Accuracy and temporal resolution of attenuation estimation from DAS VSP at CaMI Field Research Station, Alberta

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Summary

For seismic monitoring injected CO_2 during geologic CO_2 sequestration, it is useful to measure seismic attenuation. However, due to finite extents and limited sampling in the time-frequency plane, there are always strong limitations on the attainable measurement accuracy. We have used an approach for measuring attenuation by iteratively identifying a sparse set of the strongest reflections in the seismic trace and stacking their waveforms. It is data-driven and applied to the DAS VSP dataset from the CaMI Field Research Station (FRS) in Newell County, Alberta, Canada. We evaluated the errors of estimated attenuation coefficients and shown their trade-off with the desired temporal resolution.

DAS VSP at CaMI FRS

The CaMI FRS is in Newell County, Alberta, Canada. At the FRS, we focus on the development of subsurface and surface measurement, monitoring and verification technologies for the carbon capture and storage (CCS). There is one CO_2 injection well and two observation wells (OBS1 and OBS2, Figure 1a) at the FRS. Different instruments are installed at the FRS, such as DAS using straight and helical fibre optic cables with a continuous loop of about 5km in a horizontal trench and two observation wells (Lawton et al., 2019). The DAS VSP in this study was acquired on March 1st, 2021. Figure 1a shows the shot locations of this survey and this report measures the attenuation for the walk-away line 15. Envirovibe was used as the source for the March 1st survey with two sweeps of 10 – 150 Hz over 16 s for each shot location. Figure 1b is an example of a raw DAS shot gather by summing the two sweeps. This report discusses the data portion from the down-loop and up-loop straight fibre of OBS2, indicated by the dashed lines in Figure 1b.

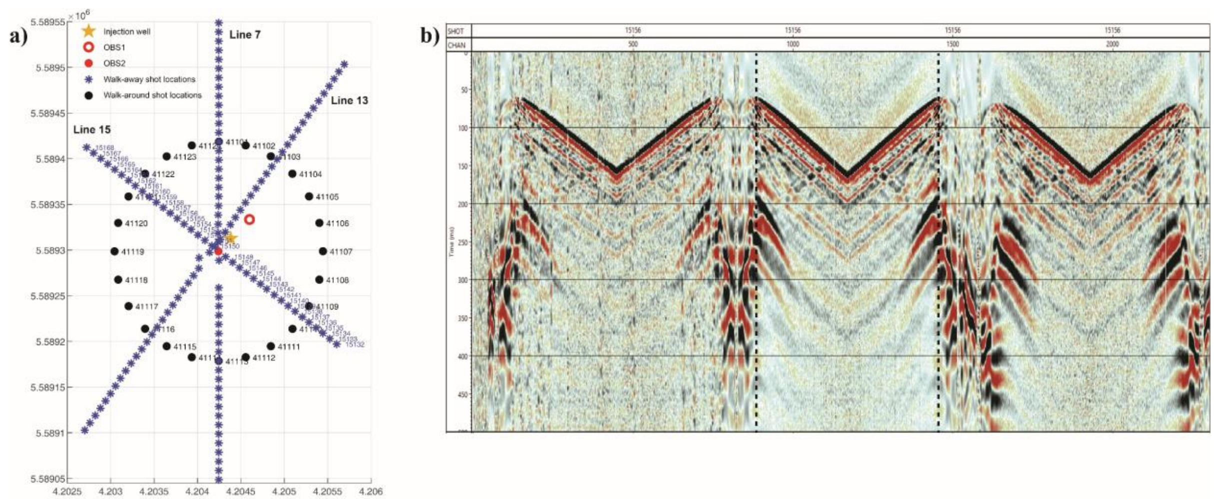

Figure 1 a) VSP layout map of the survey acquired on Match 1st, 2021 and b) one DAS shot gather of this survey.

Attenuation measurement

The non-stationary convolutional model for reflection signal in the frequency domain is

$$A(t,f)=S(f)R(t,f)\exp\left\{-\int_0^t\left[\gamma(\tau)+\pi fQ^{-1}(\tau)\right]d\tau\right\}, \tag{1}$$

where t is the two-way reflection time, f is the frequency, $A(t, f)$ is the time-frequency variant amplitude of the signal recorded at the surface, $S(f)$ is the spectrum of the source, $R(t, f)$ is the time-frequency response of the reflectivity. The Q^{-1} and its "geometric" counterpart γ describe the path effects of attenuation on the signal spectra (Morozov, 2008). With the assumption of reflectivity spectra $R(t, f) = const$, the "apparent" attenuation parameters γ_A and Q_A^{-1} can be inverted for by first taking the logarithm and then the time derivative of equation 1

$$\gamma_A+\pi fQ_A^{-1}=-\frac{\partial\ln A(t,f)}{\partial t}. \tag{2}$$

Thus, γ_A and Q_A^{-1} at time t are obtained as the coefficients of linear regression with respect to variable f. The smooth estimates of time-variant spectra $A(t, f)$ in equation 2 are derived by Wang and Morozov's (2020) approach. In this approach, a sparse set of locally strongest peaks are selected within the reflection signal and the waveforms of a certain length centered on each selected peak are extracted and stacked. The spectrum $A(t_i, f)$ is then derived from the stacked waveform at each time t_i. We use the Hann function for tapering during the waveform stacking to make the $A(t_i, f)$ smooth in time t_i. Figure 2 shows the estimated γ_A and Q_A^{-1} from the VSP CDP stack of the March 1st survey at the FRS. The BBRS in Figure 2 indicates the Basal Belly River Sandstone Formation reflection of the CO_2 injection zone at the FRS.

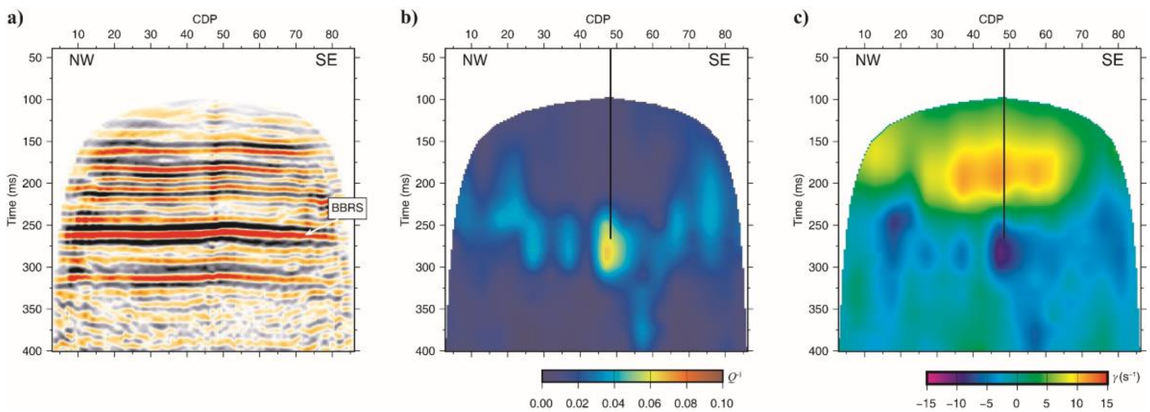

Figure 2 a) VSP CDP stack, b) estimated Q_A^{-1} values and c) estimated γ_A values. Black line in b) or c) indicates the location and depth of the CO_2 injection well at the FRS.

Accuracy and temporal resolution

As noted by White (1992), the measurements of γ and Q^{-1} always use wave trains of finite bandwidth, which are extended in time and space. Such finite extents and limited sampling in the (t, f) plane impose strong limitations on the attainable measurement accuracy. Thus, the errors of estimated Q and γ are always significant, and they trade off with the available bandwidth and temporal resolution (White, 1992).

Let us denote T the length of each waveform used in spectral measurement, B the frequency bandwidth of the data, and b the width of the elementary frequency band with the minimum value $b = 1/2T$. Let us assume that Q and γ are estimated by linear regressions with a set of $n = B/b$ frequencies f_k. To obtain uncorrelated estimates of γ and q, it is convenient to use regression with respect to a demeaned variable $\left(f_k - \overline{f}\right)$:

$$a_k = \gamma + \pi\left(f_k - \overline{f}\right)q\,, \tag{3}$$

where $\overline{f} = \sum f_k / n$, $q = Q^{-1}$, and a is the spectral quantity in the right-hand side of equation 2. If the distribution of signal amplitudes is Gaussian, the q would be normally distributed and standard statistical methods would be allowed for evaluating its measurement accuracy.

Denoting $\hat{\gamma}$ and $\hat{q}$ the estimated coefficients from regression 3, their measurement errors are

$$s_{\hat{\gamma}} = \frac{\sigma_{\hat{a}}}{\sqrt{n}} \text{ and } s_{\hat{q}} = \frac{\sigma_{\hat{a}}}{\pi\sqrt{\sum\left(f_k - \overline{f}\right)^2}} = \frac{s_{\hat{\gamma}}}{\pi\left\langle f_k - \overline{f}\right\rangle_{RMS}}\,, \tag{4}$$

where $\langle \ldots \rangle_{RMS}$ denotes the root-mean-square (RMS) average, and $\sigma_{\hat{a}}^2$ denotes the variance of the estimated quantity $\hat{a}$. The RMS average of demeaned frequencies is proportional to the signal bandwidth as $\left\langle f_k - \overline{f}\right\rangle_{RMS} = cB$. The quantity a is smoothly variable with respect to time t, and it can thus be approximated from the ratio of amplitude spectra measured at some times t_1 and t_2 separated by interval $\Delta t = t_1 - t_2$: $a_k \approx \ln\left[A(t_1, f_k)/A(t_2, f_k)\right]/\Delta t$. If the time separation Δt is selected sufficiently large, the two spectra are statistically uncorrelated, and the relative variance of the spectral ratio equals (e.g., White, 1992) $\mathrm{var}\left\{\ln\left|A(t_1, f_k)/A(t_2, f_k)\right|\right\} = 1/2bT$. Noting that $n = B/b$ and using this relative variance, relations 4 become

$$s_{\hat{\gamma}} = \frac{1}{\sqrt{2}\Delta t}\frac{1}{\sqrt{BT}} \text{ and } s_{\hat{q}} = \frac{s_{\hat{\gamma}}}{\pi cB} = \frac{1}{\pi\sqrt{2}c}\frac{1}{\sqrt{BT}}\frac{1}{B\Delta t}\,. \tag{5}$$

Equations 5 show that the errors of the estimated $\hat{\gamma}$ or $\hat{q}$ are independent of $\hat{\gamma}$ or $\hat{q}$ magnitude and inversely proportional to Δt and the square root of product BT. The key parameter determining the measurement accuracy from equation 5 is the desired temporal resolution Δt. Thus, Δt must be sufficiently large for keeping reasonable errors of $\hat{\gamma}$ or $\hat{q}$. This is a fundamental limitation for observable γ and q models as they cannot contain spatial detail smaller than $v\Delta t$, where v is the wave velocity.

In the present method, we can measure the temporal resolution Δt as half length of the Hann time window used in the waveform stacking for spectral measurements. By using Δt = 150 ms, equations 4 or 5 yield errors in Figure 3 for estimated γ_A and Q_A^{-1} of one stacked trace. Figure 3c shows the accuracy of estimated Q_A^{-1} is limited even with a limited resolution of 150 ms as the Q_A^{-1} value (black line) is below measurement error (green line) for most time depths. This indicates that the reflectivity spectra $R(t, f)$ in equation 1 might be considered as non-constant for attenuation measurement. Otherwise, we need to use a larger Δt for achieving a certain accuracy.

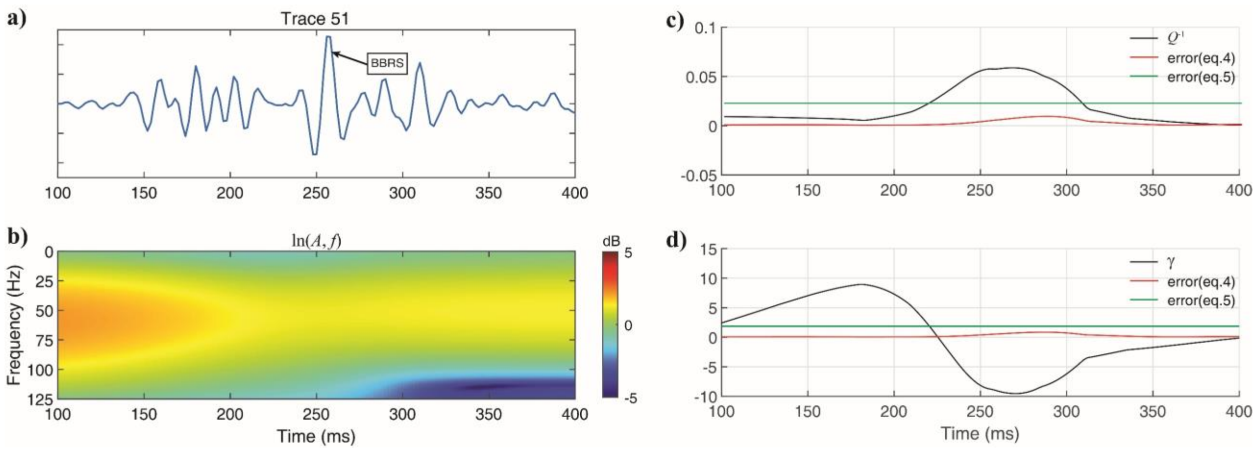

Figure 3 a) one stacked trace (CDP 51) from Figure 2a with the BBRS reflection of the CO_2 injection zone indicated, b) $\ln(A, f)$ by Wang and Morozov's (2020) approach as in equation 2, c) estimated Q_A^{-1} and its measurement errors and, d) estimated γ_A and its measurement errors.

Conclusions

Apparent attenuation parameters Q_A^{-1} and γ_A are measured from the DAS VSP data at the CaMI FRS for monitoring the CO_2 injection. Errors of estimated Q_A^{-1} and γ_A are independent of Q_A^{-1} or γ_A magnitude and inversely proportional to temporal resolution. The accuracy of estimated Q_A^{-1} is limited and is lower than the accuracy of estimated γ_A. Time-variant spectra of the reflectivity should be considered for achieving Q^{-1} measurement with satisfactory accuracy.

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