

The transformation of seabed seismic

Tim Bunting^{1*} and John Moses¹ trace the development of seabed seismic technology.

Seabed seismic surveys have been part of the hydrocarbon exploration industry for many decades. Initial implementations deployed cables which were populated with hydrophones and generally used for shallow water and transition zone projects. The cables were directly connected to a recording vessel to power the in-sea hardware, manage the spread and record the sensor measurements.

Barr et al. in the 1980s implemented a technique, first postulated in 1954 by Haggerty and Backus, which uses a dual component measurement (pressure and vertical particle velocity) to eliminate the receiver side ghost, extending the reach of the technique into deeper waters. The potential of the seabed technique was further extended to make a measurement of the shear reflectivity through the addition of horizontal particle velocity components (four-component recording or 4-C). In the late 1990s the industry started experimenting with buried seafloor cables as part of permanent seismic installations to assist in production monitoring of the reservoir.

As well as ocean bottom cable (OBC) systems, it is possible to make a seabed seismic measurement with an array of ocean bottom nodes (OBN). An ocean bottom node is an autonomous recording device with a self-contained recording system, clock and battery. As there is no connection with the surface, there is no limitation on length of the receiver line, no downtime due to telemetry/power line failures and no lost time associated with moving of the recording vessel. Ocean bottom nodes have been in use for many decades, but their use had primarily been limited to long-offset refraction surveys for studies of earth tectonics. The majority of the early node technologies

were developed in academia and were neither industrially engineered nor designed with a focus on operational efficiency. After early development by Statoil in the 1990s, the first seismic reflection ocean bottom node survey was acquired in 2004 over Pemex's Cantarell Field in the Gulf of Mexico. Ocean bottom nodes, when used for hydrocarbon exploration, were initially deployed by remotely operated vehicles (ROVs), but more recently ropes or wires have also been employed.

Understanding seabed geometries

OBS geometries can be described by the inline and cross-line source and receiver sampling and the maximum offsets required in the inline and cross-line direction. However, there are many geometry methodologies that meet these base geometry parameters, and all of these geometry methodologies must have equivalent sampling because they have the same base geometries.

Cross-spread. The cross-spread is the methodology most commonly used on ocean bottom cable surveys. In this methodology, a receiver line is laid and a source line is shot perpendicular to the receiver line. The length of the source and receiver line are dictated by the maximum required offset inline and cross-line as shown in Figure 1a. This cross-spread patch is then repeated in the inline and cross-line direction. This geometry is very source intensive because shot locations are repeated multiple times. In order to minimize the number of repeated shot locations, the general practice is to lay as many receiver lines as the cable inventory allows (as shown in Figure 1b) while ensuring there is enough spare cable to roll the spread efficiently. The source lines are extended to

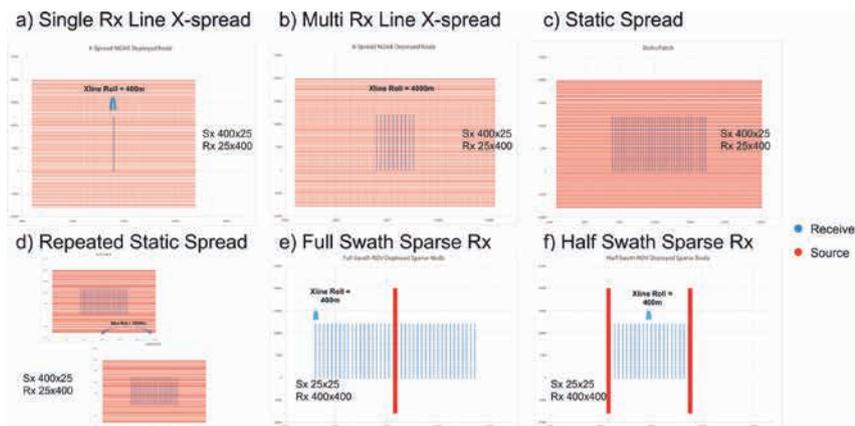


Figure 1 A selection of geometry methodologies with equivalent sampling. a) Single Rx Line X-Spread, b) Multi Rx-Line X-Spread, c) Static Rx Spread, d) Repeated Static Rx Spread, e) Sparse Rx Grid – Full Swathe, and f) Sparse Rx Grid – Half Swath.

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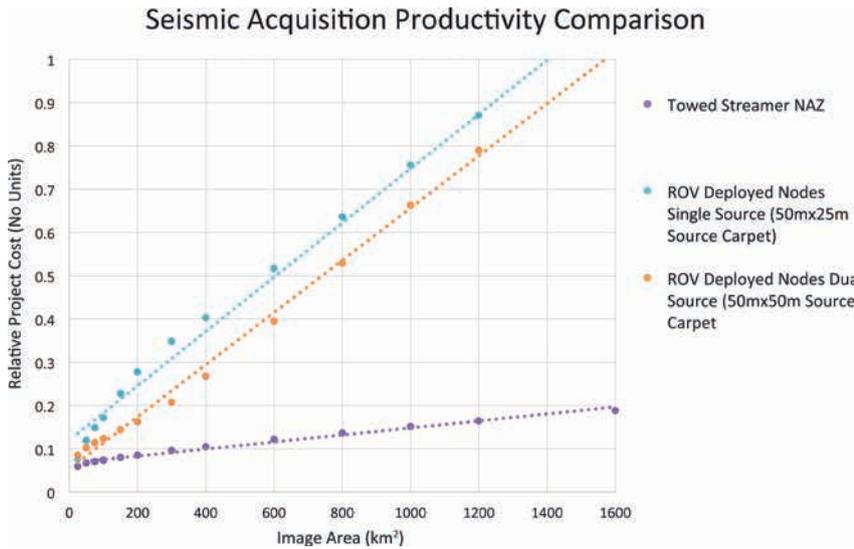


Figure 2 Graph plotting historical relative project costs against image size for two ROV-deployed seafloor node geometries (cyan and orange) and a narrow azimuth towed streamer geometry (purple) demonstrating the historical relatively high cost of deep water node projects compared to towed streamer projects. By analysing the two node geometries, we can conclude that certain node geometries are constrained by receiver efficiency.

ensure that the maximum required cross-line offset is shot into every receiver line.

Static-spread. If you expand on this idea, and the receiver inventory allows, one can completely populate the receiver area, in which case there are no repeated source points as shown in Figure 1c. From a project time perspective, this is not necessarily an efficient option because the receiver and source resources operate in series, but it can be efficient from a cost perspective if a single resource, which can deploy receivers and sources, is available. If there is not enough receiver inventory to populate the entire survey, this approach may still be attractive if the correct resource is available – then the static case would be repeated multiple times with a full offset source apron as shown in Figure 1d.

Sparse Receivers. If one accepts source and receiver reciprocity, it is possible to flip source and receiver sampling, i.e. sample the sources more densely and the receivers more sparsely. This is the most common methodology for ocean bottom nodes in which nodes are deployed with inline and cross-line intervals of 200-400 m and shots are acquired on a grid of 25-50 m in the inline and cross-line direction. If there is enough receiver inventory, a full swathe of receivers is deployed and sources shoot parallel with the receiver lines between the two central receiver lines as shown in Figure 1e. If there is not adequate inventory to deploy a full swathe of nodes, an equivalent geometry can be achieved by deploying a half swathe and shooting two sets of source lines outside the receiver spread as shown in Figure 1f. While this half-swathe geometry has a smaller demand on receivers, each source point must be repeated once.

This level of flexibility in seabed geometry methodology suggests the following:

1. Depending on the receiver inventory and base geometry sampling requirements, certain geometry methodologies may be unavailable. Larger receiver inventory results in

greater flexibility in geometry methodology and a potentially more efficient acquisition.

2. Certain geometry methodologies are more suitable for certain source and receiver technologies, and therefore, a preconception of the optimal technology may limit the geometry methodology and hence the acquisition efficiency.
3. As can be seen, there are many geometry methodologies which achieve equivalent sampling but each of these methodologies will have different demands on source and receiver resources. It may be possible to achieve acquisition efficiencies, or sampling improvements, at no additional cost by modifying the design to use under-utilized resources more aggressively, i.e. balancing the source and receiver effort.

Current positioning of seabed seismic in the industry

It is generally accepted by the industry that seismic surveys acquired using seabed seismic receivers deliver the optimum measurement of subsurface reflectivity. This is demonstrable through a review of published papers and case studies. At the measurement level, there are a number of differences between the seabed seismic technique and more commonly used towed streamer technique:

- **Broadband.** The measurement is both low noise because the receiver resides in a low noise environment, and has a flatter signal response (richer in both high and low frequencies) because the receiver ghost is separated from the primary signal using the pressure and particle velocity components.
- **Unconstrained geometry.** The fact that the seismic sources are decoupled from the seismic receivers allows for much more flexibility in geometry and accommodates both a full azimuth, long-offset measurement and improved coverage in operationally complex areas.

- Highly repeatable seafloor receivers. Both cable and node-based systems are highly repeatable. Receivers deployed by ROV can generally be placed within a few metres of the planned location.
- Multiple measurements. As the receiver sits on the seafloor, the horizontal particle motion components measure the shear modes which provide a second image of the subsurface which can complement the P-wave image and constrain fluid property inversions. Furthermore, as shear waves are less affected by gas saturation, it becomes possible to image below shallow gas features which degrade the seismic image.

However, seabed seismic surveys are currently not widely used because of the higher acquisition costs. In general, seabed surveys are only considered for the most challenging geophysical objectives such as production management projects where high repeatability is critical or complex geologies where full azimuth measurements are required.

Figure 2 details the results of a time and motion study to understand how deep water ROV-deployed nodes historically compare to other methods of acquiring seismic reflection measurements. It compares the productivity of two ROV-deployed deep water node geometries (cyan and orange) with the productivity of a narrow-azimuth (NAZ) towed streamer geometry (purple). Productivity is assessed using relative project cost which is simply the estimated duration of the project multiplied by the relative estimated operational costs. The relative project costs (y-axis) are plotted against the image area (x-axis). The towed streamer estimations are based on feasible project pricing. The ROV-deployed geometries are based on a sparse node deployment, a dense source carpet and sequential shooting. It is very obvious that, using these assumptions, the ROV-deployed methodology is significantly more expensive than the NAZ geometry, demonstrating what is already well accepted in the industry. It is worth taking some time to review the two ROV-deployed node geometries because this illustrates the historical limitations of the seabed seismic technique. The difference between these two node geometries is only the source carpet density. The 50 x 50 m source carpet

productivity (orange) is estimated assuming dual source, while the 50 x 25 m source carpet productivity is estimated using single source. The dual source option is half the source effort, but it is only incrementally more efficient than the single source option because the operation is receiver bound and more efficient source schemes do not improve acquisition efficiency. To reduce the project cost for this geometry, it is necessary to deploy and recover receivers more efficiently.

Expanding the application of seabed acquisition

While it is widely recognized that seabed data deliver superior image quality, oil companies have traditionally considered it too expensive for large scale application. In addition to the efficiency benefits associated with large receiver inventories and balanced source and receiver efforts, there is significant improvement available through recent technology innovations on both the source and receiver side.

Engineering receiver deployment for efficiency

In recent years, there have been significant engineering efforts focused on increasing the efficiency of receiver deployment and retrieval in order to address this cost differential and open seabed receiver techniques to a wider range of seismic surveys. In parallel with this receiver-focused effort, there are additional efforts to improve source efficiency and upgrade receiver inventories which, depending on the required geometry, may also impact overall survey efficiency.

These receiver-focused engineering efforts can be divided into three categories:

1. Re-engineering of the existing ROV deployed node technique
2. Node-on-a-rope deployment
3. Robotic ocean bottom nodes

Re-engineering of the existing ROV deployment model

Autonomous nodes, in which each receiver is a self-contained package, were introduced to the exploration and production (E&P) industry approximately 12 years ago. More recent engineering efforts have followed strong engineering



Figure 3 The evolution of deep water nodes. Three deep water ocean bottom nodes displayed to scale which have decreased in size over time, directly impacting ROV deployment efficiency.

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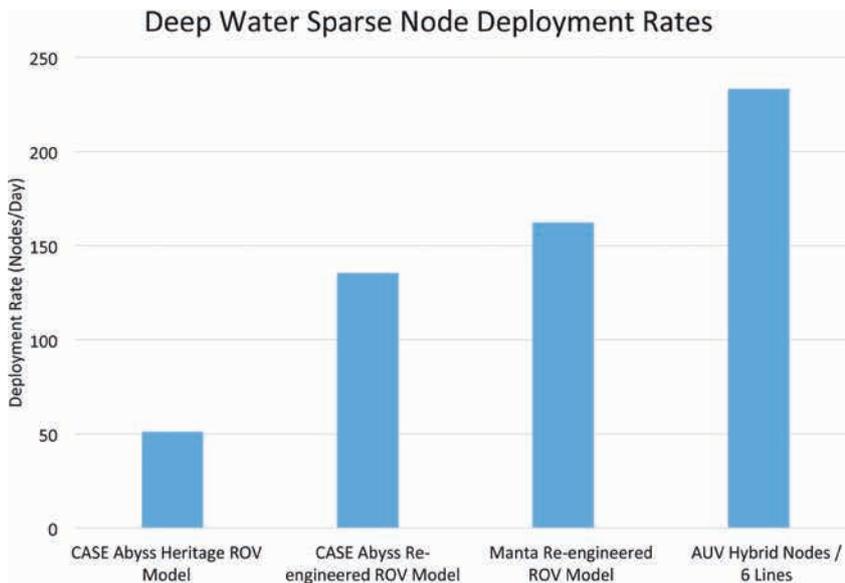


Figure 4 Bar graph detailing the increase in node deployment efficiency for the various deep water ROV node technology options based on established deployment models and a 400 m x 400 m node grid in 1500 m water depth.

protocols utilizing the latest battery technology and low powered electronics, resulting in more robust and compact products. The robust engineering results in fewer node failures, but, more significantly, the compact node has a direct impact on deployment and retrieval efficiency; smaller nodes allow for more nodes per container, more nodes per deployment basket and more nodes per ROV tray. Figure 3 details the evolution of Seabed Geosolutions' nodes plotted to scale detailing the development of the nodes over the last 15 years.

In parallel with the efforts to engineer more robust units, the ROV deployment hardware and processes have been under thorough review and upgrade. This has resulted in operations which utilize two ROVs in parallel, upgraded ROVs with higher power ROV trays, which carry more nodes and new operational best practices.

Node-on-a-rope deployment

The industry has also investigated methods to deploy nodes other than ROVs. One such method, which is highly efficient in shallow-to-medium water depth, is the node-on-a-rope method in which autonomous nodes are attached to passive ropes. The node attachment mechanism can be fully automated to accommodate fast deployment speeds of up to 3.0 knots depending on node interval, water depth, environmental conditions and receiver positioning tolerances. The node-on-a-rope solution is similar to a traditional seabed cable system but has a number of efficiency benefits which include no limitation in receiver line length, no downtime associated with power and telemetry line breakages and no downtime associated with recording vessel moves. While the node-on-a-rope solution suffers from a reduction in receiver repeatability, when compared to a ROV deployment solution, it still provides far greater receiver repeatability than a towed streamer solution.

Robotic nodes

Finally, a couple of players in the industry are developing robotic nodes which can swim to and from the pre-plot receiver location without the need for a separate deployment vehicle. Intuitively, one thinks of this as a highly attractive solution when considering the robotic developments outside the oil and gas industry, such as driverless cars, technically achievable. However, at a detailed technical level, there are two challenges which, while not insurmountable, do require further focus:

- **Node weight in water.** In order to minimize battery consumption during the transit to and from the pre-plot location, it is desirable to make the robotic node neutrally buoyant (or low weight in water). However, from a geophysical integrity perspective, the node should have some weight in order to couple with the sea-floor. In shallow water, this is not a huge concern because the node does not need to dive and surface large depths, but in deep water, this is a limiting issue.
- **Node positioning.** It is a relatively simple process to track where the robotic node is as it travels to and from the surface by using surface vehicles with acoustic positioning devices. However, this does not fully solve the problem because the robotic node needs to know where it is, requiring communication with the surface. USBL systems will solve this but can only multiplex a limited number of signals, restricting the number of swimming nodes at any one time.

Additionally, from a practical perspective, it is likely that a ROV will still be required on the crew to recover robotic nodes that fail while transiting or while on the seafloor.

Hybrid robotic nodes – basket assisted robotic nodes

In conjunction with Saudi Aramco, Seabed Geosolutions is engineering a hybrid robotic solution which does not suffer from these interim technical obstacles. In this hybrid robotic

solution, the nodes are carried to and from the surface in a basket as with normal ROV operations, but are then launched from an underwater vehicle / or directly from the basket traversing the pre-plot line. This process limits the transit duration of the robotic node and does not require the robotic node to dive or surface. Consequently, the node can be engineered to couple well with the seafloor. The underwater vehicle is positioned using a USBL acoustic system and is also equipped with USBL transducers to position and guide the robotic nodes. Using these systems, it is possible to deploy/retrieve a high number of receiver lines simultaneously. As the node positioning device and robotic node are at the same depth, positioning becomes a much simpler planar problem.

Improvements in source efficiency

As the receiver operation becomes more efficient, the potential for the source to limit the OBS project efficiency increases. In order to fully benefit from receiver operational efficiencies, it is necessary to improve source efficiency. Traditionally, the efficiency of the source operation has been limited by the requirement to separate the firing of sources in time, by the required record length, ensuring energy from different source points does not contaminate the reflection signal. It is now reasonably accepted in the industry that this is no longer a hard requirement and that sources can fire at smaller intervals than the required record length as long as the source energy from the different shots can be separated post-acquisition. If this argument is extended to its logical conclusion, it is also feasible to fire sources simultaneously. The basis of these simultaneous source techniques is to acquire the energy from different sources in a manner that facilitates the post-acquisition separation primarily by ensuring the source energy is randomized in receiver sorts. One such technique is to ran-

domize the timing of one or more sources so the interfering energy is disorganized in the receiver sorted gather; as long as the fire time is known, it is possible to randomize the energy from any of the sources. Other techniques rely on differences in geometry and natural randomization of shot firing through the normal variance present in the acquisition operation. Although simultaneous source methods were pioneered on 3D land vibroseis surveys, the method has now been successfully implemented offshore with multiple source vessels shooting simultaneously into OBS receivers. Both onshore and offshore survey geometries naturally have very well sampled 3D receiver gathers facilitating a number of the de-blending techniques.

Where will seabed seismic be positioned in the future?

Figure 4 details the improvement in deep-water node deployment efficiency in terms of the number of nodes that can be deployed per day assuming a 400 m x 400 m rx grid and 1500 m water depth. Both the continuous improvement associated with the ROV deployment method of industrially engineered nodes and the potential improvement from the basket deployed robotic node solution are evident. There is a clear and significant improvement in deployment rate associated with a more compact node and the re-engineered ROV model with an expectation that deployment rates will increase by a factor of 3. For the same geometry, the hybrid robotic node solution has the potential to deliver an additional 30% improvement in deployment efficiency, but it should be noted that this deployment model will be most beneficial with denser receiver grids where we can expect deployment rates in excess of 600 nodes/day.

Figure 5 details a further effort to evaluate node technology costs against towed streamer costs using the same

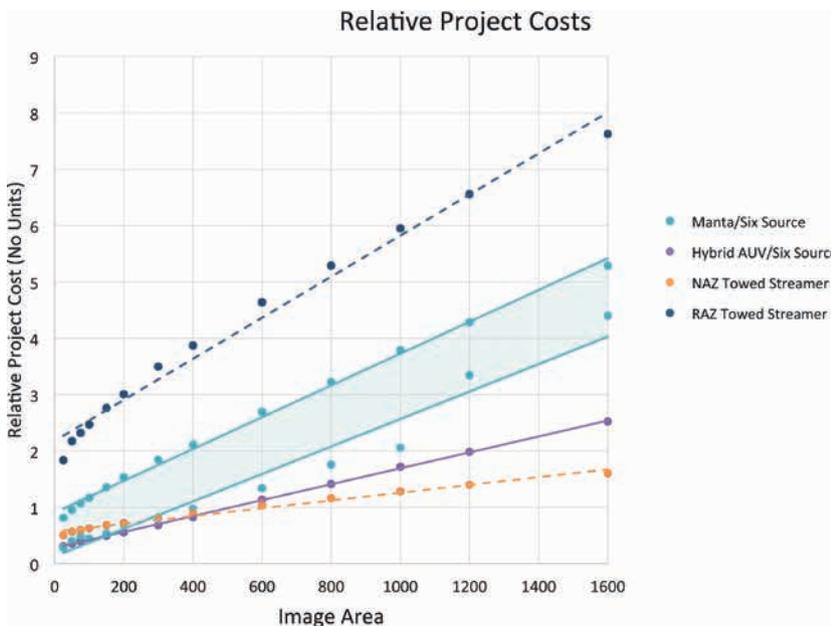


Figure 5 Graph comparing relative project cost against image size for two towed-streamer technologies (narrow azimuth towed streamer – orange dashed line and rich azimuth towed streamer – dark blue dashed line) and node technologies (solid lines). Assuming the latest technology, node solutions are much more competitive against towed streamer while delivering improved image and attribute quality.

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approach as referenced in the introduction but this time modelling the latest seabed deployment techniques. For control purposes, two streamer geometries which detail the high and low cost extents of the towed streamer solution are graphed using dashed lines.

- While none of the evaluated node solutions cost less per square kilometer than a towed-streamer narrow azimuth solution, they are all more efficient than a towed-streamer rich azimuth solution that offers similar trace density and azimuthal sampling.
- Good engineering practices during node manufacture and design realize significant uplift in project efficiency and bring node survey costs below the most expensive towed streamer costs, even for ROV-deployed surveys (upper range of Manta/six source shaded area).
- If the operator is willing to accept the compromises in receiver repeatability associated with node-on-a-rope solutions, there is potential for full azimuth OBS to approach towed-streamer narrow azimuth costs (lower range of Manta/six source shaded area).
- The anticipated uplift associated with robotic nodes, even in a hybrid solution in which robotic nodes are supported by a basket, will also drive project costs down and potentially challenge the towed streamer market.

Final comments

The ocean bottom seismic solution has traditionally only been considered for a small proportion of the total seismic market even though there are aspects of the measurement which are highly desirable. As the demands of the industry become more challenging owing to the high costs of reservoir exploitation (deep water, HPHT, more challenging reservoir characteristics) and exploration in more complex areas (sub-salt, fracture zones, basalt, etc.), oil companies have challenged providers to acquire higher quality, more cost efficient seismic data. Ocean bottom seismic contractors have responded with a new focus on resolving the factors limiting the efficiency of the seabed seismic solution, both on the source and receiver side. Ongoing engineering efforts, combined with operational innovation, have the potential to make a step change in seabed seismic efficiency and cost effectiveness, thereby opening up the seabed seismic solution to a much larger proportion of the contemporary seismic market.

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