Development and Deployment of MVA Tools

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Developing the Technologies and Building the Infrastructure for CO_2 Storage

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Presentation Outline

- Benefit to the Program
- Project Overview
- Technical Status
  - Frequency Modulated Spectroscopy (FMS)
  - $\Delta O_2/\Delta CO_2$ Ratio
  - Quantitative Seismic Monitoring
- Accomplishments
- Summary
- Appendix

Benefit to the Program

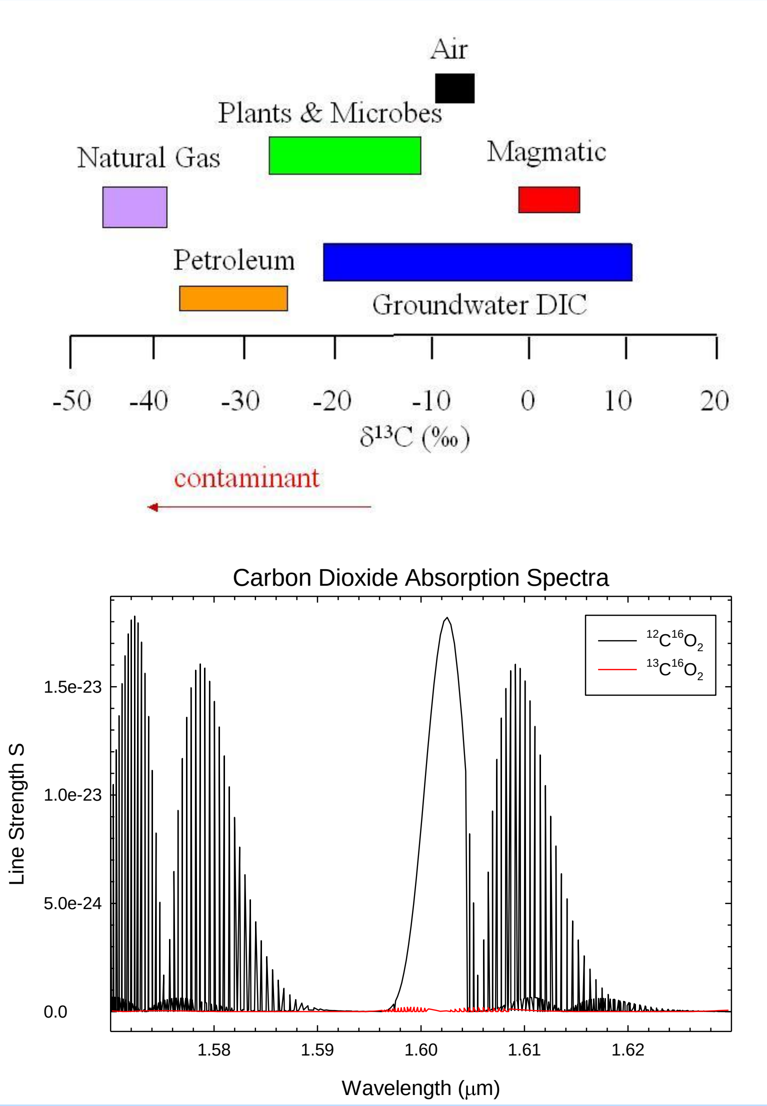
- Carbon Storage Program Major Goals
  1. Develop technologies that will support industries' ability to predict CO_2 storage capacity in geologic formations to within ±30 percent.
  2. Develop technologies to demonstrate that 99 percent of injected CO_2 remains in the injection zones.
  3. Conduct field tests through 2030 to support the development of BPMs for site selection, characterization, site operations, and closure practices.
- Project Benefits Statement.
  - The Project Goals were designed to directly meet the program major goals through Monitoring, Verification, and Accounting (MVA) technology development including; 1. Advanced Seismic Subsurface Imaging; 2. Surface seepage detection by Frequency Modulated Spectroscopy and O2/CO2 Ratios; and 3. four field experiments per year.

Project Overview: Goals and Objectives

- Surface MVA Monitoring
  - Distinguish Natural and Anthropogenic CO2 Sources
  - Stable Isotope Detection by Frequency Modulated Spectroscopy
  - $\Delta O2/\Delta CO2$ Ratio
  - Field Demonstration of the Instruments
- Subsurface Monitoring
  - Quantitative Seismic Monitoring
  - Identification of Fractures and Seepage Pathways
  - Design Seismic Field Experiments
  - Techniques will be employed by the Big Sky Partnership

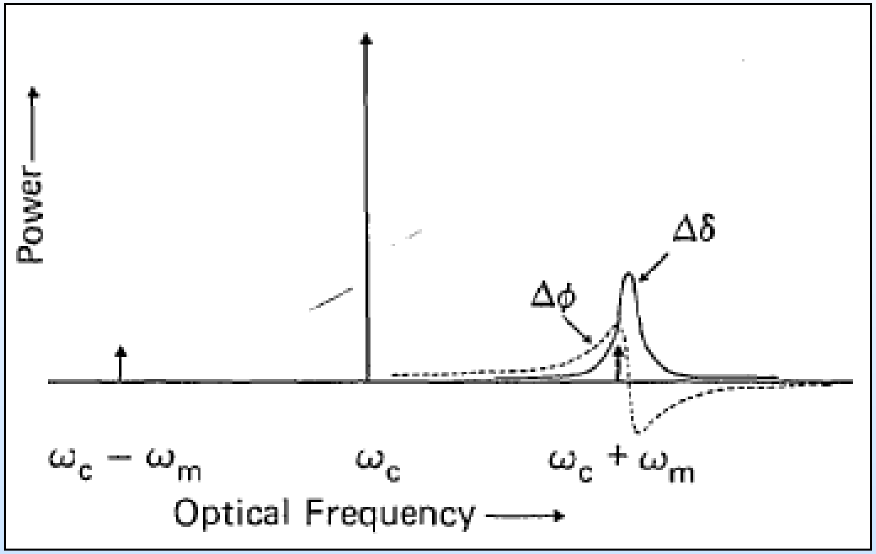
Frequency Modulated Spectroscopy (FMS)

- **Detect CO_2 Seepage**
  - At Natural CO_2 Emissions
- **Generally, the Atmosphere Contains**
  - 98.9% $^{12}C^{16}O_2$
  - 1.1% $^{13}C^{16}O_2$
- **Absorption Spectroscopy**
  - Maximum Line Strength (HITRAN)
  - $^{12}C^{16}O_2$ = 1.83x10-23
  - $^{13}C^{16}O_2$ = 2.10x10-25
- **Frequency Modulated Spectroscopy**
  - 100x to 1000x more sensitive than absorption spectroscopy

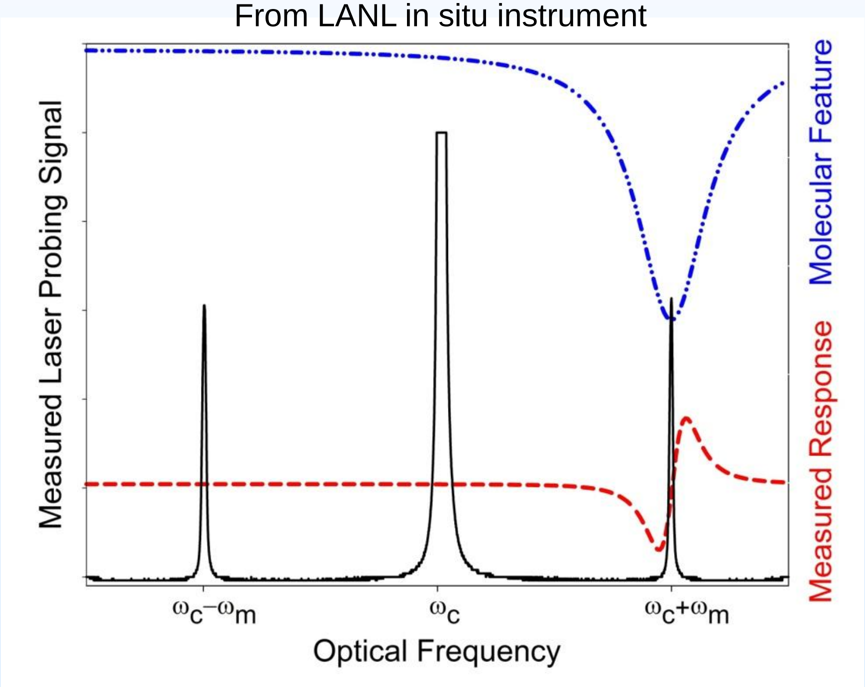


Fundamental Frequency Modulated Spectroscopy

From G.C. Bjorklund Optics Letters, 5, 15, 1980

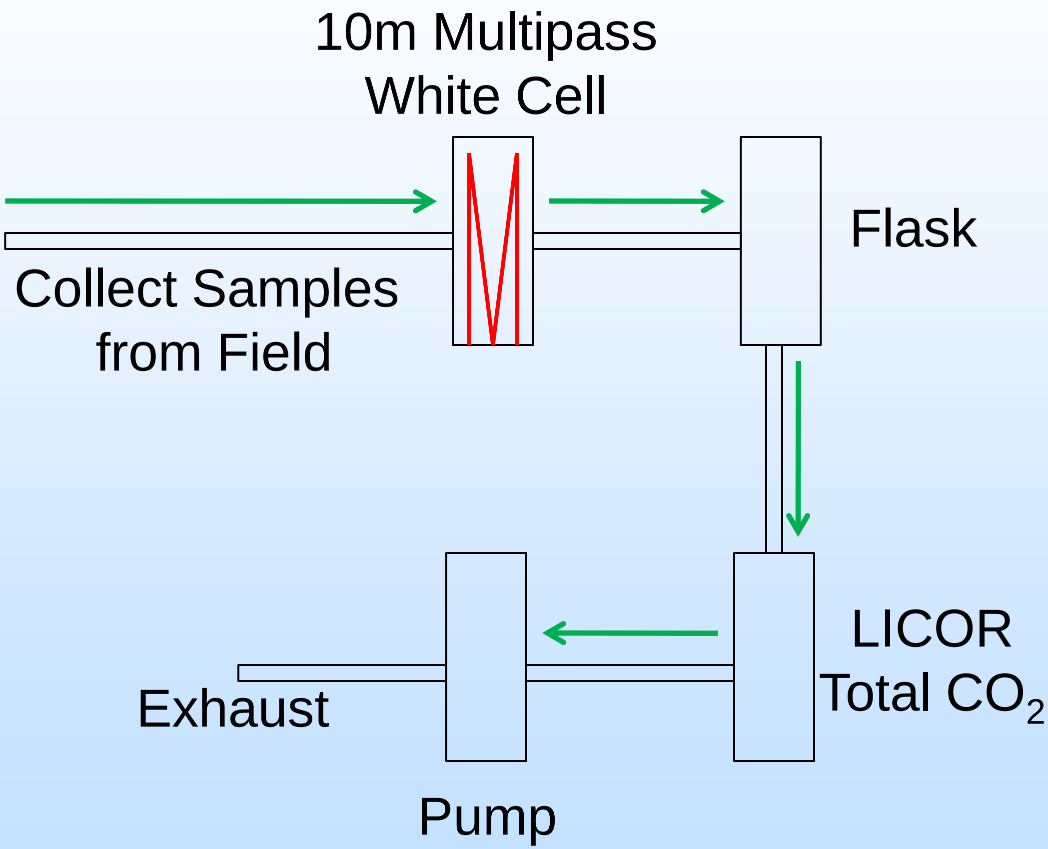


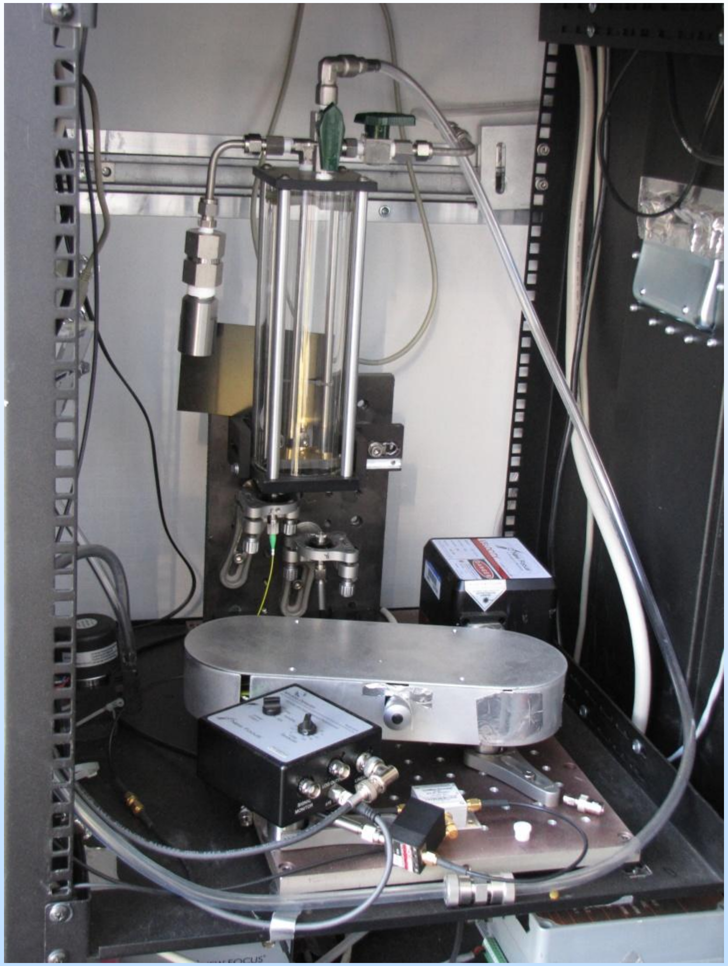
From LANL in situ instrument



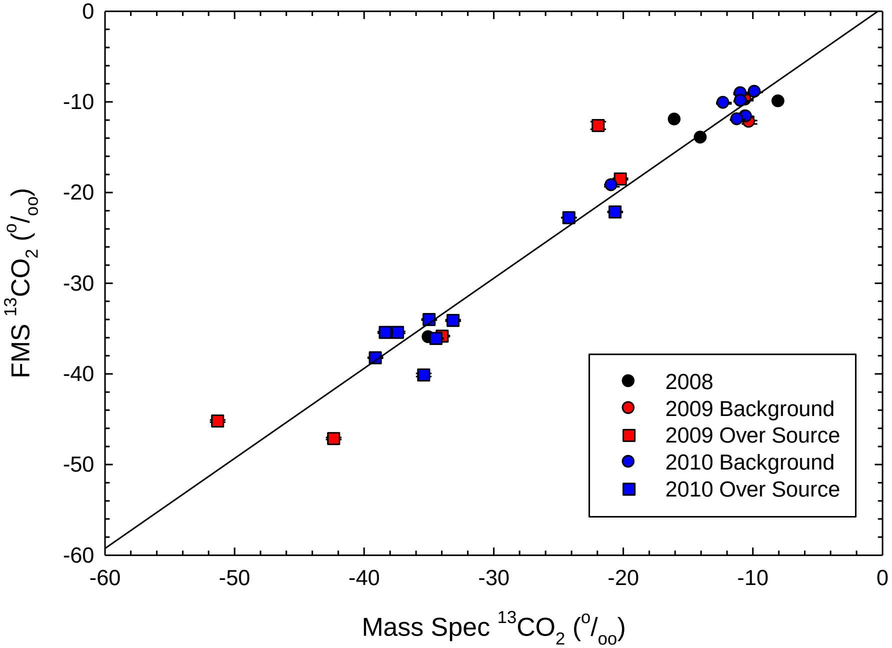
ω_c = 1607 nm
ω_m = ±2 GHz

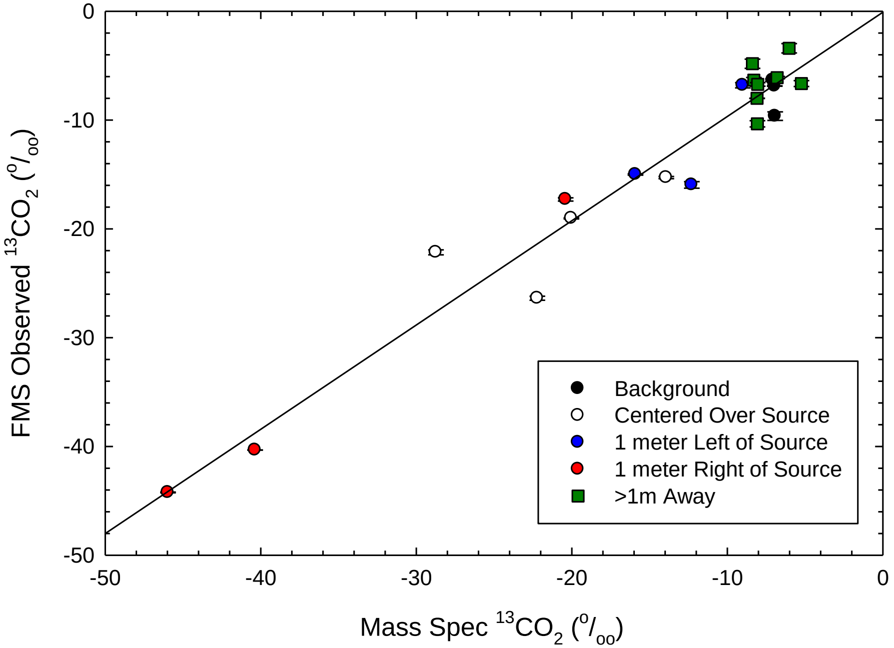
In Situ FMS Instrument Development





In Situ Observations

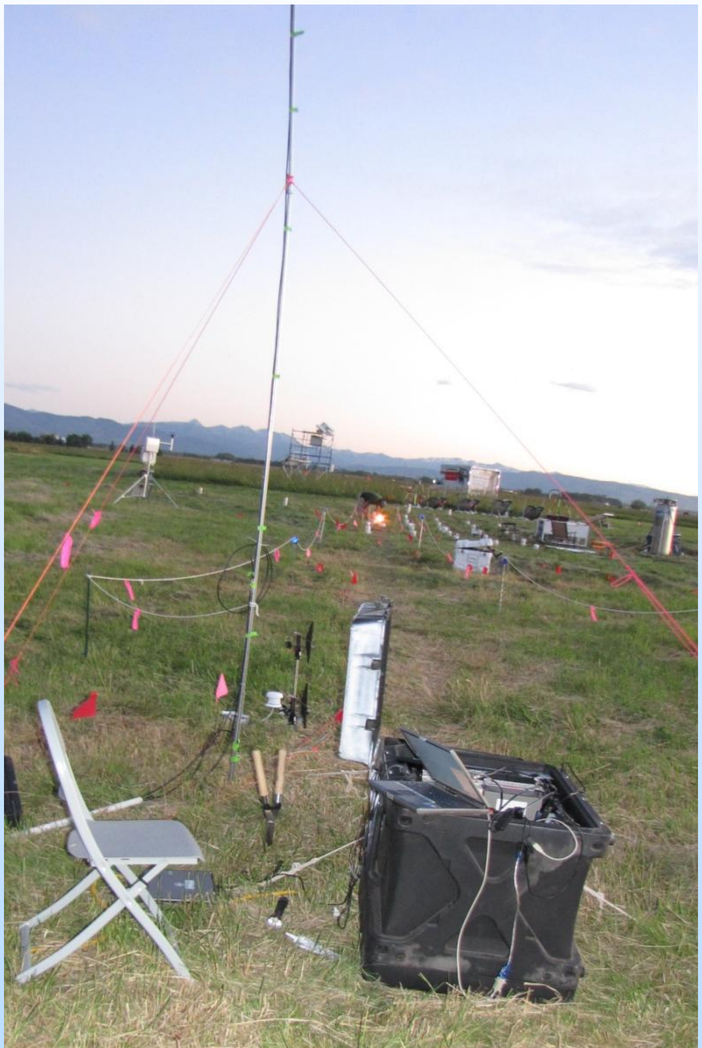


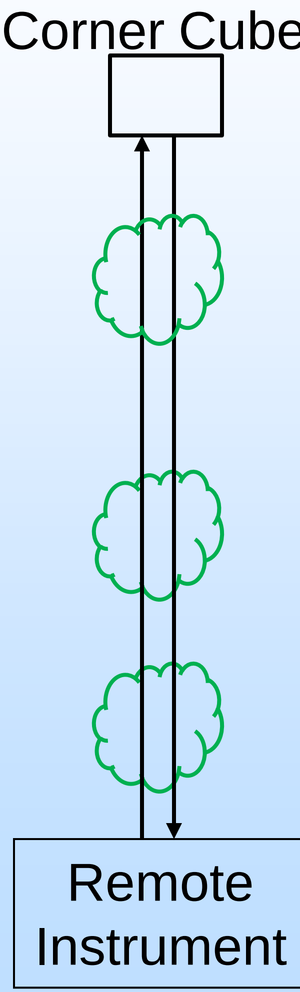


- **Background = -8 to -11$^o/_{oo}$**
- **Seepage < -15$^o/_{oo}$**

- **Background = -4 to -7$^o/_{oo}$**
- **Over Source ~ -20$^o/_{oo}$**
- **1m Away ~ -15 to -46$^o/_{oo}$**
- **>1m Away = -4 to -7$^o/_{oo}$**

Remote Instrument Development





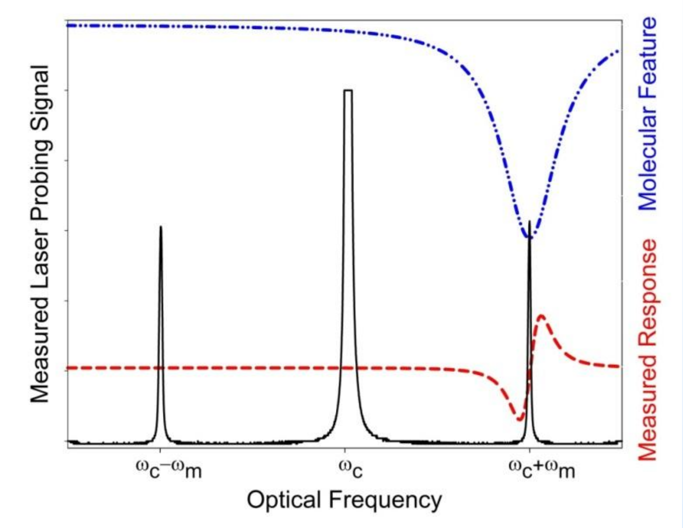
At ZERT,

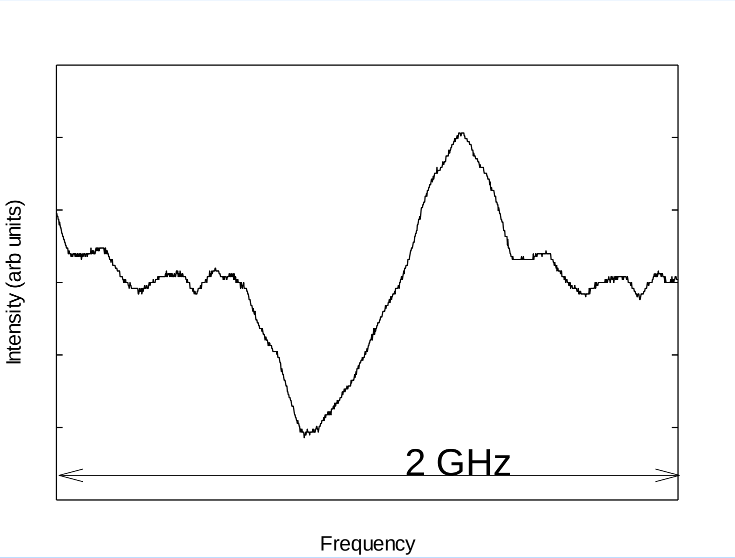
2010: $\delta^{13}C \sim -9 – -28\ ^{o}/_{oo}$

2011: $\delta^{13}C \sim -6 – -28\ ^{o}/_{oo}$

FM-LIDAR

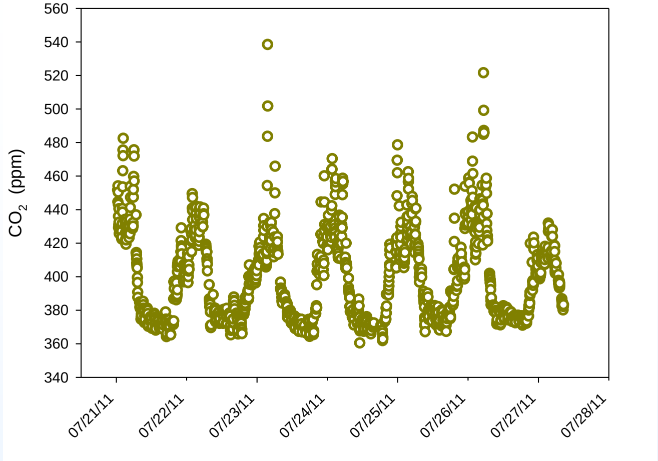
- Direct a CW Laser Across Sequestration Site
- 10ns Modulator Pulse
- Record Time Resolved Return Signal
- Convert Time to Distance

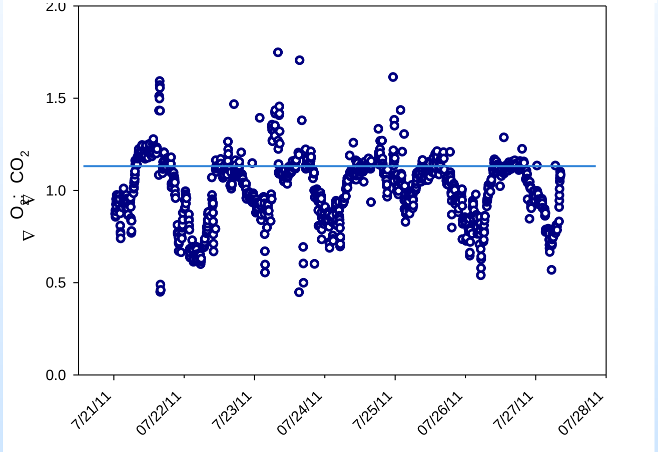




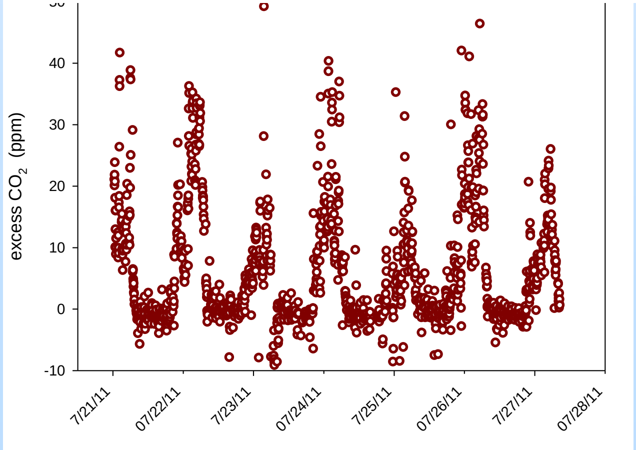
$\Delta O_2/\Delta CO_2$ Ratio

accumulation of CO_2 in the boundary layer. Attributing this CO_2 to plant and soil respiration vs. industrial sources is essentially impossible with CO_2 measurements alone.





Deviation of ΔO_2:ΔCO_2 from the nominal value of 1.1 along with the known value of CO_2 concentration allows calculation of the amount of excess CO_2 not attributable to natural sources…

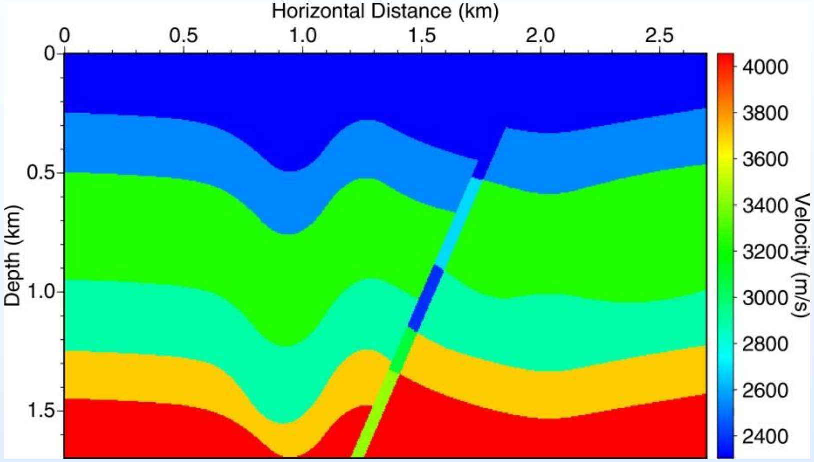


Quantitative Seismic Monitoring

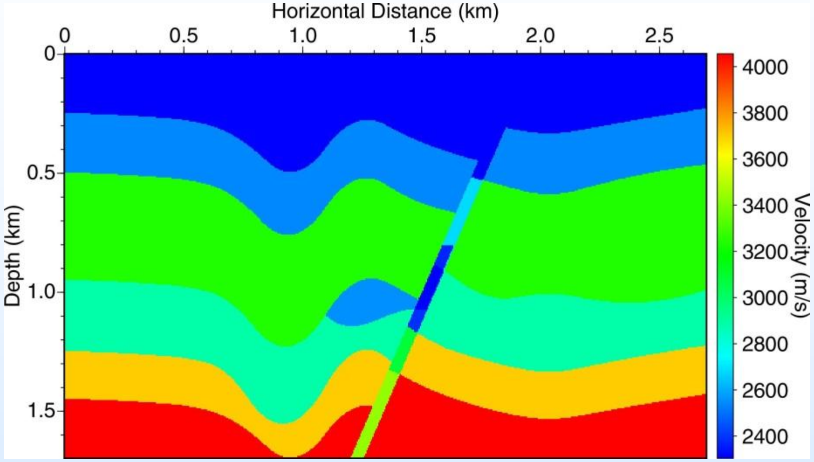
- Developed and implemented a double-difference waveform inversion method with a total-variation regularization scheme.
- Improved our double-difference waveform inversion method with a modified total-variation regularization scheme.
- Developed and implemented a wave-energy-weighted double-difference waveform inversion method.
- Studied the capability for quantifying reservoir changes caused by CO2 injection using time-lapse seismic data acquired with an optimally designed sparse array.
- Will investigate the field applicability of double-difference waveform inversion for quantitative seismic monitoring.

- Methods transitioned to the Big Sky Regional Partnership!

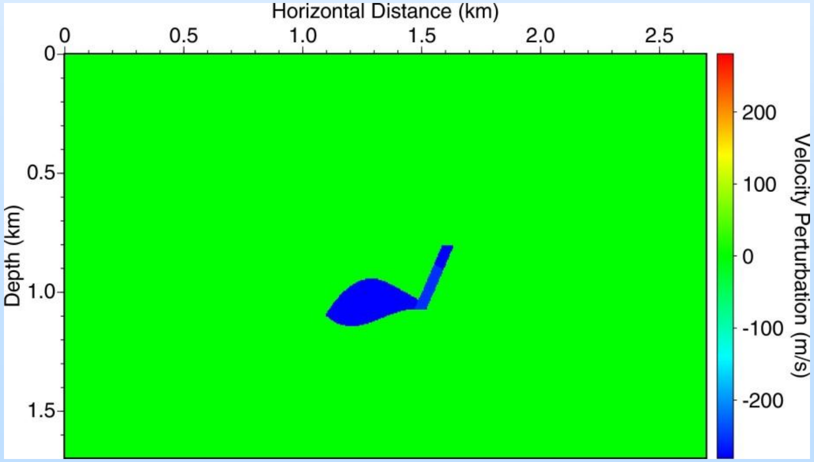
Time-Lapse Model with CO2 Leakage Through a Fault Zone



Initial Model

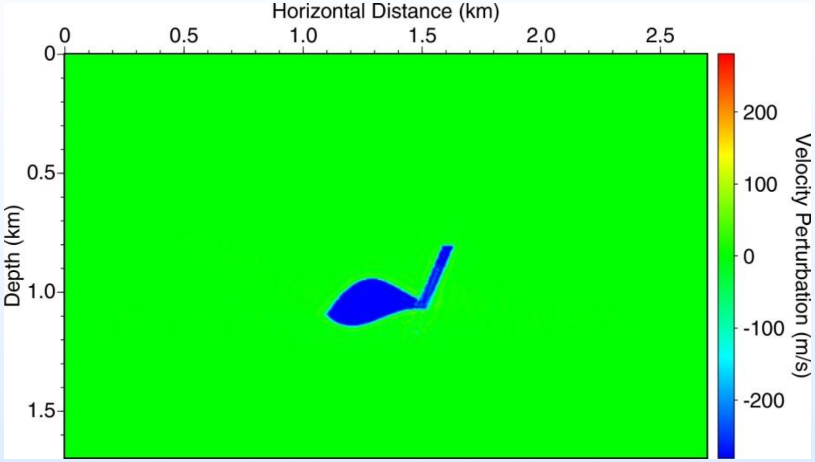


Time-Lapse Model

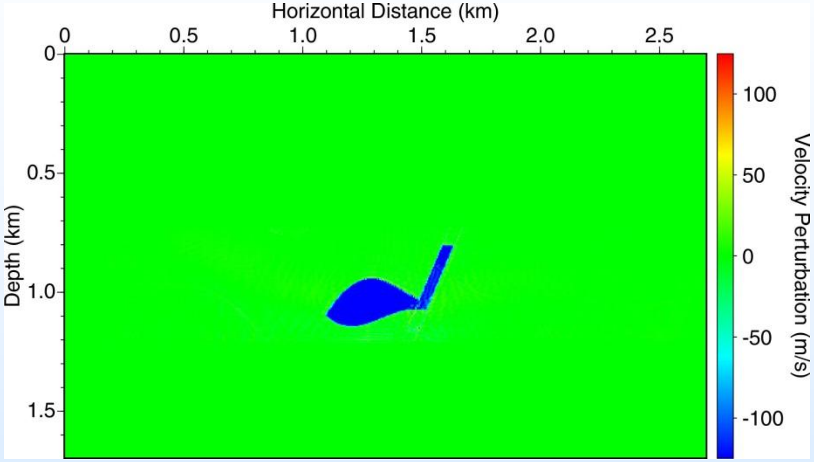


Time-Lapse Change

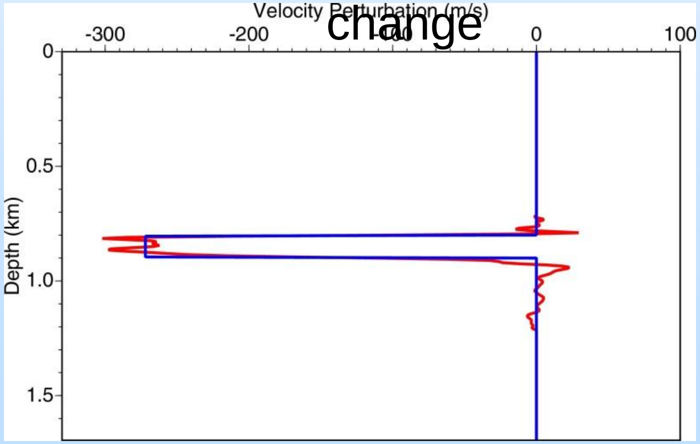
Inversion Results of Time-Lapse Changes Using Sparse-Array Data



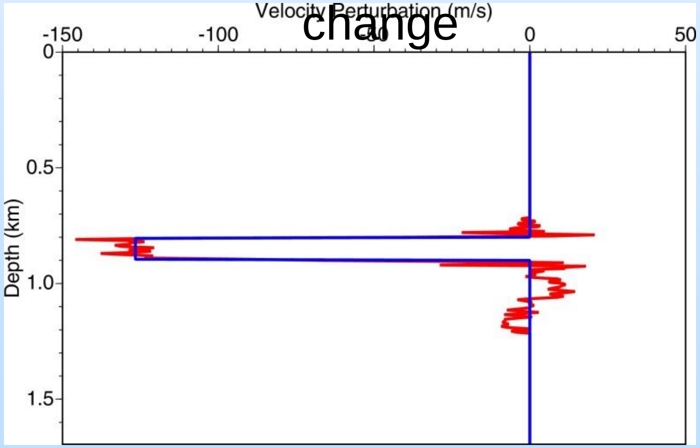
Inversion result of P-wave velocity change



Inversion result of S-wave velocity change



Vertical profile of ΔVp along the fault zone (Red: inversion)



Vertical profile of ΔVs along the fault zone (Red: inversion)

Accomplishments

- Surface Diagnostics
  - In Situ FMS Instrument Development
  - Remote FMS Instrument Development
  - LIDAR FMS Instrument Development
  - O_2/CO_2 Instrument Development
- Field Demonstration of the Instruments
- Advanced Seismic Monitoring

Summary

- Surface Measurements
  - FMS and $\Delta O_2/\Delta CO_2$ Instruments are sensitive indications of natural vs. anthropogenic sources of CO_2
- Subsurface Seismic Imaging
  - Quantitative Imaging of the Seismic Plume and potential fractures.

Summary

- Lessons Learned
  - Field Work is Critical. We learned a great deal every time we deploy the instruments.
- Future Plans
  - Extend FMS to Detect $H_2{}^{34/32}S$ (1.58 µm) and ${}^{13/12}CH_4$ (1.65 µm) to indicate seepage from EOR site
  - Subsurface Fiber Optical MVA System
  - Field Demonstrations of New Technologies
  - Quantitative EOR Seismic Monitoring

Gratefully acknowledge NETL for funding this work.

The ZERT Program for Providing the Field Location and Accommodating Our Experiments

Appendix

Organization Chart

- Frequency Modulated Spectroscopy (FMS)
  - Sam Clegg – FMS Development Lead
  - Julianna Fessenden – Stable Isotope Geochemist
  - Rhonda McInroy – Technician
- $\Delta O_2/\Delta CO_2$
  - Thom Rahn – $\Delta O_2/\Delta CO_2$ Instrument Development Lead
- Advanced Seismic Imaging
  - Lianjie Huang - Advanced Seismic Imaging Lead
- Field Work Coordination
  - Thom Rahn
  - Julianna Fessenden

Recent Publications & Presentations

- 2012
  - Shang, X. and Huang, L., "Optimal designs of time-lapse seismic surveys for monitoring CO_2 leakage through fault zones," 2012, vol.10, 419-433.
  - Zhang, Z., Huang, L., and Lin, Y., "A wave-energy-based precondition approach to full-waveform inversion in the time domain," Accepted to present at 2012 SEG Annual Meeting.
  - Carbon Dioxide Monitoring, Verification and Accounting (MVA) by Carbon Stable Isotope Measurements, Samuel Clegg et al, CCUS #409
  - High Precision O_2 Measurements as a Monitoring Tool for CO_2 Sequestration Integrity, Thom Rahn et al. CCUS #378
  - Zhang, Z., and Huang, L., "Quantitative seismic monitoring for carbon sequestration using sparse-array data," 2012 CCUS Annual Conference.
- 2011
  - Lianjie Huang organized and chaired a Special Session on CO_2 Geophysical Monitoring at 2011 AGU Fall Meeting held in San Francisco, California, on December 5-9, 2011. A total of 7 oral presentations and 24 posters were given. Both oral and poster sessions were well attended.
  - Sam Clegg presented an invited paper at the 2011 Fall AGU Meeting on the ZERT field work.
  - Thom Rahn and Anna Trugman presented a paper at the 2011 Fall AGU Meeting on the ZERT field work.
  - Lin, Y., Zhang, Z., and Huang, L., "Spatially-variant Tikhonov regulization for double-difference waveform inversion," 2011 CCS Annual Conference.
  - Zhang, Z., Lin, Y., and Huang, L., "A Gauss-Newton-Krylov method for double-difference waveform tomography," 2011 CCS Annual Conference.
  - Yang, D., Fehler, M., Malcolm, A., and Huang, L., "Quantitative monitoring of CO_2 injection using double-difference waveform inversion: Application to time-lapse walkaway VSP data from SACROC," 2011 CCS Annual Conference.
  - Shang, X. and Huang, L., "Optimal designs of time-lapse seismic surveys for monitoring CO_2 leakage through fault zones," 2011 CCS Annual Conference.
  - Zhang, Z., Lin, Y., and Huang, L., "Full-waveform inversion in the time domain with an energy-weighted gradient," 2011 SEG Annual Meeting, Expanded Abstracts.
  - Yang, D., Fehler, M., Malcolm, A., and Huang, L., "Carbon sequestration monitoring with acoustic double-difference waveform inversion: A case study on SACROC walkaway VSP data," 2011 SEG Annual Meeting, Expanded Abstracts.
  - Zhang, Z., Huang, L., and Lin, Y., "Quantitative monitoring for geologic carbon sequestration using double-difference elastic-waveform inversion," 2011 AGU Fall Meeting.