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Low-Frequency Marine Seismic Source Considerations

Driven largely by the significance of Full Waveform Inversion (FWI) in many seismic imaging workflows, several marine seismic source concepts have been developed over the years that share a common ambition of displacing a large volume of water (hundreds of liters) per cycle to yield high amplitudes in the 1-8 Hz frequency range where the output from traditional air guns decays rapidly. Most low-frequency source concepts are either large-volume pneumatic devices that variously operate at low or high pressure, or large-volume mechanical resonators or vibrators that displace the surrounding water with a flexible external surface. For reasons of practicality and to reduce cost, most low-frequency source concepts are likely to be used with sparse source lines and large 'shot' intervals. Nevertheless, it can be demonstrated that dense 3D spatial sampling of both the source and receiver wavefields will often be beneficial to multi-channel signal processing or wave equation-based imaging workflows, including FWI.

I provide a simple framework to understand the comparative merits of marine seismic low-frequency source concepts recently published at EAGE 2021 and elsewhere. Overall, finding an efficient solution that generates high-amplitude low-frequency data remains a key historical challenge, but some recent progress is evident. I briefly consider the comparative elements of two low-frequency pneumatic source concepts (the Tuned Pulse Source concept of Sercel, and the Gemini concept of ION), the Wolfspar mechanical resonator of bp, and the relevance of the eSeismic method of PGS to acquire continuous wavefields from individually triggered air guns. I also consider methods to 'manufacture' additional low-frequency amplitude content using either ambient noise interferometry or some form of machine learning and conclude with a consideration of low-frequency source deployment factors that may in fact contaminate FWI efforts and present a challenge to model convergence.

Introduction

The ultra-low frequency seismic band (1–8 Hz) is of particular interest for geophysical research due to advances in the fields of full waveform inversion (FWI), particularly in complex oil and gas settings affected by salt, and elastic impedance measurements. However, the lack of usable low frequency content (i.e., low signal-to-noise ratio at low frequencies) in seismic data is limiting the ability of conventional FWI to accurately resolve the velocity in the model, especially at depth, and slow model convergence is impacting project cycle time (possibly by many months). Conventional FWI can theoretically resolve the velocity in geobodies of thickness roughly proportional to ¼ of the wavelength, so it follows that an additional one or two octaves of usable low-frequency signal would enable FWI to more rapidly resolve very large velocity anomalies associated with salt, and thereafter more rapidly converge to a robust model that contains valid high-frequency features. Stated more concisely, the importance of low frequencies beyond model convergence is to build the full model wavenumber components, which will then admit higher resolution of the geological layers.

Ambitions to make FWI more robust have correspondingly driven the growth of ocean bottom node (OBN) acquisition in salt-affected regions, associated with an expectation of improved low-frequency low signal-to-noise ratio (SNR) in comparison to towed streamer and the ability to also record much longer offsets (if SNR allows). Nevertheless, the noise floor recorded from traditional air gun source arrays is still deemed by some to be unacceptably high—even when using the highest fidelity OBN acquisition.

Correspondingly, several emerging marine seismic source concepts share a common ambition of displacing a large volume of water (hundreds of liters) per cycle to yield high amplitudes in the 1-8 Hz frequency range where the output from traditional air guns decays rapidly. Depending upon which zealot you listen to, the most successful low-frequency source concepts are either large-volume pneumatic devices that variously operate at low or high pressure, or large-volume mechanical resonators or vibrators that displace the surrounding water with a flexible external surface. Most of these low-frequency source concepts inherently penalize the high frequency sound emissions—which although sometimes of interest in environmentally-sensitive areas, will also penalize shallow seismic imaging resolution if the source concept cannot be modified for higher-frequency output or is not complemented by broadband source mechanisms.

Furthermore, most low-frequency source concepts are likely to be used with sparse source lines and large 'shot' interval, partly because of associated large cycle times between consecutive shots, partly because the higher signal-to-noise ratio (SNR) at low-frequencies may not necessitate dense inline shot sampling, and partly because dense shot sampling may not be necessary for the low-frequencies of greatest interest to FWI. Nevertheless, dense 3D spatial sampling of both the source and receiver wavefields will always be beneficial to wave equation-based imaging workflows, including FWI—discussed in some detail at the end of this article.

Central to the discussion below, two dedicated sessions at the recent EAGE 2021 conference titled "Low Frequency Seismic Data Acquisition and its Impact on Imaging and Inversion" addressed "Hardware" and "Applications and Way Forward", respectively, and were complemented by several other relevant presentations. After elaborating upon the fundamental challenges to low-frequency source emission and how such frequencies can benefit various seismic pursuits, I attempt to provide a simple framework to understand the comparative merits of recent marine seismic low-frequency source concepts recently published at EAGE 2021 and elsewhere. I also consider the relevance of initiatives to artificially enhance the low-frequency content of broadband (multisensor streamer or OBN) marine seismic data where the signal-to-noise ratio (SNR) is unacceptably low, and briefly acknowledge the significant ongoing progress in FWI algorithms that can overcome cycle skipping challenges in data lacking the low-frequency content targeted by the source concepts discussed herein.

Traditional Pneumatic Source Fundamentals and Limitations

Originally known as the more descriptive 'Pneumatic Acoustic Repeater' (PAR), air guns have been the acoustic source mechanism used for nearly all marine seismic surveys acquired since their invention over half a century ago. The oscillation period τ for an air bubble created by an air gun determines the 'fundamental frequency' or 'characteristic frequency' (the frequency corresponding to the most significant low-end amplitude), and can be approximated by the modified Rayleigh-Willis formula (Landrø and Amundsen, 2014):

$$\tau = \mathrm{const}\,\frac{P^{\frac{1}{3}}V^{\frac{1}{3}}}{(10+z)^{\frac{5}{6}}}\left(1+\alpha\frac{\Delta T_S}{T_{S0}}\right)$$

in which P is the gun pressure, V is the gun volume, z is the source depth, $\alpha = 0.55$, T_S is the water temperature, $T_{S0} = 273.16$ K, and $\Delta T_S = T_S - T_{S0}$. The period of a near-instantaneously released bubble is therefore essentially determined by two factors: the mass of air in the bubble (controlled by air gun volume and operating pressure), with more air producing a longer period; and the hydrostatic pressure (related to the bubble depth), with larger hydrostatic pressure producing a shorter period. For traditional air guns the bubbles produced have a typical equilibrium diameter of 1 m and oscillate with a period of approximately 0.1 s. Furthermore, the state of the precursor bubble at the time of the primary release and the rate of release both directly affect the amplitude of the bubble train (discussed below). As the fundamental frequency of the amplitude spectrum associated with the source wavelet is inversely proportional to the bubble period, the fundamental frequency decreases if the firing pressure increases or if the gun volume increases and increases if the air gun depth increases. Typical volumes of individual air guns used by the exploration industry vary from 20 in^3 (0.3 l) to 800 in^3 (13.1 l).

Initially, the pressure inside the bubble greatly exceeds the hydrostatic (external) pressure, and the air bubble then expands well beyond the point at which the internal and hydrostatic pressures are equal (refer to **Figure 1**). The maximum positive pressure occurs shortly after the air is first released into the water, and the maximum negative pressure occurs close to the point of maximum bubble expansion. The subsequent collapse and expansion of the bubble initially exhibits a relatively harmonic damped oscillatory behavior, wherein the amplitude of internal pressure fluctuations is comparable to the difference in buoyancy forces on the radiation aperture, and acoustic-gravitational effects are part of its hydrodynamics. More specifically, the observed pressure is continuously modified in a frequency-dependent manner by interaction with the ghost pressure wavefield reflected towards the air gun from the free-surface of the ocean and the pressure wavefields from any other air guns in the array. Bubble oscillation with a period typically in the range of tens to hundreds of milliseconds is stopped due to frictional forces, and the buoyancy of the bubble causes it to break the sea surface.

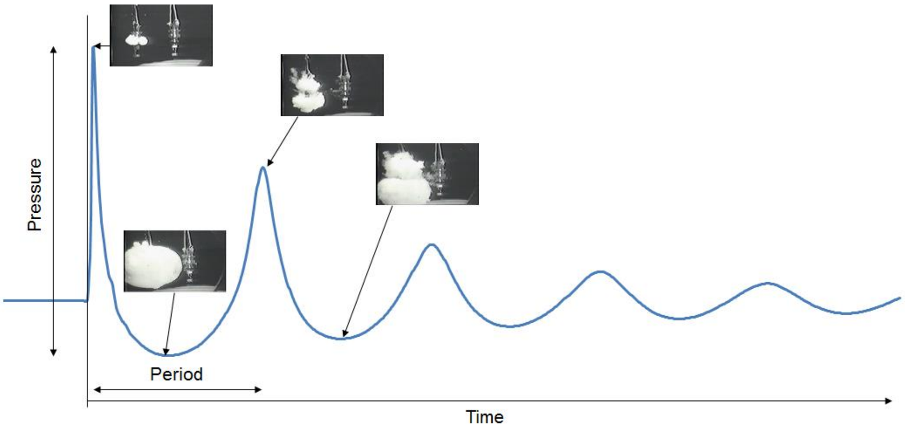

Figure 1. Schematic ghost-free notional source signature for a single air gun being fired. Note the damped harmonic oscillatory behavior.

It can be shown that the output below the fundamental frequency is essentially determined by the product of the firing pressure and the total volume of air released (the total bubble energy). The maximum volume of air that can be expelled from an air gun when the firing shuttle opens is limited by the design of the 'head' containing the external ports, and the rate of air flow is controlled by the acceleration distance of the shuttle before the ports open, as well as the design of the ports themselves. The shuttle inside a traditional air gun has a short acceleration distance over which it builds speed to maximize the rate at which the ports open and release air at typically 2000 psi into the surrounding water. The initial rise time to reach maximum pressure of the expanding air bubble dictates the amplitude of the high frequency content in the far-field source signature: a shorter rise time corresponds to higher amplitude high-frequencies, and vice-versa. Increased bubble cavitation increases high frequency content, as does expulsion of water from the firing chamber. As described in Groenaas et al. (2016), analysis of high-speed video and modeling data facilitated an understanding of the relative contributions of the precursor bubble when air is initially injected through the ports of an air gun, the main peak (initial bubble expansion), and the free bubble energy to the overall amplitude spectrum of the gun signature (see **Figure 2**). After the shuttle has re-sealed the ports, gun dynamics no longer directly influence the bubble. Nevertheless, the bubble retains a 'memory' in the sense that the conditions during its initial release affect the subsequent series of compression and rarefaction cycles of the (damped) bubble oscillation.

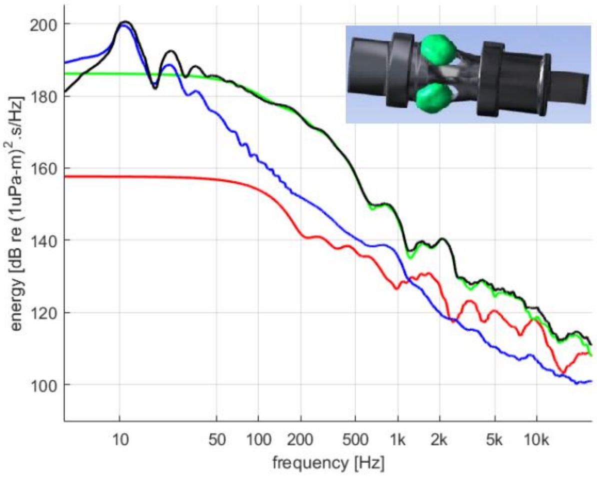

Figure 2. Decomposed amplitude spectrum showing the contributions of the precursor (red), main peak (green) and free bubble (blue) energy. The spectrum of the full far-field signature is shown in black. From Groenaas et al. (2016). The upper-right schematic inset shows the precursor bubble that forms immediately after the shuttle opens and air begins to flow out the gun ports.

Novel Air Gun Configurations

Regards the possibility of decreasing the source depth, Wehner et al. (2019) tested an increased signal for frequencies below 5 Hz of up to 20 dB for sources at a depth at which the air gun bubble bursts directly into the air and, hence, no oscillations occur. For large-volume air guns, the low-frequency signal might also be increased for slightly deeper sources because the high zero-to-peak pressure leads to strong disturbances of the sea surface caused by the acoustic pressure. This could result in a reduced ghost reflection and enhanced low-frequency signal as observed in the data. Note that it is unlikely that the source signature from extremely shallow air gun towing can be measured in a stable manner typically expected by signal processing workflows.

Hopperstad et al. (2012) also showed that a 'hypercluster' of air guns can be configured so that the released air behaves as a large bubble oscillating with a period longer than possible when firing any of the air guns in isolation. The so-called 'frequency locking' distributes the total bubble energy over a larger frequency range—with the main ambition being to reduce the fundamental frequency—potentially by about half an octave.

A Reality Check on Air Gun Volumes

Note that the total energy emitted by air guns at low frequencies (as stated above) is essentially the same whether an array of many smaller air guns is used or whether one large air gun is used. For example, when simulating the output of a 4000 in^3 array and a single 4000 in^3 air gun, the output at low frequencies is almost the same. With a single large air gun, the low-frequency output around the fundamental (resonance) frequency of the large air gun improves by about 3 dB but is limited to a very narrow frequency band around that dominant frequency. Immediately below the dominant frequency the two spectra converge almost immediately. Above the resonance frequency the array will have more output compared to the single large gun.

Two new low-frequency pneumatic source concepts are briefly considered below that incorporate various engineering initiatives to improve the low-frequency output in comparison to traditional (small) air gun designs. Unfortunately, no comparison is available with arrays of air guns configured with a comparable total volume to that of the (single) pneumatic source.

To operate these large volume low-frequency pneumatic sources on a traditional source grid the typical air compressor capability available probably needs to be improved to enable the fast-refilling demands, or an additional source vessel will be required—probably operating on a denser source grid and associated with a higher carbon footprint because of the multi-vessel operations. I discuss the spatial sampling elements of the emitted source wavefield in more detail towards the end of this article.

Ideal Source Wavelets

Given the variety of ways in which air guns can be deployed, it is worth introducing the concept of an 'ideal source wavelet' (ISW). An ISW is measurable and repeatable, such that it can be robustly removed from the recorded data during designature in signal processing. By 'measurable', I mean that the phase and amplitude response can be measured in a frequency-dependent manner over all frequencies of interest and can be robustly described for all source emission angles and azimuths of interest. By 'repeatable', I mean that the emitted source wavefield signature is not undesirably affected by the bubbles produced by preceding shots in a dynamic manner, or that the geometry and depth of the source elements does not vary in an unacceptably dynamic manner. Any source concept that yields richer low frequency content should not also be contaminated by undesirable artifacts and noise. This backbone applies to all source concepts discussed hereafter.

Quantitative Interpretation (QI) practitioners appreciate that a robust angle- and depth-dependent source wavelet needs to be estimated from seismic data so that the true elastic earth response can be understood. In addition to high SNR across a broadband range of frequencies, the ISW for QI applications comprises a wavelet of known phase with negligible sidelobe amplitudes/energy. Cyrille Reiser from PGS noted "If there are sidelobes in the source wavelet, you will invert for those sidelobes" when presenting "Additional low frequencies in broadband seismic deliver increased confidence in prestack inversion and prospect de-risking" at EAGE 2021. Although the benefits of richer low-frequency content for higher-resolution seismic interpretation of zero phase wavelets has been published by authors such as ten Kroode et al. (2013), the slopes of the low- and high-frequency spectral content were shown to also be relevant. Relevant to the low-frequency characteristics of pneumatic vs. vibrator / resonator source concepts discussed below, a harsh low-cut slope below the fundamental frequency will exaggerate sidelobe amplitudes in an undesirable manner.

Traditional Marine Vibrator Fundamentals and Limitations

Rather than displace water with long-period air bubbles containing a large mass or air, low frequencies can alternatively be generated with the moving flexible external surface of a submerged marine vibrator (emitting pressure wavefields over a range of sweep frequencies or for an extremely band-limited resonance frequency), and without any air bubble-related tuning requirements. All marine vibrator concepts rely upon the principle of a hollow body changing its volume in response to a controlled sweep signal, thereby displacing the surrounding water and emitting an acoustic wavefield. Finding an efficient solution that generates high-amplitude, low-frequency output remain a key historical challenge. Two relevant considerations when using marine vibrator concepts to generate low-frequency amplitudes are: 1. The volume of water that must be displaced per cycle, and 2. The 'air spring effect' upon the resonance frequencies (the frequencies at which energy is most efficiently emitted). Impedance matching between the surrounding water being displaced and the driver mechanism within the source is the long-standing challenge to the development of efficient marine vibrator concepts—increasingly so at low-frequencies where driver efficiency decreases exponentially. High-amplitude, low-frequency signal can either be generated by using a very high displacement of the surface of a few marine vibrator units, or by distributing a smaller displacement over the surface of several marine vibrator units. Low frequency output will also be enhanced overall by both increasing the towing depth to exploit the source ghost effect, and by designing a configuration that creates low resonance frequencies, however, both ambitions are challenged by the air spring effect (below).

To achieve a given level of output in the water, a marine vibrator typically needs to undergo a change in volume, and to work at depth while minimizing structural weight, the marine vibrator must be pressure balanced with external hydrostatic pressure. As the internal gas (typically air or nitrogen) in the marine vibrator is increased in pressure, the bulk modulus (or 'stiffness') of the internal gas in the enclosed volume also rises—acting as an 'air spring' that increases the resistance to compression and decompression. The stiffness of the acoustic components of the marine vibrator and the internal gas air spring effect are the primary determining factors in the marine vibrator's resonance frequency (**Figure 3).**

In recent years the highest profile development of marine vibrators has occurred within the Marine Vibrator Joint Industry Project (MVJIP), an industry consortium administered by TEES (Texas A&M Engineering Experiment Station), sponsored by ExxonMobil, Shell, and Total, and started in 2011. The MVJIP supported the development of three different marine vibrator technologies: General Dynamics Applied Physical Sciences (APS), PGS, and Teledyne Webb Research (TWR). PGS withdrew from the MVJIP in 2018, the TWR development status is unknown, and the APS solution may see commercial deployment in 2022,. The Teledyne T-ULF design uses flexible cylindrical membranes that act as a resonating gas-filled bubble in response to changes in the internal pressure of the sealed mechanism (driven by an electric linear motor). In contrast, the APS acoustic transducer incorporates a low-travel seal around two circular flexible membranes that are driven by opposing pistons.

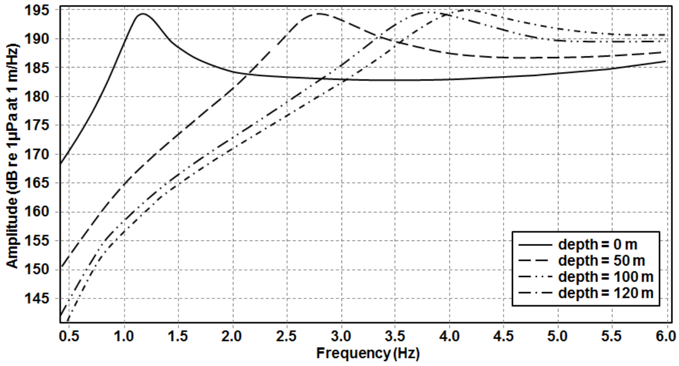

Figure 3. Amplitude vs. frequency as a function of towing depth for the flextensional marine vibrator concept discussed in Long and Tenghamn (2018): Resonance frequency increases with increasing towing depth.

Note that the relevant MVJIP low-frequency output criteria for a full array output with a 5 s sweep length were 190 dB re 1 µPa/Hz @ 1 m over the 5-10 Hz frequency range. Therefore, none of the MVJIP marine vibrators were ever designed to meet the high-amplitude very-low frequency ambitions considered here and were instead intended to offer an alternative to air guns with less environmental sound footprint, and with potential other geophysical benefits such as higher source wavelet repeatability for 4D reservoir depletion monitoring.

Roadmap for Low-Frequency Source Concepts

Joe Dellinger from bp used previously published ambient noise recordings from seafloor nodes in the Gulf of Mexico as the foundation for his EAGE 2021 talk titled "New Marine Sources: Where Are We Now?" (**Figure 4**). The 'crossover frequency' typically specified at which SNR = 1 is defined as the lowest useful frequency. Dellinger observes that air gun data typically demonstrates a natural 18 dB / octave low-frequency decay below the typical fundamental frequency peak in amplitudes at about 7 or 8 Hz. In contrast, marine vibrators or resonators demonstrate a much steeper low-frequency decay—albeit with a lower fundamental frequency than that common to air guns.

Consistent with the EAGE 2021 discussions and industry publications elsewhere, the topic of low-frequency marine seismic can therefore be sub-divided into three pursuits:

- Generating richer low-frequency content through new source concepts, all of which are either evolutions from the traditional air gun design or variations of marine vibrators / resonators. The common elements are that the fundamental frequency is moved to a lower value, and the noise floor affecting low-frequency signal amplitudes of interest is decreased.
- Enhancing the low-frequency content of recorded data, either by predicting ultra-low frequency information from active-source data, or by extracting the (low-frequency) body and diving wave information from ambient noise (recorded during OBN acquisition).
- Improving the robustness of algorithms that benefit from the desired low-frequency amplitudes, notably FWI for salt-dominated environments.

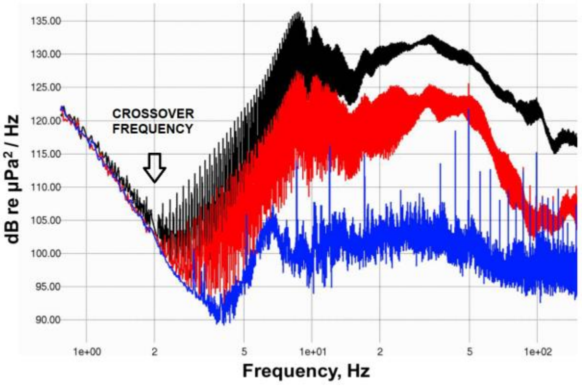

Figure 4. Three power spectral density plots calculated over a one-minute time window and averaged over an array of OBNs in the 2006 Atlantis array: (black) air gun array above the array; (red) air gun array 7 km away; (blue) no active source firing, i.e., noise floor. The frequency axis has a log scale. Modified from Dellinger (2016). The noise level for towed streamer acquisition is dependent upon mechanical and laminar flow noise levels within the streamers, residual shot energy within the water column from seismic survey activities, other anthropogenic noise sources, and the noise floor of the sensors and recording system. Improved recovery of very-low frequency signals in the 1-3 Hz range may be achieved by enhanced low-frequency seismic source output and / or improved low-frequency noise attenuation.

In practice, the pursuit of much richer low-frequency content in marine seismic data ideally involves a source mechanism capable of displacing a large volume of water per frequency cycle, and the displaced volume must exponentially increase with decreasing frequency to maintain constant sound pressure level. To date, the source concepts tested have included high volume air guns with high firing pressure (typically 2000 psi); high volume ‘pneumatic’ sources with low firing pressure (typically 600-1000 psi); and marine vibrators or resonators that displace a large net volume of water.

A common element of high volume air gun / pneumatic source concepts is the long cycle time necessitated by their compressors, so a coarse shooting grid is generally proposed—quite commonly envisaged as a two-vessel operation where one vessel tows a ‘conventional’ source array that pursues a dense shooting grid and is used to record short offsets, and one vessel tows the low-frequency source(s) that pursues a coarser shooting grid and is used to record long offsets. Similarly, the long sweep times likely to be associated with marine vibrators or resonators are likely to necessitate a sparse ‘shot’ grid. In all scenarios, a coarse shot grid implies coarse spatial sampling of the emitted source wavefields. As discussed below, sparse spatial sampling of the emitted source wavefield can translate to poor SNR at the lowest frequencies, and greater associated challenges when attempting to discriminate signal and noise.

Table 1 defines the fundamental elements of the low-frequency source concepts discussed below.

	Pneumatic Source		**Resonator / Vibrator Source**	
Mechanism	Air injected into water as the displacing mechanism		Moving external surface as the displacing mechanism	
Broadband Output	**Small Volume** **High Pressure** **Short Bubble Rise Time**		**Small Displacement** **Broadband Sweep**	
	Standard Air Gun (Reference)		MVJIP-type Designs (e.g., 5-100 Hz)	
Low Frequency Emphasis	**Large Volume** **High Pressure** **8-10 m Depth**	**Very Large Volume** **Low Pressure** **8-10 m Depth**	**Small Displacement** **Many Sources** **Band-Limited Sweep**	**Large Displacement** **Less Sources** **Resonating Frequency**
	ION Gemini (4000 / 8000 in^3, 2000 psi)	Sercel TPS (26 500 in^3, 600-1000 psi)	PGS Stacked Bender	bp Wolfspar
	Large Volume **High Pressure** **Very Shallow Depth**	**Array with Closer Spacing of Elements** **High Pressure** **Standard Depth**		
	Breaching Air Guns	hypercluster Frequency Locking		

Table 1. Contrasting elements of the various pneumatic and marine vibrator / resonator source concepts discussed herein.

Band-Limited Pneumatic Source Concepts

Two low-frequency pneumatic source concepts are briefly discussed below: The Tuned Pulse Source (TPS) concept developed by Low Impact Seismic Solutions (LISS) and now being commercialized by Sercel, and the Gemini concept developed by ION. Gemini has been used commercially several times, and the TPS is likely to be used commercially in 2022.

Sercel TPS

The Tuned Pulse Source (TPS) concept developed by Low Impact Seismic Sources (LISS) and now being commercialized by Sercel, is an evolution of the traditional air gun with significant larger volume and lower firing pressure (1000 psi). Shuki Ronen from Sercel presented "Ultra Low Frequency Signal from Pneumatic Seismic Sources: How Low Can We Go?". The volume-pressure aspect of what is referred as a 'pneumatic source' is complemented by several bespoke design features such as zero acceleration distance on the firing shuttle, features to avoid expulsion of water as the shuttle is accelerating and opening the ports, large ports, separate air refill and drainage into the firing and the operating chambers, and wider and shorter internal air passages. Collectively, these changes with a massive volume of air being released into the water produce a symmetric air bubble with minimal bubble turbulence and cavitation, a slow initial rise time of the expanding air bubble (refer also to Watson et al., 2019), a significantly stronger low-frequency output, and a weaker high-frequency output.

The largest TPS version tested to date is 7.5 m in length with a volume of 26 500 cubic inches (about 430 liters: see **Figure 5**), although larger concept designs exist with 1.8 Hz and 1.4 Hz peak frequency output (apparently corresponding to a hypothetical volume of 200 000 cubic inches, or 3300 liters). Field testing described by Chelminski et al. (2021) deployed a 26 500 cubic inch TPS at 10 m depth, and coherent diving wave and refracted events were recorded in the 1-3 Hz frequency band at up to 45 km offset. At 1 Hz the SNR falls below 1 at about 28 km offset. The oscillating bubble has a resonance frequency of 2.8 Hz, and the equilibrium radius is close to 2 m, which equates to a volume of about 33 m^3. The second and third (oscillating) bubbles will have smaller radii, the emitted low-frequency output is heavily damped by comparison to a large mechanical resonator such as the bp Wolfspar concept mentioned below.

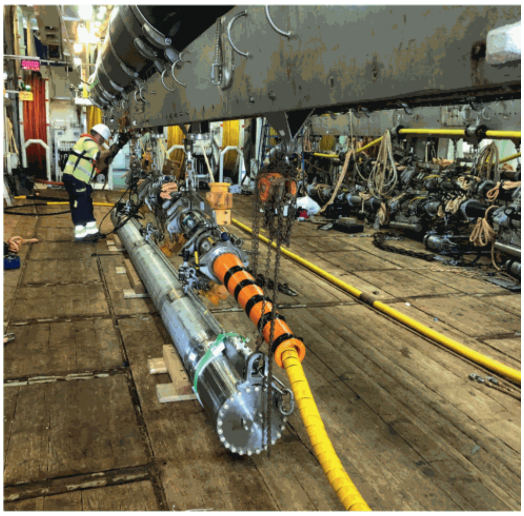

***Figure 5**. 26 500 in^3 TPS below a conventional air gun source array float. From Tellier et al. (2021), Figure 2.*

Figure 6 from Tellier et al. (2021) shows that the TPS data are more than 20 dB stronger than a reference 5110 in^3 air gun array in the 1-3 Hz range, but more than 15 dB weaker for frequencies above 40 Hz. The rapid high-frequency decay is advantageous in environmentally sensitive areas from a received sound level perspective but may be disadvantageous from a seismic imaging perspective if the band-limited TPS data cannot yield acceptable resolution on migrated images. No such images have been published yet for consideration.

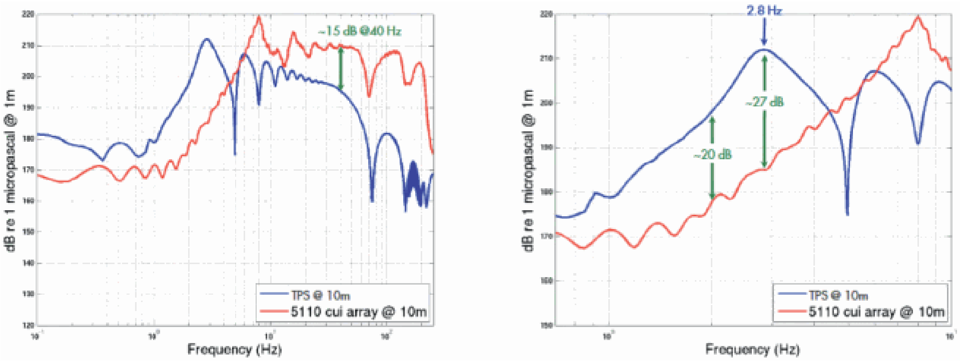

Figure 6. Spectra of the TPS compared to a conventional 5110 cu.in pneumatic source array. From Tellier et al. (2021), Figure 14.

In commercial deployment only one or two TPS units will be used in an array (one unit per float) and can be deployed from conventional streamer vessel back deck operations. In practice, the shot interval is related to the volume of the TPS and the associated refill time. This is referred to as the "frequency-dependent shot density". By comparison to low-frequency marine resonator concepts with long sweep durations, no requirement should exist during signal processing for source motion compensation (i.e., Doppler effect).

ION Gemini

John Brittan from ION (now PGS) presented “Enhanced Low Frequency Signal-to-Noise Characteristics of an Airgun Technology Based Source”. The ION Gemini ‘Extended Frequency Source’ uses a large volume modified air gun with 2000 psi operating pressure to yield a fundamental frequency of about 4.25 Hz for a 4000 in^3 version towed at 8 m depth (refer to **Figure 7**), or 3.7 Hz for a 8000 in^3 version.

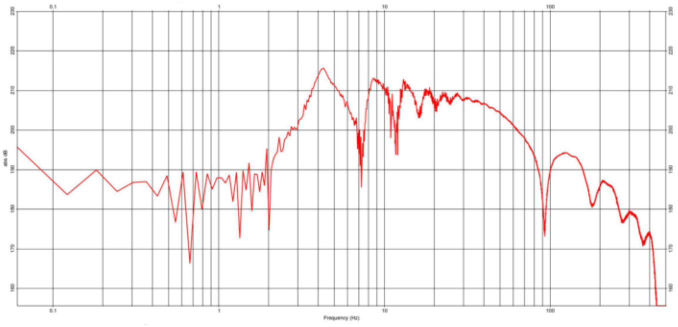

Figure 7. ION Gemini 4000 in^3 source spectrum. From their online data sheet.

The modelled survey exclusion distance in deep water for a 160 dB re 1 μPa peak sound pressure level (SPL) was 3.7 km for the 8000 in^3 Gemini source vs. 5.1 km for a reference 5100 in^3 conventional air gun array towed at 12 m depth; testament to the comparatively reduced high-frequency output for the Gemini source design.

In contrast to the TPS concept, the Gemini concept emits a sufficiently large frequency bandwidth for seismic imaging as a standalone source. Regards the comparative air flow rates and SPL, an 8000 in^3 Gemini source fired at 2000 psi yields 16 million pound-inch, and a 26 500 in^3 TPS fired at 1000 psi yields 26.5 million pound-inch. Using the modified Rayleigh-Willis formula introduced earlier, it follows that the TPS bubble period is about 18% larger—hence the lower relative fundamental frequency of the TPS concept.

Band-Limited Mechanical Resonators

Encouraged by a one-fifth scale model built in 2009, bp developed the Wolfspar marine vibrator concept in **Figure 8** (refer to Dellinger et al., 2016; Dellinger et al., 2019; Brenders et al., 2020). A working prototype was first tested in the Gulf of Mexico (GOM) during 2014, and despite encouraging tests with OBN deployments over the Mad Dog and Atlantis fields in 2018 and 2019, respectively, internal funding ran out and an upgraded commercial version is currently unlikely to occur—testament to the capital-intensive challenges of disruptive seismic acquisition technology development. The Wolfspar unit has a dry weight more than 25 tons, a submerged weight of about 6 tons, dimensions of about 8 m length x 2.5 m diameter, pressure compensated with nitrogen, and used a piston-driven design to displace about one cubic meter of water at about 2 Hz. Classed as a mechanic resonator rather than a vibrator unit, the extremely band-limited low-frequency output was primarily designed to augment Full Waveform Inversion (FWI) model building in complex salt regimes. The large size of the unit and its associated equipment is incompatible with typical towed streamer seismic vessel back deck capabilities and necessitated a custom Launch and Recovery System (LARS) mounted on a dedicated survey vessel. It should be noted that the low-frequency output of Wolfspar was intended to complement very-long offset acquisition using ocean bottom node (OBN) operations, so deployment from a streamer vessel was never a design consideration anyway.

Two key sweep parameters were about 1.4 to 2.0 Hz at 36 m towing depth, and about 1.7 to 2.4 Hz at 60 m towing depth, both acquired with coarse source line separations between about 1 and 8 km. The explicit pursuit of low frequencies for FWI enables efficient acquisition with very coarse source wavefield sampling, and the long sweep lengths of about 30 seconds enable a high SNR in the recorded data. In practice, it is envisaged that the source-constrained effort for typical air gun shooting could be reduced by half using sparse Wolfspar acquisition, however, existing cost constraints and operational limitations of OBN fleets deploying OBNs via ROVs currently make such advantages fiscally difficult to realize.

Discussions by Andrew Brenders and Joe Dellinger from bp described their experiences with Wolfspar testing in the two EAGE 2021 dedicated sessions. Both speakers described the historical progress with low frequency recovery in the GOM. The microseismic noise crossover frequency was about 2.25 Hz in 2006 using OBN acquisition, but improved to about 1.6 Hz in 2015, thanks to less aggressive lo-cut acquisition filters, better OBN sensor electronics, and longer OBN battery life enabling better parameter testing (Michell et al., 2017).

Figure 8. Wolfspar unit during testing. The nose cone is in the foreground.

Figure 9 displays common receiver gather (CRG) phase ring plots for spatially coincident Wolfspar and air gun array shots. These results can be interpreted in various ways. On one hand, it is clear than on a shot-to-shot basis, Wolfspar has a clear advantage over air guns at low-frequencies. However, denser spatial sampling of the emitted source wavefield and the stack power of FWI and migration operators improve air gun low-frequency usefulness. Whereas the Wolfspar data has coherent phase down to 1.70 Hz at long offsets using a sweep of 1.70 to 2.40 Hz, the phase becomes abruptly incoherent at 1.65 Hz and below. In contrast, the air gun phase is coherent at decreasing offsets all the way down to 1.40 Hz for 100 summed shots, and the results are still weakly coherent at the near-to-mid offsets down to 1.40 Hz for 25 summed shots.

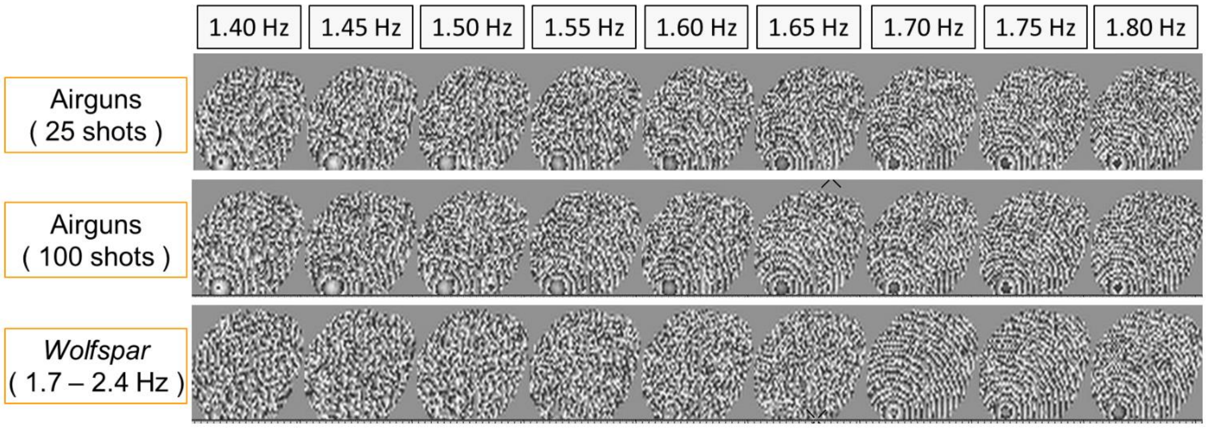

Figure 9. Phase of common shot gathers for 25 (top) and 100 (middle) stacked air gun shots and one Wolfspar shot (bottom) for frequencies from 1.4 to 1.8 Hz. The shot location is the 'bullseye' in the bottom left corner of the node patch. The maximum offsets, at the top right of the node patch, are about 18 km. The Wolfspar phase ring plots are essentially incoherent below the starting sweep frequency of 1.7 Hz, but the air gun array phase ring plots demonstrate mid-offset coherency down to at least 1.5 Hz. From Brenders et al. (2020), Figure 3.

For the FWI model results shown by bp at EAGE 2021, the low-frequency benefit of Wolfspar was most obvious at large sub-salt depths (e.g.,> 25 000 ft). Whether the recorded low-frequency amplitudes can be 'enhanced' during data preconditioning, or whether FWI can be adapted to overcome the 'missing' low-frequency amplitudes, are both also briefly considered below.

Low Frequency SNR and the Fresnel Zone

Although it is tempting to focus on the apparent improvement in low-frequency SNR for individual shot gathers, it must be remembered that many shots contribute to each subsurface image point during seismic migration. The radius of the first Fresnel zone in 3D increases in proportion to the reciprocal of the frequency being considered. For example, the Fresnel zone at 2 Hz will be about four times the size of the Fresnel zone at 8 Hz for the same depth. Therefore, there are many more data samples from many more shots and receivers contributing to each image point at low frequencies compared to the case at high frequencies—which will benefit low-frequency SNR in seismic images. Spatial sampling density of the receiver wavefield will affect operator aliasing for shot profile migration, and spatial sampling density of the shot wavefield will determine the maximum wavenumber content.

As noted in my introduction, the importance of FWI in salt-affected regions has driven much of the renewed interest in low-frequency source concepts. 3D model updates are computed from the full gradient, and additionally benefit from stacking of the individual gradients—which is relevant in the context of the Fresnel zone at low frequencies—however, computation of the residual for each shot relies upon the input data having high SNR at each frequency (starting with the lowest).

Figure 11 discussed below demonstrates how low-frequency SNR can be remarkably good for densely-sampled continuous source wavefields.

Enhancing Low Frequency Signal Amplitudes

With reference to the (blue) noise floor in **Figure 4**, there are incentives to 'manufacture' additional low-frequency amplitude content below the crossover frequency if the 'noise' can be translated to useful signal:

- Using ambient noise interferometry to extract body and diving wave information (if possible) that can 'fill in the gap' below the lowest useable signal recorded from the active source being used, or
- Extrapolate low-frequency signal from recorded higher-frequency signal using some form of machine learning (ML).

Various discussion at EAGE 2021 confirmed that only the surface wave component of ambient noise (Rayleigh waves and guided waves) has been useable in OBN studies—and probably necessitating elastic FWI (according to Fons ten Kroode from Shell). Theoretically, body waves require a dense distribution of secondary source scatterers in the subsurface. Anecdotal experience, however, suggests that passive seismic data is equi-distributed amongst all possible wave modes—so most recorded marine passive seismic data is dominated by surface waves and contains shear wave modes.

Physics suggests that low and high-frequency content is coupled in some form (otherwise velocity model building methods would be inherently unfeasible), but in a non-linear manner, so the robust prediction of low-frequency amplitudes must be inherently difficult. Nevertheless, Oleg Ovcharenko et al. presented a workflow to extrapolate low-frequency content for marine streamer data using elastic subsurface models and deep learning in "Transferring elastic low frequency extrapolation from synthetic to field data", and Z Wang also pursued a trained neural network approach in "Research on low frequency compensation method based on deep learning", with the notable difference being that the network model was trained and tested with acoustic synthetic data only.

Overall, the application of neural networks trained on seismic waveform data to real data is challenged by the requirement for accurate labels—which typically forces the development of solutions using synthetic data where solutions are readily available. However, poor performance of the synthetically trained neural network (NN) at the inference stage often occurs because the synthetic data do not capture the reality of the real field experiment. Alkhalifah et al. (2021, presented at EAGE 2021) describe a novel approach to enhance supervised training on synthetic data wherein the source synthetic data are labeled but the target data are not, so they cannot perform transfer learning. This form of 'domain adaptation' is often addressed with unsupervised ML methods by training embedding layers to transform the input features of both synthetic and real data to look more alike, granted that their conditional distributions are the same. In other words, the modeling used to generate synthetic data represents the behavior of wave propagation in the subsurface, which we often assume in most of our algorithms including FWI. Drawing on their experience with seismic data, Alkhalifah et al. devise a more direct approach based on linear transformations to migrate the input features of the synthetic data to the real ones and vice versa, so the distributions of the datasets become more aligned. In the application to the low-frequency extrapolation in active source seismic data (**Figure 10**), the transformations minimize the difference between the distribution of the training and application datasets.

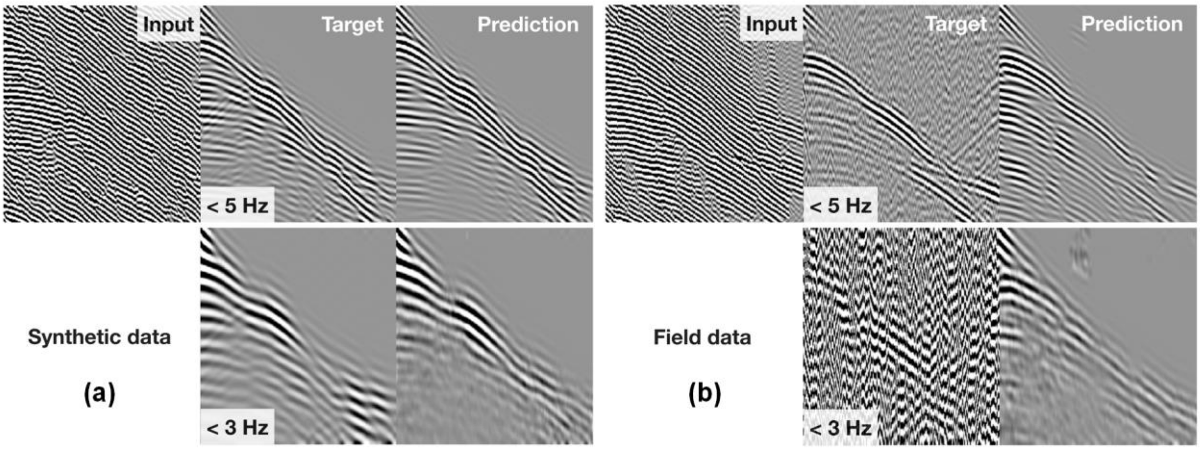

Figure 10. Prediction results for synthetic (a) and field data examples (b). The top row contains the input data and the corresponding predictions of data below 5 Hz. The bottom row contains the same predicted data low-pass filtered below 3 Hz. Courtesy of Alkhalifah, T., Wang, H., and Ovcharenko, O., 2021, MLReal: Bridging the gap between training on synthetic data and real data applications in machine learning: Submitted to arXiv.org.

In **Figure 10**, low-frequency components < 5 Hz for a complete shot gather are reconstructed from available high-frequency representation > 4 Hz in the same shot gather. In the methodology used, the acquisition parameters and (preferably broadband) source signature were extracted from the field data and then used for numerical modeling in a set of synthetic subsurface initializations. The high SNR observed on real data application is courtesy of the synthetic data training.

Group discussion in the dedicated low-frequency sessions at EAGE 2021 acknowledged that the FWI results being achieved today were unimaginable only ten years ago—when some of the source concepts mentioned here were first conceived. Necessity is the motherhood of invention, and FWI has managed to succeed without very-low frequencies in many settings, however, if better low-frequencies and longer offsets are available in a low-cost manner, FWI practitioners will gladly use such data.

Source and Receiver Wavefield Sampling versus Operational Efficiency

After consideration below of a novel method to acquire continuous wavefields from individually triggered air guns, I then consider the comparative merits of the aforementioned low frequency source concepts in terms of their likely operational deployment, and what scope improved source and receiver wavefield spatial sampling might offer to improve the recovery of very-low frequency amplitudes with high SNR.

Dense Spatial Sampling of Source and Receiver Wavefields

The ‘Continuous Wavefields Method’ (or ‘eSeismic’ method) of PGS relies upon the acquisition of continuously-emitted source wavefields that are approaching the properties of white noise. This means the emitted wavefield is nearly white both temporally and spatially. Both air-guns and marine vibrators can be used, and in the case of air-guns, individual elements are continuously triggered several times a second with random time delays. Aside from very low received sound pressure level (SPL), the very dense spatial sampling of the emitted source wavefield enables better discrimination of signal from noise—potentially quite significantly by comparison to conventional air gun array operations. **Figure 11** is relevant to the discussions throughout this article.

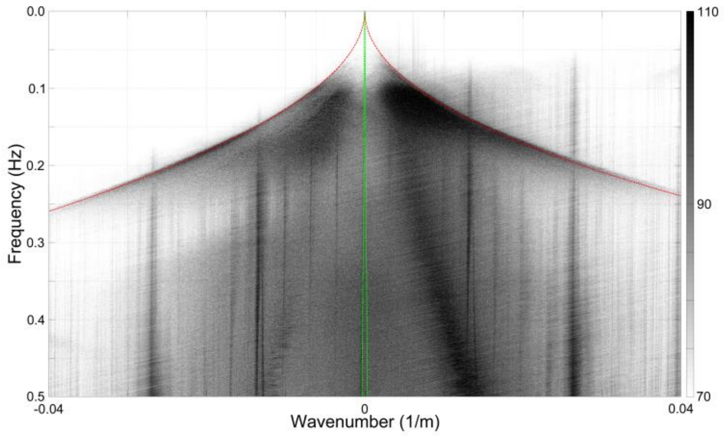

Figure 11. FK spectra for 8 hours of continuous wavefield data after correction for receiver motion. Vertical scale is 0 Hz (upper) to 0.5 Hz (lower). The contributing data were recorded along a 60 km line. The red curve shows the theoretical dispersion relationship for sea-surface waves, and the green curve shows the signal cone. An amplitude increase is observable for frequencies immediately after the dispersion curve. Amplitudes can be observed down to 0.05 Hz. Courtesy of Stian Hegna (PGS).

Results published to date challenge soome long-standing industry dogma about the ‘value’ of large air gun arrays:

- Individual air guns used to emit continuous wavefields have similar penetration to conventional air gun arrays.
- The SNR of reconstructed (common receiver) gathers can be high, despite no blending being attempted from a scheme that typically triggers a few air guns each second.

The spatial and temporal triggering of the air guns distributed among several sub-arrays (typically six) yields an emitted source wavefield that approaches the properties of white noise. As white noise only correlates with itself, the method inherently has low correlation between signal and noise, and some of the noise is attenuated during the source deconvolution step. Denser spatial sampling on the source side when signals are emitted almost continuously clearly also translates to an improved ability to distinguish between signal and noise. Additional denoise solutions have also been developed to exploit the continuously recorded wavefields. Overall, far more details can be observed in **Figure 11** than normally seen when looking at equivalent data from short individual records.

Source Halos and Sparse Shot Grids for Low-Frequency Source Concepts

Guido Baeten from Shell described new survey designs for sparse nodal surveys in "Cheaper and better long offset nodal surveys based on low-frequency enhanced sources". Using the example of long-offset OBN surveys from the Gulf of Mexico (GOM), it was noted that large 'source halos' of 20-30 km are required to enable FWI based velocity estimation utilizing refractions off basement. The pragmatic acquisition of lower-cost sparse source lines with low-frequency sources and a large source halo could complement traditional broadband source acquisition with denser source lines and a smaller 4-10 km source halo (depending upon imaging objectives). This strategy has also been proposed by other authors working in the GOM, and apparently assumes that the undersampled noise challenges in the previous paragraph are not relevant.

For example, concept dual-vessel operations to incorporate the TPS concept by Chelminski et al. (2020) showed a 50 x 100 m OBN grid, with one vessel towing triple-source air gun arrays of 5,000 cu.in with 100 m lateral source separation, and one vessel towing dual-source TPS with 300 m lateral source separation and 100 m shot interval. This would yield TPS source lines with a uniform 300 m separation.

Spatial Sampling Challenges to the Signal Processing of Sparse OBN Data

Group discussion at the conclusion of the dedicated sessions at EAGE 2021 also highlighted the symbiotic relationships between both source and receiver wavefield spatial sampling. Having worked with both the TPS and Gemini source concepts, Denis Vigh from Schlumberger observed that node sparseness is going to drive your source effort. With insufficient OBN sampling, the interference recorded from simultaneous shooting can be severe and difficult to remove during shot deblending in processing. It was appreciated that whilst sparse OBN deployments with simultaneous shooting from several low-frequency and broadband sources is desirable from a cost perspective, the residual noise from under-sampled blended data can contaminate subsequent FWI efforts and present a challenge to model convergence.in other words, the imaging tool driving the more expensive acquisition effort may no longer be as applicable

As a simplistic proxy for depth migration in complex settings where migration artifacts can be problematic, so-called 'FWI Imaging' neglects offset and azimuth considerations, assumes a simple density model, and applies directional spatial derivatives to the FWI velocity model. Henry Kerrison from CGG examined the impact of streamer acquisition geometry on FWI Imaging. Decimation testing of wide-tow multi-source data to simulated inferior 3D sampling of the source wavefields concluded that although FWI imaging may still be applicable to less "well-sampled" data, the original data were far superior.

Collectively, the complementary results in this section illustrate the following:

- Wave equation-based methods such as FWI or reverse time migration (RTM) will often explicitly benefit from a densely sampled source wavefield.
- Furthermore, there is no substitute for dense spatial sampling of both the source and receiver wavefields when attempting to separate signal vs. noise.

As also observed earlier, an accurate knowledge of the (preferably broadband) source wavelet from any source concept is essential for both FWI and QI applications. The message for low-frequency source concepts is that although the SNR at low-frequencies may be higher on a shot-by-shot basis for 'sparse' survey designs, multi-channel signal processing and imaging pursuits will nevertheless be sensitive to under-sampled noise.

Closing Comments

Each of the low-frequency source concepts here required significant engineering efforts to progress from the concept stage to either working protypes or commercialized products. Solutions with band-limited low-frequency output only are explicitly used to benefit FWI model building, and either used in standalone source mode for regional model building or in partnership with a traditional broadband source solution such as air guns. The additional cost will compound the already high cost of OBN acquisition where applicable, so there is a clear motivation to design innovative low-cost OBN solutions.

Acknowledgements

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