

# Diagnosing seismic prestack processing efficiency and bandwidth through frequency-dependent phase stability

Akshika Rohatgi\*, Andrey Bakulin, and Sergey Fomel, University of Texas at Austin

## Summary

Conventional processing quality control (QC) relies on broadband, energy-based metrics that obscure how waveform coherence varies with frequency and offset. We propose a phase-based diagnostic that evaluates prestack processing fidelity using phase variance, an amplitude-independent measure of coherence in the frequency-offset domain. Application to land data reveals strongly frequency-dependent behavior: processing improves coherence in some bands while degrading it in others, even as spectra appear broadened. Phase-variance maps provide an objective and reproducible way to identify usable prestack bandwidth, enabling targeted processing optimization and better alignment between acquisition design and processing performance.

## Introduction

Progress in seismic data processing has historically reflected a close correspondence between advances in acquisition technology and the development of algorithms capable of exploiting them. That correspondence, once taken for granted, is increasingly difficult to assume.

Core processing algorithms in widespread use today, surface-consistent processing and residual statics, were developed in the 1970s and 1980s for array-based acquisition systems (Taner and Koehler, 1981; Wiggins et al., 1976) with comparatively high prestack signal-to-noise ratios. In those settings, coherent energy is readily accessible for effective multichannel processing. Modern acquisition, however, has shifted toward dense point-receiver systems that deliver broader bandwidth by design but at the cost of substantially higher per-channel noise (Mougenot, 2004; Dean et al., 2018). As a result, prestack data now commonly operate in regimes with strongly negative and frequency-dependent SNR. Processing workflows, and critically, the quality-control tools used to evaluate them, have evolved more slowly. This has created a growing mismatch: modern broadband data are assessed using metrics conceived for a fundamentally different acquisition regime, with limited ability to determine which frequency bands remain coherent in prestack gathers and which are effectively lost before imaging. Conventional QC metrics such as signal-to-noise ratio, amplitude spectra, and stack power primarily measure energy. What is often missing is a measure that directly captures waveform coherence as a function of frequency. Phase variance, introduced by Rohatgi et al. (2025), quantifies phase consistency across a local prestack gather independently at each frequency, providing a diagnostic fingerprint that amplitude-based measures cannot replicate. Here, we apply phase variance to three representative stages of land seismic processing, demonstrating that it reveals

strongly frequency-selective processing behavior invisible to conventional QC and provides a quantitative, reproducible framework for assessing processing performance in modern broadband land data.

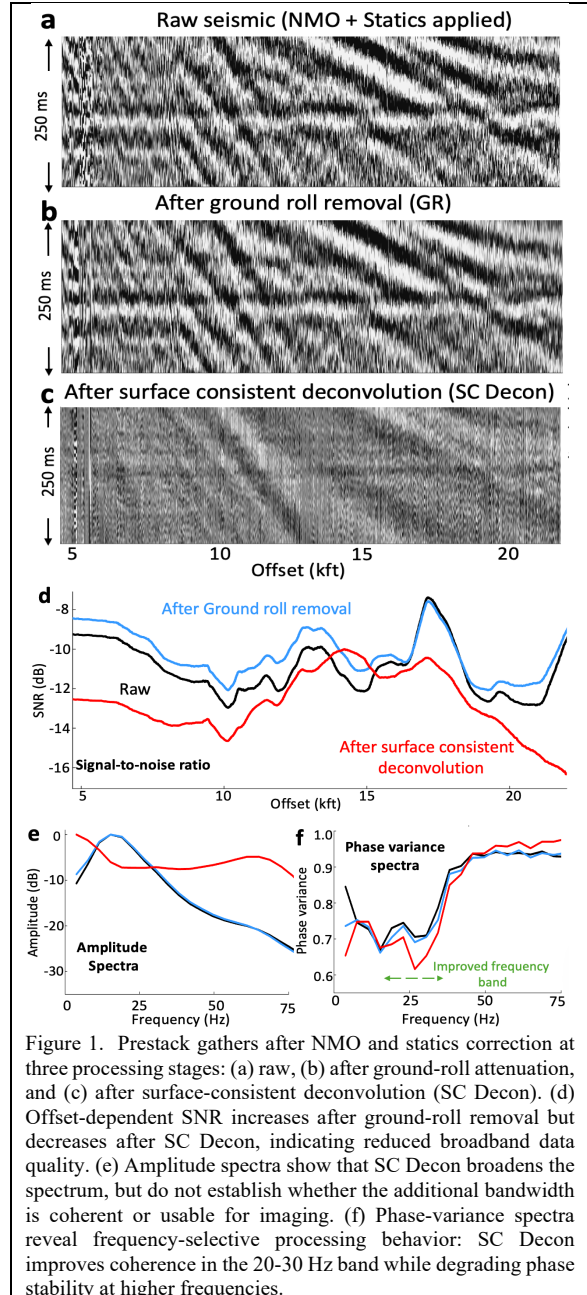


Figure 1. Prestack gathers after NMO and statics correction at three processing stages: (a) raw, (b) after ground-roll attenuation, and (c) after surface-consistent deconvolution (SC Decon). (d) Offset-dependent SNR increases after ground-roll removal but decreases after SC Decon, indicating reduced broadband data quality. (e) Amplitude spectra show that SC Decon broadens the spectrum, but do not establish whether the additional bandwidth is coherent or usable for imaging. (f) Phase-variance spectra reveal frequency-selective processing behavior: SC Decon improves coherence in the 20-30 Hz band while degrading phase stability at higher frequencies.

## Prestack processing efficiency through phase

### Assessing Processing Performance Across Frequency

Every seismic processing decision involves a trade-off between noise suppression and signal preservation, compounded by the fact that most broadband algorithms treat all frequencies similarly, even though signal and noise behave very differently across the spectrum. We apply corrections, reshape spectra, and suppress noise, yet lack a reliable, frequency-sensitive way to determine whether these steps genuinely improve prestack data quality or inadvertently degrade it.

Conventional QC metrics such as signal-to-noise ratio, amplitude spectra, and stack power primarily measure energy. They confirm that processing has changed the data but provide no indication of which frequency ranges benefit and which do not. As a result, broadband performance is often judged from final images, leading to statements about “usable bandwidth” that are substantially narrower than the acquisition band, without a prestack diagnosis of whether the limits arise from acquisition, noise, or processing.

We address this gap by introducing phase variance as a practical, frequency-resolved QC metric that measures waveform coherence rather than energy. Phase variance quantifies trace-to-trace phase consistency within a local prestack gather independently at each frequency, providing a diagnostic fingerprint that amplitude-based metrics cannot replicate. By focusing on coherence rather than power, it exposes frequency-selective processing behavior that is otherwise hidden.

### SNR as a processing quality metric

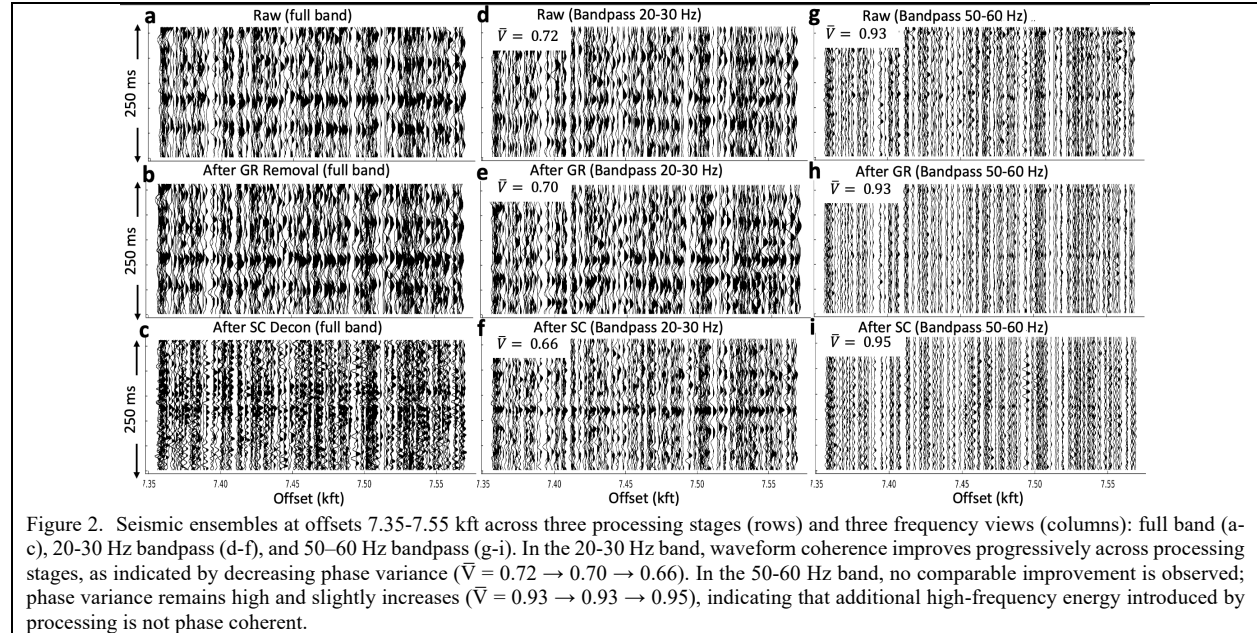
Signal-to-noise ratio (SNR) remains the standard yardstick for processing quality, and Figure 1d illustrates both its value

and its limitations. Following Bakulin et al. (2022), we estimate offset-dependent SNR at each processing stage.

In the raw data, SNR ranges from approximately  $-14$  to  $-10$  dB, indicating that incoherent noise dominates across all offsets. After ground-roll attenuation, SNR improves as expected. However, following surface-consistent deconvolution (SC Decon), SNR decreases (Figure 1d). This behavior, while counterintuitive, has been reported previously: surface-consistent corrections can degrade data quality when incoherent noise levels are too high for stable operator estimation (Cary and Nagarajappa, 2014a, 2014b). Although this trade-off is widely recognized in practice, it is rarely quantified, and mitigation remains largely ad hoc. Although SNR correctly indicates that SC Decon degrades data quality on average, it provides only a single broadband measure. It cannot identify where within the frequency spectrum degradation occurs or whether some bands still benefit from the correction. Because seismic data are broadband and noise is strongly frequency dependent, SNR alone cannot diagnose which parts of the bandwidth are preserved, improved, or lost during processing. Resolving this ambiguity requires a frequency-resolved measure of signal coherence rather than an energy-based metric.

### Why average amplitude spectra are not enough

Surface-consistent deconvolution is known to broaden spectra, and Figure 1e confirms this expected behavior. However, spectral broadening alone provides no basis for assessing whether the added energy represents coherent signal or amplified noise. As a result, bandwidth gains are often accepted ad hoc, with no quantitative basis to assess their reliability or guide improvement. Progress beyond



## Prestack processing efficiency through phase

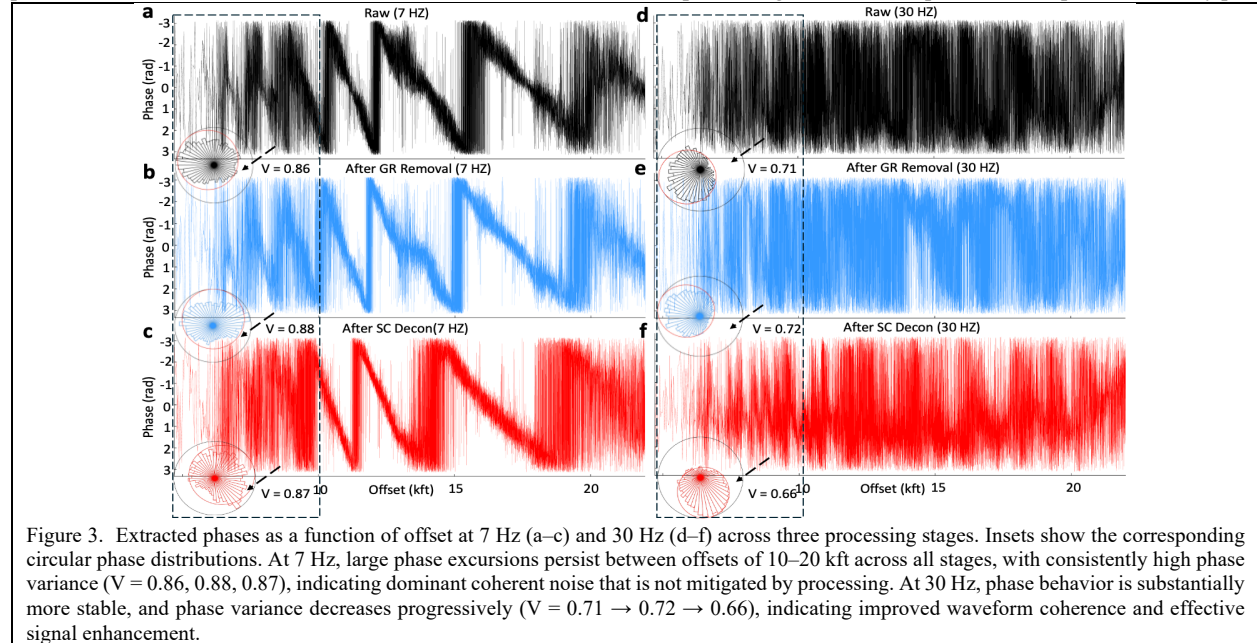
spectrum shaping requires a frequency-resolved, coherence-based diagnostic.

### Bandpass analysis: A frequency-resolved view

Bandpass panels remain the most common tool for assessing signal quality across the frequency band. They enable visual, frequency-by-frequency inspection of waveform coherence, but the assessment is inherently qualitative rather than quantitative.

Figures 2a-c shows full-band seismic ensembles at offsets of  $\sim 7.3$ – $7.5$  kft across three processing stages. Strong waveform variability is evident in the raw data and after ground-roll attenuation, reflecting significant phase distortions. After surface-consistent deconvolution, high-frequency energy is visibly increased, but the full-band view alone cannot determine whether this reflects true signal enhancement or amplified noise. Figures 2d-f shows the 20–30 Hz bandpass panels, where waveform coherence improves progressively with each processing step, indicating genuine signal stabilization. In contrast, Figures 2g-i show the 50–60 Hz bandpass panels, where interpretation remains ambiguous. Despite increased energy, it is unclear whether phase coherence has improved.

Figure 3 provides complementary insight by examining phase behavior directly. At 7 Hz (Figures 3a-c), large phase excursions persist between offsets of 10–20 kft across all processing stages ( $V = 0.86, 0.88, 0.87$ ), indicating dominant coherent noise that is not mitigated by processing. At 30 Hz (Figures 3d-f), phase behavior is substantially more stable, and phase variance decreases progressively ( $V = 0.71, 0.72, 0.66$ ), confirming genuine signal improvement. Insets show the corresponding circular phase distributions.



Together, these examples highlight the central limitation of bandpass-based QC: when coherence gains are subtle or frequency dependent, interpretation becomes subjective. Visual QC is opinion-driven, processor-dependent, and difficult to scale or automate, motivating the need for a quantitative, frequency-resolved diagnostic of prestack signal coherence.

### The role of average phase variance

To move beyond subjective visual interpretation, we quantify waveform coherence using phase variance, a frequency-dependent measure of phase consistency across a prestack gather (Rohatgi et al., 2025). Phase variance  $V(\omega) \approx 0$  indicates highly stable, coherent phase behavior, whereas  $V(\omega) \approx 1$  corresponds to random, noise-dominated phase.

In the 20–30 Hz band, phase variance decreases from 0.77 in the raw data to 0.70 after ground-roll removal and further to 0.66 after surface-consistent deconvolution, confirming progressive improvement in signal coherence where noise levels are low enough for correction operators to perform reliably. In contrast, in the 50–60 Hz band, phase variance increases after surface-consistent deconvolution, indicating growing phase instability. This behavior is diagnostic of noise amplification rather than signal recovery.

This contrast highlights how surface-consistent deconvolution interacts differently with signal- and noise-dominated frequency ranges. Where coherent signal dominates, waveform alignment improves and phase variance decreases. Where noise dominates, the same operation yields little phase stabilization and can degrade overall data quality. In this sense, surface-consistent processing broadens the spectrum in amplitude, but only part

## Prestack processing efficiency through phase

of that bandwidth remains phase-coherent and therefore useful for prestack analysis and imaging.

### Interpreting prestack data through phase

To convert qualitative bandpass observations into quantitative diagnostics, we require a measure sensitive to waveform coherence but insensitive to amplitude. Focusing on phase minimizes the influence of source strength, receiver coupling, and geometric spreading, leaving a direct measure of how consistently the wavefield behaves across a gather.

Figure 3 shows extracted phase as a function of offset at two representative frequencies, 7 and 30 Hz, across three processing stages. At 7 Hz (Figures 3a-c), pronounced phase excursions persist between offsets of approximately 10-15 kft across all processing steps ( $V = 0.86, 0.88, 0.87$ ), indicating unsuppressed coherent noise consistent with residual ground roll. While visual inspection suggests the presence of coherent noise, the phase representation makes its frequency localization explicit and unambiguous.

At 30 Hz (Figures 3d-f), phase behavior is markedly different. Phase excursions are largely absent, and stability improves progressively with processing, indicating effective suppression of coherent noise and improved waveform alignment. These contrasting behaviors motivate the need for a systematic, frequency-resolved metric that captures phase stability across the full bandwidth and offset range, rather than relying on isolated frequency snapshots.

### Quantifying phase variability across frequencies/offsets

To move from phase inspection to a fully interpretable quantitative diagnostic, we apply the phase variance measure of Rohatgi et al. (2025) over local ensembles of traces with comparable propagation paths. We use sufficiently large apertures to average over linear and crossing noise, aiming to assess overall prestack coherence rather than detect localized disturbances.

At 7 Hz, phase variance remains essentially unchanged across processing stages ( $V = 0.86, 0.88, 0.87$ ), indicating that processing has little effect where coherent noise dominates too strongly for correction operators to be effective. At 30 Hz, phase variance decreases progressively ( $V = 0.71 \rightarrow 0.72 \rightarrow 0.66$ ), confirming genuine improvement in phase coherence as processing advances.

Extending this analysis across all frequencies and offsets using a sliding window yields phase variance maps as a joint function of frequency and offset (Figure 4). These maps reveal that frequencies above approximately 40 Hz show little to no improvement even after full processing. This frequency-selective limitation is invisible to amplitude spectra and broadband visual QC but is clearly exposed by phase variance. The resulting maps provide a direct, actionable guide to where processing improves prestack coherence and where the data remain noise dominated.

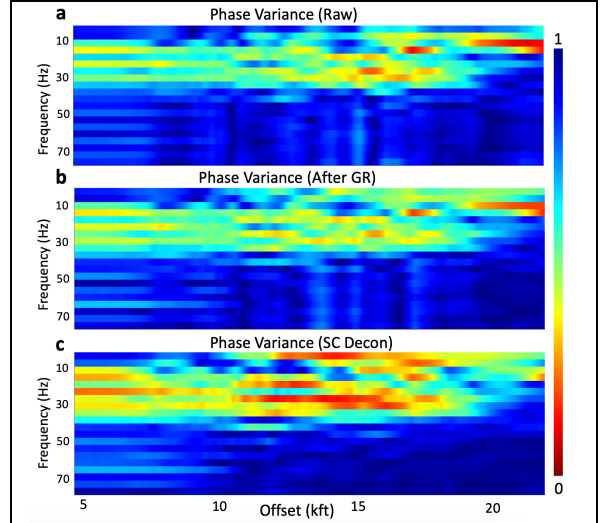


Figure 4. Phase variance maps versus frequency and offset for (a) raw data, (b) after ground-roll removal, and (c) after surface-consistent deconvolution.  $V \approx 1$  indicates high phase variability (noise-dominated), while  $V \approx 0$  indicates coherent signal. Processing improves phase coherence mainly in the 20–40 Hz band, while variance remains elevated above  $\sim 40$  Hz, revealing the frequency-dependent limits of processing performance.

### Conclusions

Processing quality in land seismic data, therefore, is inherently frequency dependent and cannot be captured by a single broadband metric. Phase variance provides a quantitative, amplitude-independent diagnostic of prestack waveform coherence as a function of frequency and offset, revealing processing behavior that conventional QC tools do not resolve. Phase-variance maps act as a practical KPI for processing optimization. They identify which frequency bands benefit from a given processing step, which remain unchanged, and where additional processing degrades coherence rather than improving it. When phase stability fails to increase with further processing, the metric flags bandwidth that is effectively unusable under the current workflow and indicates where alternative processing strategies or acquisition changes are required. By making frequency-dependent coherence measurable, phase variance places frequency-selective and octave-based processing decisions on a quantitative footing rather than heuristic judgment. In this way, the proposed phase-based QC closes a critical loop between acquisition, processing, and imaging, enabling focused improvement of usable bandwidth and more reliable assessment of processing fidelity at each step.

### Acknowledgments

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

## Prestack processing efficiency through phase

### References

Bakulin, A., I. Silvestrov, and M. Protasov, 2022, Signal-to-noise ratio computation for challenging land single-sensor seismic data: *Geophysical Prospecting*, 70, 629–638, <https://doi.org/10.1111/1365-2478.13178>.

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

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

Dean, T., J. Tulett, and R. Barnwell, 2018, Nodal land seismic acquisition: The next generation: *First Break*, 36, 47–52, <https://doi.org/10.3997/1365-2397.n0061>.

Mougenot, D., 2005, How digital sensors compare to geophones?: SEG Technical Program Expanded Abstracts, 23, 5–8, <https://doi.org/10.1190/1.1842413>.

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

Taner, M. T., and F. Koehler, 1981, Surface-consistent corrections: *Geophysics*, 46, 17–22, <https://doi.org/10.1190/1.1441133>.

Wiggins, R. A., K. L. Larner, and R. D. Wisecup, 1976, Residual statics analysis as a general linear inverse problem: *Geophysics*, 41, 922–938, <https://doi.org/10.1190/1.1440672>.