# Seismic data acquired with a novel, permanently-installed borehole seismic source

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## Summary

The Containment and Monitoring Institute's Field Research Station in Alberta, Canada is a small-scale carbon sequestration site, with the primary objective of testing various monitoring technologies. To investigate improvements to time-lapse seismic surveying, permanently-installed orbital vibrator sources have been installed at the site. We present initial results of data acquisition using a borehole orbital vibrator source and will show that this source compares favorably with surface Vibroseis data.

## Introduction

In Newell County, Alberta, Canada, the Containment and Monitoring Institute (CaMI), a division of CMC Research Institutes (CMCRI), has established a Field Research Station (FRS) where various measurement, monitoring, and verification technologies will be implemented and tested to assess their viability in the monitoring of carbon sequestration projects (e.g. Innanen et al., 2019; Hall et al., 2019). Infrastructure of interest for this paper includes the injection well, at the centre of the site, and an observation well located approximately 20 m southwest of the injector (Figure 1).

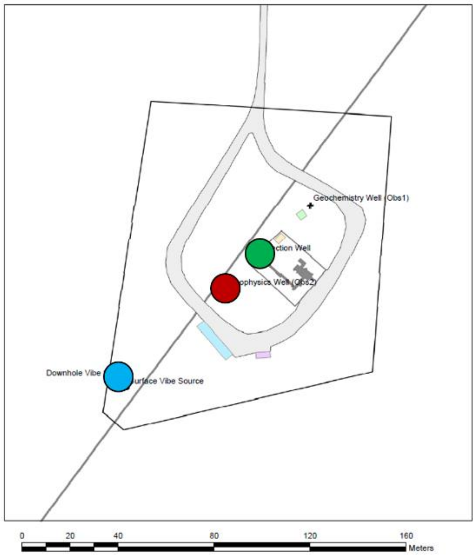

Figure 1: Schematic of CaMI FRS. Injector well (green), observation well (red), and borehole vibrator (blue) locations identified.

One of the technologies being tested at the FRS is the use of permanently-installed orbital seismic sources. An introduction to this type of source was previously presented by Spackman and Lawton (2018). These sources operate by rotating an eccentric mass about an axle over a sweep of frequencies up to 200 Hz. The rotating mass exerts a force on the axle, and, due to the coupling between the rotation axle and the ground, causes vibrations (seismic waves) to propagate through the subsurface. It is anticipated that the seismic amplitude recorded will have a quadratic relationship with the angular frequency of the rotating mass, where the amplitude is proportional to the centripetal acceleration of the mass:

$$\boldsymbol{F}_c = m\boldsymbol{r}\omega^2 \tag{1}$$

Two types of orbital vibrator sources, both under development by GPUSA, were installed at the FRS. The sources are referred to as linear vibrator sources, as the frequency of the rotating mass generally varies linearly with time. The sources were installed approximately 58 m southwest of the observation well, and each offers a unique approach to mitigating attenuative effects of the near surface. The borehole source is cemented in a shallow borehole, approximately 15 m deep. The surface vibrator is mounted on a steel helical pile, anchored to a consolidated argillaceous layer below glacial till in the near surface. This paper will focus on the data acquired with the borehole source in 2018.

## Initial borehole linear vibrator tests

In September and November 2018, the borehole linear vibrator was tested with various sweep parameters. Each phase of testing used 24 3C geophones in the observation well, along with a small surface 2D line of 1C geophones, as the receiver geometry. The borehole geophones were installed at 5 m intervals. Only the vertical components of the borehole geophones are considered in this paper.

Five sweeps with various maximum frequencies and sweep lengths were tested. Unfortunately, the source accelerometer installed on the borehole source failed during the initial testing; therefore, the true source signature is unknown, and another method of data correlation and deconvolution must be used. The traces from the surface geophone installed adjacent to the source borehole were used to approximate the source signature (Figure 2). Computing the amplitude spectra of these traces (Figure 3) displays the generally expected quadratic increase in amplitude up to the maximum frequency for each sweep, followed by an abrupt decrease in amplitude to zero. The roll-off in amplitude towards the maximum frequency is thought to be due to the anti-alias filter in the recording system used for acquisition (geodes).

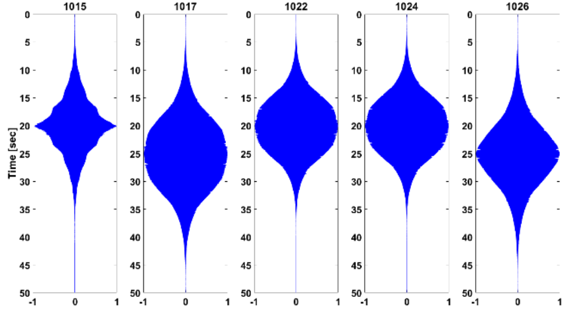

Figure 2: Traces from surface geophone nearest borehole linear vibrator for the five test sweeps.

The portion of the spectrum of each trace less than the maximum frequency of each sweep was isolated and quadratic, exponential, and sinusoidal models were fit to the spectra. For each sweep, quadratic models exhibited the highest $R^2$ value, thus confirming the quadratic relationship between the recorded amplitude and frequency of the source.

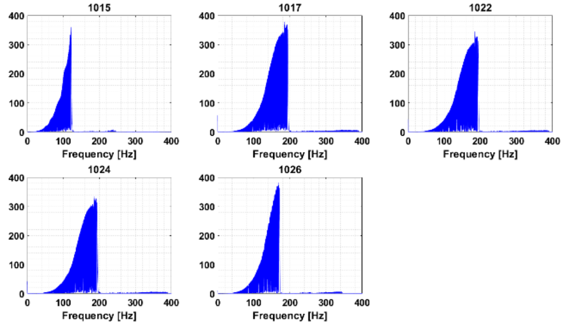

Figure 3: Amplitude spectra of traces from surface geophone nearest borehole linear vibrator for the five test sweeps.

To investigate how the source signature is being transferred from the source to the receivers, the time-frequency spectra for the surface spread of geophones was computed. A stationary high-amplitude noise band is observed on each of the displays at roughly 180 Hz, obscuring the spectrum; this is thought to be a 60 Hz harmonic. The dominant band of the time-frequency spectrum was revealed by normalizing each frequency component of the plot (Figure 4). Although quite noisy, the displays demonstrate that the linear source signature is being captured by the surface geophones.

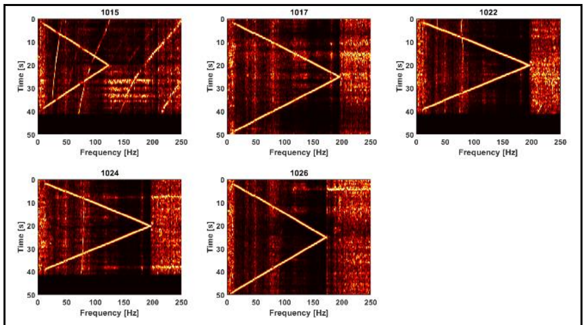

Figure 4: Time-frequency plots for surface geophone spread for the five test sweeps.

## Data processing considerations

Due to the unique acquisition features of deploying orbital vibrator sources, conventional data processing workflows must be adapted to handle these new datasets. Modifications to existing data processing workflows, particularly correlation and deconvolution algorithms, were required because the pilot trace used was that from a surface geophone.

### *Correlation*

To create correlated shot records, two different methods were tested:

1. Correlate with the surface geophone closest to the source location (i.e. a pilot trace); and,
2. Correlate with a synthetic sweep generated from known sweep parameters.

Synthetic sweeps were scaled with a quadratic amplitude modifier to satisfy the $\omega^2$ relationship from equation (1), as well as a cosine taper. While not exact match, applying both a cosine taper and $\omega^2$ quadratic scaling to a linear sweep creates a trace that closely resembles the raw pilot trace. However, it was found that correlating raw data with the field-recorded pilot trace produced a more reliable dataset (Figure 5 & 6).

### *Deconvolution*

The upgoing and downgoing wavefields are recognizable in Figure 5; however, the section displays a strong “ringy” character. The ringy character observed is likely due to the quadratic amplitude characteristics of the source (i.e. the dependence of the source amplitude on $\omega^2$). To attempt to mitigate the ringy character, the pilot trace used for correlation was subjected to various deconvolution algorithms: Weiner deconvolution, Gabor deconvolution, and deterministic deconvolution, using both the pilot trace and a synthetic sweep. It was found that Weiner and Gabor deconvolution outperformed both deterministic methods. Applying both Weiner (Figure 7) and Gabor (Figure 8) deconvolution to the borehole geophone data appears to have reduced the ringiness present in the correlated data. Comparing the deconvolved records indicates that Gabor deconvolution performed better than Weiner, as the ringy character has been more greatly reduced, particularly after the first breaks. Therefore, future data processing workflows will include Gabor deconvolution as a pre-processing step for linear vibrator data. Deconvolution algorithms could theoretically be improved by using a source accelerometer reading.

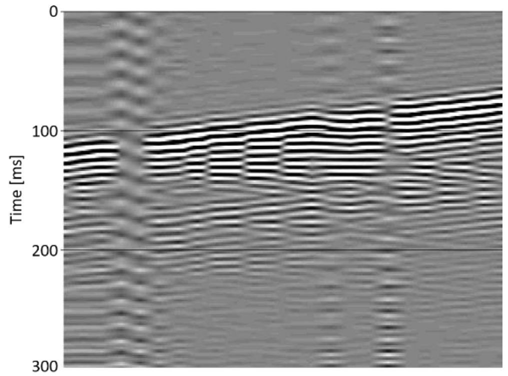

Figure 5: Vertical component of borehole geophones from borehole linear vibrator test sweep 1026. Correlated with surface pilot trace.

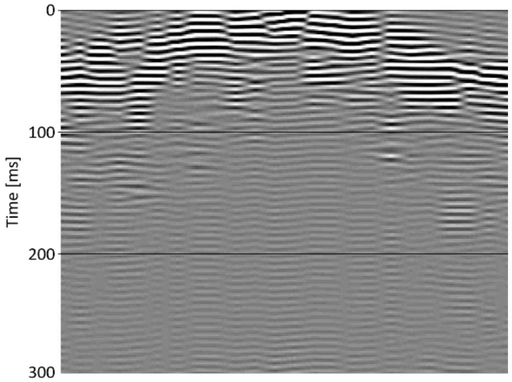

Figure 6: Surface 1C geophone data from borehole linear vibrator test sweep 1026. Correlated with surface pilot trace. Source location at centre of record.

Compared with data acquired with the same receiver geometry and source-receiver offset, the borehole linear vibrator data, after correlation and deconvolution, is similar to data acquired using a conventional linear Envirovibe sweep over approximately the same bandwidth (Figure 9). A VSP data processing flow developed for a Vibroseis source was applied to the deconvolved shot record from the borehole linear vibrator. The resultant outside corridor stack from the linear vibrator data ties fairly well with the stack from the Envirovibe source (Figure 10). A slight time delay exists between the two corridor stacks, likely due to a different source static between the borehole source and surface Vibroseis source.

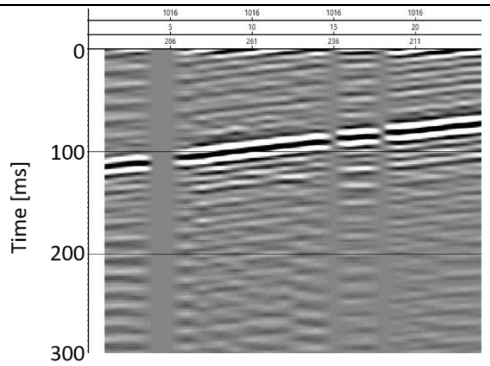

Figure 7: Borehole linear vibrator data with borehole geophones, correlated with surface pilot trace. Weiner deconvolution applied.

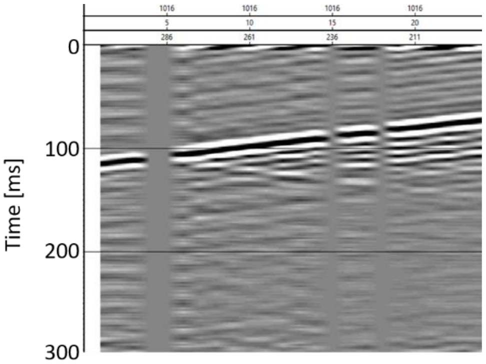

Figure 8: Borehole linear vibrator data with borehole geophones, correlated with surface pilot trace. Gabor deconvolution applied.

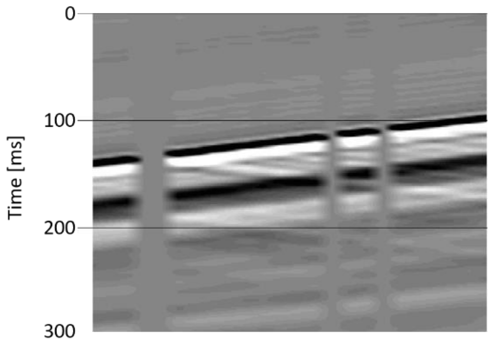

Figure 9: Envirovibe record from same offset as borehole source.

## Borehole linear vibrator data

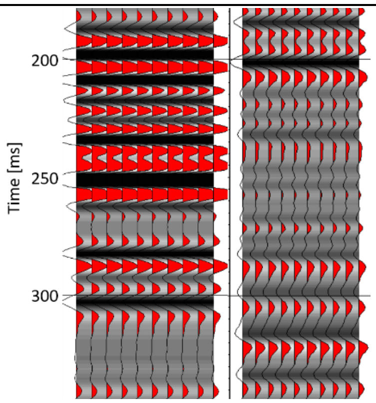

Figure 10: Corridor stack comparison between Vibroseis (left) and borehole linear vibrator (right) data.

### Source effort

In November 2018, several borehole linear vibrator sweeps were run with the same parameters to investigate the effect of increasing the source effort for orbital vibrator sources. Ten sweeps were performed, all using a 0-150 Hz upsweep over 20 s with a symmetric downsweep. The vertical component of the borehole geophones was correlated with the nearest surface geophone trace for each sweep. Strong ringy character is observed throughout the gather for each sweep, including above the first breaks. This ringy character is not observed above the first breaks on correlated records from the initial source testing.

As described previously, three major processes must be applied to raw, uncorrelated data before it is able to be processed using previously developed workflows: correlation, deconvolution, and stacking. It is unclear in what order to apply these processes; however, from the prior study of using a single linear vibrator sweep, deconvolution should be applied after correlating raw data with the pilot trace. Three cases, where the stacking process is the first, second, or third step in the workflow, were tested. Applying Gabor deconvolution to correlated records from each sweep, then stacking the results (Figure 11) performed better than the other workflows. Improvement using this workflow is illustrated by a more readily identified upgoing wavefield and the reduction in ringy character in the downgoing wavefield below the first breaks. However, more work is needed to more completely reduce the ringy character present in the data.

### Conclusions

A novel borehole orbital vibrator seismic source was tested at the CaMI FRS in Newell County, Alberta, Canada in 2018. Initial testing indicates that the intended source signature supplied to the borehole vibrator is captured by the receiver array. In the absence of a source accelerometer recording, it was found that correlating raw data with a pilot trace and applying Gabor deconvolution results in data that is comparable to conventional Vibroseis datasets.

While stacking deconvolved datasets has shown improvement compared to other workflows, generally, increasing the source effort of borehole linear vibrator data has not proven successful to this point. It is thought that if source accelerometer recordings were available, both correlation and deconvolution algorithms should improve. Additionally, small time differences may exist between subsequent sweeps. A correlation-based alignment process, as described by Freifeld et al. (2016), could help improve the resultant stacked dataset.

### Acknowledgements

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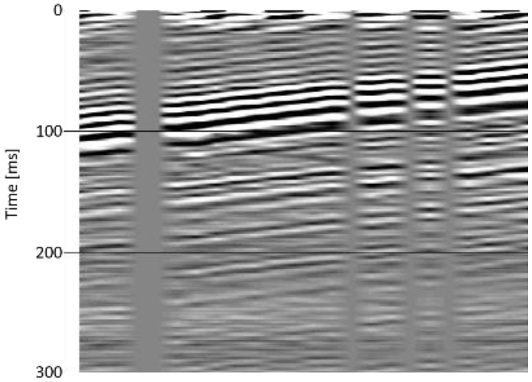

Figure 11: Linear vibrator source effort test. Data were correlated, deconvolved, then stacked.