How good is a signal-strength estimate formula for 3D seismic survey design on land?

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Summary

We present a workflow for an automated feasibility study of different acquisition geometries based on a data-driven SNR estimation on depth-migrated volumes. The workflow utilizes realistic elastic modeling of signal and noise and provides an unbiased quantitative comparison of different field geometries. We compared this approach with the analytical method based on the signal-strength estimate formula. We observed a good correspondence between them for synthetic and field datasets. Remarkably, the synthetic data at hand possess only “geological near-surface noise” and does not contain any random additive noise as hypothesized by the signal-strength estimate model. We conclude that the signal-strength estimate formula is indeed a helpful approximation for predicting how SNR improvement/degradation depends on various acquisition parameters.

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Introduction

Seismic acquisition cost is a dominant geophysical expense. Optimizing acquisition through careful survey design is of paramount importance. On land, noise considerations are among the most decisive factors affecting the survey decisions. Although significant knowledge has been gained (Vermeer, 2012), many of its parts remain qualitative, making the onshore acquisition design more art than science. Comparison of different survey designs by several industry practitioners revealed diverse opinions and the lack of accepted quantitative metrics (Hornman and Vermeer, 2000). The analytic approach by Meunier and Gillot (2000) became one of the most popular for 3D land acquisition since it provided a single formula containing most acquisition parameters and resulted in the Signal-Strength Estimate (SSE) of the final image. The SSE formula is based on the simple assumption of random noise being suppressed according to the square-root law and assumes that organized noise is suppressed similarly or stronger. However, these assumptions remain largely unverified. Nevertheless, practitioners like the SSE formula since it allows them to compute relative quality (SSE) vs. acquisition costs. Lately, High-Performance Computing has enabled 3D seismic modeling to model 3D surveys and evaluate the image directly. Regone et al. (2015) popularized such a numerical approach to land acquisition. They assumed that prestack depth migration with an actual velocity model could be a reliable proxy for seismic processing. However, they still rely on a non-quantitative assessment of resulting images prone to human biases.

This study brings different approaches to a common denominator by introducing data-driven signal-to-noise ratio (SNR) estimation. With that, we make the numerical approach fully automated and remove any human bias. Finally, we compare predictions of the analytical SSE approach and numerical method for one field and one complex synthetics 3D land dataset. We conclude that most assumptions of analytical approach were successfully vindicated.

Method

Signal-Strength Estimate (SSE) is derived through the simple square-root combination rule and is expressed as:

$$\boldsymbol{SSE(f) = SS(f)\sqrt{SD\ NR\ RA} = SS(f)\sqrt{TD\ RA}} \quad , \tag{1}$$

where *RA* is the area of the receiver station, *NR* the number of receivers per shot point (SP), *SD* is the source density (number of shot points per surface unit). *SS* is the frequency-dependend source strength proportional to the number of vibrators (*Nv)* in the source array (*SS~Nv)*. The product of $\boldsymbol{SD \cdot NR}$ is called a trace density (TD), leading to a more concise second expression above. *SSE* is proportional to signal-to-noise ratio (SNR) and is often used for its theoretical estimation $\boldsymbol{SNR^t_{dB} = 20\log_{10}(SSE)}$ in dB. While based on a simple assumption of random noise, such a formula quantifies various trade-offs occurring in seismic acquisition between different parameters at play. In addition, SSE includes direct effects of the receiver array enabling straightforward comparison between legacy acquisitions with source groups and the latest acquisitions with point sensors.

The actual SNR can be estimated directly from the data by combining adjacent traces and extracting the signal and the noise levels from them in a data-driven way. Several previous techniques were introduced for this, including those based on cross-correlations, stacking, or singular-value decomposition approaches. Among those techniques, the stacking-based approach that considers the semblance as the measure of signal energy to the total energy tends to be one of the most robust in case of very weak signals, typical for modern dense surveys with small field arrays or single sensors (Bakulin et al., 2022b). Stack-based method SNR can be calculated as follows:

$$\boldsymbol{SNR^e = \frac{S}{1-S};\ SNR^e_{dB} = 10\log_{10} SNR^e}, \tag{2}$$

where S is the semblance calculated in a moving window running throughout the 3D data volume. As a result, the 3D volume of SNR is generated for each data volume.

With the SNR volumetric estimation, the survey-design approach based on realistic forward modeling can be automated, removing any human bias, as illustrated in Figure 1. Realistic modeling both signal and noise is the base of the process. Data processing is substituted by depth migration with the true velocity model (Regone et al., 2015). Ultimately, the data-driven SNR is applied to provide a quantitative measure of the final SNR values in the volume or along target horizons. The result is compared with the analytical SSE formula to estimate the latter's applicability. Closing the loop is essential for validating the economic model for survey cost based on the analytical approach.

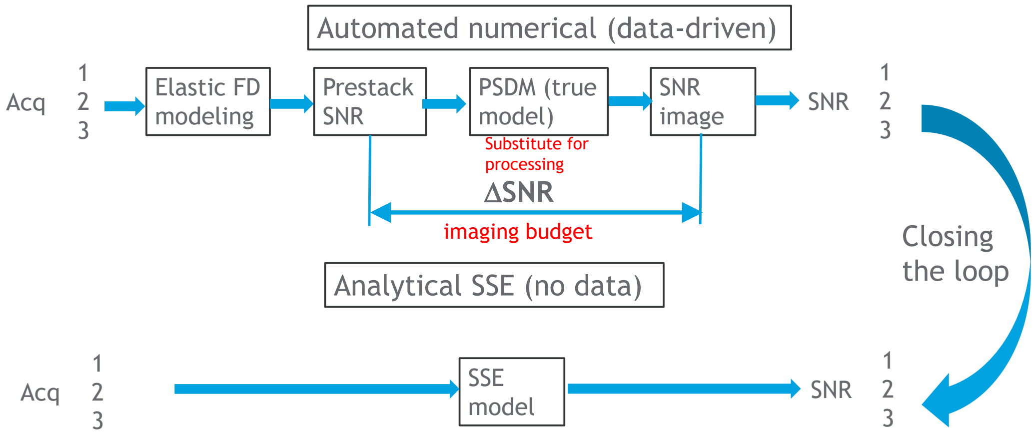

Figure 1 *An automated data-driven scheme allowing to compare different survey designs based on realistic forward modeling and depth migration.*

Examples

In the first example, we demonstrate the proposed methodology using realistic synthetic data obtained with the SEAM Arid 3D model replicating challenges from the desert environment (Oristaglio, 2012; Bakulin and Silvestrov, 2021). We consider six 3D acquisition geometries with different sources and receivers spacing and with and without field arrays (Bakulin et al., 2022a). Following the approach by Regone et al. (2015), the processing sequence is restricted only to prestack depth migration of raw data volumes with the true velocity model. Figure 2 suggests that increasing density can eventually resolve imaging in the shallow part. However, exact progression is non-uniform, and arrays play an essential role. Instead of subjective qualitative discussion, the second row in Figure 2 provides a measured SNR metric that allows us to evaluate the results and validate the usefulness of the square-root equations used for acquisition design. Cross-plotting the measured and the predicted SNR reveals good agreement between the two. Although some deviations are present, the points mostly cluster around the diagonal line (Figure 3). To “calibrate” the predicted and measured SNR scales, we elect to align them for the densest single-sensor geometry. One immediate conclusion is that the SSE equation fails to describe the effects of aliasing, preventing effective noise reduction. At the same time, the SSE formula underestimates the SNR uplift in the deeper part by the single-sensor acquisition with the 25m x 25 m receivers’ grid.

We compare the theoretical SSE-based SNR formula in the second example with the data-driven estimation using field data. The random blended source acquisition with one vibrator per sweep was jointly acquired with the conventional production seismic survey, in which two vibrators per sweep were used. Although the trace density of the blended acquisition was three times higher than the conventional one, the SSE formula (1) predicts an SNR decline of - 1.4 dB because blended acquisition used a single vibrator instead of the 2-vibrator array. As a result source strength SS proportional to the number of vibes in the array (Meunier, 2011) is reduced by a factor of ½, while trace density increases

SSE by only 1.7. So the net effect is that blended single-be data hase SSE of ~ 0.85 of production data. Figure 4 shows the actual comparison of the migrated images after comparable data processing flow was applied to both datasets. The corresponding volumetric SNR values were estimated using formula (2). The distribution of the SNR values (Figure 4e) extracted from the vertical time window clearly show a decrease in the SNR of the blended acquisition result compared to the production survey. Figure 4f shows the difference between these estimated SNR values more closely. The best-fitted horizontal line provides the average SNR decrease of the blended acquisition to be -2 dB, which is in good agreement with the analytical SSE prediction of -1.4 dB.

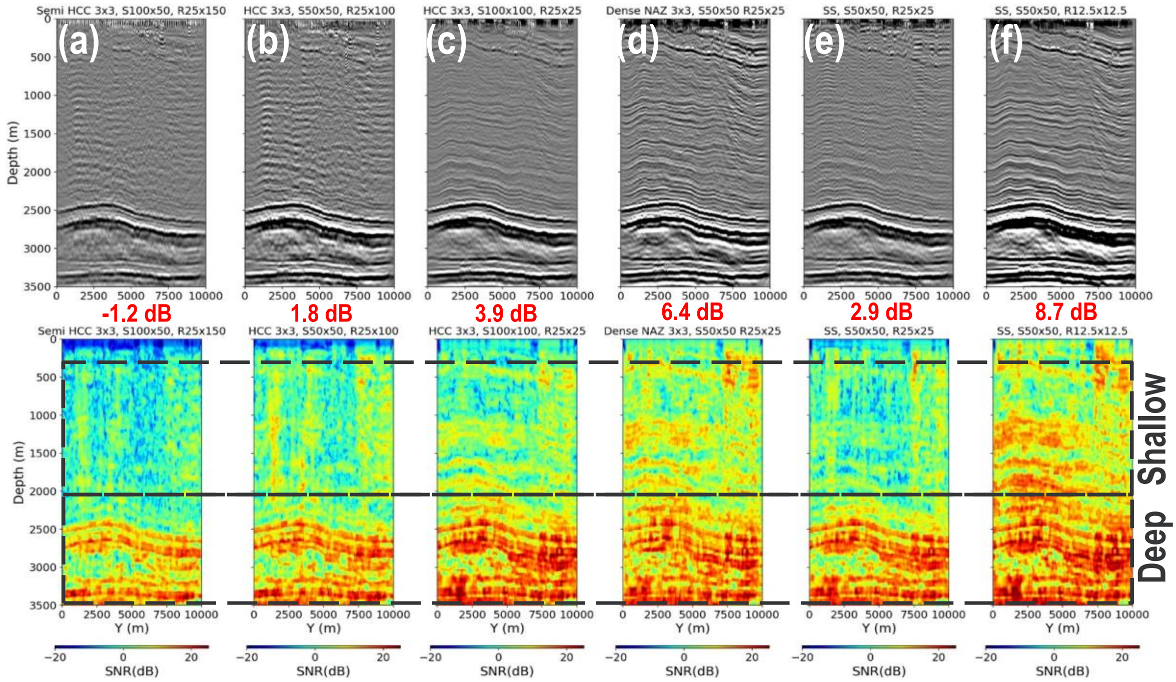

Figure 2 *Cross-sections from a 3D PSDM volume (top row) and SNR volumes (second row) obtained by migrating raw data with different acquisition geometries: (a) Semi-high-channel count (3x3 geophone array) S100x50m, R25x150m; (b) high-channel count (3x3 geophone array) S50x50m, R25x100m; (c) Nodal high-channel count (3x3 geophone array) S100x100m, R25x25m; (d) Narrow-azimuth high-channel count (maximum crossline offset is ¼ of inline offset) S50x50m, R25x25m; (e) single-sensor (intermediate) S50x50m, R25x25m; (f) single-sensor (dense) S50x50m, R12.5x12.5m (from Bakulin et al., 2022a).*

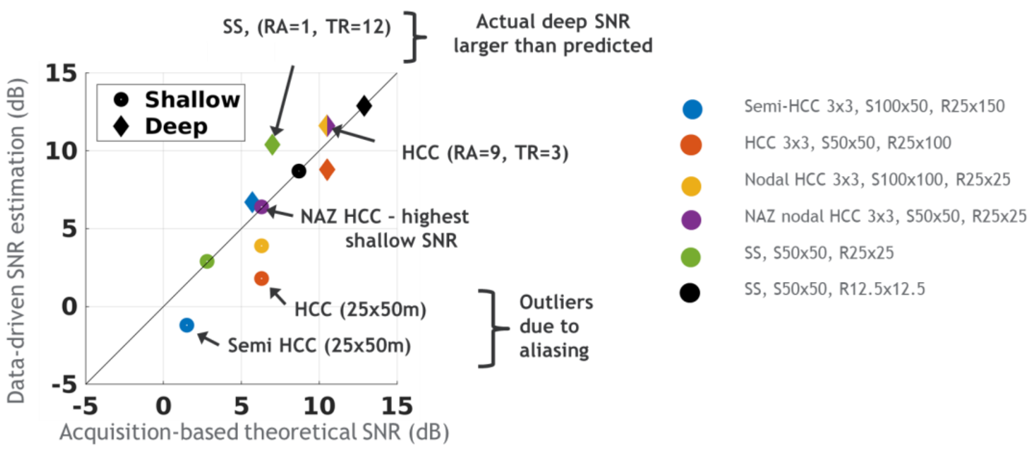

Figure 3 *Cross-plot of theoretical SNR based on the SSE formula and experimentally measured SNR based on the direct estimation from the migrated images. Colors correspond to the acquisition geometries described in Figure 2. The circles show the SNR values in the shallow part of the image (700m-2000m), while the diamonds correspond to the deeper part (2000-3750 m).*

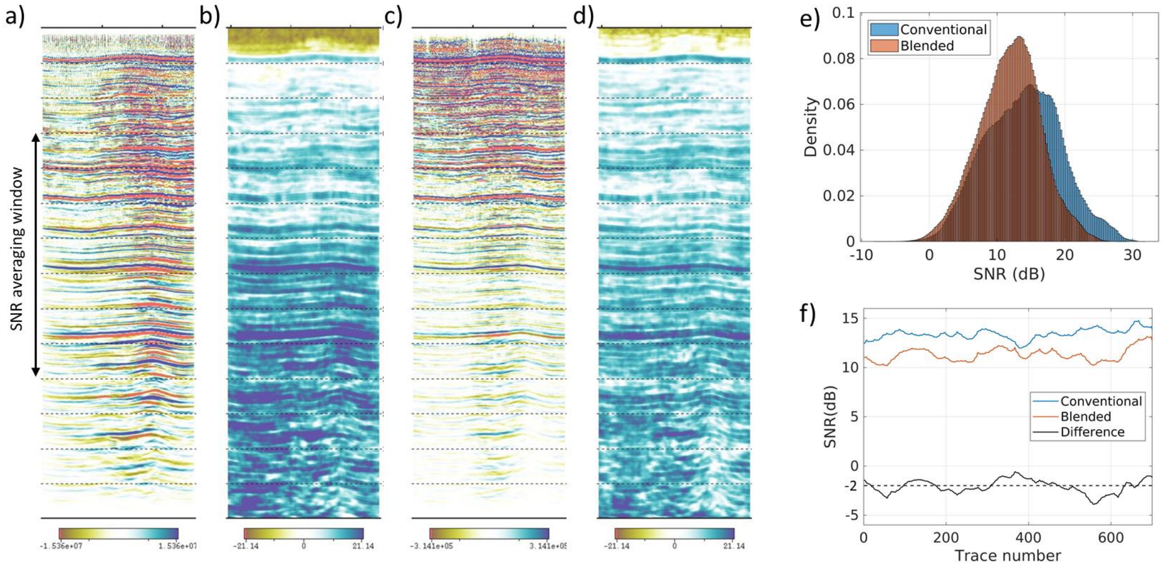

Figure 4 *Migrated images and the data-driven SNR volumes for the conventional acquisition (a, b) and the blended acquisition (c, d). The histograms in (e) shows the distribution of the SNR values in the vertical time window marked by the arrow. The SNR curves in (e) show averaged values over this window. The average difference (blended minus production, shown as dashed black line) between the SNR curves shown in (e) is around -2dB, which is comparable to -1.4 dB predicted by SSE equation.*

Conclusions

We presented a workflow for an automated feasibility study of different acquisition geometries based on a data-driven SNR estimation on depth-migrated volumes. The workflow utilizes realistic elastic modeling of signal and noise and provides an unbiased quantitative comparison of different field geometries. We compared this approach with the analytical method based on the signal-strength estimate formula. We observed a good correspondence between them for synthetic and field datasets. Remarkably, the synthetic data at hand possess only “geological near-surface noise” and does not contain any random additive noise as hypothesized by the SSE model. We conclude that the SSE formula is indeed a valuable survey-design approximation for a simple and fast SNR evaluation.

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