Reducing waveform variability in seismic data using circular-statistics-based phase masking

Akshika Rohatgi[1], Andrey Bakulin[1], Andrew Peterson[2], and Sergey Fomel[1], University of Texas at Austin, [2]TGS*

Summary

Seismic phase is highly sensitive to near-surface effects, including scattering and other noise sources, leading to trace-dependent distortions that degrade waveform coherence. These distortions occur at short spatial scales, vary rapidly from trace to trace, and appear statistically independent rather than surface consistent. We propose a phase-masking method based on circular statistics that treats phase as a wrapped variable and estimates local reference phase using the circular mean of neighboring traces. Applied in the frequency domain, the method stabilizes phase without altering amplitudes or kinematics. Synthetic and land field examples demonstrate significant reduction in phase variability and improved prestack and stack coherence.

Introduction

Land seismic data are strongly affected by small-scale near-surface heterogeneities that scatter the wavefield and produce complex, trace-dependent phase distortions. Conventional processing mitigates these effects using surface-consistent corrections, residual statics, and deconvolution (Taner and Koehler, 1981; Cary and Lorentz, 1993). Cary and Nagarajappa (2014a, 2014b) showed that surface-consistent deconvolution can leave substantial residual phase errors and proposed additional phase corrections coupled with residual statics estimation. These approaches primarily target medium- to long-wavelength, surface-consistent behavior and do not explicitly address short-scale, rapidly varying phase distortions that fluctuate from trace to trace. These methods, however, generally apply deterministic trace-wise corrections or rely on global stack-power optimization.

More recently, near-surface scattering has been reframed as a multiplicative process that randomizes seismic phase, producing speckle-like behavior (Bakulin et al., 2022; Rohatgi et al., 2025). Statistical characterization is essential here because forward scattering on meter-scale heterogeneity generates multiple near-ballistic arrivals whose interference produces rapid, trace-to-trace phase variations that cannot be fully captured by deterministic or amplitude-based approaches. Techniques such as super-grouping and nonlinear beamforming (Bakulin et al., 2018, 2020) exploit multi-trace redundancy to enhance coherent signal, but do not explicitly model the phase distribution or distinguish coherent phase trends from symmetric random perturbations. Bakulin et al. (2023) introduced seismic time-frequency masking to mitigate speckle-like noise, enabling both amplitude and phase conditioning, though phase stabilization remained coupled to amplitude weighting and broadband time-domain behavior.

In this paper, we build on that framework by focusing explicitly on phase. We introduce a phase-only masking operator in which reference phase is estimated from local phase ensembles using circular statistics, allowing phase to be treated independently of amplitude and stabilized frequency-by-frequency. The mask is constructed from the circular mean of neighboring trace phases, while the circular variance quantifies phase scatter and tracks the effect of masking before and after application.

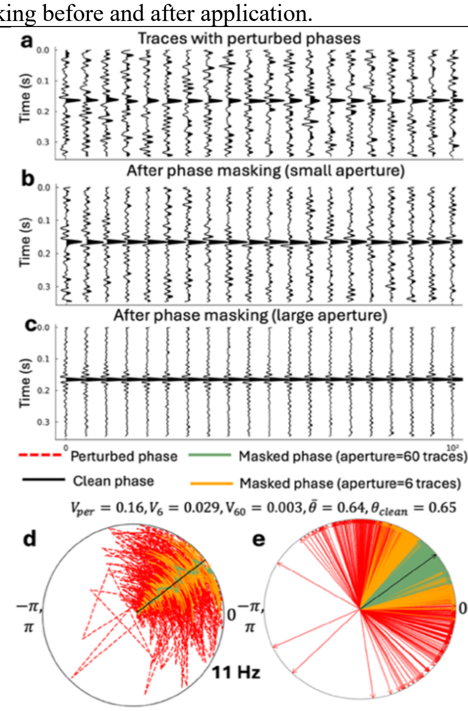

Figure 1: Demonstration of phase masking for suppressing stochastic phase distortions in seismic traces. (a) Input traces with perturbed phases. (b) Result after phase masking using a small spatial aperture (6 traces), (c) Result after phase masking using a larger aperture (60 traces), showing phase stabilization and improved waveform continuity. (d) Polar representation of phases at 11 Hz, compared with clean reference phase and masked phases. (e) Phase vectors after masking illustrating increased phase concentration and coherence with aperture size.

Phase masking operator and circular mean

To illustrate the phase masking approach, we begin with the seismic synthetic traces with phase perturbations (Figure 1a), modeled as multiplicative seismic speckle noise following the formulation of Bakulin et al. (2022). The imposed phase perturbations generate traces with visibly distorted waveforms in the time domain even though the underlying signal and amplitude spectra remain unchanged.

Seismic signal phase masking

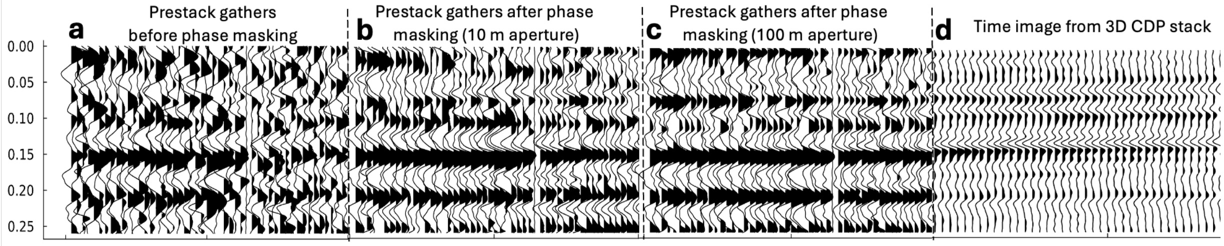

Figure 2: Effect of phase masking on prestack CDP gathers: (a) Prestack gathers before masking, showing strong trace-to-trace phase variability and limited waveform continuity. (b) Gathers after phase masking using a small spatial aperture (≈10 m), exhibiting partial stabilization while retaining local variations. (c) Gathers after masking with a larger aperture (≈100 m), showing markedly improved phase alignment and lateral continuity. (d) Time image from the corresponding 3D CDP stack for validation..

This highlights that phase variability alone is sufficient to destroy waveform coherence and render single-trace phase information unreliable. Recovering coherent phase behavior requires an approach that operates exclusively on phase. A critical first step is therefore the isolation of phase information from amplitude, ensuring that masking is governed solely by phase behavior and remains unbiased by amplitude variations.

Let $\boldsymbol{a_k(t)}$denote trace $\boldsymbol{k}$in a prestack gather and $\boldsymbol{A_k(\omega)}$its Fourier transform. For each trace $\boldsymbol{k}$, we define a local neighborhood $\boldsymbol{N(k)}$of $\boldsymbol{n}$ nearby traces with comparable propagation paths, for example traces with similar offsets and source-receiver azimuths within CDP super-gathers or cross-spread domains.

Phase is treated as a wrapped variable and analyzed across this local ensemble. A reference phase is estimated at each frequency using the circular mean of unit phasors,

$$\bar{U}_k(\omega) = \frac{1}{n} \sum_{j \in N(k)} \frac{A_j(\omega)}{|A_j(\omega)|}, \bar{\theta}_k(\omega) = \arg\{\bar{U}_k(\omega)\}.$$

Phase masking is applied as a unit-magnitude multiplicative operator in the complex frequency domain,

$$PM_k(\omega) = \exp\left(i[\bar{\theta}_k(\omega) - \theta_k(\omega)]\right), |PM_k(\omega)| = 1,$$

so that the masked spectrum is

$$\tilde{A}_k(\omega) = A_k(\omega)\, PM_k(\omega) = |A_k(\omega)|\; e^{i\bar{\theta}_k(\omega)}.$$

By construction, the operation replaces the original trace phase with the local reference phase at each frequency while preserving amplitudes exactly. The strength of phase stabilization is controlled by the neighborhood size $\boldsymbol{n}$: small apertures suppress rapid trace-to-trace phase fluctuations while retaining local variability, whereas larger apertures enforce stronger phase coherence across the ensemble. A small aperture (e.g., 6 traces) reduces phase fluctuations while preserving the local variations (Figure 1 b), whereas a larger aperture (e.g., 60 traces) enforces stronger reduction in phase variability across the ensemble (Figure 1c). This, aperture size acts as a direct control on the trade-off between local adaptability and global phase coherence.

This behavior can be visualized in polar domain. Prior to masking, phase vectors form a dispersed cloud around the clean phase direction, indicating strong phase distortions. After masking, vectors cluster progressively as aperture increases (Figures 1 d, e). This indicates reduced directions dispersion. This stabilization is quantified using circular variance, which measures angular spread while properly accounting for phase periodicity. For synthetic example at 11 Hz, the perturbed seismic exhibits a variance of V = 0.16. Applying masking with a small aperture reduces the phase variance to V = 0.029, while a larger aperture further suppresses variability to V = 0.003, indicating highly coherent phases. The synthetic experiment shows that phase masking suppresses symmetric random phase perturbations without altering amplitudes , and that the degree of stabilization is controlled directly by the spatial aperture. These results provide controlled validation of the method prior to application to field seismic data.

Land seismic example 1: Phase stabilization of prestack CPD gathers

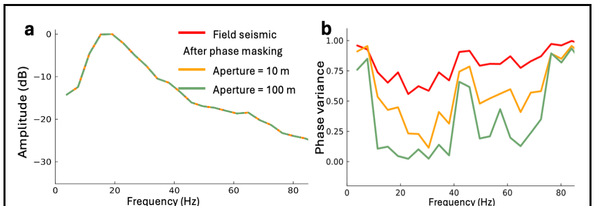

Figure 3. (a) Amplitude spectra of the original field data and the data after phase masking with 10 m and 100 m apertures, showing no impact on the amplitude. (b) Phase variance as a function of frequency for the same cases, demonstrating substantial reduction in phase variability with increasing aperture size

We apply phase masking to land field data using a 3x3 common-depth-point (CDP) super-gather composed of nine neighboring CDPs, sorted by increasing offset, after ground-roll attenuation and NMO correction. This configuration provides a sufficiently large ensemble of traces with comparable subsurface illumination and similar kinematic content. Within a time-window around a representative reflector, the input super-gather exhibits trace-to-trace waveform variability and limited lateral continuity

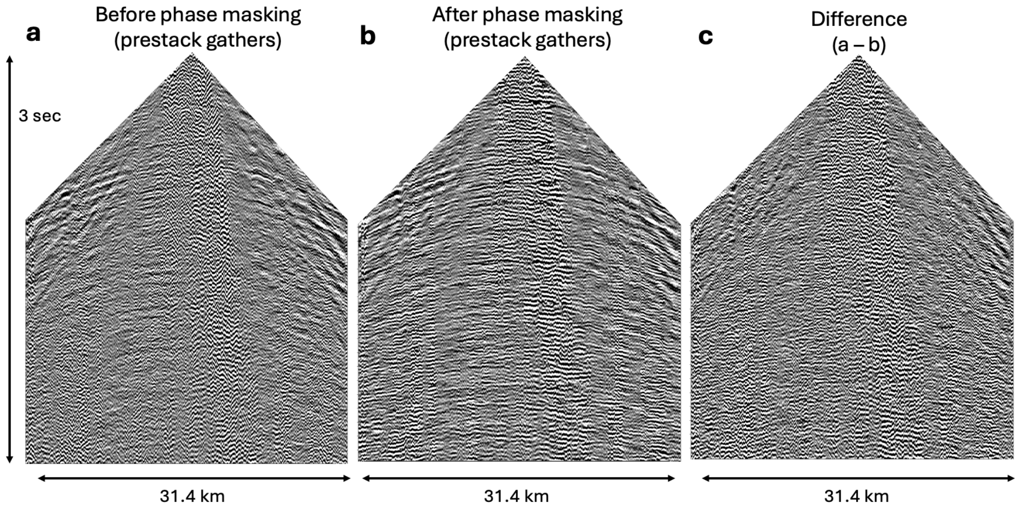

Figure 2: Effect of phase masking on prestack CDP gathers: (a) Prestack gathers before masking, showing strong trace-to-trace phase variability and limited waveform continuity. (b) Gathers after phase masking using a small spatial aperture (≈10 m), exhibiting partial stabilization while retaining local variations. (c) Gathers after masking with a larger aperture (≈100 m), showing markedly improved phase alignment and lateral continuity. (d) Time image from the corresponding 3D CDP stack for validation..

(Figure2a). waveform variability and limited lateral continuity (Figure2a). Although reflection energy is present, unsuppressed near-surface effects, residual coherent noise, and scattering disrupt waveform alignment, making reflection events difficult to track consistently across offsets. Phase masking is applied in a sliding window along the trace axis using two spatial apertures: 10 m (~20 neighboring traces) and 100 m (~ 200 neighboring traces). Since the traces are ordered by offset, each window samples data with similar reflection geometry and a common depth point, providing a physically consistent ensemble for estimating local reference phase. The smaller aperture reduces phase variability while preserving offset-dependent variations (Figure 2b), whereas the large aperture produces markedly stronger reduction in phase variability and improved reflector continuity (Figure 2c). These visual changes are reflected quantitatively in terms of phase variance estimated over full frequency band (Figure 3b). Prior to masking, the field gathers exhibit elevated variance across most of the band, with values range 0.7-1.0, indicating substantial phase variability. Applying the 10 m aperture masking reduces the variance over the dominant frequency band. The 100 m aperture yields a further reduction to roughly 0.15-0.25, corresponding to strongly reduced phase variability. In contrast, amplitude spectra before and after masking are identical (Figure 3a), confirming that the method is phase only. Together, these results demonstrate that phase masking can substantially stabilize the prestack field data.

Land seismic example 2: Phase masking in cross-spread domain with azimuth preservation

Building on the CDP super-gather example, we next examine phase masking in the cross-spread domain. In this organization, trace ensembles are constructed to provide dense spatial sampling in two lateral directions while maintaining similarity in both offset and source–receiver azimuth, ensuring that the grouped traces share comparable propagation paths (Bakulin et al., 2020).This provides statistically robust yet physically meaningful phase estimates. Phase masking is applied to NMO-corrected cross-spread gathers using a 300 ms sliding time window. Phase ensembles are defined as compact two-dimensional neighborhoods in source–receiver coordinates, with footprints of approximately 20 × 20 m (~20 traces) and 100 × 100 m (~200 traces) and are evaluated as the window moves across the domain. Figure 4 illustrates the effect of phase masking using the smallest spatial aperture. The masked data (Figure 4b) show a mild but systematic reduction of trace-to-trace phase variability, leading to improved waveform coherence while retaining local character. The difference panel (Figure 4c) is dominated by small-scale, rapidly varying fluctuations with no coherent reflection energy, indicating that the operator primarily removes incoherent phase jitter rather than signal. No systematic signal leakage is observed, and the removed components are consistent with incoherent phase distortions that inhibit constructive interference across traces. To evaluate how this phase stabilization propagates to stack images, we compute CDP stacks before and after phase masking (Figure 5). Because stacking relies on constructive interference of aligned waveforms, it is highly sensitive to trace-to-trace phase inconsistencies. Residual phase jitter therefore manifests as reflector roughness, diminished continuity, and reduced stack efficiency.

The stack obtained from unmasked data exhibits noticeable reflectors irregularity and localized incoherent variations

(Figure 5a, d). As the masking aperture increases, lateral continuity progressively improves, the smaller aperture yields more organized events, and the larger aperture produces even more continuous reflections with stronger trace-to-trace alignment and constructive stacking.

In addition to improving continuity, phase masking enhances effective seismic resolution by reducing destructive interference caused by trace-to-trace phase distortions. High-frequency components that were previously jittered and partially canceled during stacking are now better aligned, allowing this energy to be preserved and reinforced. This results in sharper reflector boundaries, improved delineation of thin beds, and an apparent increase in usable bandwidth in the stacked image. Importantly, this resolution gain does not arise from spectral boosting or amplitude manipulation, but from more coherent summation of existing high-frequency energy that was previously incoherent.

Discussion

This work builds on the seismic time–frequency masking framework introduced in earlier studies (Bakulin et al., 2023), but differs in how phase stabilization is defined and applied. In earlier implementations, phase behavior was inferred from locally stacked or beamformed traces, which implicitly couples phase estimation to amplitude weighting and broadband time-domain behavior, limiting isolation of purely phase-driven effects and frequency-by-frequency control. In the present formulation, phase stabilization is implemented explicitly as a phase-only substitution mask derived from local phase ensembles using circular statistics. The circular mean provides a stabilized phase estimate that is substituted for the original trace phase at each frequency, with no involvement of amplitude information.

Conclusions

In this work, we developed a new type of phase mask within the phase-masking framework, based on circular statistics and strictly independent of amplitude. By treating phase as a wrapped directional variable and applying a phase-only substitution mask, the approach enables frequency-by-frequency phase stabilization without altering amplitudes, kinematics, or spectral content.

Synthetic examples show effective suppression of short-scale, symmetric phase perturbations, with stabilization strength governed by aperture size as a statistical effect. Applications to land field data demonstrate substantial reduction in trace-to-trace phase variability in both CDP super-gather and cross-spread domains, leading to improved prestack coherence, enhanced lateral continuity, and more constructive stacking. In stacked images, improved effective resolution arises from preservation and reinforcement of high-frequency energy that was previously incoherent and canceled during stacking.

More broadly, circular-statistics-based phase masking provides a transparent and flexible framework for phase conditioning, linking aperture size directly to statistical phase stabilization. Beyond the circular-mean substitution used here, the framework enables development of additional phase-based masks and processing workflows for phase-sensitive applications such as waveform inversion and high-resolution imaging.

Acknowledgments

We thank TGS for providing selected datasets used in this study and Justin Simmons and Christopher Egger for helpful guidance.

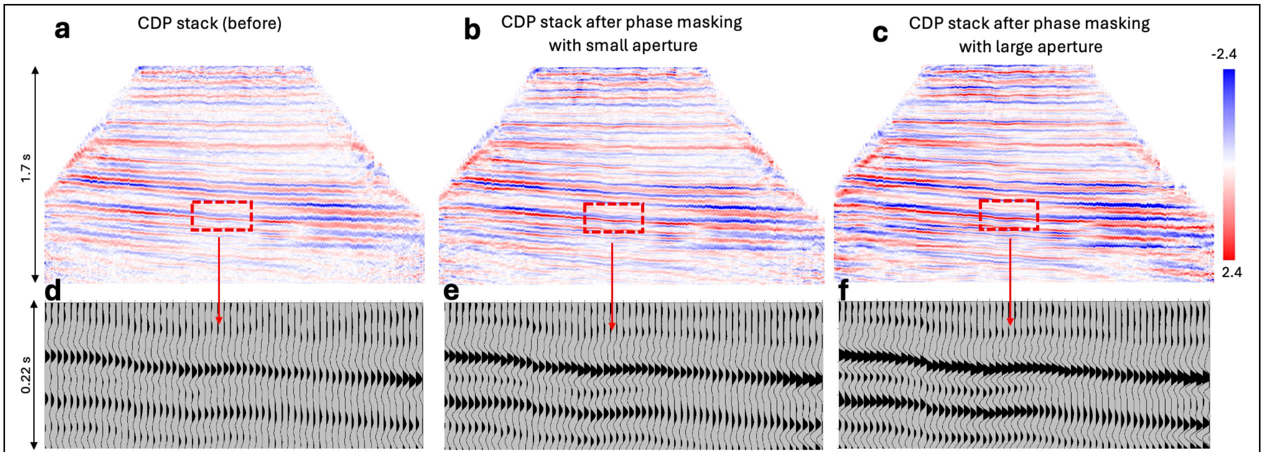

Figure 5. CDP stacks (a) before masking and after phase masking with (b) a small aperture and (c) a large aperture. Increasing aperture improves reflector continuity and coherence. (d–f) Zoomed waveform views of the highlighted regions show progressively stronger lateral continuity and constructive stacking.

References

Bakulin, A., D. Neklyudov, and I. Silvestrov, 2022a, Multiplicative seismic noise caused by small-scale near-surface scattering and its transformation during stacking: Geophysics, 87, V419–V435, doi:10.1190/geo2021-0632.1.

Bakulin, A., P. Golikov, M. Dmitriev, D. Neklyudov, P. Leger, V. Dolgov, and others, 2018, Application of supergrouping to enhance 3D prestack seismic data from a desert environment: The Leading Edge, 37, 200–207, doi:10.1190/tle37030200.1.

Bakulin, A., I. Silvestrov, I. Dmitriev, D. Neklyudov, M. Protasov, K. Gadylshin, and others, 2020, Nonlinear beamforming for enhancement of 3D prestack land seismic data: Geophysics, 85, 1MJ–Z13, doi:10.1190/geo2019-0631.1.

Bakulin, A., D. Neklyudov, and I. Silvestrov, 2023, Seismic time-frequency masking for suppression of seismic speckle noise: Geophysics, 88, V371–V385, doi:10.1190/geo2022-0701.1.

Cary, P. W., and G. A. Lorentz, 1993, Four-component surface-consistent deconvolution: Geophysics, 58, 383–392, doi:10.1190/1.1443421.

Cary, P., and N. Nagarajappa, 2014a, Robust surface-consistent residual statics and phase correction - Part 1: GeoConvention 2014, FOCUS: Adapt, Refine, Sustain, Calgary, Alberta, Canada.

Cary, P., and N. Nagarajappa, 2014b, Robust surface-consistent residual statics and phase correction - Part 2: GeoConvention 2014, FOCUS, Calgary, Alberta, Canada.

Mardia, K. V., and P. E. Jupp, 2000, Directional statistics: John Wiley & Sons.

Rohatgi, A., A. Bakulin, and S. Fomel, 2025, Data-driven analysis of seismic phase using circular statistics: The Leading Edge, 44, 683–691, doi: 10.1190/tle44090683.1.

sTaner, M. T., and F. Koehler, 1981, Surface-consistent corrections: Geophysics, 46, 17–22, doi: 10.1190/1.1441133.