

Rolling Variable-Density Acquisition: A Targeted Solution to the Near-Offset Noise Cone

Andrey Bakulin, Independent Researcher, Austin, TX, USA

Summary

I present rolling variable-density acquisition as a practical response to one of the most persistent challenges in land seismic data: low prestack signal-to-noise ratio in the near-offset noise cone. In conventional rolling 3D geometries, these offsets are further disadvantaged by low trace density, compounding the problem and limiting the effectiveness of downstream processing and interpretation. Rather than increasing sampling uniformly, variable-density infill is introduced within the rolling framework to selectively reinforce near offsets while preserving the base geometry and operational efficiency. The amount and extent of densification are guided by measured, offset-dependent prestack signal-to-noise behavior, allowing acquisition effort to be applied where it has the greatest impact. The result is a variable-density dataset in which offsets that are most critical for processing are selectively densified, providing sufficient redundancy for effective prestack conditioning and enabling a near-flat prestack signal-to-noise ratio across offsets, rather than inheriting chronically low-SNR, low-density near-offset data. The near-offset noise cone is addressed directly, without uniform escalation of acquisition resources or departure from standard rolling survey practices.

Introduction

Modern land seismic acquisition has moved steadily toward denser spatial sampling, with increasingly tight receiver spacing, broader azimuths, and extended offsets becoming standard practice in high-end surveys (Meunier, 2011; Vermeer, 2012; AlMesaabi, 2021). These designs have proven effective for imaging and characterization, but their uniform application across large survey areas is increasingly difficult to justify in terms of cost and operational complexity.

A key question is whether this uniform densification is actually required everywhere. While fully dense 3D geometries remain essential for many objectives, a growing body of work shows that seismic data quality does not degrade uniformly with offset or position. Instead, limitations are localized and systematic, varying strongly with offset, reflecting predictable interactions between acquisition geometry, near-surface conditions, and wavefield characteristics (Bakulin et al., 2020, 2022; Rohatgi et al., 2025).

These observations motivate a more targeted acquisition strategy. Rather than increasing sampling density indiscriminately, effort can be focused where it has the greatest impact on data quality. In this paper, I explore rolling variable-density acquisition (RVDA), a concept that

preserves the operational simplicity of conventional rolling land surveys while selectively increasing sampling density only where it is needed. The rolling infill concept is illustrated schematically in Figure 1, emphasizing redistribution rather than uniform escalation of sampling. The goal is not to replace established geometries, but to augment them in a controlled, physics-driven manner that improves data quality without incurring the full cost of uniform infill.

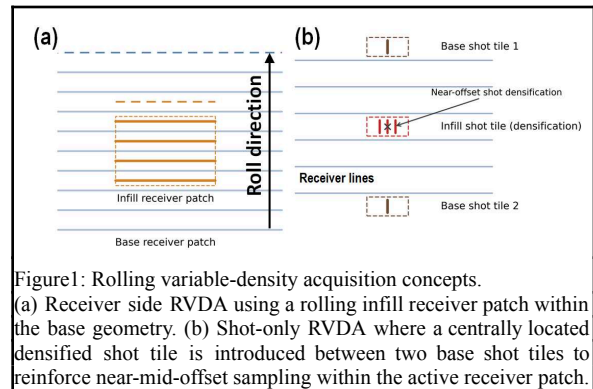


Figure 1: Rolling variable-density acquisition concepts. (a) Receiver side RVDA using a rolling infill receiver patch within the base geometry. (b) Shot-only RVDA where a centrally located densified shot tile is introduced between two base shot tiles to reinforce near-mid-offset sampling within the active receiver patch.

Distilling the problem

Modern full-azimuth land surveys routinely deliver high-quality images. However, data quality is not uniform across the offset spectrum. Near and intermediate offsets are often disproportionately affected by linear, offset-dependent noise in typical land settings, and this portion of the data frequently controls the performance of prestack imaging and characterization workflows.

When data quality is examined explicitly as a function of offset, the pattern is consistent. Signal-to-noise ratio degrades systematically at small offsets and remains deficient even after aggressive processing. This behavior is persistent and predictable, indicating that it reflects acquisition-level sampling effects rather than processing artifacts (Meunier, 2011; Bakulin and Silvestrov, 2023).

This imbalance has practical consequences. Weak near offsets limit the reliability of prestack inputs for time processing, velocity model building, reflection FWI, AVO analysis, and prestack inversion. While stacked images may appear robust, the underlying prestack information required for resolution, angular diversity, and quantitative interpretation is often compromised. Uniform densification can overcome the near-offset deficiency, but only by increasing sampling everywhere, requiring a large and

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inefficient escalation in acquisition effort to compensate for a highly localized weakness.

Conventional orthogonal geometries further reinforce this imbalance by producing a strongly offset-dependent trace-count distribution, as illustrated in Figure 4a (purple curve). The offsets most affected by linear noise are also those with the lowest trace density, compounding the limitation at the acquisition stage. This observation motivates a targeted acquisition response that explicitly addresses offset-dependent weaknesses at the acquisition stage, rather than relying on additional uniform densification.

Acquisition parameters	Base acquisition	Infill modification
Live receiver patch	6 km × 6 km	Same as base
Roll grid	100 m × 100 m	Same as base
New-shot tile	100 m × 100 m	Same as base
Receiver spacing	10 m × 100 m	5 m × 50 m (within 2 km × 2 km window)
Receiver extent	full live patch	Centered 2 km × 2 km infill window
Shot pattern per tile	single salvo (10 m × 100 m)	two salvos (5 m × 50 m)
Shots per tile	10	40 (local)
Shot-tile activation	every roll	every 4th roll
Firing lattice (roll space)	Not applicable	2 × 2
CMP bin size	5 m × 5 m	Same as base

Table 1: Summary of acquisition parameters for the rolling variable-density acquisition (RVDA)

Rolling variable-density acquisition (RVDA): concept and reference implementation

Rolling variable-density acquisition (RVDA) addresses the offset-dependent imbalance identified above by selectively increasing sampling density only where it is most needed while preserving the operational structure of conventional rolling land acquisition. The concept is illustrated schematically and then demonstrated using the reference implementation summarized in Table 1.

RVDA redistributes acquisition effort as the receiver spread rolls rather than uniformly densifying the entire survey. A conventional live receiver patch forms the base geometry advancing across the survey area, while a smaller infill window introduces locally increased receiver and source sampling. The rolling receiver framework and the relationship between base and infill patches are illustrated in Figure 1a and 2a with acquisition parameters summarized in Table 1. The base and infill components roll

together so that all locations are sampled by both configurations without requiring uniformly dense coverage. In the reference implementation evaluated here, densification combines receiver infill with periodic source densification. Within the infill window, additional receiver lines increase local spatial sampling (Figure 2a), while a centrally located infill shot tile introduces denser shot sampling with reduced spacing (Figure 2b). The shot layout and densification pattern are illustrated in Figure 2b, with acquisition parameters summarized in Table 1. Infill shots are activated periodically in roll space, concentrating source effort within the offset range of interest while limiting survey-level effort. This hybrid configuration (Figures 1a and 2) forms the reference implementation evaluated in the numerical experiments that follow.

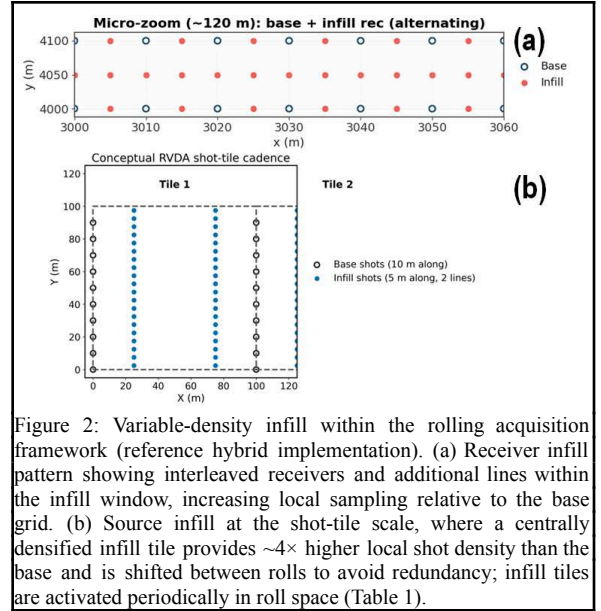


Figure 2: Variable-density infill within the rolling acquisition framework (reference hybrid implementation). (a) Receiver infill pattern showing interleaved receivers and additional lines within the infill window, increasing local sampling relative to the base grid. (b) Source infill at the shot-tile scale, where a centrally densified infill tile provides ~4× higher local shot density than the base and is shifted between rolls to avoid redundancy; infill tiles are activated periodically in roll space (Table 1).

RVDA can also be implemented using source densification alone (Figure 1b), a configuration particularly suited for deeper targets where the near-surface noise cone expands outward and suppresses prestack SNR over a broader offset range. In this configuration, base shot tiles extending above and below the receiver patch (Figure 1b) provide mid- and far-offset coverage, while a centrally located dense infill tile concentrates sampling in the near and mid offsets most affected by this expanded noise cone. In the example considered here, the base tiles contribute 20 shots while the infill tile adds 60 shots, producing a fourfold increase in shot density. Effective fold increases from roughly 1800 to about 7200 traces per CMP, corresponding to a ~7–8× increase in trace density within the 0–3.5 km offset range, while leaving longer offsets largely unchanged and extending coverage to ~6.5 km. This targeted redistribution boosts sampling where needed while preserving the offset

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range required for deeper targets, delivering a comparable prestack SNR uplift of roughly 7–8 dB.

Assessing RVDA: sampling, resources, and fold

From a sampling and resource perspective, RVDA represents a controlled escalation relative to a conventional rolling geometry. As summarized in Table 2, the reference base acquisition deploys approximately 36,000 live receivers. RVDA increases this to approximately 48,000 live receivers, corresponding to about a 30% increase. This increase is achieved by selectively densifying receivers within a limited infill window that rolls with the base patch, rather than by tightening spacing uniformly across the entire spread.

Source effort is increased in a similarly bounded manner. Within the infill window, shot density is locally increased, but infill shot tiles are activated only once every four rolls, following a 2×2 firing lattice in roll space (Table 1). As a result, although local shot density is higher when the infill tile is active, the survey-level effective source effort increases by only a factor of two. By contrast, uniform densification requires a fourfold increase in both receivers and source effort across the entire survey area (Table 2). RVDA therefore reinforces near offsets through an explicitly defined activation mechanism rather than uniform escalation of acquisition resources.

Crucially, this targeted densification does not compromise illumination. Figure 3 shows that RVDA preserves the broad, well-distributed wide-azimuth coverage of the base geometry, while substantially increasing trace density at near and intermediate offsets. The azimuthal character of the survey remains essentially unchanged, but the offsets most affected by linear noise benefit from higher redundancy. This combination, preserving what already works while selectively strengthening what does not, is central to the RVDA concept.

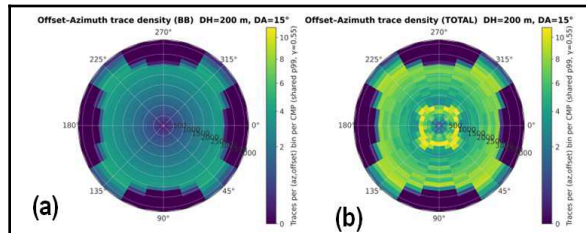


Figure 3. Offset-azimuth trace-density distribution for the baseline geometry (a) and RVDA (b). Both geometries exhibit broad, well-distributed azimuthal coverage. Relative to the baseline, RVDA substantially increases trace density at near and intermediate offsets, while producing a much smaller change at far offsets, indicating that densification is concentrated where it is most needed without altering the overall azimuthal character.

The analysis above establishes that RVDA delivers targeted densification at manageable cost while maintaining

wide-azimuth integrity. The next step is to quantify whether this redistribution of sampling translates into a measurable improvement in prestack signal-to-noise ratio, particularly within the near-offset noise cone. However, fold alone does not quantify whether this redistribution actually delivers the intended prestack SNR improvement analysis that follows.

Linking acquisition design to prestack SNR performance

The final step is to link the geometry-driven densification in Figure 4 to expected prestack SNR behavior. Figure 5 (black curve) shows a representative prestack SNR versus offset trend observed in land seismic data, characterized by a near-offset deficit associated with the near-surface noise cone. SNR is systematically depressed at small offsets and improves toward mid and far offsets as near-surface noise influence diminishes. This behavior is persistent and well documented, and although processing can raise SNR broadly, it does not eliminate the near- to far-offset imbalance (Bakulin et al., 2022; Rohatgi et al., 2025).

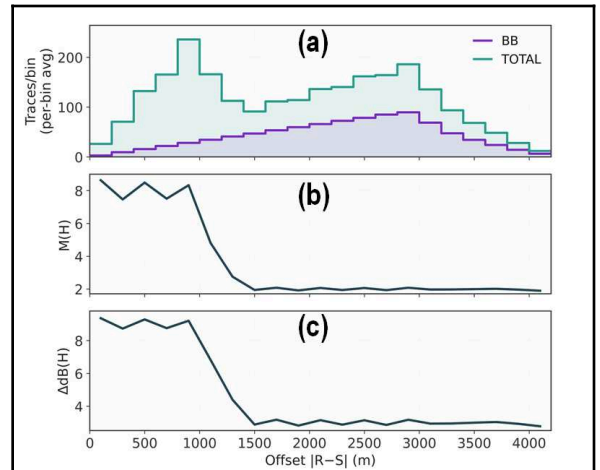


Figure 4. Geometry-driven densification where it matters most. (a) Average trace count per CMP bin versus offset for the baseline geometry and RVDA, using 200 m offset bins. (b) Offset-by-offset ratio of RVDA to baseline trace density, highlighting where additional sampling is introduced. (c) Corresponding offset-dependent prestack SNR uplift, illustrating how targeted densification translates into improved conditioning at the offsets most affected by noise.

Design	Live receivers	Receiver s (x base)	VPs (x base, effective)	Fold (5×5 m CMP)
Base orthogonal (10 m × 100 m)	36,000	1.00	1.00	900
Uniform dense (5 m × 50 m)	144,000	4.00	4.00	14,400
RVDA (reference design)	48,000	1.33	2.00	2,400

Table 2: Resource requirements and effective fold for baseline, uniform densification, and RVDA

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Figure 4 provides the quantitative link between acquisition geometry and offset-dependent SNR. Figure 4a shows offset-dependent trace density for the baseline and RVDA geometries, while Figure 4b expresses their ratio, here denoted $M(H)$, highlighting where densification is introduced. Figure 4c is obtained by converting this ratio into prestack SNR uplift using a signal-strength estimate (SSE) framework, showing that the gain is concentrated in the near and mid offsets where the noise cone dominates.

To quantify this transformation, I apply the SSE framework in offset bins (Meunier, 2011; Bakulin and Silvestrov, 2023). For each offset bin H_i ,

$$M(H_i) = \frac{N_{TOT}(H_i)}{N_{BB}(H_i)},$$

where N_{BB} and N_{TOT} are the trace counts per CMP bin for the baseline and RVDA geometries (Figure 4a). Under standard SSE assumptions that signal is coherent while noise is at least partially uncorrelated (Meunier, 2011), the corresponding prestack SNR uplift is given by

$$\Delta SNR(H_i) = 10 \log_{10}[M(H_i)],$$

which directly yields the curve shown in Figure 4c.

In this example, I isolate the effect of trace density by holding all other acquisition and processing parameters fixed, so that geometry-driven variations translate into additive prestack SNR uplift in decibel space. Applying $\Delta SNR(H_i)$ to the baseline SNR trend in Figure 5 yields the predicted RVDA response (purple), isolating the contribution of targeted densification.

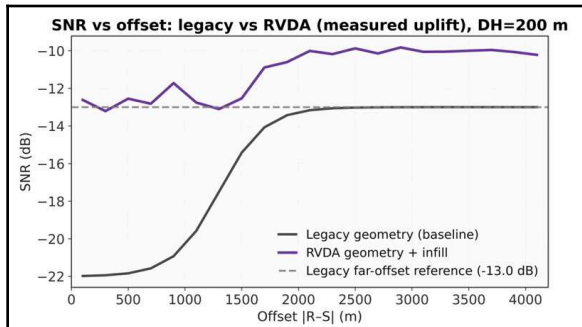


Figure 5. Representative prestack SNR versus offset for a conventional rolling geometry (black) and the corresponding RVDA reference (hybrid receiver-source infill) prediction (purple). The baseline exhibits a pronounced near-offset SNR deficit associated with the near-surface noise cone, while RVDA selectively raises near-offset SNR toward the far-offset reference without materially altering far-offset behavior. The RVDA curve is obtained by applying the geometry-driven uplift from Figure 4c to the baseline SNR trend under stacking-equivalent assumptions.

The resulting behavior highlights the central design outcome. RVDA raises near-offset SNR toward the

far-offset reference while leaving far offsets largely unchanged (Figure 5). Rather than uniformly densifying, RVDA conditions the dataset by lifting its weakest portion, improving suitability for prestack applications such as reflection FWI, AVO, and quantitative interpretation.

This framework also enables controlled design iteration. Infill density controls uplift magnitude, while infill window size, placement, and firing cadence control the offset range of transition. These parameters are evaluated using the same geometry diagnostics (Figure 4), providing a quantitative stopping criterion while preserving rolling acquisition efficiency.

Conclusions

Rolling variable-density acquisition provides a practical, data-driven approach to correcting a fundamental imbalance in conventional land seismic designs. By using offset-dependent diagnostics to guide acquisition effort, RVDA selectively reinforces near-offset sampling while preserving the wide-azimuth and long-offset characteristics of a conventional rolling geometry. In the reference hybrid implementation presented here, effective fold increases locally where it is needed, bringing near-offset prestack SNR into balance with far offsets without incurring the cost and complexity of uniform densification. The result is a more uniformly conditioned prestack dataset, better suited for early-arrival conditioning, shallow imaging, and AVO-driven interpretation.

More broadly, RVDA should be viewed not as a fixed geometry but as a flexible, diagnostics-driven framework. The examples shown here are conceptual demonstrations, including a reference hybrid implementation and a source-only variant, and would be adapted in practice based on survey economics, terrain, and operational constraints. Densification may be implemented through receivers, sources, or a combination of both, with activation cadence and infill extent tailored to site-specific noise behavior. This enables a shift from geometry-driven design toward closed-loop optimization, where acquisition is adjusted quantitatively to meet explicit prestack SNR targets. The result is a more efficient, purpose-built acquisition strategy that delivers required data quality without unnecessary escalation of resources.

RVDA therefore reframes acquisition design as a targeted conditioning problem rather than a uniform sampling problem. Instead of increasing density everywhere, acquisition effort is directed where the data are weakest, using measurable diagnostics to define both magnitude and extent of densification. This distinction is central: it separates RVDA from conventional densification approaches and establishes a practical pathway toward scalable, cost-effective land acquisition designs.

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