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Persistent Microseismic Monitoring Using Robust Permanent SADAR Arrays

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Abstract

Traditional methods for monitoring microseismicity use networks of surface sensors and downhole sensor strings. Sparse networks of permanently emplaced compact volumetric phased arrays of sensors (SADAR arrays) represent a fundamentally new approach. In November 2021, Quantum Technology Sciences installed a sparse network of four dual-use permanent SADAR arrays at Carbon Management Canada's Field Research Station (FRS) proving ground between 9m-19m depth to demonstrate passive and active-source seismic monitoring at an active CO_2 storage facility. SADAR array field components and system design provide a redundancy protecting against sensor attrition without a loss of key capabilities for monitoring. A record of 36 months of passive monitoring are presented in this study.

Introduction

Traditional methods for microseismic monitoring, measurement, and verification (MMV) of the area of review identified for geologic carbon storage (GCS) sites use networks of surface sensors and downhole sensor strings (Eaton, 2018, 136). These passive monitoring approaches are in wide use in a variety of production and disposal facilities.

Sparse networks of permanently emplaced compact volumetric phased arrays of sensors (SADAR arrays) represent a fundamentally new approach for reservoir surveillance. SADAR systems provide superior data and information compared to surface networks and downhole strings resulting in lower magnitude microseismic detection thresholds over larger geologic volumes with more certain locations while occupying a smaller footprint. The SADAR arrays are deployed in shallow boreholes below the weathering layer taking advantage of this layer for damping the industrial noise fields.

Not shown in this discussion, the arrays also serve to process active sources, providing an image of the reflection point from an active source. The multiple sensors in the arrays can beam the incoming signals, targeting a specific reflection at depth to provide additional clarity to the subsequent image. The poster in this meeting is: Active Source Sparse Imaging Using Permanent SADAR Arrays.

Background

The Containment and Monitoring Institute (CaMI) of Carbon Management Canada (CMC) operates the Newell County Field Research Station (FRS) in Southern Alberta (Figure 1), a GCS storage pilot site for evaluating MMV technologies (Lawton *et al.*, 2019; Macquet *et al.*, 2019).

A small volume of CO_2 is injected into the Basal Belly River Sandstone (BBRS, z=300m), enabling development and testing of MMV tools toward minimizing risks associated with GCS (Macquet *et al.*, 2022). A comprehensive suite of MMV tools is deployed at the site providing direct comparisons of effectiveness and utility.

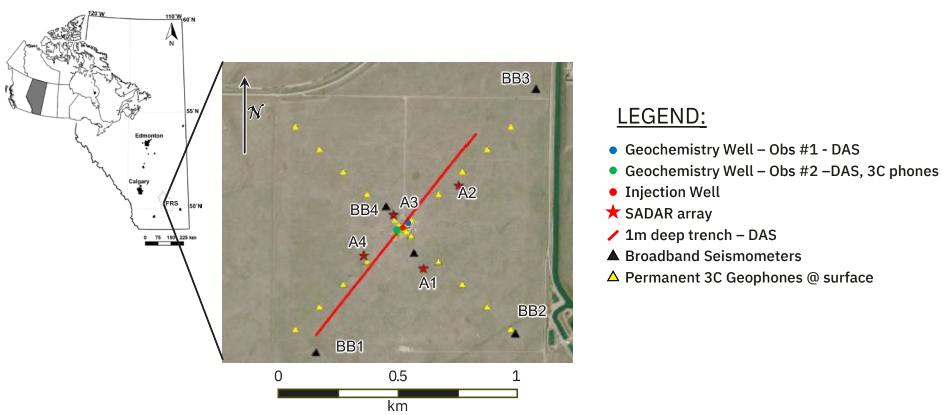

Figure 1. Location of the Carbon Management Canada Newell County Field Research Station (FRS), Alberta, Canada. The zoomed view indicates the injection well (red square) and the four SADAR arrays (stars), as well as other instruments. Arrays A1 and A4 are 200 m from the injection well, and array A2 is 300 m from the well.

In November 2021, Quantum Technology Sciences installed a sparse network of four dual-use permanent SADAR arrays at the site to demonstrate compact volumetric phased arrays for MMV at an active GCS facility (Nyffenegger *et al.*, 2025; Nyffenegger *et al.*, 2023a; Zhang *et al.*, 2023; Hutchenson *et al.*, 2023; Nyffenegger *et al.*, 2022).

The elements of the uniform cylindrical arrays are comprised of vertical 10 Hz geophones installed in shallow boreholes between 9m-19m depth and grouted in place; the vertical extent of the arrays is contained within the Pleistocene-Holocene sediment and glacial till layer below the weathering zone.

SADAR array field components and system design provide a redundancy protecting against sensor attrition without a loss of key capabilities for microseismic monitoring. For the recording period, the system has been operating at 98.7% or above with no down time for maintenance.

Methods

The phased array design enables beamforming, maximizing the SNR of the received signal by suppressing incoherent noise and coherent clutter signals, as well as providing measured attributes not provided by traditional systems (Nyffenegger *et al.*, 2023a). Analyst reviewed bulletins are constructed containing location (Bratt and Bache, 1988) (latitude/longitude/depth), error ellipse parameters, origin time, and a magnitude (Mw) using the Brune (1971, 1970) method to determine moment.

Using a well-located shallow -1.52 Mw event with ~6 dB SNR, we demonstrate effects of losing n array elements from the total arrangement of elements a_l in array A1 with element index $l = [1,2, \dots 54]$. The effect of the loss is quantified using the measured angle of arrival (azimuth and dip) and phase velocity features extracted from beamformed waveforms as the measured value difference from the baseline. The unit vector normal to the wavefront (also the beam main response axis (MRA)) is decomposed into an azimuth relative to North, and the dip or depression angle defined as the vertical angle component measured down from the horizontal plane. The phase velocity is the true measured velocity of the signal as it crosses the array. The procedure is repeated for 10 trials for each $n, n = [1, 2, \dots 35]$ to produce an ensemble of differences from the baseline. This statistical approach demonstrates the robustness of the system.

With the network configuration and determination of Mw, we can construct a performance model for the area AND validate the model with the observations. The model allows the determination of the minimum magnitude locatable event as a function of position within the network.

Results

In 36 months of persistent monitoring, an analyst-vetted automated processing pipeline generated a bulletin with an approximately -2.5 Mw completeness containing locations, magnitudes, and attributes of 1522 high-confidence events with SNR>~10 dB and clear phase arrivals (P phase) observed at four arrays, excluding surface activity associated events (Figure 2). With the surface events, better than 9878 events have been located through the human analyst. Many of the excluded events are from the surface and potentially represent mechanical equipment noise, human traffic, etc. However, these events cannot be excluded from a catalog without an accurate means of identification. Events from known sources, i.e., active source testing, surface experiments, etc. may also excluded from a catalog or marked as human activity.

The magnitudes for these events are calculated between -0.25 and -3.0 Mw (Figure 2).

Loss trial results for robustness show the phased array measured attributes are not greatly degraded through loss of 15 sensors (27% of total). Azimuth and dip deviations average ~5° and measured phase velocity deviations average ~75 m/s. Degradation of array gain against random noise is within ~1.5 dB difference. Larger deviations become apparent only after losses of 20 or more sensors (Figure 3).

The performance model constructed for the area is shown as Figure 4 (left). This area is unique, in that the model can be validated. In Figure 4 (right), we see the gridded results using actual data. The comparison between the data and model are a good fit. The implications suggest this model can be used for other areas taking advantage of locally measured parameters since the results support the model (Nyffenegger, *et al.*, 2023b).

Conclusion

The sparse SADAR network is demonstrated as a very effective system for microseismic monitoring, delivering a uniform event bulletin with locations, uncertainties, and attributes continuously since its installation. The network provides a persistent coverage of ~156,000 m^2 surface area using a footprint of only ~150 m^2. Because of the dual-use capability, the reduced footprint, the robust system components and array design, and the ability to operate continuously under industrial noise conditions, the SADAR system reduces operational and financial risks for GCS monitoring.

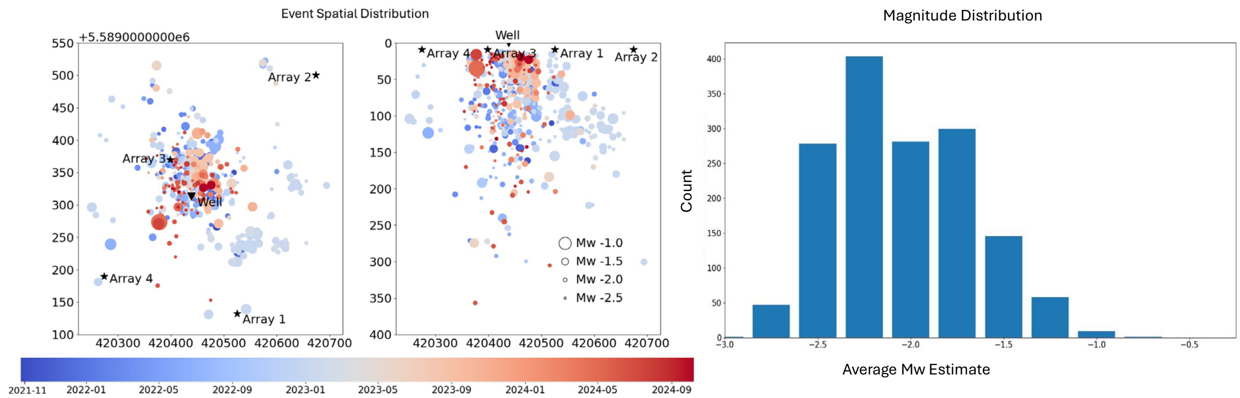

Figure 2. Seismic bulletin for 36 months (Nov 2021 – Oct 2024) for events with Z > 15 m, sorted by time and magnitude. The spatial field is shown on the left with the locations of the four arrays and the injection well. In the middle, a vertical profile-depth view,. Colors show the time of occurrence with the Mw as the size of the circle. On the right, event Mw distribution

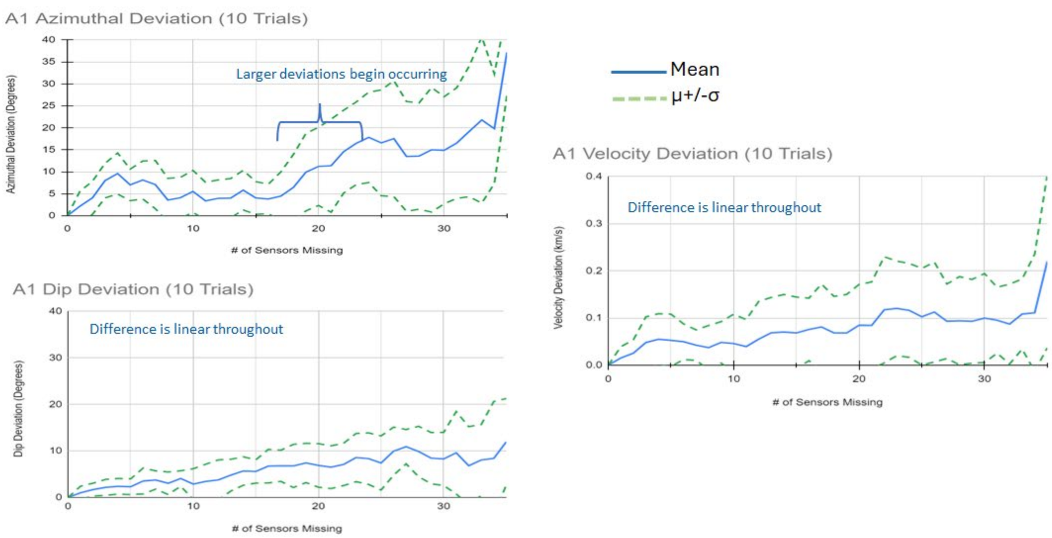

Figure 3. Array robustness. Azimuth deviation (top left), dip deviation (bottom left), and velocity deviation (right) as a function of sensor loss. The results are statistically determined from an average of 10 trials for each value of *n* sensors missing.

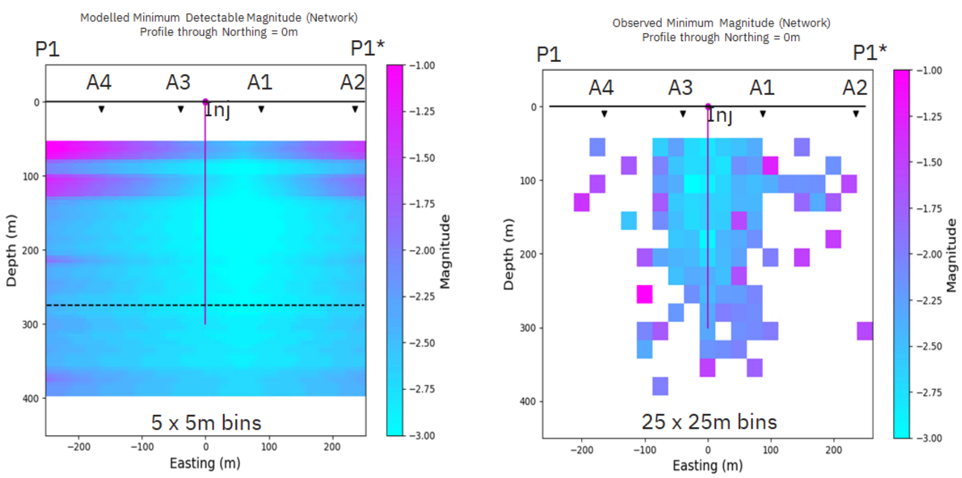

Figure 4. Network model (left) vs. the Observed data (right). While sparse, the observed data supports the model, suggesting the model can be used in other areas to predict performance.

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