Intelligent Monitoring Systems and Advanced Well Integrity and Mitigation

Project Number DE-FE-00026517

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Archer Daniels Midland Company

U.S. Department of Energy

National Energy Technology Laboratory

Mastering the Subsurface Through Technology Innovation, Partnerships and Collaboration:
Carbon Storage and Oil and Natural Gas Technologies Review Meeting

August 14, 2018

Presentation Outline

- Project Overview
  - Technical Status
  - Accomplishment to Date
  - Lessons Learned
  - Synergy Opportunities
- Project Summary
  - Key Finding
  - Next Steps

Technical Status

New vs. Conventional Technology

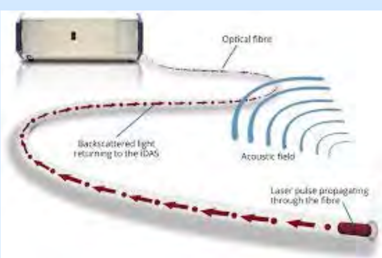
Seismic surveys are considered the backbone technique for CO_2 storage monitoring programs.

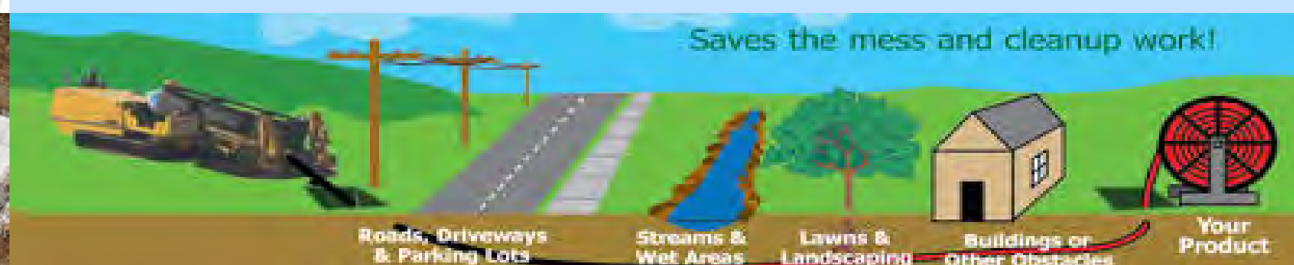
Stringing thousands of cables and running thumper trucks every few years can test the limits of good neighbors. Costs are high.

Permanent reservoir monitoring offers a way to obtain higher quality information with minimal intrusion into surrounding lands –

- DAS provides high spatial and temporal resolution.
- Installation can be in horizontal directionally drilled boreholes beneath bodies of water, existing infrastructure.
- Excitation of DAS cables can be achieved through permanent fixed rotary sources for continuous monitoring.

DAS Seismic

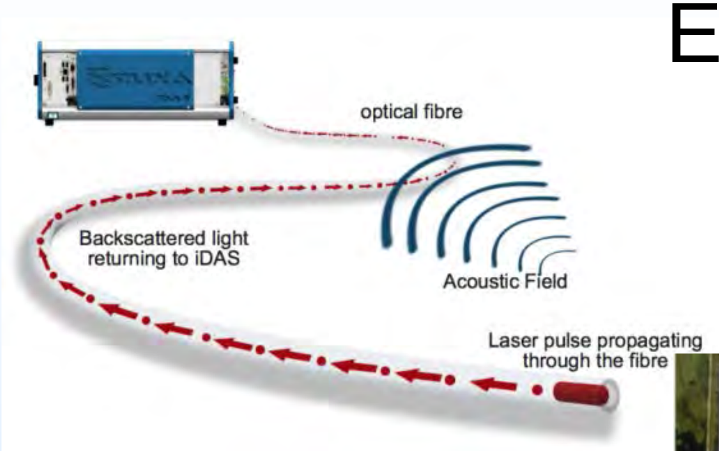


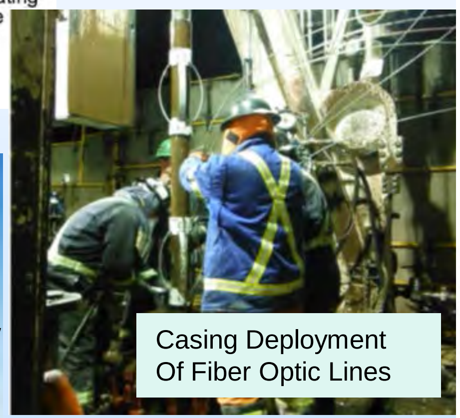


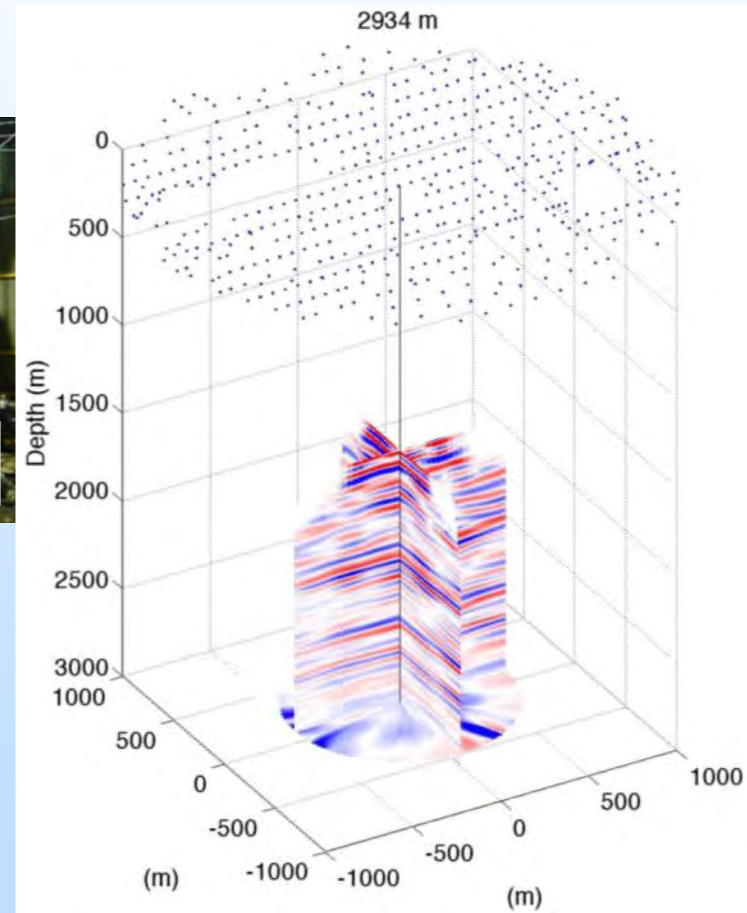
Distributed Acoustic Sensing (DAS)

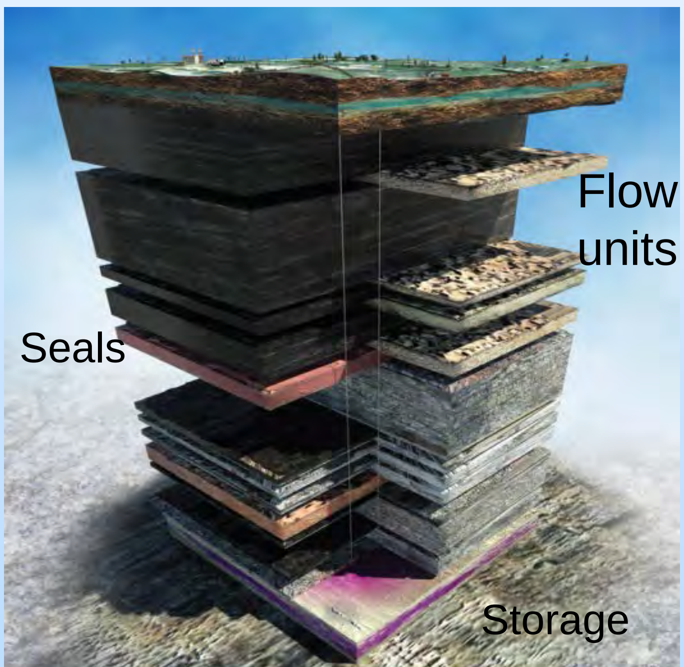
Example from PTRC Aquistore

DAS Baseline 3D-VSP





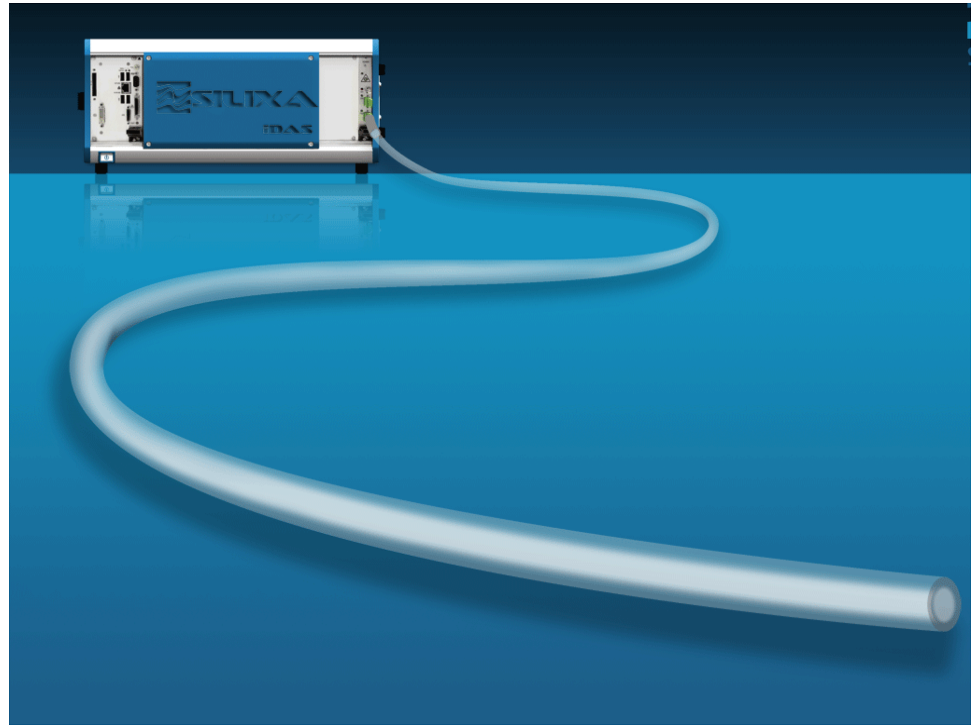


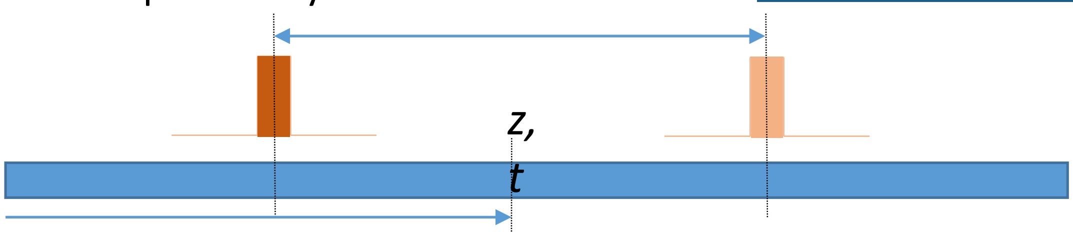


DAS VSP is becoming accepted technology.

Distributed Acoustic Sensing

- Standard optical fibre acts as the sensor array
  - Typical sampling at 10kHz on 10,000m fibre
  - Standard gauge length of 10m
  - Spatial sampling of 25cm
  - DAS measures change in average elongation per 10m gauge length per 0.1ms acoustic time sample, sampled every 0.25 m in distance

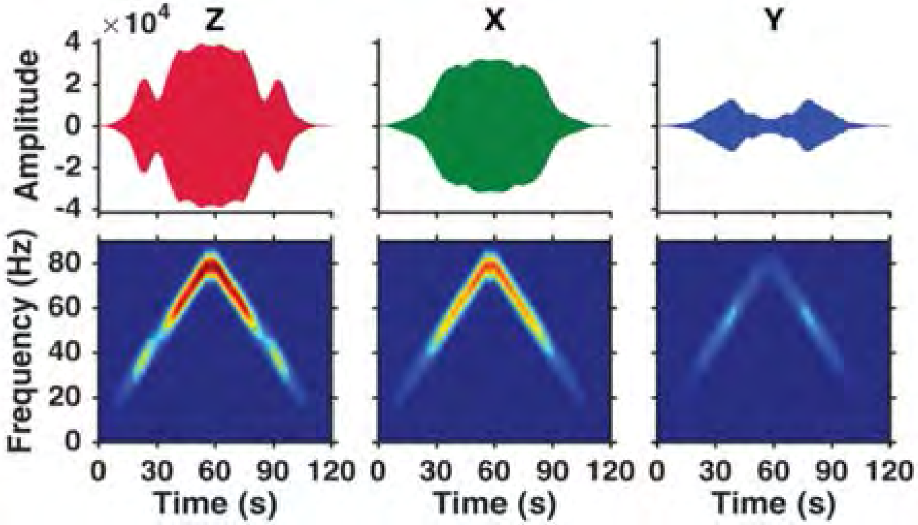




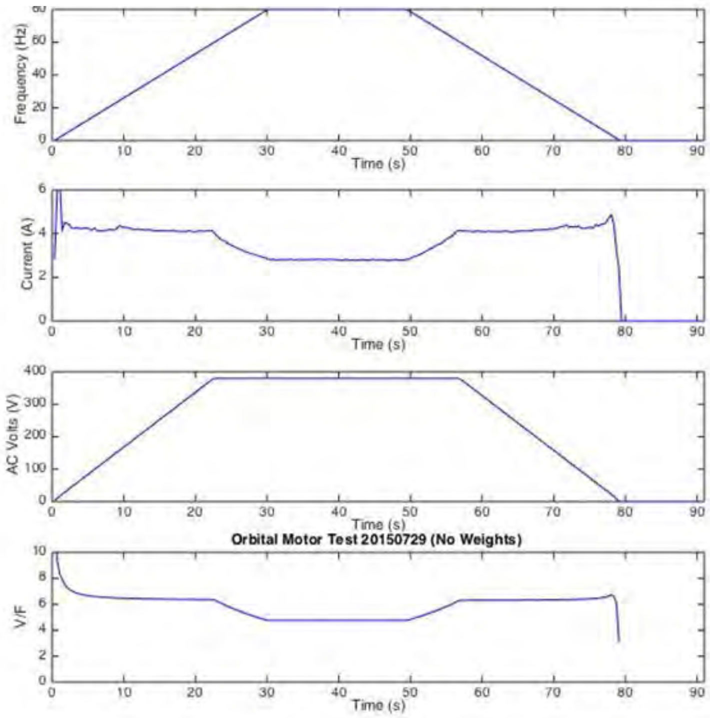
$$\left[u\left(z+\frac{dz}{2},t+dt\right)-u\left(z-\frac{dz}{2},t+dt\right)\right]-\left[u\left(z+\frac{dz}{2},t\right)-u\left(z-\frac{dz}{2},t\right)\right]$$

Parker et al., Distributed Acoustic Sensing – a new tool for seismic applications, *first break* (32), February 2014

Surface Orbital Vibrator – VFD Controlled AC Induction Motor



Max Frequency 80 Hz, Force (@80Hz) 10 T-f
Phase stability is not maintained. Operate 2.5 hr/d

Force is adjustable

$F=m\omega^2 r$

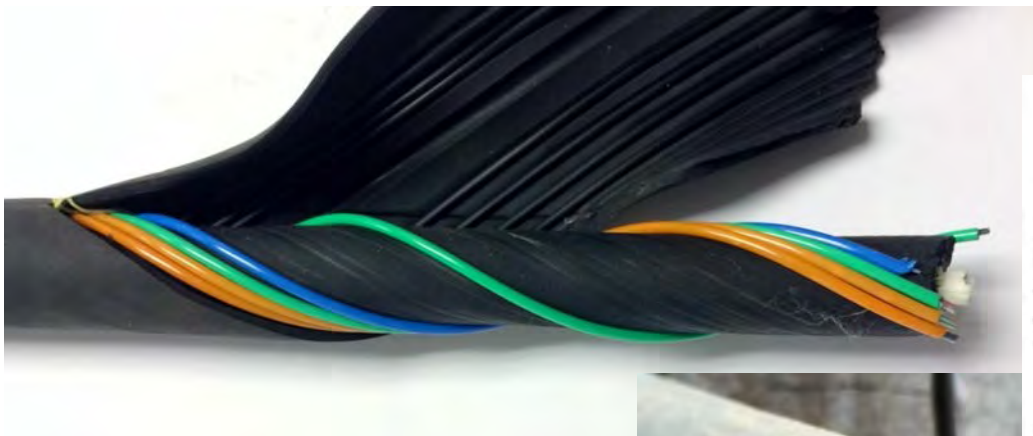
FAT Helical Wound Cable

Anderson and Shapiro – HWC on soft mandrel 1980 US Patent 4375313

Hornman et al. (2013 75th EAGE) introduced a helical wound FO cable

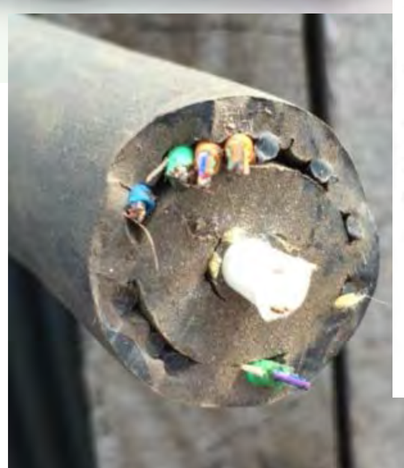
LBNL trialed multiple designs with varying physical properties

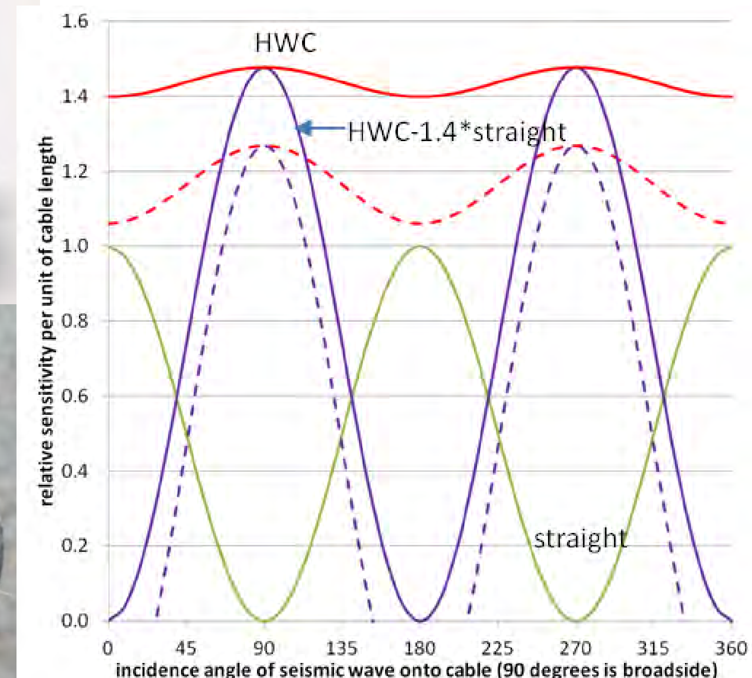
Line 5 installed one length of HWC for comparison to straight fiber



30° spiral wound on 58 Shore A rubber mandrel.

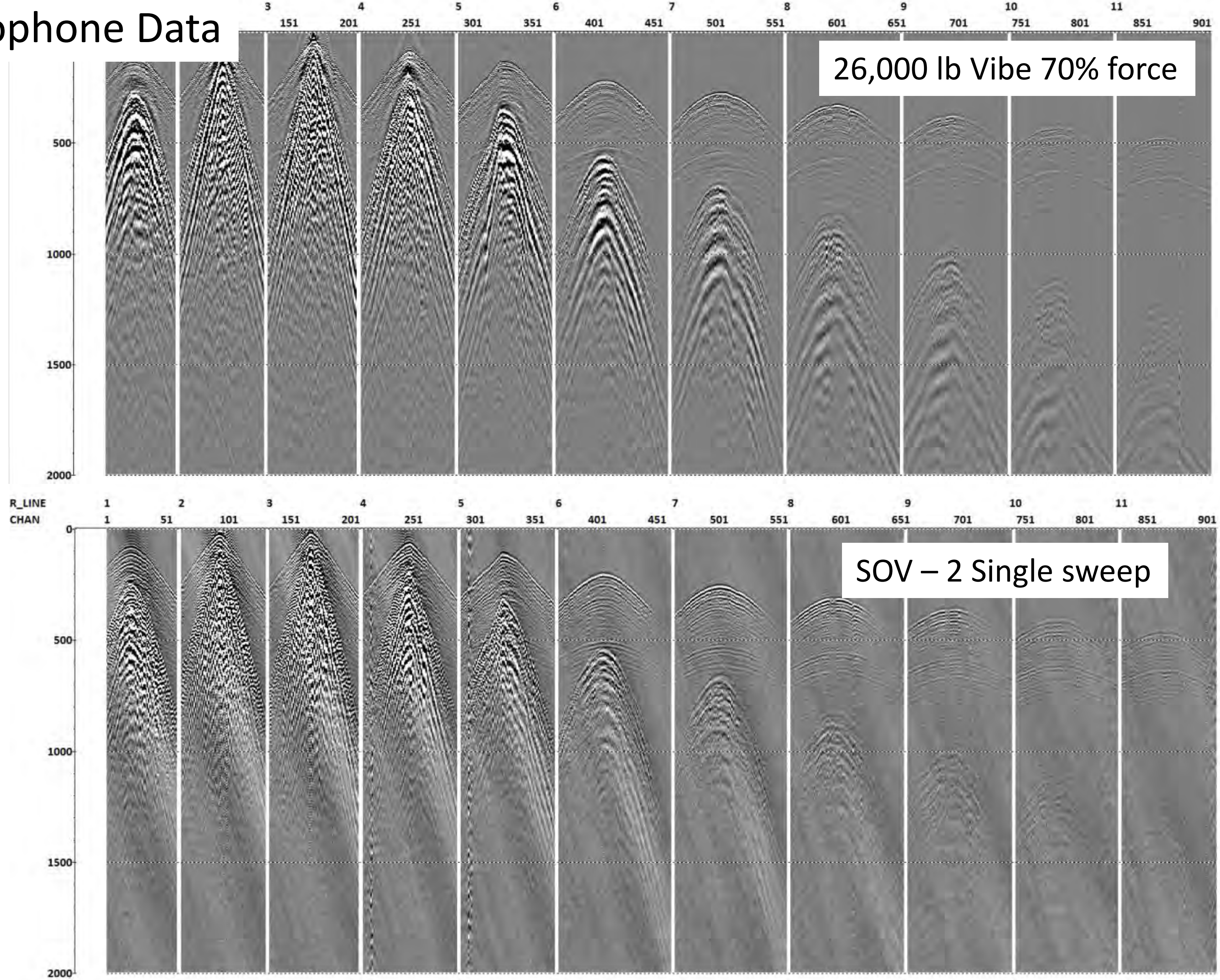
Lessons learned – acoustic impedance of cable and surrounding soil is important



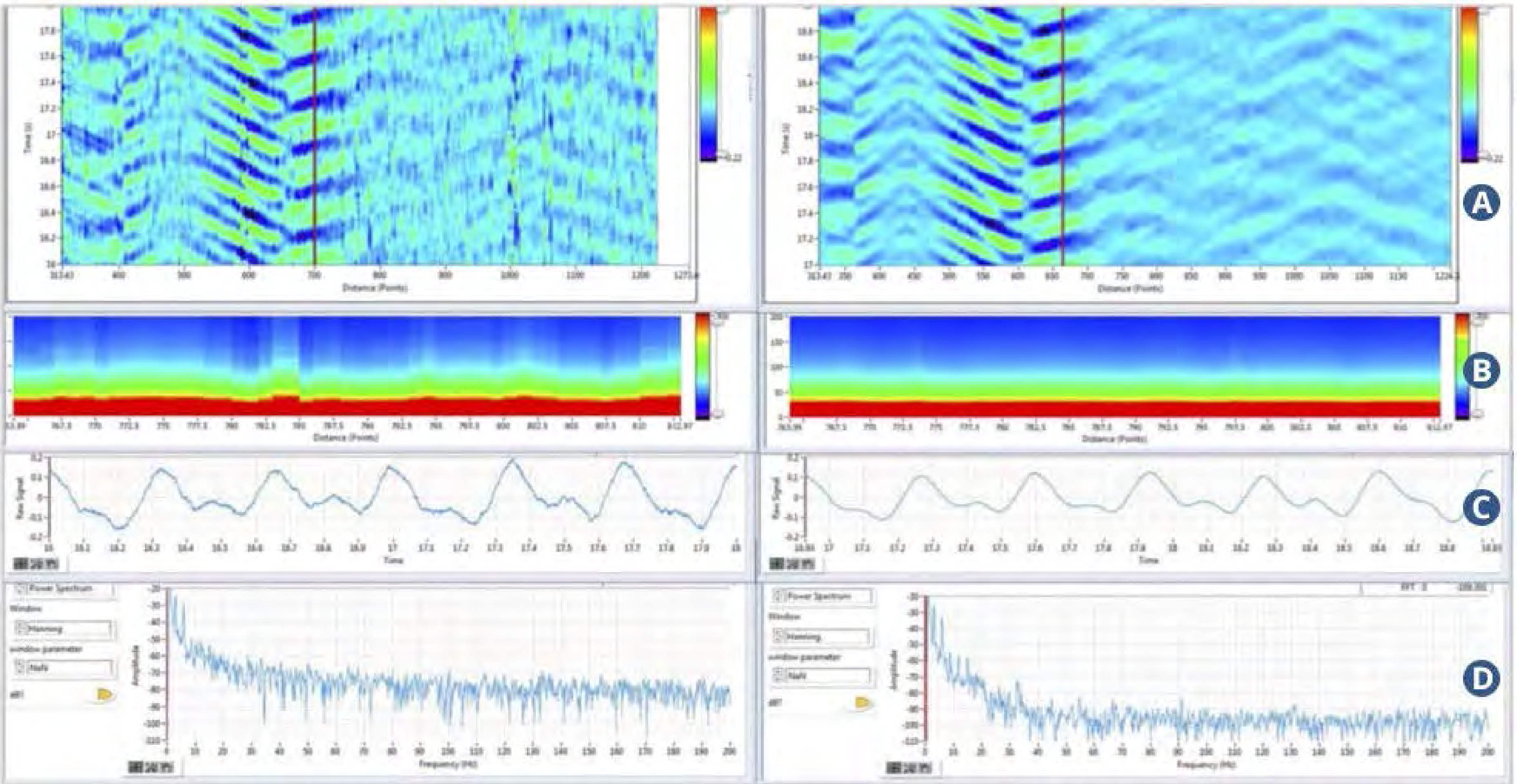


Hornman et al. 75th EAGE 2013

Geophone Data

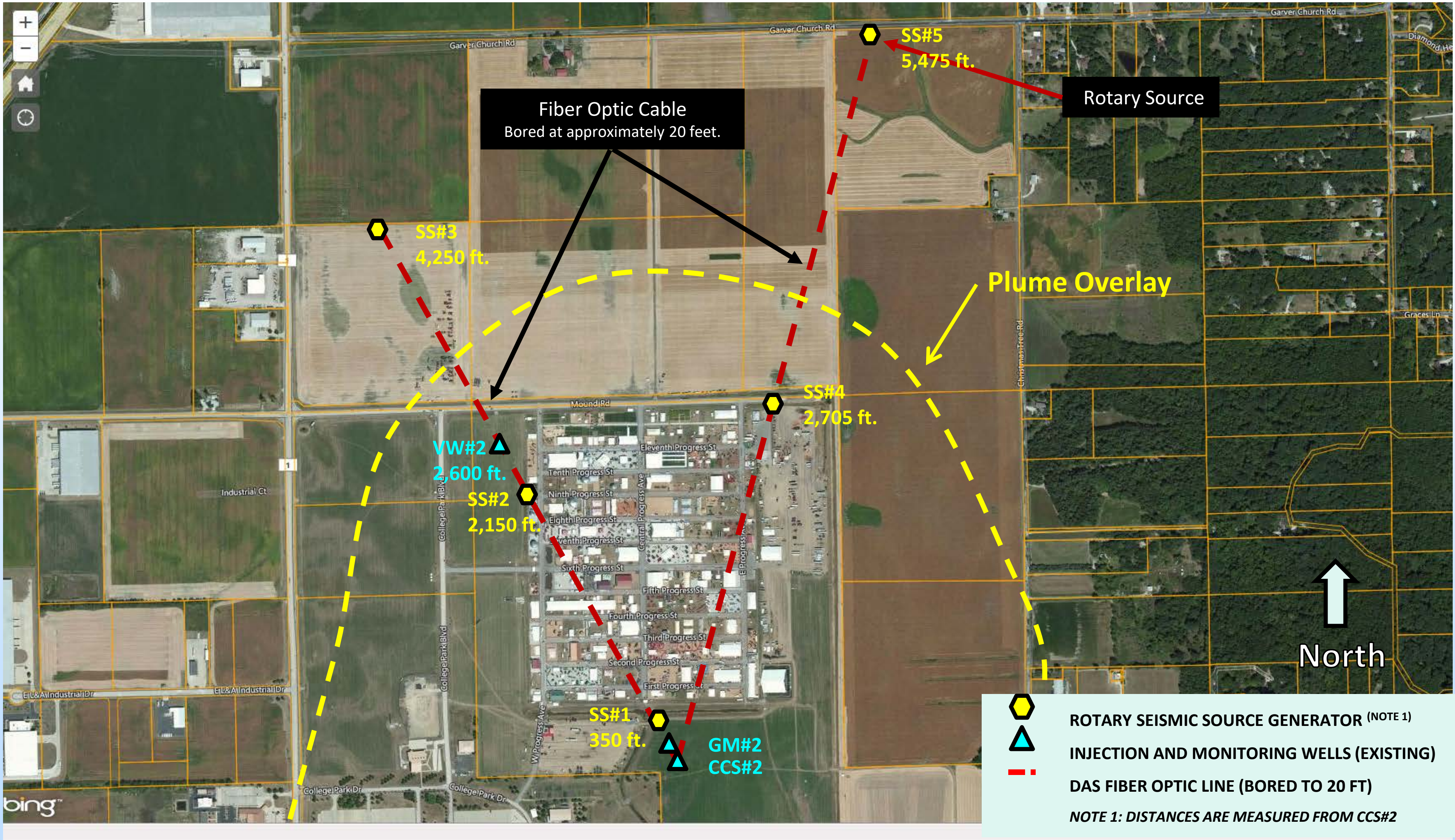


New Silixa Ltd. Carina Sensing System 100X Lower noise floor



Data collection courtesy Aquistore Project: PTRC/GSC/LBNL and JOGMEC

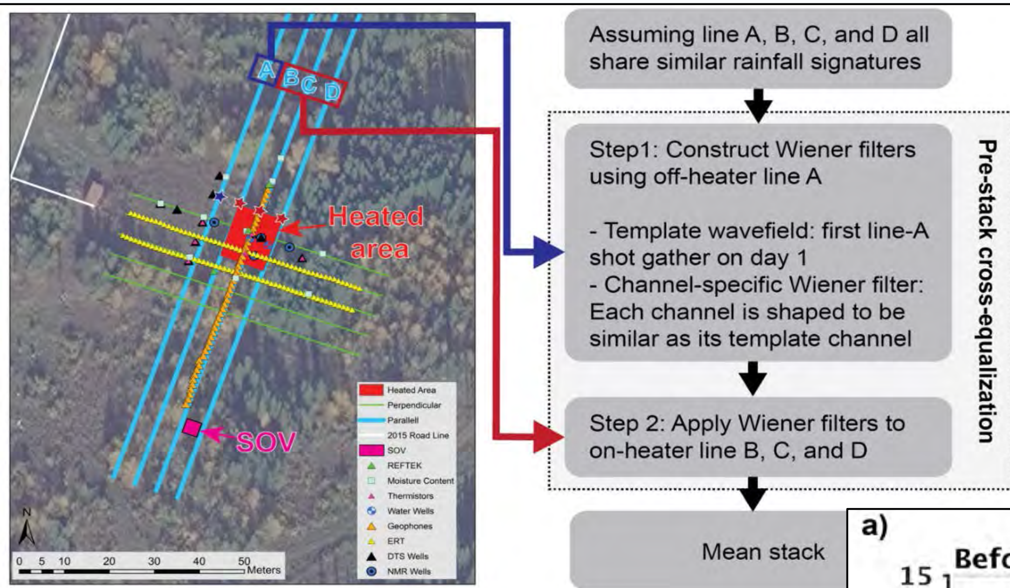
IMS Fiber Optic and CASS Layout



Accomplishments to Date

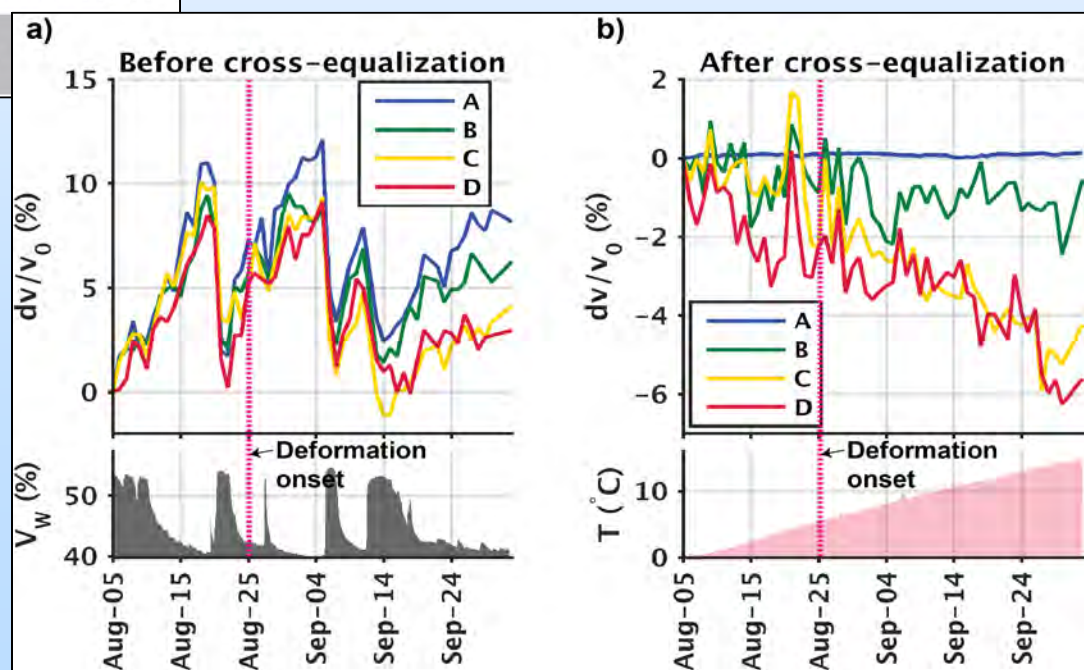
- TASK 2.0 IMS Design - Completed
  - Design and specification DAS cable, rotary sources CASSM, instrumentation, data acquisition and associated subsystems
  - Development of an IMS architecture and the demonstration of its operation using synthetic data feeds
  - Function testing of microseismic monitoring system and real-time event detection system
  - Detail real-time DAS cross-correlation and stacking algorithm and provide analysis of synthetic data evaluation with different levels of synthetic noise
  - Final design review, constructability, and HAZOP meeting

Subtask 2.3 Software Design and Development

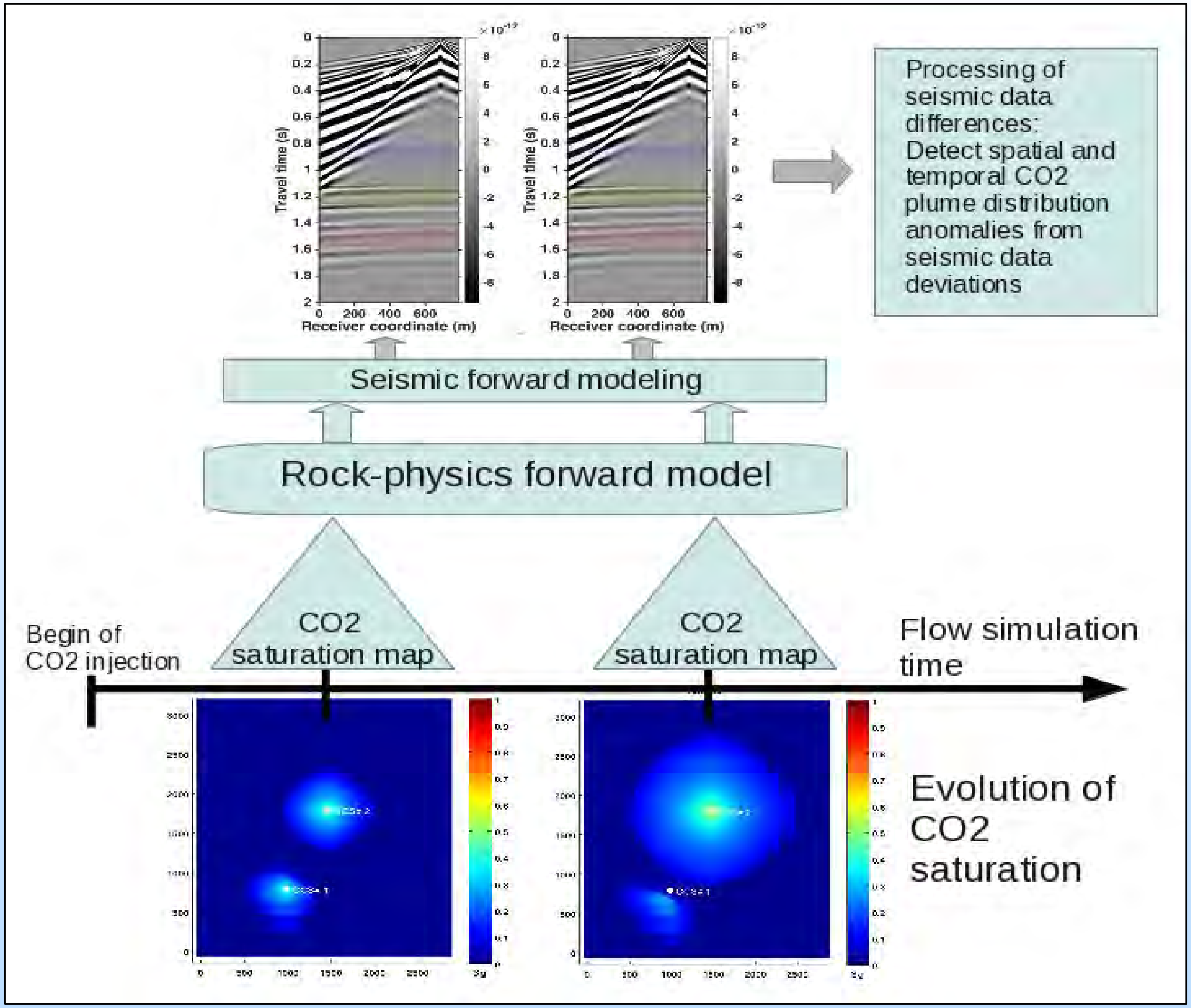


Workflow of pre-stack cross-equalization.

Use of Wiener filter to minimize the influences of precipitation on the SOV generated DAS data.



Subtask 2.3 Software Design and Development

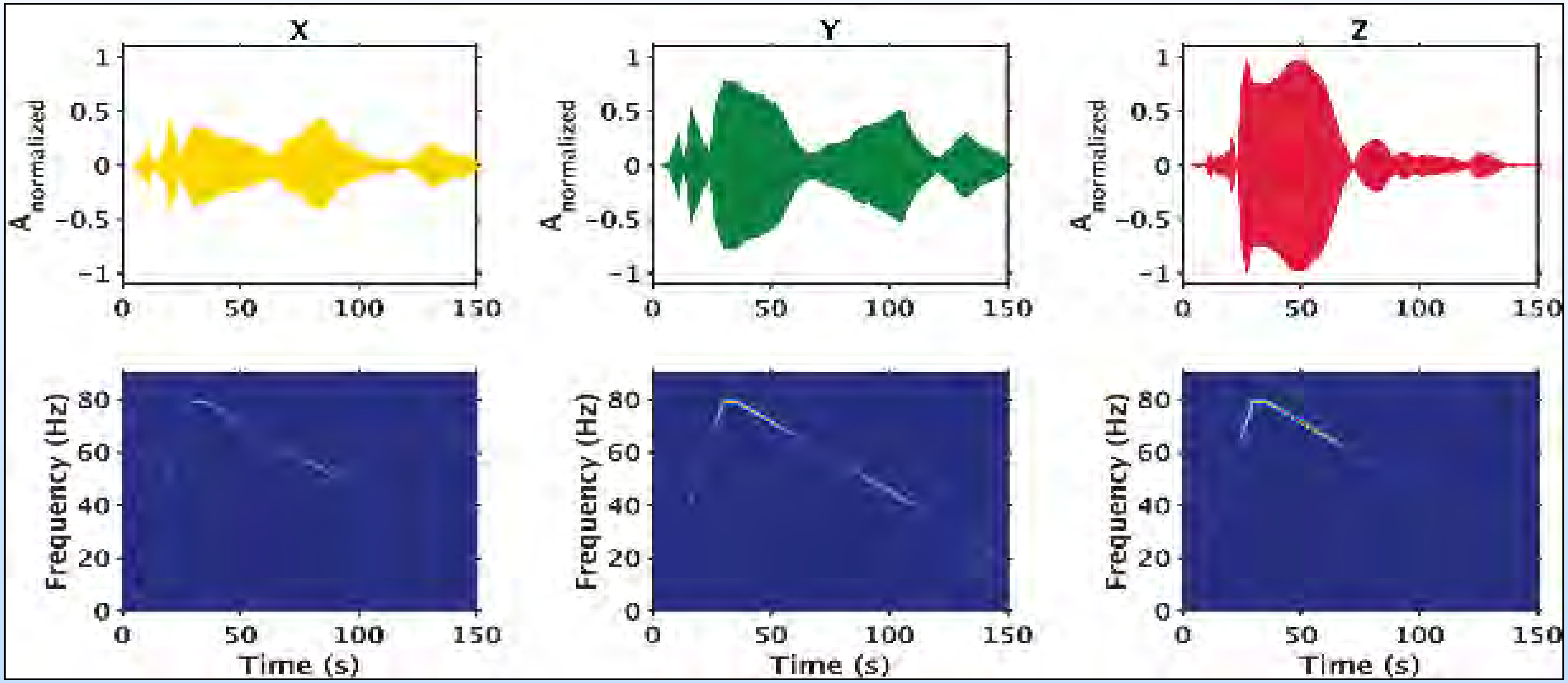


Hydrological-seismic modeling framework

Close-link software merge of both simulation modules allows for full exploitation of efficient parallel computing in both simulators

Subtask 2.3 Software Design and Development

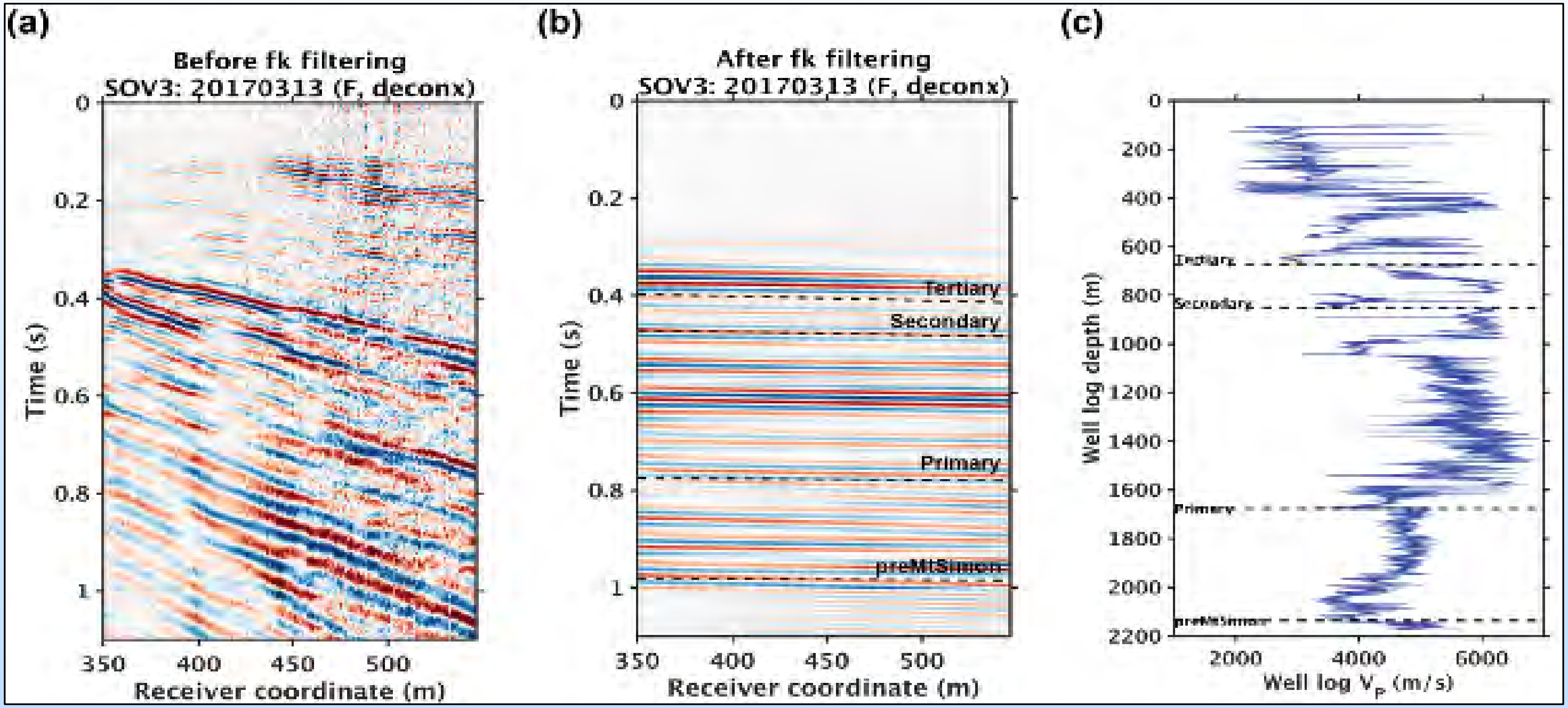
Testing of SOVs and preliminary data acquisition using the 250-meter-long section of surface DAS array (Testing Array).



SOV source sweeps recorded by pilot geophone
Top panel = time series; Bottom panel = time-frequency spectra.

Subtask 2.3 Software Design and Development

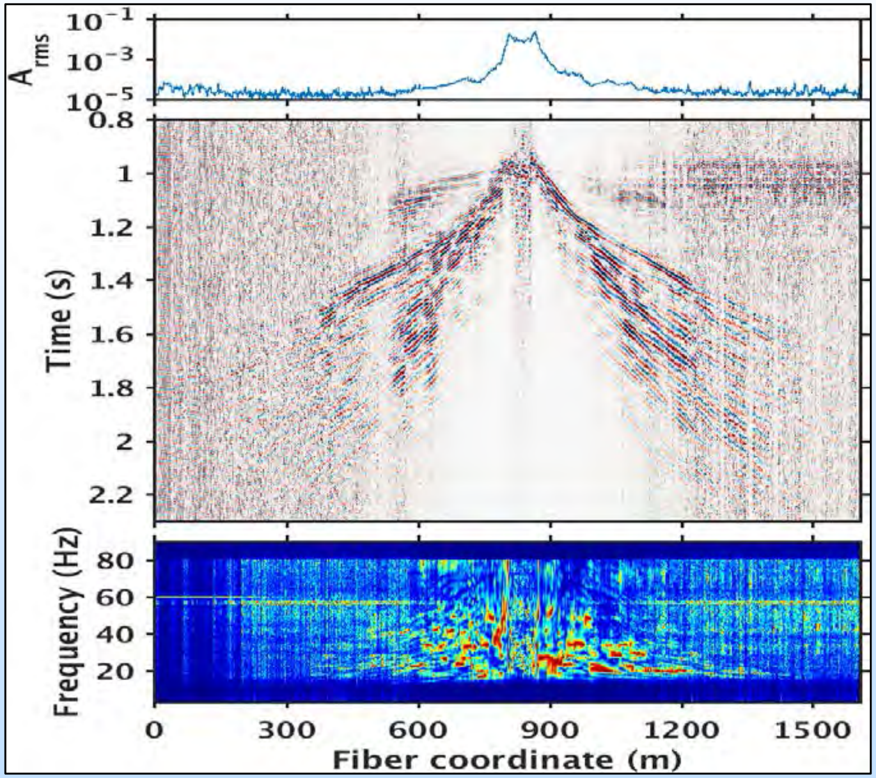
Common shot gather acquired on the Test DAS array.



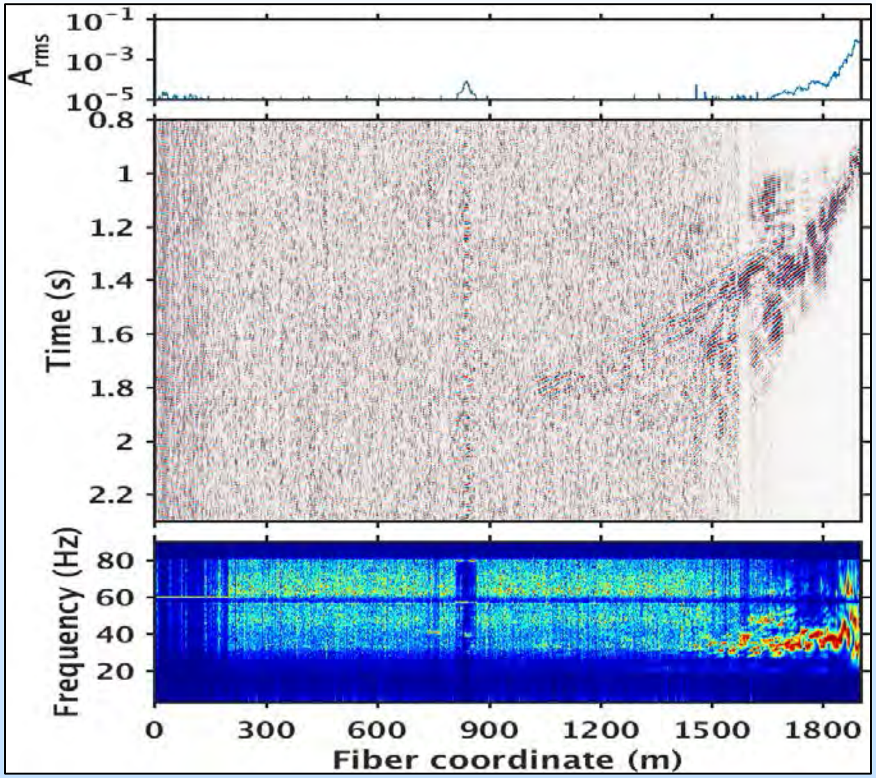
Common shot gather acquired on the test DAS array. (a) Raw shot gather without fk dip filtering. (b) Data after fk dip filtering. (c) VP profile extracted from sonic well log of CCS2. Dash lines in (b) denote travel time predictions of key reflectors. Dash lines in (c) denote the depths of the key reflectors. Tertiary, secondary, and primary = tertiary, secondary, and primary seals; pre Mt. Simon = bottom of the Mt. Simon reservoir.

Subtask 2.3 Software Design and Development

SOV sweep recorded by the permanent N/E DAS surface array.



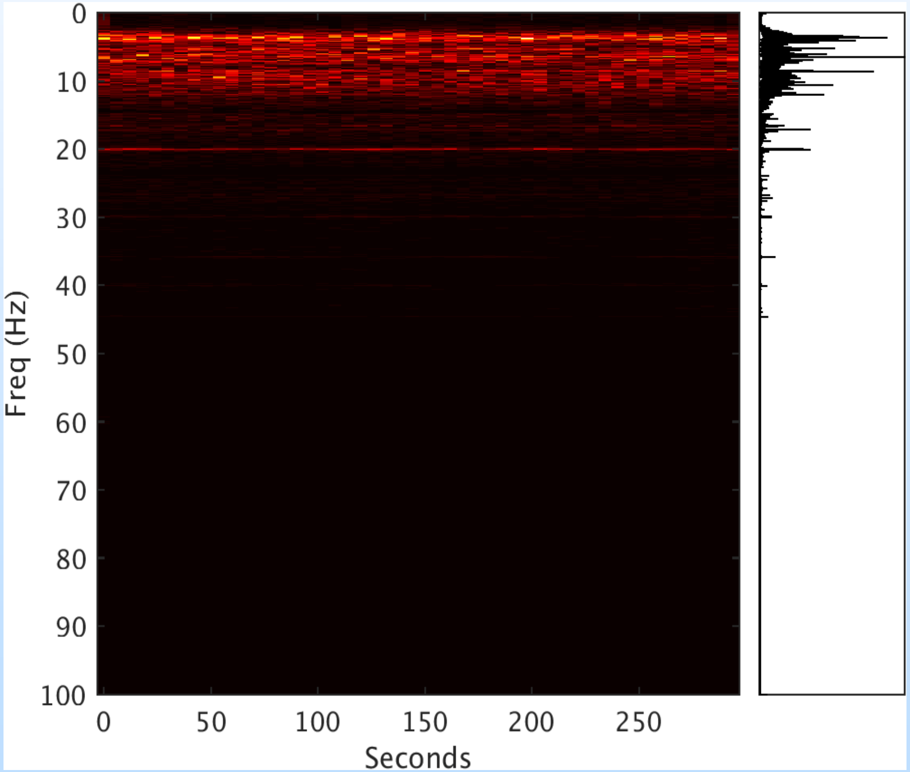
SOV4 sweep recorded by the northeast DAS surface array.



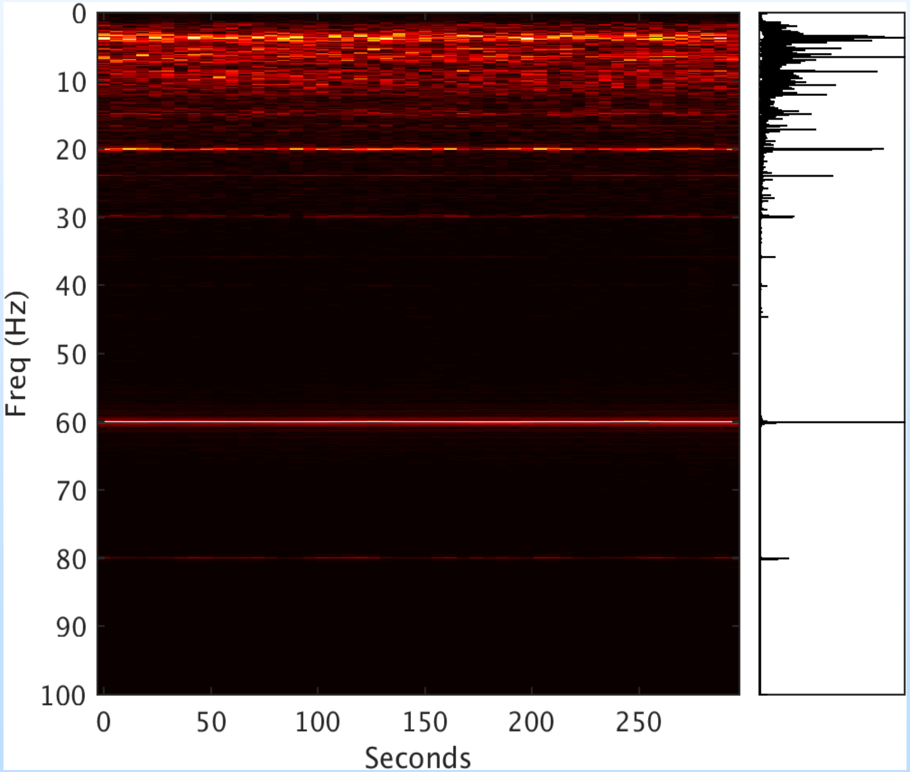
SOV5 sweep recorded by the northeast DAS surface array.

Subtask 2.4
Design Passive Microseismic Monitoring system

Data filter improvements for the deep borehole seismic network array increase the detection of microseismic events by removing frequencies of repetitive noise.



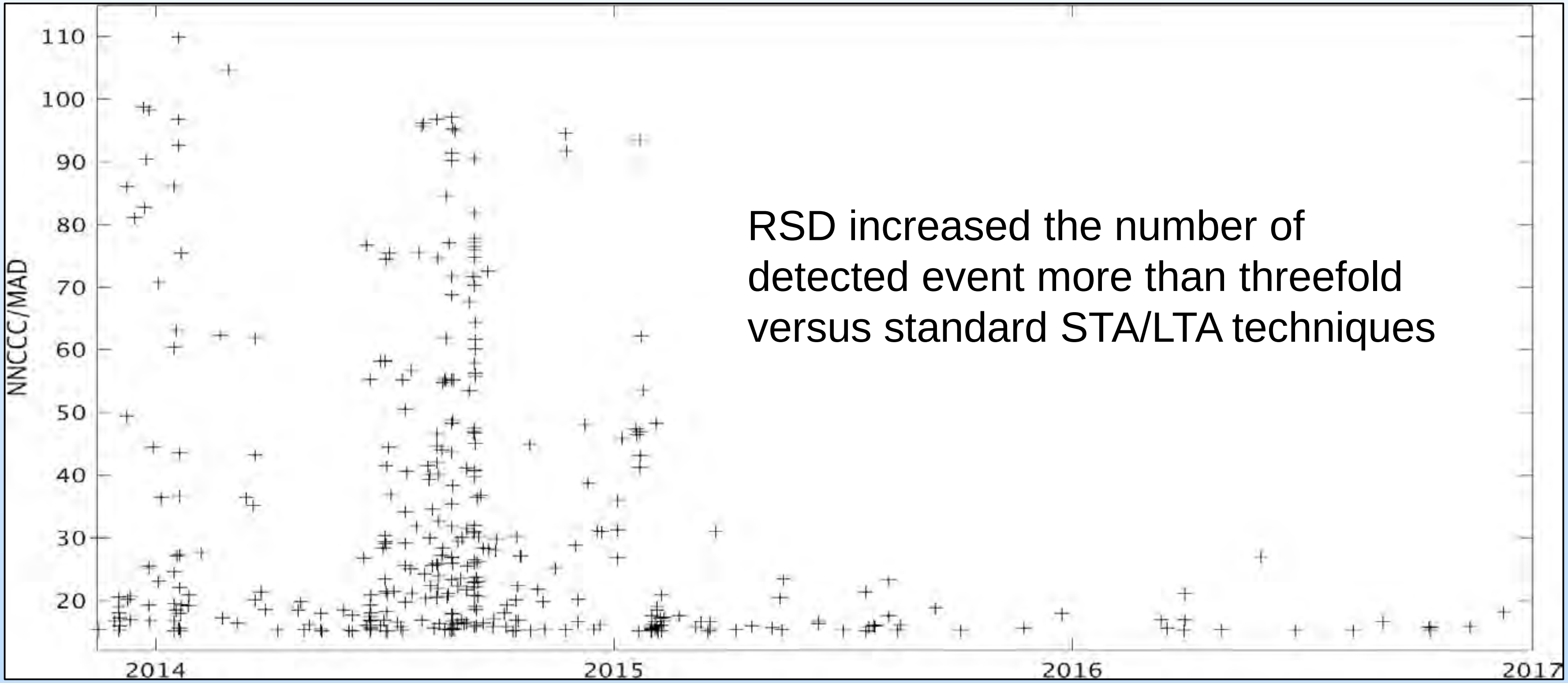
Spectra for filtered data



Spectra for raw data

Subtask 2.4
Design Passive Microseismic Monitoring system

Expanding the use of repeat signal detector (RSD) algorithm to the deep borehole array will increase the number of detected events.



Additional events detected using the shallow borehole network from November 2014 through December 2017 and plotted against the normalized cross-correlation coefficient divided by the median absolute deviation.

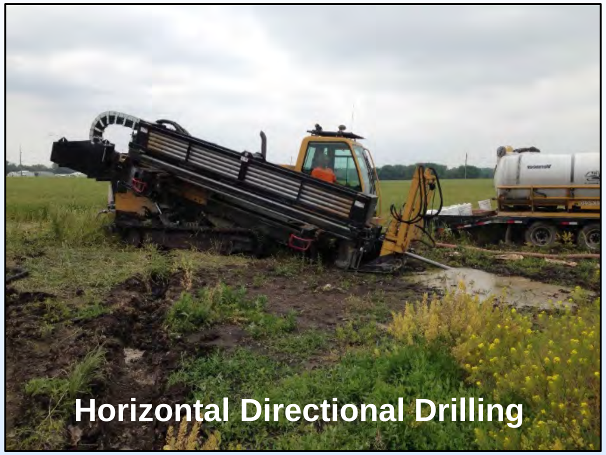
Accomplishments to Date

- **TASK 3.0 IMS Installation - <u>Completed</u>**
  - **Develop final construction plan for IMS equipment**
  - **Installation of data acquisition and processing equipment**
  - **Installation of DAS surface cable and rotary sources CASSM**
  - **Installation of instrumentation, electrical, and communications subsystems**
  - **Installation of control, monitoring, and data acquisition software**
  - *Installation of dedicated private network*
  - *Installation of shallow geophone and accelerometer*

Subtask 3.2 Installation of IMS data acquisition and processing equipment

Setup of the IMS Server & iDAS units in the CCS#2 building and SOV#2 & 3's Ethernet switch inside the VW#2 building.

Subtask 3.2 Installation of IMS DAS surface cable


Horizontal Directional Drilling

Location and Depth Monitoring

Prep for DAS cable and grouting conduit pull back


Cable and Conduit pull back


Cable reels feeding DAS cable and grouting conduit into bore hole

Grouting DAS Cable

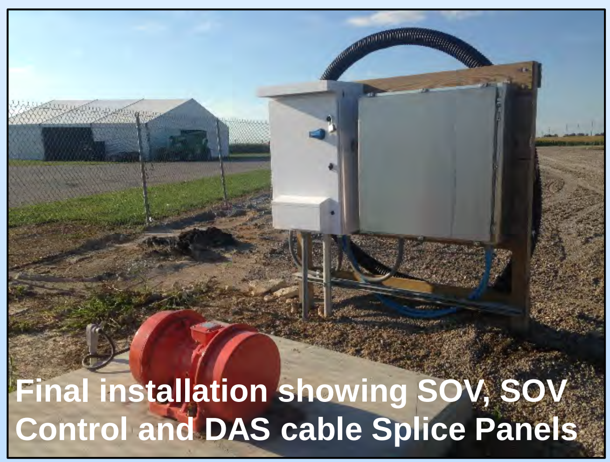
Subtask 3.2 Installation of rotary sources CASSM

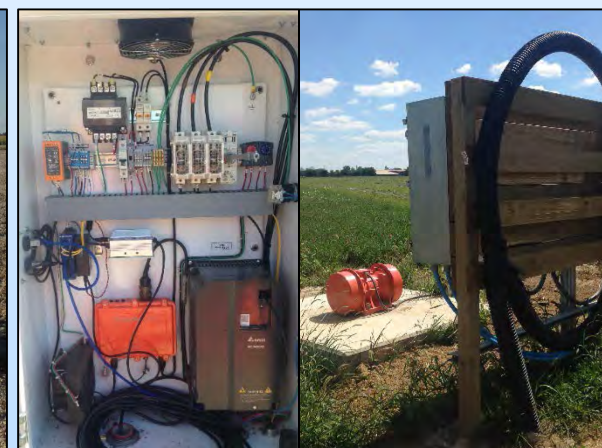

Foundation excavation


Structural SOV Anchor Assembly


SOV Installation

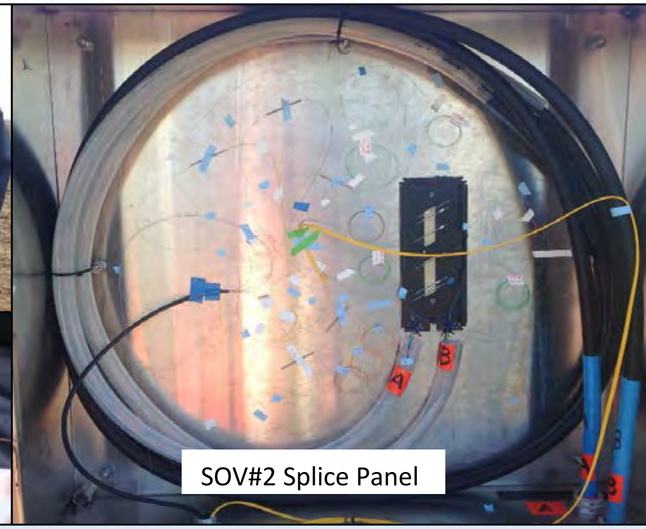

Drilling boreholes for the SOV Geophones


Final installation showing SOV, SOV Control and DAS cable Splice Panels



Setup of the IMS Server & iDAS units in the CCS#2 building and SOV#2 & 3's Ethernet switch inside the VW#2 building.

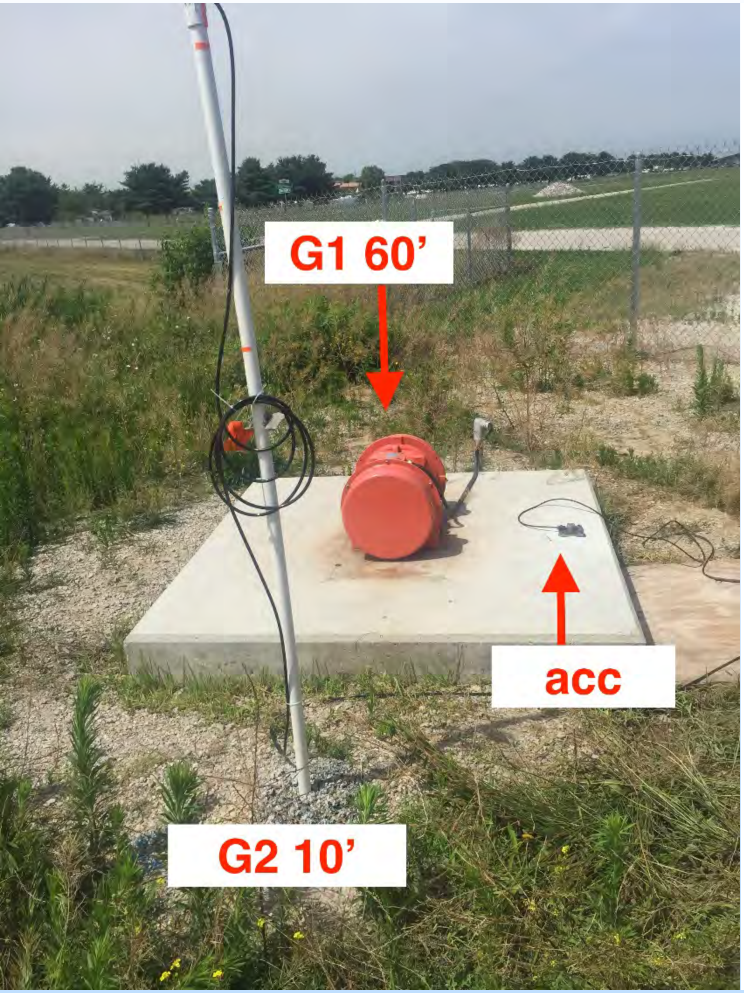
Subtask 3.2 DAS Cable Fusion Splicing & Acquisition of Geospatial Coordinates

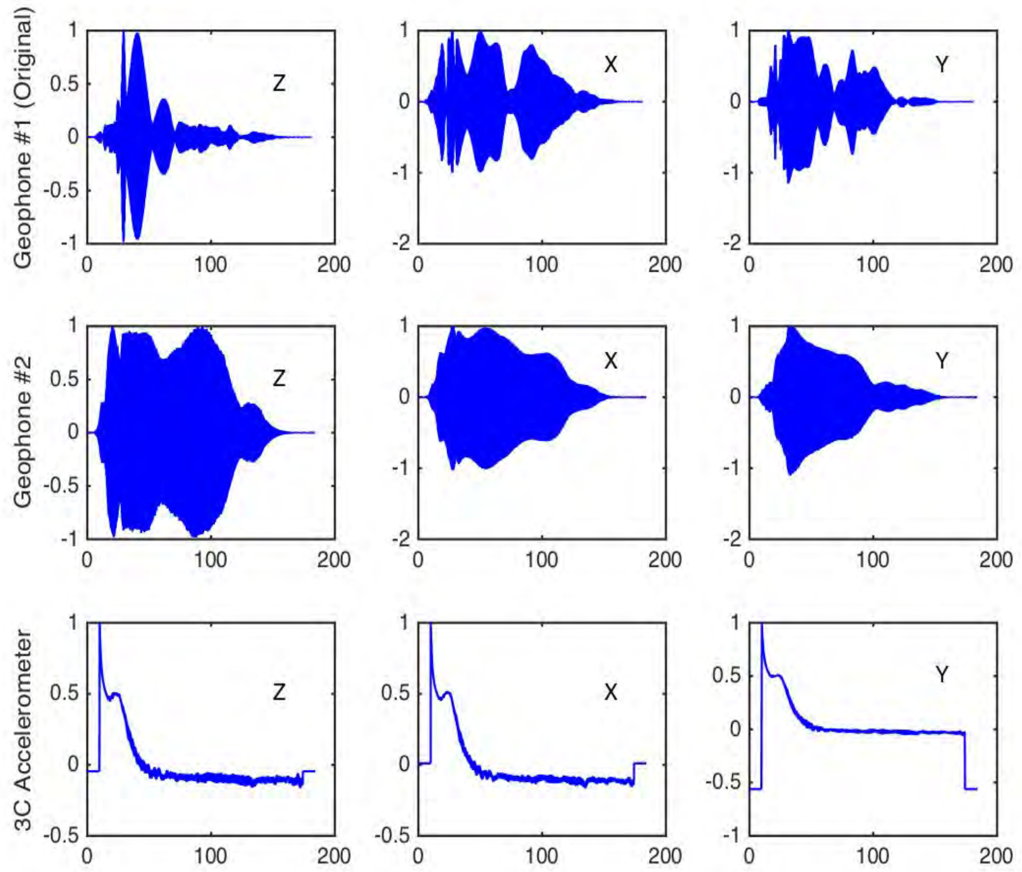


Latitude	Longitude	Elevation State Plane	Measured Depth	Description
39.86796082	-88.93735679	703.856		
39.89403148	-88.8933887	682.305	4.67	A1
39.89407516	-88.8934155	682.166	9.33	A2
39.89411459	-88.89344233	682.027	14.17	A3
39.89414933	-88.89346661	682.013	17.92	A4
39.89418369	-88.89348809	682.114	20.08	A5
39.89421791	-88.89350799	682.387	22.17	A6
39.8942585	-88.89353313	682.574	23.33	A7
39.89429177	-88.89355323	682.706	24.33	A8
39.89432836	-88.89357783	682.95	24.83	A9
39.89436734	-88.89360194	683.163	25.33	A10
39.89439969	-88.89362575	683.513	26.08	A11
39.89443629	-88.89365188	683.864	26.25	A12
39.89447276	-88.89367372	684.192	26.58	A13
39.89450985	-88.8936978	684.342	26.25	A14
39.89454721	-88.89372334	684.423	26.17	A15
39.89458542	-88.89374677	684.406	26.08	A16
39.89462194	-88.89377023	684.404	25.92	A17
39.89465936	-88.89379712	684.449	25.75	A18
39.8946986	-88.89382227	684.353	25.75	A19

Over 60 fusion splices required for installation of DAS array and networking of SOV panels.
Over 700 GPS coordinates with DAS cable depth used to develop of the geospatial model.

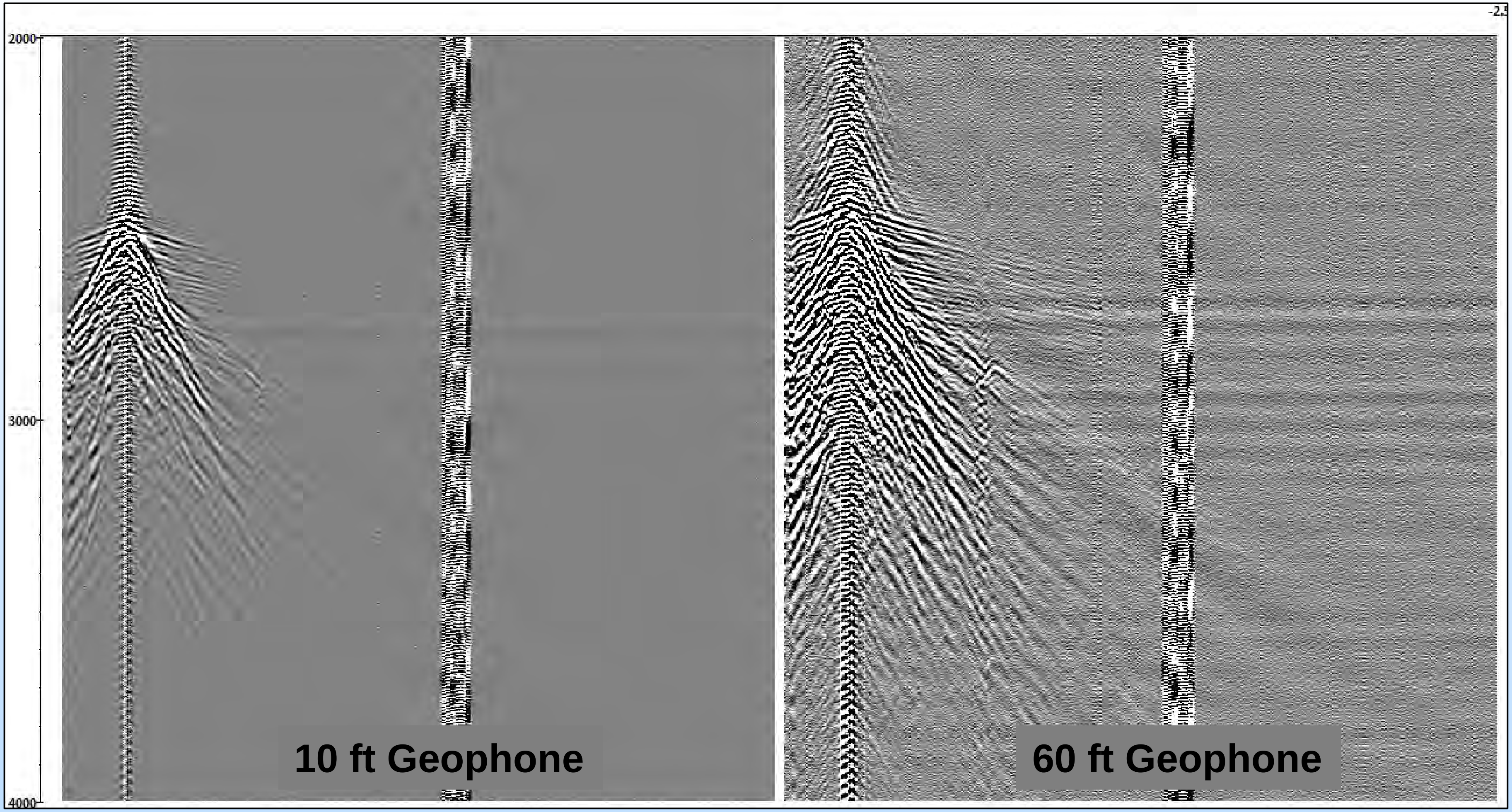
Subtask 3.3 – SOV#1 Shallow geophone and accelerometer installation





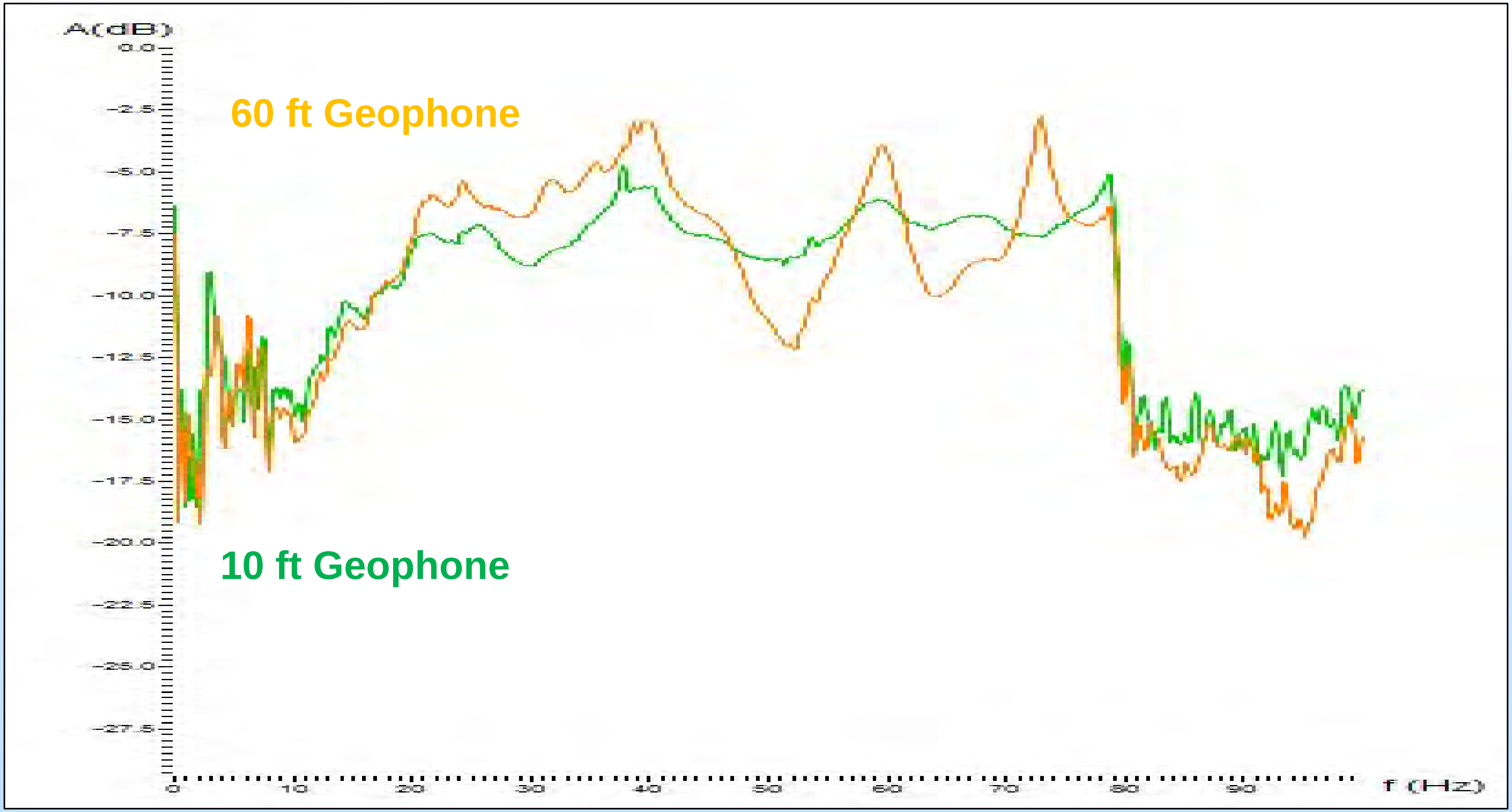
Installed shallow geophone and accelerometer at SOV to reduce impact of surface reflections on CASSM pre-stack data.

Subtask 3.3 – Deconvolved sweep comparison - shallow versus deep geophone



Comparison of deconvolved sweeps for the new shallow geophone versus deeper geophone. record present less noise and ringing, comparatively to the "old geophone record

Subtask 3.3 – Deconvolved sweep comparison - shallow versus deep geophone



Comparison of the frequency spectrum calculated for the DAS deconvolved data for the new shallow geophone (green) and the old deeper geophone (orange).

Accomplishments to Date

- **TASK 4.0 IMS Commissioning and Operation**
  - **Subtask 4.1 – Commissioning of the CASSM Equipment -** *Completed*
  - *Subtask 4.2 – Commissioning of the CASSM and Joint Inversion Modules – Underway*
  - *Subtask 4.3 – Commissioning of the Passive Seismic Monitoring System – Completed*
  - *Subtask 4.4 – Operation of the CASSM Equipment – Underway*
  - *Subtask 4.5 – Operation of the Passive Seismic Monitoring System – Underway*

No cost project extension through September 2019.

Lessons Learned

- **Data Management, CASSM data procession, and equipment installation.**
  - **The project encounter challenges in transferring terabyte data sets from the ADM network to the LBNL server at speeds that allow the interactive analysis needed to troubleshoot and optimize the system.**
  - **The project team took the IMS Server off the ADM network and uses a separate ISP connection to reduce system latency and allowing LBNL researchers to conduct interactive data processing and analysis.**
  - **SOV geophone depth is critical in reducing destructive interference cause by surface " ghost" reflections.**
  - **Installation of deep fiber optic critical for optimal data generation.**

Synergy Opportunities

- **Tested 2nd generation iDAS unit using Carina fiber optic cable.**
- **Future testing of 3rd party DAS units.**

Project Summary

- **Next Steps**
- *Installation of shallow geophones at SOVs*
- *Operation of IMS equipment and related controls*
- *Optimization of CASSM seismic module and integration with the reservoir inversion module.*
- *Comparison of real time IMS data with state of the art detailed models*
- *DAS data feed integration into the passive seismic monitoring system and system optimization*

Appendix

Benefit to the Program

- **Carbon Storage Program Goal Support:**
- **Goal (1) Develop and validate technologies to ensure 99 percent storage permanence by reducing leakage risk through early detection mitigation.**
- **Goal (2) Develop technologies to improve reservoir storage efficiency while ensuring containment effectiveness by advancing monitoring systems to control and optimize CO2 injection operations.**
- **Goal (4) Contributing to the Best Practice Manuals for monitoring, verification, and accounting (MVA) with regard to IMS.**

Benefit to the Program

- Reduce overall storage cost.
- Increase monitoring sensitivity.
- Increase monitoring reliability by using an integrated system.
- Optimize operation and maintenance activities.
- Reduce project risk during and after the injection of CO_2.

Project Overview
Goals and Objectives

- **Develop an integrated IMS architecture that utilizes a permanent seismic monitoring network, combines the real-time geophysical and process data with reservoir flow and geomechanical models.**
- **Create a comprehensive monitoring, visualization, and control system that delivers critical information for process surveillance and optimization specific to the geologic storage site.**
- **Use real-time model calibration to provide reservoir condition forecasts allowing site optimization.**

Project Overview

Specific Project Objectives

1. **Design an IMS using a real-time multi-technology architecture that fully integrates and enhances the site's existing monitoring infrastructure that includes multi-level 3D seismic arrays, distributed acoustic sensing (DAS), multi-level pressure/temperature sensors, distributed temperature sensing (DTS), borehole seismometers, and surface seismic stations**
2. **Augment the sites monitoring capabilities by installing several rotary seismic sources and integrating a network of surface DAS with the existing seismic system to create a continuous active source seismic monitoring (CASSM) array covering over two square kilometers and extending to a depth of 6,300 feet.**
3. **Develop terabyte level data processing solutions for real time monitoring of reservoir conditions and time lapse imaging of the CO2 plume.**

Project Overview
Specific Project Objectives

4. **Commission and operate the monitoring system in an industrial setting under actual conditions.**
5. **Validate and document the economic and environmental benefits of the monitoring system.**
6. **Update the monitoring verification and accounting best practices guide to include IMS and CASSM monitoring systems.**
7. **Incorporate DAS channels in routine location of microseismicity using the combination of borehole and surface seismic stations.**
8. **Develop near real-time data processing techniques to overcome passive seismic monitoring limitations of low signal-to-noise ratio on DAS array.**

IMS Organization Chart

- ADM has overall project responsibility and is accountable for:
  - Task 1 Project management and planning
  - Task 3 IMS Installation
  - Task 4 IMS Commissioning and Operation

- LBNL's team will be accountable for:
  - Task 2 IMS Design
  - Subtask 3.3 IMS DAS Surface Cable and Rotary Sources CASSM
  - Subtask 3.4 IMS Control, Monitoring, and Data Acquisition Software
  - Subtask 4.2 Function test of IMS DAS Surface Cable and Rotary Sources CASSM
  - Subtask 4.5 Validate IMS real-time reduced order models

- USGS's team will be accountable for:
  - Subtask 2.4 Design of Passive Microseismic Monitoring System
  - Subtask 4.6 Operation Passive Microseismic Monitoring System

IMS Organization Chart

- **Silixa's team will be accountable for:**
  - **Subtask 2.1 IMS Data Acquisition and Processing Equipment,**
  - **Subtask 3.2 IMS Data Acquisition and Processing Equipment,**
  - **Subtask 4.1 IMS Instrumentation, Controls, and Data Network,**

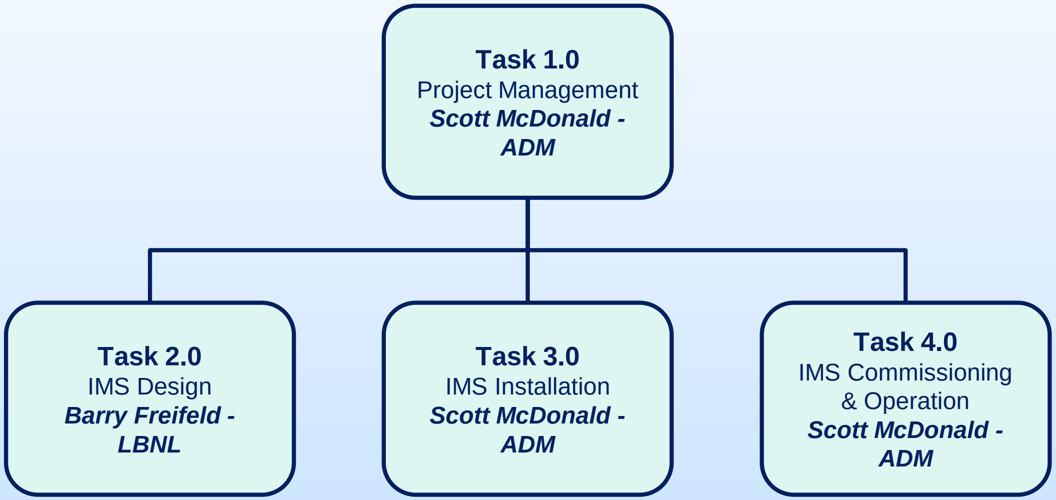
- **RCC's team will be accountable for:**
  - **Subtask 1.4 Project Outreach and Education.**

- **ISGS's team will participate in:**
  - **Subtask 1.4 Project Outreach and Education,**
  - **Subtask 2.4 Design of Passive Microseismicity Monitoring System**
  - **Subtask 4.6 Operating Passive Microseismicity Monitoring System**

- **SLB's team will participate in:**
  - **Subtask 2.1 Data Acquisition and Processing Equipment**
  - **Subtask 4.5 Validate IMS real-time reduced order models**

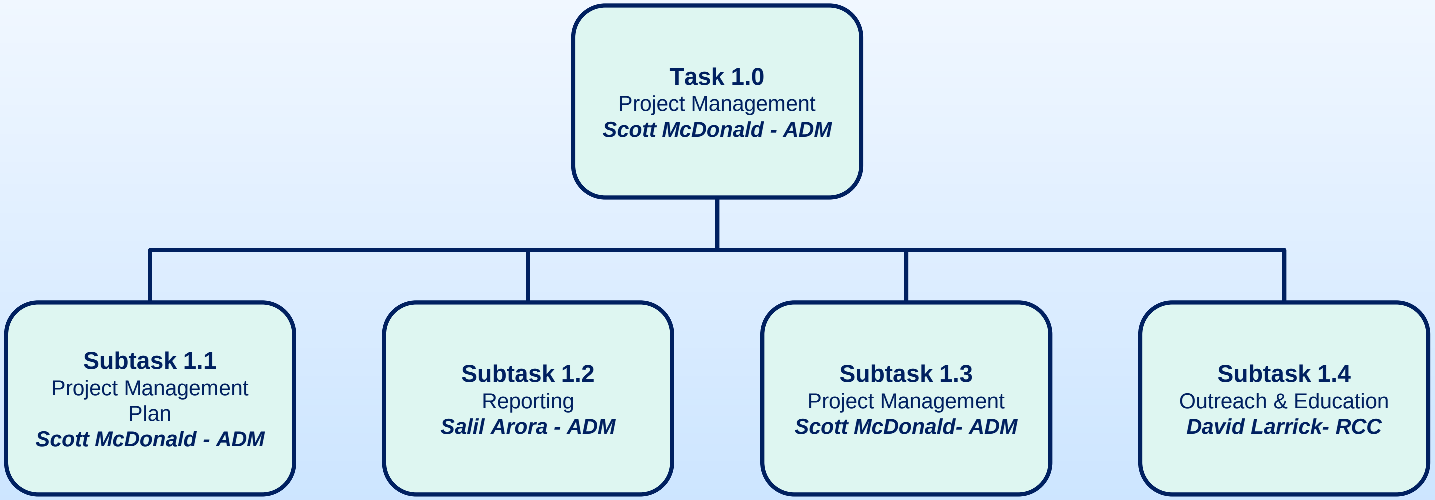
IMS Organization Chart

General Task Overview



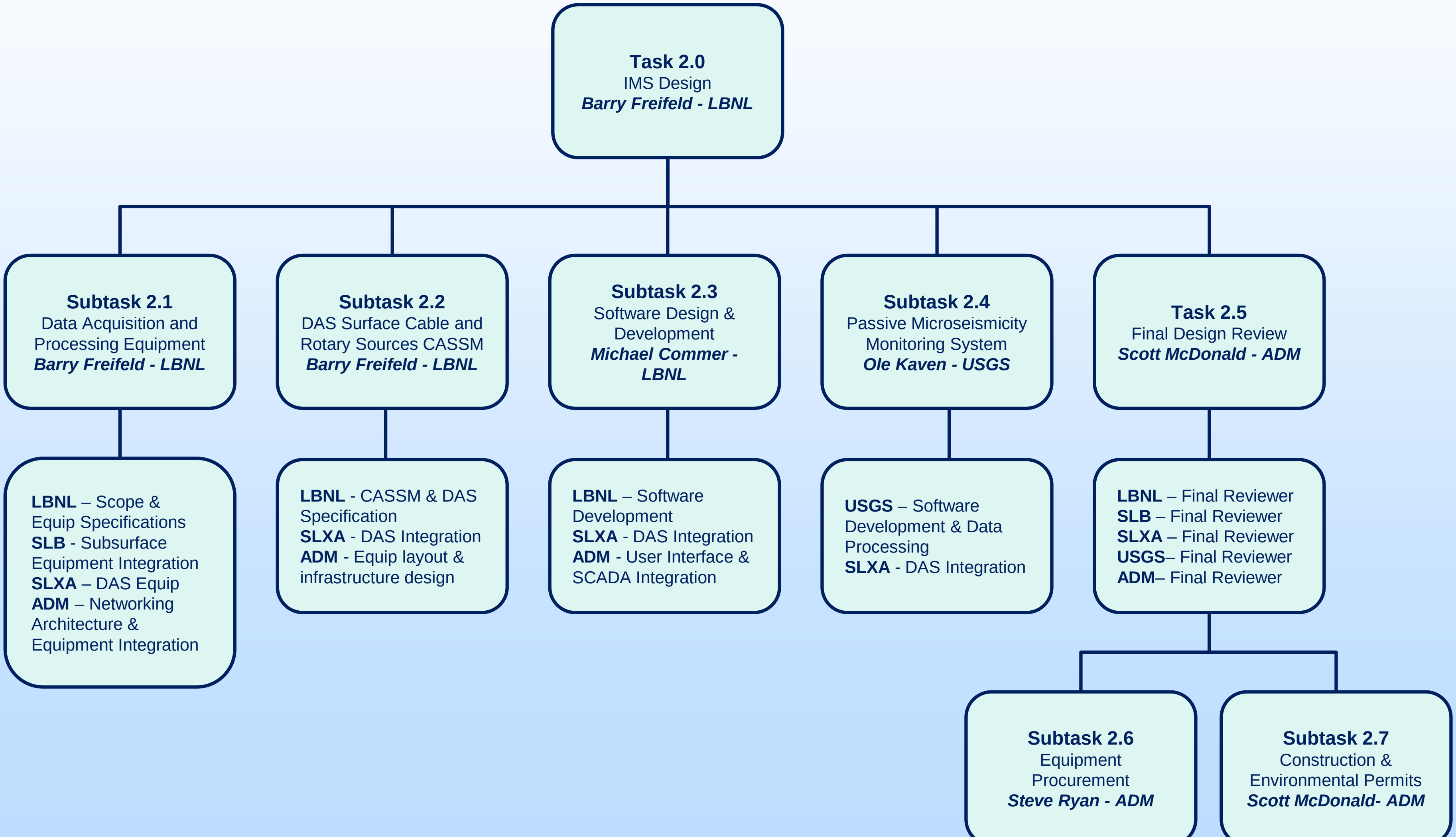
IMS Organization Chart

Task 1.0 - Project Management



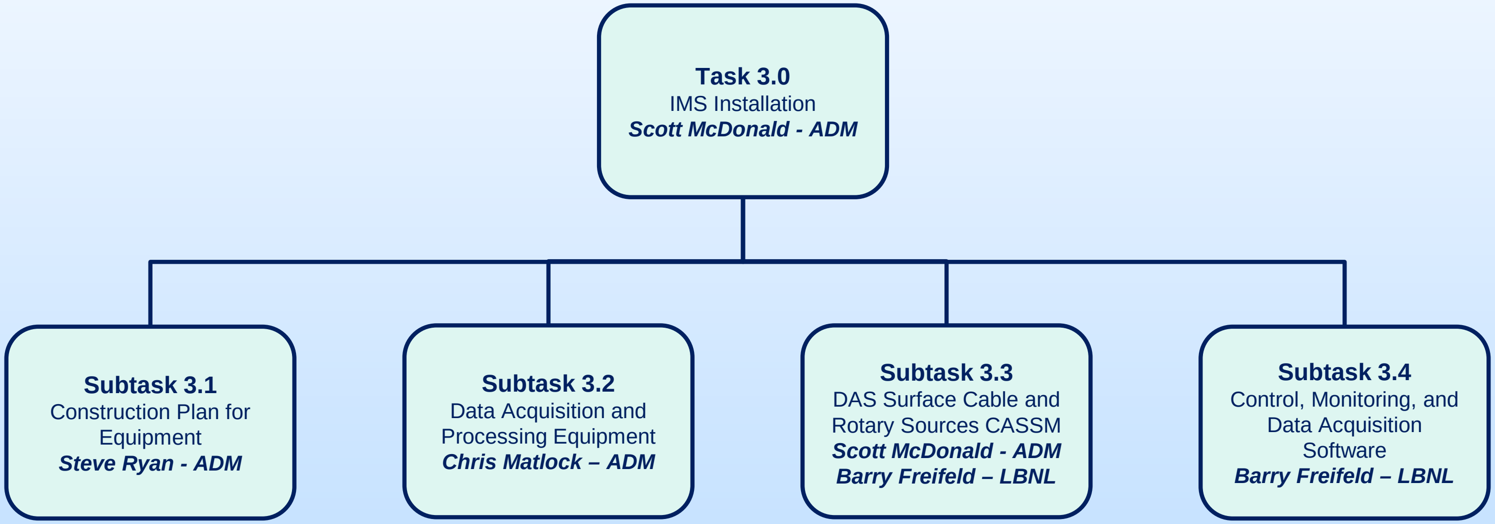
IMS Organization Chart

Task 2.0 - IMS Design



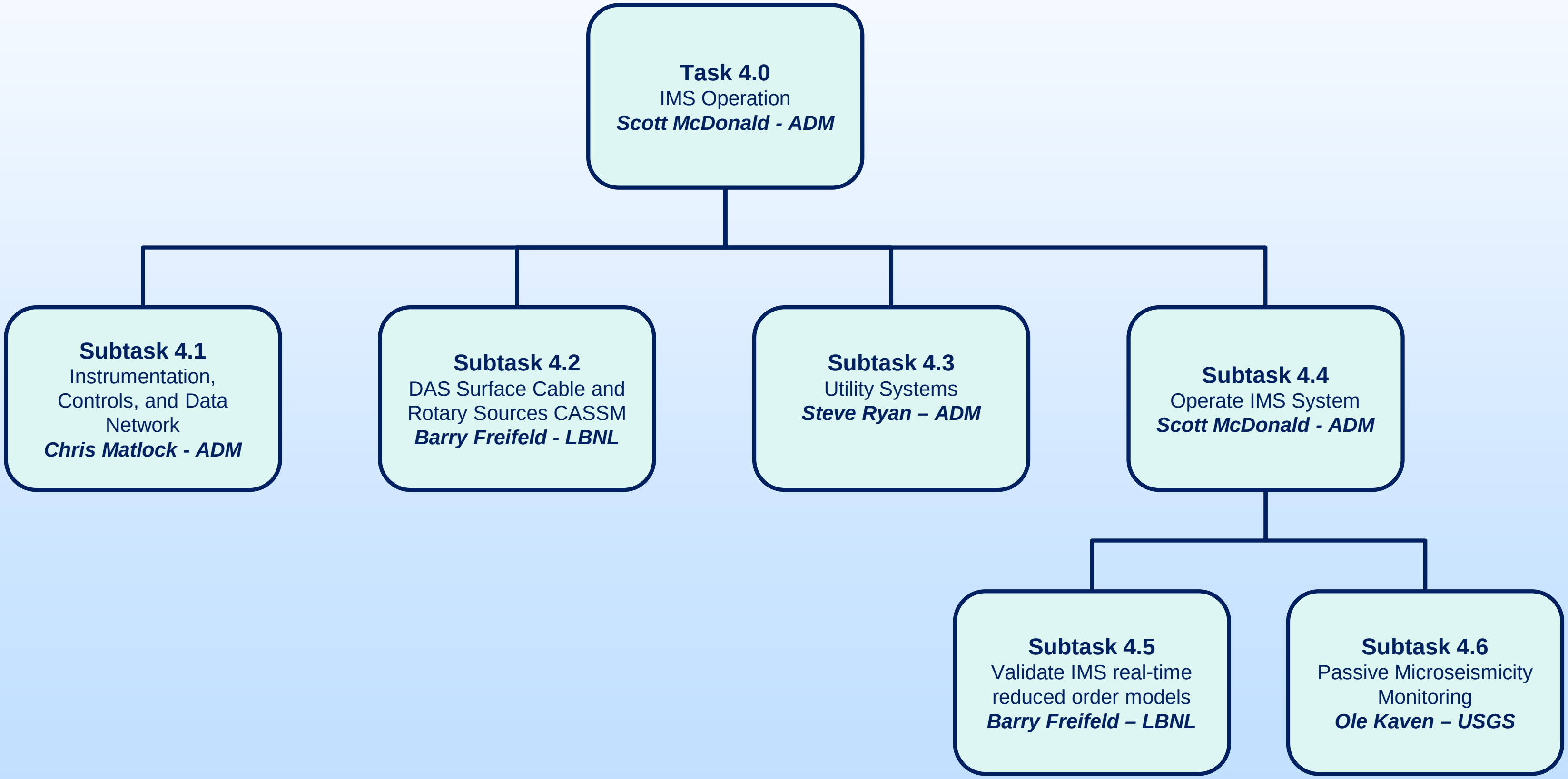
IMS Organization Chart

Task 3.0 - IMS Installation



IMS Organization Chart

Task 4.0 - IMS Operation



IMS Gantt Chart

ID	Task Name	Resource Names	Start	Finish	Duration
1	Task 1.0 – Project Management and Planning		10/01/2015	10/1/2015	0d
2	Subtask 1.1: Project Management Plan	ADM	10/01/2015	03/31/2016	183d
3	Subtask 1.2: Reporting	ADM	10/01/2015	09/30/2019	1461d
4	Subtask 1.3: Kickoff Meeting	ADM	10/01/2015	12/31/2015	92d
5	Subtask 1.4: Project Outreach and Education	RCC	10/01/2015	09/30/2018	1096d
6	Complete Project Prerequisites		04/01/2016	04/01/2016	0d
7	Task 2.0 – IMS Design		10/01/2015	10/01/2015	0d
8	Subtask 2.1: IMS Data Acquisition and Processing Equipment	LBNL	01/01/2016	09/30/2016	274d
9	Subtask 2.2: Design CASSM	LBNL	01/01/2016	09/30/2016	274d
10	Subtask 2.3: IMS Software Design and Development	LBNL	01/01/2016	09/30/2016	274d
11	Subtask 2.4: Design Passive Microseismicity Monitoring system	USGS	03/01/2016	03/31/2017	396d
12	Subtask 2.5: IMS Final Design Review	ALL	10/03/2016	10/19/2016	17d
13	Subtask 2.6: IMS Equipment Procurement	ADM	07/22/2016	03/31/2017	253d
14	Subtask 2.7: Construction and Environmental Permits	ADM, RCC	08/01/2016	09/30/2016	61d
15	Complete IMS Design		10/20/2016	10/20/2016	0d
16	Task 3.0 – IMS Installation		10/20/2016	10/20/2016	0d
17	Subtask 3.1: Develop Construction Plans	ADM	10/20/2016	11/17/2016	29d
18	Subtask 3.2: IMS Data Acquisition and Processing Equipment Installation	ADM, LBNL	11/18/2016	03/31/2017	134d
19	Subtask 3.3: IMS DAS Surface Cable and Rotary Sources CASSM Installation	ADM, LBNL	11/18/2016	06/30/2017	225d
20	Subtask 3.4: IMS Control, Monitoring, and Data Acquisition, Software Installation	LBNL, ADM	04/03/2017	06/30/2017	89d
21	IMS Installation Complete		07/01/2017	07/01/2017	0d
22	Task 4.0 – IMS Commissioning and Operation		07/01/2017	07/01/2017	0d
23	Subtask 4.1: Commissioning of DAS, SOV, Instrumentation, Controls, & Data Acquisition	ADM	07/01/2017	09/30/2017	92d
24	Subtask 4.2:Commissioning of CASSM System and Joint Inversion Module	ADM	07/01/2017	06/30/2018	365d
25	Subtask 4.3: Commission of Passive Seismic Monitoring Network	ADM	07/01/2017	09/30/2017	92d
26	Subtask 4.4: Operation of IMS Equipment and Data Acquisition System	ALL	10/01/2017	09/30/2019	730d
27	Subtask 4.5 Operation of integrated CASSM System with Joint Inversion Module		07/01/2018	09/30/2019	457d
28	Subtask 4.6 Operation of Passive Seismic Monitoring Network	USGS, ADM	10/01/2017	09/30/2019	730d
29	IMS Commissioning and Operation Complete		10/01/2019	10/01/2019	0d
30	Final Project Reporting		10/01/2019	10/31/2019	31d
31	PROJECT COMPLETE		11/01/2019	11/01/2019	0d