Geophysical Prospecting EUROPEAN ASSOCIATION OF GEOSCIENTISTS & ENGINEERS

Geophysical Prospecting, 2019 doi: 10.1111/1365-2478.12774

Low-frequency pneumatic seismic sources

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Received March 2018, revision accepted February 2019

ABSTRACT

Pneumatic seismic sources, commonly known as airguns, have been serving us well for decades, but there is an increasing need for sources with improved low-frequency signal and reduced environmental impact. In this paper, we present a new pneumatic source that is designed to achieve these goals by operating with lower pressures and larger volumes. The new source will release more air creating larger bubbles with longer bubble periods than airguns. The release of the air will be tuned so that the rise time will be longer and the sound pressure level and its slope will be lower. Certain engineering features will eliminate cavitation. Larger bubbles increase low-frequency content of the signal, longer rise times decrease mid-frequency content and the elimination of cavitation reduces high-frequency content. We have not yet built a full-scale version of the new source. However, we have manufactured a small-scale low-pressure source incorporating most of the engineering features, and tested it in a lake. Here, we present the lake data that, as expected, show a significant reduction in the sound pressure level, increase in rise time, decrease in slope and decrease in high-frequency content while maintaining the same low-frequency content when the source prototype is operated at low pressure compared with high pressure. Synthetic data produced by numerical modelling of the full-scale proposed pneumatic source suggest that the new source will improve the low-frequency content and can produce geophysically useful signal down to 1 Hz.

Key words: Acquisition, Seismics.

INTRODUCTION

Active seismic surveys provide valuable data for hydrocarbon exploration, development and production. Currently, airguns (Chelminski 1961) are the main seismic source used in active offshore surveys. The airgun, when introduced in the 1960s, was a significant safety and environmental improvement over the explosives that had been used before. At the time, what limited the low-frequency content was receiver technology. However, since the introduction of the airgun, progress in offshore seismic source technology has been much less than the progress in receiver technology and in data processing, and the airgun has become the limiting factor on low-frequency content. With increasing need for broader band seismic data (Ziolkowski *et al.* 2001; ten Kroode *et al.* 2013) and greater public awareness of the environmental impact of airguns, it is time to improve the seismic sources.

Onshore, the seismic industry has moved (partially) from explosives to Vibroseis, and there is an expectation that Marine Vibroseis will be the future offshore seismic source. There has been extensive work on developing Marine Vibroseis (Haldorsen, Desler and Chu 1985; Hampson and Jakubowicz 1990; Noss *et al.* 1999; Chelminski 2013; Schostak and Jenkerson 2015; Dellinger *et al.* 2016). However, in spite of significant research and development investment over decades, marine vibrators are not yet widely used, and airguns remain the predominant source offshore. One reason

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for the slow acceptance of marine vibrators is that in order to produce the low-frequency content that is required to discover, develop and produce the remaining hydrocarbons, marine vibrators must be very large, heavy, and use very long sweeps. This presents engineering, operational and data processing challenges. Meanwhile, the motivation for broader band seismic data and reduced environmental impact is mounting.

When airguns were introduced, the oil industry expected and demanded sources that would produce wavelets (so-called source signatures) that were similar to the explosives that they replaced. Therefore, air guns were designed to be filled with as high-pressure air as practical, which was 207 bar, and with a shuttle that travels a certain acceleration distance, so that their ports would open rapidly, quickly expose high-pressure air to ambient pressure water and produce a short rise time. Furthermore, in order to be similar to dynamite, airguns were deployed in arrays of a large number of small guns. Such arrays produced a source signature characterized by a large initial peak with a short rise time followed by much smaller bubble oscillations. A high primary-to-bubble ratio (PBR) was desired (Dragoset 2000) because at the time of the introduction of the airgun, bubble oscillations were considered noise due to the limited dynamic range of recording systems and consequently the limited ability of data processing to turn the bubble from noise to low-frequency signal.

Following the early introduction of air guns operating at 207 bar, it was found that operating at 172 bar and subsequently at 138 bar did not compromise geophysical quality. Lower pressure did reduce the wear and tear, and so within a decade or two of their introduction, all air guns were operating at 138 bar.

Advances in receiver technology since the 1960s when airguns were introduced include more channels, better sensors, increased dynamic range (24 and even 32 bits), multi-sensors, near-field hydrophones, slanted streamers, solid streamers, wide azimuth geometry and ocean bottom nodes (OBN). The progress in receiver technology has improved the useful low-frequency content of the data, such that it is now limited by the source. Better dynamic range has enabled broadband processing that includes improved deghosting and designature. Deghosting removes the surface reflection (ghost), while designature turns the bubble oscillations from noise to signal. Advanced designature should make high PBR requirement obsolete.

In parallel to the geophysical consideration above, the public became more aware of the environmental impact of seismic surveys. The 50-year-old "just-like-dynamite" requirement caused airguns to produce waves at high frequencies that are attenuated and scattered in the overburden and are therefore useless for imaging deep targets. However, the high-frequency waves are likely disruptive to marine life. Therefore, it is desirable to reduce the high-frequency component of the source signature.

Despite the above geophysical and regulatory developments, the heavy design for up to 207 bar, the acceleration distance, the arrays of many-small-guns and the high PBR requirement became entrenched in the seismic industry and source technology has not advanced significantly in the last 50 years. Here, we present a pneumatic source that we propose as a replacement for airguns.

MECHANICAL ENGINEERING OF THE NEW SOURCE

The Tuned Pulse Source (TPS; Chelminski 2016, 2017), shown in Fig. 1, is designed to operate at lower pressures and larger volumes than airguns. The low pressure of the TPS enables large volumes with acceptable weight. The TPS internal design, shown in Fig. 2, is very different from the airgun design. It has a cup-shaped flange and extended ports that go almost 360° around the operating housing. The large port area is feasible due to the low operating pressure. The airflow is directly into the firing and operating chambers with a check valve that eliminates the risk of auto-fires and accidental fires and enables quick filling of large firing chambers. In comparison, the airflow method in conventional airguns is via the operating chamber and the shuttle, which limits the volume that can be filled between shots, carries the risk of accidental fires and is prone to auto-fire when draining the air. Also, the acceleration distance is eliminated in the TPS. Thanks to the low pressure, the cup-shaped flange and the elimination of the acceleration distance, we expect the TPS to eliminate or at least significantly reduce cavitation generated by thin jets of water and air produced by current airguns. The length of the firing chamber tunes the rise time of the first peak. The longer firing chamber increases the rise time, which decreases the slope and the high-frequency content.

PHYSICS AND NUMERICAL MODELLING OF PNEUMATIC SOURCES

Pneumatic sources radiate energy with a low-frequency limit set by their bubble frequency and a high-frequency limit set

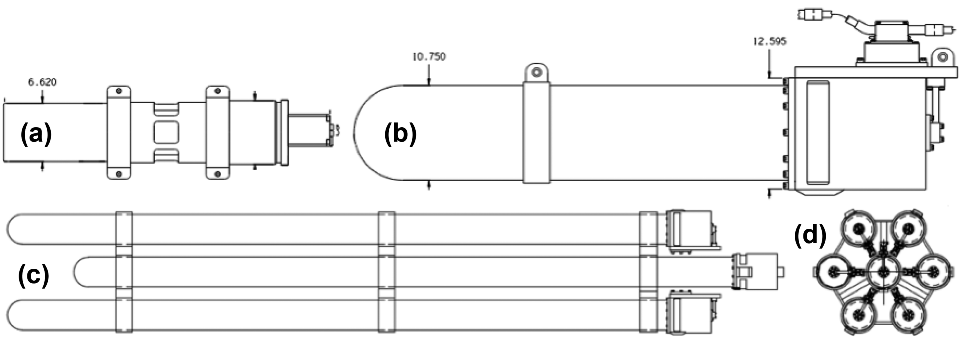

Figure 1 (a) An airgun with a 5.74 L firing chamber. The diameter is 168 mm. (b) A Tuned Pulse Source with a 65 L firing chamber drawn on the same scale. The diameter of the TPS firing chamber is 273 mm. (c) Side view of an ultra-low-frequency (ULF) 7 × 328 L TPS cluster drawn at a smaller scale; the length of each 328 L firing chamber is 6 m. (d) Front view of the ULF; the diameter of each firing chamber is 273 mm.

by their rise times and cavitation, if any. The bubble period is proportional to $(PV)^{(1/3)}$, where P is the firing pressure and V is the volume (Willis 1941; Watson, Dunham and Ronen 2016). The quantity PV is related to the mass of air that is ejected from the airgun into the water. An airgun with higher pressure or larger volume will discharge more air and produce a bigger bubble. The oscillation period of the bubble is proportional to the size (Rayleigh 1917). A larger bubble oscillates slower and hence generates signal with a lower dominant frequency. When airguns are close enough for their bubbles to interact or merge, the guns are referred to as a cluster. In this case, the bubble period is approximately proportional to the cubic root of the total volume of the cluster (Strandenes and Vaage 1992; Barker and Landrø 2014). Airgun clusters have been used to increase the low-frequency content of airgun arrays and improve imaging of deep targets (Shimizu *et al.* 2009). In Fig. 3 we show results from numerical modelling (details in Appendix) of an airgun array (pressurized at 138 bar, volume of 3 × 2 × 5.74 L) and two TPS clusters (one at 55 bar and 3 × 0.16 L and the other at 69 bar and 7 × 0.32 L). The Tuned Pulse Source (TPS) has reduced pressure but significantly increased volume compared with an airgun. The airgun array shown in Fig. 3 has a PV value of 0.46 MJ compared with 2.71 MJ for the Very Low Frequency (VLF) TPS cluster and 15.8 MJ for the Ultra-Low-Frequency (ULF) TPS cluster. The large PV value of the TPS clusters means that the amplitude spectra are shifted to lower frequency values such that the TPS generates more low-frequency signal and less high-frequency noise.

The reduced operating pressure of the TPS decreases the mass flow rate out of the airgun, which means that the bubble initially expands slower, increasing the rise time of the first peak of the source signature and hence decreasing the high-frequency signal generated. This is seen in simulations (Fig. 3) that are then overlaid on field data (Fig. 4).

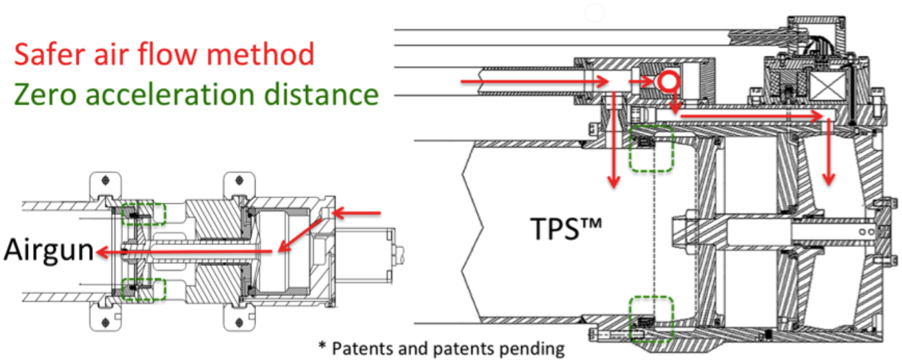

Figure 2 A comparison of the different internal designs of the TPS and the airgun. Out of a number of different design features, two are highlighted here. The safer airflow method (red) and the zero acceleration distance (green).

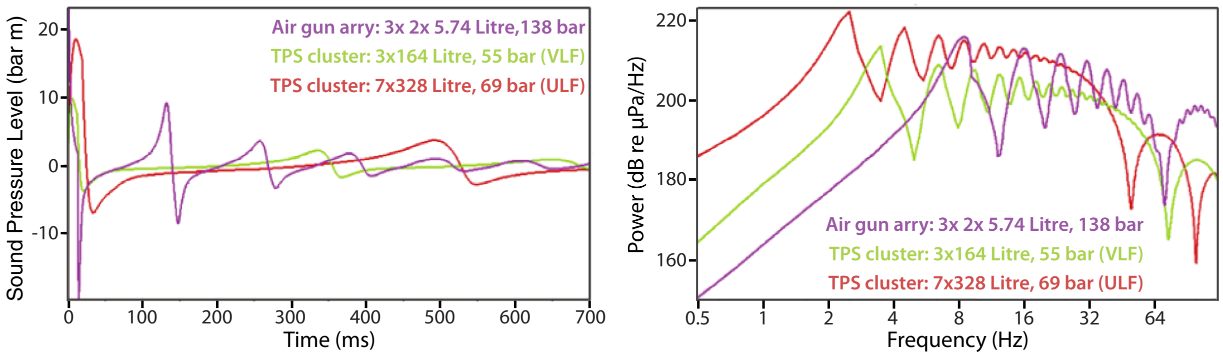

Figure 3 Time domain (left) and spectra in dB re uPa-M (right) modelled signatures of ultra-low-frequency (ULF), very-low-frequency (VLF) and 3 × 2 × 5.74 L airgun array. We estimate that the operational depth of the VLF will be 10 m and that of ULF 15 m. Signatures are simulated using the modelling framework of Watson, Dunham and Ronen (2016).

MARINE OPERATIONS OF THE NEW SOURCE

In addition to the internal design features described above, an important feature of Tuned Pulse Source (TPS) is that fewer elements are needed per array. Airgun arrays typically have three sub-arrays with about ten guns under each float. A TPS array will have fewer elements and these will be located under a single float. This will simplify deployment and retrieval, improve source steering and positioning control and accuracy, reduce the shot-to-shot variations that are due to sub-arrays drifting cross-line, improve cross-line sampling and increase tolerance to bad weather.

Given the industry experience with old pneumatic sources (conventional airguns), upgrading to TPS will have a relatively small impact on seismic operations. The current operational and processing technologies that were developed for air guns can be used. Small to no change in data processing is needed. Like airguns, the TPS bubbles are not moving laterally while radiating seismic waves, so there is no need for source motion correction in processing. To take full advantage of TPS, seismic crews will need to change to low-pressure and high-volume compressors and use different umbilicals. These changes are expected to be able to be completed with little delay and at a reasonable cost. Such changes are

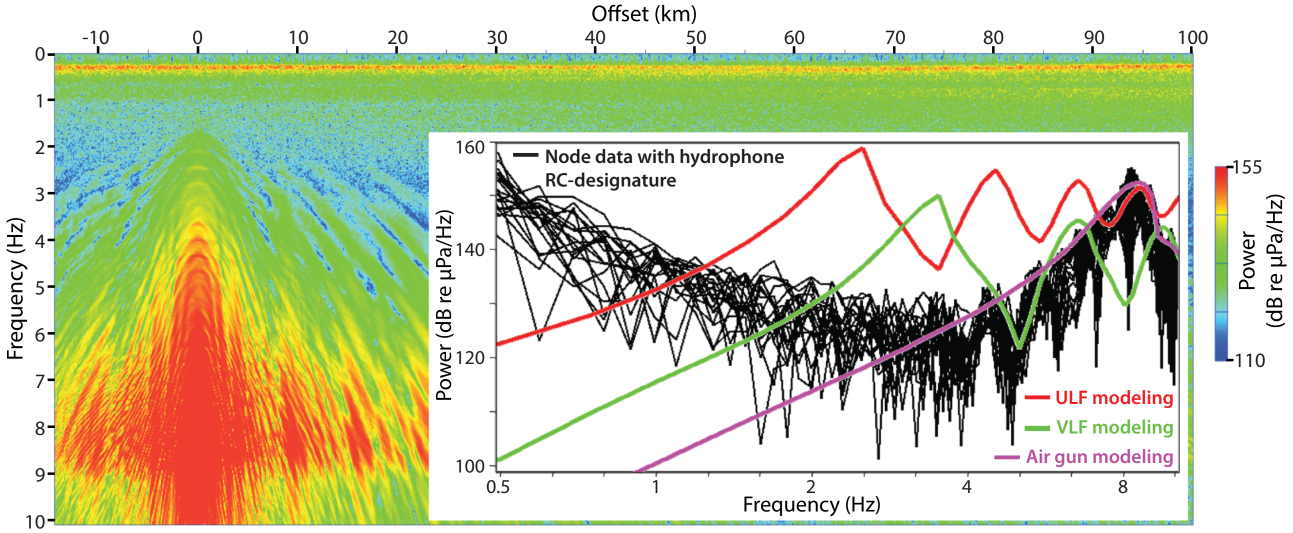

Figure 4 Power spectra dB re uPa of modelled ULF, VLF and airgun overlaid on node data with airguns 30 km away (in black). Hydrophone RC analogue low-cut designature was applied to the node data in processing. The background image is the "FX" spectra of all shots up to 100 km offset from the node. Note that the frequency at which the airgun signal crosses under the ambient noise is about 4 Hz, that of VLF is 2 Hz and the ULF is 1 Hz.

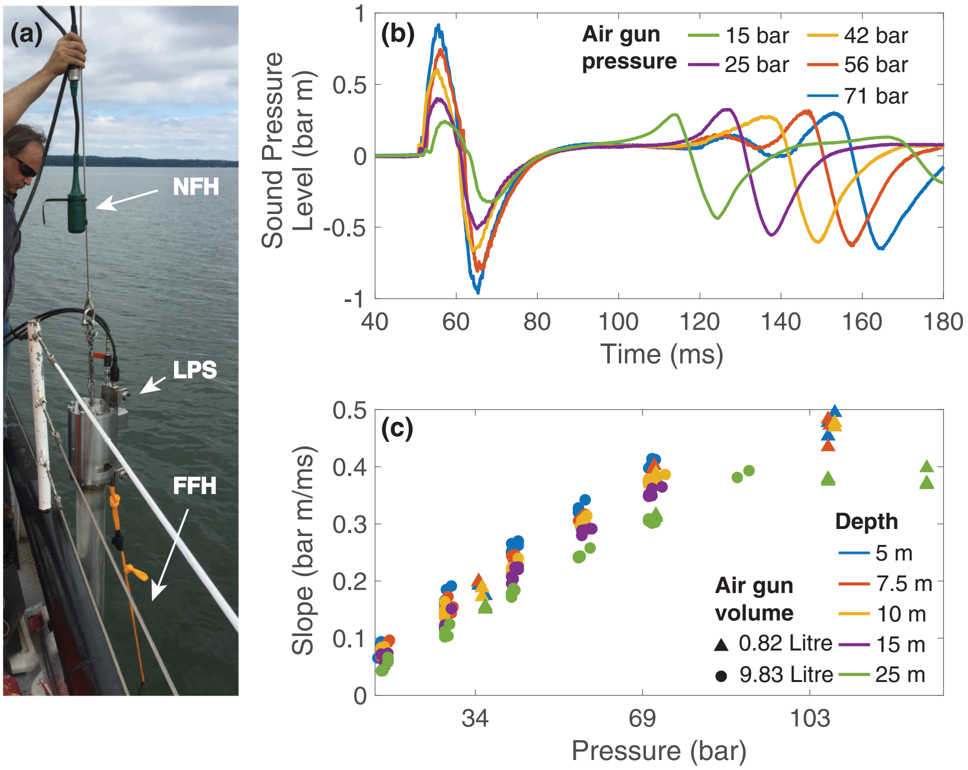

Figure 5 (a) Tuned Pulse Source (TPS) prototype deployed in Seneca Lake. A 9.83 L firing chamber is hanging below the operating housing of the TPS. Above the source, there is a (dark green) near-field hydrophone (NFH). Below the source, already in the water (hanging on an orange nylon rope) there is a vertical array of 24 far-field hydrophones (FFH). (b) FFH data for 9.83 L TPS deployed at 7.5 m, with various air pressures. The maximum sound pressure level bubble period and slope depend on the operating pressure. (c) Slope plotted as a function of operating pressure. The slope is independent of volume and is proportional to the difference between initial air pressure and ambient pressure.

relatively small compared with replacing pneumatic sources altogether by new sources such as marine vibrators.

To optimize compressor capacity on the source vessel, we would recommend shooting the lower frequency TPS with larger firing chambers less often than the smaller ones which emit higher frequencies. We will see in the next section that such frequency-dependent shot interval fits the geophysical requirements and not just the operational constraint of limited compressor capacity.

GEOPHYSICAL CONSIDERATIONS AND IMPLICATIONS

To explore deeper, under complex overburdens such as salt and basalt, and to build blocky reservoir models, the seismic industry and their clients need improved low-frequency signal (Ziolkowski *et al.* 2001). In particular, velocity model building with a family of methods known as Full-Waveform Inversion (FWI) are prone to local minima in matching data to model—a problem known as cycle skips since the days of residual statics. While great progress has been made to overcome cycle skips in processing (Biondi and Almomin 2013; Warner, Guasch and Yao 2015), having data with improved low-frequency content can significantly help to avoid local minima. Following ten Kroode et al. (2013), our ambition level for the ULF source is 1 Hz signal at far offsets.

Spectra of high-quality ocean bottom node (OBN) data (courtesy of Seabed Geosolutions) show that the conventional airguns that were used in this survey had 8 Hz dominant bubble frequency. The frequency at which the signal from the airguns is crossing under the ambient noise is 4 Hz. At low frequencies, the airgun signal is lower, and the ambient ocean noise is higher. By overlaying the data with spectra of modelled spectra, we estimate that the VLF and ULF sources, as shown in Fig. 3, will provide one and two octaves, respectively, of additional low-frequency signal compared with conventional air guns. Figure 4 shows the modelled Tuned Pulse Source (TPS) signal overlaid on recorded OBN

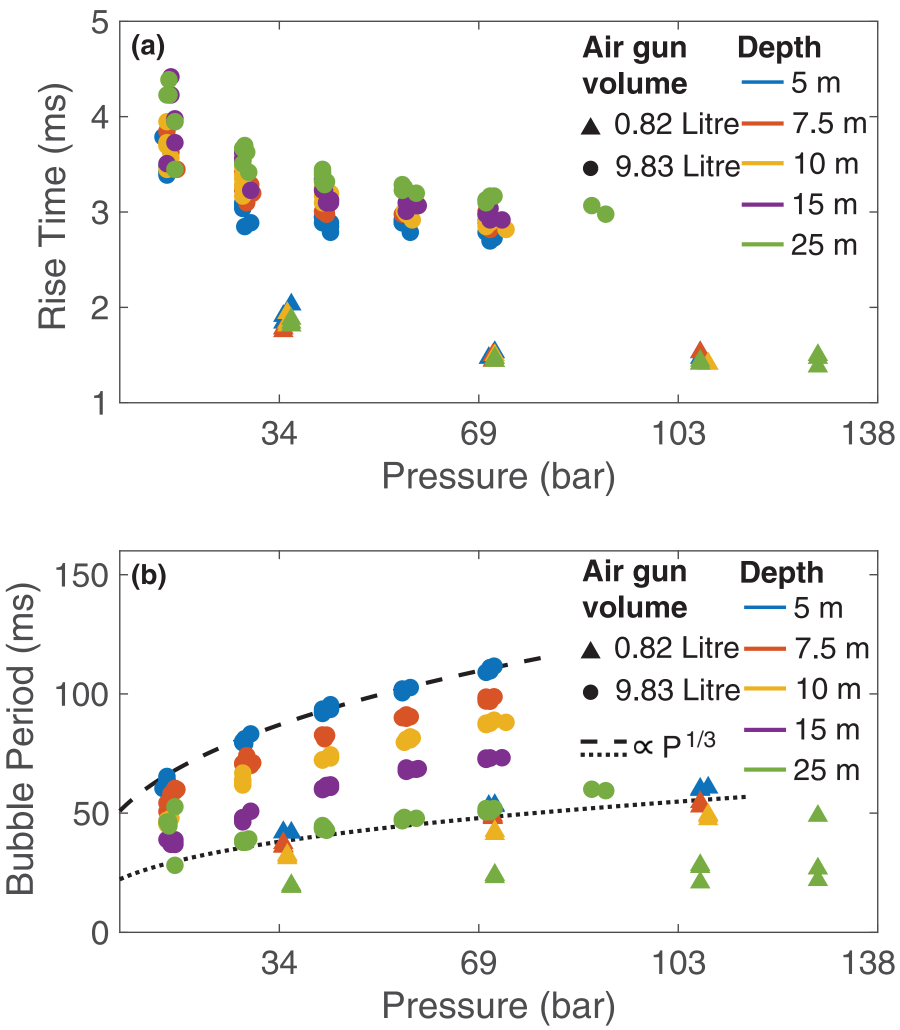

Figure 6 Data from Tuned Pulse Source prototype tests in Lake Seneca. (a) Rise time as a function of airgun pressure for various firing depths and two different airgun volumes. (b) Bubble period as a function of airgun pressure for various firing depths and two different airgun volumes. The black lines indicate $a(PV)^{1/3}$ for $V = 9.83$ L (dashed) and $V = 0.82$ L (dotted). The proportionality constant a is chosen to match the $V = 9.83$ L data.

data with ambient ocean noise and airguns 30 km away. According to this analysis, the VLF source will generate signal with amplitude greater than the ambient ocean noise down to 2 Hz while the ULF source can potentially broaden the usable bandwidth down to 1 Hz.

We predict that TPS will be deployed in somewhat different arrays compared with airguns. As mentioned above, airguns are deployed in arrays of sometimes 30 guns of various sizes. This achieves a high PBR, but is a wasteful deployment because small guns with high-frequency content have the same shot interval as large guns with low-frequency content. Smaller volume TPS, emitting higher frequency content and shorter waves, require denser spatial sampling than larger volumes emitting longer waves. Also, the low-frequency signal is reflected from deeper targets and requires longer listening time. Therefore, in addition to the operational reason (limited compressor capacity) to have frequency-dependent shot interval, there are also geophysical reasons to do so. Note that in practice this leads to self-interference because the high-frequency sources will be fired before the low-frequency echoes will have time reflect from deeper targets. Frequency-dependent shot intervals are therefore dependent on data processing methods that will deblend the data or image blended data. Fortunately, different signatures of interfering sources provide an opportunity in deblending by using the different signatures as done in

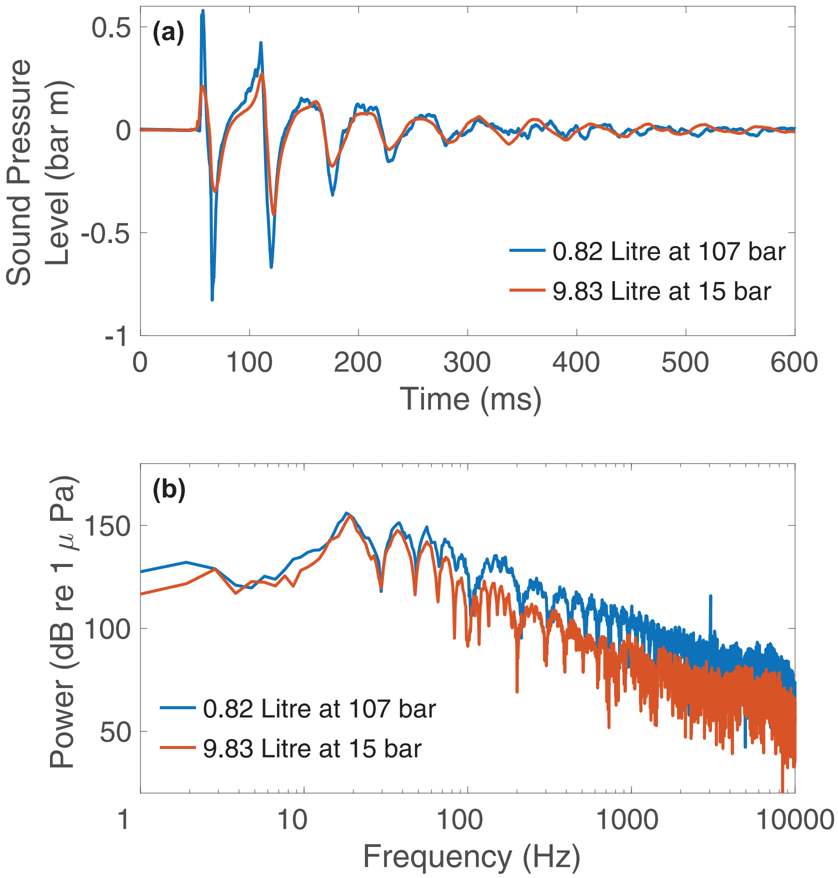

Figure 7 Comparison between modeled low-volume high-pressure shot (blue) and high-volume low-pressure shot (red) in the time (a) and frequency (b) domains. The two shots have a similar bubble frequency, which is expected as the two airgun configurations have a similar $(PV)^{(1/3)}$. The high-volume low-pressure shot has reduced sound pressure level, by approximately a factor of two, and significantly reduced high-frequency content while maintaining essentially the same low-frequency content. The source was located at a depth of 7.5 m and the far-field hydrophone 75 m further below.

voice recognition (Pramik *et al.* 2015; Jennings and Ronen 2017).

SAFETY

When airguns replaced explosives, safety was greatly improved; the rise time of an airgun source signature is longer than that of explosives, and the overall energy released on each shot is smaller. A small airgun releases energy that is equivalent to just a few grams of dynamite. A large airgun releases energy that is equivalent to a few tens of grams of dynamite. This becomes dangerous if an airgun is accidently shot onboard with people nearby. There have been far fewer accidents with airguns than with explosives, and the accidents that occurred were accidental firing or auto-fires. A problem is that airguns auto-fire when the air pressure is draining out. This happens in airguns because their operating chambers drain before their firing chambers. With the large airguns that are required for achieving low-frequency signal, safety is a great concern. Like airguns, Tuned Pulse Source (TPS) must have a large volume to produce low frequencies, and although the air pressure is lower, a large TPS will release energy that is equivalent to 800 g of dynamite. It will release it much slower, yet it can blow a person off the back deck if it is fired accidentally or automatically by itself. Therefore, a safer airflow method is a requirement for large TPS. The new airflow method (Fig. 2) eliminates the risk of auto-fires because the check valve makes sure the firing chamber drains before the operating chamber. Accidental-fire risk is eliminated because the operating chamber is charged first and the firing chamber is charged only when the source is in the water and away from people.

ENVIRONMENT

The air pressure in the Tuned Pulse Source (TPS), a factor of 2 to 3 lower than in airguns, generates a lower peak sound pressure level (SPL). We predict that a TPS array will generate SPLs that are approximately half that of a typical airgun array. As significantly, the long firing chambers generate long rise times, and this reduces the slope and the frequency content in the hundreds of Hz and kHz range. The TPS will, if deployed in an Ultra-Low-Frequency configuration, increase the low-frequency content (below 7 Hz) – the effect of which on marine life is a concern to be studied (Watson *et al.* 2017). Frequency content of TPS higher than 7 Hz will be the same as airguns until approximately 50 Hz and lower at higher frequencies. Marine Vibroseis will have a lower SPL and lower slope than TPS, but longer duration and higher duty cycle—the effect of which on marine life is similarly a concern to be studied.

Airguns generate cavitations (Landrø, Amundsen and Barker 2011) which, although they may be a source of high-frequency signal, are undesirable, from both an environmental and operational perspective because cavitations can be damaging to life and equipment in the water. The cup-shaped flange of the TPS, the zero acceleration distance and the larger ports will greatly reduce, if not completely eliminate, cavitations coming directly from the source. Ghost cavitations (Landrø, Ni and Amundsen 2016) will also be reduced thanks to the smaller number of sources in an array, and the frequency-dependent shot interval.

LAKE TESTING

We tested a small-scale low-pressure source (LPS) in Seneca Lake. We had two firing chambers: a 0.82 L and a 9.83 L. The large volume was shot at pressures varying from 14 to 69 bar, and the small volume from 34 to 138 bar. Data were recorded by near-field and far-field hydrophones (NFH and FFH). The NFH was tied above the LPS and recorded data at $\Delta t = 0.5$ ms sampling interval (2 kHz sampling rate and 1 kHz Nyquist frequency). The FFHs were a vertical array of 24 hydrophones. The nearest one was 75 m below the LPS and the furthest one was 121 m away with 2 m vertical interval between hydrophones. The FFH, with $\Delta t = 31.25\ \mu$s sampling interval (32 kHz sampling rate) provided excellent data up to its Nyquist frequency of 16 kHz. We recorded approximately 300 shots. Shots at the same depth, volume and pressure were repeated 3–6 times to test repeatability.

We extracted and analysed several attributes from the Seneca Lake data. In Fig. 5 we show one key attribute, the slope, which is how fast the wave pressure rises. Sound pressure levels (SPLs) are given in Bar-Meters (BarM), which is measured SPL in Bars multiplied by the distance from the source to the receiver in metres. SPL is proportional to particle velocity (multiplied by the acoustic impedance). Slope is measured in BarM per millisecond and is proportional to particle acceleration and hence to the force that the acoustic wave applies on marine life and equipment. The slope is therefore an important indicator of environmental impact in the form of direct damage to marine life. A higher slope corresponds to increased high-frequency content, which is hypothesized to be more damaging to marine life. The wave-pressure slope is lower with lower gun pressure.

Figure 6 shows two more attributes picked from the Seneca Lake data. The rise time depends strongly on the source volume and weakly on the pressure. The rise time is an indicator of high-frequency content generated and hence can be used as a proxy for environmental impact, as marine mammals are likely most sensitive to the high frequencies generated by seismic sources. We claim that the significant parameter is not the volume but the length of the firing chamber as all volumes tested had the same diameter and only differed in length. The other attribute that we show in Fig. 6 is the bubble period, which is an indicator of the low-frequency limit. The bubble period is proportional to $(PV)^{(1/3)}$ (Willis 1941; Watson *et al.* 2016).

A high-pressure low-volume shot is compared with a low-pressure high-volume shot in Fig. 7. It is shown that for the same bubble frequency and low-frequency content, the high-frequency content was much reduced with lower pressure and larger volume.

CONCLUSION

There is a pressing need to improve existing marine seismic source technology in order to meet the dual goals of improved low-frequency content for imaging more challenging targets and to reduce the high-frequency noise to minimize the environmental impacts of active seismic surveys.

We expect that the new pneumatic source presented here will be capable of producing low-frequency signal down to 1 Hz and will have a lower environmental impact compared with airguns in use today. We used data from a small-scale low-pressure source and numerical modelling to support our expectations. Future work will involve manufacturing and testing a full-scale Tuned Pulse Source.

ACKNOWLEDGEMENTS

The authors thank Eric Dunham for his assistance with the modelling work. The modelling code used in this work is available at https://github.com/leighton-watson/SeismicAirgun. We thank Shearwater Geophysical and Low Impact Seismic Sources (LISS) for the data. S. Chelminski and S. Ronen

declare a conflict of interest as partners in LISS, which is a commercial equipment manufacturing company.

REFERENCES

Babu V. 2014. *Fundamentals of Gas Dynamics*, 2nd edn. John Wiley and Sons, Chichester.

Barker D. and Landrø M. 2014. An alternative method for modeling close-range interactions between air guns. *Geophysics* **79**, P1–P7.

Biondi B. and Almomin A. 2013. Tomographic full-waveform inversion (TFWI) by combining FWI and wave-equation migration velocity analysis. *The Leading Edge* **32**, 1074–1080.

Chelminski S. 1961. Acoustic wave impulse generator repeater. US Patent 3249177 A.

Chelminski S. 2013. Marine vibratory sound source for beneath water seismic exploration. US Patent 8570835 B2.

Chelminski S. 2016. Device for marine seismic explorations for deposits. US Patent 8971152 B2.

Chelminski S. 2017. Method and apparatus for tuning the rise time of the initial pulse of an airgun. US Patent 9804280 B2.

Cole R.H. 1948. *Underwater Explosions*. Princeton University Press, Princeton.

de Graaf K.L., Penesis I. and Brandner P.A. 2014. Modelling of seismic airgun bubble dynamics and pressure field using the Gilmore equation with additional damping factors. *Ocean Engineering* **76**, 32–39.

Dellinger J., Ross A., Meaux D., Brenders A., Gesoff G., Etgen J. et al. 2016. Wolfspar, an "FWI-friendly" ultralow-frequency marine seismic source. SEG Technical Program Expanded Abstracts, 4891–4895.

Dragoset B. 2000. Introduction to air guns and air-gun arrays. *The Leading Edge* **19**, 892–897.

Haldorsen J., Desler F. and Chu D. 1985. Use of vibrators in a marine seismic source. SEG Technical Program Expanded Abstracts, 509–511.

Hampson G. and Jakubowicz H. 1990. Effects of source and receiver motion on seismic data. SEG Technical Program Expanded Abstracts, 859–862.

Herring C. 1941. Theory of the pulsations of the gas bubble produced by an underwater explosion. Office of Scientific Research and Development report 236.

Jennings J. and Ronen S. 2017. Simultaneous source deblending with the radiality and source-similarity attributes. SEG Technical Program Expanded Abstracts, 4909–4913.

Landrø M., Amundsen L. and Barker D. 2011. High-frequency signals from air gun arrays. *Geophysics* **71**, Q19–Q27.

Landrø M., Ni Y. and Amundsen L. 2016. Reducing high-frequency ghost cavitation signals from marine air-gun arrays. *Geophysics* **81**, 1–14.

Laws R.M., Hatton L. and Haartsen M. 1990. Computer modelling of clustered air guns. *First Break* **8**, 331–338.

Li G.F., Cao M.Q., Chen H.L. and Ni C.Z. 2010. Modeling air gun signature in marine seismic exploration considering multiple physical factors. *Applied Geophysics* **7**, 158–165.

Noss T., Ronen S., Jenkerson M., Allen P., Houck R. and Johnson G. 1999. Marine vibrator motion correction in the frequency-space domain. SEG Technical Program Expanded Abstracts, 1142–1145.

Pramik B., Lee Bell M., Grier A. and Lindsay A. 2015. Field testing the AquaVib: an alternate marine seismic source. SEG Technical Program Expanded Abstracts, 181–185.

Rayleigh L. 1917. On the pressure developed in a liquid during the collapse of a spherical cavity. *Philosophical Magazine Series* **6**, 94–98.

Schostak B. and Jenkerson M. 2015. The marine vibrator joint industry project. SEG Technical Program Expanded Abstracts, 4961–4962.

Shumizu S., Tsukuda K., Shibata H., Mizota A. and Miura S. 2009. Short cluster airgun array for shallow to deep crustal survey. *International Journal of Offshore and Polar Engineering* **19**, 60–65.

Strandenes A. and Vaage S. 1992. Signatures from clustered airguns. *First Break* **10**, 305–312.

ten Kroode F., Bergler S., Corsten C., de Maage J.W., Strijbos F. and Tijhof H. 2013. Broadband seismic data – the importance of low frequencies. *Geophysics*, **78**, WA3–WA14.

Vokurka K. 1986. Comparison of Rayleigh's, Herring's, and Gilmore's modeling of gas bubbles. *Acta Acustica united with Acustic* **59**, 214–219.

Warner M., Guasch L. and Yao G. 2015. Adaptive waveform inversion – FWI without cycle skipping. 2015 Workshop: Depth Model Building: Full-waveform Inversion, Beijing, China, 18–19 June 2015, 11–14.

Watson L.M., Dunham E.M. and Ronen S. 2016. Numerical modeling of seismic airguns and low-pressure sources. SEG Technical Program Expanded Abstracts, 219–224.

Watson L.M., Ronen S., Goldbogen J. and Dunham E.M. 2017. Comparing whales to marine seismic sources: low-frequency sound generation by fin whales. SEG Technical Program Expanded Abstracts, 90–95.

Willis H.F. 1941. Underwater explosions: the time interval between successive explosions. British Report WA-47-21.

Ziolkowski A. 1970. A method for calculating the output pressure waveform from an air gun. *Geophysical Journal of the Royal Astronomical Society* **21**, 137–161.

Ziolkowski A.M., Hanssen P., Gatliff R., Li X. and Jakubowicz H. 2001. The use of low frequencies for sub-basalt imaging. SEG Technical Program Expanded Abstracts, 74–77.

APPENDIX: NUMERICAL MODELLING

The airgun/bubble dynamics are simulated following a similar treatment to the seminal work of Ziolkowski (1970). We use a lumped parameter model where the internal properties of the airgun and bubble are assumed to be spatially uniform. We solve the Euler equations governing the motion of a compressible fluid and evaluate the solution on the bubble wall to obtain a nonlinear ordinary differential equation for the bubble dynamics (Herring 1941; Cole 1948; Vokurka 1986; Watson *et al.* 2016):

$$R\ddot{R} + \frac{3}{2}\dot{R}^2 = \frac{p_b - p_\infty}{\rho_\infty} + \frac{R}{\rho_\infty c_\infty}\dot{p}_b, \tag{A1}$$

where R, $\dot{R} = \mathrm{d}R/\mathrm{d}t$ and $\ddot{R} = \mathrm{d}^2 R/\mathrm{d}t^2$ are the radius, velocity and acceleration of the bubble wall, respectively, p_b is the pressure inside the bubble, $\dot{p}_b = \mathrm{d}p_{b/\mathrm{d}t}$ and p_∞, ρ_∞ and c_∞ are the ambient pressure, density and speed of sound in the water. The ambient pressure at the depth of the airgun, D, is given by $p_\infty = p_{\mathrm{atm}} + \rho_\infty g D$, where p_{atm} is the atmospheric pressure and g is the gravitational acceleration. The bubble motion is driven by the pressure difference across the bubble wall. The $\dot{p}_b$ term describes the loss of energy from the bubble to the water by acoustic radiation.

Mass flow from the airgun to the bubble is governed by the ratio between the airgun pressure, p_a, and the bubble pressure. If the pressure ratio is greater than a critical value (Babu 2014):

$$\frac{p_a}{p_b} \geq \left(\frac{\gamma+1}{2}\right)^{\frac{\gamma}{\gamma-1}}, \tag{A2}$$

where γ is the ratio of heat capacities, then flow through the port is choked (choked flow is when the flow through a nozzle has a velocity equal to the sound speed, the maximum possible velocity for fluid flow through a nozzle). Otherwise, the flow is unchoked. For air, $\gamma = 1.4$, and the critical pressure ratio value is $p_a/p_b \approx 1.9$. The mass flow rate from the airgun into the bubble is given by

$$\frac{\mathrm{d}m_b}{\mathrm{d}t} = \begin{cases} p_a A \left(\dfrac{\gamma}{QT_a}\right)^{1/2} \left(\dfrac{2}{\gamma-1}\right)^{1/2} \left[\left(\dfrac{p_a}{p_b}\right)^{(\gamma-1)/\gamma} - 1\right]^{1/2} & \\ \qquad\qquad\qquad\qquad \text{if flow is unchoked,} & \text{(A3a)} \\ p_a A \left(\dfrac{\gamma}{QT_a}\right)^{1/2} \qquad \text{if flow is choked,} & \text{(A3b)} \end{cases}$$

where A is the airgun port area, Q is the specific gas constant (287.06 J/kg/K for dry air) and T_a is the airgun temperature.

The internal energy of the bubble, E_b, changes according to the first law of thermodynamics for an open system:

$$\frac{\mathrm{d}E_b}{\mathrm{d}t} = c_p\, T_a \frac{\mathrm{d}m_b}{\mathrm{d}t} - 4\pi M\kappa R^2 (T_b - T_\infty) - p_b \frac{\mathrm{d}V_b}{\mathrm{d}t}, \tag{A4}$$

where c_p is the heat capacity at constant volume, κ is the heat transfer coefficient, M is a constant that accounts for the increased effective surface area over which heat transfer can occur as a result of turbulence at the bubble wall (Laws, Hatton and Haartsen 1990), and $V_b = \frac{4}{3}\pi R^3$ is the volume of the spherical bubble.

The airgun and bubble are coupled by conservation of mass:

$$\frac{\mathrm{d}m_a}{\mathrm{d}t} = -\frac{\mathrm{d}m_b}{\mathrm{d}t}, \tag{A5}$$

where m_a is the mass of air inside the airgun, and conservation of energy:

$$\frac{\mathrm{d}E_a}{\mathrm{d}t} = -c_p T_a \frac{\mathrm{d}m_b}{\mathrm{d}t}, \tag{A6}$$

where E_a is the internal energy of the airgun.

The airgun and bubble governing equations are closed with the ideal gas equation of state:

$$p = \frac{mQT}{V}, \tag{A7}$$

and the relationship between the internal energy and temperature:

$$E = c_v\, mT, \tag{A8}$$

where c_v is the heat capacity at constant volume.

The system of ordinary differential equations is initialized using the Ziolkowski (1970) initial conditions, which are commonly used in the seismic airgun modelling literature (e.g. Li *et al.* 2010; de Graaf, Penesis and Brandner 2014). The initial bubble volume is set equal to the airgun volume. The initial bubble wall velocity is set as zero, and the initial temperature and pressure inside the bubble are equal to the ambient values in the water. The initial temperature of the airgun is also assumed to be equal to the ambient water (since the air travels a long distance in a submerged umbilical hose from the compressor to the airgun).