Field trial of a sparse and automated seismic acquisition system with permanent anchored vibratory sources

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Summary

Sparse seismic acquisition with a permanent source is increasingly recognized as a cost-effective alternative to conventional 4D seismic surveys. A successful field trial of such a system was conducted in November 2024 in California, demonstrating the feasibility and effectiveness of a novel surface linear vibrator (SLV) installed on helical anchors. This system, integrated with automated receivers, offers a promising solution for various applications, including carbon capture, utilization, and storage (CCUS) and enhanced oil recovery (EOR).

Introduction

Sparse seismic acquisition has recently gained popularity thanks to its potential cost savings. With careful planning, novel equipment, and fit-for-purpose processing, it could achieve comparable results as, or even exceed, conventional dense 4D surveys (Berron et al., 2015, White et al., 2015, Roach et al., 2017, Wang et al., 2020, Cheng et al., 2021, Richards et al., 2022). Some of its applications include carbon capture, utilization, and storage (CCUS), enhanced oil recovery (EOR) such as steam assisted gravity drainage (SAGD), and geothermal energy development.

To achieve high sensitivity and time-lapse repeatability at a reduced turnaround time and cost, we develop a sparse seismic acquisition system combining a unique phase-controllable vibrator and autonomous seismic sensors. Our Surface Linear Vibrator (SLV) is a small but powerful source that delivers up to 23,000 lbs. of linear P-wave force at up to 100Hz to the tip of a deep helical anchor, which is coupled with consolidated formations beneath the attenuating weathering layers. The automated seismic receivers having the Internet-of-Things (IoT) capabilities enable continuous 24/7 cloud-based real time data streaming (Li et al., 2023). Once installed, the system requires minimal maintenance and can be run remotely for years. It acquires daily sweeps, accumulating a rich number of stackable seismic traces for processing. The receivers serve a dual purpose by also monitoring passive seismic events.

A field trial of this system was conducted in November 2024 near Stockton, California, in an active agriculture area without subsurface operations such as CO2 injection or hydraulic fracking. The field trial aimed to evaluate system feasibility and repeatability in a realistic 4D land sparse survey set-up.

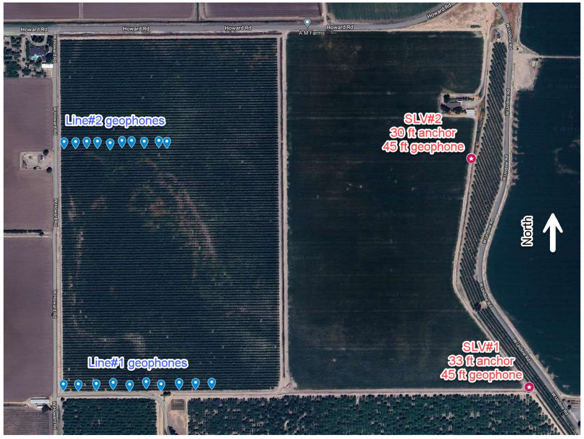

Figure 1a: Map view of acquisition. The test field is near Stockton, California. SLV sources in red pins and sparse surface receivers in blue pins.

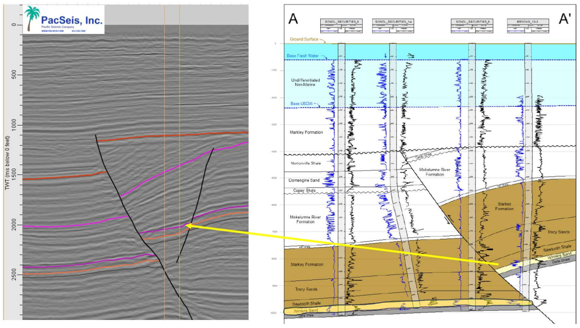

Figure 1b: Legacy 3D seismic stack and interpretation. The deepest target of interest for field trial is Winters Sand at approximately 2.25 sec TWT / 8500 feet TVDSS.

Acquisition

The acquisition consisted of two 2D lines running East to West, with maximum offsets of about 3,700 feet (Figure 1a). Legacy 3D seismic (Figure 1b) and numerical modeling indicated that a minimum offset of 2,500 feet was necessary to avoid surface wave interference, which is challenging to address due to sparse spatial sampling.

Two helical anchors were installed for each 2D line at depths of 33 feet and 30 feet, respectively. Prior to anchor installation, a 45-foot geotechnical survey was conducted at each SLV location, and a source monitoring geophone was

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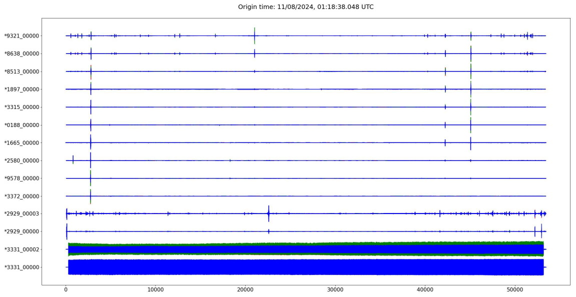

Figure 2: Overnight data from all receivers, offset from near (bottom) to far (top). Each station is individually scaled for plotting purposes.

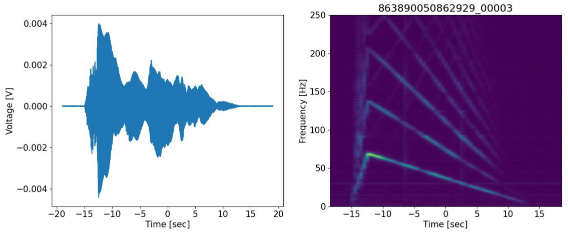

Figure 3: Example overnight sweep as recorded by the source monitoring geophone, Z-component. Spectrogram shows linear acceleration and deceleration, as programmed, as well as high order harmonics.

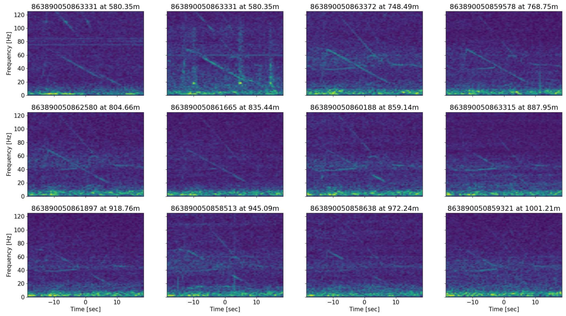

Figure 4: Offset surface geophone data spectrogram, Z-component. Offset from near (upper left 2550 ft) to far (lower right 3750 ft). Sweep was visible in all offsets, also various types of cultural noises.

placed in the borehole to serve as a virtual source for subsequent processing. Each 2D line had 10 sparsely spaced offset geophone receivers shallowly buried. These receiver stations were powered by solar charged batteries, and the SLVs were powered by generators, with an option for solar or grid-based operation.

For each 2D line, the corresponding SLV was remotely programmed to sweep overnight from local time approximately 5:30 PM to 8:30 AM for a total of 1400 repeatable and stackable sweeps each (Figure 2). All sweeps were configured the same: 3 seconds linear acceleration to peak frequency followed by immediate linear deceleration in 27 seconds, then 6 seconds listening time. Following on-site equipment tuning and trial sweeps, we set the peak frequencies at 75 Hz and 70 Hz for the two SLVs.

Processing

Our analysis focused on the vertical (Z) component, although all geophones recorded three-component data. Processing was straightforward thanks to sparsity in space and redundancy / repeatability in time. Basic steps were cross-correlation with virtual source, deconvolution then vertical stacking. Each offset receiver was processed independently and later combined to form a 2D line.

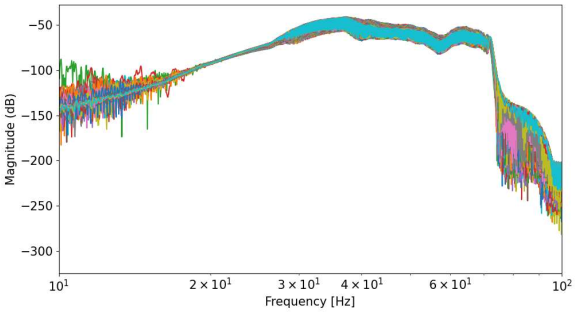

Figure 5a: Virtual source geophone auto-correlation (Klauder wavelet) spectrum of all 1400 overnight sweeps.

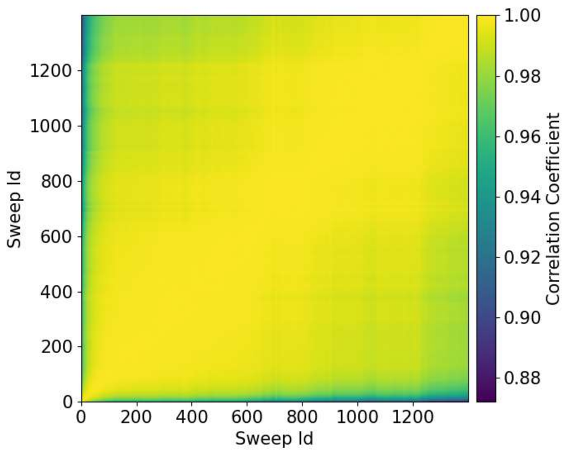

Figure 5b: Correlation coefficient of Klauder wavelets. The 1400 SLV sweeps proved to be highly repeatable.

Figures 2-4 show one night's continuous recorded data during SLV sweeps. We chose nighttime because it typically has a lower cultural noise level compared to daytime. Clearly

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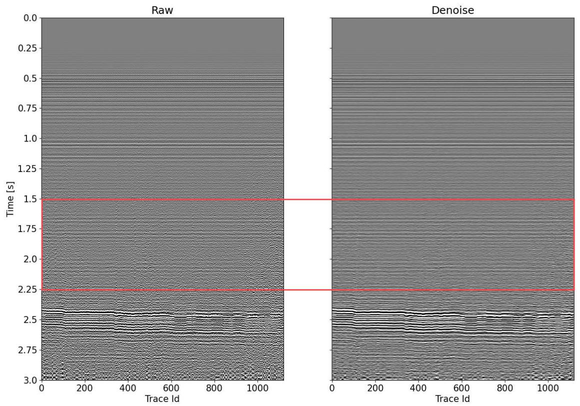

Figure 6: Gather view of an offset surface receiver data (2700 ft). It can be qualitatively estimated that signal-to-noise ratio was acceptable till approximately 2.25 second two-way time, or approximately 8500 feet depth. High amplitude events around 2.5 seconds were surface waves.

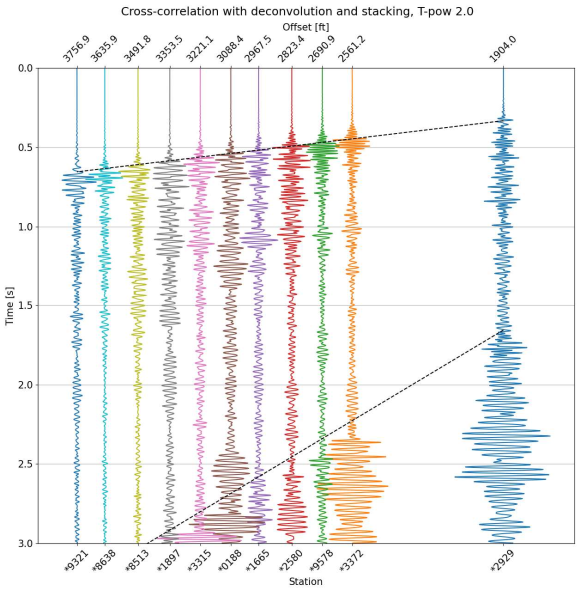

Figure 7: Processed 2D line, overlaying dashed lines show direct arrival of 5740 ft/s and surface wave of 1150 ft/s.

each offset station's signal-to-noise ratio was different, but stacking repeatable sweeps would greatly improve the result.

To quantify SLV source repeatability, Figures 5a and 5b examine the spectrums and correlation coefficients of virtual source Klauder wavelets. There was no misfire, and all sweeps were very repeatable except at frequencies below 20Hz.

For offset receiver data, each sweep was deconvolved then formed a common-receiver-gather, where signals were expected to be coherent horizontal events due to the consistent source signature and stable surface conditions. This assumption, however, is not valid for surface waves based on our observations in many tests including this field trial. Figure 6 shows the common-receiver-gather of one offset with zone of interest highlighted in red box (1.5 to 2.25 seconds). Finally, stack over sweeps after denoising in the common-receiver-gather domain results in one trace per offset station (Figure 7).

For benchmarking, we compared SLV field trial results with raw data from legacy 3D seismic surveys. Figure 8a presents a shot gather from the legacy 3D dataset closest to Line 1, while Figure 8b compares traces at equivalent offsets. The strong consistency between SLV and legacy 3D seismic waveforms highlights the effectiveness and applicability of the SLV source.

Discussion

We noticed non-negligible cultural noise during the field test. As we have discovered from other tests, burying geophones deeper as part of a more permanent monitoring array will improve the signal-to-noise ratio by several dB and help mitigate effects from changes in near-surface conditions that lead to non-repeatability.

A simple sparse 2D acquisition design was used for this field test. To sample the subsurface away from well control, where changes in impedance are anticipated because of CO2 plume growth, we must coordinate the sparse acquisition layout for applications like CO2 sequestration monitoring. We may move the SLV and receivers in accordance with this dynamic and iterative process. When compared to conventional time-lapse techniques, the system's low environmental impact and disturbance are advantageous. Therefore, moving the sparse system is expected to have minimum environmental impact.

Conclusions

This field trial successfully demonstrated the feasibility and effectiveness of a permanent active-source sparse acquisition system. The system proved to be a reliable and cost-effective alternative to conventional 4D surveys, showing strong potential for applications in land seismic time-lapse monitoring.

Acknowledgments

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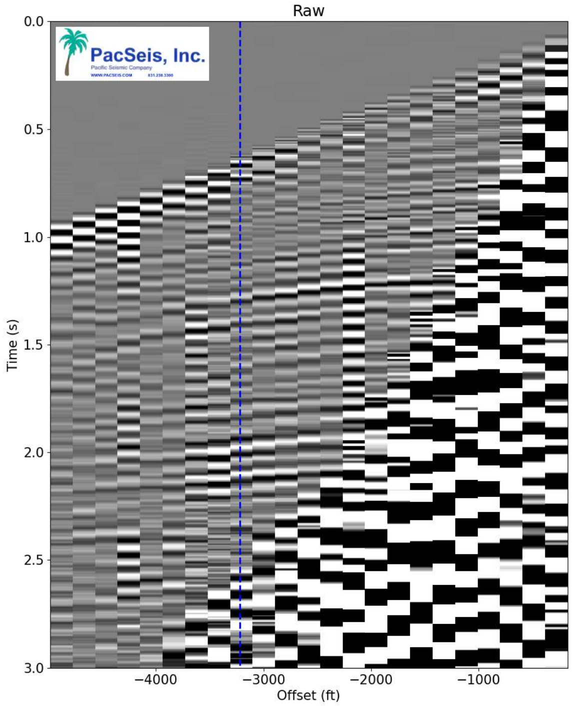

Figure 8a: A shot gather of legacy 3D survey with source located nearest to line 1 SLV. Dashed blue line indicates the offset chosen (3221 feet) for zoom-in comparison against that of field trial processed 2D line.

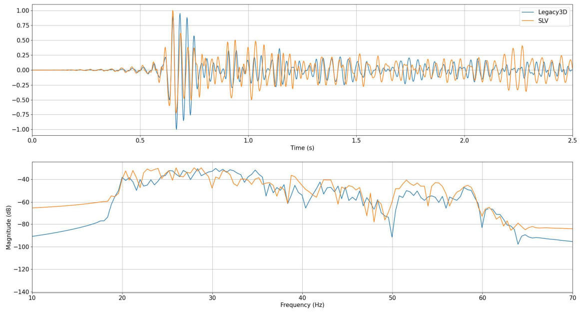

Figure 8b: Trace comparison between legacy 3D seismic and field trial. Data has been filtered to common bandwidth but without spectral balancing.

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