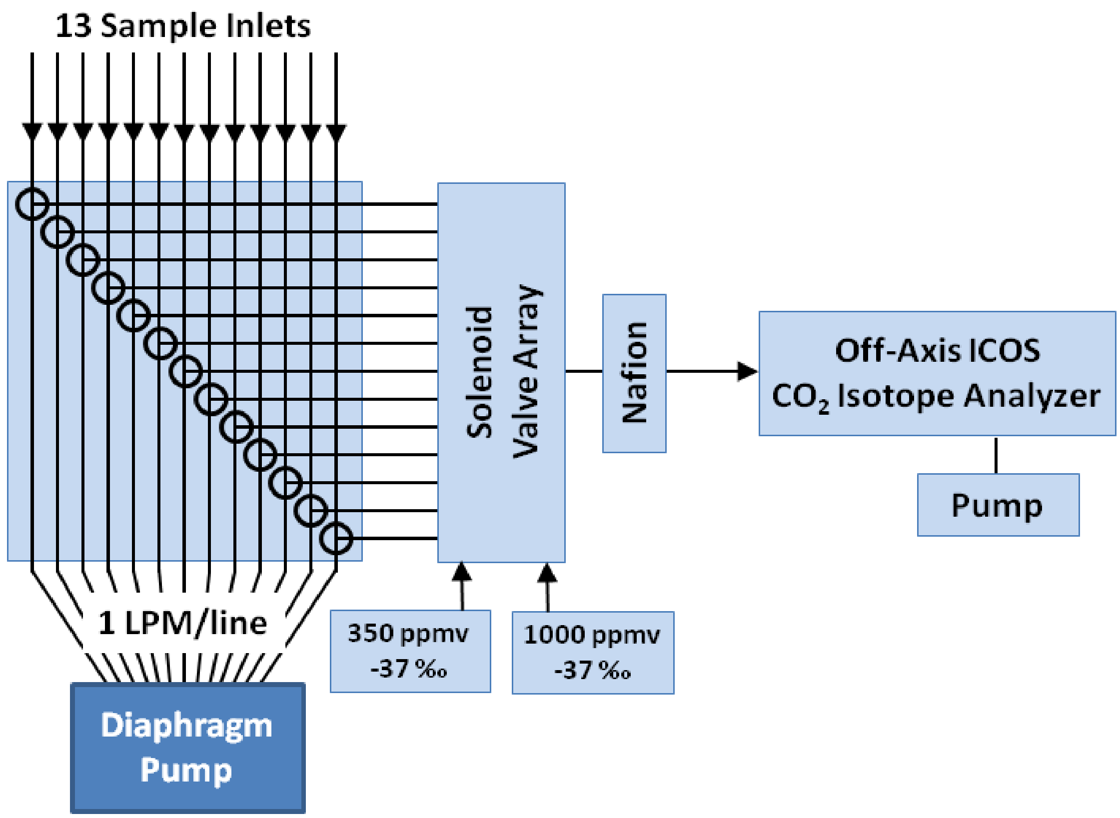


Figure 33. Schematic layout of the Multiport Input Unit (denoted MIU on figure) used to sample several inlet lines to the Carbon Dioxide Isotope Analyzer (denoted CCIA on figure) at ZERT (and to the Fast Acetylene and Methane Analyzer at the Altamont Landfill site).

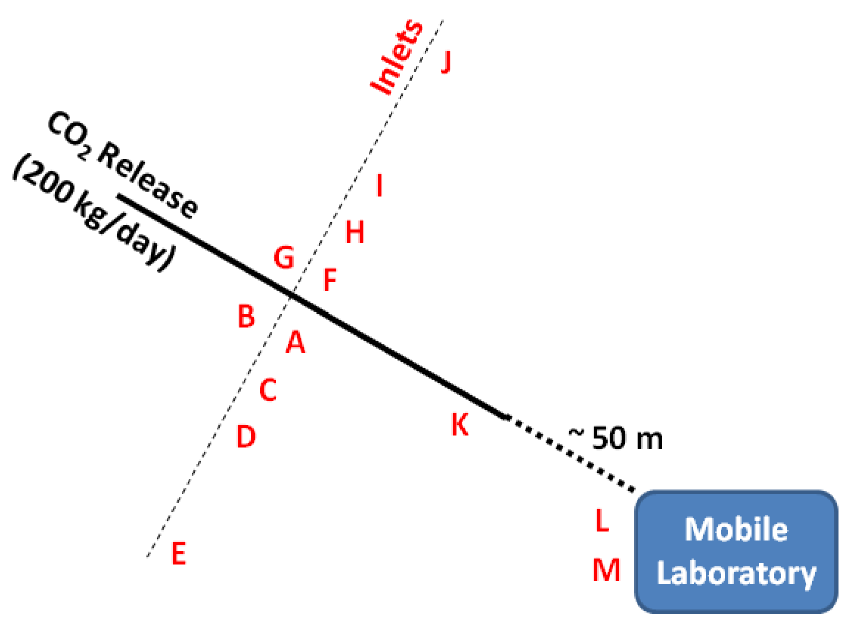


Figure 34. Schematic layout of the various measurement locations sampled automatically using LGR's Carbon Dioxide Isotope Analyzer and Multiport Input Unit at ZERT.

Figure 35. Carbon Dioxide Isotope Analyzer, Inlet manifold, and Multiport Input Unit (MIU) used to sample from multiple inlets automatically using a single analyzer.

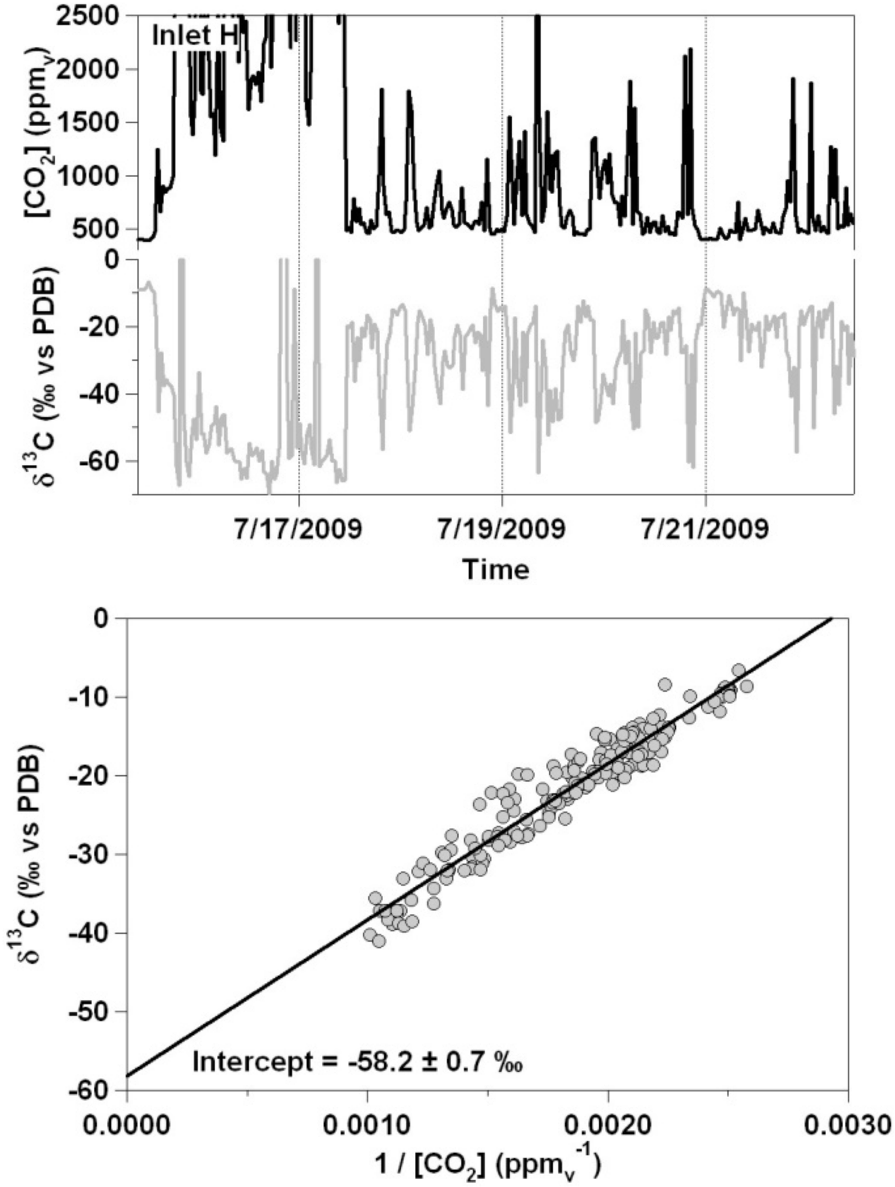


Figure 36. Measurements of carbon dioxide and $\delta^{13}C$ near the ZERT leak point demonstrating the ability to record real-time Keeling plots in the field. The intercept yields the isotopically depleted value (-58‰) of the source CO_2 released at ZERT.

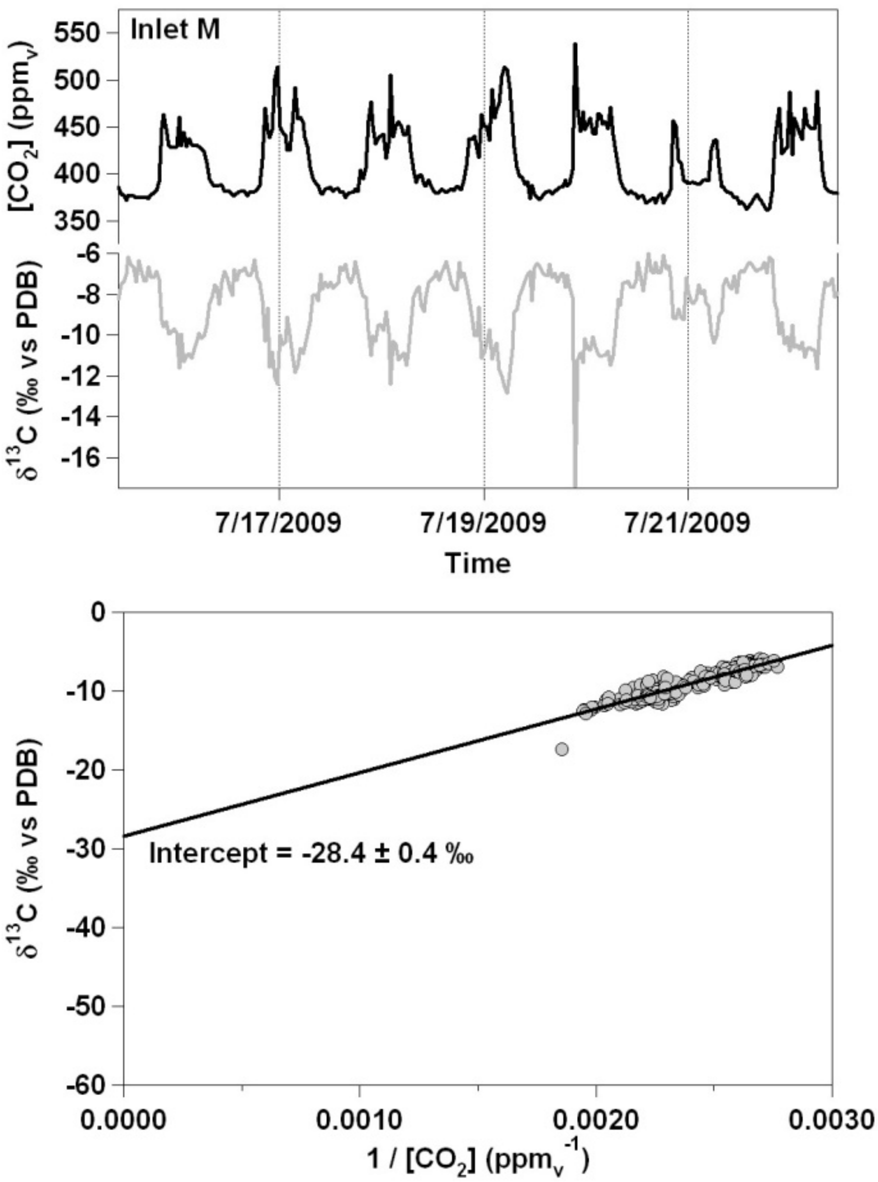


Figure 37. Measurements of Carbon Dioxide and $\delta^{13}C$ far from the leak point demonstrating the ability to record real-time Keeling plots in the field due to plant respiration. The intercept yields the isotopic value (-28‰) of the C3 plants.

Deploy Mobile Emissions Lab at Landfill Sites

Deployment at Landfill Site

On 19-22 October 2009, LGR deployed the Mobile Emissions Laboratory that included LGR's Fast Acetylene and Methane Analyzer (FAMA) at the Altamont landfill site (10840 Altamont Pass Rd, Livermore, CA). The deployment, in collaboration with researchers from the California Air Resources Board, characterized the magnitude and variations of methane fugitive emissions and of acetylene tracers due to an intentional (plume) release. Photographs of the deployment are shown below.

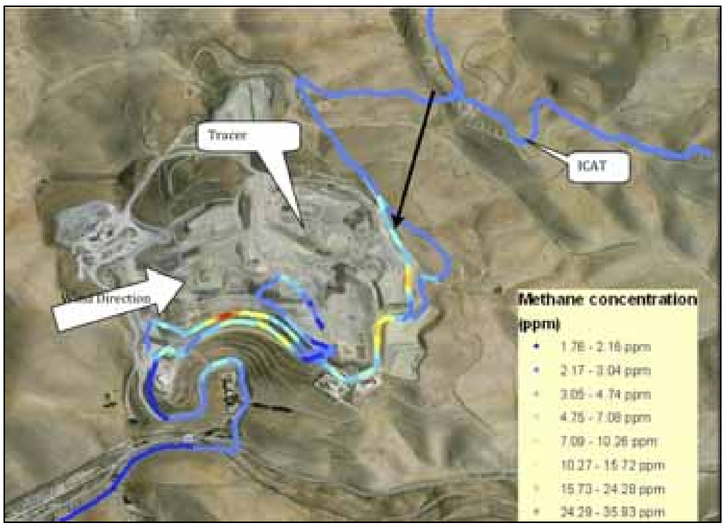


Figure 38. Mobile Emissions Laboratory deployment at the Altamont Landfill site to characterize fugitive methane emissions and quantify the flux of acetylene tracers.

Measurements of acetylene (C_2H_2) and methane (CH_4) (shown in the figures below) indicate the ability of the Fast Acetylene and Methane Analyzer (FAMA) to record precise measurements of C_2H_2 (natural abundance and as a tracer) and CH_4 quickly and with extremely high precision. The FAMA was located in the Mobile Emissions Laboratory and, in conjunction with LGR's MIU, was used to sample the two gases from multiple locations continuously over three days using only on-board battery power contained in the Mobile Emissions Laboratory. The FAMA automatically sampled ambient air using a pair of Teflon inlet lines spaced 100 feet apart. Measurements from each location were recorded alternately every 2-3 minutes at a rate of 2 seconds per data point.

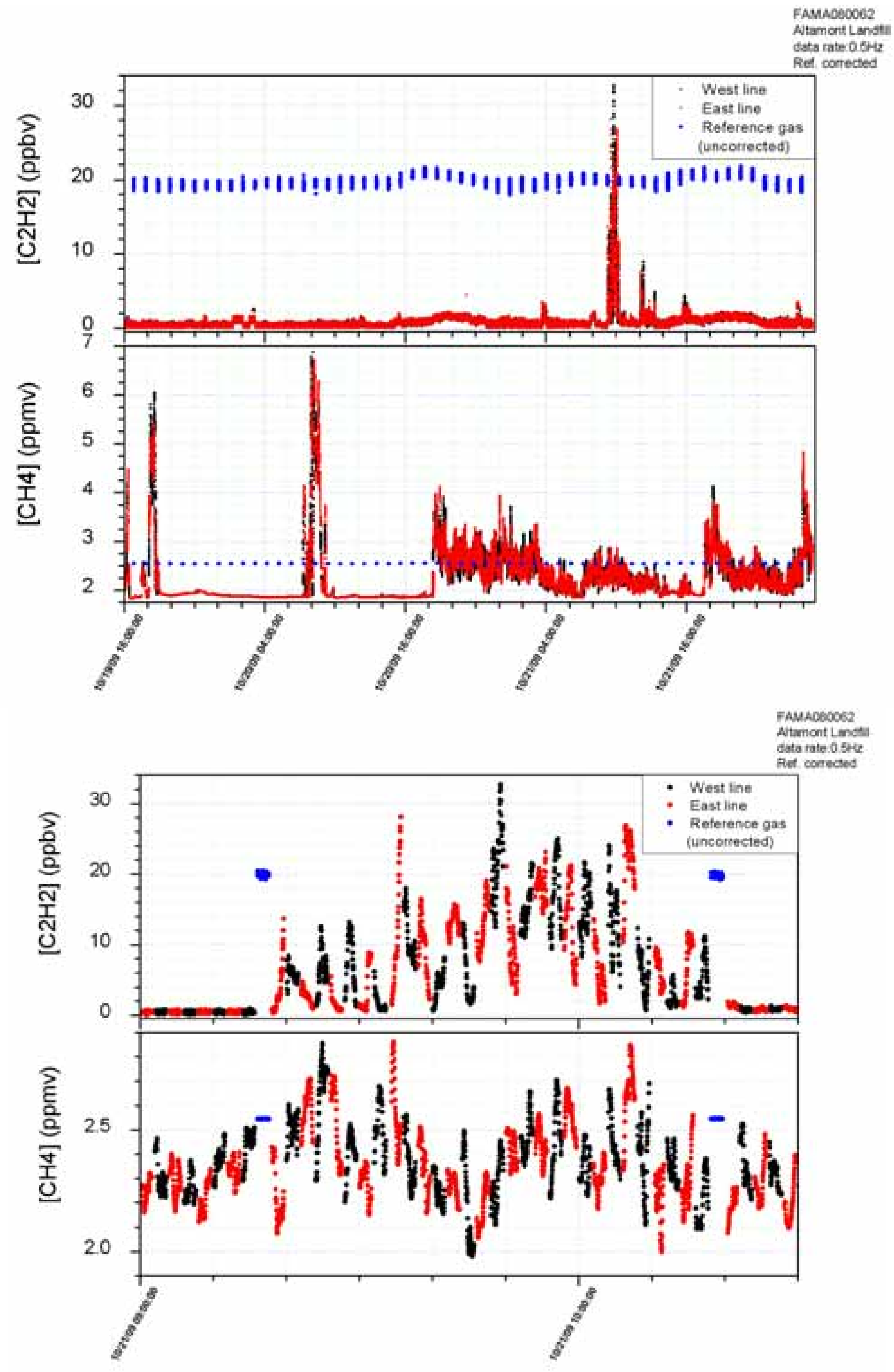
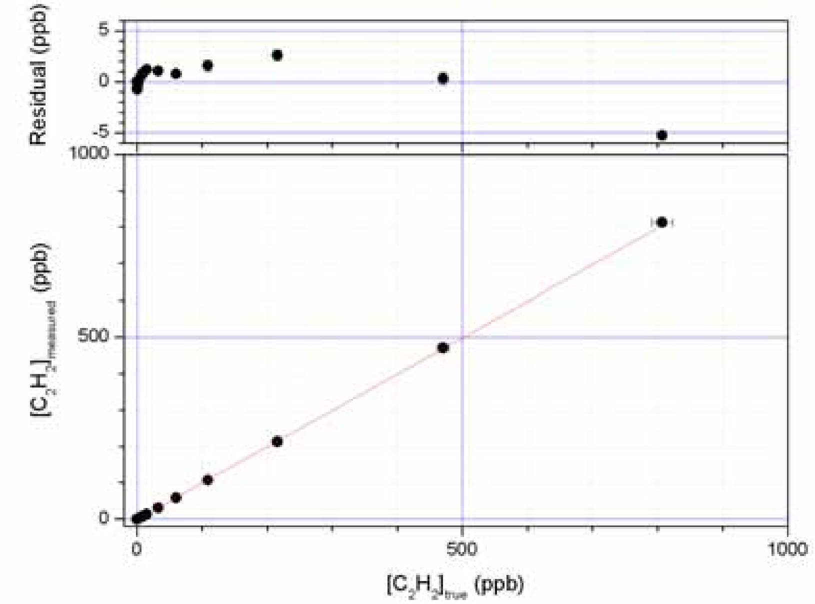
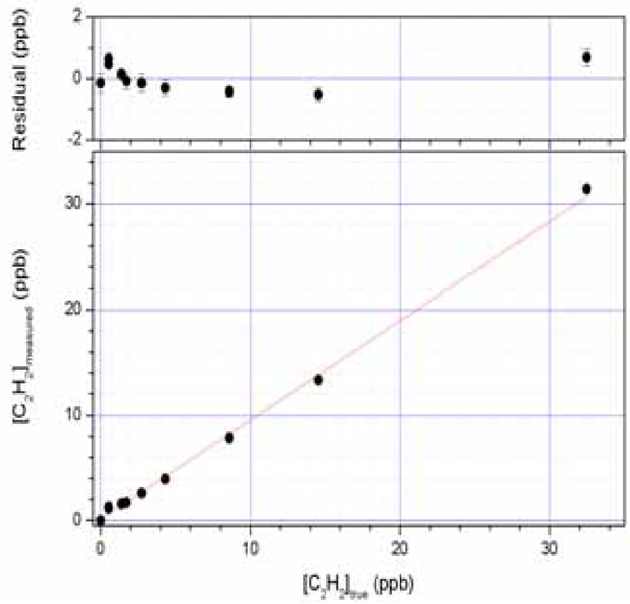


Figure 39. Measurements of methane and acetylene (as a tracer) recorded from two locations (East line, West line) 100 feet apart using LGR's Fast Acetylene and Methane Analyzer (FAMA) and LGR's Multiport Input Unit. Two locations were sampled to demonstrate the ability to record ambient air from multiple locations automatically using a single analyzer.



Residual (ppb)
5
0
-5
1000
500
0
$[C_2H_2]_{measured}$ (ppb)
0
500
1000
$[C_2H_2]_{true}$ (ppb)



Residual (ppb)
2
0
-2
30
20
10
0
$[C_2H_2]_{measured}$ (ppb)
0
10
20
30
$[C_2H_2]_{true}$ (ppb)

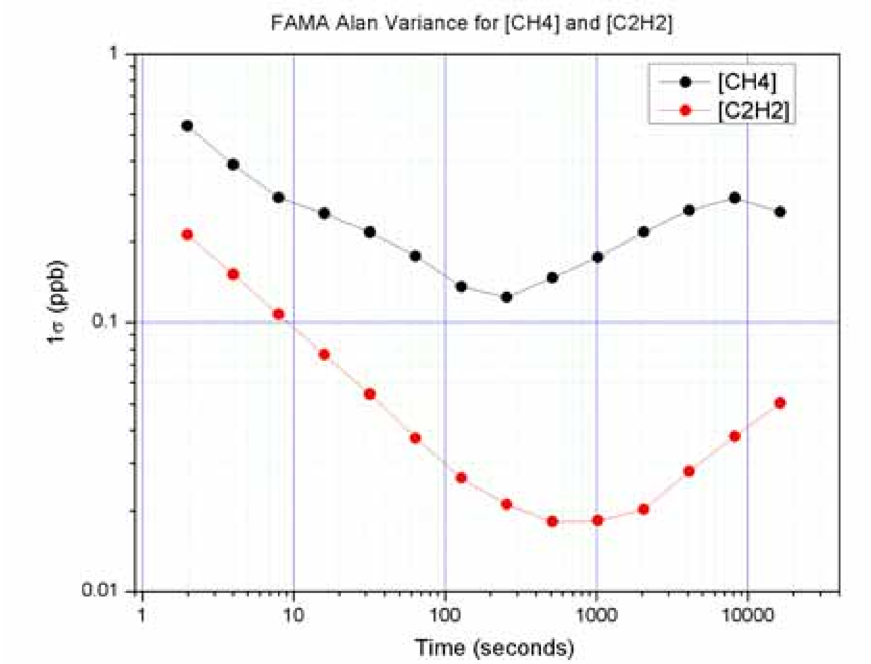


Figure 40. Performance plots for the novel Fast Acetylene and Methane Analyzer (FAMA) for measurements of methane and acetylene simultaneously during landfill tracer releases. The linearity plots (top, middle) show the FAMA provides ppbv-level sensitivity over an extremely wide range of acetylene concentrations. The Allan Variance (bottom) plot shows the ability to record fast, sensitive measurements with high precision (σ_{CH4} = 0.6 ppbv and σ_{C2H2} = 0.2 ppbv in 2 seconds measurement time) as well as stable measurements over long averaging intervals. Note that the FAMA has sufficient sensitivity (better than 0.1 ppbv in a 10 seconds measurement time) to reliably record ambient levels of acetylene in ambient air. Higher precision may be recorded with longer averaging times.

Results and Conclusions

Los Gatos Research developed and deployed a novel Mobile Emissions Laboratory for measurements at several urban, rural, and landfill sites in California, under the support of the California Air Resources Board. LGR's Mobile Emissions Laboratory is capable of simultaneous and continuous measurements, during stationary operation and while moving, of several important gas species including, but not limited to, methane (CH_4), carbon dioxide (CO_2), nitrous oxide (N_2O), carbon monoxide (CO), water vapor (H_2O), acetylene (C_2H_2), and the stable isotope ratios in carbon dioxide ($\delta^{13}CO_2$) and water vapor (δ^2H, $\delta^{18}O$). On-board batteries (18 kWh) allow the LGR Mobile Emissions Laboratory to operate without external power for extended periods (e.g., 3-8 days, exact number depends on electrical load), if desired. As a result, the Mobile Emissions Laboratory enables detailed measurements and long-term monitoring of mobile and fixed-location (fugitive) emissions and pollutant sources with high accuracy, precision and sensitivity in real time. These measurements will provide the ability of regulatory agencies, monitoring stations, scientists and researchers to report temporally and spatially resolved data (measurements of important greenhouse gases and pollutants) necessary for compliance monitoring, as well as cap and trade, at practically any location.

Status of the Technology

Following the success of the present grant, Los Gatos Research has begun to commercialize the technology (Mobile Emissions Lab) described in this report as an accessory to our leading-edge product line of high accuracy analyzers (www.LGRinc.com). In addition to the Mobile Emissions Lab and associated technology developed in this project, LGR now offers, as a service to government, industry and university groups, real-time measurements of all important greenhouse gases and pollutants at any location for extended duration for applications including compliance monitoring, cap and trade, and pollutant credit accounting.