A Novel and Low-Cost Seismic Acquisition System Consisting of Permanent Controlled Linear Vibratory Sources and New Autonomous Seismic Sensors for CCS/CCUS Site Characterization, Plume Front Mapping and Real-Time Seismicity Monitoring

Siwei Li[1], Nicholas Brooks[1], Tianrun Chen[1], Xinding Fang[1], George Knapo[1] and Howard Wilkinson[2]
1. SensorEra Inc., 2. GPUSA

Summary

We have developed a dedicated low-cost, solar-powered, fully autonomous seismic system for CCS/CCUS site characterization, CO2 plume front mapping and real-time seismicity monitoring. This IoT system consists of unique, permanent and remotely controlled autonomous Surface Linear Vibrator (SLV) seismic sources and novel autonomous always-on smart six-component (6C) ground motion sensors.

Introduction (Optional)

Sparse seismic acquisition has been identified by multiple authors as a cost-effective solution for CO2 plume front mapping. By substituting spatially dense 3D seismic acquisition with a temporally dense and spatially sparse source-receiver geometry, targeted midpoint single trace reflection analysis can be performed remotely and on a daily basis. With fixed sources and receivers that are immune to environmental and near surface temporal changes any time lapse changes can be attributed to the passing of the CO2 plume through the targeted part of the subsurface. Richards et al (2022) describe this as a Scalable, Automated, Sparse Seismic Array (SASSA).

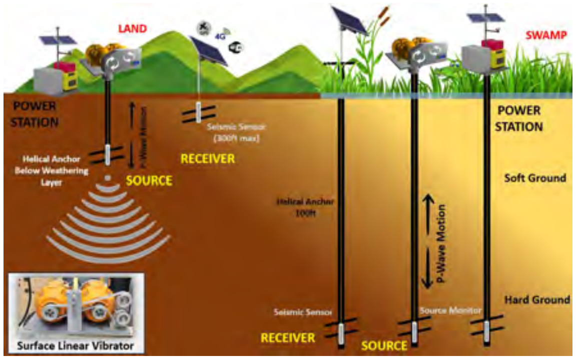


Figure 1: The SLV source is bolted to the top plate of a deep helical anchor allowing it to be deployed on land or in a swamp environment. It is powered by a standalone power station that is ground or anchor mounted. The sensors are deployed in augered holes on land or inside piles in a swamp. A sensor is deployed at the base of the pile as a source monitor.

The chosen seismic source must be repeatable, reliable, low cost, easily installed in various environments and operated remotely. We describe how a Surface Linear Vibrator (SLV) is a suitable source for SASSA and has a number of advantages compared to the Surface Orbital Vibrator (SOV) and traditional seismic sources (SOV described by Correa et al 2021).

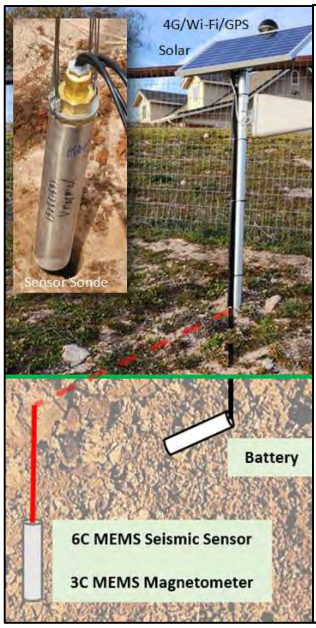
The permanent seismic sensors must be sufficiently sensitive to provide high quality seismic reflection data from CO2 injection depths. The sensors need to be fully autonomous, with automated cloud-based processing and operated remotely. The chosen sensors also need have a sufficiently low self-noise to be able to monitor the site for low energy seismicity events.

We describe a MEMS-based 6C sensing solution that will be combined with SLV sources for repeatable CO2 plume mapping on a daily basis for cost-effective long-term monitoring for both land and swamp environments.

Method

The permanent linear vibrating source (SLV) contains two vibratory motors at the surface mounted on a hollow helical anchor/pile up to 150ft-long that penetrates into the ground (Fig. 1). Linear vibrations are generated by the two powerful, long-lasting vibration motors at the surface. The IoT source controller is capable of customizable sweep patterns from 0-100Hz. The rotating motor masses generate vertical compressional forces that are converted to seismic waves that emanate at depth through the base of the buried helical pile and out in to the subsurface. The MicroVib™ source is capable of generating 11,000 lbs. force at 100Hz. Three phase 480V/240V power is supplied locally with a proprietary solar-charged battery autonomous power station.

The electrically-powered source weighs just 300lbs and needs to be anchored to the ground in order to transfer the vibrations through the subsurface. This is achieved with a novel technique using a helical anchor adapted from the civil engineering world. Helical anchors are commonly used worldwide to support heavy structures and foundations. The anchor can be thought of as an ‘earth screw’ that is screwed in to the ground using a high-torque drive head to depths of more than 100ft. Helical blades pull the anchor in to the ground and provide extremely effective seismic coupling below the attenuating weathering layer. Phase-controlled linear P-wave motion is transferred from the SLV on the surface to the tip of the pile where it exits and emanates through the subsurface.



Bandwidth:
DC-4kHz | Sample Rate: 100-2000Hz
Measurement range:
±2g (A) ±15o/s (G)
Self-noise (A):
Generation I: 8ug/√Hz (obsolete)
Generation II: 1.0ug/√Hz (current)
Self-noise (G):
5urad/√Hz
Timing:
GNSS (GPS, GLONASS, GALILEO)
Sensor clock accuracy:
<0.5ms
Transmission:
4G/Wi-Fi/Starlink
Onboard O.S.:
Embedded Linux
Cloud control & storage:
AWS
Onboard Storage:
32GB
Orientation:
3C magnetometer
Power Consumption:
4W
Install Time:
1 hour
Install to Monitoring Time:
Instant

Figure 2: The low-cost MEMS 6C seismic stations include a 3C magnetometer and can be deployed in any orientation in the augered hole that is commonly 3ft deep. The only surface expression is the mast with communication antenna, GPS and solar charging.

The seismic sensors are ruggedized new low-noise, six-component, microelectromechanical system (MEMS) sensors that record 3C translational acceleration and 3C rotational velocity (6C). Each station is fast and simple to deploy and self-oriented via an on-board 3C magnetometer. The low power IoT buried sensors run continuously via battery/solar transmitting real-time reflection and passive seismic data via 4G data networks or local Wi-Fi for cloud-based data processing. In addition, a sensor is secured at the base of the helical anchor as a vibratory source signal monitor.

This new holistic solar-powered, source-receiver seismic system is deployed and operated continuously at off-grid locations and remotely controlled and operated at will, on-site field personnel are not required.

The new autonomous seismic station technology has been rigorously tested in the laboratory and then subsequently through a number of field trials in Texas and California in 2022. Figure 2 describes the novel seismic sensing system suitable for active and passive seismic applications.

Results, Observations

A number of field experiments were conducted to validate the new system and include:

(1) A multi-faceted trial was conducted in Texas to evaluate the new low-cost sensors for induced seismicity (IS) monitoring. 30 sensors were installed at multiple locations across Texas near active water injection wells, salt domes, hydraulic frac' operations or co-located with existing and expensive force-balance seismometers. The co-located stations demonstrated that the new low-cost sensors are highly consistent with the traditional seismometers (Fig. 4) down to 0.03Hz and can achieve a magnitude of completeness down to 0ML at a 10km distance.

(2) In the second experiment, 1 source and 9 6C sensor stations were installed at a 500-acre private test site in California. We investigated the suitability of the new seismic source-receiver system for monitoring of stored gas or fluids. MicroVib^{TM} is light, with a unique hold down mechanism requiring different sweep designs to conventional vibroseis. We investigated varying frequencies to identify the optimum penetration, monitored for unwanted noise and assessed signal attenuation vs. distance.

The first test of the seismic sensing stations was to optimize ground coupling. Augered holes were drilled to 3-4ft depths near an active salt dome storage operation in SE Texas. The

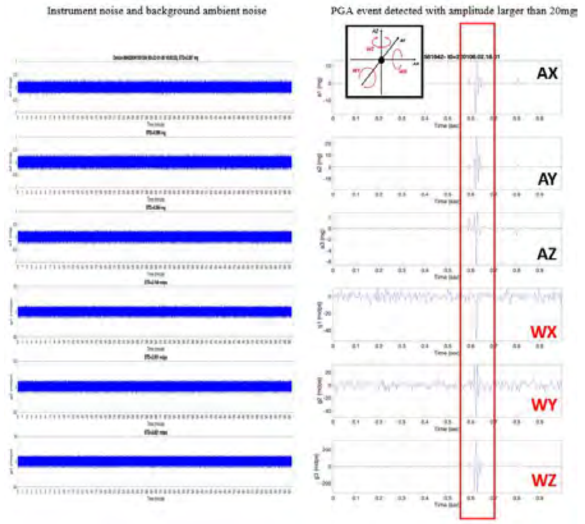


Figure 3: Peak ground acceleration (PGA) alert recorded on all six components at one of the stations at our first test site (January 2021)

following scenarios were tested; sand-filled, soil-filled, PVC casing & sand-filled, PVC casing & soil-filled. Simple back fill and packing of the excavated solid without PVC casing was found to give the best coupling. All further installations were deployed in this manner. Figure 3 peak ground acceleration (PGA) alert recorded on all six components at one of the stations at this first test site.

A benchmark test against traditional force-balance seismometers was carried out over a three-month period in Howard County, TX. The new MEMS seismic stations were co-located with public and private seismometer stations and recorded induced seismicity in the area. The results compared favorably with a cross-correlation coefficient of the three translational channels of the MEMS and traditional seismometers of 99%. During the trial a teleseismic earthquake was recorded. With high frequencies naturally attenuated we were able to look at the very low frequency comparison and found excellent correlation between the MEMS accelerometers and the traditional seismometers down to 0.03Hz. Figure 4 shows a field setup and data comparison examples.

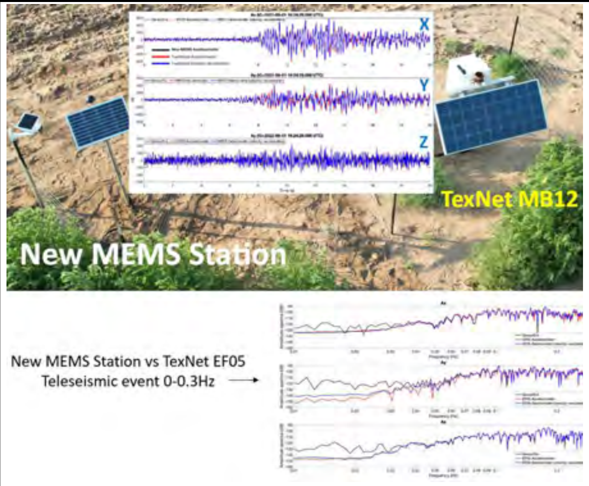


Figure 4: Over 3 months we compared the new low-cost, rapid-deplotyment MEMS technology with taditional seismometers in public and private networks. The correlation coefficient was 99% even at very low frequencies. All events reported by traditional seismometers were observed at the new stations (Brooks et al 2023)

A 500-acre working ranch and vineyard was used as a test site for SLV source and receiver testing. Nine autonomous seismic stations were installed as two perpendicular receiver lines of 2200ft and 3400ft. The apex of the lines is the SLV source location. 4G signal is weak in the area and the hilly nature of the site permitted a satellite-based Starlink system with a signal booster that sends Wi-Fi signal to the stations. Local ground condition restrictions meant that we could only install the helical anchor down to 15ft but a series of discrete frequency source tests were carried out using the SLV. A supply-chain delay with the high-power source drive meant that a smaller drive was used and we could only run to about 60% power and up to 65Hz. Nevertheless, we recorded test data at a near offset station that clearly shows the expected power increase with increasing angular velocity of the synchronized motors (Fig. 5). Testing is ongoing at this site and a second site near Houston, TX that will be fully autonomous and solar-powered will be available August 2023. Better control of subsurface geology at the Texas site will allow for more meaningful interpretation of recorded data and full power 100Hz data will be used to test various linear and non-linear sweep designs.

Figure 5: The SLV source installed on a helical anchor at the SensorEra/GPUSA 500 acre test facility in California. A series of tests were performed at dicrete frequency bands and amplitudes were onserved at the surface sensor. After correlation reflected energy was seen at 7000ft depth. Testing is ongoing.

Conclusions

In the California test, the seismic waves from the new source were reflected at depths of up to ~7,000ft and detected by the new near-surface sensors. Penetration of the helical pile through the weathering layer effectively eliminates the variable near surface attenuation, making this buried system ideal for 4D seismic monitoring of CO2 plume injection. Furthermore, deployment on helical anchors permits installations in transition zones and swamps as well as solid ground.

The new IoT system of low-cost, fully autonomous linear vibratory sources with new 6C seismic stations was demonstrated to be well suited to local induced seismicity monitoring and deep sparse seismic reflection surveying. The remotely-operated, solar-powered and field-personnel-free operations can fulfil the dual requirements for both passive seismicity monitoring and active CO2 plume tracking in a variety of environments.

Novel Acquisition Hardware for Seismicity Monitoring & CO2 Plume Mapping

Acknowledgements

We thank everyone at GPUSA, SensorEra, HighPeak Energy, SM Energy, Birch Resources and of course the test site land owners.