Bandwidth Controlled Sources and OBN MEMS – A Perfect Symbiosis in Seismic Surveying

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Summary

MEMS (Micro-Electro-Mechanical Systems) -based sensors, initially introduced in seismic streamers, are now also used in Ocean Bottom Nodes (OBN) for benefits such as flat amplitude and phase spectra across the seismic bandwidth, high vector fidelity, low power consumption and more. MEMS measure acceleration and are by design without gain settings making the topic of sensor saturation and its effects important to consider. Any sensor exposed to signal exceeding its maximum scale will exhibit some form of saturation effects. In the case of MEMS one may experience clean clipping or a wavefield perturbation of short duration. This paper demonstrates that source energy beyond the seismic bandwidth can saturate sensors, particularly in shallow waters or with large source volumes, and explores how bandwidth-controlled sources can delay saturation and maximize MEMS sensor performance. Field trials in the North Sea confirm that such sources allow for higher source volumes without compromising data quality, particularly for near-offset recordings. Hydrophones, geophones, DAS, and other rate-of-change sensors benefit from these findings too, as they allow us to maximize dynamic range utilization and enable gain settings with lower noise floors. Moreover, a reduced high-frequency output aligns with environmental goals by minimizing the seismic source's sound footprint supporting sustainability.

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Introduction

It has been over a decade ago that MEMS (Micro-Electro-Mechanical Systems) -based particle acceleration measurements entered the commercial marine seismic market, first as particle acceleration measurements in streamers (Paulson et. al, 2015) and later in Ocean Bottom Nodes (Hager, et. al, 2022, Tellier et. al, 2023). MEMS technology boasts several key advantages, making it a high-fidelity alternative to geophones. Its flat and undistorted amplitude and phase spectrum over the entire desired bandwidth all the way down to 0 Hz does not just enable the highest signal fidelity but also allows for real-time pitch and roll information directly from the sensor itself, thus eliminating the need for separate measurements. The three orthogonal components can be calibrated to a very high precision and consequently offer the highest vector fidelity and true verticality after rotation. Moreover, MEMS devices can be engineered for low power consumption, making them very suitable for OBN where battery life extension is always an engineering quest. However, MEMS sensors for seismic also must be carefully designed to effectively capture the smallest signals on the sea floor from weak and deep reflections at long offsets and the strongest signals at near offsets emitted by potentially large impulsive sources. It is essential to recognise that the achievable dynamic range for any sensor technology is not limitless. When evaluating sensor performance, it is crucial to consider the noise floor and maximum amplitude in conjunction. In environments with minimal noise, such as the deep-sea floor, prioritising a low sensor noise floor becomes more critical than emphasising the maximum scale. A versatile node that can be used in both very quiet deep water (where we quest for the faintest signals) and shallow water environments (where we have exposure to very high amplitudes from impulsive sources) offers highly desirable operational efficiency and flexibility. In this paper we'll show how smart source design allows for maximizing sensor performance in shallow waters when large volumes are needed for geophysical requirements. This can be achieved by understanding seismic sources not only from the perspective of hydrophone or geophone measurements but also from a MEMS perspective.

In Figure 1 we show the measured far field signature of a 2880in^3 airgun source array at a 25m vertical distance to the array once at the bandwidth from 0-2000 Hz (limit set in the NFH recording) and then the same signature band limited to the upper end of conventional seismic at 250Hz. One can see that one third of the zero to peak amplitude output by this source does not contribute to the seismic image for hydrophone measurements (Figure 1 left). This effect gets amplified when measuring acceleration, as MEMS do (Figure 1, right). The out-of-bandwidth high frequencies scale disproportionally and now more than half of the released seismic acceleration will not contribute to the seismic image. Moreover, this energy can also saturate an accelleration sensor to its maximum amplitude disproportionately faster. Note that a MEMS based node with a flat response to 2000Hz at 25m water depth under this source could see accelerations higher than 6g. There is no MEMS in the OBN market that can bear such large amplitudes and still have a low enough noise floor to sense the faintest of signals we are primarily interested in.

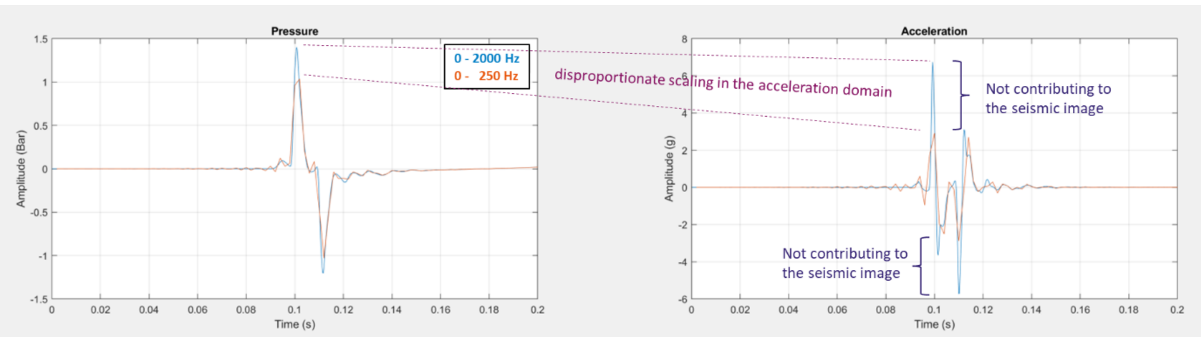

Figure 1: The far-field signature of a 2880in^3 source array at a 25m vertical distance to the array in pressure (left) and acceleration domain (right).

To demonstrate the extent of high frequencies in field data, we enabled some ultra-high 16kHz recording on our MEMS based streamer and recorded the acceleration in the maximum recordable bandwidth available to us at 150m distance to the source array. The recording of two shots (flip-flop) are shown in Figure 2.

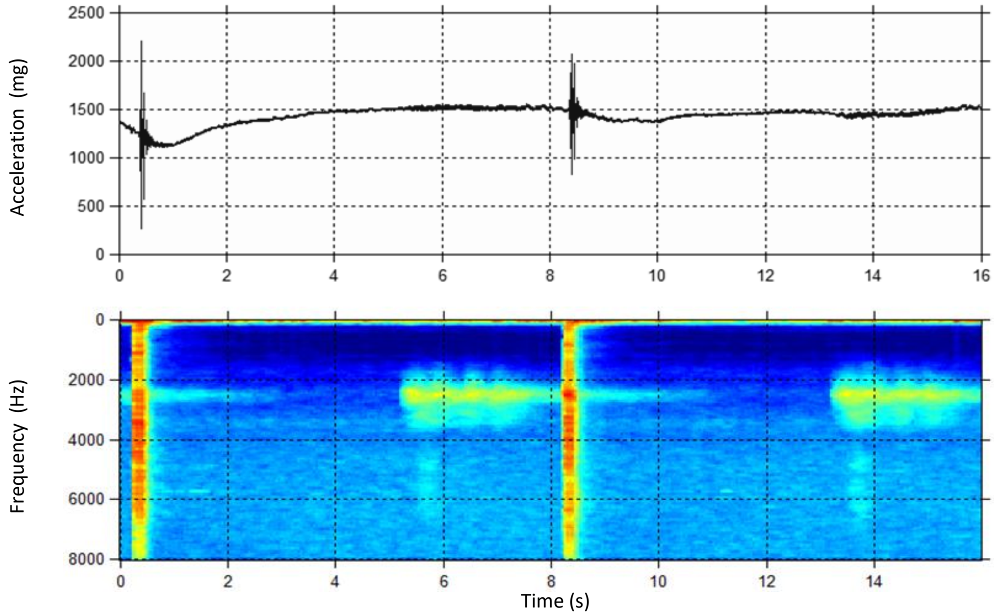

Figure 2: MEMS 16kHz recording in a seismic streamer at 150m from the source. Top panel shows the acceleration time series of one MEMS, and the bottom panel shows the corresponding spectrogram.

It is clearly visible in Figure 2 that the signal arriving at 150m distance contains a large amount of high frequencies. Moreover, the observed zero-to-peak amplitude (ignoring the gravity and tow noise contributions) is still in the order of 1g at 150m and hence would have been even larger at smaller distances.

So, what would be the consequences here? Any sensor that is exposed to signal exceeding its maximum scale will exhibit some form of saturation effects. This also holds true for MEMS which measure acceleration. The vertical component, bearing also the maximum of the gravity component (up to 1g depending on orientation), is usually more exposed than horizontal components. A saturated MEMS may clip cleanly or experience a very short temporary loss of its force feedback control loop (often referred to as overdrive). MEMS have a mechanism engineered into them that ensures stability of the control loop is regained as fast as possible. We have over 15 years of experience with MEMS technology for seismic, first in streamers and more recently in OBN and see that control is typically regained within 1-5ms but can take slightly longer in very extreme cases. Signals recorded during this time can experience wavefield perturbations around the direct arrival and shallow reflections. While these perturbations may not be immediately visible in the acceleration domain they can be exaggerated during the integration to velocity. This may be acceptable in some cases, however, it is undesirable. A survey design strategy for delaying saturation and overdrive is discussed in the next sections. A complementary data processing approach is discussed in JafarGandomi et al. (2025).

Bandwidth Controlled Sources

We have seen the effects on the maximum observed amplitudes for hydrophone and MEMS acceleration when limiting a far field signature to the seismic bandwidth in Figure 1. Sources with bandwidth-limiting capabilities are not just a thought experiment but exist in the seismic market (the two major types of bandwidth controlled sources are called eSource and BluePulse). More information about such sources can be found in Laws 2013, Coste et. al, 2014, and Tellier et. al, 2021. So, when considering how to optimally maximise sensor performance for OBN MEMS technology, we cannot ignore the opportunities bandwidth-controlled sources bring to the table. In fact, we propose to actively include such considerations in the survey design as the gains to be made are quite significant. Moreover, the considerations should also be applied to hydrophones (as shown in Figure 1) and other sensor technology. We run several source models comparing standard sources and band-width controlled sources for various array sizes. A representative result for an eSource is shown in Figure 3. Note we would have liked to include the BluePulse source versions in the modelling, but they were not available yet in our version of the modelling tool at the time of writing this paper.

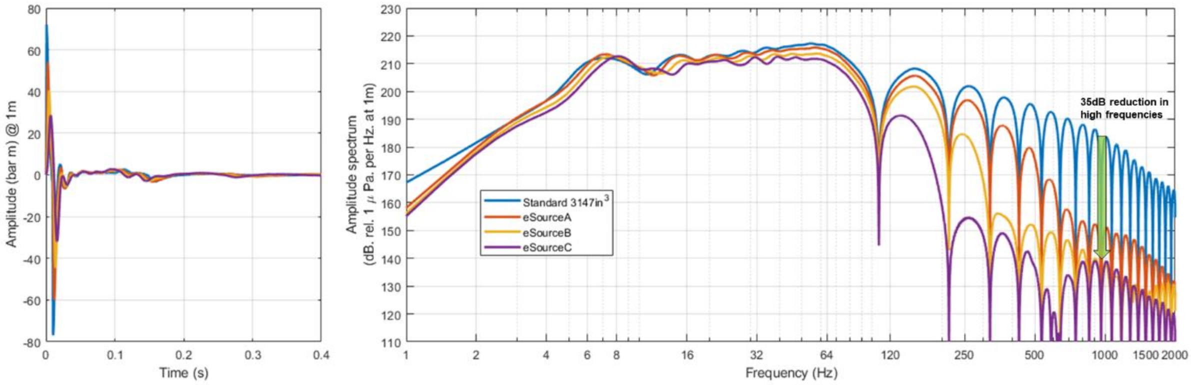

Figure 3: Amplitude time series and corresponding spectra for a widely used typical source of 3147in^3 modelled using standard sources as well as using bandwidth controlled sources with three different levels of high-frequency suppression. For reproducibility purposes, we highlight that the modelling tool used was Oakwood Computing Associates' Gundalf.

Field trials

To calibrate modelling predictions with actual measurements we conducted a number of experiments in the North Sea in a water depth of around 100m using nodes with MEMS technology. We configured two source arrays to be shot flip-flop with one array consisting of standard sources and the other one of its bandwidth controlled twin of the eSource A type (as shown in Figure 3). The arrays were configured to test multiple source volumes and strengths without reconfiguring. We then repeatedly shot directly over a receiver line in order to have matching source points for both source types, i.e. a SP that was shot by the standard array going eastward is matched by its bandwidth controlled source equivalent shooting westwards (see Figure 4).

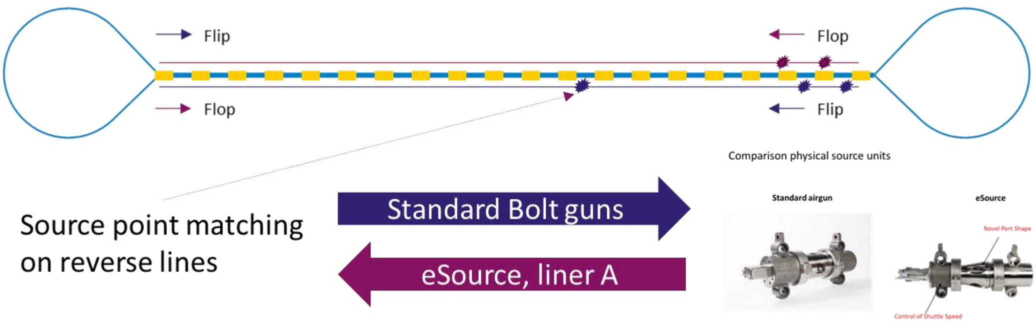

Figure 4: Sketch of acquisition with matching source points for both source types.

We tested four different source volumes of 720, 1049, 2098 and 3147in^3. The results are shown in Figure 5. We see that for the smallest tested source volume the source type did not make a notable difference. However, above 2000in^3 we see a clear difference between source types where the standard sources' extra frequency content systematically creates more sensor saturation on the vertical MEMS component over a notable near-offset range than the bandwidth-controlled version of the same size source array. We note that the induced saturation effect is of very short duration and typically limited to a few samples after the direct arrival. For the largest tested source strength sensor saturation on the vertical component could be observed up to 250m offsets. This is a remarkable field observation and confirms the opportunities and importance of actively including source bandwidth considerations into the survey design. It will not just be MEMS-based nodes that will benefit from it but as shown at the beginning of this paper also the hydrophone maximum scale will be saturated later and hence may allow to use gain settings that come with lower noise floors. Moreover, any measurement sensing a rate of change (e.g., DAS cables) would also reap these benefits.

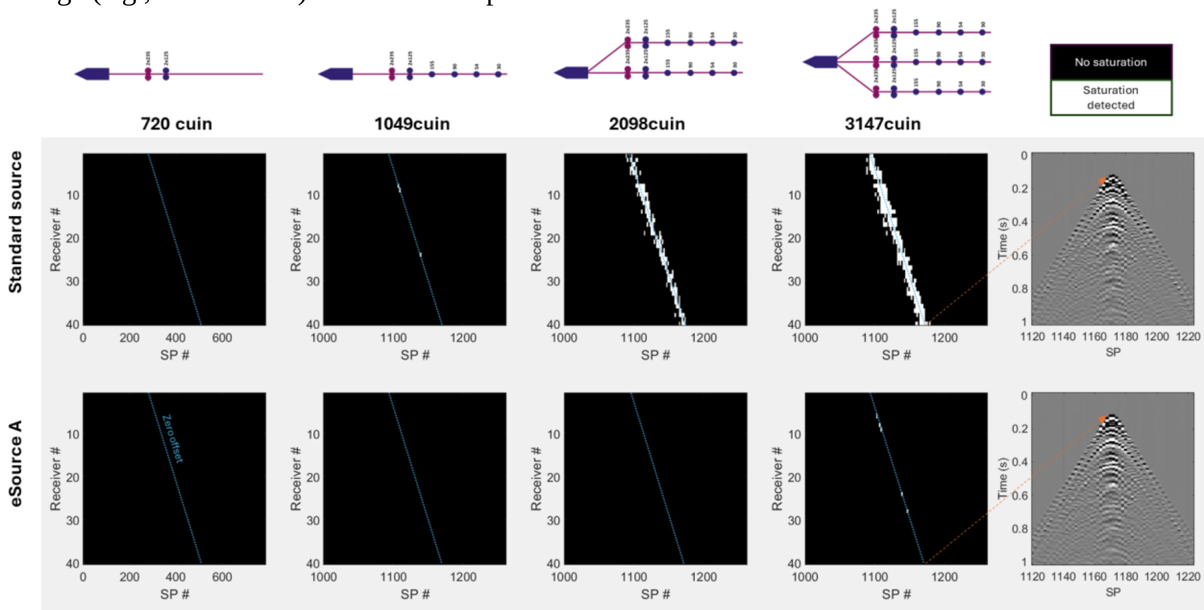

Figure 5: Heatmap showing results of detected vertical sensor saturation for all SP and Receivers. Detected saturation is colour-coded in white. A zoom of the last receiver gather on the right panels.

Conclusions and discussions

Our study highlights the significant impact of source energy beyond the seismic bandwidth on sensor saturation. While we emphasize MEMS technology for particle acceleration measurements in ocean bottom nodes, our findings also bear relevance to hydrophones, geophones, PRMS systems and even DAS cables. Through theoretical analysis of measured far-field signatures, source modelling and a field test, we demonstrate how intellegent source design can optimize sensor performance especially in shallow waters, even when large source volumes are necessary to meet geophysical objectives. This approach enables the use of more potent sources in shallower waters without compromising the precise recording of the direct arrival. While our field trials were limited to eSources due to our available inventory, we expect similar outcomes for other bandwidth controlled sources. Additionally, our findings have implications for equipment with gain settings, where optimizing for large amplitudes may lead to compromises in noise floor performance at certain settings. By employing bandwidth-controlled sources, we can better balance these trade-offs, ensuring data quality across diverse operating conditions. Moreover, this will also reduce our source-sound footprint in alignment with the industry's commitment to environmental stewardship.

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