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SEG 2018: Five Key Takeaways

The 88th annual SEG conference was held in Anaheim, California, on October 14-19. Total attendance in 2018 was significantly lower than previous years thanks to the location, commitments made by various companies in 2017 not to exhibit in 2018, and the prevailing weak industry climate (reportedly about 3,800 registrations on the first day). Nevertheless, a record 1852 abstracts were submitted to the Technical Program, from which 768 oral presentations were given in 96 technical sessions, and 372 posters were shown.

Event details are hosted online, with the technical program, and the post-convention workshop program.

The standout conference theme in 2018 was 'machine learning' (and to a lesser extent, cloud computing), with 13 technical, workshop and poster sessions. The keynote presentation in the opening session was also given by Darryl Willis, VP for Oil, Gas and Energy at Google Cloud. I will dedicate the *next edition* of Industry Insights to machine learning-related topics.

In this paper I discuss five other key topics arising from SEG 2018 that are particularly relevant to marine towed streamer seismic:

- Various source deployment strategies, complemented by the use of compact source concepts for two main reasons: Increased operational flexibility and reduced environmental impact,
- Several presentations given by each of the participants in the marine vibrator joint industry project (MVJIP), with APS and Teledyne both having working scale model versions of their marine vibrator concepts. Other related presentations were given by IHI Corporation of Japan, Schlumberger and PGS,
- How survey efficiency affects the environmental impact,
- The widespread industry adoption of multisensor streamers, and
- How collaboration between industry, academia and governments are increasingly the enabler for new technology development.

Many references quoted have hyperlinks at the end of this paper to PDF versions of the relevant literature.

Marine Source Strategies are Evolving

A large focus for marine source design over the past decade has been on the development of 'broadband' solutions that reduce the effects of the source-side ghost. Cambois et al. (2009) describe how multi-level source (MLS) arrays can be configured by firing sub-arrays of air guns at different depths at strategically incremental time intervals (typically 2 or 4 milliseconds depending upon the depth separation between sub-arrays), moving the source-side ghost notch frequency to twice its typical value, and partially removing ghost effects at both the low and high frequencies. The nominal shot interval is unaffected, in contrast to early industry deployments of 'over-under' source arrays fired at two different depths as independent source events with twice the conventional shot interval. The ability to preserve shot interval meant there was no compromise in CMP fold or the frequency of pre-stack spatial sampling in the common offset, common receiver, and common midpoint domains. Parkes and Hegna (2011) subsequently described how the combination of simultaneous shooting with sub-arrays at different depths enables full source-side deghosting, again without compromising shot interval or survey efficiency. Most recently, Hegna et al. (2018) and Klüver et al. (2018) introduced a methodology named 'eSeismic' that uses continuous source wavefields from the randomized firing of individual air guns (or alternative source concepts) coupled with the use of continuously recorded receiver wavefields during signal processing to deliver data that is fully deghosted, free of all acquisition system effects, and that may be efficiently acquired with a variety of new survey design concepts.

Continuous recording coupled with advances in shot deblending technology have also facilitated more efficient acquisition with blended sources. A particularly interesting example is the compressed seismic imaging (CSI) methodology published by Mosher et al. (2017) and Li et al. (2017). The strategic use of non-uniform streamer separation and non-uniform shooting interval, coupled with the sparse inversion principles of compressive sensing, enabled highly blended data acquired with nominally coarse 3D spatial sampling to be reconstructed during data processing with dense and uniform 3D spatial sampling. This survey method is operationally efficient from the perspective that the acquisition effort required to acquire the equivalent spatial sampling without data reconstruction would be prohibitively expensive. A notable challenge to towed streamer implementations of CSI is that the sources and receivers are physically coupled to the same vessel, limiting the flexibility in how they may be configured. In contrast, the sources and receivers are physically decoupled for both land 3D and ocean bottom seismic 3D surveys, and significant efficiency gains have been demonstrated using the CSI methodology. Note that conventional shot deblending is required as a component of the CSI methodology. In contrast, the continuous wavefield (eSeismic) methodology makes no effort to deblend the data, is able to reconstruct pre-stack gathers on any nominal shot grid, and is therefore able to sail the vessel at faster speeds without being constrained by specific shot intervals. From an environmental perspective, the peak sound pressure level (SPL) and the sound exposure level (SEL) for individual air guns being fired is less than for arrays of air guns being fired, and the continuous wavefield methodology may therefore be able to operate in sensitive areas, whereas conventional air gun operations cannot.

Triple-source shooting, first used by PGS in the mid-1990s, has regained popularity in recent years because it allows less streamers to be towed by comparison to dual-source shooting, but with comparable survey efficiency and cross-line spatial sampling. The operational penalty is that the inline shot interval must be reduced by a factor of one-third to preserve common midpoint (CMP) fold and pre-stack spatial sampling. As a consequence, the time interval between consecutive shots is reduced, the amount of ‘shot overlap’ increases, and therefore ‘shot deblending’ may be required during signal processing to separate the interfering records. Historically, all three sources (typically comprised of six sub-arrays fired two at a time) were placed between the innermost two streamers, but more recently the industry has been interested in placing the outermost sources arrays outside the innermost two streamers in an effort to improve the near offset distribution and potentially improve survey efficiency in predictable fashion (refer to Long, 2017b; Widmaier et al., 2017; Long, 2018). Logistically, it follows that more compact source arrays (either comprised of air guns or towed marine vibrators) will facilitate easier deployment of wide-tow source arrays, and will emit less energy in environmentally sensitive areas. More compact arrays of air guns can be built using less sub-arrays, and with less individual air guns being activated (e.g. Dhelie et al., 2017). The ultimate scenario involves only one air gun being fired at a time.

Dhelie et al. (2018a,b,c) presented thee abstracts on air gun source design at SEG 2018. Dhelie et al. (2018b) recycles the study of compact array designs introduced in Dhelie et al. (2017), and Dhelie et al. (2018c) describe the towing of a triple-source array with somewhat increased lateral source separation over a deep-tow streamer spread. Each ‘source’ is built from two sub-arrays. A more interesting test is described in Dhelie et al. (2018a), wherein six sub-arrays were towed with a uniform sub-array separation of 60 m; corresponding to 300 m lateral separation between the outermost sub-arrays, with each sub-array used as an individual source. A variety of sub-array volumes were tested from 368 in^3 to 1725 in^3, and the actual volumes used in the 3D test were 834 in^3 and 891 in^3. Sail line separation was reduced from the nominal value so that the lateral separation between all source lines in the 3D area was a uniform 60 m. The test focus was therefore on greatly increasing the cross-line source density by comparison to conventional 3D surveys.

Three presentations addressed the firing of individual air guns. Abma (2018) described firing strategies for his methodology referred to as ‘popcorn shooting, and Hegna et al. (2018) and Klüver et al. (2018) described theoretical and practical considerations for their method using continuous source and receiver wavefields, and referred to as eSeismic. Before explaining the difference between the two methods I provide a brief history on the use of individual air gun sources.

Ziolkowski (1984, 1987) published academic studies that showed it is possible to recover a coherent source wavelet from a ‘detuned’ air gun array in which the guns were out of synchronization by up to 100 milliseconds (a so-called ‘machine-gun’ array). In the decades since, various authors have shown interest in ‘encoded’ source sequences that facilitate the recovery of shot gathers from various forms of interfering (overlapping) source events. Motivations to pursue overlapping source sequences may include a desire to increase the inline density of shot gathers and/or improve survey efficiency. For example, Műller (2016) proposes that each source is encoded by activating the individual air guns independently over a short period of time with benefits in seismic processing that include source-side deghosting and the robust recovery of shot gathers. A common aspect of such methods is the use of randomized time delay sequences that vary at each source location to reduce artifacts contaminating the recovered shot gathers. In another example, Abma and Ross (2013, 2015) introduce their ‘popcorn shooting’ method that (again) distributes the air gun array energy over time by activating the individual air guns sequentially to reduce the environmental impact of seismic operations on the marine environment—the 'received sound levels—measured in terms of Sound Pressure Level (SPL) and Sound Exposure Level (SEL). The activation sequence at each reference shot location may be as short as 400 milliseconds.

So how did the different methodologies differ? For the various 'popcorn shooting' concepts the survey is designed such that the common shot gathers are referenced to a nominal shot grid—which implies that the vessel speed is regulated accordingly. As noted, each shot gather is recovered during seismic processing at the reference shot location as if all the air guns have been activated together in the traditional manner at that shot location.

For the PGS eSeismic methodology, each air gun from all available sub-arrays is activated in rapid succession with small randomized time intervals between the activation of each air gun (refer to Figure 1). It is typically the case that several air guns are activated per second. Note that there is no reference shot point grid used, and the vessel speed therefore is not regulated. Continuous recording of each sail line produces one continuous seismic record. Appropriate corrections are applied in seismic processing to compensate for the fact that the acquisition system is moving during the acquisition of each sail line. Appropriate signal recovery methods are then used to reconstruct common receiver gathers wherever the user specifies.

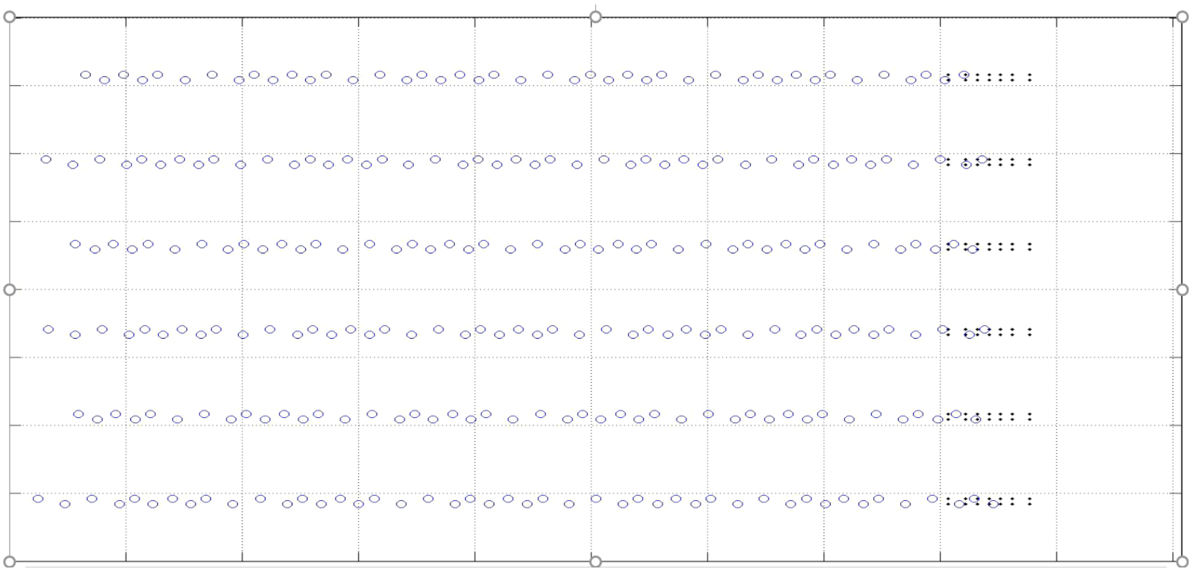

Figure 1. Schematic of six sub-arrays being towed behind a vessel, and one air gun from all available air guns is activated at a time in the manner of Hegna et al. (2018) and Klüver et al. (2018). As such, both the inline (horizontal axis) and cross-line (vertical axis) spatial directions are sampled very densely, and a continuous source wavefield is emitted during the acquisition of each sail line.

It follows that in addition to reducing the environmental impact of seismic operations, eSeismic also has advantages for the efficiency of operations: the vessel speed is no longer regulated, and the management of the air guns is simpler. As only one air gun is activated at a time, there are no logistical complications to maintain air compressor supply, and each sub-array can be deployed more flexibly—including 'wide tow' source operations that reduce survey duration—as well as optimizing three-dimensional spatial sampling of the emitted source wavefield (refer also to Figure 1). As the energy from all air gun activations contributing to each common receiver gather is integrated, deep signal penetration is equivalent to 'conventional' data (refer to Figure 2).

The eSeismic development has been sponsored by a DEMO 2000 project in Norway, with Equinor being the industry partner. I refer to the value of collaborative R&D later in this newsletter.

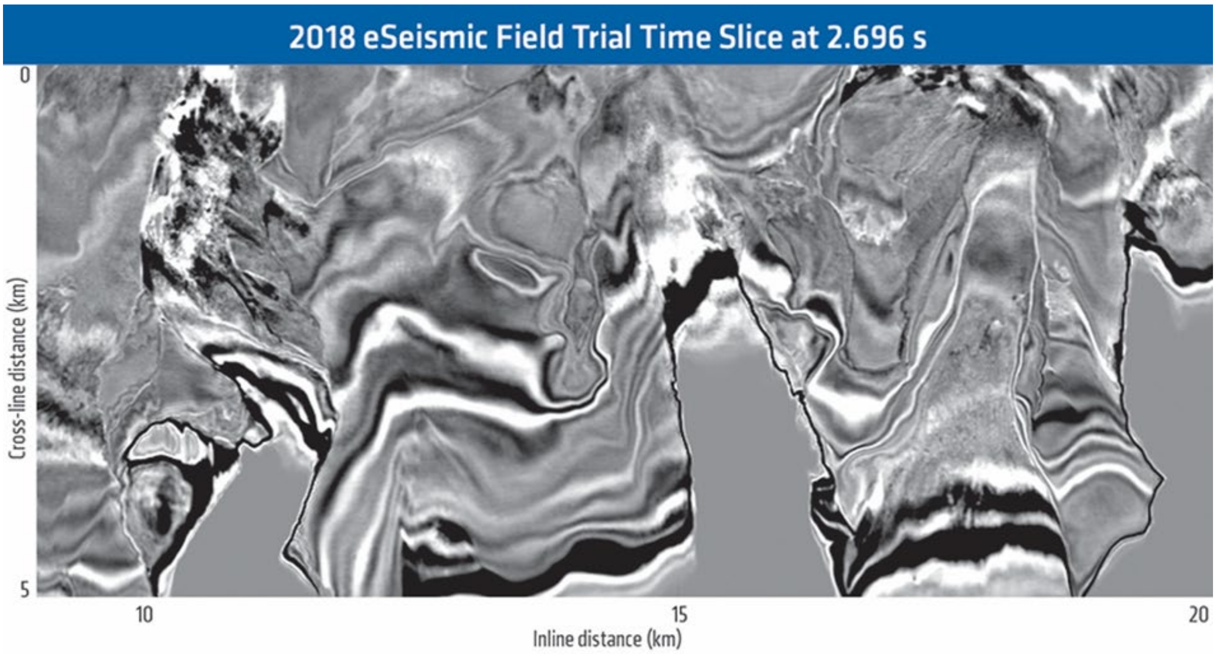

Figure 2. eSeismic time slice from a recent 3D field trial in Brazil.

Marine Vibrators are Back, Again

Although the zero-peak output of air gun arrays roughly scales in proportion to the number of air guns used, the use of a small number of air guns to reduce output is historically challenged by the necessity to mitigate unwanted reverberating bubble energy with ‘array tuning’: By using air guns of several different volumes that are spaced optimally relative to one another, air gun arrays may be ‘tuned’ to increase the amplitude of the primary peak and simultaneously decrease the relative amplitudes of the subsequent bubble pulses. The most obvious exception to this perspective is the eSeismic concept.

In contrast, however, the use of towed marine vibrator sources rather than air guns has long-promised to offer a marine source concept with comparable frequency bandwidth to air guns (about 5-100 Hz)—but without any air bubble-related tuning requirements, and conceivably only using a small number of source elements. 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. Despite several decades of intermittent industry development, several different marine vibrator concepts have failed to reach commercialization. Finding an efficient solution that generates high-amplitude, low-frequency amplitudes remains 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). High-amplitude, ultra-low frequency amplitudes can either be generated by using a very high displacement of the surface of one (huge) marine vibrator unit, 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).

In order to achieve a given level of output in the water, a marine vibrator typically needs to undergo a change in volume. In order to work at depth while minimizing structural weight, the marine vibrator must be pressure balanced with external hydrostatic pressure. As the internal gas (e.g. air) in the marine vibrator is increased in pressure, the bulk modulus (or ‘stiffness’) of the internal gas also rises. Increasing the bulk modulus of the internal gas also increases the air-spring effect within the marine vibrator. As used herein, the term ‘air spring’ is defined as an enclosed volume of air that may absorb shock or fluctuations of load due to the ability of the enclosed volume of air to resist compression and decompression. Increasing the stiffness of the air in the enclosed volume increases the air-spring effect and thus the ability of the enclosed volume of air to resist compression and decompression. This increase in the air-spring effect of the internal gas tends to be a function of the operating depth of the source. Further, the stiffness of the acoustic components of the marine vibrator and the internal gas are the primary determining factors in the marine vibrator's resonance frequency. Accordingly, the resonance frequency generated by the marine vibrator may undesirably increase when the marine vibrator is towed at depth.

The highest profile ultra-low frequency marine vibrator concept in the past two years has been the BP Wolfspar concept first published by Dellinger et al. (2016). Two related BP presentations were given at SEG 2018 (Pool et al., 2018; Brenders et al., 2018), with the main ambition related to the augmentation of ultra-low frequency signal that will in theory stabilize Full Waveform Inversion (FWI). Wolfspar has a dry weight in excess of 27 tons, and is a cylinder more than 6 m in length, has a diameter of about 1.5 m, and uses a hemispherical nose cone with a maximum throw of about 1 m to displace water using sweeps of about 1.7 to 2.4, and 1.4 to 2 Hz. The unit is pressure compensated with nitrogen, and towed at maximum depth of about 60 m. Field trials were viewed as operationally successful, but a compelling demonstration (a 'killer slide') that FWI profoundly benefits from stronger ultra-low frequency signal is still lacking… One long-term ambition is that regional ultra-low frequency surveys would augment velocity model building efforts in challenging areas such as the Gulf of Mexico, but FWI software is evolving so rapidly that ultra-low frequency signal is decreasing (but still relevant) in priority.

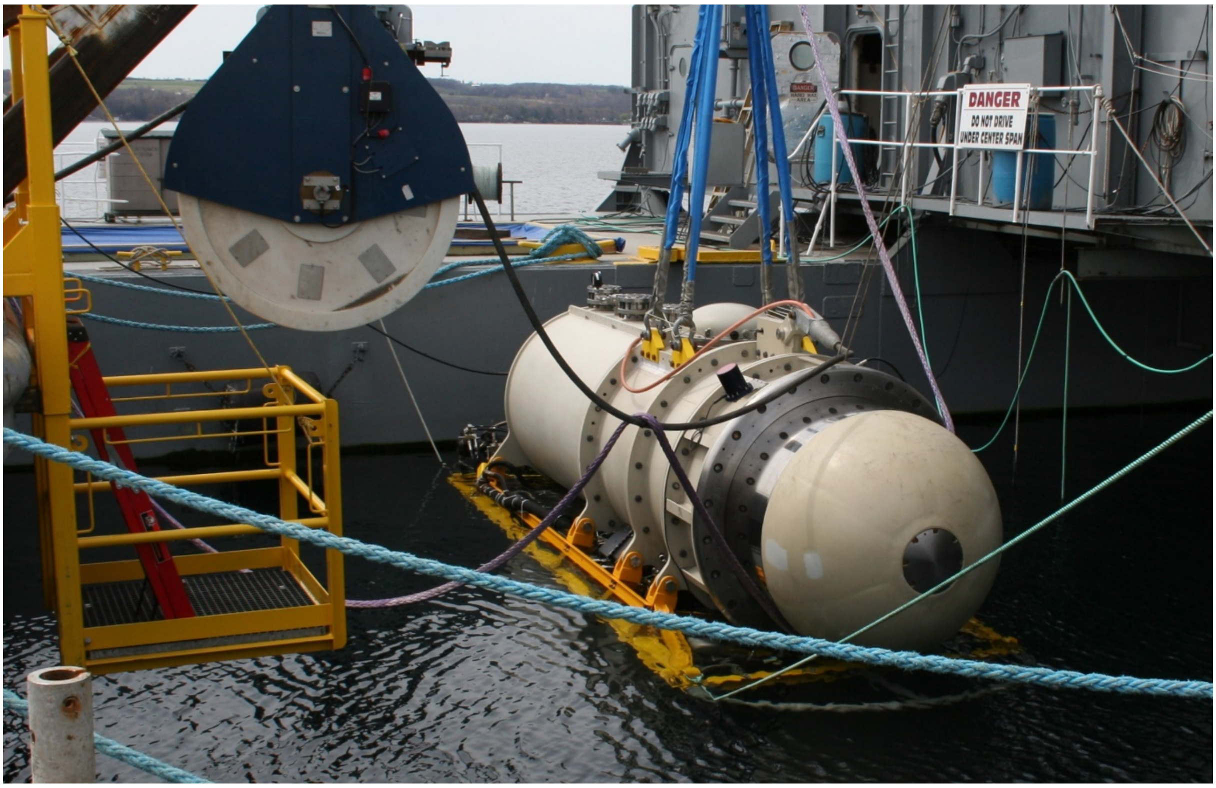

Figure 3. The BP Wolfspar ultra-low frequency marine vibrator.

Most marine vibrator attention, however, remains focused upon 'full bandwidth' alternatives to air guns that may reduce most types of environmental impacts. Marine animal behavioral and auditory effects of most types are expected to be reduced, regardless of water depth or other environmental conditions—if robust commercial solutions can be developed. The Marine Vibrator Joint Industry Project (MVJIP) is an industry consortium formed in 2013 that selected three marine vibrator concepts for sponsored development. Feltham et al. (2018) provide an update on progress, and Jenkerson et al. (2018) and Roy et al. (2018) represented two of the MVJIP participants, with PGS having withdrawn from the MVJIP in 2018. A commercial solution still remains elusive, and opinions remain mixed regarding which concept is 'best', but superficially, most marine vibrator concepts under development are visually similar, and rely upon a round membrane that is forced to flex and displace water in response to an internal driver mechanism. All three original MVJIP participants would need to tow of the order of 12-18 units to meet the amplitude and frequency specifications of the MVJIP, thereby challenging logistical efficiency by comparison to how air gun arrays are deployed and managed today.

Other relevant marine vibrator presentations at SEG 2018 were by IHI Corporation from Japan, who presented their hydraulically-driven concept with the ambition of emitting 3-300 Hz signal (Ozasa et al., 2018); by Schlumberger, who presented their phase-sequencing method to use several marine vibrators simultaneously (Halliday et al., 2018); and by PGS, who described how the use of spread-spectrum sweeps can facilitate improved efficiency whilst using less marine vibrator units (and therefore with less emitted energy; Tenghamn et al., 2018).

Survey Efficiency and Environmental Management Go Together

As I discussed in an Industry Insights newsletter titled 'Increasing Towed Streamer Survey Efficiency' at https://www.linkedin.com/pulse/increasing-towed-streamer-survey-efficiency-andrew-long/, and contained in a full PDF newsletter by Long (2018), non-uniform CMP geometry at various scales is inevitable as towed streamer surveys attempt to tow wider streamer spreads and/or wider source geometries. Examples include adaptations of compressive sensing, wider towing of source arrays (see also the earlier discussion), or the pursuit of dispersed source arrays (most likely facilitated using additional source vessels. As also discussed, the ambition to tow dispersed sources will be facilitated if source concepts can be developed that enable the use of compact sources—preferably not reliant upon large air compressors (e.g. using marine vibrators). It is also evident that the acquisition of highly blended shots is inevitable in the drive for greater survey efficiency, and solutions that can either deblend highly complex blended data or that can simply use such data without deblending (e.g. eSeismic) will be highly advantageous.

Several seafloor seismic vendors exhibited at SEG 2018, and industry adoption of the methodology is slowly growing. The largest program commissioned to date is a multi-year survey in offshore Abu Dhabi by ADNOC, using about 17,000 ocean bottom nodes (OBNs) and with a total budget in excess of one billion dollars. Technology solutions including various forms of automated deployment and retrieval to improve efficiency. Bathellier and Haumonté (2018) and Manin and Haumonté (2018) both discussed the Kietta FreeCable concept where multisensor cables are suspended between small autonomous vessels in the water, and used in a manner analogous to 'floating ocean bottom cables'. Shear wave energy cannot be recorded as there is no seafloor receiver coupling, but one ambition is that the technology may be a more efficient full-azimuth solution in some scenarios. Chalenski et al. (2018) also proposed a fully automated and robotized 4D OBN solution using autonomous source vessels.

Increased marine seismic survey efficiency also reduces the cumulative environmental impact in sensitive areas—measured not only in terms of received sound levels, but also in terms of the impact upon commercial fishing operations. This point is often overlooked when planning seafloor seismic surveys, which remain highly inefficient by comparison to towed streamer surveys, despite the advances mentioned above, and therefore may have very long survey durations and involve several vessels. There are of course several scenarios where towed streamer surveys cannot be considered, such in shallow water areas or where obstructions such as production platforms affect the survey area, and there are strong geophysical arguments for full-azimuth (FAZ) OBN acquisition. Nevertheless, efficient towed streamer seismic using compact source concepts offer the minimum environmental disturbance today.

Multisensor Streamers are Now Accepted Industry Best Practice

The SEG 2018 exhibition was notable because a few large service companies declined to attend, and Shearwater GeoServices were in the process of taking over the WesternGeco arm of Schlumberger. But all four large marine seismic companies (PGS, Shearwater, CGG and Polarcus) are now either using (PGS, Shearwater, CGG) or actively testing (Polarcus) multisensory streamers. PGS use GeoStreamer (Carlson et al., 2007; Day et al., 2013; Long et al., 2017a) across their entire fleet, Shearwater have purchased several IsoMetrix streamer spreads (and vessels) from WesternGeco (refer to Robertsson et al., 2008; Vassallo et al., 2010; Özbek et al., 2010; Caprioli et al., 2012), and CGG have started using and promoting Sentinel MS (Poole and Cooper, 2018; Firth et al., 2018). The benefits of robust wavefield separation extend to increased operational flexibility (Lesnes et al., 2014; Widmaier et al., 2015) geophysically optimum broadband imaging, time-lapse (4D) reservoir monitoring, and quantitatively accurate reservoir characterization (Long, 2017a).

Collaboration is the Future of R&D

Each of the marine seismic acquisition platforms discussed above required significant vessel time and R&D investment to progress over several years from the concept stage to commercialization. Furthermore, oil companies increasing design bespoke seismic programs that require significant synthetic modeling and simulations to parameterize what are typically expensive and prolonged programs. So collaboration between service companies, oil companies, academia and/or government is increasingly common as technology enablers.

As examples, the recent resurgence in marine vibrator development has largely been driven by the MVJIP; an industry consortium administered by TEES (Texas A&M Engineering Experiment Station), and Schlumberger have been using DEMO 2000 research funding administered by The Research Council of Norway, with Statoil as the industry partner. Similarly, the PGS eSeismic development has also received DEMO 2000 funding, with Statoil again as the industry partner.

Dhelie et al. (2017) presented collaborative results between WesternGeco and Lundin Petroleum, Dhelie et al. (2018a,b,c) presented collaborative results between CGG and Lundin Petroleum, the BP Wolfspar field trial presented by Brenders et al. (2018) and Pool et al. (2018) involved several operational partners, the Kietta FreeCable concept presented by Bathellier and Haumonté (2018) and Manin and Haumonté (2018) needs collaborative funding and field testing to progress beyond the prototype stage, as indeed does the eSeismic concept presented by Hegna et al. (2018) and Klüver et al. (2018), and the spread-spectrum marine vibrator methodology proposed by Tenghamn et al. (2018).

Summary

This article considers key themes emerging in the direction of marine seismic exploration. Ambitious source and receiver deployment strategies are overwhelmingly driven by survey efficiency and environmental impact considerations—the two being related. Towed marine vibrator concepts are once again making a resurgence, primarily driven by environmental considerations, but commercialized versions could facilitate robust ‘dispersed source’ implementations. The most notable technology developments are in the area of using compact air gun source deployments to improve the cross-line shot density. It is increasingly clear that close collaboration between industry, academia and government will be the necessary driver to maintain future R&D momentum and the commercialization of new marine seismic technologies.

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