Assessing Uncertainty and Repeatability in Time-lapse Vertical Seismic Profile (VSP) Monitoring of CO₂ Injection in a Brine Aquifer, Frio Formation, Texas—A Case Study

21 June 2017
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Cover Illustration: Shot hole drilling in the woods of Texas for the Frio vertical seismic profile (VSP) sources.


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Assessing Uncertainty and Repeatability in Time-lapse Vertical Seismic Profile (VSP) Monitoring of CO₂ Injection in a Brine Aquifer, Frio Formation, Texas—A Case Study

Siamak Nazari¹ and Thomas M. Daley²

¹University of California, Berkeley, Department of Civil and Environmental Engineering, 760 Davis Hall, Berkeley, CA 94720
²Earth Sciences Division, Lawrence Berkeley National Lab, 1 Cyclotron Road, Berkeley, CA 94720

NRAP-TRS-III-023-2017

Level III Technical Report Series

21 June 2017
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<th>Description</th>
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<td>3-D</td>
<td>Three-dimensional</td>
</tr>
<tr>
<td>4-D</td>
<td>Four-dimensional</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon dioxide</td>
</tr>
<tr>
<td>GOM</td>
<td>Gulf of Mexico</td>
</tr>
<tr>
<td>GOR</td>
<td>Gas-to-oil ratio</td>
</tr>
<tr>
<td>NRMS</td>
<td>Normalized root mean squared</td>
</tr>
<tr>
<td>RMS</td>
<td>Root mean squared</td>
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<tr>
<td>VSP</td>
<td>Vertical seismic profile</td>
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Acknowledgments

This work was completed as part of the National Risk Assessment Partnership (NRAP) project. Support for this project came from the U.S. Department of Energy’s (DOE) Office of Fossil Energy’s Crosscutting Research program. The authors wish to acknowledge Traci Rodosta (Carbon Storage Technology Manager), Kanwal Mahajan (Carbon Storage Division Director), M. Kylee Rice (Carbon Storage Division Project Manager), Mark Ackiewicz (Division of CCS Research Program Manager), Darin Damiani (Carbon Storage Program Manager), Robert Romanosky (NETL Crosscutting Research, Office of Strategic Planning), and Regis Conrad (DOE Office of Fossil Energy) for programmatic guidance, direction, and support.

This work was performed as a Masters Degree project by Siamak Nizari with guidance from Prof. J. Rector of the University of California, Berkeley.

The authors would like to thank Dr. Susan Hovorka of the Bureau of Economic Geology, the Gulf Coast Carbon Center, and the University of Texas, Austin, for her guidance and support of the Frio project and the VSP work.
ABSTRACT

This study was performed to assess the repeatability and uncertainty of time-lapse vertical seismic profile (VSP) response to carbon storage (CO₂) injection in the Frio formation near Houston, Texas. A workflow was built to assess the effect of time-lapse injected CO₂ into two Frio brine reservoir intervals, the “C” sand (Frio 1) and the “Blue” sand (Frio 2). The time-lapse seismic amplitude variations with sensor depth for both reservoirs Frio 1 and Frio 2 were computed by subtracting the seismic response of the base survey from each of the two monitoring seismic surveys. Source site 1 has been considered as one of the best sites for evaluating the time-lapse response after injection. For site 1, the computed time-lapse normalized root mean squared (NRMS) levels after processing were compared to the estimated time-lapse NRMS level before processing for different control reflectors, and for brine aquifers Frio 1, and Frio 2 to quantify detectability of amplitude difference.

Three different scenarios have been considered to analyze the time-lapse amplitude variations: the base survey which was performed before injection, monitor 1 performed after the first injection operation, and monitor 2 which was performed after the second injection. The first scenario was base - monitor 1, the second was base - monitor 2, and the third was monitor 1 - monitor 2. Three “control” reflections above the Frio were considered to assist removal of overburden changes, and this study concluded that control reflector 3 is the most favorable for the first scenario in terms of the NRMS response, and control reflector 1 is the most favorable for the second and third scenarios in terms of the NRMS response. The NRMS parameter is shown to be a useful measure to assess the effect of processing on time-lapse data. The overall NRMS for the Frio VSP dataset was found to be in the range of 30–80% following basic processing. This could be considered an estimated baseline in assessing the utility of VSP for CO₂ monitoring without advanced 4-D processing.

This study shows that the CO₂ injection in brine reservoir Frio 1 (the “C” sand unit) induced a relative change in amplitude response, and for Frio 2 (the “Blue” sand unit) an amplitude change was also detected. In both cases the uncertainty, as measured by the NRMS, indicates the reservoir changes are, at best, only slightly above the noise level, and often below the noise level of the overall dataset.
1. INTRODUCTION

Time-lapse seismic surveying is a series of repeated reflection seismic surveys over the same location and serves, among other uses, as a constraint to reservoir simulation models for identifying fluid flow. This kind of survey has become a widely-used method for monitoring reservoir fluid behavior during production and development stages of a reservoir.

Although three-dimensional (3-D) seismic imaging, using surface sources and receivers, has been the primary tool used for geophysical reservoir monitoring to date, vertical seismic profiling (VSP) has characteristics that are particularly suitable for time-lapse surveying (Hardage, 2000). In particular, the use of downhole receivers provides some potential advantages: 1) increased frequency content improves vertical and lateral resolution, allowing the examination of the reservoir in greater detail, both statically and dynamically; and 2) improved signal-to-noise ratio permitting the measurement and quantification of time-lapse changes in the reservoir with a higher degree of confidence.

The objectives of this study are to: 1) analyze the two Frio VSPs in a consistent manner for the detection of carbon dioxide (CO₂) induced changes in seismic reflectivity, and 2) quantify the uncertainty in the VSP data which controls the quantitative interpretation of the time-lapse change. The normalized root mean square (NRMS) method of Kragh and Christie (2002) was used to quantify time-lapse uncertainty. NRMS is a measure of data similarity, expressed as a percentage (from 0–200%) with lower values having greater similarity. NRMS will be defined and discussed in Section 5.
2. **TIME-LAPSE VSP MONITORING – ASSESSING RISK**

The motivation for VSP can be demonstrated using a methodology developed by Lumley et al. (1997) as a “risk analysis spreadsheet.” An enhanced version of the spreadsheet has been developed for both time lapse VSP and four-dimensional (4-D) seismic reservoir monitoring projects by Lumley et al. (2000). In Figure 1, the significant new parameters developed for this study include measures of vertical and lateral resolution, source and receiver repeatability and image aperture area, relevant for both VSP and 3-D seismic acquisition. A scoring system quantifies the risk measured in each new parameter for both types of methods. These parameters were quantified for six injection scenarios in different types of reservoirs around the world (Figure 1A). The six scenarios include CO₂ injection in land-based carbonate reservoirs, steam injection in land-based sand reservoirs, and waterflood in marine-based sand reservoirs, all focused on monitoring a 7-m thin target zone. The six scenarios are fully evaluated in terms of reservoir and seismic parameters, and cross-plotted in a final combined analysis of all parameters. The results show that VSP has the potential to be of much lower risk than 4-D seismic for all six scenarios, provided that VSP surveys are highly repeatable, and attain excellent frequency content, areal coverage, and image quality.

<table>
<thead>
<tr>
<th>Reservoir Parameters</th>
<th>Seismic Parameters</th>
</tr>
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<tbody>
<tr>
<td>Porosity</td>
<td>Vertical resolution</td>
</tr>
<tr>
<td>Dry rock bulk modulus</td>
<td>Horizontal resolution</td>
</tr>
<tr>
<td>Fluid compressibility contrast</td>
<td>Source repeatability</td>
</tr>
<tr>
<td>Fluid saturation changes</td>
<td>Receiver repeatability</td>
</tr>
<tr>
<td>Predicted impedance changes</td>
<td>Survey repeatability</td>
</tr>
<tr>
<td>Structural dip</td>
<td>Image aperture area</td>
</tr>
<tr>
<td></td>
<td>Image quality</td>
</tr>
<tr>
<td></td>
<td>Imaging of fluid contacts</td>
</tr>
</tbody>
</table>

The spreadsheet that was presented by Lumley et al. (2000) focuses on understanding two aspects of the geophysical approach:

1) Quantify the impact of doing time lapse VSP
2) Compare the effectiveness of VSP surveys versus 4-D seismic surveys for a given monitoring objective

Reservoir and seismic parameters for the VSP method have been categorized by a scoring system to attain an acceptable risk analysis in terms of the relationship between both sets of parameters (Figure 1). Both reservoir and seismic parameters are assigned a score of 0–5 points depending on how they improve the chance of success of a reservoir monitoring project. According to Figure 1A, favorable reservoir candidates for seismic monitoring have high porosity, low dry-rock bulk modulus (high compressibility), large fluid compressibility contrast between the fluids being monitored, large saturation change (reservoir sweep), large changes in predicted seismic
impedance or travel time, and low structural dip. A suitable technique for reservoir monitoring should have high vertical and horizontal resolution, excellent repeatability for source, receiver and overall survey acquisition, large image aperture area, excellent image quality, and ability to image fluid contacts.

Figure 1: A risk analysis spreadsheet and chart for time-lapse VSP and 4-D seismic, (A) scoring of reservoir and seismic parameters, and (B) risk analysis of seismic scores versus reservoir scores for six projects (from Lumley et al., 2000).
In all cases in this study, the VSP score for each scenario exceeds the 3-D seismic score. This is, in part, because the reservoir scenarios favor VSP by focusing on a thin 7-m thick target zone. The difference in scores is also partially due to VSP surveys having better receiver repeatability, somewhat better source and overall survey repeatability, and the potential for better image quality. However, these aspects of image quality depend critically on whether the VSP data are recorded with high enough frequency content, fold, and signal-to-noise ratio. In comparison, 3-D seismic surveys tend to have a wider image aperture area and higher signal-to-noise ratio than VSP, but have lower resolution and acquisition repeatability. In general, the land surveys score better than the marine surveys. This is because seismic acquisition repeatability, both 3-D and VSP, was traditionally more easily achieved on land than at sea (Lumley et al., 2000). However, development of marine seismic technology (both location tracking and active control of streamers) has in the last 10+ years reversed this situation in most cases. For new, or very recent marine surveys, the expectation of repeatability is typically better than land surveys. Additionally, marine surveys are more likely to employ permanent or semi-permanent sensor arrays (located on the sea floor). Nonetheless, the comparison of surface and borehole surveys under the Lumley methodology is still valid.

Using the rule of thumb that a project scenario must score greater than 60% on its seismic parameters to proceed with a monitoring project, Lumley et al. (2000) shows that none of the 3-D seismic scenarios pass this test, whereas all of the VSP scenarios exceed this risk threshold. Finally, it is concluded that VSP projects can be more cost-effective than 3-D seismic surveys. The total project risk, including factors such as gas-to-oil ratio (GOR), lithology, location (e.g. Gulf of Mexico (GOM) vs. San Joaquin) and type of enhanced oil recovery (steam or water flood), is shown in Table 2.

Table 2: Total project risk (Lumley et al., 2000)

<table>
<thead>
<tr>
<th>Project Setting and Type</th>
<th>4-D</th>
<th>VSP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indonesia sand, steam injection</td>
<td>Med-High</td>
<td>Low</td>
</tr>
<tr>
<td>GOM-Nsea soft sand, high-GOR oil, waterflood</td>
<td>High</td>
<td>Med-low</td>
</tr>
<tr>
<td>San Joaquin sand, steam injection</td>
<td>High</td>
<td>Med-low</td>
</tr>
<tr>
<td>W. Texas vuggy carbonates, CO₂ injection</td>
<td>High</td>
<td>Med-low</td>
</tr>
<tr>
<td>GOM/Nsea medium sand, low-GOR oil, waterflood</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td>W. Texas granular carbonates, CO₂ injection</td>
<td>High</td>
<td>Medium</td>
</tr>
</tbody>
</table>
3. FRIO VSP BACKGROUND

The Frio Brine Pilot, an early test geosequestration in a brine reservoir, is described in Hovorka et al. (2006). There were two injections of CO₂ in reservoir intervals known as the C sand and the Blue sand, hereafter named “Frio 1” and “Frio 2,” located in the Frio Formation, at depths ~5,000 ft and ~5,400 ft respectively near Houston, Texas. Injection into reservoir Frio 1 was in 2004 and Frio 2 injection was in 2009. Three VSP surveys were acquired, a pre- and post-injection for Frio 1 and a post injection for Frio 2. Acquisition and initial analysis of the Frio 1 VSP is described in Daley et al. (2008), while initial results from the Frio 2 VSP were presented by Daley and Hovorka (2010). Other studies based on the Frio Pilot are described in Hovorka et al. (2006), Zhou et al. (2010), and Daley et al. (2011). The three VSP surveys all used the same sensor string (an 80-level, 3-component borehole geophone array) and all used explosive sources located at the same location to the extent possible with shothole drilling in a forested area.
4. DATA PROCESSING

This study begins with data preprocessed to provide upgoing reflectivity sections, with consistent parameters to preserve amplitudes (SR2020, 2009). Figure 2 describes the general processing work-flow used in this study, with specific steps summarized here.

- **Data preparation and quality control:** Raw VSP datasets were input into the processing software and checked to ensure that the three datasets, hereafter called base, monitor 1, and monitor 2, have consistent geometry information in the trace headers. The software used for this purpose is called ECHOS, supported by Paradigm Ltd., which is developed for processing of seismic data.

- **Preprocessing of data:** The three sets of data have been processed using the same parameters. The flow developed is shown in Figure 2 and includes data alignment, data flattening, median filtering, and static shift. The data flattening is performed to align the upgoing reflections at a constant time by applying a shift equal to twice the first arrival time for each depth recording. The median filtering is done to smooth the trace-to-trace variations in the upgoing reflection. The static shift is applied to a control reflector to remove shallow velocity variations, which are not due to the reservoir processes (CO₂ injection). These shallow variations include source variability and near-surface saturation changes.

- **Data subtraction:** Three datasets have been subtracted from one another to get the difference section. Different control reflectors have been picked and compared and the shot gathers have been flattened based on those control reflectors to enhance the signal-to-noise ratio and the level of NRMS.

- **NRMS calculation:** The NRMS amplitude level for subtracted base - monitor 1, base - monitor 2, and monitor 1 - monitor 2, has been calculated to assess the improvement in time-lapse amplitude normalization before and after preprocessing.

- **Time-lapse amplitude interpretation:** Relative NRMS amplitude levels have been computed and compared for several control reflectors, and the reflections from reservoir Frio 1 and reservoir Frio 2.
Figure 2: Schematic flow-chart of the time-lapse work-flow.
5. DATA PREPARATION AND PREPROCESSING

VSP data have been time-shifted for different source sites by adding the first break time to the trace header of the data. This aims to have all the reflected events horizontally aligned for better processing and interpretation.

Figure 3 depicts the original upgoing “raw” data and the aligned data for base survey of time-lapse study. The first break time has been added to the time trace header to apply a shift, which leaves the reflected events horizontally aligned. Figures 4 and 5 also show the aligned data for monitor 1 and monitor 2 surveys.
Figure 4: Raw data (left) and aligned data for monitor 1 survey (right) for site 1.

Figure 5: Raw data (left) and aligned data for monitor 2 survey (right) for site 1.

The data smoothing (median) filter has been applied to all base and monitors datasets to enhance the spatial coherence of the control reflector for time selection.
The next step was selecting a control reflector horizon to use for time shifting the three datasets. In this regards, different control reflectors have been selected and tested to improve the level of NRMS of the signal amplitude.

Figure 6 shows the smoothing (median filter) and flattening (time shift) processes for the base survey at site 1.

Figure 6: Data smoothing (middle) and flattening (right) for base scenario (left) for site 1.

Figure 7: Data smoothing/flattening for monitor 1 (with arrows showing reservoirs 1 and 2, upper and lower) for source site 1.
Figures 7 and 8 show the smoothing and flattening processing data for monitor 1 and monitor 2 data.

Three datasets, base, monitor 1, and monitor 2, have been processed with the same parameters. The processing steps include median filter smoothing, flattening, and applying static time shifts to monitor 1 and monitor 2 datasets to shift the control reflector for all three datasets to the same travel time. The time shift should result in more accurate time-lapse amplitude difference as both base and monitors should be aligned at the same level for subtraction.
Figure 9: Applying static time shift to the flattened data, monitor 2 for site 1.
5.1 DATA SUBTRACTION

After applying static time shift to the monitor datasets, data differencing is done to enhance the effect of time-lapse amplitude response after CO₂ injection for each base - monitor 1, base - monitor 2, and monitor 1 - monitor 2 scenario. An Echoes processing flow has been written for subtracting the data (Figure 10). Figure 1 shows data that have been prepared and are ready for subtraction from one another.

![Processing flow for subtracting base, monitor 1, and monitor 2 datasets.](image)

![Base, monitor 1, and monitor 2 for reservoirs Frio 1 (arrows above) and Frio 2 (arrows below).](image)
The flow in Figure 10 has been run for each pair of data to calculate the subtracted section shown in Figure 12.

![Figure 12: Difference between each pair of datasets for base - monitor 1, base - monitor 2, and monitor 1 - monitor 2 for site 1.](image)

### 5.2 NRMS AMPLITUDE CALCULATION

NRMS criterion (Kragh and Christie, 2002) has been used to evaluate the repeatability of seismic response after injection. The root-mean-squared (RMS) amplitude values have been calculated for all scenarios, base, monitor 1, and monitor 2, for specific windows of control reflectors as well as reservoir time interval windows. The formula for calculating the NRMS is as follows:

\[
NRMS = \frac{200 \times RMS(a_i - b_i)}{RMS(a_i) + RMS(b_i)}
\]

where the RMS operator is defined as:

\[
RMS(x_i) = \sqrt{\frac{\sum_{t_i}^t x_i^2}{N}}
\]

where N is the number of samples in interval t1–t2.

Data repeatability can be estimated by comparing the NRMS level of each pair of datasets (base - monitor 1, base - monitor 2, and monitor 1 - monitor 2). NRMS estimates can also show the
possible effect of injected CO₂ underground, since the time-lapse change measured by NRMS can be due to reservoir changes. First, NRMS levels (plotted in percentage, with a range of 0–200) versus sensor depth were used, before and after preprocessing, to observe how a chosen preprocessing flow could enhance the time-lapse signal. This study began with source site 1.

5.3 ANALYSIS OF CONTROL REFLECTION

Different control reflectors have been selected, time-shifted for alignment, and analyzed in terms of their NRMS level to find the best one in terms of minimizing NRMS level. The purpose of selecting the best control reflector is to remove the effect of overburden from the data so that the maximized change in signal is due to the effect of injected CO₂. After time shifting to remove overburden variation, the repeatability of the control reflector can also be assessed with NRMS, and the reflector can be analyzed for amplitude normalization between each pair of surveys.

NRMS has been calculated in percentage versus sensor depth for several control reflector time windows, with three analyzed completely and two (1,161–1,168 ms and 1,355–1,370 ms) described here. The NRMS response was used to choose the best control reflector among the three. Control reflector 2 was not effective in terms of improving the NRMS level of signal in the control reflector or the reservoir intervals. Control reflectors 1 and 3 have been studied and analyzed for NRMS responses after preprocessing.

5.4 CONTROL REFLECTOR 1

Figure 13 shows that there is not much improvement in NRMS using the control reflector 1 (1,161–1,168 ms) and analyzing the base-monitor 1 pair. The effect of the median filter can be seen, but not an overall decrease in NRMS.

Figure 13: NRMS plot for before and after preprocessing for base-monitor 1 of control reflector 1 (1,161–1,168 ms).
Figure 14 compares the improvement from control reflector 1 for the base - monitor 2 pair, which shows that the average level of NRMS improved from 50% before preprocessing to 25% after preprocessing. Thus, it shows 50% improvement in the NRMS level. Figure 15 depicts the monitor 1 - monitor 2 pair, and the average level of NRMS improved from 60% before preprocessing to 20% after preprocessing. In this case, there is a clear improvement in data repeatability with the preprocessing using control reflector 1.

![Figure 14: NRMS plot for before and after preprocessing for base - monitor 2 of control reflector 1 (1,161–1,168 ms).](image1)

![Figure 15: NRMS plot for before and after preprocessing for monitor 1 - monitor 2 of control reflector 1 (1,161–1,168 ms).](image2)
5.5  ANALYSIS OF RESERVOIR REFLECTION USING CONTROL REFLECTOR 1

NRMS plots for reservoir intervals have been also analyzed versus sensor depths to see the effect of injection on Frio 1 and Frio 2 reservoirs. This analysis could also help to distinguish the effect of injected CO2 plume into reservoir. The main focus in this part of the project is to interpret the NRMS response after preprocessing (red curves).

The effect of CO2 plume in Frio 1 reservoir should be observed in base - monitor 1 and base - monitor 2 scenarios, as the injection happens in monitor 1 stage and the effect of the CO2 plume remains in the reservoir until monitor 2 occurs (assuming no migration of CO2). Figure 16 shows the NRMS curve versus sensor depth for reservoir Frio 1 interval (1,380–1,400 ms).

![NRMS plot for before and after preprocessing for base - monitor 1 of control reflector 1 for reservoir Frio 1 (1,380–1,400 ms).](image)

Figure 16: NRMS plot for before and after preprocessing for base - monitor 1 of control reflector 1 for reservoir Frio 1 (1,380–1,400 ms).

NRMS plots for reservoir intervals have been also been analyzed versus sensor depths to see the effect of injection on Frio 1 and Frio 2 reservoirs. Figure 17 shows the NRMS for base - monitor 2 for the Frio 1 reservoir zone. Figure 18 represents the NRMS level of reservoir Frio 1, for the third scenario (monitor 1 - monitor 2). It shows that the repeatability between these two surveys, monitor 1 and monitor 2 is improved by preprocessing. In Figures 16, 17, and 18 there is no clear indication of increasing NRMS due to CO2 injection.
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Figure 17: NRMS plot for before and after preprocessing for base - monitor 2 of control reflector 1, for reservoir Frio 1 (1,380–1,400 ms).

The black circle on Figure 17 also shows where a time-lapse effect after CO2 injection would be expected for reservoir Frio 1 (sensor depth ~4,900–5,000 ft). No clear indication is seen of NRMS rising above the background level (a rise that could be caused by the CO2 injection).

Figure 18: NRMS plot for before and after preprocessing for monitor 1 - monitor 2 of control reflector 1 for reservoir Frio 1 (1,380–1,400 ms).

For the Frio 2 reservoir (~5,400–5,500 ft), Figure 19 shows that there is not much improvement in the NRMS values from before to after preprocessing for the first scenario, base - monitor 1. There is an increase in the circled zone, but it is not above the background level. For the second scenario base - monitor 2 (Figure 20), an improvement can be observed in the NRMS level from
70% before preprocessing to 40% after preprocessing in reservoir Frio 2. An increase in NRMS from 4,500–5,000 ft and also from 5,300–5,400 ft (near top reservoir Frio 2) in Figure 20 shows the possible effect of CO₂ injection with NRMS rising to over 100% in the preprocessed data.

![NRMS plot for before and after preprocessing for base - monitor 1 of control reflector 1 for reservoir Frio 2 (1,480–1,490 ms).](image1)

**Figure 19:** NRMS plot for before and after preprocessing for base - monitor 1 of control reflector 1 for reservoir Frio 2 (1,480–1,490 ms).

![NRMS plot for before and after preprocessing for base - monitor 2 of control reflector 1 for reservoir Frio 2 (1,480–1,490 ms).](image2)

**Figure 20:** NRMS plot for before and after preprocessing for base - monitor 2 of control reflector 1 for reservoir Frio 2 (1,480–1,490 ms).
Figure 21 represents the NRMS level for the third scenario, monitor 1 - monitor 2. The injection in reservoir Frio 2 occurred at monitor 2 survey. The NRMS fluctuation observed at depth 2,250 ft cannot be due to CO2 injection effect as it is repeated in both base - monitor 1 and monitor 1 - monitor 2 scenarios. An increase in the NRMS level occurred at the top of reservoir Frio 2 from 5,000–5,300 ft (large circle) could indicate the injection response.

Figure 21: NRMS plot for before and after preprocessing for monitor 1 - monitor 2 of control reflector 1 for reservoir Frio 2 (1,480–1,490 ms).
5.6 CONTROL REFLECTOR 3

Figure 22 and 23 show that using control reflector 3, the NRMS levels for before and after preprocessing steps have slightly improved for the first and second scenarios. Apparently, control reflector 1 improves the NRMS level for the first, base-monitor 1, and second base-monitor 2 scenarios. Although comparing scenario 1 and scenario 2, it appears that the average NRMS in second scenario slightly improved over 3,100–4,200 ft sensor depths with 50% (from 80% to 40%), whereas there is not much improvement for the first scenario (Figure 22) on the same depth range.

Figure 22: NRMS plot for before and after preprocessing for base-monitor 1 of control reflector 3 (1,355–1,370 ms).

Figure 23: NRMS plot for before and after preprocessing for base-monitor 2 of control reflector 3 (1,355–1,370 ms).
Figure 24 shows the third scenario (monitor 1 - monitor 2) with an average improvement of 30% in the NRMS level from about 60% before preprocessing to 40% after. It is more promising than the other two scenarios for control reflector 3 in terms of improvement in the NRMS level.

![NRMS plot for before and after preprocessing for monitor 1 - monitor 2 of control reflector 3 (1,355–1,370 ms).](image)

**Figure 24:** NRMS plot for before and after preprocessing for monitor 1 - monitor 2 of control reflector 3 (1,355–1,370 ms).

### 5.7 RESERVOIR FRIO 1 REFLECTION USING CONTROL REFLECTOR 3

Figure 25 depicts the NRMS for Frio 1 reservoir reflector (1,380–1,400 ms) using the control reflector 3. An improvement in the NRMS average level from 50% to 25% is seen for shallower sensors (2,000–3,500 ft), but not for the deeper sensors where the CO2 effect is expected (e.g. black circle in Figure 25). Comparing two control reflectors 1 and 3, this study concluded that for the first scenario (base - monitor 1) control reflector 3 has smaller NRMS values, and for second (base - monitor 2) and third (monitor 1 - monitor 2) scenarios control reflector 1 shows a better response in terms of the NRMS level.
Figure 25: NRMS plot for before and after preprocessing for base - monitor 1 of control reflector 3 for reservoir Frio 1 (1,380–1,400 ms).
Figure 26 shows that the average NRMS level for the second scenario, base - monitor 2 of reservoir Frio 1, improved from about 60% to 40% after preprocessing. It also shows that the level of NRMS for reservoir Frio 1 (4,900–5,000 ft) remains low about 45% (black circle). Comparing Figures 25 and 26 at depth 4,800–5,000 ft (reservoir Frio 1), it is confirmed that there is comparable change in terms of the NRMS values between base - monitor 1 (80%) and base - monitor 2 (60%) scenarios. Therefore, the time-lapse response of the CO2 plume that could be seen in the NRMS level for base - monitor 1 scenario is possible, while in base - monitor 2 scenario there is minimal change (no injection in monitor 2 survey in Frio 1 reservoir).

Figure 26: NRMS plot for before and after preprocessing for base - monitor 2 of control reflector 3 for reservoir Frio 1 (1,380–1,400 ms).
Figure 27 represents the NRMS curve for the third scenario, monitor 1 - monitor 2 before and after preprocessing with control reflector 3 (1,355–1,370 ms). The NRMS level of reservoir Frio 1 (sensor depth about 4,900–5,000 ft) for third scenario (monitor 1 - monitor 2) is 80% which is identical in comparison with the second scenario. The first scenario and third are almost at the same NRMS level.

Figure 27: NRMS plot for before and after preprocessing for monitor 1 - monitor 2 of control reflector 3 for reservoir Frio 1 (1,380–1,400 ms).
5.8 RESERVOIR FRIO 2 USING CONTROL REFLECTOR 3

Figure 28 shows the NRMS level for the Frio 2 reservoir reflector (1,480–1,490 ms) for the base-monitor 1 scenario. There is some improvement in the NRMS over the 2,000–2,500 ft depth range, but not much improvement at the reservoir depths.

![NRMS plot for before and after preprocessing for base-monitor 1 of control reflector 3 for reservoir Frio 2 (1,480–1,490 ms).](image)
Figure 29 shows the base-monitor 2 scenario processed with control reflector 3 analyzed in the window of the Frio 2 reservoir (1,480–1,490 ms). The effect of injected CO₂ in reservoir Frio 2 (black circle) is not observable. Overall, the oscillation and increasing trend as shown by dashed arrow line in the NRMS curve (green circle) indicates that the sensors above the reservoir had improvement in the NRMS, and the NRMS level dramatically increased from 30–40% to 80–90% in average for sensors closer to top reservoir Frio 1 (depth ~ 5,000 ft) and Frio 2 (depth ~5,400 ft). This phenomenon could be seen in both Figures 29 and 30 below the sensor depth ~4,300 ft.

![NRMS plot for before and after preprocessing for base-monitor 2 of control reflector 3 for reservoir Frio 2 (1,480–1,490 ms).](image)

Figure 29: NRMS plot for before and after preprocessing for base-monitor 2 of control reflector 3 for reservoir Frio 2 (1,480–1,490 ms).
Figure 30, the NRMS for monitor 1 - monitor 2 (scenario 3) represents that there is an increase in the NRMS level for top reservoir Frio 2, which has been shown by a black circle, but it is not above the background variation.

5.9 AMPLITUDE CORRECTION

Like the static time shift applied in the above analysis, the reflection amplitude was expected to change due to temporal changes in the overburden. This study attempted to remove this change by applying an amplitude correction based on analysis of the control reflector. Amplitude for all the seismic surveys has been corrected using a scaling factor. This factor has been calculated for all control reflector and reservoir windows. For all base, and monitor surveys, the first control reflector window has been selected. Then the average RMS amplitude in that window (1,100–1,280 ms) has been calculated. Finally all the sample amplitude values of the dataset are divided by that average RMS value. This amplitude correction procedure has been applied to data from site 1 and site 4. The correction (inverse of average RMS amplitude values) for site 1 for base, monitor 1, and monitor 2, are 13.20, 12.01, and 8.74, respectively. For site 4, the values for base, monitor 1, and monitor 2 are 15.36, 18.11, and 11.94, respectively.

Figure 31 shows the NRMS level after amplitude correction for the first scenario, base - monitor 1 for site 1. The entire section has been corrected using a scale factor calculated in the 1,100–1,280 ms window for the control reflector 1. It seems that the level of NRMS after correction has slightly increased.
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Figure 31: NRMS plot for before and after preprocessing for base - monitor 1 of control reflector 1 after amplitude correction.

Figure 32 also shows the level of NRMS for the second scenario, base - monitor 2, after amplitude correction. It depicts that the NRMS level has been slightly improved (decreased) over 3,000–4,200 ft of sensor depth.

Figure 32: NRMS plot for before and after preprocessing for base - monitor 2 of control reflector 1 after amplitude correction.
Figure 33 represents the level of NRMS amplitude for the third scenario, monitor 1 - monitor 2, after amplitude correction. It depicts that the NRMS level has been improved over 2,500–4,500 ft of sensor depth.

**Figure 33: NRMS plot for before and after preprocessing for monitor 1 - monitor 2 of control reflector 1 after amplitude correction.**
6. ANALYSIS AND DISCUSSION

Summarizing the analysis, the processed (time-shift and amplitude correction) data was used to compare the NRMS values for the two reservoir reflectors, first using control reflector 1 for the three scenarios: base - monitor 1 (Figure 34), base - monitor 2 (Figure 35), monitor 1 - monitor 2 (Figure 36); and then using control reflector 3 for the three scenarios: base - monitor 1 (Figure 37), base - monitor 2 (Figure 38), monitor 1 - monitor 2 (Figure 39). Figure 34 compares the control reflector 1, the Frio 1 and Frio 2 reflectors, and found the NRMS level for both reservoirs Frio 1 and Frio 2 to be above control reflector 1. Higher level of NRMS in these two reservoirs compared with control reflector could be either due to higher level of noise or the effect of injected CO2 gas. NRMS values of 80% for reservoir Frio 1, (seen when normalizing by both control reflectors 1 and 3), indicates that the injection at reservoir Frio 1 may be detected (black circle in Figure 34). On the other hand the NRMS trend for reservoir Frio 2 remains stable as expected since no injection occurred in Frio 2 between base and monitor 1. Some changes in Frio 2 curve (in both Figures 34 and 37) could be possibly due to the effect of CO2 gas injection into reservoir Frio 1, located above the reservoir Frio 2. However, the overall high NRMS values and data variability limit interpretation quality.

For reservoir Frio 2 and specifically in the second and third scenarios for that reservoir, an increasing trend in NRMS with depth as shown in Figure 35 for sensors immediately above the reservoir (circle in Figures 35 and 36) could be observed. This is a possible indicator that CO2 gas injection occurred in that reservoir. This trend could also be observed in Figures 38 and 39.

![NRMS plot for before and after preprocessing for base - monitor 1 scenario of control reflector 1 for reservoirs Frio 1 and Frio 2.](image-url)
Figure 35: NRMS plot for before and after preprocessing for base-monitor 2 scenario of control reflector 1 reservoirs for Frio 1 and Frio 2. An increasing trend in the NRMS from ~4,500–5,400 ft is indicated by an arrow.
Figure 36: NRMS plot for before and after preprocessing for monitor 1 - monitor 2 scenario of control reflector 1 reservoirs for Frio 1 and Frio 2. An increasing trend in the NRMS from ~4,500 ft - 5,400 ft is indicated by an arrow.
Figure 37: NRMS plot for before and after preprocessing for base - monitor 1 scenario of control reflector 3 for reservoirs Frio 1 and Frio 2.
Figure 38: NRMS plot for before and after preprocessing for base - monitor 2 scenario of control reflector 3 for reservoirs Frio 1 and Frio 2. An increasing trend in the NRMS from ~4,500–5,400 ft is indicated by an arrow.
Figure 39: NRMS plot for before and after preprocessing for monitor 1 - monitor 2 scenario of control reflector 3 for reservoirs Frio 1 and Frio 2. An increasing trend in the NRMS from ~4,500–5,400 ft is indicated by an arrow.
7. CONCLUSIONS

The use of NRMS to quantify detectability in time-lapse VSP data was tested on the Frio Pilot data. Basic processing of static time-shifts and amplitude corrections, calculated on a control reflector did prove useful in reducing the time-lapse noise. The overall data repeatability was in the range of 30–80% NRMS. This relatively high level of time-lapse noise limited the interpretation of the data. Suggestions of detectable changes via NRMS values could be found in the Frio data where the NRMS values increased for deeper sensors, which correspond to reflection points near the injection well where CO₂ saturation is expected to be high.

The NRMS calculation was shown to be a useful measure of a given processing algorithm’s ability to reduce time-lapse noise. Uncertainty in CO₂ detection remains high following the basic processing applied here. While changes in reflections at the injection level could be detected, they remain approximately equal to the time-lapse noise in the entire dataset, as measured by the NRMS. The overall NRMS for the Frio VSP, in the range of 30–80%, following basic processing, could be considered as an estimated baseline in assessing the utility of VSP for CO₂ monitoring. However, it is expected that further processing has the potential to reduce the estimated NRMS values for this dataset.
8. **REFERENCES**


NRAP is an initiative within DOE’s Office of Fossil Energy and is led by the National Energy Technology Laboratory (NETL). It is a multi-national-lab effort that leverages broad technical capabilities across the DOE complex to develop an integrated science base that can be applied to risk assessment for long-term storage of carbon dioxide (CO₂). NRAP involves five DOE national laboratories: NETL, Lawrence Berkeley National Laboratory (LBNL), Lawrence Livermore National Laboratory (LLNL), Los Alamos National Laboratory (LANL), and Pacific Northwest National Laboratory (PNNL).

**Technical Leadership Team**

*Diana Bacon*
Lead, Groundwater Protection Working Group
Pacific Northwest National Laboratory
Richmond, WA

*Jens Birkholzer*
LBNL Lab Lead
Lawrence Berkeley National Laboratory
Berkeley, CA

*Grant Bromhal*
Technical Director, NRAP
Research and Innovation Center
National Energy Technology Laboratory
Morgantown, WV

*Chris Brown*
PNNL Lab Lead
Pacific Northwest National Laboratory
Richmond, WA

*Susan Carroll*
LLNL Lab Lead
Lawrence Livermore National Laboratory
Livermore, CA

*Abdullah Cihan*
Lead, Reservoir Performance Working Group
Lawrence Berkeley National Laboratory
Berkeley, CA

*Tom Daley*
Lead, Strategic Monitoring Working Group
Lawrence Berkeley National Laboratory
Berkeley, CA

*Robert Dilmore*
NETL Lab Lead
Research and Innovation Center
National Energy Technology Laboratory
Pittsburgh, PA

*Nik Huerta*
Lead, Migration Pathways Working Group
Research and Innovation Center
National Energy Technology Laboratory
Albany, OR

*Rajesh Pawar*
LANL Lab Lead
Lead, Systems/Risk Modeling Working Group
Los Alamos National Laboratory
Los Alamos, NM

*Tom Richard*
Deputy Technical Director, NRAP
The Pennsylvania State University
State College, PA

*Josh White*
Lead, Induced Seismicity Working Group
Lawrence Livermore National Laboratory
Livermore, CA
Sean Plasynski
Executive Director
Technology Development and
Integration Center
National Energy Technology Laboratory
U.S. Department of Energy

Heather Quedenfeld
Associate Director
Coal Development and Integration
National Energy Technology Laboratory
U.S. Department of Energy

Traci Rodosta
Technology Manager
Strategic Planning
Science and Technology Strategic Plans
and Programs
National Energy Technology Laboratory
U.S. Department of Energy

Darin Damiani
Program Manager
Carbon Storage
Office of Fossil Energy
U.S. Department of Energy

NRAP Executive Committee

Cynthia Powell
Executive Director
Research and Innovation Center
National Energy Technology Laboratory

Donald DePaolo
Associate Laboratory Director
Energy and Environmental Sciences
Lawrence Berkeley National Laboratory

Roger Aines
Chief Energy Technologist
Lawrence Livermore National Laboratory

Melissa Fox
Program Manager
Applied Energy Programs
Los Alamos National Laboratory

George Guthrie
Chair, NRAP Executive Committee
Earth and Environmental Sciences
Los Alamos National Laboratory

Alain Bonneville
Laboratory Fellow
Pacific Northwest National Laboratory

Grant Bromhal
Technical Director, NRAP
Research and Innovation Center
National Energy Technology Laboratory