

Data-driven SNR and repeatability assessment of submarine DAS for monitoring and characterization

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Summary

Submarine distributed acoustic sensing (DAS) offers unprecedented spatial aperture for offshore characterization and monitoring, yet its performance as a receiver remains largely unquantified. We present a data-driven assessment of signal-to-noise ratio (SNR) and repeatability for a shallow-water telecommunication DAS cable using teleseismic earthquake energy as an analog of an active seismic signal. Despite being dominated by ocean-wave noise, accounting for more than 90 percent of the recorded energy, dense DAS sampling enables effective wavefield separation and noise suppression. Data-driven SNR estimates reveal initial signal levels as low as -30 dB, which can be improved by up to ~ 40 dB through simple FK-based processing, yielding repeatability levels suitable for monitoring. Spatial variations in SNR and repeatability are strongly modulated by seabed stiffness, with softer sediments exhibiting elevated noise amplification. By linking SNR and repeatability through unbiased, data-driven diagnostics, this study provides a practical framework for qualifying submarine DAS for amplitude-based characterization and monitoring under realistic offshore noise conditions.

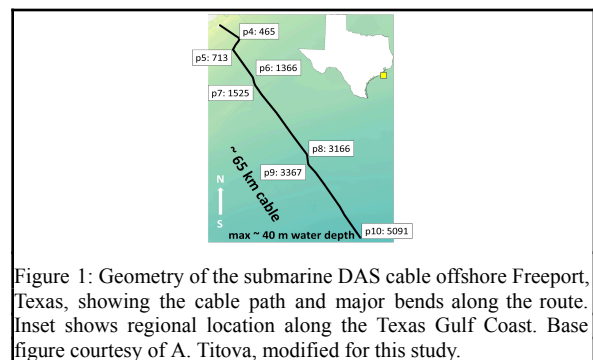
Introduction

Distributed acoustic sensing (DAS) is rapidly expanding across geophysical applications, spanning both subsurface characterization and long-term monitoring. Existing submarine DAS studies, however, have largely focused on specific observational modes rather than systematic evaluation of receiver performance. Passive deployments have emphasized oceanographic and seabed wavefield studies using ambient noise (e.g., Williams et al., 2019; Cheng et al., 2021; Spica et al., 2020), while active-source experiments have demonstrated the feasibility of using DAS as a seabed array for airgun imaging (Raknes et al., 2025). Although these studies establish submarine DAS as a large-aperture receiver system, they do not quantitatively assess prestack signal-to-noise ratio (SNR), or repeatability.

As a receiver technology, DAS differs fundamentally from conventional geophones. Its effective sensitivity depends strongly on coupling, seabed properties, orientation, and environmental noise, making objective performance qualification essential. Yet, unlike land and marine seismic receivers, submarine DAS has not been systematically evaluated using data-driven metrics. As a result, key questions remain unresolved: what SNR levels are achievable, how much processing gain can be realized, how repeatable the measurements can be made, and whether

amplitude information can be trusted for monitoring applications.

The novelty of this study is the application of data-driven diagnostics, originally developed for land seismic data, to quantitatively evaluate submarine DAS as a receiver array, with explicit emphasis on amplitude fidelity and repeatability rather than event detection alone. While individual channels or stacked subsets can be made to look clean, such views mask the spatial variability that ultimately governs monitoring performance; here, all diagnostics are computed over the full array to capture that variability. Using large-volume field data from an offshore telecommunication cable, we estimate SNR and repeatability in a fully data-driven manner following the framework of Bakulin et al. (2022, 2024, 2025). This approach moves beyond qualitative observations by systematically quantifying array performance, processing effectiveness, and achievable monitoring-relevant amplitude behavior along the entire cable. By treating a teleseismic earthquake as an analog of an active seismic signal, we establish objective benchmarks for signal detectability, processing gain, and repeatability under realistic shallow-water noise conditions, enabling direct comparison with established land and marine seismic practice and providing a consistent basis for qualifying submarine DAS for characterization and monitoring tasks.



Telecommunication DAS, Texas Coast Field Test

This study uses field data from an offshore telecommunication DAS system in shallow water along the Texas Gulf Coast (Figure 1). A trenched submarine fiber-optic cable was connected to a DAS interrogator, providing continuous strain measurements along approximately 65 km of cable, extending from the shoreline to a maximum water depth of about 40 m. Water

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depth increases gradually offshore, placing the system entirely within a shallow-water coastal setting. Data were acquired on existing telecommunication infrastructure; the authors thank project partners for access. The DAS acquisition employs a channel spacing of 12.76 m with a gauge length approximately twice that value, forming a densely sampled, large-aperture seabed array. No active seismic sources are used. Instead, teleseismic earthquake recordings serve as an analog signal for evaluating DAS receiver performance under realistic noise conditions. We analyze an Mw 7.8 teleseismic earthquake originating in the Kamchatka region. The wavefield propagates approximately parallel to the cable with an apparent velocity of about 3.5 km/s, producing a laterally coherent arrival along the array whose kinematics and arrival times are consistent with regional broadband seismic observations. Kinematically, this event is analogous to high-apparent-velocity signal energy observed in reflection seismic data and provides a well-defined target for receiver-centric performance evaluation. In the analysis that follows, the teleseismic wavefield is treated as the target signal, while all remaining ocean-induced energy, is treated as noise, enabling a controlled, data-driven evaluation of signal separation, noise suppression, and signal-to-noise ratio across the full DAS array.

Data description and signal–noise separation

The recorded DAS dataset is dominated by strong, spatially coherent low-frequency energy associated with ocean gravity waves and Scholte waves, which account for the majority of the recorded energy (Bakulin et al., 2026). Figure 2a shows the full cable record comprising 5,091 DAS channels over approximately 3,500 s. Against this background, the teleseismic earthquake signal is present but heavily obscured and exhibits highly variable visibility along the cable.

Rather than dissecting individual noise modes, we treat all non-earthquake energy as noise and the teleseismic arrivals as an analog of reflection-seismic signal. We apply a two-stage FK workflow, analogous to linear noise attenuation in seismic processing, to remove (1) ocean-gravity-wave energy (~ 10 m/s) concentrated in 0.1–0.3 Hz and (2) Scholte-wave energy (~ 500 m/s) associated with ocean wave breaking (Francoeur et al., 2025) concentrated in 0.3–3 Hz. The teleseismic signal is broadband with a dominant frequency near 0.08 Hz, so signal and noise overlap in frequency and collide in the record. The two FK passes exploit moveout differences to separate the teleseismic wavefield, removing >95% of total recorded energy. This separation yields a noise component dominated by ocean-related energy, shown in Figure 2b, and a signal component containing the teleseismic wavefield, including the Rayleigh wave and weaker phases, shown in Figure 2c. Despite the $\sim 10,000$ km source

distance and expected lateral amplitude uniformity, the extracted signal varies strongly along the cable, indicating control by local noise conditions and coupling rather than source effects. The dataset therefore provides a stringent test for data-driven DAS receiver evaluation. Although operating at lower frequencies than land seismic data, the workflow parallels standard seismic noise-attenuation practice adapted to the shallow-water submarine environment and underpins the quantitative SNR and repeatability analysis.

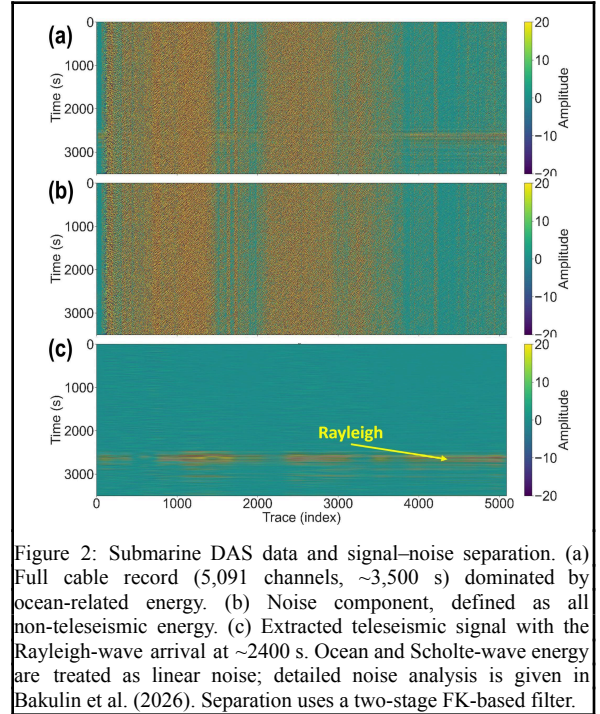


Figure 2: Submarine DAS data and signal–noise separation. (a) Full cable record (5,091 channels, $\sim 3,500$ s) dominated by ocean-related energy. (b) Noise component, defined as all non-teleseismic energy. (c) Extracted teleseismic signal with the Rayleigh-wave arrival at ~ 2400 s. Ocean and Scholte-wave energy are treated as linear noise; detailed noise analysis is given in Bakulin et al. (2026). Separation uses a two-stage FK-based filter.

Data-driven estimation of SNR and repeatability

To quantify signal strength in a fully data-driven manner, we compare two independent SNR estimation approaches. The first is a stacking-based method that estimates signal through local spatial stacking and treats residual energy as noise (Bakulin et al., 2022), making it well suited for receiver-centric assessment when the true signal is unknown. The second is a direct method in which SNR is computed from FK-separated signal and noise components. Both methods use local spatial windows of 101 traces and temporal windows of 51 samples (approximately 12.2 s). Following Bakulin et al. (2022), the windows track the locally coherent signal moveout rather than assuming horizontally aligned events. The resulting SNR estimates are shown in Figures 3a and 3b, with corresponding normalized RMS (NRMS) repeatability in Figure 3c. NRMS is computed in the same windows by evaluating pairwise NRMS between all channel pairs within each

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101-trace window and reporting the mean value (Bakulin et al., 2025). Despite their different assumptions and supports, the two SNR estimates show strong agreement. Although the FK-based approach operates with global support across the full record and aperture, while the stacking-based estimate relies only on local windows, both preferentially enhance laterally coherent, low-wavenumber energy and suppress incoherent noise.

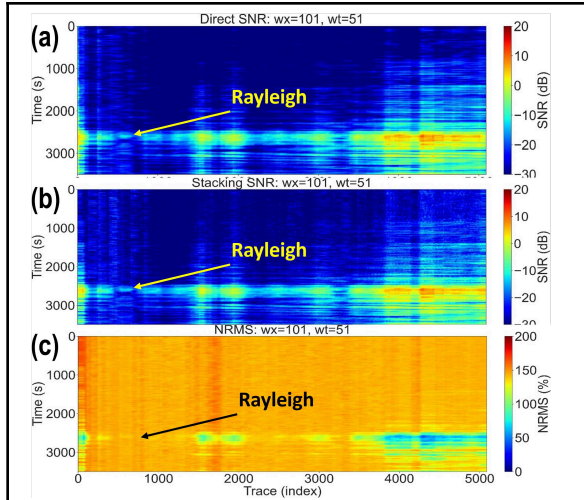


Figure 3: Data-driven SNR and repeatability estimates for the submarine DAS dataset. (a) Direct SNR estimate obtained from FK-separated signal and noise components. (b) Stacking-based SNR estimate computed using local spatial stacking as a proxy for signal estimation. (c) Corresponding NRMS estimate. All metrics are computed using spatial windows of 101 traces and temporal windows of 51 samples. The two SNR estimates show strong consistency despite their different assumptions and supports, revealing large spatial variability in signal quality along the cable, particularly for the Rayleigh-wave arrival.

The pre-attenuation SNR maps show uniformly low signal levels across the array. Early teleseismic phases are consistently below -30 dB. Even the dominant Rayleigh wave remains weak: only the best-performing cable segments reach marginally positive SNR of about 0 – 7 dB, while over most of the array the Rayleigh-wave SNR averages between -10 and -20 dB. Because the source is distant and propagates nearly parallel to the cable, the signal itself should be laterally uniform, indicating that the observed variability is controlled by local noise conditions and coupling rather than source effects. In terms of SNR, the pre-attenuation DAS data closely resemble land seismic pre-stack data prior to noise removal. The strong agreement between direct and stacking-based SNR estimates independently validates the stacking-based approach as a robust, fully data-driven metric. SNR also shows a systematic correspondence with NRMS repeatability (Bakulin et al., 2025), with higher SNR consistently associated with lower NRMS. Together, these measures

establish a quantitative baseline for assessing processing effectiveness and monitoring feasibility.

Assessing processing effectiveness and monitoring limits

Starting from the low-SNR baseline, reapplying the stacking-based SNR and NRMS analysis after noise attenuation reveals a clear improvement in both signal detectability and repeatability (Figures 4a,b). SNR shifts predominantly into positive values within the Rayleigh-wave window, while NRMS decreases substantially, indicating improved consistency between neighboring channels. At the same time, residual spatial variability and striping persist, demonstrating that noise cannot be perfectly removed and repeatability cannot be made uniform along the array. The magnitude and spatial structure of these gains are quantified by the one-dimensional extractions in Figure 5. Noise attenuation increases SNR locally by up to 35 – 40 dB, lifting signal levels from well below -20 dB into positive values, with corresponding reductions in NRMS. These improvements are strongly non-uniform, ranging from about 20 dB to more than 35 dB along the cable. Rather than representing a limitation, this variability provides a quantitative diagnostic of processing effectiveness and defines realistic bounds on achievable monitoring performance under the prevailing noise conditions.

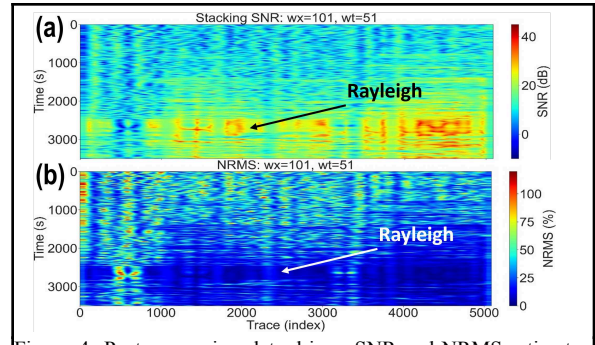


Figure 4: Post-processing data-driven SNR and NRMS estimates after noise attenuation. (a) Stacking-based SNR computed from the signal-enhanced data, showing a substantial increase in detectability of the Rayleigh-wave arrival relative to the raw data. (b) Corresponding NRMS estimate, indicating improved repeatability between neighboring channels. Although overall signal quality improves markedly, residual spatial variability and striping remain, providing a quantitative measure of the limits of noise separation and repeatability enhancement.

SNR–repeatability relationship for monitoring

SNR and NRMS provide complementary measures of signal detectability and repeatability. Their relationship, noted in earlier monitoring studies (e.g., Pevzner et al., 2011; van Gestel et al., 2015), was formalized by Bakulin et al. (2024, 2025) through a theoretical SNR–NRMS curve derived under Gaussian noise assumptions. We evaluate this relationship for submarine DAS by cross-plotting SNR

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and NRMS values from the full dataset before and after noise attenuation.

Prior to noise removal, most measurements cluster at high NRMS values near 150%, consistent with largely uncorrelated records and very low SNR (Figure 6a). After noise attenuation, the distribution shifts along the theoretical SNR–NRMS trend toward higher SNR and lower NRMS (Figure 6b). Most measurements cluster near ~25% NRMS and above ~12 dB SNR, defining a regime where repeatability becomes sufficient to detect subtle amplitude variations relevant for monitoring.

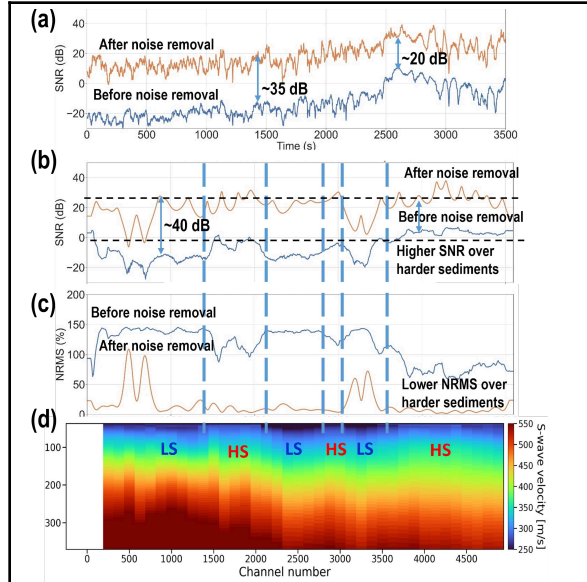


Figure 5. One-dimensional extractions illustrating the impact of noise attenuation on SNR and repeatability. (a) Vertical extraction of stacking-based SNR at channel index 4300, shown before and after noise removal. (b) Horizontal extraction of stacking-based SNR along the Rayleigh-wave arrival at approximately 2640 s. (c) Corresponding horizontal extraction of NRMS along the same time slice. Noise attenuation increases SNR locally by up to ~35–40 dB with corresponding reductions in NRMS, but the improvement is strongly spatially variable, ranging from ~20 dB to >35 dB along the cable. (d) Shear-wave velocity (V_s) model from Scholte-wave inversion (Bakulin et al., 2026), where LS and HS denote low- and high-stiffness seabed segments. Zones of lower SNR and higher NRMS coincide with LS regions, while HS segments exhibit higher SNR and improved repeatability, highlighting the control of seabed stiffness on effective signal quality.

Despite the expectation of laterally uniform teleseismic signal amplitude, substantial spatial variability in SNR and NRMS persists along the cable. Comparison with the shear-wave velocity model (Figure 5d) shows that zones of lower SNR and higher NRMS coincide with softer seabed sediments, while the highest SNR and lowest NRMS occur in stiffer segments. This indicates that seabed stiffness strongly modulates ambient and wave-generated noise,

fundamentally controlling effective signal quality and repeatability. These observations underscore the importance of explicitly accounting for seabed properties when evaluating submarine DAS for amplitude-based characterization and monitoring.

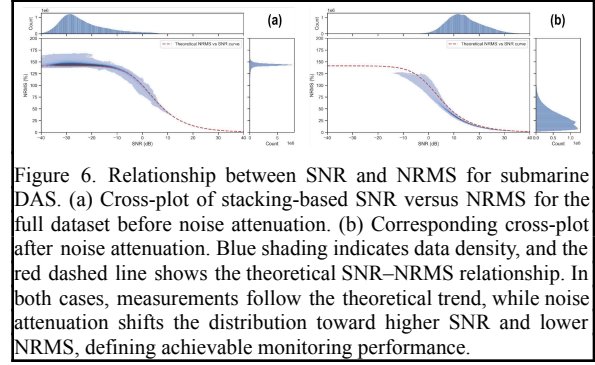


Figure 6. Relationship between SNR and NRMS for submarine DAS. (a) Cross-plot of stacking-based SNR versus NRMS for the full dataset before noise attenuation. (b) Corresponding cross-plot after noise attenuation. Blue shading indicates data density, and the red dashed line shows the theoretical SNR–NRMS relationship. In both cases, measurements follow the theoretical trend, while noise attenuation shifts the distribution toward higher SNR and lower NRMS, defining achievable monitoring performance.

Conclusions

We present a data-driven assessment of signal-to-noise ratio and repeatability for a submarine DAS telecommunication cable, using a teleseismic earthquake as a kinematic and SNR analog of high-apparent-velocity pre-stack reflection signal encountered in land and marine seismic, where detectability and repeatability govern imaging and monitoring performance. To our knowledge, this is among the first studies to jointly quantify detectability and repeatability of submarine DAS under realistic shallow-water noise conditions. Stacking-based SNR estimation provides stable, fully data-driven estimates down to very low levels, reaching below -30 dB. These results are independently validated using direct SNR estimates derived from FK-separated signal and noise components. The dense spatial sampling and large DAS aperture enable effective separation of dominant ocean-related noise, yielding SNR improvements of up to ~40 dB through simple FK-based processing. By coupling SNR with ensemble-based NRMS repeatability estimates, we establish a quantitative link between signal detectability and monitoring performance. The observed SNR–NRMS relationship closely follows the theoretical trend derived previously, providing an objective basis for defining repeatability thresholds and assessing monitoring feasibility prior to active-source acquisition or time-lapse deployment. We further observe strong spatial variability in SNR and repeatability along the cable that correlates with seabed stiffness. Softer sediments exhibit enhanced noise modulation and reduced repeatability, while stiffer seabed segments show higher effective SNR and improved repeatability. These findings highlight the role of seabed properties in controlling submarine DAS performance and the need to account for coupling and sediment stiffness when designing and evaluating DAS-based characterization and monitoring systems.

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