Predicting the success of 4D projects in complex near-surface settings

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Summary

The design of 3D seismic surveys is grounded in a quantitative approach, utilizing the Signal-Strength Estimate (SSE) model to link the final signal-to-noise ratio (SNR) of the seismic image with input acquisition parameters. However, this type of quantitative relationship does not exist for 4D seismic. By adopting the same assumptions of random additive noise as used in the SSE model, we can establish a straightforward relationship between Normalized Root Mean Square (NRMS) and SNR that reflects the fundamental connection observed in previously reported SNR and NRMS data. We corroborate this relationship through the analysis of a 3D land seismic survey, which could serve as a baseline for future 4D seismic efforts. Our findings reveal a strong correlation between SNR and NRMS maps, aligning with theoretical expectations and enabling the prediction of 4D survey success in specific areas. Crucially, by associating NRMS with SNR, we unlock a quantitative tool for survey design akin to what the SSE model provides, enabling the selection of trace density and source strength to achieve success in targeted regions. While this relationship is straightforward and approximate, it lays the groundwork for quantitative 4D survey design in new territories without extensive prior data. It also provides a means to refine acquisition strategies to address variations in overburden and near-surface conditions that could otherwise compromise 4D results if not properly considered.

Introduction

The design of 3D seismic acquisition is based on the robust Signal-Strength Estimate model (Meunier et al., 2011), which forecasts the relative signal strength using parameters like trace density, source power, receiver array size, and more. This model has recently been validated against data-driven signal-to-noise ratio (SNR) measurements, proving its capability for making excellent quantitative predictions on both synthetic SEAM Arid data and real datasets (Bakulin and Silvestrov, 2023). SNR was further shown to be an important predictor for achieving success in any quantitative seismic interpretation task, such as horizon picking, amplitude maps interpretation, etc. (Raaban et al., 2023).

In 4D seismic, repeatability stands as a crucial factor for success, with the Normalized Root-Mean Square (NRMS) serving as a key metric for assessing it (Kragh and Christie, 2002). Ronen et al. (1999) highlighted the relationship between NRMS and signal-to-noise ratio (SNR), suggesting that NRMS is a significant indicator of repeatability in seismic data. Pevzner et al. (2011) demonstrated experimental correlations between SNR and NRMS that echoed the findings of Ronen et al. (1999) without referencing them. Furthermore, Van Geustel (2015) introduced an empirical metric, 3DNRMS, derived from the baseline volume, positing it as a plausible predictor of NRMS for 4D seismic applications. The 3DNRMS calculation involves comparing a dataset to a smoothed version of itself, which is achieved by flattening the data along a horizon and implementing 3D smoothing techniques.

In our study, we demonstrate the direct correlation between data-driven SNR, obtained through a stack-based method commonly applied in survey design, and NRMS, following the groundwork laid by Ronen et al. (1999) and explored further by Pevzner (2011). The data-driven SNR metric, as established by Bakulin et al. (2020), provides a well-defined and robust approach for predicting NRMS, presenting a more straightforward alternative to the 3DNRMS methodology proposed by Van Gestel (2015). The integration of SNR effectively bridges the gap between the design of 3D surveys, the ultimate quality of 3D seismic images, and the anticipation of 4D NRMS, thus underpinning the quantitative framework for 4D survey design. We validate this approach through a case study of a 4D seismic survey planned in a complex desert setting, showcasing the practical application and data-driven confirmation of our method.

Relationship between SNR and NRMS

Ronen et al. (1999) delineated a relationship between linear SNR and NRMS, mathematically expressed as:

$$\boldsymbol{SNR_{lin}} = \frac{\boldsymbol{2-NRMS^2}}{\boldsymbol{NRMS^2}} \quad . \qquad (1)$$

This equation assumes certain conditions for its derivation, such as the signals and noise having a zero mean and being uncorrelated. Figure 1b illustrates this relationship

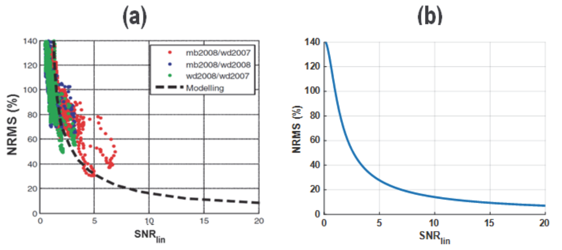

Figure 1: NRMS vs. SNR: (a) a figure from Pevzner et al. (2011) displaying their version of numerical simulation (black) and real data points (dots) from land seismic surveys; (b) the theoretical relationship as described by equation (1), assuming random, uncorrelated noise with similar levels for both baseline and monitoring surveys.

graphically. Pevzner et al. (2011) engaged in numerical simulations that reflected the relationship between SNR and NRMS, albeit without deriving the formula or citing Ronen.

Their approach involved conducting tests with a constant signal combined with additive random noise at specified SNR levels, followed by plotting the correlation between SNR and NRMS (illustrated in Figure 1a, black). The comparison between theoretical predictions (Figure 1b, blue) and numerical modeling results (Figure 1a, black) reveals a close similarity at mid and high SNR levels (above ~3). However, a more significant discrepancy is observed at lower SNR levels, corresponding to higher NRMS values.

In our study, we opt not to dwell on the slight differences between theoretical and numerical models. Rather, our focus is on exploring the relevance and applicability of this relationship for crafting 4D survey designs in settings characterized by complex overburden or challenging near-surface conditions. Our objective is to illustrate the integration of 3D seismic design principles with 4D seismic strategies, enabling direct predictions of success for actual 4D projects, especially in complex desert environments.

Predicting NRMS from SNR

In our study, we examine an onshore dataset comprising high-channel-count 3D onshore seismic data. This dataset acts as a baseline for assessing the success of 4D surface seismic projects within the specific desert environment under consideration. The acquisition geometry is depicted in Figure 2. The receiver station is represented by a 9-geophone array, while the source point is represented by a two-vibrator group.

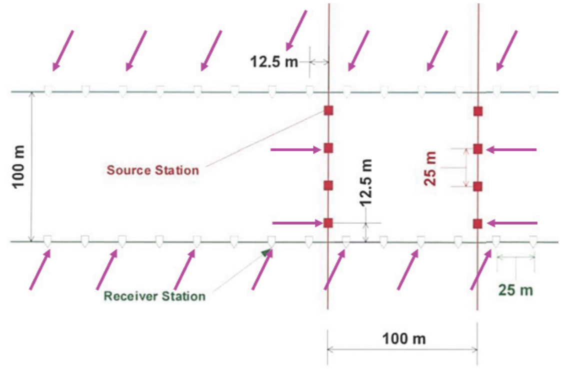

Figure 2: Land survey 3D acquisition geometry. Arrows indicate alternate sources and receivers selected for Volume 1, with the remaining sources and receivers allocated to Volume 2. These two volumes were used to assess zero-time repeatability.

Figure 3a presents the imaged seismic volume, and Figure 3b quantifies the SNR employing the method outlined by Bakulin et al. (2022). This volume effectively captures the ultimate image quality at various points throughout. Our analysis then shifts to examining the SNR and NRMS for a horizon of interest, highlighted in red. Figure 4a illustrates the SNR extracted along this horizon, with a histogram showing an average SNR of ~7 dB (~5 in linear scale) across the area. Notably, areas of low SNR are identified, correlating with complex geological features in the near-surface and shallow overburden layers.

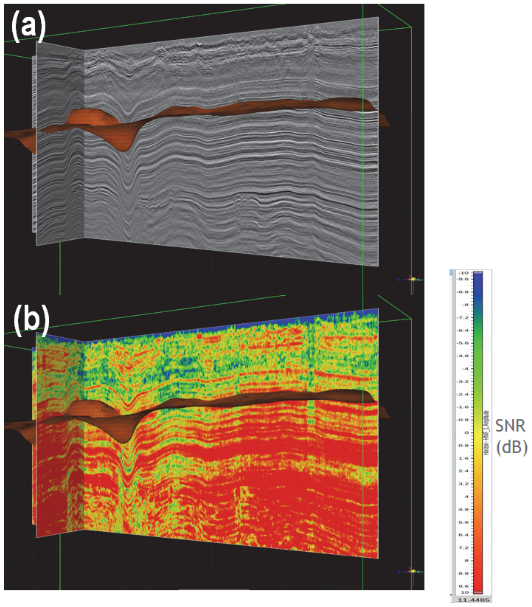

Figure 3: The imaged seismic volume (a) and the SNR volume (b), which was derived using a stack-based approach. The red horizon marks our area of interest, with extraction performed within a specific window surrounding this horizon for further analysis.

To simulate "zero-time" 4D repeatability without conducting an actual monitoring survey, we partitioned the 3D seismic volume into two distinct, non-overlapping sub-volumes. This partitioning involved allocating every odd-numbered source along the line (1, 3, 5, etc.) to the first sub-volume, and every odd-numbered receiver along the orthogonal receiver line (1, 3, 5, etc.) to this same sub-volume, as indicated by pink arrows in Figure 2. The remaining sources and receivers were assigned to the second sub-volume. This method resulted in the creation of two staggered surveys, each displaced by 25 meters in two orthogonal directions. Figure 4b illustrates the NRMS measurements between these two simulated 4D volumes, offering insights into the data repeatability achievable under these designed conditions.

The mean NRMS of 35% is quite reasonable for an onshore desert environment case, yet this figure must be interpreted cautiously. Firstly, it reflects "zero-time" repeatability under identical near-surface conditions. However, real data indicate a gradual increase in NRMS over time, known as the "return curve" (Bakulin et al., 2014), hinting that this estimate might be overly optimistic. On the other hand, the precision of source and receiver placements onshore can achieve sub-meter accuracy, rather than the constant 25 m shift used for sources and receivers in this study. Consequently, with more precise replication of geometry, the NRMS could decrease, indicating improved repeatability. This assumes that all shot and receiver positions remain unobstructed, which may not always be feasible due to the ongoing development of new infrastructure.

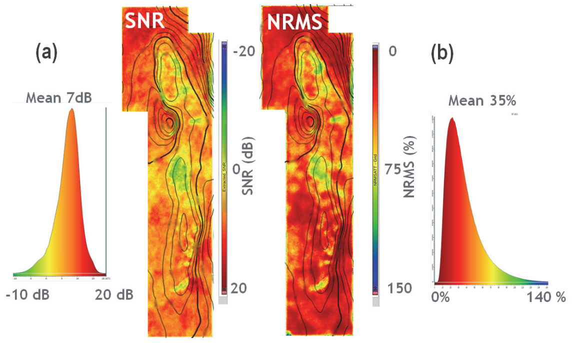

Figure 4: Comparison between the data-driven SNR calculated along a specific horizon within a 3D imaged volume and the NRMS metric derived by dividing the 3D volume into two sub-volumes. A clear correlation is observed between the two attributes, where higher SNR values correspond to lower NRMS, and conversely, lower SNR values are associated with higher NRMS.

Even without concrete field 4D feasibility studies, this estimate serves as a valuable guideline for planning and design. Figure 5 illustrates that the average SNR and NRMS values align with the theoretical model. The red triangle represents the SNR calculated from the full volume, which tends to overestimate the theoretical SNR. For a more equitable comparison, we should utilize the SNR of a decimated volume, which is the same volume used for calculating NRMS. This adjustment is necessary because the full volume has a trace density four times greater than the split volumes. By transitioning from S100x25m R25x100m to S100x50m R50x100m, we must modify the linear SNR from the full volume downwards by a factor of 0.5 (or equivalently, multiply by 1/√4) to account for this discrepancy. The green triangle, representing the new estimate, and the red triangle, indicating the original estimate, effectively bracket the theoretical curve.

Now that a connection between SNR and NRMS has been established, it's worth considering the value this brings. Figure 4 demonstrates a strong correlation between SNR and NRMS maps, particularly highlighting that areas with low SNR correspond to high NRMS. These anomalies often align with near-surface complexities, as evidenced by surface topography and observed in the shallow parts of the seismic volumes themselves. Predicting these areas during the 4D survey design phase might be challenging, yet they can be readily identified using the proposed workflow on 3D seismic data. Areas marked by low SNR are likely to pose challenges for monitoring. Should the 4D acquisition geometry remain unchanged, these would be the areas where our confidence in the 4D seismic results might wane. However, having this insight beforehand offers a unique advantage; it allows us to tailor acquisition parameters specifically in these regions, ensuring we achieve the desired NRMS for monitoring our objectives effectively.

Reasonable alignment with the theoretical model also suggests that real-world noise patterns are not too dissimilar to the white additive noise assumed in the derivation. This observation is supported by the findings of Bakulin and Silvestrov(2023), who noted that the decay of coherent noise during imaging and stacking adheres to the square-root law embedded by the SSE model of Meunier et al. (2011).

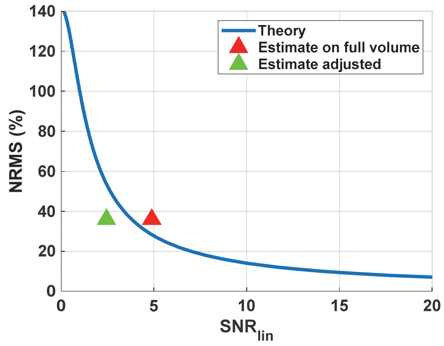

Figure 5: Horizon-averaged mean SNR and NRMS values derived from Figure 4 before (red) and after (green) adjustment, plotted against the theoretical relationship outlined in Figure 1b.

Simple recipe

Typically, the NRMS value of 4D noise should be compared with the 4D signal, which can also be quantified as NRMS. If the anticipated 4D signal significantly exceeds the noise NRMS, the situation is favorable. Conversely, if noise dominates, exploring alternative acquisition geometries or monitoring configurations might be necessary.

While simulation-to-seismic workflows typically estimate NRMS of the 4D signal (Calvert, 2005; Johnston, 2013), expected 4D noise NRMS requires feasibility study or trials. Fortunately, the direct correlation between SNR and the Signal-Strength Estimate (SSE) model for survey design facilitates the straightforward assessment of required geometrical adjustments to achieve the desired SNR and, consequently, an optimal NRMS value. While the 3DNRMS attribute suggested by van Gestel (2015) can serve as an approximate surrogate of SNR, its calculation includes various user-specified parameters, making standardization difficult. On the other hand, SNR estimation is generally more uniform, and methods beyond stack-based approaches usually yield consistent outcomes for medium to high SNR scenarios (Bakulin et al., 2022).

Crucially, if the selected baseline survey lacks the necessary SNR for achieving the desired repeatability, the SSE model provides a detailed method for adjusting the survey geometry to meet this requirement (Meuner, 2011). Bakulin and Silverstrov (2023) have illustrated specific cases of how this approach can be efficiently applied onshore, especially when legacy surveys with varying acquisition parameters are available for the areas in question. This facilitates the direct utilization of legacy surveys in the creation of efficient 4D survey designs.

The choice of imaging algorithms and processing techniques can influence the absolute values of SNR and NRMS. However, they are anticipated to follow a similar relationship. For instance, employing more advanced imaging that enhances SNR is likely to similarly boost NRMS, assuming consistent processing is applied to both surveys. Therefore, it is advisable to incorporate the anticipated processing and imaging sequence in the feasibility study, as it would be applied in the analysis of 4D surveys.

Conclusions

Our evaluation rigorously examined the formula that delineates the relationship between Signal-to-Noise Ratio (SNR) and Normalized Root Mean Square (NRMS) using land seismic data. Despite being based on the basic premise of uncorrelated additive noise, this formula successfully captures the dynamics between SNR and NRMS. Utilizing this connection, we introduced a groundbreaking method to predict the anticipated repeatability (NRMS) from a singular 3D baseline data volume. This method was applied to a 3D onshore dataset from a complex desert environment, demonstrating its predictive power by dividing the volume into two to calculate the actual zero-time NRMS. Our findings reveal a distinct correlation between areas of low SNR and high NRMS, and vice versa, shedding light on varying acquisition needs for monitoring different regions. The interplay between SNR and NRMS is pivotal, as it forges a link between 4D survey aims and main acquisition parameters such as trace density and source strength via the Signal-Strength Estimate model, fundamental in crafting 3D surface seismic survey strategies on land. The potential to extend this relationship to marine surveys and 3D VSP presents an exciting avenue for subsequent investigations.

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