Statistical imaging through strongly scattering near-surface with path summation techniques

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Summary

This study investigates the challenges of imaging deep subsurface targets below complex near surface, described as random clutter. Our synthetic example, designed to simulate random clutter, reveals significant scattering distortions and defocusing effects, similar to those observed in complex field seismic data. We explore the use of statistical imaging through path summation as a heuristic method for achieving subsurface imaging without the need for an accurate velocity-depth model. This method utilizes an ensemble of random near-surface models that reflect the statistical complexity of the actual near-surface, without individually replicating the exact conditions. A statistical image is produced by summing the images obtained from the ensemble. We show that image traces undergo symmetric phase perturbations, which cancel out during the summation process, thus emphasizing true geological interfaces, albeit with a slight attenuation of higher frequencies. We establish an important connection between statistical imaging with small-scale heterogeneity and speckle scattering noise, highlighting the relationship between statistical imaging, small-scale heterogeneity, and speckle noise.

Introduction

In land seismic exploration, the quality of depth seismic images is significantly compromised by scattering from small- and medium-scale near-surface heterogeneities (Xie et al., 2016; Bakulin et al., 2020, 2022a; Stork, 2020). Imperfections in the migration velocity model introduce phase errors, hampering proper wavefield focusing (Xie et al., 2016), and fully mapping near-surface complexities is beyond current algorithm capabilities. Thus, a practical solution treats the near-surface as stochastic media (Ikelle et al., 1993), with imaging algorithms leveraging its statistical properties to overcome challenges and enhance deep horizon imaging. Techniques like time-reversed wave propagation for more stable seismic images in random media (Borcea et al., 2003) and modified cross-correlation migration for better imaging in rapidly varying overburden velocities (Sava and Poliannikov, 2008) reflect this strategy.

Landa et al. (2006) introduced a novel imaging method using path-integral summation, stacking images from various velocity distributions and applying weights to highlight probable image parts. This concept has been applied in several time-domain areas, including zero-offset stack (Landa, 2004; Keydar, 2005; Yilmaz, 2018), time-migration (Landa et al., 2006), velocity analysis (Schleicher and Costa, 2009; Burnett et al., 2011), and diffraction imaging (Merzlikin and Fomel, 2015; Decker and Fomel, 2019), with depth imaging posing additional challenges in sampling and weighting across multidimensional velocity model spaces. Early depth imaging results using this method have been promising for subsalt imaging (Landa et al., 2005, 2006; Protasov et al., 2017).

Our study explores the path-summation technique for depth imaging in regions characterized by intricate near-surface scattering (Bakulin et al., 2022b), considering the surface layer as an indeterminate, statistically estimable cluttered environment. Not only do we showcase the effectiveness of statistical imaging on complex examples, but we also provide a potential explanation for why this method is beneficial for imaging through areas of intense scattering near the surface that exhibit small-scale heterogeneity. This rationale establishes a link between statistical imaging and the modeling of speckle noise in imaging, potentially paving the way for further advancements.

Statistical imaging with path-summation method

Rather than aiming to perfectly reconstruct the velocity model as suggested by Xie et al. (2016), the path-summation method, introduced by Landa et al. (2006), generates multiple depth model realizations to capture accurate segments of subsurface velocity. Each model highlights a specific subsurface section, and the final image is created through summation of the images of this diverse velocity models ensenle, allowing each to contribute essential details. In desert environments with intricate near-surfaces, this is achieved by aggregating weighted, migrated images from various near-surface migration velocity model realizations.

$$\boldsymbol{I_w}(\boldsymbol{x}) = \sum_{\boldsymbol{k}} \boldsymbol{w_k}(\boldsymbol{x})\boldsymbol{I_k}(\boldsymbol{x}) \; . \qquad (1)$$

In this process, $\boldsymbol{I_w}$ represents the final image at point $\boldsymbol{x}$, $\boldsymbol{I_k}$ is the image from the k -th model realization, and $\boldsymbol{w_k}$ is the corresponding weighting function. This approach essentially performs statistical averaging across a collection of potential near-surface model scenarios. We construct these near-surface model realizations through statistical modeling of random anomalies, termed clutter. Given that the anomalies we're interested in are on a scale comparable to or smaller than the dominant source wavelength, we employ reverse-time migration (RTM) for accurate wave propagation handling. For simplicity, our analysis focuses on post-stack RTM, though the findings are applicable to pre-stack scenarios as well.

Synthetic example

We create a detailed near-surface model incorporating random clutter (see Figure 1a), by adding velocity perturbations to a uniform model. These perturbations follow a Gaussian distribution, characterized by a correlation length that specifies the average size of heterogeneities and a standard deviation indicating the extent of velocity changes. The base model has a constant velocity of 2000 m/s, with heterogeneities having a correlation length of 35 m and a standard deviation of 400 m/s. To simulate input for imaging, we generate zero-offset seismic data using acoustic finite-difference methods that follow the exploding reflector concept (depicted in Figure 1b). This synthetic data mimics the challenging scattering effects commonly found in real seismic data (Bakulin et al., 2020, 2022a).

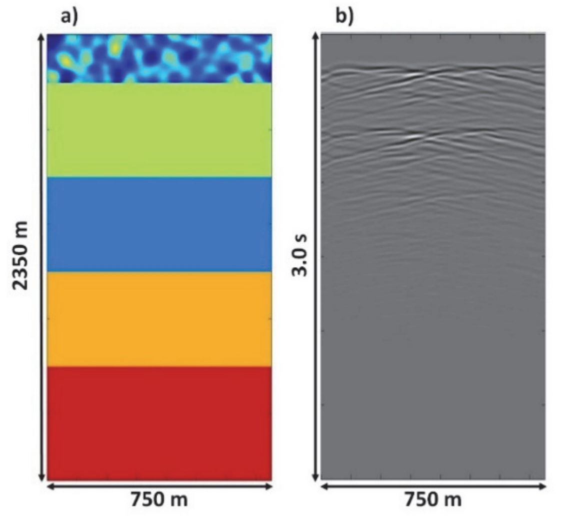

Figure 1: (a) A true model representing the complex near-surface environment, modeled as a constant clutter realization with a spatial correlation length of 35 meters, an average velocity of 2000 meters per second, and a velocity standard deviation of 400 meters per second. (b) Zero-offset data calculated based on the true model described in (a).

The ideal image is derived by convolving the model's reflectivity with the source impulse, as depicted in Figure 2a. Figure 2b also presents the actual reverse-time migration (RTM) result from zero-offset data using the true clutter model, which includes both genuine subsurface reflectors and some imaging artifacts. For benchmarking, the ideal image serves as the precise reference solution, and the image produced in the true clutter model represents the optimal outcome attainable.

For statistical imaging via path summation, a method to create a variety of potential models is essential. We start with the assumption that typical seismic velocity model construction yields a smooth or "tomographic" model (not shown) that approximates the true model but misses finer details. We then assume, without formal demonstration, that the deviations between this background model and the true model follow a Gaussian distribution, from which we can directly estimate two key parameters using the data. In our approach, we maintain the correlation length at 35 m but adjust the standard deviation to 257 m/s, a figure derived from comparing the "tomographic" model to the actual clutter model. This method enables the creation of numerous velocity models by introducing random perturbations to a smoothed "tomographic" model, utilizing specified parameters for the modifications. Figure 3 displays images from three realizations performed in this manner. While each alone may not be especially noteworthy, we aim to show that their aggregated knowledge, acquired through statistical imaging, can yield enhancements in imaging quality.

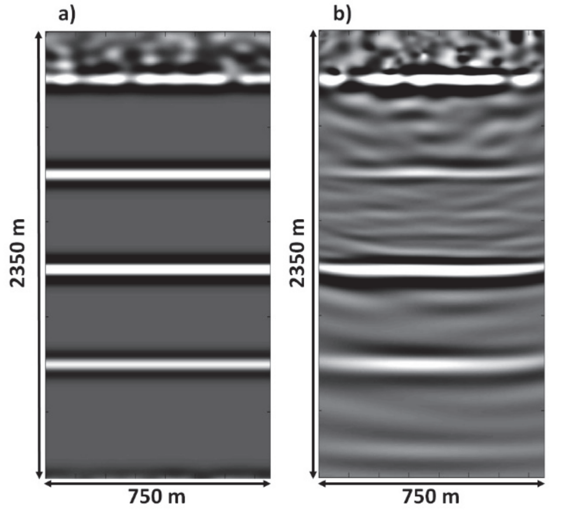

Figure 2: (a) The reflectivity of the true model, serving as the benchmark for ideal image quality, and (b) the zero-offset RTM image obtained within the actual clutter model, representing the optimal migrated image achievable.

Figure 4a displays a statistical zero-offset RTM image obtained through the summation of 100 images from 100 distinct model realizations. This statistical image represents a clear improvement over both the smoothed tomographic model and single realization images, suggesting that constructive interference has successfully highlighted the actual reflectors, while destructive interference has attenuated the artificial ones.

Justifying statistical imaging

Drawing inspiration from the study of optical and ultrasonic speckle noise (Goodman, 2007), Bakulin et al (2022a) proposed that seismic data also undergoes similar distortions. These distortions are likely caused by the near-ballistic forward scattering of multiple wave arrivals, which we termed as "seismic speckle." This concept focuses on how the seismic signal itself becomes distorted as it bounces off small heterogeneities. The overlapping of multiple forward-scattered waves leads to a complex pattern of interference near the initial ballistic arrival. These patterns are unique for each wavepath and break away from the usual assumptions of surface consistency often applied in time processing. Typically, speckle is thought of as a type of multiplicative noise.

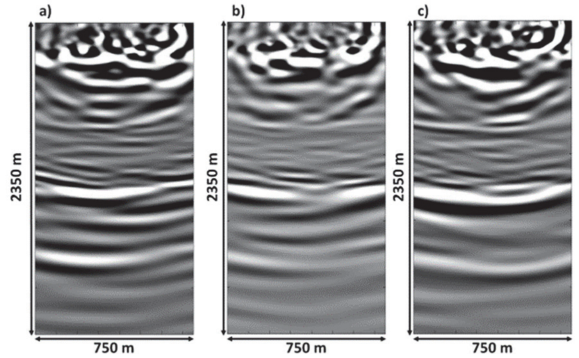

Figure 3: RTM images produced using three distinct single realizations from the clutter ensemble employed in statistical imaging.

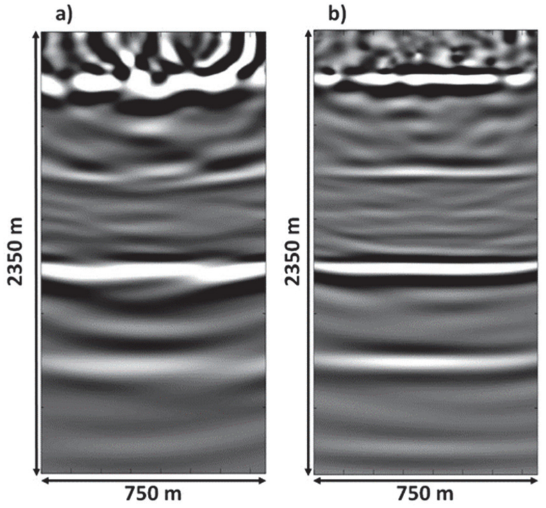

Figure 4: (a) Statistical images generated through straightforward stacking via path summation. (b) The zero-offset RTM image within the goundtruth clutter model, representing the optimal migrated image achievable.

In a similar vein, we can understand the distortions seen in images after conducting depth migration of such data. This can be likened to the way image gathers vary across different model realizations (Figure 5). We can observe random-like perturbations typical for speckle noise (Bakulin et al., 2022a).

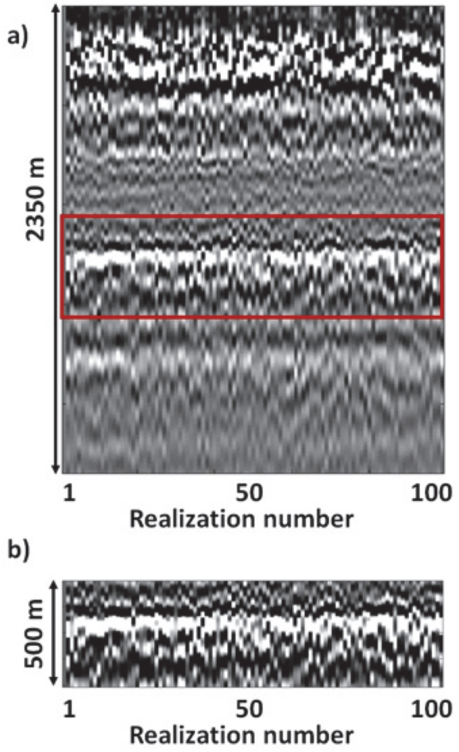

Figure 5: (a) A common-image gather from zero-offset migration corresponding to the model realizations at x=375 meters; (b) Focuses on the portion around the reflector at a depth of 1250 meters.

To delve deeper into these relationships, we analyze the distribution of the residual phase for a window in Figure 5b. The residual phase measures the deviation of the phase at a specific frequency compared to the clean signal phase obtained from the true model or the average phase achieved through stacking. Figures 6b and 6c demonstrate that the residual phase behaves as a random Gaussian-like variable, aligning with expectations from the speckle model of phase perturbation as outlined by Bakulin et al. (2022a). Unlike previous studies that analyzed residual phase by reducing prestack data crossing roughly the same near-surface zone, in statistical imaging, we maintain a fixed realization of the wavefield but generate multiple model realizations of near-surface models, leading to slightly varied images as shown in Figure 5. This necessitates a better understanding of the relationship between the two different statistical approaches using data and image domains. Nevertheless, numerical results underscore a clear relationship.

Bakulin et al. (2022a) have demonstrated that stacking leads to the recovery of the true clean signal phase, mirroring the mechanism observed in the statistical image, which appears more coherent than individual realizations. Furthermore, summation results in the suppression of higher frequencies, as observed in Figure 6a, which compares the spatial frequency spectrum of the stacked image with the average spectrum of the input traces. This similarity reveals a trend consistent with multiplicative noise accompanied by phase perturbations.

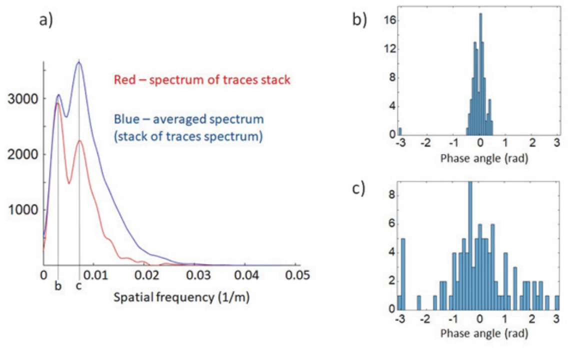

Figure 6: (a) The amplitude spectra of common-image gather traces before and after summation; (b) and (c) display histograms of phase angle fluctuations for two peak frequencies.

Conclusions

We apply statistical imaging to synthetic land data affected by a complex near surface, represented by a random clutter model with Gaussian heterogeneity distribution. We demonstrate that unaccounted near-surface clutter significantly degrades reflection images. While migration using an exact velocity model of the clutter can recover reflections, albeit with artifacts, such an exact model is practically unattainable. Conventionally smoothed background models lead to substantially compromised images. However, statistical imaging can markedly enhance reflector recovery if the statistical parameters for velocity realizations are accurately estimated or guessed. Future research should focus on the impact of statistical parameter accuracy on imaging quality and explore geological inputs for realistic near-surface statistical modeling. We also establish a link between statistical imaging using a randomized near-surface model and seismic speckle noise, uncovering a significant insight. This link explains how statistical imaging manages to recover the correct phase while also highlighting the loss of higher frequencies during the summation of images.

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