Exploring the real-world performance of recent advanced seismic sources

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Summary

The environmental impact of air-gun sources has long been debated, with a growing focus on reducing unnecessary high-frequency emissions that provide no imaging benefits. These redundant frequencies contribute to the overall sound footprint of seismic operations, prompting efforts to develop sources that minimize environmental impact while maintaining data quality fit for a survey's objective. This is particularly relevant in regions with stringent environmental regulations, such as Brazil, where reducing high-frequency emissions can help facilitate permitting and regulatory compliance.

Seismic source selection is influenced by several factors, including survey objectives, geological conditions, and environmental considerations. Recent advancements in source technology have led to the development of bandwidth-controlled airguns, low-frequency-rich broadband sources, and marine vibrators, all of which aim to optimize seismic output while minimizing unnecessary sound emissions.

These innovations bring the industry closer to achieving the ideal seismic source - one that delivers only the necessary energy for high-quality imaging without excessive and unused out of band sound emissions. In this paper we are showcasing how some recent technological improvements perform in real-world applications and whether they effectively balance imaging requirements with environmental responsibility.

Introduction

The environmental impact of air-gun sources has been a topic of debate for many years. While some concerns may be overstated, it is widely accepted that high-frequency emissions outside the seismic bandwidth offer no benefit to imaging or attribute inversion, although the desired bandwidth's upper limit varies by region and target. These unwanted high frequencies are primarily caused by the rapid, abrupt release of air, which generates a seismic pulse with a steep rising edge. As a rule of thumb, the steeper the rise, the more high frequencies are present.

In line with industry-wide ESG (Environmental, Social, and Governance) goals to reduce the environmental footprint of seismic exploration, there is an ever-growing focus on minimizing unnecessary sound emissions. Reducing the source sound footprint of seismic operations not just aligns with broader sustainability objectives but also helps to address increasing regulatory and societal pressure to operate responsibly in sensitive marine environments. This is especially relevant in regions like Brazil, where strict environmental regulations govern source emissions. Here, reducing unnecessary high-frequency output could aid in obtaining source permits in environmentally sensitive areas, enabling operators to comply with local requirements while maintaining the high-quality imaging necessary for exploration and development projects.

The selection of a seismic source for a survey involves several critical considerations to ensure the acquisition of fit-for-purpose data. The survey's primary objective plays a key role in defining the required data quality, while geological and environmental conditions, such as subsurface complexity and marine life sensitivity, influence the choice of source characteristics. High-frequency sources provide better resolution for shallow targets, while low-frequency sources are better suited for imaging deeper structures. Source directivity and repeatability are also vital for consistent and reliable data acquisition, particularly for time-lapse (4D) surveys. Additionally, operational and regulatory constraints, including equipment availability, logistical challenges, and environmental permits, shape the source configuration to meet both technical and compliance requirements.

The ideal seismic source would precisely emit the energy required to meet the survey objectives, without generating any excess or unnecessary output.

Recent advancements in source technology have brought the industry closer to achieving the ideal seismic sources capable of delivering targeted energy output tailored to specific survey objectives. Bandwidth-controlled airguns were first introduced in 2014 in the form of eSources and followed in 2021 by BluePulse sources (Coste et. al, 2014, and Tellier et. al, 2021). Both designs aim to mitigate high-frequency emissions by carefully controlling the air release and thus reducing spectral amplitude by up to 30 dB outside the conventional seismic bandwidth while preserving the frequencies and energy essential for seismic surveying. The Tuned Pulse Source (TPS) operates with lower pressure and larger volumes than conventional high-pressure pneumatic sources, enhancing low-frequency content to improve imaging of challenging subsurface targets while at the same time minimizing high-frequency output (Ronen and Chelminski, 2017). The TPS's output reduction compared to standard sources starts from about 7Hz. Another category of recent source advances are the low-frequency-rich broadband sources in the form of Gemini and Harmony, which achieve a reduction of the high out-of-band frequencies by releasing large volumes of air from significantly less number of firing heads compared to large conventional arrays (Udengaard et al., 2023, Rentsch et. al, 2022). Lastly, there are significant recent advances on marine vibrators, which are recognized as a promising alternative to traditional airgun sources, offering controlled sound emissions tailored to specific survey objectives (Jafargandomi et al., 2024 and Alfaro et al, 2023). With all these technological source advancements the question arises on how they translate into real-world seismic performance and data quality?

The Real-World Performance of Advanced Seismic Sources

The authors of this paper had the opportunity to gain firsthand experience with all the mentioned source types, with the exception of the TPS source. Our experiences are shared in this paper.

Bandwidth controlled sources

Multiple comparison tests have been conducted to evaluate image quality for bandwidth-controlled sources. The first published study, by Laws et al. in 2017, compared 2D lines acquired in a flip-flop test. In this test, the flip source was equipped with standard airguns, while the flop source used bandwidth-controlled eSource Type A, designed to suppress high frequencies, particularly above 120 Hz. The final migrated images from the two subsurface lines are presented in Figure 1. While minor differences between the images are observed, these can largely be attributed to variations in source positions due to the flip-flop acquisition method. Overall, the images are highly comparable, with similar event continuity and signal-to-noise ratios. Another comparison we were involved in was published in Cocker et al, 2023, showing the eSource full array of 2098cuin and a reduced size of 1049cuin eSource option both provide very similar final stack and migrated gather quality to the full standard source array (2480cuin). These studies and unpublished experiences give great confidence that the use of a bandwidth-controlled airgun array does not result in a geophysical tradeoff in conventional seismic surveying.

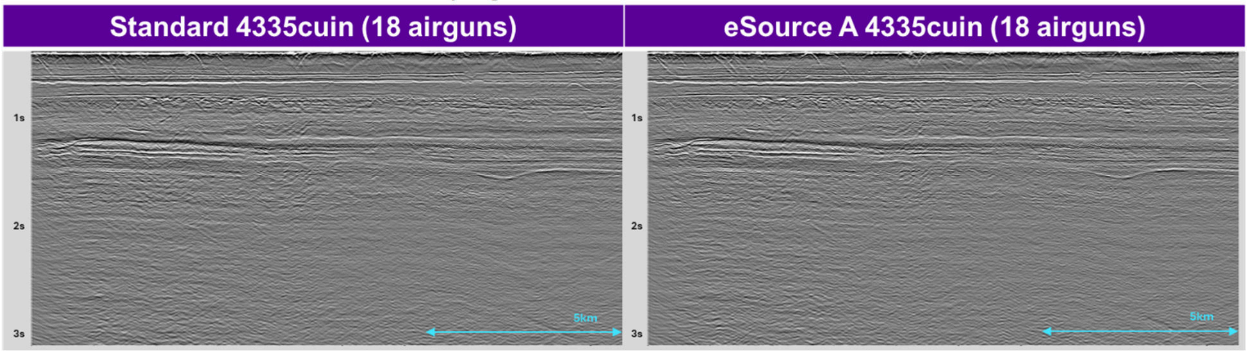

Figure 1 *2D Final migrated images (15km wide). Conventional left and the bandwidth-controlled source (of eSource type A)right.*

Low-frequency-rich sources

In regions affected by penetration challenges, such as the Kerala-Konkan basin, the continuity of base basalt and sub-basalt horizons in structurally complex geological formations poses significant interpretation challenges. Low-frequency (LF) seismic waves are advantageous as they penetrate deeper and enhance continuity. To assess the impact of LF-rich broadband sources in the sub-basalt, two 2D lines were acquired as part of a larger regional 2D survey. These lines followed the same path as the production 2D with a reasonable feather match, making it not a perfect experiment; however, other parameters remained consistent. Even when compared to a substantial production 2D source as a benchmark (5488 cubic inches, 32 elements), the single sub-array LF-rich broadband source (6000 cubic inches, 6 elements) exhibited improvements (Figure 2). Its performance in the post-basalt Tertiary was particularly intriguing, showing an equitable signal-to-noise ratio compared to the conventional source for higher frequencies.
Rentsch et al, 2024 showed further examples from other geological environments demonstrating the broadband imaging quality of low-frequency-rich broadband sources both in the shallow and the deep. The combined observations suggest that low-frequency-rich broadband sources are indeed suitable for broadband 3D surveys, where a single sub-array low-frequency-rich broadband source can match or even outperform the largest 3D sources deployable, compressor capacity notwithstanding, thus enabling multi-source (>2) designs. For 2D surveys, dual sub-array variants could also be considered. Thus this type of source can be considered an evolution over conventional source designs.

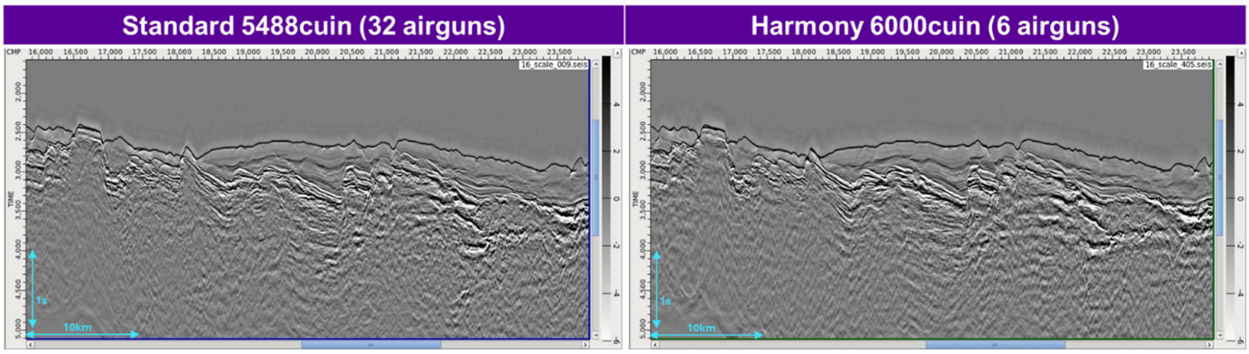

Figure 2 *2D Pre-stack time-migration images (50km wide). Conventional (left) and the low-frequency-rich broadband source (right).*

Marine vibrators

In 2023, a 3D survey using towed marine vibrators (MVs) was conducted over a field equipped with a permanent reservoir monitoring system in the North Sea. The survey had many objectives, however the one we focus on here is the comparability of a marine vibrator image to that of a 4D baseline shot with bandwidth-controlled airgun arrays. Processing details can be found in JafarGandomi et al, 2024. Figure 3 shows the comparison of a 2D slice from a 3D

PSDM volume for both sources. Again, we find the images essentially the same in both structural character and detail, and event continuity. The signal to noise ratio is slightly lower in the MV data set. as a single marine vibrator unit emits less energy than the legacy controlled bandwidth airgun source and additionally the MV data set experienced some seismic interference from a nearby survey.

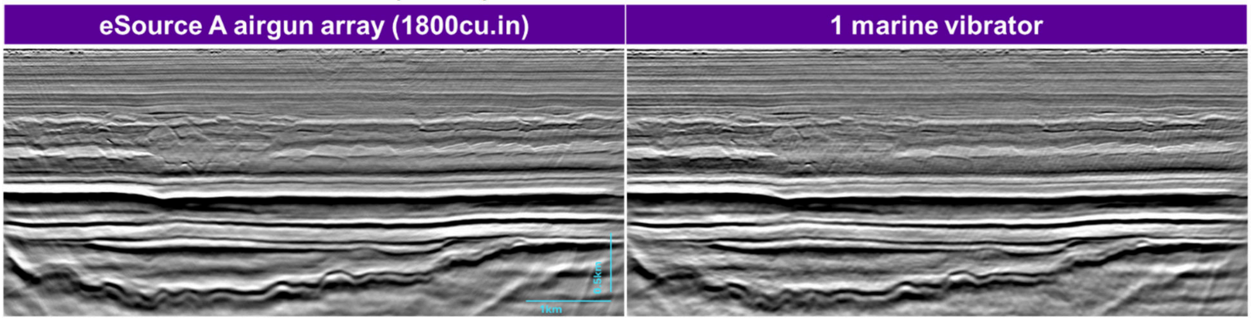

Figure 3 *A 2D vertical slice from a 3D PSDM volume (2.5km deep x12km wide), legacy airgun data on the left and marine vibrator data on the right.*

Conclusions

The seismic sources presented in this paper demonstrate strong performance within the seismic bandwidth, meeting essential criteria for source selection, including energy output, repeatability, and adaptability to diverse survey objectives. Recent advancements in source technology have not only enhanced seismic imaging capabilities but also enabled better control of high-frequency emissions that contribute to the overall sound footprint. By minimizing unnecessary high-frequency output, these innovations help address environmental concerns while maintaining the data quality required for exploration and reservoir characterization. This progress is particularly relevant in regions with stringent regulatory frameworks, where reducing high-frequency emissions can aid in obtaining permits and ensuring compliance with evolving industry standards. As the demand for both high-quality seismic data and environmentally responsible operations continues to grow, further refinements in source technology will play a key role in shaping the future of marine seismic exploration.

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