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A Novel Routine for Generating and Calibrating Random Noise in 4D Seismic Data

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Abstract

Accurate noise modeling is crucial for validating 4D seismic workflows and interpreting time-lapse reservoir changes. This work presents a novel routine for generating and calibrating random noise in 4D amplitudes of base-monitor pairs derived from simulation models, achieving user-defined Normalized Root Mean Square (NRMS) values. The routine integrates four steps: (1) replicable noise generation using the Xoshiro256StarStar pseudo-random generator with Behrens' formula for amplitude scaling; (2) optional FFT-based frequency filtering to match seismic bandwidth; (3) structural smoothing algorithms for spatial correlation; and (4) precise NRMS calibration through Nelder-Mead minimization with a logarithmic initial guess to avoid local minima. Implemented within a commercial plugin, the routine provides a user-friendly interface for parameter customization. Validation on synthetic and real field datasets demonstrates reproducibility, spectral accuracy, structural alignment, and NRMS precision within 0.1% of target values.

Introduction

Time-lapse (4D) seismic surveys are essential for monitoring reservoir changes, such as fluid movements and pressure variations (Lumley, 2001). Modeled time-lapse seismic data are commonly used in simulation-to-seismic workflows to support feasibility studies, seismic signal interpretation, and the assessment of models' accuracy. By calculating 4D synthetic amplitudes from simulation models, the results can be compared with seismic data acquired in the field. However, since seismic data is inherently noisy, realistic noise modeling may be vital for detecting subtle time-lapse signals or evaluating different acquisition scenarios (i.e., with different noise levels). The noise can be obtained from the observed data, e.g., seismic inversion residuals (Rosa et al., 2024) or generated as white Gaussian noise. The Normalized Root Mean Square (NRMS) metric quantifies noise levels in 4D seismic data, however, generating noise that matches a desired NRMS level while preserving geological coherence remains challenging (Kragh and Christie, 2002).

This paper introduces a routine for generating and calibrating random noise in 4D seismic base-monitor pairs, according to a desired NRMS level, offering a flexible tool for geophysical applications. The routine combines four key steps:

- Replicable noise generation using the Xoshiro256StarStar pseudo-random generator.
- Frequency filtering to align noise with seismic bandwidth.
- Structural smoothing for geological coherence.
- Precise NRMS calibration via Nelder-Mead minimization with a logarithmic initial guess.

This approach enhances the reliability of 4D seismic interpretation by modeling noise that mimics real-world conditions. It builds upon previous studies of noise modeling (Abma and Yan, 2009; Rosa et al., 2024) and NRMS calibration (Cantillo, 2012), providing a practical solution for seismic data analysis.

Methodology

The process consists of four steps to create customized noise for 4D seismic datasets. Each step is user-configurable, ensuring flexibility across diverse geophysical scenarios.

Replicable Random Noise Generation. The random noise is generated using the Xoshiro256StarStar pseudo-random number generator (Blackman & Vigna, 2018), selected for its high-quality statistical properties, speed, and suitability for large-scale seismic applications. Users specify distinct seeds for base and monitor cubes, ensuring reproducibility across runs. The noise amplitude range is calculated using Behrens' formula, which relates Signal-to-Noise Ratio (SNR) and NRMS (Behrens et al., 2002).

$$SNR = \frac{\sqrt{2 - NRMS^2}}{NRMS}$$

After calculating the SNR, we compute the root-mean-square (RMS) amplitude of the seismic cube. This allows us to derive the RMS amplitude of the seismic noise cube, which helps determine the range of noise amplitudes present in the data. The RMS of the mean-centered reference seismic cube is calculated within the reservoir interval over a 2D map (inline × crossline). Assuming a zero-mean Gaussian distribution, the RMS equals one standard deviation (Papoulis and Pillai, 2002) and multiplying by 3 captures 99.7% of the amplitude range per the three-sigma rule. The noise RMS is then:

$$RMS_{noise} = \sqrt{\frac{(RMS_{seismic})^2}{(SNR)^2}}$$

The noise amplitude range is set to $\pm 3 \times RMS_{noise}$, ensuring statistical alignment with the reference dataset for realistic 4D seismic noise modeling.

Frequency Filtering. To match the target seismic data's spectral content, an optional Fast Fourier Transform (FFT)-based bandpass filter is applied. Users specify low and high cutoff frequencies with a fixed slope transition to mitigate Gibbs effects (Yilmaz, 2001). This filter preserves frequencies within the defined band while attenuates others, ensuring the noise aligns with the seismic signal's bandwidth.

Structural Smoothing. Preserving geological coherence is essential in 4D seismic processing to avoid artifacts that obscure time-lapse signals. To address this, an optional structural smoothing step is included to address spatial correlation, using structural algorithms — Plain, DipGuided, and DipGuideEdge (Slb, 2025). These methods enhance seismic continuity by aligning Gaussian smoothing with local structural orientations, computed via principal component analysis of dip and azimuth (Hale, 2009). Smoothing can be applied in inline (I), crossline (J), and time/depth (K) directions, giving users control over its extent. Three smoothing modes are available:

This step minimizes artifacts by aligning noise with geological structures, improving time-lapse interpretation.

NRMS Calibration. To simulate realistic time-lapse noise, random noise is scaled to achieve a user-defined Normalized Root Mean Square (NRMS) difference using the Nelder-Mead optimization algorithm (Nelder & Mead, 1965). This step is needed since the previous step (filter) may change the noise level (SNR) initially configured. The NRMS is defined as:

$$NRMS = \frac{200 \cdot RMS(f_t - g_t)}{\sqrt{RMS(f_t)^2 + RMS(g_t)^2}}$$

where f_t and g_t represent the base and monitor traces with added noise, respectively.

The calibration process begins by adding the generated noise to the simulation model-derived synthetic seismic amplitudes for both surveys. The objective is to determine the optimal scaling factor α such as:

$$f_t = baseCube + \alpha \cdot baseNoiseCube$$

$$g_t = monitorCube + \alpha \cdot monitorNoiseCube$$

The $baseCube$ and the $monitorCube$ are the volumes of synthetic amplitudes, obtained from the simulation model, whereas $baseNoiseCube$ and $monitorNoiseCube$ are the created noise volumes. The RMS parameters for the NRMS equation are obtained as maps, whose calculation window depends on the definition of the overburden and underburden intervals in the simulation-to-seismic workflow. The noise application strategy also depends on this definition:

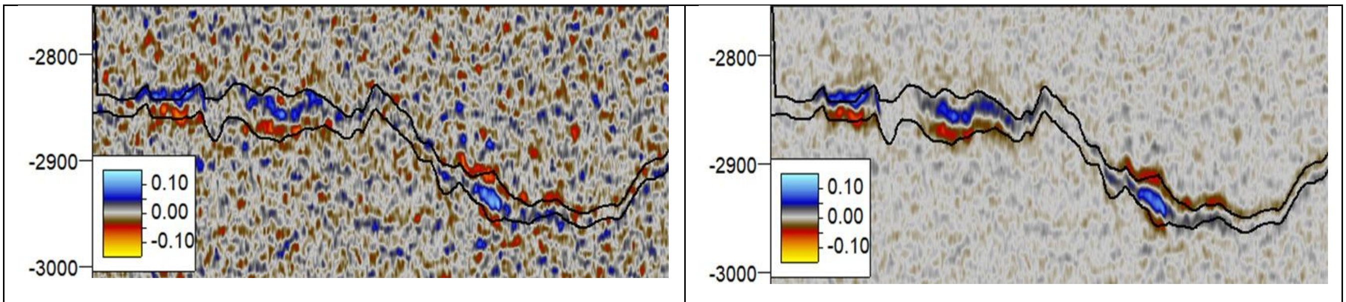
- Case (i): Inversion-filled overburden and underburden, RMS maps are computed from 100 ms above the reservoir top to the reservoir top.
- Case (ii): Constant elastic value to fill overburden and underburden, RMS maps are computed from 25 ms above the reservoir top to 25 ms below the reservoir bottom, balanced by the ratio between the 100 ms RMS above the top and the RMS inside the reservoir (r). Specifically for the calibration process, $f_t = baseCube \cdot r + \alpha \cdot baseNoiseCube$ and $g_t = baseCube \cdot r + \alpha \cdot monitorNoiseCube$. However, the final monitor cube is given by $g_t = monitorCube + \alpha \cdot monitorNoiseCube$. For more details, see Rosa et al. (2024).

The scalar α adjusts the noise amplitude to achieve the target NRMS. To find the optimal α, the routine uses the Nelder-Mead minimization algorithm, a derivative-free method that iteratively adjusts α to minimize the difference between the calculated NRMS and the target (Nelder & Mead, 1965).

To mitigate convergence issues, such as getting trapped in local minima, an optimized initial guess for α is computed using a logarithmic search. This method evaluates NRMS at two bounding values of α and iteratively narrows the range on a logarithmic scale, accounting for the non-linear relationship between α and NRMS. This approach ensures efficient convergence, typically achieving NRMS values within 0.1% of the target. Calibration is performed independently for each angle stack interval, ensuring consistent noise levels across the dataset, which is critical for reliable 4D seismic interpretation (Lumley, 2001).

Implementation and Results

The described routine is implemented within a Pugin in a very used commercial software (Slb, 2025) offering a user-friendly interface to execute Petro-Elastic Modeling (PEM) using reservoir simulation outputs, compute reflectivity, and create seismic amplitude traces by convolving the reflectivity with a user-selected wavelet. For the random noise, users define seeds, NRMS targets, frequency bounds, and smoothing options, with the plugin supporting multiple angle stacks and base-monitor pairs across different dates, each with a different noise configuration. Validation on a benchmark and Albacora Leste field 4D seismic datasets confirmed: (1) reproducibility using Xoshiro256StarStar, with identical noise cubes across runs (when using the same seed); (2) spatial correlation via DipGuided smoothing; and (3) NRMS calibration precision within 0.1% of targets, as shown in Figure 1.



NRMS = 25 %	NRMS = 10 %

Figure 1: Vertical sections of 4D amplitude difference cube with noise added at NRMS levels of 25% and 10%, illustrating the routine's noise calibration in the Albacora Leste field.

Conclusion

The developed routine provides a robust solution for generating and/or calibrating random noise in 4D seismic data, combining replicable noise generation, spectral shaping, structural smoothing, and precise NRMS calibration. By enabling geophysicists to model noise with high fidelity to acquisition settings, it enhances the reliability of seismic interpretation and allows a better reservoir monitoring. Validation on synthetic and real field datasets confirms its effectiveness, and ongoing enhancements promise broader applications in geophysical workflows.

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