The increasing appeal of single-element pneumatic point sources

Marc Rocke[1*], Carsten Udengaard[1], David Brookes[1] and Curt Schneider[1] demonstrate the diversity of uses for single element pneumatic point sources and the promise they hold in opening up flexibility in survey design.

Abstract

The resistance of low frequency seismic energy to scattering and absorption, and its resulting ability to be recorded over long ray paths through attenuating media is well established. This relative resistance to scattering and attenuation makes it vital for capturing information with depth and offset, both for model-building and illumination. There is likely to be no better example of this than modern long-offset OBN (ocean bottom node) surveys of the Gulf of Mexico – however the importance of high-quality low frequencies in unravelling imaging challenges below complex overburden such as shallow gas, carbonates, salt, and volcanics is well documented. Consequently, interest in recording low frequencies in the field extends beyond OBN surveys to include single-vessel and multi-vessel towed-streamer designs. We have seen strong focus on designing sources that produce rich low frequencies over the last decade as a result.

Introduction – The case for broadband via low-frequency octaves

One area of focus for low-frequency seismic data in the last decade is as an effective mitigation against cycle skipping in full waveform inversion (FWI). Although some processing mitigations have been developed, the availability of good low frequencies significantly reduces the risk and effort required to arrive at an accurate velocity model in a broad range of settings. This was a clear driver for investment in improving low-frequency data quality retrieved in the field early on. Dellinger et al 2016, Brenders et al 2018 and others described the use of Wolfspar, a marine vibratory source in the form of a large mechanical bubble which was designed, built, and tested over an eight-year period starting in 2007. Wolfspar produced long sweeps in the 1.4 Hz to 2.5 Hz range on a very sparse grid suited for dedicated FWI velocity model-building, with the migrated image produced using airgun array data. Ronen and Chelminski 2017 described the tuned pulse source (TPS), a single-element pneumatic point source which produced rich low frequencies by emitting a large oscillating air bubble. Brittan et al 2020 described the successful use of a single element pneumatic point source, Gemini, to achieve improved FWI results as a result of enhanced signal-to-noise between 1.5 Hz and 4 Hz.

In addition to discussing the benefits of good low frequencies for FWI model-building, and arguably of comparable importance, ten Kroode et al (2013) demonstrated the importance of low frequencies in reducing source wavelet sidelobes, thereby increasing the resolution of the final image. Notably, extending the source bandwidth to include additional low-frequency octaves also means retaining good signal-to noise at other seismic frequencies typically present after migration. These recorded imaging frequencies are no doubt a function of the geology being surveyed, the density of the survey geometry, and the noise floor of the acquisition system being used. However, a broadband source wavelet that includes additional low octaves ensures sharper resolution and a more interpretable image with clearer definition of seismic events.

If we can accept that low-frequency content is indeed important in the context of a broadband source output, it is interesting to consider that airgun arrays, by design, are comparatively ineffective at generating rich low frequencies. When designing an array, the largest cluster in the array, or primary tuning element, is selected based on the desired resonance frequency or low frequency peak in the target signature. A diversity of gun volumes is then selected to attenuate the bubble energy and flatten the amplitude spectrum of the farfield signature. On the time domain farfield signature, this results in a sharp peak with minimal trailing bubble, at which point the array is said to have a large peak to bubble ratio. The total number of available stations within an array, 18 to 21 in the case of a three-string array, and available compressor capacity limits the range of volumes that can be used to achieve a flat spectrum, thereby limiting the size of the primary tuning element and thus the low-frequency amplitudes that can be achieved. Operationally, there is also a significant downtime consideration to using large (approximately greater than 300 in^3) guns within arrays.

By contrast, single-element pneumatic point sources (SEPPS) leverage the low-resonance frequencies of very large bubbles emitted from a single firing chamber with each shot. As opposed to incorporating a diversity of guns to suppress the bubble of the primary tuning element, as is the case with array design, the entire air budget for the source is directed to a single large element. Similarly to the mechanical bubble of Wolfspar, a large rever-

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berating air bubble is generated. In contrast to Wolfspar, which requires the impulsive signature of airgun arrays to provide mid-band frequencies for imaging, the acoustic signature generated by single element pneumatic sources is led by an initial pulse which provides mid-frequency amplitudes for imaging. Gemini in particular uses industry standard bolt guns mated to its large firing chamber, which results in mid-frequency spectral characteristics comparable to conventional arrays albeit at reduced amplitudes.

Looking at a time series comparison of the farfield signatures of a typical 5000 in^3 airgun array compared to Gemini, the difference in primary peak output is quite noticeable. This is understood by the relationship of peak pulse amplitude of a single element source which varies as a function of the cube root of bubble volume and bubble pressure to the three quarter, as shown in equation (1) based on Vaage et al (1983). Comparatively, the primary pulse amplitude of an array scales as the square root of the number of elements in the array. Thus, the airgun array has significantly greater primary pulse amplitude on account of the large number of guns used. This comparative reduction on primary pulse amplitude has significant environmental benefits considering that the sound pressure level (SPL) of this primary peak drives high-frequency amplitudes output by the source, which are typically associated with environmental and regulatory implications.

$$A_{gun} = K\ V^{1/3} P^{3/4} \tag{1}$$

As a means of demonstrating the character of these high-frequency amplitudes, Figure 6 shows signature spectral plots of an approximately 5000 in^3 airgun array and an 8000 in^3 Gemini each recorded into their respective calibrated nearfield hydrophones at 0.5 ms. For frequencies above the seismic band amplitudes recorded from the Gemini source are observed to be diverging away from those of the airgun array as a function of frequency. Gemini amplitudes are observed to be 5 dB, 20 dB, and 30 dB below array amplitudes at 40 Hz, 250 Hz, and 700 Hz respectively.

Imaging with SEPPS

It is interesting to note that despite the comparative reduction in amplitude in the imaging band, several authors have demonstrated the use of single element pneumatic point sources like Gemini as imaging sources in addition to providing rich low-frequency content. Udengaard et al (2023) demonstrated the use of a Gemini 8000 in^3 source to produce a comparable migration result to a 5000 in^3 array. Arguably, the Gemini source produced a superior image in terms of resolution, illumination and event continuity. Ou et al (2023) demonstrated the use of 8000 in^3 Gemini as the only source in a WAZ (wide azimuth) towed-streamer design for FWI velocity model-building and imaging of sub-salt targets in the East Mediterranean Sea. Four Gemini sources were deployed in a flip-flap-flop-flup configuration on a 12.5 m shotpoint interval between the primary streamer vessel and remote source vessel. The authors noted a 3 to 4 dB boost in frequencies below 4 Hz for Gemini compared to a conventional airgun array on legacy data. While using the Gemini data to image up to 70 Hz, the potential for shallow hazard identification after application of Q-compensation was also noted.

The suitability of these reduced amplitudes generated by Gemini for imaging appears to be threefold. Firstly, arrays with increasingly large total outputs were being designed in attempts to increase low-frequency output. However, the constraints of large peak-to-bubble ratios and flat amplitude spectra would still limit achievable resonance frequencies. Secondly, the last decade of multi-source acquisition and deblending has highlighted the possibility that array outputs have grown to be too large given modern low-noise acquisition technology. This is arguably true in the imaging band and above given the established deficiency in low frequency signal. Rogers et al (2020) discussed the use of single-string airgun arrays, a reduced output of approximately 10 dB in the imaging band compared to the standard three-string array, concluding that, based on deep water clastic, shallow water carbonates, and pre-salt objectives examples, the raw source output may be less of a factor given much of the recorded noise is source generated. Dhelie et al (2019) drew similar conclusions in comparing 3500 in^3 dual source configuration to distributed 875 in^3 hexa-source, also noting the improvement in image resolution due to the increased spatial sampling. Thirdly, the broadband nature of Gemini with its additional low-frequency amplitudes appears to enhance resolution even in the presence of complex or highly attenuating geology as noted by ten Kroode et al (2013).

Both Rogers et al (2020) and Dhelie et al (2019) noted the flexibility in survey design and field operations to be gained if moving from multi-string arrays to single-string, compact sources that better leverage the six gun strings available on contemporary seismic vessels. These arguments for reduced source outputs hold true and seem more compelling if the inherent lack of low frequencies in airgun arrays is addressed. In addition to extended octaves provided by the Gemini source, it is importantly a true point source at seismic frequencies resulting in an omni-directional farfield signature. Figure 1 below shows

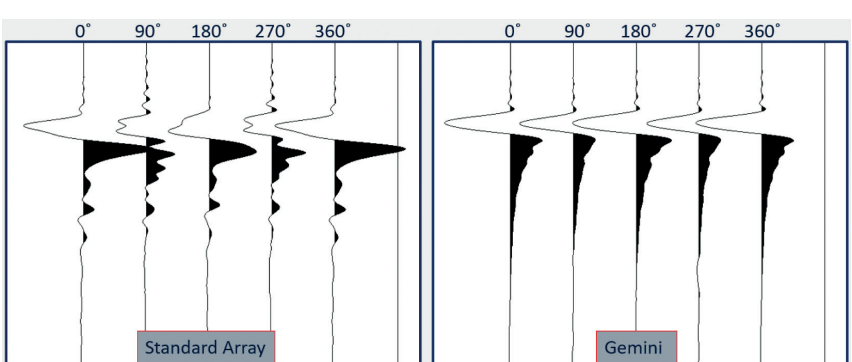

Figure 1 Figure showing farfield signatures at a range of azimuths for a two-string airgun array on the left and a Gemini 8000 in^3 on the right. The homogenous nature of the Gemini signatures with azimuth can be observed.

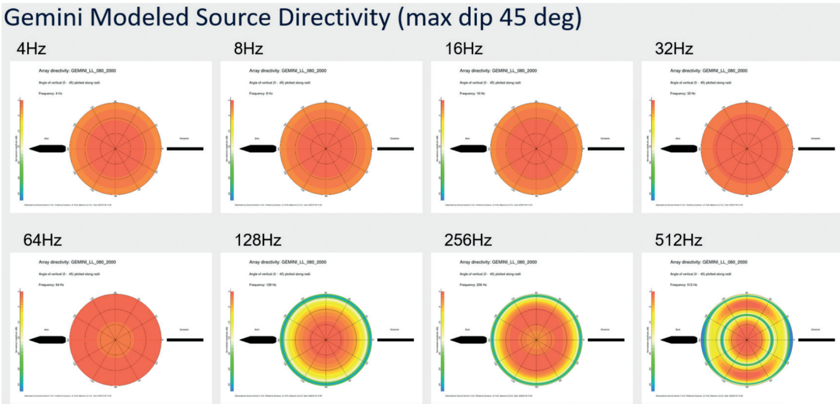

Figure 2 Modelled source directivity of a Gemini 4000 in^3 unit showing point source nature for frequencies of 256 Hz and below.

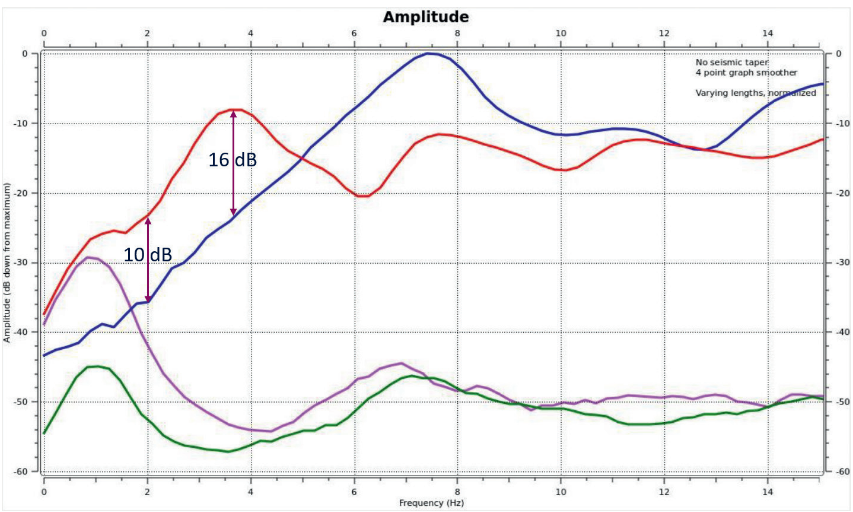

Figure 3 Spectral comparison of a large airgun array and Gemini 8000 in^3.

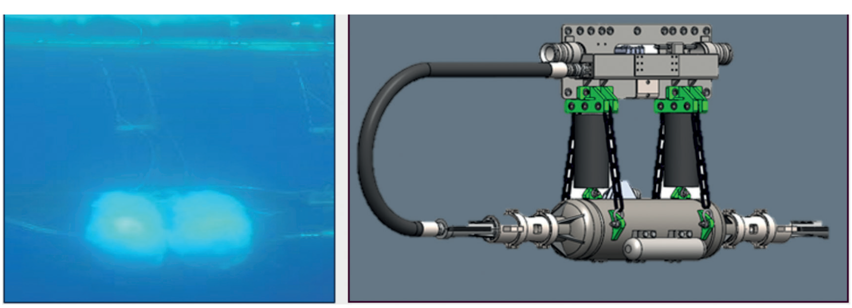

Figure 4 Gemini units shown at time of shot on left as well as computer modelled design on right. Gemini consists of a large air chamber containing a dividing diaghram and orifice and with twin airguns attached at the head and tail.

the azimuthal homogeneity of the Gemini farfield as recorded by OBN data when compared to a large airgun array. This confirms the modelling result which shows an absence of directivity below approximately 250 Hz. This wavelet simplicity means that the source can be characterised very reliably from shot to shot, potentially mitigating errors inherent in de-signature. Additionally, processing steps, which work under the assumption of a point source, can benefit from less variability in the source wavelet. This is particularly true in the presence of complex media as it is virtually impossible to truly retrieve the source wavelet with signal processing techniques once it is exposed to spatially varying ray paths which do not honor angular, straight-ray assumptions.

Operational and Survey Design Considerations

Operationally, SEPPS like Gemini, brings opportunities for survey duration and cost efficiencies on both towed-streamer and OBN surveys. Removing the constraints of multi-string source arrays enables effective use of modern wide-tow and distributed source technology. If using dual or triple source Gemini, three or four umbilicals remain available which can be used to maximise efficiency, either by facilitating the use of hot spares, or by moving source maintenance on an extra unit while online, thereby eliminating source maintenance during line change. Sources are then simply rotated during line changes, potentially making for a less hectic source maintenance effort for the handling crew. In cases where maximised trace density or efficiency is of value through the use of more than three sources, up to six Gemini sources can be deployed as part of the active source effort as vessel compressor capacity for the selected Gemini chamber volume and shotpoint interval allows.

The decreased HSE exposure of dealing with significantly less source elements on each gun string must be highlighted.

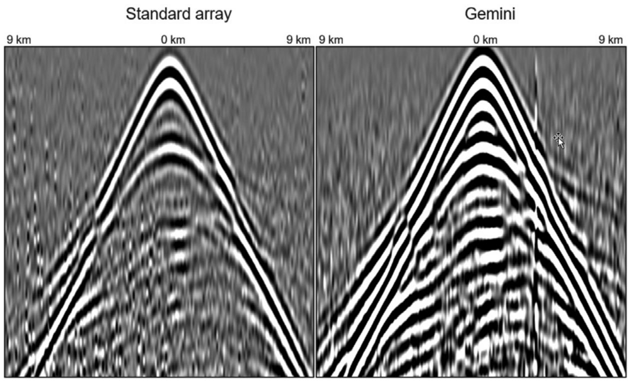

Figure 5 Common receiver gather of standard large OBN array on left compared to Gemini 8000 in^3 on the right. Both images had a 2Hz high cut filter applied. The enhanced signal-to-noise and signal continuity achieved with Gemini can be observed.

Crews describe 20-minute deployment and retrieval compared to three times that with airgun arrays and there are many fewer moving parts on the gun deck.

Looking at the spectral content of the 8000 in^3 Gemini unit in Figure 3, a resonance frequency of approximately 3.4 Hz can be observed. That is approximately 1 octave less than the resonance frequency of a typical large OBN source array. The amplitude of signal at frequencies lower than the resonance frequency in both cases is seen to decay at roughly 18 dB per octave. There is also a 10 to 12 dB separation between 8000 in^3 Gemini and the large airgun array at 4 Hz and below. Although 8000 in^3 and 4000 in^3 Gemini units are already in commercial use in the field, chamber volumes between 1000 in^3 and 14000 in^{3}cu are arguably trivial to produce. A 14,000 in^3 Gemini source, for example, could achieve a theoretical resonance frequency of approximately 2.8 Hz, a roughly 5 dB increase in amplitudes compared to the Gemini 8000 in^3 for frequencies below resonance. Such a large volume, however, would come with significant operational complexities for use on any surveys other than dedicated sparse-shot velocity surveys.

When considering the SEPPS parameters to be used during the survey design process, the resonance frequency at nominal tow depth, chamber pressure and volume is likely a good place to start. As described by the Rayleigh-Willis equation in (2) below, the resonance frequency of the source bubble reverberation is inversely proportional to the cube root of the product of air pressure and volume (mass, or amount of air) in the firing chamber at the time of firing. Adjusting either the chamber volume or pressure will thus shift your resonance frequency to the right or left accordingly, with a corresponding 18 dB/Octave difference in amplitude at any frequency below resonance frequency. Using the example of the 8000 in^3 and 4000 in^3 Gemini sources towed at 8 m, their resonance frequencies are 3.4 and 4.2 Hz respectively, with an approximately 6dB difference in amplitude between them below resonance frequency, an additional four to 6 dB above large airgun array amplitudes. For survey design purposes, it should be noted that the firing pressure of Gemini can be modulated between 1500 and 2000 psi. At 1500 psi firing pressure, the Gemini 8000 in^3 achieves a resonance frequency of 3.7 Hz with a 2.5 dB drop in amplitudes for frequencies below resonance frequency compared to the nominal 2000 psi firing pressure, roughly equivalent to between 8 and 10 dB above low frequency amplitudes of a large airgun array.

$$T_{buble} = K \frac{P_0^{1/3} V^{1/3}}{P_H^{5/6}} \quad (2)$$

This relationship between amount of air with each shot and amplitudes at low frequencies raises practical considerations for chamber fill-time versus shot density and efficiency achievable in the field. Arguably, the 8000 in^3 Gemini occupies a 'sweet spot' that allows it to achieve 25 m flip-flop shooting on modern towed-streamer and dedicated source vessels as shown in Figure 7. Triple source with 16.67 m shotpoint interval is also achievable on modern high-spec source and streamer vessels. The total volume under use and the frequency with which a source can be fired is a function of compressor capacity on the source vessel. Figure 7 shows the achievable shotpoint intervals (independent of number of sources) achievable with different total compressor capacities assuming 80% utilisation. A 6600 cfm compressor capacity would be needed to drive 3 x 8000 in^3 Gemini sources at a 16.67 m shot point interval at nominal vessel speed.

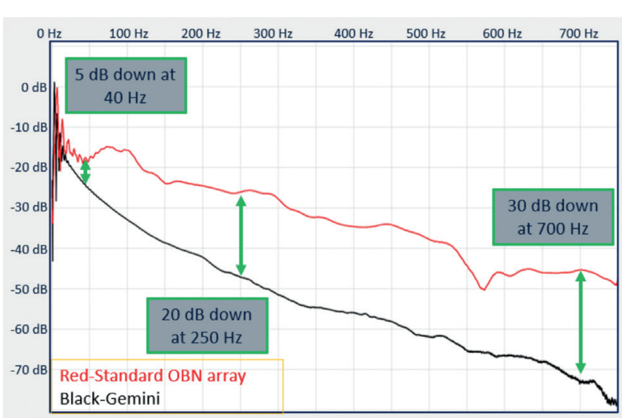

Figure 6 Spectral comparison of large airgun array and Gemini 8000 in ^{3} recorded into their respective calibrated nearfield hydrophones. The diverging trend between Gemini and airgun array amplitudes above imaging frequencies can be seen and speaks to the potential reduced environmental impact due to reduced high-frequency amplitudes emitted into the water column.

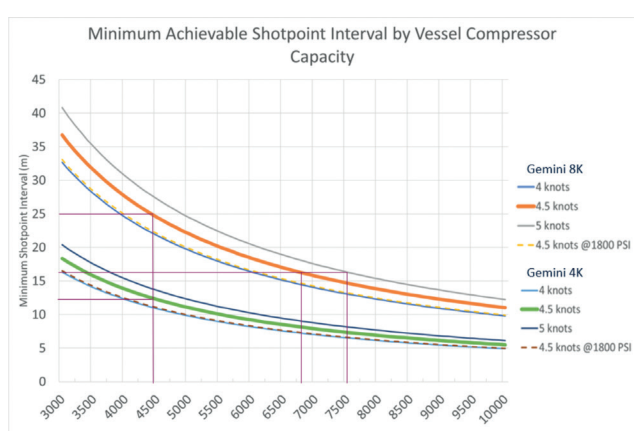

Figure 7 Plot of vessel compressor capacity vs achievable average shotpoint interval for Gemini 8000 in^3 and 4000 in^3 assuming 80% compressor utilisation as well as 100% chamber evacuation with each shot (a conservative scenario).

Umbilical Length (m)	300	600	900	1200
Fill time using 1 inch umbilical (s)	10	14	18	20
Fill time using 1.25″ umbilical (s)	6	8	10	12

Table 1 Time to refill 8000 in^3 Gemini unit to nominal firing pressure using umbilicals of differing dimensions. 300 m, 60 0m, and 1200 m are meant to depict dedicated source, streamer, and wide-tow-capable vessels respectively.

Separate from compressor capacity, the dimensions of the gun umbilicals are an important consideration as they determine how frequently each source can be filled and fired. Aznar et al. (2022) describe a useful mathematical relationship between umbilical dimensions (length and diameter) and the time required to fill its source. Table 1 shows this relationship for typical source, streamer, and wide-tow equipped vessels currently in operation. It becomes readily apparent that accessing SEPPS technology via a wide cross section of vessel capabilities while maintaining conventional shot grids makes 8000 in^3 a realistic starting volume while still maintaining operational flexibility. In basins with shallower targets that require denser spatial sampling, the Gemini 4000 in^3 can be used in triple source configuration with a 12.5 m shot point interval (37.5 m in line shot point interval). In cases requiring even denser shot sampling, 6x 4000 in^3 Gemini units can be used. These can also be spread out in a wide-tow fashion to maximise efficiency which applies across the full spectrum of survey types.

Conclusion

A closer look at single element pneumatic point sources reveals their diversity of uses and the promise they hold in opening up flexibility in survey design. Although the initial driver for their development appears to have been for building rich low frequencies for accurate velocity modelling and FWI, an array of other benefits have been identified as noted in this article. The simplicity of processing point source omnidirectional farfield signatures, the environmental mitigations of diminished frequencies above the seismic band, the extended octaves for better resolution and a more interpretable image, and good signal at imaging frequencies have all been documented by various authors. In terms of survey design, the one-string-one-source approach is ideal for exploiting vessel wide-tow capability to produce well sampled shot grids through the use of distributed sources. Vessel compressor capacity and umbilical dimensions are a key consideration during the design stage but by no means should be considered a barrier to entry given the commercial availability of operationally favourable volumes, such as the Gemini 8000 in^3 and 4000 in^3 which can be operated at between 1500 PSI to 2000 PSI chamber pressure according to vessel capability. With the increasing momentum towards distributed point sources and the effectiveness of multi-source decoding technology, such as seismic apparition (Robertsson et al 2016), as well as deblending, it appears that single-element pneumatic point sources like Gemini are here to stay.

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