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U.S. Department of Energy Efforts to Advance Remote Sensing Technologies for Monitoring Geologic Storage Operations

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Abstract

The United States Department of Energy (DOE) is the lead federal agency for the research, development, demonstration, and deployment (RDD&D) of carbon storage technologies. Monitoring, verification, accounting and assessment (MVA) is an essential element of geologic CO_2 storage projects, since without MVA it is not possible to understand the fate of CO_2 in the injection formation or to monitor any potential CO_2 releases to underground sources of drinking water (USDW) or the atmosphere. Determining the location of CO_2 in the subsurface and identifying indicators of the potential release of CO_2 to the atmosphere are significant challenges requiring the adoption of existing technologies as well as novel approaches for monitoring large areas above a storage reservoir. Remote sensing technologies could offer a solution. Remote sensing refers to the use of monitoring tools that can gather data at a location remote to the area of interest, and could provide an option for non-invasive and large scale spatial monitoring.

The National Energy Technology Laboratory (NETL) has been developing and deploying remote sensing applications over the past decade to improve monitoring of both geologic and terrestrial carbon storage projects. MVA remote sensing tools being developed or improved by NETL sponsored research include interferometric synthetic aperture radar (InSAR), tiltmeters/GPS, remote operated vehicles (ROVs), SEQURE™, light detection and ranging (LIDAR), and multi-spectral/hyper-spectral scanning. Benefits associated with NETL's remote sensing effort include development and deployment of non-intrusive tracking and monitoring technologies, reduced manpower requirements needed to meet potential regulated MVA requirements, and reduced costs to implement monitoring technologies. These technologies can provide early detection of CO_2 releases which, in turn, will allow for further refinement of project monitoring protocols using more conventional detection and mitigation technologies to better pinpoint CO_2 location.

This paper addresses selected remote sensing techniques under NETL development and field deployment of these technologies.

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Introduction

The United States Department of Energy (DOE) is the lead federal agency for the research, development, demonstration, and deployment (RDD&D) of carbon storage technologies. The Carbon Storage Program implemented by the DOE's Office of Fossil Energy and managed by the National Energy Technology Laboratory (NETL) is helping to develop technologies to capture, separate, and store CO_2 in order to reduce greenhouse gas emissions without adversely affecting energy use or hindering economic growth [1]. This effort is implemented through several activities, including applied research and development, demonstration projects, and technical support. The goal of the program is to develop a suite of technologies and protocols by 2020 that:

- Support industry's ability to predict CO_2 storage capacity in geologic formations to within ±30 percent.
- Develop and validate technologies to measure and account for 99 percent of injected CO_2 in the injection zones.
- Develop technologies to improve reservoir storage efficiency while assuring containment effectiveness.
- Develop Best Practice Manuals for site selection, characterization, site operations, and closure practices [2].

Carbon capture, utilization, and storage (CCUS) technology development requires MVA technologies to understand the dynamics of the CO_2 injection formation before, during, and after injection. These tools allow operators the ability to track the CO_2, pressure front and to monitor for any potential signs of CO_2 release from the injection formation [3]. NETL is advancing MVA capabilities through designing and developing reliable and cost-effective technologies that can confirm permanent storage of CO_2 in geologic formations.

Existing technologies are being applied and novel approaches are being developed through NETL's Carbon Storage Program to determine the migration and extent of CO_2 in the subsurface and identify indicators of its migration out of a storage formation to overlying groundwater and the atmosphere. Remote sensing refers to the use of monitoring tools that can gather data at a location remote to the area of interest and could provide an option of non-invasive and large scale spatial monitoring. Remote sensing provides a means to rapidly obtain data for a large area of interest or obtain data not otherwise available from sensors located more proximal to the area of interest. MVA remote sensing tools under development or improvement by NETL sponsored research include interferometric synthetic aperture radar (InSAR), tiltmeters and global positioning system (GPS), remote operated vehicles (ROVs), passive multi-spectral scanners (SEQURE^{TM}), and multi-spectral/hyper-spectral scanning. The continued development of these technologies contributes to the set of MVA tools available for CCUS projects to cost effectively, efficiently, and accurately track CO_2 to ensure that it is safely and permanently stored. The benefits of remote sensing and a discussion of each technology's individual contribution to the continued development of CCUS toward a commercially viable industry are discussed below.

An effective MVA program for a carbon storage site is essential for adequately tracking CO_2 plume migration and monitoring potential releases. Key parameters and the reasons for monitoring them include:

- Monitoring injected or displaced fluids to update and validate subsurface models.
- Formation pressure and in situ stress monitoring aids detection of breaches in the confining zone(s).
- Monitoring zone (immediately above the confining zone(s)) pressure and temperature allows for early detection of CO_2 movement outside the confining zone(s).
- Well integrity monitoring increases confidence that fluid movement is not occurring via the wellbore outside the injection tubing.
- Monitoring CO_2 concentrations and fluxes and fluid composition enables detection of CO_2 in the groundwater or at the surface [4].

Benefits of Remote Sensing Technologies to MVA

NETL is providing funding to develop and refine remote MVA technologies for addressing the technical monitoring challenges through the Core R&D and Regional Carbon Sequestration Partnership (RCSP) efforts. This includes the deployment of these technologies at CO_2 injection field sites, both domestic and internationally. Remote MVA sensing technologies are a significant part of this effort due to their unique benefits and capabilities. The following is a list of some of the benefits of remote sensing technologies:

- The ability to monitor large areas from a remote location. These technologies can be used to monitor large commercial-scale carbon storage CO_2 plumes, typically up to 100 km^2 in size [5].
- Allows for MVA in storage settings where on-site access may be difficult or restricted due to topography, offshore conditions, or have surface/access restrictions.
- Provide an early warning system that indicates potential releases. At that point, a more focused approach can be used for a more detailed assessment.
- Reduced labor requirements to implement, maintain, and monitor. Remote sensors do not require large- scale deployment over the areal extent of a carbon injection site when compared to more intrusive methods.
- Relatively inexpensive when compared to other monitoring methods. Deployment of in situ sensors on a carbon storage site-scale requires much more infrastructure and maintenance than a single remote sensing platform.

The following table provides a summary of the remote sensing MVA technologies and performers that are part of ongoing NETL funded RDD&D efforts.

Table 1. NETL funded remote sensing technology summary.

Technology	Performer	Definition	MVA Applications	Limitations
Surface Displacement - InSAR (Interferometric synthetic aperture radar)	• Lawrence Berkeley National Laboratory • Lawrence Livermore National Laboratory • University of Miami • TRE Canada and BP	Satellite-based technology used to measure surface deformation at CO_2 injection sites.	• CO_2 plume and pressure front tracking • Detect geomechanical effects on storage formation and caprock.	Data processing can be time consuming. Sensitive to land use changes and availability of benchmarks. Works best on level, low vegetation ground surfaces.
Surface Displacement Tiltmeter/GPS	• Lawrence Livermore National Laboratory • University of Miami • Advanced Resources International	Surface-based technology used to measure surface deformation or subsidance at CO_2 injection sites.	• CO_2 plume tracking • Detect geomechanical effects on storage formation and caprock	Labor-intensive process can lead to increased costs. Requires onsite surface and subsurface access. Reliability of tiltmeters can be effected by drift.
ROV (Remotely Operated Vehicles)	• SCRIPPS	Customizable remote platform used to conduct multiple surveys of inaccessible locations.	• Gravity fluctuation measurements for CO_2 plume tracking • Leak detection	ROV requires a large support platform (and labor force) to conduct operations. Limited capabilities due to potential lack of attenuation.
Multi-Spectral/ Hyper-spectral Scanners (LANDSAT, SPOT, Quickbird, LIDAR)	• Lawrence Livermore National Laboratory • West Coast Regional Carbon Sequestration Partnership • Midwest Geological Sequestration Consortium • Nature Conservancy • Montana State University • University of Michigan	Multi-platform scanner used to measure changes in floral cover, surface features, and land forms.	• Pipeline and underground leak detection • Surface vegetation monitoring for terrestrial storage.	Data processing can be time consuming and high-resolution imagery may not be able to detect subtle features and variations based on study area. Soil gas data required to interpret CO_2 concentration/flux results.
Passive Scanners (SEQURE^{TM})	• NETL	Airborne-based platform used to detect CH_4 and CO_2 leaking from the subsurface.	• Pipeline and underground leak detection • Abandoned wellhead identification	Scanner effectiveness can be limited by resolution, size of study area, and method of deployment. Short duration CO_2 release may not be detectable. Requires determining background concentrations.

Surface Displacement Monitoring

Injected CO_2 causes the fluid pressure of the injection formation to increase which, in turn, can cause small-scale deformation (uplift) of the ground surface above. The pressure front caused by the injected CO_2 can be detected by measuring these uplift displacements using high precision sensors that include InSAR, tiltmeters, and global positioning system (GPS) sensors [6]. A potential leak may be identified when small-scale subsidence of the ground surface due to a reduction in pressure within the delineated plume is measured.

Interferometric Synthetic Aperture Radar (InSAR)

InSAR is a satellite-based technology in which radar waves are sent to the ground. The measured reflection of those waves provides high-precision information on the position of the ground surface [7]. Specifically, the satellite or airborne vehicle transmits a pulse of electromagnetic radiation (typically microwave-band) and measures amplitude and phase of the signal returns. The amplitude of the return can be used to characterize the roughness of the terrain and the phase return is a function of the distance of the satellite to the ground surface. Several commercial InSAR satellites are currently available and are able to examine up to a 100 square kilometer review area, sufficiently broad for even the largest geologic storage project. Provided the repeat orbit of one area of review is close enough to that of a later pass over the same specific area, the data from the two passes can be processed to produce an image of the vertical surface deformation of the earth that has occurred between the time the first data set is collected and the time the second data set is collected. InSAR methods work best in environments with minimal changes in elevation, vegetation, and land use. Adaptive methods, such as reflectors, can be deployed where these conditions are not met [8]. The sensitivity of InSAR is typically on the centimeter scale, and Permanent Scatterer InSAR (PSInSAR) has an accuracy of up to 1 millimeter/year for long-term monitoring [9]. The benefits of this method are that it can be used to analyze large areas, requires little to no access to the site, and logistic and labor related costs (especially when compared to more traditional 3-D seismic plume delineation) are minimized.

InSAR is being employed at the In Salah project—a large-scale commercial CO_2 storage project located in the Algerian Central Sahara and run by BP, Sonatrach, and Statoil—to track the extent of the CO_2 plume within the subsurface. This project has begun to inject and store over 17 million metric tons of CO_2 over 20 years in a carboniferous formation that has common analogues in Europe and North America. Currently, three injection wells are being used to inject approximately 1 million metric tons of CO_2 per year into a gas producing formation and four wells are actively extracting natural gas from other portions of the formation. As Figure 1 shows, monitoring revealed surface uplift rates of approximately 5 millimeters per year over all three CO_2 injection wells (KB-503, KB-502, and KB-501) for the injection period 2003 through 2007, with corresponding subsidence observed in the gas production area [5]. InSAR results were compared to other MVA methods (including 3-D seismic) at the site and results correlate well. The process proved to be very cost-effective when compared to commonly used, complex, and expensive 3-D seismic [10]. Results of this effort demonstrate that InSAR is a powerful tool for gaining insight into fluid fate in the subsurface, but also highlight the need for detailed, accurate static geomodels [11].

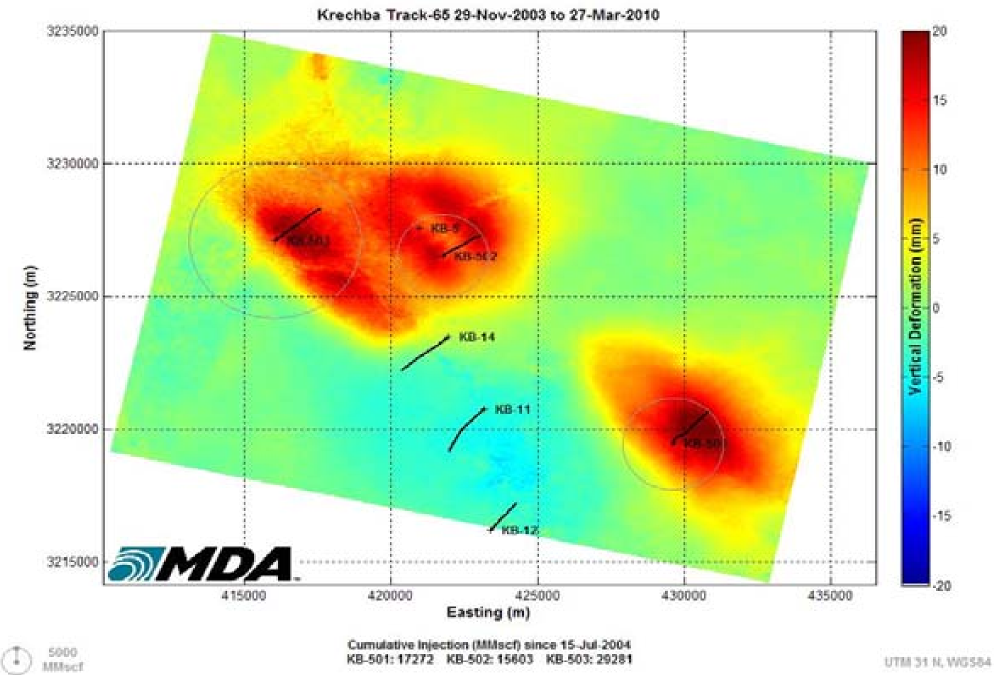

Figure 1: Image generated from InSAR data that depicts cumulative surface deformation at Krechba due to ~3.2 million metric tons of injected CO_2 [12].

NETL has partnered with the University of Miami to develop an integrated, low-cost methodology for assessing the fate of CO_2 pumped into various geologic reservoirs. Project participants are assisting in integrating geodetic, seismologic, and geochemical data by using InSAR data to construct interferograms (photographic records of optical interference phenomena) at the Hastings enhanced oil recovery (EOR) field in Hastings Texas. The primary objective is to develop an integrated approach for MVA of CO_2 in deep geologic formations. A key element of this study is to use InSAR data from selected sites and analyze it using newly developed algorithms and models to accurately track the CO_2 plume behavior. This effort is integrating reconnaissance-scale space techniques (Global Positioning System [GPS] and InSAR) with ground-monitoring seismic and geochemical techniques to measure subtle surface displacements. InSAR data have been acquired from selected field sites and is currently being processed using the new algorithm and model. Comparison of these results with the other CO_2 tracking techniques will help to determine the feasibility of and refine this method to accurately track CO_2. The goal of this effort is to develop a low cost, robust, real-time monitoring tool that combines the benefits of multiple technologies for deployment at most CO_2 storage sites.

The Midwest Geological Sequestration Consortium has partnered with the Archer Daniels Midland (ADM) Company to conduct a large-volume, saline reservoir storage test at ADM's ethanol production facility located in Decatur, Illinois. The test involves the injection of 333,000 metric tons of CO_2 per year (for three years) recovered from the fermentation plant into the Mt. Simon Sandstone, a major regional saline formation in the Illinois Basin. InSAR will be used to detect surface deformation and for plume delineation. This work is being performed by TRE Canada, Inc. and BP. This site differs from InSalah in that increased surface vegetation hinders accurate detection of displacement. An array of radar targets was installed at the site to compensate for the increased vegetation and improve the potential for accurate measurement of surface displacement. The baseline InSAR survey for the site was acquired prior to injection operations and subsequent surveys will be performed during injection operations. This effort is helping to refine InSAR techniques for sites with more extensive ground cover.

Tiltmeters/GPS

Tiltmeters are designed to measure very small changes from the horizontal level, either on the ground or in structures. They are highly sensitive and can measure tilt in units of microradians (sensitivity up to 0.00006 degree). GPS is a network of satellites surrounding the earth that emits signals that allow a sensor on the ground to measure a user's position on the Earth to within millimeters. By combining GPS with tiltmeters, small uplift or subsidence at a specific location on the Earth's surface can be measured and geospatially referenced. Challenges for tiltmeters include calibration, positioning, and orientation; satellite coverage and position are challenges for GPS [13]. NETL is funding projects for installing this combination of sensors across active CO_2 injection sites to spatially assess surface deformation resulting from injection operations and subsequent pressure formation increase.

An array of 71 tiltmeters and 3 GPS units is being deployed by LLNL at the In Salah site to track CO_2 plume migration, caprock integrity, and the development of pressure within the injection area [14]. The system is being installed and results will be used to calibrate InSAR satellite data acquired at the project site.

In 2008 the Southwest Regional Carbon Sequestration Partnership (SWP) completed a CO_2-enhanced coalbed methane (ECBM) pilot in the San Juan Basin of New Mexico. Project personnel injected 16,700 metric tons of CO_2 and used GPS and tiltmeter stations to monitor possible surface deformation caused by small-scale injection [15]. ECBM pilot test efforts were designed to study if the coal would swell as a result of CO_2 injection, potentially leading to a reduction in the quantity of CO_2 injected and an increase in surface deformation above the affected coal seam [16]. Prior to the start of CO_2 injection, surface tiltmeters were installed in shallow boreholes on an over one square mile grid surrounding the injection well. A baseline measurement was taken prior to injection and measurements continued for approximately three months after injection. Two GPS stations were integrated to constrain absolute changes in elevation and confirm long-term deformation measurements. Data indicated no significant cumulative change in elevation during the injection period. Findings indicated net subsidence, likely caused by methane production in nearby wells, which exceeded the volume of CO_2 injected. The results should not discount this technology as a potential MVA tool since only a small amount of CO_2 was injected, the nearest tiltmeter was over 600 feet from the injection well, and the methane recovery effort did not allow for pressure to build in the injection formation as it would under a large-scale injection. However, these results do indicate that this method may not be applicable for sites that are not expected to experience a significant pressure increase as a result of injection operations.

Remotely Operated Vehicles (ROV)

These monitoring systems include land and air remote operated vehicles (ROVs) that can be outfitted with different sensors depending on the type of data required. These sensor platforms are needed to conduct MVA in deep sea or high elevation areas or under extreme environmental conditions where other remote or in situ technologies are not feasible.

The more hostile offshore environment increases the challenges associated with selecting appropriate MVA technologies for CO_2 storage operations. One of the options considered for use in offshore environments is remotely operated underwater vehicles. The Sleipner field in the North Sea is operated by Statoil, Norway's largest oil company. The Sleipner field produces natural gas and condensate (light oil) from the Heimdal sandstones, which are about 2,500 meters (m) below sea level. The natural gas contains about 9% CO_2 and all of the CO_2 extracted since gas production started has been injected deep underground into a 200-meter-thick sandstone layer called the Utsira formation, about 800 meters beneath the bottom of the North Sea. The Utsira formation has high porosity and permeability, so the CO_2 moves rapidly sideways and upward through the rock layer, replacing the water between the sand grains [17]. Since 1996, about 10 million metric tons of CO_2 have been injected into the Sleipner reservoir.

At Sleipner, researchers funded by DOE and others are partnering with European scientists to track injected CO_2 using an ROV-mounted deep ocean gravimeter. Researchers from the Scripps Institution of Oceanography (Scripps) and the Lamont-Doherty Earth Observatory (LDEO) are conducting these gravity surveys to detect changes in gravity caused by the introduction of CO_2 into the formation. The CO_2 displaces the formation water, causing a small change in the strength of the Earth's gravitational pull. These changes are detected by the ROV, which collects data from the 30 seafloor station gravimeters located above the Sleipner CO_2 plume, and a map of the variation in gravity can be generated to show the outline of the CO_2 plume (Figure 2). Gravity surveys have been performed three times (in 2002, 2005, and 2009) to provide snapshots of the CO_2 plume's migration deep below the seafloor [18] [19]. The surveys performed by Scripps were able to delineate the plume, validating the gravity technique as an effective monitoring tool.

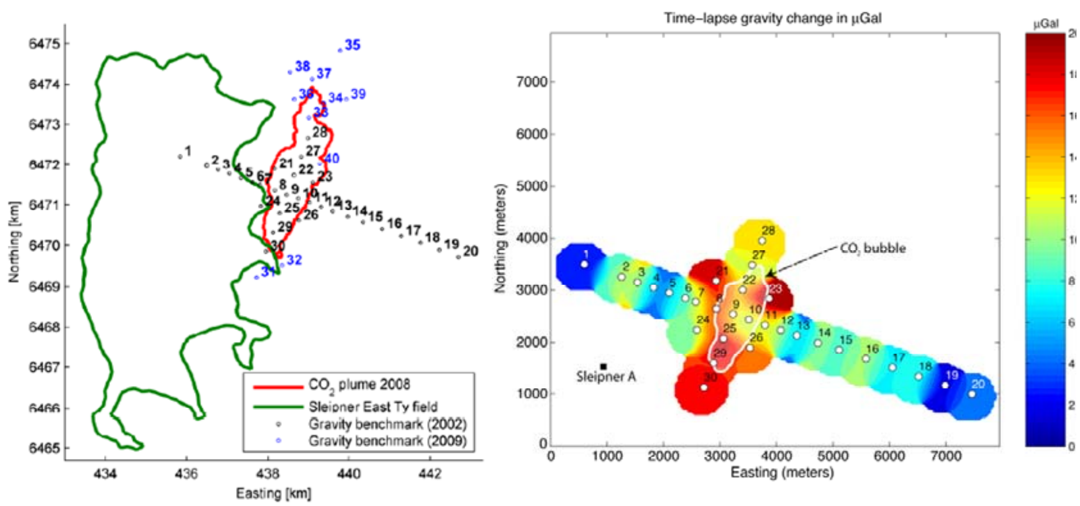

Figure 2. Image generated from ROV gravity survey data that depicts changes in gravity between 2002 and 2005 due to injection of CO_2 at the Sleipner storage field. Seabed benchmark locations are shown by white circles with a smoothed version of the gravity changes after correcting for depth and a long wavelength trend Note the spatially coherent gravity decrease in the central part of the survey where the CO_2 plume is located [20].

Additional sensors (underwater cameras and seawater sampling) can be added to the ROV to detect potential CO_2 leakage from the subsurface via underwater cameras and seawater sampling. Again, utilizing ROVs to perform this type of MVA is essential in settings where access is restricted do to environmental conditions.

Multispectral/Hyper-Spectral Imaging

A conventional photograph contains data from the range of the spectrum that includes visible light, while multi- and hyper-spectral images can capture data from a broader portion of the electromagnetic spectrum. This allows for observations and data to be collected to detect phenomena not clearly observable using conventional photography. For example, vegetation that is struggling can be detected using spectral imaging and variations in chemical composition of soil, plants, water, and air can be observed when data from various spectra are captured and analyzed.

Multispectral imaging obtains data from several portions of the spectrum (infrared, near infrared, radar, and other intervals) at discrete and somewhat narrow bands. “Discrete and somewhat narrow” is what distinguishes multispectral in the visible from color photography and allows for specific, targeted conditions to be observed. Multispectral imaging may be simpler and less costly, and it affords continuous daytime operation in both clear and cloudy weather [21]. Hyper-spectral imaging captures narrow spectral bands over a continuous spectral range and produces the spectra of all pixels in the scene. Hyper-spectral images provide a more complete image of a study area because an entire spectrum is acquired at each point. The operator needs no prior knowledge of the sample, and post-processing allows all available information from the dataset to be mined.

Spectral remote sensing techniques (including laser optical and light detection and ranging [LIDAR]) have the ability to detect vegetative stress related to CO_2 releases, in addition to detecting atmospheric and soil CO_2 gas concentrations that may have occurred via pipelines, natural CO_2 vents, and carbon storage projects [22]. There are numerous multi- and hyper-spectral technologies that can be used to measure vegetative stress by measuring variations in vegetation over time and area. NETL funded efforts are supporting the continued development of these technologies.

Spectral imaging has been tested at the Zero Emissions Research and Technology Center (ZERT) site when 300 kg/day of CO_2 was released for 29 days from a 100-meter long horizontal injection well buried 1 to 2.5 meters underground. The ZERT facility, operated by the University of Montana, is an outdoor laboratory that is used to simulate CO_2 leakage from underground and buried pipelines. The vegetation at the ZERT site began to show visible signs of stress within four days of CO_2 injection, with various plant species responding differently to CO_2 stress [23].The study used field spectrometers and airborne hyper-spectral imaging to detect stressed vegetation and found a direct correlation between the amount of stressed vegetation and the concentration of CO_2 in the soil surrounding the injection well. Efforts to develop and refine cost-effective remote leak detection systems continue at the facility [24].

NETL supported an LLNL project to develop hyper-spectral geobotanical and radar remote sensing techniques for detecting and discriminating leaks and monitoring pipeline system reliability. NETL supported this effort by sponsoring a natural gas leak detection demonstration at the Rocky Mountain Oilfield Testing Center (RMOTC) near Casper, Wyoming. Hyper-spectral imaging of vegetation was used to detect plant stress due to a natural gas release on a simulated pipeline. The sensors were mounted on two areal platforms flying at 5,000 and 1,000 feet over the site. The technology was able to accurately image the stressed vegetation, although with limited success due, in part, to sparse vegetation. Although natural gas was used for this test, the imaging system shows promise for CO_2 detection as well. The method has the potential to cover large expanses of pipeline with minimal effort, thus reducing the potential likelihood that a leak would go undetected. The amount of gas leakage from a site can be reduced by increasing the effectiveness and efficiency of leak detection, resulting in decreased environmental impact from fugitive emissions of gas, increased safety and reliability of gas delivery, and an increase in overall available gas as less product is lost from the lines.

Although not a current focus of the NETL CCUS program, these methods also can be used to measure terrestrial storage capacity of an area by measuring the density of surface vegetation. NETL, through its support of the RCSPs and core research and development efforts, has helped to fund numerous terrestrial storage capacity research and development efforts designed to capture data using these imaging techniques to determine the degree of carbon capture that is represented by surface vegetation and associated carbon. Examples of these efforts include:

- The Big Sky Regional Carbon Sequestration Partnership used Landsat Thematic Mapper images as part of its Cropland Field Validation Test. Landsat satellites provide repetitive coverage of continental Earth surfaces in the visible, near-infrared, short-wave, and thermal infrared regions of the spectrum.
- The Big Sky Regional Carbon Sequestration Partnership used data from the RapidEye satellite system and time series airborne LIDAR to assess forest status, measure the environmental and economic sustainability of forest operations, monitor logging and deforestation, and infer aboveground carbon storage rates.
- WESTCARB used high resolution optical panchromatic images obtained from the SPOT Earth orbiting satellite system as a tool to observe land uses, identify stressed vegetation, catalogue geologic features, estimate above ground carbon loading, and document time-lapse changes in surface features.
- The Nature Conservancy used aerial-based LIDAR and satellite-based (QuickBird) technologies to determine the carbon storage potential of forestry projects in the United States and Belize. The QuickBird satellite system collects high-resolution panchromatic and multispectral images of the Earth's surface.

Passive Scanners

Passive scanners are used to detect naturally emitted energy. One of the key tasks that these scanners are being considered for is the characterization of potential carbon storage sites prior to injection. A proposed CO_2 storage site can encompass a land area of hundreds of square kilometers and contain numerous existing wells that may or may not be identified. Before CO_2 can be stored in a geologic formation, every well in the vicinity must be checked for leaks. Past well-searching techniques, such as ground penetrating radar and portable hydrocarbon analyzers, were time consuming, expensive, and, as a result, only practical for small areas. SEQURE™ Well Finding Technology (Figure 3)—which was developed by NETL in conjunction with an international team of researchers from Apogee Scientific Inc., Fugro Airborne Surveys, and LaSen Inc.—is both a time-saving and cost-effective way to locate abandoned wells for evaluation by ground teams [25].

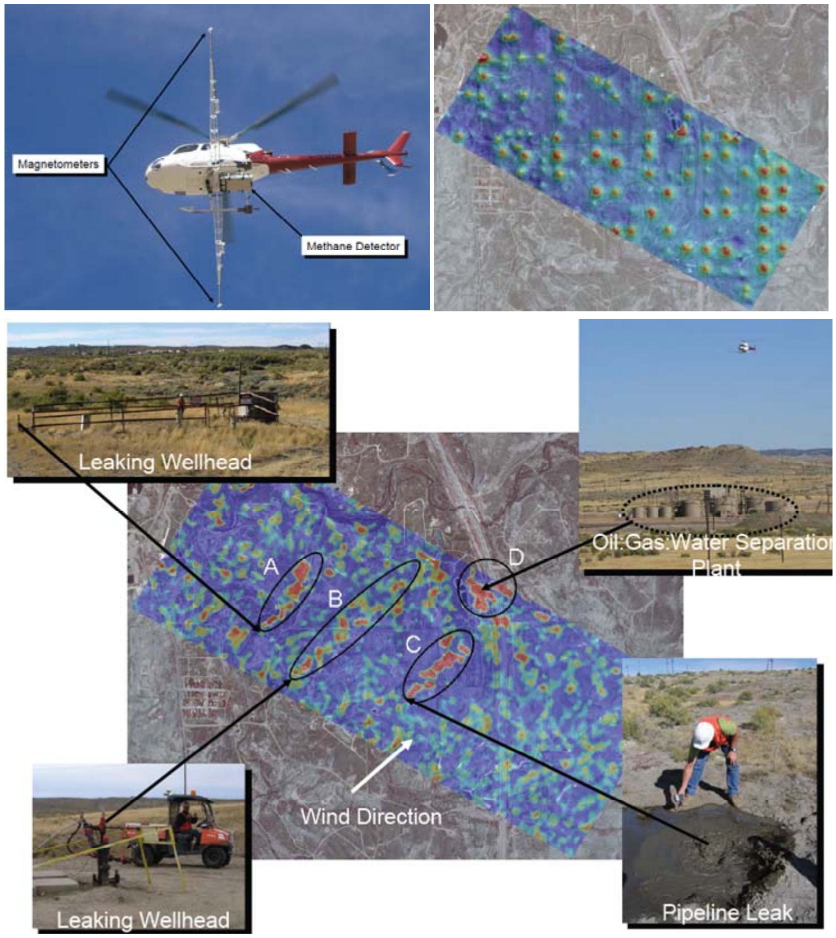

Figure 3. NETL's SEQURE™ Technology includes a helicopter mounted with data acquisition systems (top left). Magnetometers can be used to detect the locations of buried or concealed wellbores or other infrastructure at candidate geologic storage sites (top right). Data acquired from a 2005 "proof-of-concept" flight over the Salt Creek Oilfield in Wyoming (bottom) aided the detection of two leaking wellheads and a leaking production pipeline, and identified a majority of the existing wellbores in the study area.

SEQURE™ magnetic sensors detect any steel well casings in the area, which are then depicted on maps that are used for ground reconnaissance. The magnetic sensors are able to detect at least 95 percent of the wells present in oil and gas fields. Since all potential leaks must be detected to ensure permanent CO_2 storage, SEQURE™ methane detectors then fill in the gaps. The detectors, which can locate a leaking well regardless of whether a steel casing is present, are designed to locate leaks by detecting volatile components that have migrated to the earth's surface via the well bore. In a proof-of-concept flight over the Salt Creek Oilfield in Wyoming, SEQURE™ magnetic sensors detected 133 of 139 wells. The remainder of the wells remained hidden because of corroded or removed casing, were plugged or abandoned, or because the casing was made of a non-magnetic material, such as wood.

Conclusion

Cost-effective, efficient, and robust MVA is critical to ensure long-term storage of CO_2. EPA requirements related to geologic storage define the need for repeatable, reliable, cost-effective technologies to demonstrate storage permanence and document CO_2 behavior. Remote sensing technologies have high potential to supplement other technologies due to their ability to (1) perform under non- or minimally intrusive conditions; (2) efficiently obtain data from relatively large areas with low relative effort; (3) be used as a cost-effective alternative to other options; and (4) be used in special applications where other forms of MVA may not be feasible. However, more research and development is needed to refine these technologies and overcome or mitigate their weaknesses so that they perform reliably under varying conditions. NETL realizes these potential benefits and continues to play a key role in the development and testing of remote sensing MVA technologies that have application to geologic carbon storage. For more information on NETL's remote sensing research, please visit the Carbon Storage Program's website: http://www.netl.doe.gov/technologies/carbon_seq/index.html

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