Beneficial impacts of receiver arrays on suppressing seismic speckle noise from near-surface heterogeneity

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Summary

Our study tackles the issue of seismic speckle noise in arid environments, arising from near-surface heterogeneity. This noise, characterized by random phase and amplitude perturbations, complicates seismic data processing. We examined the use of receiver arrays, traditionally employed for coherent noise suppression, for their effectiveness in reducing speckle noise.

Analysis of field data indicated increased signal complexity when transitioning from larger arrays to smaller ones or single sensors. This finding challenges previous beliefs about the benefits of single-sensor recording, pointing to the significant impact of multiplicative speckle noise on data quality. A key discovery in our research is the $1/\sqrt{N}$ law for phase spread reduction. This law, especially relevant for smaller arrays like the 9-geophone groups often used in desert settings, reveals that even modest array sizes can greatly reduce phase variability. While larger arrays further this reduction, their impact lessens with size.

These results underscore the essential role of receiver arrays in conditioning seismic data in environments with speckle noise. The identification of the $1/\sqrt{N}$ law for phase spread reduction represents a major stride in seismic data analysis, paving the way for efficient processing techniques tailored to these unique geological challenges.

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Introduction

Seismic data collection in arid regions faces challenges due to near-surface heterogeneity that scatters seismic waves. This study shifts focus from traditional views of such noise as mere near-surface arrivals to be removed, recognizing it as 'seismic speckle noise'. This phenomenon, akin to optical speckle, distorts reflection signals through small-scale scattering, leading to random phase and amplitude variations. We revisit the use of receiver arrays, typically employed for suppressing coherent noise, and highlight their extended role in effectively mitigating seismic speckle noise.

Methodology

Analysis of field data from desert environments shows a trend of increasing signal complexity when downsizing from larger arrays to smaller ones or single sensors, contradicting initial expectations. Bakulin et al. (2022) suggested speckle noise, caused by small-scale surface scattering, as a key factor. This study applies their multiplicative noise model to reassess the impact of receiver arrays on data quality amid speckle noise.

Field data from desert environments reveal a trend of increasing complexity in seismic signals when downsizing from larger to smaller arrays or single sensors (Figure 1). It was initially presumed that smaller arrays would primarily improve recording of near-surface arrivals without significantly altering reflections. However, unexpectedly, the reflections became more fragmented. This deviation led Bakulin et al. (2022) to propose speckle noise as a key factor. Stemming from small-scale near-surface, speckle noise induces random phase and amplitude variations from trace to trace. Employing the multiplicative noise model from their research, we reassessed the influence of receiver arrays on data quality in the presence of speckle noise. This approach helped us understand that speckle noise could plausibly explain the observed trend in real data, thus shedding new light on the impact of array sizes in seismic surveys.

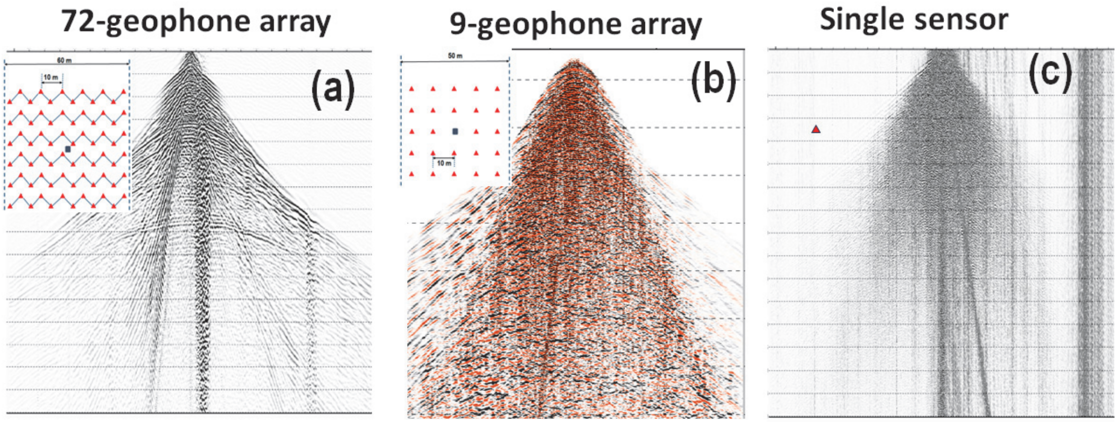

Figure 1 *Prestack gathers from different arrays: (a) 72-geophone; (b) 9-geophone; (c) single sensors. Observe decreased coherency and escalating complexity from left to right.*

Multiplicative noise model for speckle noise

In the frequency domain, speckle noise is modeled as a multiplicative component, as defined by $X_k(\omega) = R_k(\omega)S(\omega)$, where $S(\omega)$ is the clean signal and $R_k(\omega)$ represents random multiplicative noise that alters the signal through scattering-induced phase and amplitude perturbations. This model distinguishes two types of noise: Type 1, characterized by frequency-dependent phase fluctuations $R_k(\omega) = e^{i\varphi_k(\omega)}$, and Type 2, representing residual statics $R_k(\omega) = e^{-i\omega\tau_k}$. In both cases, normal distributions are assumed and defined by standard deviation of phase (σ_φ in radians) and time perturbations (σ_τ in seconds). This approach reflects the effects of scattering on small-scale heterogeneities, leading to phase and amplitude distortions from trace to trace in a manner that traditional models might not fully capture.

Figure 2 showcases two key types of multiplicative noise affecting seismic signals. The first, shown in Figure 2a, is residual statics or Type 2 noise, marked by linear phase changes. The second, depicted in Figure 2b, involves more intricate phase fluctuations which vary randomly across different frequencies and escalate linearly with the frequency. This latter pattern mirrors what is commonly observed in both theoretical models and real-world seismic data, as detailed in studies by Bakulin et al. (2022, 2023a). Figure 2c underscores that Type 2 noise allows for greater variability as perturbations differ from one frequency to another. In the process of stacking, both types of noise result in amplitude attenuation. Interestingly, the impact on amplitude can be indistinguishable if the general trend of phase perturbations follows a similar pattern, as demonstrated in Figure 2d. However, Type 1 noise introduces more realistic trace-to-trace variations, akin to actual data (Figure 1), in contrast to the mere constant waveform shifts of static noise. Regarding phase, Bakulin et al. (2022) demonstrated that stacking effectively cancels out these random perturbations, restoring the true phase of the signal unaffected by scattering. However, their research stopped short of quantifying the phase's variability or standard deviation in relation to the cumulative number of traces. The statistical analysis of phase variability is essential because it governs both the complexity and the turnaround time required for data processing.

Figure 2f displays the outcomes of numerical simulations where Type 1 speckle noise with linearly increasing phase perturbations is subjected to array stacking. These results clearly show that array stacking stabilizes the phase and enhances trace-to-trace similarity, with larger arrays exerting a more substantial effect. Although the simulation focuses on Type 1 noise, the general findings are applicable to the simpler Type 2 noise as well, underlining the utility of array stacking in managing different types of speckle noise.

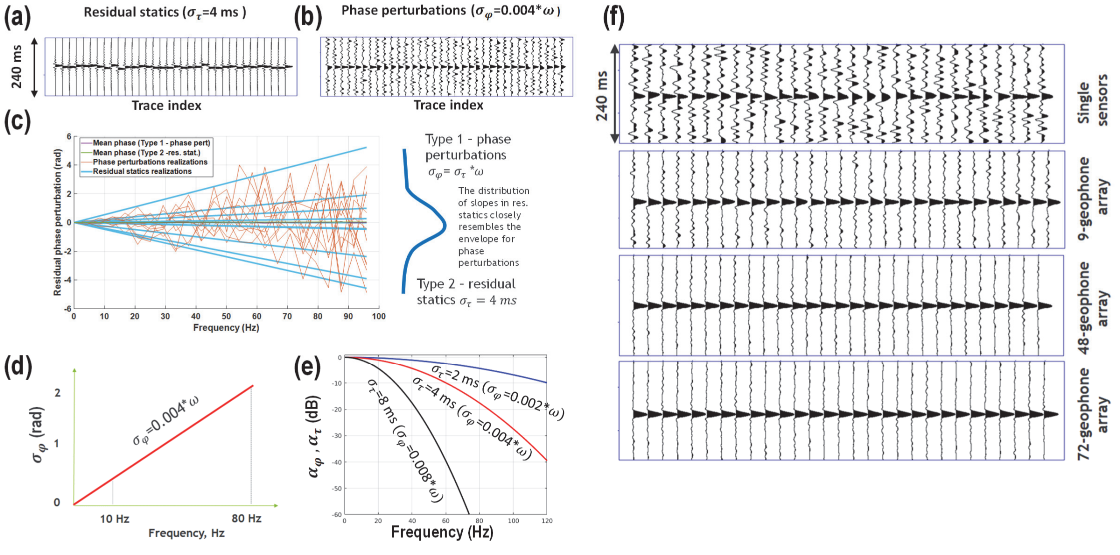

Figure 2 *Synthetic data with random multiplicative noise types: (a) 4 ms residual statics (Type 2); (b) phase perturbations (Type 1) with increasing standard deviations, more closely resembling real data (Figure 1). (c) Shows the first ten residual phase realizations for both noise types. (e) Highlights amplitude decay at various frequencies due to both noise types, with similar decay patterns for statics and phase perturbations. (f) Simulated waveforms from various array sizes (single-sensor, 9-, 48-, and 72-geophone) show progressive improvement in coherency and similarity as array size increases.*

Figure 3a encapsulates the results of 10,000 such experiments, illustrating the relationship between array size and the diminishing spread of phase perturbations. Notably, the phase consistently aligns with the correct signal phase across all array sizes. However, the spread rapidly decreases as the size of the array increases. Figure 3b demonstrates a consistent reduction in phase spread across all frequencies, conforming to the $1/\sqrt{N}$ law for small phase perturbations. Figure 3c further distills these findings by displaying the normalized phase spread reduction, relative to single-sensor data, as a function of array size at selected frequencies. This visualization confirms the adherence to the $1/\sqrt{N}$ law, aligning with theoretical expectations for minor phase fluctuations.

These findings are especially significant as they underscore the efficiency of smaller arrays, like those with nine geophones, in substantially decreasing the spread of phase perturbations. Such 9-geophone arrays are commonly employed in 3D seismic acquisition in desert environments (Dmitriev et al., 2017; Al Mesaabi et al., 2022). While expanding the array size further diminishes the spread, the degree of reduction becomes more subtle in larger arrays.

Additionally, our research demonstrates that stacking seismic data using receiver arrays not only decreases phase dispersion but also significantly reduces amplitude dispersion. This dual effect underscores the profound impact of receiver arrays in enhancing the clarity and fidelity of seismic data critical for processing.

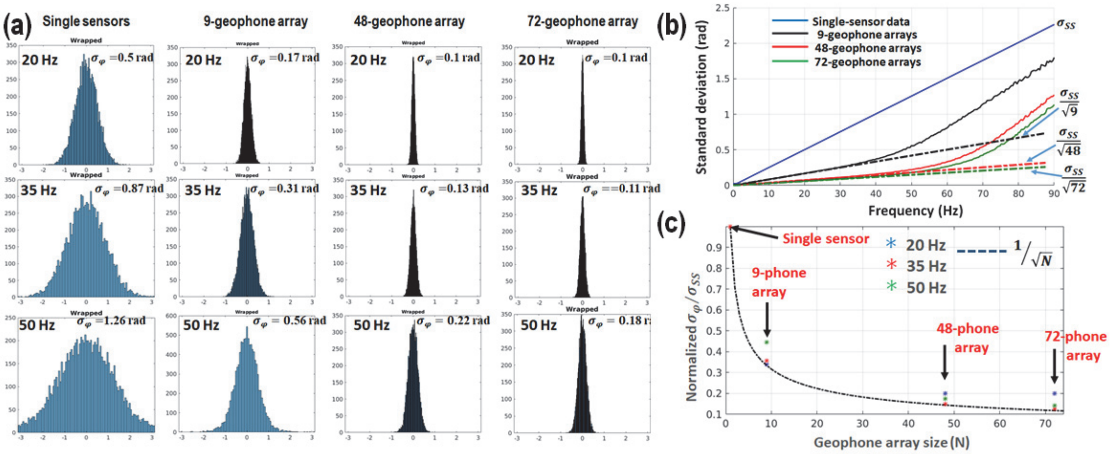

Figure 3 *Phase distributions (a) in synthetic recordings with speckle noise for different array sizes (single-sensor, 9-, 48-, and 72-geophone), showing a noticeable reduction in phase spread as array size increases, particularly at frequencies 20 Hz, 35 Hz, and 50 Hz. (b) Phase spread reduction is quantified across the entire frequency band, highlighting the stabilizing influence of larger arrays. (c) The normalized spread, relative to the single sensor, demonstrates a significant reduction in phase spread, even with the smallest 9-geophone array. This effect diminishes with larger arrays, following a* $1/\sqrt{N}$ *trend.*

Discussion

The trend of deteriorating data quality observed when moving towards smaller arrays and single sensors can plausibly be attributed to speckle noise. Had this trend been solely due to increased coherent, yet additive near-surface noise, conventional noise removal techniques would have been sufficient to mitigate it. However, the increased complexity and longer processing times associated with this data indicate that we are dealing with a more intricate type of noise, one that was not previously recognized. Understanding speckle noise is key, and with this knowledge, novel decluttering techniques can be developed for its effective processing on single-sensor data, as suggested by Bakulin et al. (2023b). Implementing these techniques, however, necessitates a re-evaluation and adaptation of traditional processing workflows.

Conclusions

Our study concludes that receiver arrays are essential in effectively combating seismic speckle scattering noise. Crucially, they enable conventional processing workflows to function efficiently, which would otherwise be hindered by variable phase. The introduction of the 1/√N law for phase spread reduction distinctly advances our research, offering vital insights for array design and implementation. Arrays markedly reduce trace-to-trace variability in phase and amplitude, a key factor in ensuring the reliability and effectiveness of standard processing methods. Conversely, in scattering environments, single-sensor data becomes problematic to process without addressing speckle noise. Given the recent acknowledgment of speckle noise in seismic data, the evolution of processing techniques specifically tailored to manage this noise is still progressing.

Acknowledgments

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