A Multisensor Plume Monitoring Schema for Carbon Sequestration Sites in Subsurface Engineered-Natural Systems

29 January 2018
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Cover Illustration: An open field on the northern Montana prairie is an ideal location for a large geophysical carbon dioxide (CO₂) monitoring survey.


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https://edx.netl.doe.gov/carbonstorage
A Multisensor Plume Monitoring Schema for Carbon Sequestration Sites in Subsurface Engineered-Natural Systems

Paul Vincent, Esteban Bowles-Martinez, Adam Schultz

College of Earth Ocean and Atmospheric Sciences, Oregon State University, Corvallis, OR 97331

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NETL Contacts:
Adam Schultz, Principal Investigator
Grant Bromhal, Technical Portfolio Lead
David Alman, Executive Director, Acting, Research & Innovation Center
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<tr>
<td>2-D</td>
<td>Two-dimensional</td>
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<tr>
<td>3-D</td>
<td>Three-dimensional</td>
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<tr>
<td>AMT</td>
<td>Audiofrequency magnetotelluric</td>
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<tr>
<td>ATV</td>
<td>All-terrain vehicle</td>
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<td>CO₂</td>
<td>Carbon dioxide</td>
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<tr>
<td>CR</td>
<td>Corner reflectors</td>
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<tr>
<td>CSEM</td>
<td>Controlled source electromagnetic</td>
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<tr>
<td>CSAMT</td>
<td>Controlled source audio magnetotelluric</td>
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<tr>
<td>DC</td>
<td>Direct current</td>
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<tr>
<td>DInSAR</td>
<td>Differential interferometric synthetic aperture radar</td>
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<tr>
<td>DInRAR</td>
<td>Differential interferometric real aperture radar</td>
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<tr>
<td>EGS</td>
<td>Engineered Geothermal System</td>
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<tr>
<td>EM</td>
<td>Electromagnetic</td>
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<tr>
<td>EPA</td>
<td>U.S. Environmental Protection Agency</td>
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<tr>
<td>ERT</td>
<td>Electrical resistivity tomography</td>
</tr>
<tr>
<td>GPRI-2</td>
<td>Gamma Portable Radar Interferometer-2</td>
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<tr>
<td>InRAR</td>
<td>Interferometric real aperture radar</td>
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<tr>
<td>InSAR</td>
<td>Interferometric synthetic aperture radar</td>
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<tr>
<td>IP</td>
<td>Induced polarization</td>
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<tr>
<td>LiDAR</td>
<td>Light detection and ranging</td>
</tr>
<tr>
<td>MSU</td>
<td>Montana State University</td>
</tr>
<tr>
<td>MT</td>
<td>Magnetotellurics</td>
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<tr>
<td>MVA</td>
<td>Monitoring, Verification, and Accounting</td>
</tr>
<tr>
<td>NATCARB</td>
<td>National Carbon Sequestration</td>
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<tr>
<td>NETL</td>
<td>National Energy Technology Laboratory</td>
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<tr>
<td>NRAP</td>
<td>National Risk Assessment Partnership</td>
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<tr>
<td>OSU</td>
<td>Oregon State University</td>
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<tr>
<td>PSI</td>
<td>Persistent scatterer interferometry</td>
</tr>
<tr>
<td>RC</td>
<td>Resistor capacitor</td>
</tr>
<tr>
<td>RFMT</td>
<td>Radiofrequency magnetotelluric</td>
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## Acronyms, Abbreviations, Symbols (cont.)

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
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<tbody>
<tr>
<td>TEM</td>
<td>Transient electromagnetics</td>
</tr>
<tr>
<td>TSX</td>
<td>TerraSAR-X</td>
</tr>
<tr>
<td>UIC</td>
<td>Underground Injection Control</td>
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Acknowledgments

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The authors also wish to acknowledge Stacey Fairweather and Lee Spengler of Montana State University who helped facilitate our partnership and provided background information on the Kevin Dome CO₂ site.
EXECUTIVE SUMMARY

The primary goal for this project was to provide a modeling and data-justified strategy (schema) for monitoring geologically sequestered carbon dioxide (CO₂) plume migration in subsurface engineered-natural systems. The long-term goal was to provide a method to help demonstrate the integrity of and reduce the risk for long-term CO₂ storage in underground reservoirs. With this primary goal in mind, and focusing on monitoring and interpreting both surface deformation and subsurface resistivity changes phenomena measurements, the project was divided into three tasks:

1. Candidate Sensor Investigation - select the best monitoring sensor types
2. Sensor Sensitivity Modeling and Analysis - determine monitoring strategy for each sensor type
3. Scoping - next phase site-specific pilot study

Task 1 - Candidate Sensor Investigation results, including the details on the reasons for the sensor types chosen and a detailed description of each sensor type, their capabilities and primary noise sources are provided in the Phase I report titled, “Underground CO₂ Sequestration Monitoring Using Radar Interferometric and Electromagnetic Geophysical Methods” (Bowles-Martinez and Vincent, 2013). These findings are not repeated in this final report and readers are encouraged to read that report for those details.

Task 2 - Sensor Sensitivity Modeling and Analysis details are provided in this report and comprise the bulk of the work on this project.

Task 3 - Scoping Next Phase Site-Specific Pilot Study details are also provided in this report and detail new collaborations formed with Montana State University (MSU) and the Big Sky Carbon Sequestration Group. Although no formal plans have been made, a path forward for this work includes actual monitoring of the Kevin Dome carbon sequestration site in Montana.

Each of the following sections of this report subdivide these results and analysis into two categories: 1) Surface Deformation Monitoring, and 2) Electromagnetic (resistivity change) monitoring.

Results from the surface deformation monitoring analysis show that the magnitude of surface deformation predicted from various models of carbon plume injection and leakage in realistic underground storage reservoirs, at realistic injection depths (~1 km) exceed 1 cm vertical displacement at the ground surface. This magnitude of surface deformation is sufficient for detection by current and past operational interferometric synthetic aperture radar (InSAR) satellites, in dry areas with little vegetation, without the need for installation of an array of radar corner reflectors (CRs), and this predicted deformation is sufficient in vegetated areas if an array of radar CRs are installed in the manner described in this report. In addition, augmenting InSAR satellite observations with ground-based radar interferometers (same ground vegetation cover criteria applies) can: 1) provide horizontal component of surface deformation for plume migration direction monitoring, and 2) provide real-time, on-demand data acquisition for identifying and characterizing caprock or other detected CO₂ leakage.

Results from the electromagnetic (EM) monitoring analysis show that the change in electrical resistivity introduced by the CO₂ plume and its chemical reaction with groundwater is sufficient to be monitored with EM methods. The CO₂ displaces pore fluid, making its storage formation
more resistive. Simultaneously, the formation becomes more conductive in places where the CO₂ is not as concentrated, but has interacted chemically with groundwater, producing carbonic acid and mobilizing ions. The EM monitoring methods must be sensitive to one or both of these changes.

The resistivity was modeled in three-dimensional (3-D) simulated surveys using magnetotellurics (MT) and borehole-to-surface direct current (DC) resistivity methods designed to take advantage of the favorable features of the Kevin Dome study area. Both methods result in underground resistivity models, but take different approaches to determining resistivity, resulting in differing degrees of sensitivity to subsurface features. Overall, DC resistivity produces a clearer image of the CO₂ plume. However, the field logistics of a 3-D DC resistivity survey make it more challenging to implement than an entirely surface-based MT. An MT survey is also easier to expand as the injection progresses beyond the initial area. Because very little additional fieldwork is needed to convert the DC resistivity sensor array to an MT sensor array, it is recommended that both methods be used until the plume becomes approximately 2 km in diameter. At this size, the plume is large enough that DC resistivity becomes prohibitively impractical and MT is preferable.
1. **INTRODUCTION**

The National Carbon Sequestration (NATCARB) Monitoring, Verification, and Accounting (MVA) program is tasked with monitoring CO₂ storage sites for compliance with the U.S. Environmental Protection Agency’s (EPA) Underground Injection Control (UIC) Program to ensure that potable groundwater sources and sensitive ecosystems are protected. The major monitoring technology areas are atmospheric, remote sensing and near surface, subsurface, and intelligent monitoring networks and protocols. The primary objective of the National Energy Technology Laboratory (NETL)-led National Risk Assessment Partnership (NRAP) is to develop simulation-based risk assessment tools needed for safe, permanent geologic CO₂ storage, as well as monitoring and mitigation protocols to reduce uncertainty in the predicted long-term behavior of a storage site (https://edx.netl.doe.gov/nrap). This multi-sensor monitoring assessment project addresses three technology focus areas within the NATCARB MVA program:

1. Remote sensing and near surface - (surface deformation, near surface electric resistivity structure) using ground and satellite interferometric radar, airborne transient electromagnetic (TEM), ground-based audiofrequency/radiofrequency natural and controlled source audio magnetotelluric/radiofrequency magnetotelluric(CSAMT/RFMT) methods
2. Subsurface - (surface deformation, electrical resistivity structure from 100–15,000 ft below ground level) using ground and satellite interferometric radar, audiofrequency magnetotelluric (AMT) and controlled source electromagnetic (CSEM) methods
3. Intelligent monitoring networks and protocols - (the optimized multi-sensor deployment and data acquisition schema), as well as the monitoring protocols focus area of the NRAP program

The technologies evaluated in this project were selected based on their suitability for monitoring CO₂ plumes, well leaks, and contamination of freshwater aquifers, as well as the experience and expertise of the team in working with them. Choosing the right technologies and determining their maximum sensitivity and resolution from various array configurations is part of the solution. Knowing which sensor variants, deployment configurations, and operating parameters to use comes from extensive experience in using them for various targets of interest. This is particularly important for engineered-natural geologic systems where anthropogenic sources of noise and the introduction of forced fluids play a dominant role in increasing the complexity of the subsurface being monitored. This approach leverages work the Oregon State University (OSU) and NETL/Albany team has conducted for DOE in Engineered Geothermal Systems (EGS), but seeks to tailor and refine the approach to evaluate its viability for monitoring CO₂ in the subsurface. The sensor array configurations we evaluated were drawn from the following geophysical methods:

1) *Differential interferometric real aperture radar, DInRAR (ground-based), and differential interferometric synthetic aperture radar, DInSAR (satellite-based) for surface deformation monitoring*

With the huge success of satellite-based differential interferometric synthetic aperture radar (DInSAR) for measuring surface deformations from a variety of natural and anthropogenic sources with sub-centimeter sensitivity over 1–100 km horizontal distances (e.g., Vincent, 1998, 2005; Vincent et al., 2003, 2011) the need for a ground-based radar interferometer with on-
demand data acquisition, portability, and higher resolution and sensitivity, motivated the development of ground-based real-aperture radar interferometer. The Gamma Portable Radar Interferometer-II (GPRI-2), recently acquired by OSU, is a second-generation, ground-based radar interferometer developed by Gamma Remote Sensing® in Gumligan, Switzerland (Werner, et al., 2008; Weismann, 2011). It operates at 17.2 GHz (0.0176 m wavelength) and was designed to measure sub-millimeter deformations using differential interferometric real aperture radar (DInRAR) from a wide range of targets and distances (20 m to 6 km).

2) Audiofrequency magnetotellurics (AMT) and related electromagnetic (EM) induction methods for fluid presence and migration

The ground-based class of methods involves measuring time-variations in natural and artificially induced electric (E) and magnetic (M) fields at a grid of survey locations above the reservoir. By transforming time series of EM fields into the frequency domain, where induced signals of lower frequency penetrate more deeply into the subsurface than those of high frequency, the 3-D (and if repeated over different measurement episodes, the 4-D, i.e. 3-D + time) variations in subsurface electrical resistivity structure can be imaged. Resistivity is a sensitive indicator of several subsurface conditions, but it is particularly sensitive to fluid content. Measurements can extend from the shallow near surface in the radiofrequency band, down to the base of the reservoir and below in the low end of the audiofrequency band and below, albeit with diminished spatial resolving power with greater depth. Such methods are used routinely for groundwater, mineral and hydrocarbon exploration as well as for larger scale geodynamic investigations, and in recent years these methods have been successfully applied to monitoring fluid injection at engineered geothermal systems (e.g. Peacock et al., 2012).

3) Electrical resistivity tomography (ERT) for CO₂ leak/brine detection, near-surface fluid mapping

Both cross-borehole and surface-to-borehole transmitter-receiver array configurations have been examined in preliminary sensitivity studies using direct current (DC) signal sources, with resulting electric fields detected by arrays of voltage sensing electrodes. Examples include the modeling work of Ramirez et al. (2003), who considered vertical arrays of point electrodes, use of metal-cased wells as electrodes, and measurements within directional (i.e. horizontal arrays). The use of down-hole voltage sensing electrodes, with surface arrays of grounded current transmitting electrodes has been examined in a study by Labitzke et al. (2012) at the Ketzin CO₂ storage pilot in Germany. In both cases, it was concluded that permanently installed electrode arrays in cased holes could offer the possibility for continuous time-lapse measurements to image fluid-flow processes over a much larger radius of sensitivity than borehole logging tools. While very promising, much work remains to determine the optimal array configuration including source-receiver geometry, signal source waveforms, and signal levels. This study will also consider EM induction (i.e. AC signal) tomography as well as DC resistivity configurations.

4) Airborne transient electromagnetics (TEM) for near-surface CO₂ leak detection and brine displacement of groundwater

Two wire coils, one transmitter and one receiver, are mounted either directly on an aircraft or in a towed instrument pod suspended from an aircraft. The transmitter’s EM field induces secondary electrical currents in conductive bodies on the ground that in turn generate a secondary EM field which is detected by one or more receiver coils. The strength of the secondary field, and the build-up and decay time are related to the conductance of the material in
the subsurface. Changes in conductance with time such as that from a CO₂ leak or from displacement of fresh groundwater with brine are potentially detectible. To the best of the authors’ knowledge this technology has not yet been explored for detecting near-surface fluids, but given the relatively rapid deployment and data acquisition that could be beneficial in time-critical leak detection and remediation efforts, and given NETL capabilities in helicopter deployed TEM, the potential advantages warrant serious investigation.
2. METHODS

This project was divided into three primary tasks:

Task 1: Candidate Sensor Investigation (2 months)

This study investigated candidate technologies applicable for monitoring CO₂ plumes in underground geologic storage sites. The list of technologies described above were evaluated by their performance on well-to-reservoir length scales in resolving pressure, CO₂ plume and/or displaced brines in time and space, choosing a subset of sensor array configurations for a detailed sensitivity analysis accomplished by computational forward and inverse modeling using numerical solvers appropriate to each sensor array type and configuration. Using previous deployment experiences associated with these technologies from the authors’ experience and from those of others, deployment and monitoring practices are recommended for each of the sensor array configurations selected that this study concluded are most likely to meet design objectives.

Surface Deformation Monitoring:

Methods considered include standard geodetic point measurement techniques (tiltmeters, strainmeters, and GPS) and remote sensing techniques (optical, multi-spectral, ground and airborne light detection and ranging (LiDAR)).

Point Measurement Techniques: The advantage of the point measurement techniques are they provide a continuous time series of position with time with very high precision. The disadvantage with these techniques (and the reason they were not selected) is the lack of continuous spatial coverage of the surface being measured. In addition, and largely because they are not spatially averaging the ground over wide areas, they can be contaminated by small-scale expansion and contraction of the local ground cover from thermal and moisture changes between day and night and between dry and wet conditions. Mitigating soil expansion/contraction can be done by digging vaults or pouring concrete pads, but this was considered impractical, too expensive, and still does not address the lack of spatial coverage provided by point measurements unless a very large number of instruments was deployed which would also be prohibitively expensive.

Remote Sensing Techniques: The advantage of remote sensing techniques—optical, multi-spectral imaging, and LiDAR—are that they provide a spatially continuous, wide-area coverage of the area of interest, and thus average out small perturbations from changes in the environment. Furthermore, environmental changes can usually be easily detected or known just by looking at the imagery itself. Image processing techniques can be applied to filter out environmental noise sources. The disadvantage of these techniques is that while (e.g., LiDAR) they can achieve high resolution (1 m pixels) they do not directly measure surface displacements. The only remote sensing technique available that does measure surface displacements is differential radar interferometry (both satellite—InSAR and ground-based interferometric real aperture radar, InRAR). Combining high spatial resolution (1–10 m pixels), wide-area coverage (>10,000 km²), with relatively low cost and ease of data acquisition (satellite DInSAR data are purchased at relatively low cost compared to point measurements covering the same area without spatially continuous coverage; ground based radar data are relatively inexpensive to collect after a modest ($250,000 initial investment of the radar equipment). The remainder of the project focused on these two remote sensing technologies and provide details of the data sources, methods, noise
sources, and satellite missions in the Phase I Report (Bowles-Martinez and Vincent, 2013) (see below).

**Subsurface Electromagnetic (EM) Resistivity Monitoring:**

The EM sensor candidates were narrowed down to two monitoring methods, DC resistivity (also known as electrical resistivity tomography or ERT) and magnetotellurics (MT). Details of other EM methods and their suitability for CO2 monitoring, as well as the down-selection process used to arrive at DC resistivity and MT as the methods of choice are given in the Phase I Report (Bowles-Martinez and Vincent, 2013). DC resistivity was also chosen because of its successful use in earlier CO2 monitoring projects that established its proficiency in monitoring CO2 on a small to moderate scale (Hovorka et al., 2013; Carrigan et al., 2013; Bergmann et al., 2012) in early stages of injection and on its potential to be scaled up to monitor a larger plume later in the injection. MT was also chosen because its successful use in monitoring geothermal fluids (Peacock et al., 2012) shows that it has the potential to be similarly useful in CO2 monitoring. The two methods were also chosen for practical reasons if a field implementation of this study is done, OSU has a fleet of instruments that are capable of collecting both types of data with very little labor required to switch between the two once the instruments are installed. The open prairie of the Kevin Dome field area (which has been selected as the preferred target implementation area) also allows for expeditious fieldwork, unobstructed by the physical obstacles that often make large 3-D surveys prohibitively impractical. This combination of unique instrument capabilities and an accommodating field area make these methods the optimal monitoring strategy.

**DC Resistivity:** A specialized electric current transmitter was used to inject approximately 10 A of current through the ground and an array of receiver electrodes was used to measure how the ground’s voltage varies across a survey area as the injection electrodes are relocated. Because electric current prefers to flow through the path of least resistance, these voltage measurements can be used to create an electrical resistivity model of the subsurface. This method is effective on scales ranging from the upper few meters to a few kilometers. It can generally resolve resistivity variations on the order of the spacing between receiver electrodes, known as the a-spacing. Because DC resistivity data collection can be very labor-intensive for large surveys, it is most often used on a smaller scale to image shallow targets in the upper 50 m. Large surveys to image targets in the upper few kilometers are mainly done for mineral exploration, especially in the copper mining industry. These surveys are almost always done as two-dimensional (2-D) profiles because the rough terrain of most mining regions does not offer the accessibility required for an efficient 3-D survey. A true 3-D survey requires a grid of wires to be placed over the survey area, which must be moved around manually as the survey progresses. Small-scale surveys simplify this by using multi-core cable, but that is not possible for a survey this size because the electrodes will be spaced 150 m rather than the 1 to 5 m typical of small surveys, the use of different electrode types for transmitter and receiver, and the high voltage and current used. When possible, wires are laid out along the ground by an operator driving an all-terrain vehicle (ATV). Care is taken to ensure transmitter and receiver wires only cross at orthogonal angles to minimize coupling by EM induction. The easily accessible terrain of the prairie minimizes the challenges normally associated with 3-D DC resistivity and is a significant reason why Kevin Dome is an excellent location for such a study.
One very compelling advantage of conducting a DC resistivity survey is it allows for simultaneous collection of induced polarization (IP) data, which treats resistivity as a complex quantity in order to evaluate phase. In IP, the Earth’s capacitor-like ability to hold electric charge is studied by measuring the time it takes for the Earth’s voltage to recover to background levels after the transmitter is turned off. This is analogous to treating the earth as a filtering resistor capacitor (RC) circuit, with each mineral grain or pore acting as a capacitor plate and the interface between grains or the gap between pores acting as the dielectric between plates. It is likely that dissolution of minerals when groundwater chemistry changes during injection will have a significant effect on chargeability. It has been shown that mineral surface area is altered significantly by CO2-related reactions in laboratory experiments (Wigand et al., 2008), but the effect this has on CO2 reservoir chargeability has never been quantified. With no basis to create a CO2 plume chargeability model, IP modeling has not been included in this report. However, it is worth collecting this data, as it should be useful in CO2 monitoring with some additional theoretical development, and would require no additional work in the field.

*Magnetotellurics:* The change in voltage across the Earth’s surface that accompanies the natural variations in Earth’s magnetic field was measured. This is done measuring the voltage drop across two orthogonal electric dipoles, which can be the same dipoles as those used in the DC resistivity survey. Simultaneously, the magnetic field variations are measured using induction coil magnetometers oriented in the x, y, and z directions.

MT is sensitive to changes in resistivity directly below it and around it, with the depth and radius of sensitivity increasing with lower frequency signals. Since each station samples a large region of the subsurface, using MT data alone, it is usually difficult to determine if a deep resistivity transition is abrupt or gradual, even with dense station spacing. One can address this by combining MT data with other geophysical measurements, such as overlying seismic stratigraphic information, and using the MT data, e.g., to constrain changes in fluid content within defined structures.

However, in addition to resistivity, MT offers a means to determine where changes in the dimensionality of the geological structure or its fluid content occur. A CO2 plume would present a sharp change in the effective dimensionality of the electrical structure at Kevin Dome. The background stratigraphy near the injection site is very flat, providing an essentially 1-D background of broad, flat layers. Emplacing a 3-D CO2 plume will mark a clear boundary in the dimensionality of electrical properties. In particular, the introduction of the plume will lead to electric charges being distributed along the boundaries of the plume that will be evidenced in the MT data as strong 3-D effects. These 3-D effects will be key to monitoring the CO2 plume.

**Task 2: Sensor Sensitivity Modeling and Analysis (8.5 months)**

For each of the sensor technologies and array configurations chosen in the preliminary investigation phase, analytical and numerical forward models were developed to simulate the detection of synthetic (hypothetical) plume sources of various sizes at various depths for sensitivity analysis. These models were used for synthetic resolution tests to determine theoretical and practical limits on each technology’s ability to resolve heterogeneity and structure within a given plume.
**Surface Deformation Monitoring:**

Satellite-Based DInSAR: Figure 1 shows the basic scanning and imaging geometry associated with DInSAR, the derivation of azimuth (flight or scanning direction) resolution for synthetic and real aperture radar systems, and an example of the sensitivity of DInSAR showing < 1 cm-scale subsidence occurring over one-to-several kilometers horizontal distance over a period of 5 years. Important differences between satellite and ground-based radar interferometers, including advantages and disadvantages of each are given in our Phase I Report (Bowles-Martinez and Vincent, 2013).

![Figure 1](image-url)

**Figure 1:** (A): InSAR repeat-pass imaging geometry. (B): InSAR repeat-pass scanning and subsurface cavity detection (Vincent, 2005). (C): Azimuth resolution derivation for synthetic and real aperture radars (McCandless and Jackson, 2004). (D): DInSAR signals of centimeter-level subsidence over past underground nuclear test at the Nevada Test Site (Vincent et al., 2003).
Ground-Based Differential Interferometric Real Aperture (Real Time) Radar (DInRAR): Figure 2 shows a schematic and example differential interferometry results of rapid (cm/hour) deformation measured by the scanning (rotating antenna) ground based radar system GPRI2 (Gamma Portable Radar Interferometer-2) instrument.

Figure 2: (A,B): Ground-based real aperture radar interferometer imaging the Tessina Landslide in Switzerland. (C): Schematic of the Gamma Portable Radar Interferometer -2 (GPRI-2) instrument. (Gamma Remote Sensing, Switzerland).
**Subsurface Electromagnetic (EM) Resistivity Monitoring:**

Computational tests were carried out for electromagnetic monitoring using simplified geologic settings and using existing carbon storage sites as a guide. Digital induction well logs were acquired from Regional Carbon Sequestration Partner sites to use as the basis to help constrain the lithology, mechanical parameters and electrical resistivity structure of the forward models used in the computational study. Geologic layer model data of the (planned) Kevin Dome carbon sequestration site were also acquired from the recent collaboration with MSU and the Big Sky Carbon Sequestration Group to construct a site-specific model for the Kevin Dome site in Northwestern Montana (see Task 3 below). While the site-specific plume models could not be fully completed within the relatively short project period (~11 months), this study was able to employ simplified geologic models for the resistivity forward modeling and analysis, and also used recently published predictive modeling results of surface deformation under different scenarios, including leakage from fractured caprock. It is hopeful that this work will continue during subsequent follow-on work, with completion of the Kevin Dome site-specific model and plume simulation, plus an actual monitoring of the Kevin Dome site.

**DC Resistivity:** There are many common electrode configurations in 2-D DC resistivity, but 3-D studies usually limit themselves to variations on the common 2-D electrode arrays. This is because multi-core cables are used in shallow surveys, which force electrodes to be arranged in parallel lines. This study is not subject to this restriction. In order to truly take advantage of the 3-D nature of this study, many electrode configurations were looked at, and after considering sensitivity to the target, ease of converting the array to MT, and practicality of field implementation, a final electrode array was decided upon. In order to image the CO₂ plume, an array with a transmitter electrode was used in a borehole at a depth that allows current to pass through the plume as it travels to its oppositely polarized electrode at the surface. The surface transmitter electrode is moved throughout the survey area to control the direction of current flow until the entire area has been covered. The receiver and borehole electrodes remain stationary. Figure 3 shows an example of how electric fields vary within the earth and along the surface, with equipotential lines and current vectors showing how electric fields and current flow are distorted by changes in resistivity along the current’s path between two surface transmitter electrodes. These distortions are what give us the subsurface structure in a DC resistivity survey.

The array of receiver and transmitter electrodes is shown in Figures 4 and 5. This array uses blocks of transmitter and receiver electrodes centered about a 6-channel receiver unit. These instruments are made by Zonge International and are equipped with radio transmitters for wireless instrument control across the survey area. Each block also has four transmitter electrodes located around the receivers. These are located in a way that minimizes the chance of inducing a distorting signal in the receiver wires created by the magnetic field from the current in the transmitter wire. A suggested plan for data collection logistics is presented later in this report.
Figure 3: Electric current travels between electrodes A and B. Electrodes M and N measure the change in voltage along the surface caused by the current flow. Using an array of many M-N dipoles across the field area, resistivity variations can be located.

Figure 4: Map view schematic of survey configuration with axes in meters, using an electrode spacing of 150 m. Black dots are electrode locations. Where dots are circled there is a recording instrument. Red marks are transmitter electrode locations. The blue triangle represents the borehole.
A Multisensor Plume Monitoring Schema for Carbon Sequestration Sites in Subsurface Engineered-Natural Systems

Figure 5: A single 6-channel receiver unit and associated electrodes, including wires for connecting electrode pairs as dipoles. Transmitter electrode locations are represented by lightning bolt symbols. This pattern is repeated across the survey area.

*Magnetotellurics:* Figure 6 shows a schematic diagram of an MT site at another location on the Northern Montana prairie. Through Faraday’s law of electromagnetic induction, the resistivity of the subsurface can be determined. Because the measured signals are produced by EM induction, MT tends to be more sensitive to conductive bodies than resistive ones.

Figure 6: This is a schematic of an MT instrument installation. The Ex and Ey dipoles are typically 100 m, but can be longer or shorter, and they need not intersect. Magnetometers are within a few meters of the instrument. A 12 V car battery powers the system. The background photo is of an MT station on the Montana prairie near Great Falls from an unrelated MT project by the authors in 2008. The CO₂ injection site has similarly open terrain and instrument installation should be very easy.

Unlike DC resistivity, whose sensor components are wired together in a large array, each MT measurement point is independent of the others. This allows stations to be located arbitrarily, allowing for an area of interest to be easily targeted or for the survey to be expanded as needed. Since natural signals are measured, no transmitter is required, vastly simplifying field logistics.

DC resistivity’s strong capability in resolving all types of targets and MT’s versatility in the field, combined with the fact that both survey types can be done with the same instruments makes this the optimal combination of survey methods.
Task 3: Scoping Next Phase Site-Specific Pilot Study (1 month)

Collaboration was initiated with MSU and the Big Sky Carbon Sequestration Group after investigating several candidate sites. This study was able to leverage the work done by this collaboration in constructing a geologic model of the subsurface used to construct a forward plume model for Kevin Dome, Montana. This model is currently in development and it is hoped that this study will be able to formalize what is currently a technical collaboration between OSU and MSU on the Kevin Dome site plume modeling and monitoring.
3. OBSERVATIONS

Surface Deformation

In order to determine if CO₂ plumes injected at plausible depths and at plausible rates could be observed over various timescales using radar interferometry (both satellite—DInSAR and ground-based—DInRAR) a modeling analysis was performed using recently published results for predicted surface deformation for two different reservoir settings.

This study began simulations using the Kevin Dome, Montana sequestration test site as the reservoir setting, but delays in data sharing, unanticipated delays from file and grid format conversion challenges, and technical challenges were experienced arising from stacking actual dataset layers with anomalous spikes and non-uniform grid sizes, etc. The time spent constructing the geologic model given these technical challenges delayed progress enough that this study turned to the latest modeling results in the literature to complete this analysis. However, these recently published results were compared with simulation results of symmetric versus elongate underground inflation/deflation expansion/contraction sources to ensure accuracy of the published results were used in this analysis. Furthermore, in addition to an intact reservoir system, the detectability difference between a fractured and unfractured caprock layer reservoir scenario was also explored, which was beyond the original scope of investigation. Thus, a wider range of scenarios were explored than would have been otherwise if this study had persisted with trying to complete the Kevin Dome, site-specific simulation.

In the first scenario analyzed, CO₂ is injected into a homogeneous poroelastic aquifer at different depths from 1–2.5 km at rates from 0.5–2.5 million metric tons per year (Mt/yr) (Rohmer and Raucoules, 2012). Figure 7 shows plots of maximum surface displacement (mm) and lateral extent of the detectable zone (km) (assuming a 5 mm vertical displacement detectability threshold) as a function of injection depth (km) for the geomechanical parameters listed in Table 1. This scenario predicts the minimum threshold (5 mm) vertical surface displacement is exceeded for rates of 1.0 Mt/yr or higher for injection depths above 1,500 m at 1 year of injection, and it is exceeded below 1,500 m injection depth at 1.5 Mt/yr injection rates or higher after 1 year of injection. In addition, this detection threshold is exceeded at a lateral distance of 2.5 km from the surface projection of the injection hypocenter for injection rates of 1 Mt/yr or greater from year 1 through year 10 of the injection.

These predictions suggest that for dry areas with little-to-no vegetation radar interferometry is suitable for monitoring this injection scenario.
A Multisensor Plume Monitoring Schema for Carbon Sequestration Sites in Subsurface Engineered-Natural Systems

Figure 7: A) Maximum vertical displacement (using Table 1 properties) reached at the surface respectively after 1 and 10 years (top and bottom panels respectively) considering different CO2 injection scenarios (mass injection rates and depths). B) Corresponding lateral extent (km) (using Table 1 properties) of the detectable zone at the surface after 1 and 10 years (top and bottom panels), after Rohmer and Raucoules (2012).

Table 1: Aquifer homogeneous properties used for the spatio-temporal analysis of the surface vertical displacements

<table>
<thead>
<tr>
<th>Aquifer Property</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intrinsic permeability</td>
<td>$k$</td>
<td>1.e-13</td>
<td>m$^2$</td>
</tr>
<tr>
<td>Porosity</td>
<td>$\omega$</td>
<td>15</td>
<td>%</td>
</tr>
<tr>
<td>Thickness</td>
<td>$H$</td>
<td>50</td>
<td>m</td>
</tr>
<tr>
<td>Salinity</td>
<td>$sal$</td>
<td>150</td>
<td>g/l</td>
</tr>
<tr>
<td>Rock matrix compressibility</td>
<td>$C_{rock}$</td>
<td>4.5e-10</td>
<td>Pa$^{-1}$</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>$E$</td>
<td>15</td>
<td>GPa</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>$\nu$</td>
<td>0.25</td>
<td>-</td>
</tr>
<tr>
<td>Biott’s coefficient</td>
<td>$b$</td>
<td>1.0</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 8 shows pressure (Pa) and vertical ground displacement (mm) as a function of lateral distance from the injection point (km) for different times post injection from 1 month to 25 years, for a laterally-moving CO2 plume front depicted in the accompanying cartoon. At an injection rate of 1 Mt/yr at 1,500 m depth, at least 2 years of injection are required for detection within 10 km distance from the injection epicenter, with lateral detection distance increasing exponentially with time to a maximum distance of approximately 10 km.
In the second scenario, CO₂ is injected into a layered subsurface geologic setting with and without a through fracture in the reservoir caprock layer immediately above the injection layer. Figure 9 shows the multi-layered geologic profile and model geometry, including a caprock layer above the saline injection aquifer, of a coupled-multiphase fluid flow simulation of a hypothetical 5-year, 6.89 MPa (1,000 psi) pressure differential (equivalent to about 5.4 Mt/yr or 27 Mt total) of CO₂ injection into a 1-km deep, 107°F saline aquifer. Figure 10 shows the predicted surface displacements (meters) from injection of CO₂ into the layered model geometry shown in Figure 9 for the case with and without a simulated fractured zone in the caprock layer. This simulation predicts a ten-fold increase in the surface displacement for the case of a through crack in the containment caprock layer compared to an intact caprock layer with no leak. This relatively large increase in predicted surface deformation from the leakage through the caprock layer is due in part to the lateral length of the caprock fracture. This conclusion is based on the authors’ modeling experience of predicted surface deformation from underground cavities and tunnels (Vincent, 2004). When the horizontal surface projection aspect ratio of an underground source of surface displacement is consistent with a tunnel or fracture (e.g., a leak through an elongate caprock fracture) the magnitude of resulting surface deformation grows exponentially with aspect ratio (Vincent, 2004).

The results from these two injection scenario environments strongly suggest that DInSAR has the sensitivity and spatially continuous coverage to adequately monitor CO₂ injection plumes.
over time periods of months to years provided that sufficient temporal data sampling is high enough for adequate interferometric correlation.

Figure 9: Multi-layered geologic profile (A) and model geometry (B) of a coupled poroelastic-multiphase fluid flow simulation of a hypothetical 5-year, 6.89 MPa (1,000 psi) pressure differential (~5.4 Mt/yr) of CO₂ injection into a 1-km deep, 107°F saline aquifer, from Siriwardane et al. (2013).
Figure 10: Vertical displacements (m) caused by injection of CO\textsubscript{2} without (A) and with (C) a simulated fractured zone in the caprock layer. (B) Plot of predicted surface displacements (ground uplift) caused by CO\textsubscript{2} injection for different offsets of caprock fracture from the injection point, from Siriwardane et al. (2013).
Surface Deformation Monitoring Strategy

With the establishment that the predicted surface deformation from various plausible CO$_2$ injection scenarios is at or above a reasonable vertical displacement detection threshold (5 mm), important aspects of and requirements for long-term monitoring in various environmental settings are discussed. A satellite-based DInSAR monitoring strategy must account for differences in vegetation cover and adapt accordingly by installing an array of radar CRs to be used as point-scatterers that maintain interferometric correlation with time when radar backscatter from vegetation will not maintain correlation with time. In addition, since carbon sequestration reservoirs require monitoring for up to 25 years or more, exceeding the life expectancy of SAR satellite missions, any strategy must utilize multiple and successive SAR satellite data sources.

Such a monitoring strategy has been suggested for a vegetated area in the Paris basin in France and similarly vegetated areas of Europe by Grataloup et al. (2009). Figure 11 shows the location of the PICOREF sector in the Paris basin with concentric circles of expected detectable (5 mm threshold) zones of surface deformation for different time durations up to 40 years for a 2 Mt/yr injection scenario. This area is moderately covered with vegetation and presents a challenge for standard radar interferometric methods, thus requiring the installation of an array of radar CRs for long-term monitoring of carbon storage monitoring.

Figure 11: Location of a prospective carbon sequestration site in the Paris basin (red outline) with concentric rings of detectability zones (progressively larger darker concentric circles) expanding outward from the proposed injection location (red cross), from Rohmer and Raucoules (2012).

Figure 12 depicts the multi SAR satellite mission data source overlap strategy necessary for long-term (>5 years) monitoring of carbon storage sites with moderate-to-heavy vegetation cover. Vegetated areas require the use of advanced data processing techniques referred to as persistent (or permanent) scatterer processing whereby a large number of strong and persistent radar backscatter ground targets (including an array of radar CRs) are processed as a stack in the
time dimension for statistical averaging canceling out of noise sources such as atmospheric noise. For each monitoring epoch (typically the duration of a SAR data source mission) a set of persistent scatterer interferometry (PSI) points must be chosen over the course of about a year of data collection for statistical robustness, at which point they can be used to monitor a single epoch’s worth of carbon storage. Then, at the beginning of the subsequent SAR satellite mission data source, a new set of points must be chosen (though many of the same points will wind up in the new set of points). This process can be repeated for many observation epochs.

Figure 12: Multi-sensor data collection and processing strategy for long-term CO₂ storage reservoir monitoring. Stars denote PSI baseline processing where a set of PSI points are selected for each observation epoch and must be repeat selected for each subsequent observation epoch, from Rohmer and Raucoules (2012).

Figure 13 shows photos of radar CRs deployment and presence in TerraSAR-X (TSX) SAR satellite imagery used at the Newberry Crater Enhanced Geothermal Systems project from 2012–present. The TSX image is an interferometric correlation image where dark purple = very low correlation, and yellow = high correlation. The study team installed 100 aluminum trihedral radar CRs (seen photos) in pairs in large trees below branch level. Each pair of reflectors had one pointed at the ascending orbit track of the TSX satellite, and the other pointed at the descending track. Approximately 47 CRs can be seen in the TSX correlation image suggesting a successful deployment of the CRs array in this heavily forested region.

Figure 14 shows photos of, and imagery from OSU’s GPRI-2 ground-based radar interferometer deployed near the top of Paulina Peak (visible in the background in the upper right CR photo), 6 km to the southwest of, and looking Northwest imaging the EGS stimulation zone.
Figure 13: Radar CRs visible in TerraSAR-X satellite coherence image. Approximately 47 reflectors (yellow dots) can be seen in this descending orbit image, from Vincent (2014).

Figure 14: (A) Photos of radar CRs deployed in the heavily forested Newberry Crater EGS stimulation zone with Paulina Peak visible in the distance in the top center photograph. (B) GPRI-2 ground-based radar interferometer deployed on Paulina Peak (6 km distant from ETS zone) during warm and cold conditions. (C) Radar backscatter image from GPRI-2 instrument looking NW from Paulina Peak toward Newberry EGS stimulation zone. (Vincent, 2014).
**Electrical Resistivity**

Modeling: Two different software programs were used to evaluate the two different methods of modeling. DC resistivity was analyzed using ZondRes3D, a 32-bit Windows program for 3-D DC resistivity inversion. MT was analyzed using ModEM, a 64-bit parallelized Unix operating system based MT inversion program that operates from a command line. Matlab was used to view the output of ModEM’s processing. The two programs use completely different model and data formats, so they had to be worked with independently of each other. Additionally, the memory limitations inherent in 32-bit computer programs required simplifications to be made to the DC resistivity model in order to avoid computer errors. This required the two methods to use slightly different model geometries, but the differences are not significant enough to affect the analysis. Both programs use finite-difference algorithms to solve for resistivity.

The geologic model of the stratigraphy of Kevin Dome provided by partners in Montana was resampled and converted to a resistivity model of the background material before injection. Several well logs from the area were examined to determine resistivity values for each formation. A detailed resistivity model was created, but the overall structure is as follows: the upper 600 m is fairly conductive, with resistivity of 15 to 20 Ω m. The next 500 m is more resistive, with resistivity ranging from 40 to 110 Ω m. Next is the target formation whose resistivity is 30 Ω m. Below this formation is 300 m of resistive material with resistivity of 200 Ω m. And below this layer is the crystalline bedrock, which was not sampled by well logs, but is expected to be highly resistive, so a value of 800 Ω m was assigned to it. Topography was not modeled, as it is insignificant at Kevin Dome.

The MT model was created directly from the stratigraphy of the geologic model provided by partners. It was divided into cells 95 m wide, 95 m long, and 30 m thick. The limitations of the DC resistivity program required a coarser model to be used. This model uses cells 150-m wide, 150-m long, and thicknesses varying from 30 m to 150 m, with more detail near the injection zone. The slight variations in subsurface topography were also ignored for the DC resistivity model, with the slightly dipping layers made flat. It would have been preferable to use the same model geometry for both methods, but software limitations prevented this. In the end, this did not affect the success of the experiment.

Three stages of plume injection were modeled for each method. The first corresponds to a plume diameter of 300 m, a plume diameter of 650 m is used for the second, and the third plume model is 1,100 m in diameter, corresponding to the expected size at the end of CO2 injection after 4 years. The model’s basic shape is a disc of resistive material at the top of the storage formation, where CO2 saturation is high. Resistivity is greater and the plume is thicker near the plume’s center.

The plume model also has a zone of increased conductivity surrounding the area of high saturation. This corresponds to the zone where CO2 has interacted chemically with groundwater to make the fluid more conductive (Börner et al., 2013) and CO2 saturation is too low to increase resistivity by fluid displacement. This conductive zone encircles the plume and fills the space immediately below it. This conductive zone is crucial to the success of MT imaging CO2. Its presence depends largely on the pre-injection salinity. A storage formation in a highly saline aquifer will see no decrease in resistivity and CO2 detection will depend solely on a method’s sensitivity to a resistive target. If the storage formation contains water like a potable aquifer, the resistivity contrast from chemical change will be very strong, but the increase in resistivity from
fluid displacement will not be as strong, and a method sensitive to conductive bodies will be more successful. The moderately saline groundwater of Kevin Dome calls for an intermediate plume model that includes both conductive and resistive parts (Börner et al., 2014). Figure 15 shows the shape of the plume filling the top of the storage formation for the three injection stages as used in MT. The plume models used in DC resistivity are similar, but with slightly different geometry to accommodate that program’s requirements.

![Figure 15: Models of resistivity change caused by the CO2 plume for the three different injection stages. The plume is modeled in layers 30-m thick. The uppermost layer is on the left and the lowest layer is on the right. The earliest stage of injection is the small series of plots at top (A). Interim stage (B). Final stage of injection is at bottom (C). Each cell is approximately 100 m square. The high-concentration of the plume center has a resistivity increase of up to six times the pre-injection level, while the areas where CO2 has affected water chemistry without accumulating have a resistivity drop by up to 0.15 times.](image)

**DC Resistivity:** DC resistivity is more successful overall at imaging the plume. Its non-reliance on induction allows it to be very sensitive to both conductive and resistive regions, which is a huge advantage in high-salinity formations where the plume will not have a conductive fringe. In the moderately resistive Kevin Dome area, DC resistivity successfully images the conductive and resistive features of the CO2 plume in the latter two injection stages, but the earliest stage of the injection remains undetectable.

Different electrode arrays were considered, however because of the desire to use the same instrument configuration for both DC resistivity and MT, and because the gridded electrode array is capable of measuring voltages equally well in both x and y directions, the locations of surface
electrodes were not altered. This left the borehole electrode depth as the main variable to adjust. With an injection depth of 1,150 m and a storage formation 100-m thick, the optimal electrode depth was found to be 1,400 m. This was determined by forward calculating the response to the model with the plume present, then inverse using a smoothness-constrained least squared inversion method to try to recover the plume when starting from a model with no plume. The ideal solution would result in a model that contains the original plume. But because the inverse problem is underdetermined, there are many solutions that satisfy the least squares minimization equally well. Therefore, it is impossible to recover the exact plume that was modeled, but something similar should appear. Smoothing is used to avoid regions of high contrast that make mathematical sense, but are geologically unrealistic. Models resulting from inverse solutions tend to have smooth boundaries.

One thing that was noticed is that an anomaly appears immediately around the borehole electrode that has some resemblance to the plume, even though it is at the wrong depth. The shape of this anomaly appears to be influenced by the resistivity structure of the entire subsurface between the surface and borehole electrodes, not just the plume (Figure 16). It is important to be aware of this and avoid placing the electrode at a depth where this anomaly will overlap the true location of the plume. Through experimentation, it was determined that locating the electrode 200 to 300 m below the storage formation provided the clearest image of the plume. Results of inverse modeling demonstrating that the final large plume is recovered are shown in Figure 17. This figure shows a horizontal cross-section at injection depth for both the actual plume and the plume recovered by the inversion. Not only is the plume’s presence detected, but the breaks in its radial symmetry are also imaged, indicating that elongation and non-symmetric plume migration should be imageable. The amplitude of the resistivity change is reduced significantly, from a contrast of tens of $\Omega \text{ m}$ to just a few $\Omega \text{ m}$, but this is within the detectable range. It is also noteworthy that the plume’s depth is well-constrained. A larger overview of the recovered plume model is shown in Figure 17.

Figure 16: At the depth of the borehole electrode, this “false plume” appears. It is roughly the same size and shape as the true plume, but at the wrong depth. Interestingly it appears to contain resistivity information integrated along the entire current path, with elements visible of all the model layers that represent the plume.
The effectiveness of DC resistivity in imaging a CO₂ plume that has expanded well beyond the original injection site was also explored. After several years, longer than the initial four years of the Kevin Dome study, the plume’s edge will be too far away from the borehole electrode for it to be useful, so a surface-only array was examined. At this stage of injection, the plume will be so large as to be impractical to cover it with a grid of electrodes. Instead lines of electrodes running in only the east-west direction were modeled. This was done to address the desire to quickly cover a large area and because the goal is only to detect the presence of the plume, not image any details. A pole-pole electrode array was used, which requires minimal labor and can be done in less field time than other arrays. Modeled this way, it is similar to creating several parallel 2-D profiles rather than a 3-D survey.
Applying this array over the large and intermediate plume stages gives encouraging results. In the east-west direction, a broad anomaly is visible that gradually intensifies above the plume. A weaker version is visible for the smaller plume, shown in Figure 19. This could be sufficient for imaging the plume’s extent in the long term if it is sufficient to locate the boundary only within a few hundred meters. While this array requires less labor than the borehole-surface survey, it is still subject to the limitations that make DC resistivity logistically challenging, namely the use of cumbersome long wires, a powerful transmitter, and inflexibility with measurement locations. MT is never subject to these limitations, so MT may yet prove to be more useful in long-term monitoring. A discussion of MT’s capabilities follows.

Figure 19: Results from surface-only pole-pole array, which could be helpful for locating the plume’s extent in much later stages of injection. (A) final plume model, (B) is an intermediate-sized plume.

Magnetotellurics: The plume was also detected with MT, but this portion of the study had less success at imaging it through inverse modeling. It is visible in the final stage of injection as a very broad and weak region of low resistivity, demonstrating that the resistive zone of high CO₂ saturation is not imaged (Figure 20). This low resistivity zone is visible even with 5% noise added to the data. The depth is poorly constrained and the inversion also adds a false plume zone in the shallowest 500 m. The plume’s conductive zone is very faintly visible in the intermediate injection stage (Figure 21), but when noise is added it nearly vanishes, and what is visible does not accurately fit the true shape of the plume.
Figure 20: MT inverse model recovers only a very broad, gradual plume shape with only the conductive parts imaged. This includes 5% noise added. Axes units are in meters and resistivity is given in $\Omega \text{ m}$. 
Figure 21: (A) Intermediate plume is barely visible with inversion when no noise is added. With 5% noise (B), there is still an anomaly, but it is no longer the correct shape, which could be misleading in showing plume migration. Axes units are meters and resistivity is given in $\Omega\text{ m}$.
The weak imaging of the plume is due to the very minor change it adds to the conductance of the subsurface. Therefore, instead of imaging the plume through inversion to produce a model of resistivity, the data are analyzed to look for difference in the magnetotelluric impedance tensor before and after injection. The impedance tensor is a transfer function that relates the electric and magnetic fields through the following equation:

\[
\begin{bmatrix}
E_x \\
E_y
\end{bmatrix} =
\begin{bmatrix}
Z_{xx} & Z_{xy} \\
Z_{yx} & Z_{yy}
\end{bmatrix}
\begin{bmatrix}
H_x \\
H_y
\end{bmatrix}
\]

Where \( E \) is the electric field and \( H \) is the magnetic field, both measured in the \( x \) and \( y \) direction. \( Z \) is a rank 2 tensor whose elements are complex. The magnitude of the tensor elements gives us the apparent resistivity and their phase angle suggests where boundaries between higher or lower resistivity layers are located. The values of the impedance tensor’s elements can also indicate changes in dimensionality. A 1-D layered earth will have \( Z_{xy} = -Z_{yx} \) and \( Z_{xx} = Z_{yy} = 0 \). Two-dimensional structures will produce different values for \( Z_{xy} \) and \( Z_{yx} \), but \( Z_{xx} \) and \( Z_{yy} \) will remain 0. If all tensor elements are nonzero, the station is located above a 3-D structure. These values are typically plotted against frequency, so changes in dimensionality with depth are visible at each station. However, converting frequency to depth requires a resistivity model. Without one, depths can only be estimated. A plot of impedance tensor elements converted to apparently resistivity and phase is shown in Figure 22. This figure shows a station in a highly 3-D part of the survey area, and the before-and-after difference in the diagonals of \( Z \) is much greater than the off-diagonals. This demonstrates the sensitivity to changes in dimensionality.

Examining how the tensor elements vary with distance across the survey area and with frequency as a representation of depth, pre- and post-injection impedance tensors can be used to determine the extent of the CO₂ plume. Figure 23 shows this as a plot of the normalized before-and-after difference of the four elements of \( Z \) as they vary across the survey area for several representative frequencies. It is important to note that the magnitude of the difference is very small, so this method’s effectiveness will depend on having low-noise data. It is also important that the difference between diagonal elements is much larger than the off-diagonals, as shown by the color scales, so these may be the key to successful use of this method in a noisy setting. Because the diagonals tell us where the subsurface structure becomes 3-D, this method requires that the survey is done with a 3-D target in mind. That is, it must cover an area rather than be done as a profile. Figure 24 shows this now with the intermediate plume. The signal is much weaker and the off-diagonals will almost certainly be overwhelmed by noise. Because noise is so pivotal to the success of this method, Figure 24 shows an attempt to maximize the signal by summing the impedance tensor difference for all frequencies. This allows the plume-related anomaly to be much bigger, as shown by the color scale, but all information regarding depth is lost.
Figure 22: Plots of each component of the impedance tensor $Z$ from left to right: (A) $Z_{xx}$, (B) $Z_{xy}$, (C) $Z_{yx}$, and (D) $Z_{yy}$. This shows a station along a diagonal edge of the plume, where the 3-D effect is strongest. The main thing to look at is the apparent resistivity curves. Two curves are shown in each plot, one from before injection and one after. The curves show that the relative change in apparent resistivity is much greater for $Z_{xx}$ and $Z_{yy}$ (the diagonal tensor elements) than for $Z_{xx}$ and $Z_{yx}$ (the off-diagonals). The difference is so large that even when different scales are used for the plots, the off-diagonals have a negligible difference in this area of the survey. This shows that the 3-D effect is very strong and the diagonals are responsible for most of what the inversion recovers.
Figure 23: Normalized before-and-after differences in impedance tensor $Z$ at four different frequencies in the final plume stage. Each pixel represents one MT station on a 30 x 30 grid of 900 stations spaced 95 m apart. This is more than a realistic survey would use, but it illustrates the method. A realistically reduced survey would show a similar but more pixelated image. 

A): 19 Hz. This represents a skin depth of approximately 650 m, well above the CO$_2$ injection. Very little plume-related signal is visible. 

B): 5.7 Hz. This frequency corresponds to a skin depth of about 1,250 m, very close to the injection depth. The off-diagonals show a plume shape clearly, but the magnitude is very small. The diagonals show a signal that traces the outline of the plume, where dimensionality changes. 

C): 2.8 Hz. At about 2 km skin depth, the plume is still visible with almost the same magnitude as at 1,250 m. The diagonals trace the outline even more clearly. 

D): 0.7 Hz. The skin depth of 3.5 km still shows the plume, showing that it is difficult to resolve the bottom of conductors with MT. Plume diameter here is 12 pixels. See Figure 15 for actual plume size and characteristics.
While the plume’s presence is more obvious through this method than through inverse modeling, it suffers from the same problem of gradually appearing with no sharp boundaries. The overall shape is clear, but it is difficult to say with certainty where the edge of the plume is. If it is sufficient to know the boundary to within a few hundred meters, this method will be acceptable.

This method was also used to determine if MT is suitable for locating a leak. A CO₂ leak was modeled as a narrow vertical conductive feature. It is entirely conductive with no resistive area because the CO₂ concentration would be low enough that the decrease in resistivity from chemical alteration would dominate. In the model, this feature begins at the top of the capping formation with a width of one cell (95 m). At a point halfway to the surface it expands to 3 cells in diameter. Figure 25 shows that it is very clearly visible as an anomaly in the stations near the leak. MT sensitivity depends on the conductance, the product of conductivity and thickness, so a vertical column of moderate conductivity shows up very clearly against the background.
Figure 25: The method employed in Figure 24 is used to locate a narrow leak in the capping formation. Because the leak-related anomaly is so strong, this figure uses a different color scale than the previous figures. Even a much coarser survey grid would easily image the leak.

**EM Monitoring Plan:** A plan that makes the most of these two methods will take advantage of the ease of access at Kevin Dome and the capabilities of the instruments to monitor the CO₂ plume in 3-D. Both methods will use the same instruments without relocating any equipment to switch between DC and MT. A baseline set of measurements must be made before injection, then once per year during injection.

Because the field work involved in DC resistivity is more complicated, it is described first and then the modifications needed to make it an MT survey are discussed. Located within 500 m of the injection site and at a place where it can be accessed again for future surveys will be the borehole electrode at a depth of 1,400 m. This is a piece of copper, usually plumbing pipe, attached to an insulated wire and lowered to the bottom of the borehole where it will make contact with the ground. Drilling mud can be used to improve contact resistance with the surrounding rock. Next, wires are laid across the ground to form the grid shown in Figure 4 connecting receiver electrodes with their associated instruments. This is efficiently done by an operator driving an ATV that drags pre-cut wires along straight lines and drops them off where they will be connected to an electrode or instrument. Receiver electrodes can also be installed and instruments can be dropped off when the ATV operator reaches each dipole’s end point. Next, the transmitter wires will be placed to connect the surface electrode to the transmitter. Since only one surface transmitter electrode is active at a time, there need only be enough wire laid out to power one at a time, which can then be moved to the next electrode as the survey progresses. Additional transmitter wire can also be laid out to expedite manual electrode switching during the survey. It is important to ensure that transmitter and receiver wires only cross orthogonally to avoid distortion by induction. Transmitter electrodes can be built in advance or as the survey progresses, depending on available manpower. These are typically made of 5 to 10 steel pipe segments about half a meter long that are hammered into the ground in a cluster and wired together.
Once the survey equipment is set up, recording can begin. There must always be one person at the transmitter and at least one person along the grid to switch electrodes and move wires. The most important thing is good communication between the transmitter operator and the electrode worker to confirm whether the transmitter is powered on or not, or else electrocution may occur. The transmitter operator must also record how much current was transmitted at each electrode position if this is not recorded by the electronics. The instruments are equipped with radio transmitters that allow them to communicate start and stop signals to each other without an operator manually turning each one on and off. Once data collection has finished at every electrode position, the array can be converted to record magnetotellurics.

Converting to MT involves disconnecting three of the receiver dipoles and plugging induction coil magnetometers into them, which must be oriented parallel to $x$, $y$, and $z$ directions. The electric field dipoles can be two of the remaining orthogonal dipoles that were not replaced by magnetometers, and they should make an L shape with the instrument in the corner of the L. Recording should take place for at least a day. If additional resolution is desired, more stations can be added easily by moving all recorders and magnetometers diagonally across the survey area so that they are now in the place where a transmitter electrode was located and recorded for another day. They can be connected to other electrodes already installed for the DC survey by moving the wires. Wire moving can be done while the MT data are recorded.

If future expansion is desired when the plume has expanded far beyond the original survey area, MT is recommended. Its simple field logistics and independent stations allow a large area to be covered efficiently. By this time in the injection, it is expected that a few hundred meters of uncertainty is acceptable, so the detail of surface-borehole DC resistivity is not needed.
4. CONCLUSIONS

The results from this study can be used as a guide for geophysical monitoring of carbon sequestration sites worldwide. Drawing on both the latest studies published in the scientific literature as well as these modeling results, this study assembled a monitoring schema that incorporates both mechanical and electromagnetic phenomena monitoring methods that can be used to help plan monitoring activities for various types of underground reservoir carbon storage sites.

Surface Deformation Monitoring

New information about what can be detected, and how to detect it under different conditions, using satellite and ground-based differential radar interferometry is highlighted in this report. Specifically, a surface deformation monitoring schema is presented, with examples drawn from the scientific literature, these simulation results, and the authors’ own experience monitoring enhanced geothermal systems at Newberry Crater, Oregon. The practicalities of the technologies selected as best for this monitoring are detailed in this report, and the details of the data sources available as well as the most important noise sources are provided in the Phase I Report (Bowles-Martinez and Vincent, 2013).

For dry areas with little vegetation cover, this study concluded that no array of radar CRs are needed to provide sufficient persistent scatterers; the ground return and correlation with time is deemed stable in these areas to use standard conventional data collection and processing techniques. Given that the areal coverage (swath width) of current and historic satellite SAR missions to date cover areas extending 10,000 km², there is no need to adjust the monitoring area covered by these SAR satellites with time as the plume spreads outward as there is ample areal coverage at high resolution for all monitoring epochs envisioned (over multiple SAR satellite data sources).

For areas with moderate to heavy vegetation cover, installation of an array of 100 or more (as many as cost effective and practical given potential permitting and logistic constraints) aluminum trihedral radar CRs is recommended, similar to those shown above, spread out according to the time-dependent monitoring schema presented in this report. Specifically, during the first observation epoch of 5 years or so, an array aperture of approximately 1–3 km radius from the injection well would capture 90% of the expected surface deformation from underground plume migration. For each successive epoch, the array should be expanded according to Figures 7 and 8. While the spatial density of CRs can be reduced with each epoch, it is recognized that installation labor considerations might prefer to leave those CRs already installed where they are and simply add additional CRs radially outward at decreasing spatial density with each successive monitoring epoch.

This report has provided a set of guiding principles for the mechanical monitoring of the surface deformation expected from subsurface CO₂ plumes, which also equally apply to monitoring for unexpected leaks through caprock layers. Since every potential site will be different, the exact monitoring strategy will deviate to accommodate different reservoirs and monitoring situations. However, it is recommended that in all situations, this monitoring schema for surface deformation be used both as a guiding principal and monitoring scoping tool.
Resistivity (EM) Monitoring

The EM portion of this study clearly shows the strengths of the DC resistivity and MT methods in imaging a CO\textsubscript{2} plume. It is clear that only DC resistivity is sensitive to the CO\textsubscript{2} itself, with MT, using conventional inverse modeling methods, sensitive directly to the conductive fringe around the CO\textsubscript{2}. The presence of this zone depends on the chemistry of the groundwater, and it might not exist in groundwater whose pre-injection resistivity is already very low due to high salinity levels. This suggests that MT becomes less effective as salinity increases. This makes DC resistivity a safer bet if only one method is available.

A novel application of MT used successfully in this study is to look for changes in dimensionality rather than resistivity. This highlights the difference between before and after injection by emphasizing the diagonals of the impedance tensor, which are usually close to zero unless 3-D structure is below. Plotting dimensionality change across the area has shown to be a useful tool for showing the plume’s lateral extent, but the plume depth is poorly constrained. It is also an effective way to detect CO\textsubscript{2} leaks.

The versatility of the proposed survey grid is another important result of this study. Instruments that are capable of radio communication between each other to efficiently record both MT and DC data across a large area have only been introduced very recently, no previous surveys of this type have been done. It would be very useful to implement this in a real study and evaluate its real-world effectiveness. The Kevin Dome area’s open accessibility makes it the ideal location for this.

Some of the uncertainty in this study was in modeling the electrical properties of a CO\textsubscript{2} plume. Very little work has been done to show how rock resistivity changes in different rock types and groundwater chemistries when CO\textsubscript{2} is introduced. Because this study is working close to the critical point of CO\textsubscript{2}, it is also important that a range of temperatures and pressures are examined. Such a study would go a long way to ensuring the CO\textsubscript{2} is accurately modeled. This problem has been partially addressed in laboratory experiments by Börner et al. (2013), but only a few scenarios were tested. Along with the resistivity changes that CO\textsubscript{2} brings, it would also be useful to have laboratory experiments to measure the change in rock chargeability during injection. This would allow IP to be modeled. IP could show where mineral dissolution has occurred, effectively highlighting the trail of CO\textsubscript{2} even if the groundwater becomes resistive again due to either chemical change (Dafflon et al., 2013) or subsurface groundwater flow.

However, no work has been done to show how chargeability will be affected at in situ conditions. This will be important to know, because this property is highly dependent on the chemistry and mineralogy of each aquifer.

Next Steps

An improved ΩMT approach for future development. For the conventional inverse modeling problem, as done for the present study, the data is the impedance, and the model is the resistivity of the subsurface. For the case of an introduced CO\textsubscript{2} plume, where the change in resistivity structure is small, a promising future development would be to re-pose the MT inverse modeling problem. Rather than inverting the impedance (the data) directly for the resistivity (the model), this study suggests inverting the change in impedance for a plume scenario relative to a baseline impedance without a plume (the Δdata) directly for the change in resistivity relative to the baseline resistivity (the Δmodel). As seen from Figures 23–25, the change in the off-diagonal terms of the impedance tensor, which is overwhelmingly attributed to inductive effects, is quite
small (well below 1%, or below the expected levels of confidence limits for impedance tensor values), but the change in the diagonal elements of the impedance tensor, which is attributed to 3-D effects, including galvanic terms due to charge distributions along the boundaries of the CO₂ plume, is quite large. The ∆impedance therefore present a strong target for a 3-D inverse modeling effort for an inversion for ∆resistivity. Testing this concept will be the focus of ongoing work at the enhanced geothermal systems project at Newberry volcano in Oregon, but it is equally applicable to follow-on work for CO₂ sequestration at Kevin Dome, Montana, and elsewhere.

**Field Program.** The next step to continue this work is to monitor an actual carbon storage site. In this regard, given the initial collaboration with MSU and the Big Sky Carbon Sequestration Group, the next step would be to formalize the collaboration between OSU and MSU and the Big Sky Carbon Sequestration Group in the form of a joint proposal to the U.S. Department of Energy to do geophysical monitoring of the Kevin Dome carbon sequestration site in Northern Montana.
5. **REFERENCES**


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