An enhanced frequency source for modern marine seismic surveys

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Summary

Many new marine seismic surveys are acquired with the intent for both FWI velocity model building and traditional imaging using the recorded reflection seismic data. To improve the results of FWI there is a desire to generate better signal to noise at lower frequencies. Several methods have been attempted to enhance lower frequency energy, for example using marine vibrators or tuning a standard air gun array with much larger guns in a specific manner. Most methods of generating lower frequency peak energy sacrifice mid and high frequency energy, limiting the potential uses of the acquired survey. The Gemini Enhanced Frequency Source is designed to generate more low frequency energy than conventional air gun arrays while maintaining energy in typical imaging frequencies. In this paper we demonstrate, via the use of both time and depth images, that data acquired with the enhanced frequency source are enhanced at the low end and comparable at higher frequencies relative to conventional marine source data.

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Introduction

Many new marine seismic surveys are acquired with the intent for both Full Waveform Inversion (FWI) velocity model building and traditional imaging using the recorded reflection seismic data. To improve the results of FWI there is a desire to generate better signal to noise at lower frequencies. Several methods have been attempted to enhance lower frequency energy, for example using marine vibrators (Dellinger et al, 2016; Tenghamn et al, 2022) or tuning a standard air gun array with much larger guns in a specific manner (Hopperstad et al, 2012). Most methods of generating lower frequency peak energy sacrifice mid and high frequency energy, limiting the potential uses of the acquired survey. The Gemini Enhanced Frequency Source (EFS) is designed to generate more low frequency energy than conventional air gun arrays while maintaining energy in typical imaging frequencies. In this paper we demonstrate, via the use of both time and depth images, that data acquired with the enhanced frequency source are enhanced at the low end and comparable at higher frequencies relative to conventional marine source data.

From the Rayleigh-Willis formulation (Willis, 1941) we know that increasing the chamber volume of an air gun source will lower the peak frequency of the source. The Gemini EFS source is a single large chamber air gun with fore and aft ports separated by approximately two meters, the examples in this paper are with an 8000 cubic inch chamber operated at 2000 psi. The peak frequency of the bubble is expected to be near 3.4 Hz. The source is designed to be directly compatible with existing source boats, without significant modifications of equipment on the vessels needed and maintaining safe operating pressures throughout the systems.

Method

We compare a standard air gun source and the enhanced frequency source using a collection of more than 500 nodes, spaced on a 1200 m by 1200 m grid, extracted from a field trial performed at the end of the Engagement 1 sparse node survey in the Gulf of Mexico, acquired in 2020. As a part of this test, long offsets exceeding 50 km were acquired using both sources. The data from both sources are used to compare their azimuthal and angular signatures, by examining wavelet frequency content, and through Reverse Time Migration (RTM) results. Both sources were equipped with near field hydrophones (NFH) to determine source signatures. Comparable source lines were acquired using both sources. The analysis of the data is limited to the hydrophone component. Minimal additional adaptive signal processing is applied to maintain fair comparisons, although varied source spacings and variable seismic interference from other nearby surveys remain in place.

Examples

Figure 1 shows collocated shot points from the two sources into a common node location. No wavelet processing has been applied to the data, so that the original recorded signatures remain untouched. The examples in Figure 1(a) and 1(c) show the near offset data out to 5 km offset. In Figures 1(b) and 1(d) the offset range is increased to 43 km to 52 km. These figures show even with a single gun long offset data can be recorded successfully. This dataset is useable for FWI purposes because both direct arrivals and diving waves are clearly observed with good signal to noise ratios. From the raw data in the short-offset window higher frequency reflection data can be clearly seen in the enhanced frequency source as well.

Observations

The enhanced frequency source is a single chamber source and thus can be treated as a point source. This significantly simplifies many processing steps as there is no angular or azimuthal variation of the source signature, other than standard source ghost effects. Figure 2 shows the extracted signatures of the reference and the enhanced frequency sources for shots with source take-off angle of 50 degrees and azimuths every 90 degrees. The signature of the point source is stable across all azimuths. More than that, the signature of the point source is consistent across all azimuths and take-off angles. An angularly isotropic source can significantly simplify many processing steps such as source designature and zero phasing, which become a 1-D operation. Moreover, a single wavelet can be used as the target wavelet for FWI workflow. Since no deviation from the vertical wavelet is assumed in other angles and azimuths, a reduction of noise and uncertainty in the inversion results is expected.

Figure 3(a) shows the amplitude spectra of the vertical source wavelets extracted from traces with less than 10 degrees of take-off angle. The enhanced frequency source shows a peak frequency around 3.5 Hz, compared to 7 Hz for the reference source. At low frequencies, the enhanced source generates more than 6 dB additional energy than standard arrays which improves the signal to noise at lower frequencies. In general, the amplitude spectrum remains relatively flat up to 45 Hz. The NFH data is also used to investigate the ultra-high frequency energy generated by the two sources. As demonstrated in Figure 3(b), at frequencies above 750 Hz, the enhanced frequency source produces 32 dB less amplitude than the reference source. This is a significant reduction in marine mammal impact. Additionally, the overall Sound Exposure Level (SEL) and Sound Pressure Level (SPL) are lower.

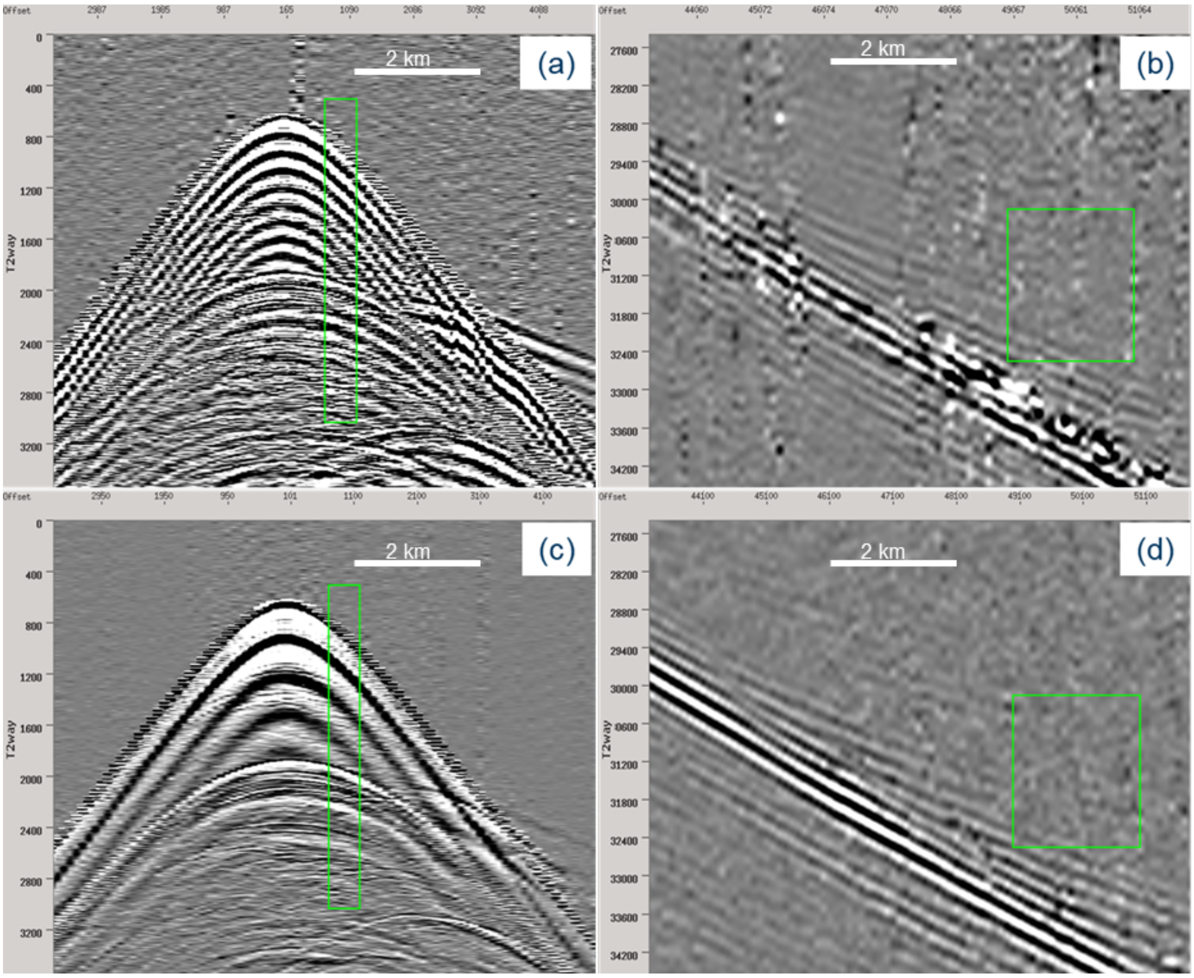

Figure 1 *Single OBN gather illustrating reference source near offset (a), long offset (b), and enhanced frequency source near offset (c) and long offset (d). The long offset displays show offsets from 43 km to 53 km.*

RTM images were generated from both data volumes, using the same FWI derived velocity model, after applying source designature and debubble. To improve the signal to noise ratio (S/N) of the reference source, 3 adjacent source lines are combined to create a single source line with 50 m interval to match the spacing of the enhanced frequency source. As illustrated in Figure 4(a) and 4(b), for a 45 Hz RTM image there is no loss of signal with the enhanced frequency source. Figures 4(c) and 4(d) compare both amplitude and coherency of the enhanced frequency source against the reference source after application of a 5 Hz low pass filter to RTM input. The improvement of S/N in the low frequency band can be considered as supporting evidence for the improvements in FWI expected from the enhanced frequency source.

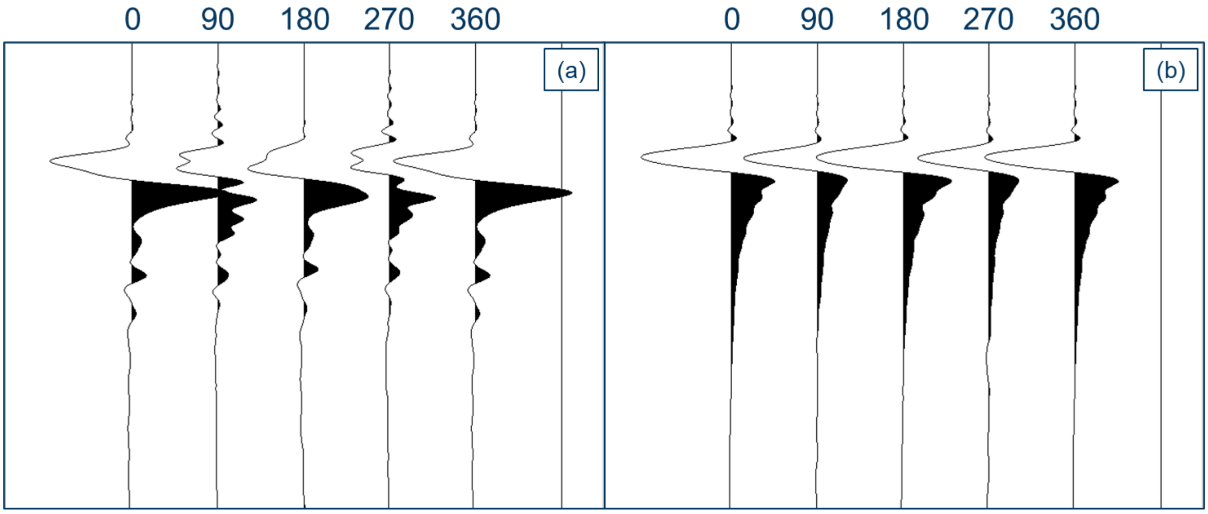

Figure 2 *Source signatures extracted from node data at 50 degree take-off angle. Source to receiver azimuth, relative to source vessel direction, is shown above the wavelets. Notice the variability in source signature on the reference source (a), and the stability of the source signature on the enhanced frequency source (b).*

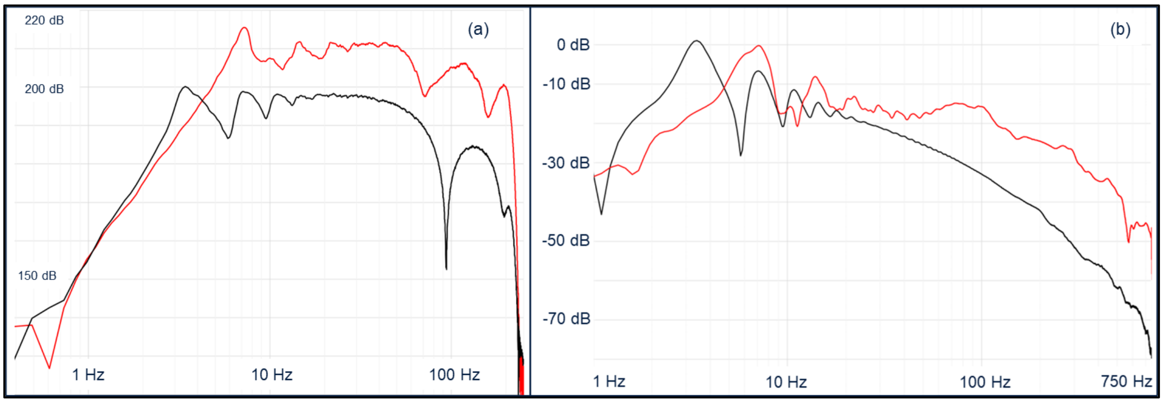

Figure 3 *Amplitude spectra of the vertical source wavelets from the reference source (red), and the enhanced frequency source (black). (a) Spectra from wavelets extracted from the node data, where we can see significantly more low frequency energy from the enhanced frequency source, and a relatively flat spectrum up to about 45 Hz. (b) Signatures extracted from NFH data, showing significant reduction in amplitude above 200 Hz of the enhanced frequency source.*

Conclusions

The enhanced frequency source satisfies many current and future requirements of marine acquisition and imaging: generating more low frequency energy with better signal to noise ratio; maintaining typical imaging frequencies; and significantly reducing ultra-high frequencies, which reduces the impact on marine mammals. This source will improve both FWI and imaging of the subsurface, while reducing the impact on the environment and marine life. The source is a point source, which is beneficial to many processing steps. As surveys are acquired with increasingly longer offsets and rich in angle and azimuth coverage, signature stability at high angles becomes crucial for long offset full azimuth FWI. An angularly isotropic source can improve wavelet matching at all angles, resulting in lower noise and uncertainty in the derived velocity model.

Operationally, the source has shown less downtime than standard air gun source arrays as there are fewer components that can fail, and the source can be quickly replaced by bringing in a single string. This is operationally safer and simpler than standard source arrays. The enhanced frequency source has been used in several surveys with impressive uptime and source signature repeatability.

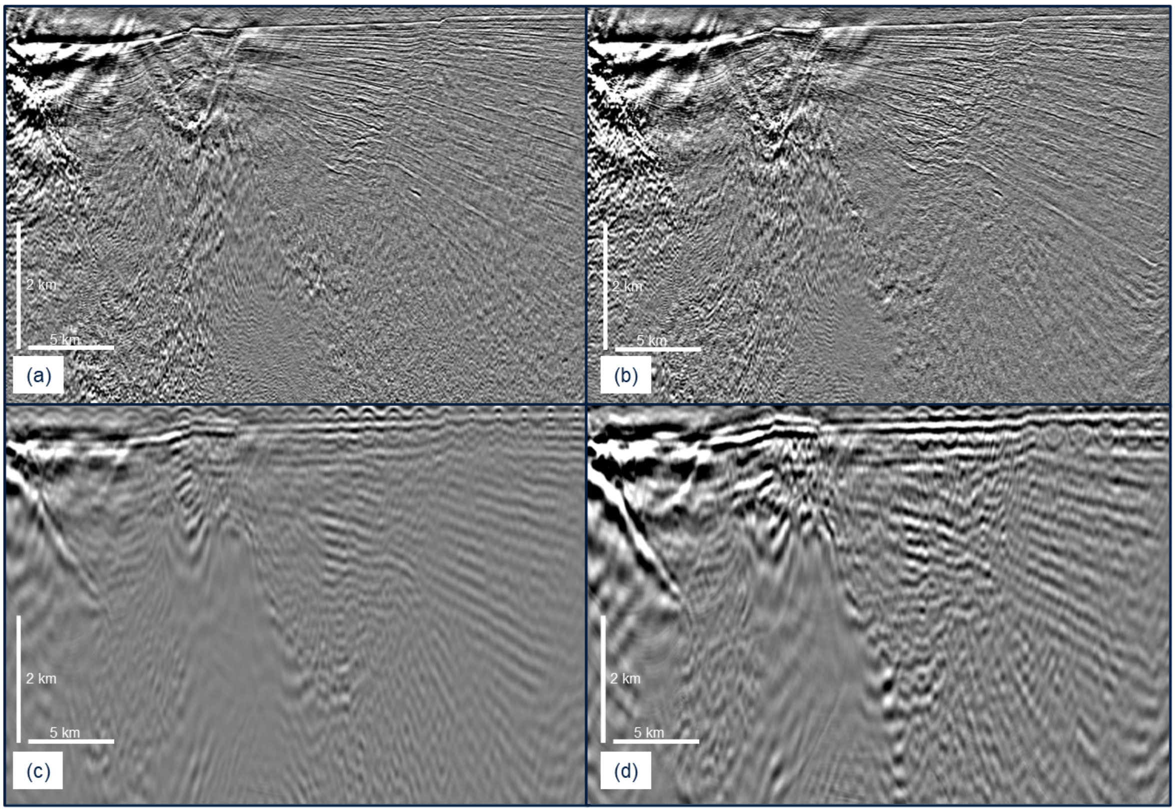

Figure 4 *RTM images of reference source (a) and (c) compared to enhanced frequency source (b) and (d). (a) and (b) show up to 45 Hz while (c) and (d) show input with 5 Hz high cut filter.*

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