An overview of marine seismic operations

Report No. 448

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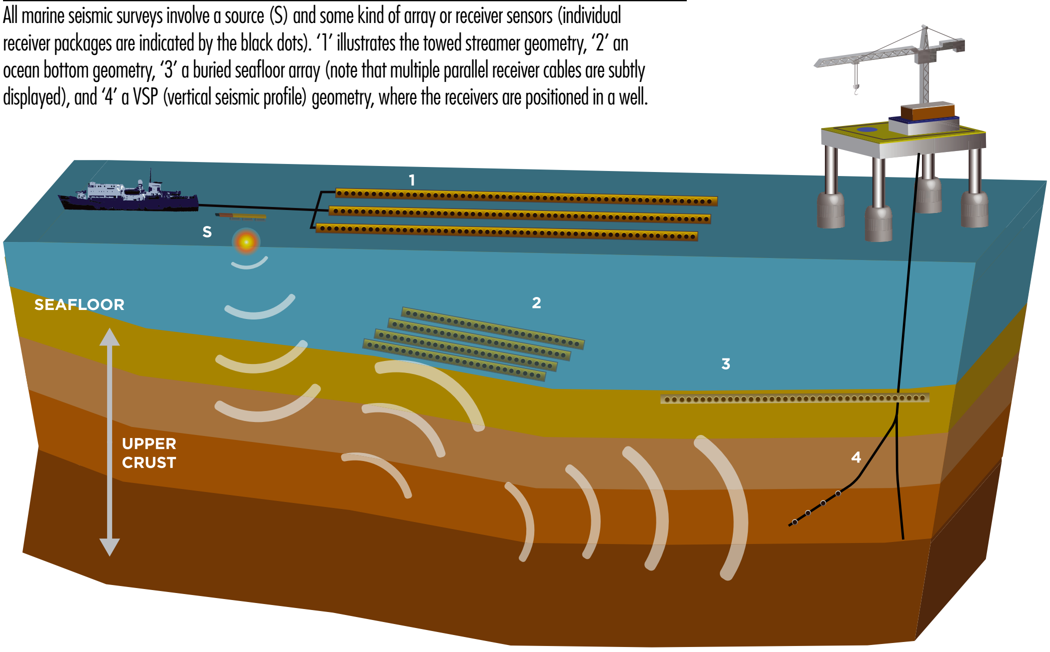
1 Introduction and underlying principles

In seismic surveying, sound waves are mechanically generated and sent into the earth (Figure 1). Some of this energy is reflected back to recording sensors, measuring devices that record accurately the strength of this energy and the time it has taken for this energy to travel through the various layers in the earth's crust and back to the locations of the sensors. These recordings are then taken and, using specialised seismic data processing, are transformed into visual images of the subsurface of the earth in the seismic survey area. Just as doctors use x-rays and audio- or sonograms to "see" into the human body indirectly, geoscientists use seismic surveying to obtain a picture of the structure and nature of the rock layers indirectly.

Figure 1 *(credit: Jack Caldwell)*

All marine seismic surveys involve a source (S) and some kind of array or receiver sensors (individual receiver packages are indicated by the black dots). '1' illustrates the towed streamer geometry, '2' an ocean bottom geometry, '3' a buried seafloor array (note that multiple parallel receiver cables are subtly displayed), and '4' a VSP (vertical seismic profile) geometry, where the receivers are positioned in a well.



Seismic surveys are conducted for a variety of reasons. They are used to check foundations for roads, buildings and large structures, such as bridges. They can help detect groundwater. They can be used to assess where coal and minerals are located. One of the most common uses of seismic data is in connection with the exploration, development, and production of oil & gas reserves to map potential and known hydrocarbon-bearing formations and the geologic structures that surround them. Most commercial seismic surveying is conducted for this purpose. Oil & gas exploration and production is conducted in many places on the earth's surface, in both the onshore (land) and offshore (marine) domains. Although the principles are identical, the operational details differ between the two domains. In this overview, only marine operations will be addressed.

All seismic surveys involve a source and some configuration of receivers or sensors. Surveys may be differentiated on the basis of

1. the geometry of the receiver system;
2. the density of measurements made over a given area; and
3. the type of sensor used.

Figure 1 illustrates the different receiver geometries used in marine seismic surveying, while Figure 2 provides a list of the different types of surveys. Towed streamer operations represent the most significant commercial activity, followed by ocean bottom seismic (including arrays placed on the seafloor and arrays buried a metre or so below the seafloor). Shallow water/transition zone seismic is a complex seismic operation as it is undertaken in shallow water areas such as tidal zones, river estuaries, marshes and swamplands. Vertical seismic profiling is an additional category of seismic survey where the receivers are placed in one or more well holes and a source is hung off the well platform, or deployed using a source vessel.

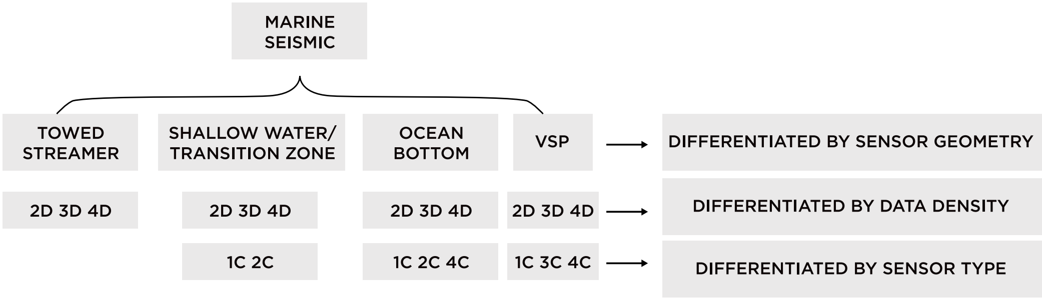


Figure 2 *(credit: Jack Caldwell & Chris Walker)*

This table summarises the majority of the different types of marine seismic surveys, and it suggests that there are quite a few varieties of survey used by the oil & gas industry.

Seismic surveys may also be differentiated by the density of the measurements made over a given area; 3D surveys have a much denser number of measurements than 2D surveys. There are also surveys that are acquired repeatedly over the same area, the duration between surveys being on the order of months or years. These are known as 4D surveys or time-lapse surveys, and hence the data density is higher over the same area, over a period of time because there are multiple data points over the same location. In general, 4D data density per unit area is higher than 3D, which in turn is higher than 2D.

Finally, surveys can be differentiated by the type of sensor that is used. In most marine work, the sensor is a hydrophone that detects the pressure fluctuations in the water caused by the reflected sound waves. The cable containing the hydrophones, called a streamer, is towed or 'streamed' behind a moving vessel. These streamers are typically 3 to 8 kilometres long, although they can be up to 12 kilometres long depending on the depth of the geophysical target being investigated. In ocean bottom surveys, typically the receiver system will have a hydrophone and a 3-component geophone at each receiver station and the data are processed either as 2-component data, or 4-component data. This 'component' concept will be discussed in the next section.

2 Some wave propagation fundamentals

There are a couple of fundamentals about wave propagation that will be important in order to understand a few topics that will be addressed later in this paper. When energy from a sound source is released in the marine environment, pressure waves are created in the water column. The magnitude of the pressure is called 'amplitude', and the excited waves are P-waves, or compressional waves. To a first approximation, water will only propagate P-waves and the sensors that make accurate measurements of the amplitudes of P-waves are hydrophones. The velocity of sound in seawater and density of seawater can vary as a result of changes in salinity, temperature, and gas and sediment content. under certain hydrohgrapic conditions layers can be formed that can reflect P-waves, and that can also trap certain frequencies of P-waves. In this latter case, the trapping layer will be called a waveguide. Although the terms amplitude (pressure) and energy are often used interchangeably (as in 'the P-wave pressure, or the P-wave energy'), energy is proportional to the square of the amplitude.

Rocks underlying the seafloor have rigidity: water does not. When P-waves enter the rock, they can be transmitted and reflected as in water, but they can also convert to S-waves or shear-waves. It is impossible for P-waves to propagate in rocks without mode-converting (converting from P-wave mode to S-wave mode) to S-waves, but most seismic surveying is accomplished using pressure sensors in the water column, so no direct S-waves are recorded in that situation. However, S-waves contain information of use to geoscientists that is not contained in P-waves, so sometimes it is advantageous to record S-waves. This can be done by placing sensors on the seafloor and catching the S – wave energy that has been created by the initial production of P-waves from the marine source.

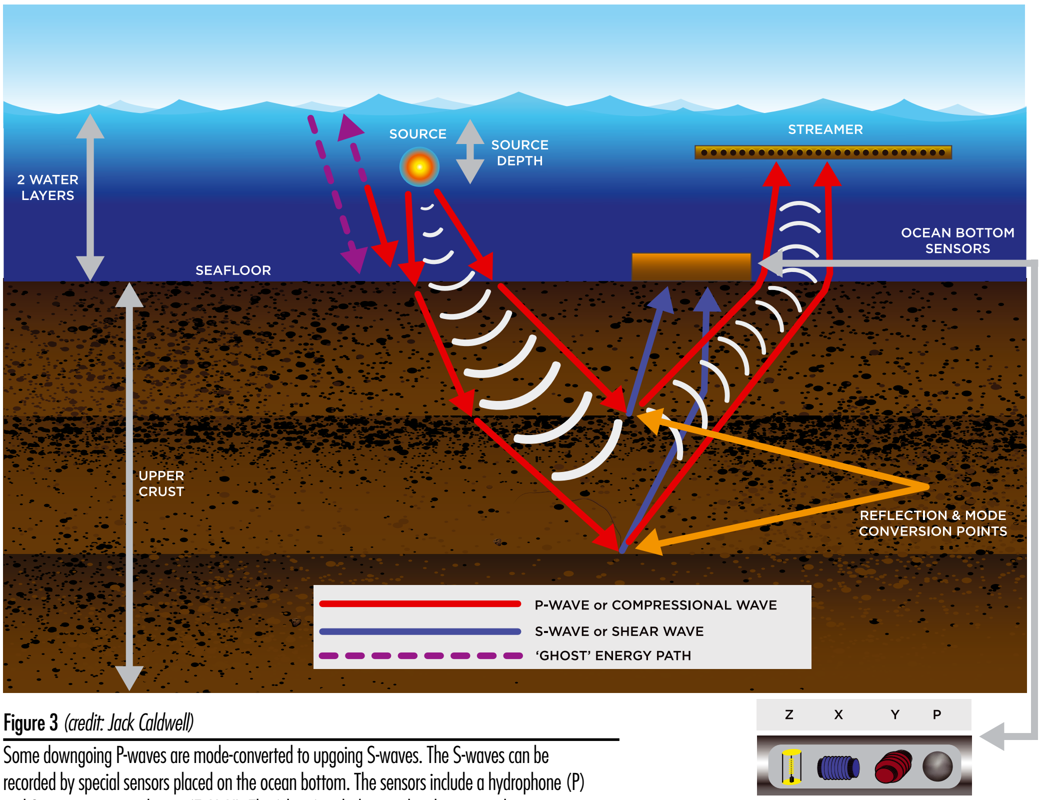
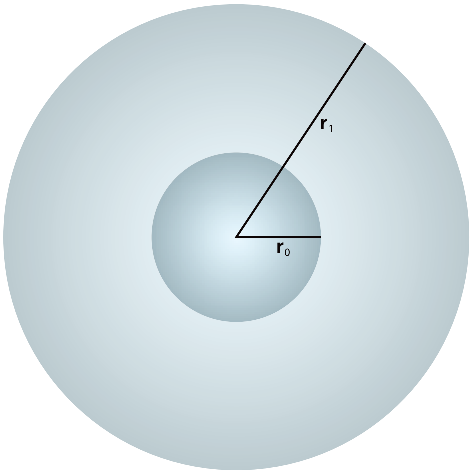


Figure 3 *(credit: Jack Caldwell)*

Some downgoing P-waves are mode-converted to upgoing S-waves. The S-waves can be recorded by special sensors placed on the ocean bottom. The sensors include a hydrophone (P) and 3-component geophones (Z, X, Y). The 'ghost' path that is taken by energy that propagates upwards from the source and is almost completely reflected at the air-sea surface interface.

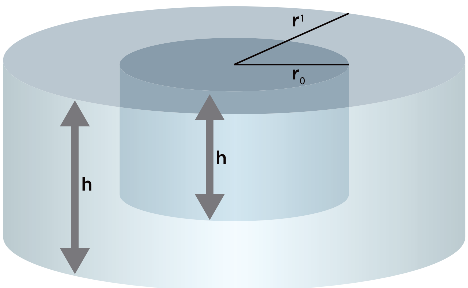
The sensors used on the seafloor typically comprise hydrophones, and 3-component geophones. A hydrophone measures only pressure and most do not measure the direction from which a pressure pulse arrives. Geophones measure ground motion and therefore the direction from which P-waves and S-waves arrive. Using three geophone components aligned in orthogonal directions; the vertical direction, the horizontal direction, and the other horizontal direction that is at right-angles to the first one (generally denoted as Z, X, and Y)measurements can be made in each of the three dimensions of space. Figure 3 illustrates these basic concepts and lays the groundwork for the discussion of ocean bottom surveys.

Figure 4 *(credit: Jack Caldwell)*



Spherical spreading

The area of a sphere is $\frac{4}{3}\pi r^2$, so the area increases at the same rate as r^2 increases. The amount of energy is constant, hence it diminishes per unit area at the same rate as the area increases, which is proportional then to $1/r^2$. Energy is the square of the amplitude, hence amplitude (or pressure) decreases as $1/r$.



Cylindrical spreading

The area of a cylinder is $2\pi rh$ and, in this case with h constant, the area increases at the same rate as r increases. The amount of energy is constant, hence it dimishes per unit area at the same rate as the area increases, which is proportional then to $1/r$. Energy is the square of the amplitude, hence amplitude (or pressure) decreases as $1/\sqrt{r}$

As energy propagates away from a source, several processes act on it. It diminishes due to friction in the earth, this process is termed absorption. Its frequency content decreases as absorption varies with increasing frequency. The largest effect is termed geometrical spreading. This is the process by which, if energy truly were conserved, the amount of energy per unit area becomes less since the area it is being spread over is getting larger and larger as the pulse propagates away from the source. This is analogous to a ripple effect on the water surface following a stone being dropped in the water. There are two simplified models of geometrical spreading, neither of which is a completely accurate way to model the process due to the numerous interactions between a moving energy wave and its surrounding environment. They are however relatively simple to understand and commonly used to correct received data crudely during data processing. The two models are known as spherical spreading and cylindrical spreading (refer to figure 4). The former applies reasonably well to deep water; the latter less accurately to shallow water. There is also the special situation when a waveguide exists, allowing amplitudes to propagate with less loss than either of the geometrical models would suggest. One main point to understand is that amplitudes diminish with distance from a source, and in general, they fall off slightly faster than either of these two models might suggest. The other main point to understand is that the resolution of the images able to be produced from seismic data decreases as the energy propagates away from the source, because it is getting weaker and because the total frequency bandwidth is getting smaller.

The 'source ghost' is created by the pressure pulse which leaves the marine seismic source in an upward direction, and is almost perfectly reflected at the interface between the sea surface and the air (see Figure 3). It is delayed from the down-going pulse by the time it takes to travel from the source depth to the surface and back down to the same depth, about 10 milliseconds, which is about the time duration of the initial pulse. The amplitude of this 'ghost" is the same magnitude, but opposite in sign, from the initial down-going pulse. What this effectively does is double the amplitude of the initial pulse, because it ends up coming so close after the initial pulse that the two look like one right after the other, the first with a pressure (or amplitude) of +A and the second with a pressure of –A. The total pressure excursion therefore goes from zero to +A to zero to –A, so the total pressure pulse is 2A. As well as essentially doubling the amplitude of the pulse, this process also causes the removal of a certain frequency band (ghost notch effect) of the pressure pulse, with more and more low frequencies being removed as the source depth is increased. This dictates the operational situation of not towing the source any deeper than a few metres. (The same thing occurs at the receiver as well, as a pressure pulse arrives from below the streamer and the pulse continues on up to the sea surface and again is perfectly reflected, with the opposite amplitude. Again, to prevent loss of too much of the low frequency pressure, it is desirable not to tow the streamer deeper than a few metres.)

3 Towed marine seismic methods

Within a given exploration zone, the details of a specific survey operation can vary enormously. There are, however, two principal categories of seismic surveying. These are two-dimensional (2D) seismic surveys and three-dimensional (3D) seismic surveys. 2D can be described as a fairly basic survey method, which, although somewhat simplistic in its underlying assumptions, has been and still is used very effectively to find oil & gas. A sub-category of 2D is the site survey where ultra-high resolution data is acquired in the immediate vicinity of an intended well to identify both seabed and shallow subsurface hazards. Ultra-high resolution here means that the survey is intended to provide more detailed information about the seafloor and the conditions of the rock down to a depth of a few hundred metres beneath the seafloor. 3D surveying is a more complex method of seismic surveying than 2D and involves greater investment and much more sophisticated equipment than 2D surveying. Until the beginning of the 1980s, 2D work dominated in oil & gas exploration, but 3D became the dominant survey technique in the late 80s with the introduction of improved streamer towing and positioning technologies. 4D surveys (or time-lapse 3D) are simply 3D surveys which are repeated over the same area, some period of time elapsing between the initial survey and the subsequent surveys. There might be several repeated surveys, depending on the specific oil or gas field in question. The purpose of this type of survey is to obtain images of how the hydrocarbon reservoir is changing over time due to production in order to maximize hydrocarbon recovery from the field. 4D surveys have become increasingly used since the mid-1990s, and now represent a significant percentage of overall seismic activity. More recently, increasingly sophisticated towed streamer acquisition schemes – multi-azimuth, wide azimuth and rich azimuth – have been developed to provide improved subsurface imaging in geologically and geophysically challenging environments.

3.1 Towed streamer 2D acquisition

In 2D operations, a single seismic cable or streamer is towed behind the survey vessel together with a single sound source (the specifics of both streamers and sources will be given in sections 8 and 9). The reflections from the subsurface are assumed to lie directly below the sail line that the survey vessel moves along, providing an image in two dimensions (horizontal and vertical) – hence the name '2D'. The processing of the measurements recorded by the streamer sensors is, by the nature of the method, less sophisticated than that employed for 3D and 4D surveys. 2D data acquisition lines are typically acquired several kilometres apart (see Figure 5) on a relatively sparsely spaced grid of lines and usually over a large area. This method is generally used today in frontier exploration areas to produce a general understanding of the area's geological structure before drilling is undertaken.

It is worth noting that due to the action of tides and currents, the seismic streamer does not normally tow directly behind the survey vessel but deviates laterally from the ship track or nominal sail line. This is referred to as 'streamer feathering' (Figure 6), and whilst such lateral displacements are not typically crucial to the success of 2D surveys, they are important in 3D and critically so for 4D surveys. Such detailed knowledge and repetition of the positions of both sources and receivers is fundamental to the successful application of the 4D technique. A typical 2D survey is illustrated in Figure 5; the 2D lines are shown as a grid. From each of the

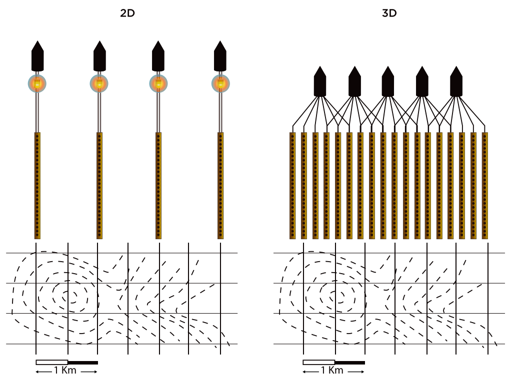


Figure 5 *(credit: Jack Caldwell & Chris Walker)*

This illustrates the basic difference between the 2D survey geometry and the 3D survey geometry. The dashed lines suggest subsurface structure contour lines, indicating that the area covered by each of the two survey geometries is the same. The spacing between adjacent ship tracks for 2D will typically be 1km or greater. While the distance between ship tracks for 3D will depend on several factors, such as the number of airgun arrays being used (typically two) and the number of streamers being towed, the intent of 3D is to have the distance between the streamers be on the order of 25-75 meters. When one figures where the subsurface image points occur, the data density will be 15 to 20 times greater in the left-to-right dimension than for 2D. The data density in what is the up-and-down dimension of this figure will be the same (or about the same) for the two types of survey.

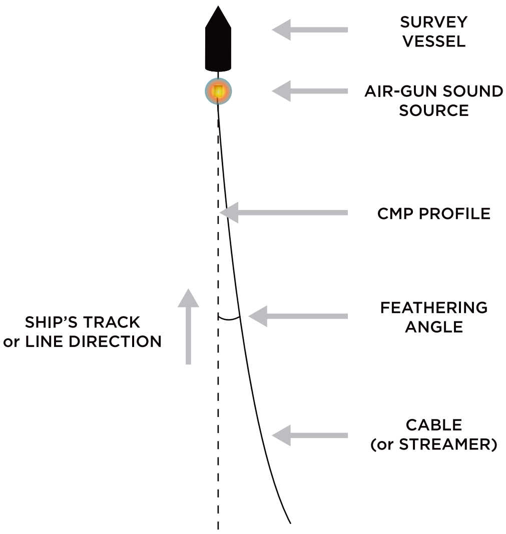


Figure 6 – feathering *(credit: Chris Walker)*

2D lines, sub-surface geologic horizons are identified, positioned and contoured by the interpreter. The weakness in the 2D method lies in the gaps in knowledge caused by the large spacing between the grid lines. Typically the lines are not much closer than one or two kilometres, so interpreting the sub-surface between these sample locations can prove problematic, and can be very inaccurate. 3D data, which have a much closer spacing of the grid lines, removes much of this uncertainty and/or error.

3.2 Site surveys

Figure 7a *(credit: EdgeTech)*

View of a side scan sonar system – the tow "fish' and shipboard control unit.

Before a well is drilled, there is both a legal and operational need to have detailed information about the seabed in the area immediately surrounding the well location and the geological layers immediately below the subsurface. The information about the nature of the seabed is needed to ensure that the drilling equipment – or related equipment such as anchors – will not encounter any problems when they are emplaced, and that the seafloor will provide the necessary stability for such equipment. This information is also used to help the drillers anticipate the condition of the rock into which the well is spud and how the initial drilling will be accomplished. If the well is successful, this information will also be needed for all subsequent structures that will be installed to accomplish production from the location of that well, or nearby wells. The near subsurface data are needed to ensure that there are no unforeseen hazards such as shallow gas pockets or buried river channels that could have catastrophic effects if penetrated during the drilling process. The sudden release of gas below a drill rig has caused the loss of the entire rig in the past, with consequent loss of life.

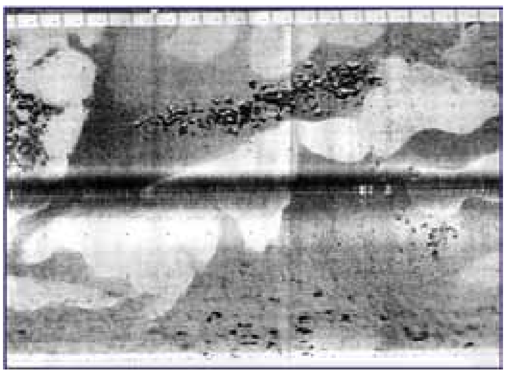


Figure 7b – Side scan sonar image of the sea bed *(credit: Fugro Survey)*

The resolution of data from conventional 2D or 3D seismic surveys is not sufficient for these purposes and therefore a high resolution or site survey is undertaken. This technique is simalar to conventional 2D marine, except for the source used. Generally a small volume compressed air seismic source is used, typically 40 to 400 cubic inches. Alternatively, a 'sparker', a device that generates an acoustic pulse from an electrical discharge, is used. The receiver streamer is much shorter compared with conventional marine seismic methods; between 600 and 1,200 metres due to the shallow depth of the target geology. The source and streamer are also towed at a depth of only two or three metres, corresponding to the much shallower depth of investigation.

The shallow tow depth allows higher frequency or higher resolution data to be generated, but limits operations to very good weather conditions. Survey durations are usually on the order of four or five days. Other equipment may be deployed from the survey vessel during the course of the site survey. This may include side-scan sonar (Figures 7a and 7b) to determine the texture, topography and character of the seabed sediments and to detect debris such as boulders, outcrops, pipelines, wellheads and other equipment lying on, attached to, or shallowly buried beneath the seafloor. A 'boomer' which employs an electro-mechanical system to generate a low-power, high frequency acoustic pulse is used to provide a higher resolution image of the very near surface sedimentary layers. Increasingly, a 'chirp profiler' – essentially a small-scale marine vibrator (see section 8.2) – is replacing boomers as it produces a more consistent input acoustic signal. Multibeam echosounders are also commonly used to create densely-sampled digital terrain models that can be used to further define topography and assist in the oilfield development phase when planning the location of wellheads, platforms, pipelines, etc. Seafloor coring is also carried out to determine the seabed conditions. Operating frequencies of side scan sonar systems vary according to manufacturer and application but are in the range 60-400 kHz, with acoustic output sound pressure levels on the order of 220dB re 1 μPa at 1m (GeoAcoustics Model 196 transducer).

3.3 Towed streamer 3D acquisition

A 3D survey covers a specific area, generally with known geological targets, that have been identified by previous 2D exploration (Figure 5). Prior to the survey, careful planning will have been undertaken to ensure that the survey area is precisely defined. Since time, money and effort will be put into the acquisition, processing and interpretation of the survey, it is very important that it is designed to achieve the survey objectives. The result of the detailed planning will be a map defining the survey boundaries and the direction of the survey lines. Specific acquisition parametres such as energy source effort and receiver station intervals, together with the data recording or 'listening' time, will also be defined. In 3D surveying, groups of sail lines (or swaths) are acquired with the same orientation, unlike 2D where there is typically a requirement for the lines to be acquired in an orthogonal direction relative to the dominant structural grain. Simplistically, 3D acquisition is the acquisition of many 2D lines closely spaced over the area.

The 3D sail line separation is normally in the order of 400 to 800 metres, depending on the number of streamers deployed and their cross-line separation. By utilising more than one source and many streamers from the same survey vessel, the acquisition of many closely spaced, sub-surface 2D lines, typically between 25 and 50 metres apart, can be achieved by a single sail line. A 3D survey is therefore much more efficient, in that many times more data are generated than for 2D per survey vessel sail line . The size of a 3D survey is usually referred to in square metrekilometrekilometres or sometimes the number of line kilometres acquired. A small 3D survey size is on the order of 300 square kilometres, or 1,000 sail line kilometres, or 12,000 sub-surface 2D kilometres. A larger 3D survey may cover 1,000 to 3,000 square kilometres.

3D surveys are typically acquired as shown in Figure 8, with a 'racetrack' pattern being employed. This allows, adjacent sail lines to be recorded in the same direction (swath), whilst reducing the time necessary to turn the vessel in the opposite direction. A seismic vessels may be of the order of 100 metres

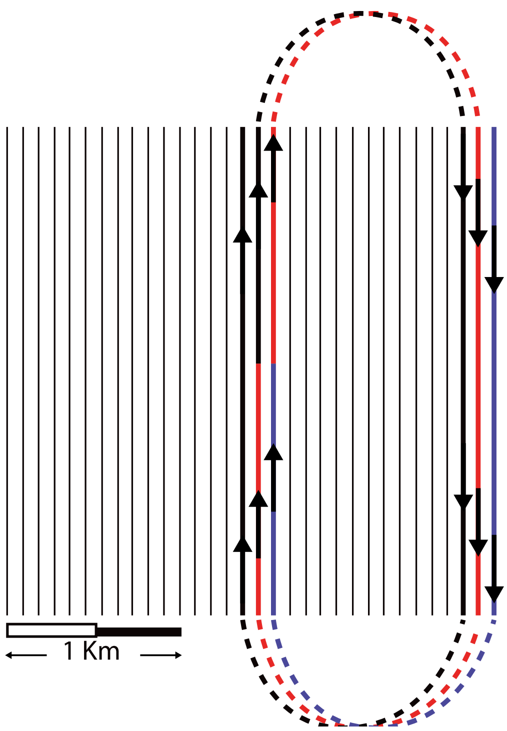


Figure 8 *(credit: Jack Caldwell & Chris Walker)*

3D survey 'racetrack' pattern of how the survey is acquired. Each line represents a ship's track line, so the vessel tracks down one line, skips over several soon-to-be-shot lines and tracks back up another line.

long and 30 metres wide and are towing several kilometres of streamers behind them, it takes a large area for them to make a turn. This increases the efficiency of acquiring the data and minimises processing artifactsthat could adversely affect the interpretation of the data. With the number of sail line kilometres involved, 3D surveys can take many months to complete. The way in which the data are acquired greatly affects the efficiency of the acquisition and considerable planning goes into this aspect. Whilst a 'racetrack' approach is commonly used, size and shape of the survey, obstructions, tides, wind, weather, fishing vessels and client specifications, amongst others, will clearly affect the efficiency of the operation. Usually, a survey is broken into areas and swaths of lines are completed in phases or individual groups of 'racetracks', but there is no rigid procedure which is followed by all surveys and all areas.

Powerful computers are required to process the large volume of data acquired and to produce a three-dimensional or 3D image of the subsurface – hence the term 3D seismic. 3D surveys have now become the preferred method for providing the geoscientist with subsurface information and account for more than 90% of marine seismic data acquired worldwide. 3D surveys are used in all phases of hydrocarbon exploitation from identifying geological structures which are considered likely to contain hydrocarbons (Exploration 3D) to, in areas of established production, delineating those portions of the reservoir which are not being drained by existing wells (Production 3D). As noted above, repeat 3D surveys – 4D - are being used regularly on established fields to monitor the production from the field: so-called 'Time Lapse' surveys.

3.3.1 Multi-streamer operations

In 1984, the first twin streamer operation was undertaken, which effectively doubled the data acquisition efficiency of the vessel by generating two subsurface lines per vessel sail line. By moving to twin source/twin streamer configurations in 1985, the output was increased to four subsurface lines per vessel sail line or pass. The next logical step of towing three streamers and two sources behind a single vessel, thus acquiring six lines per pass, was achieved in 1990. The number of deployed streamers has consistently increased with as many as 16 streamers having been towed. A schematic diagram of a typical eight streamer/dual source operation is shown in Figure 9. The heavy lines represent the streamers. The small circles represent the sources. Obviously each streamer and source are attached to the vessel, but for clarity, the towing links are not shown. The dashed lines represent the subsurface lines or Common Mid Point (CMP) lines that are derived from data being recorded by the streamers. These lines indicate the loci of points that are located halfway between the source and

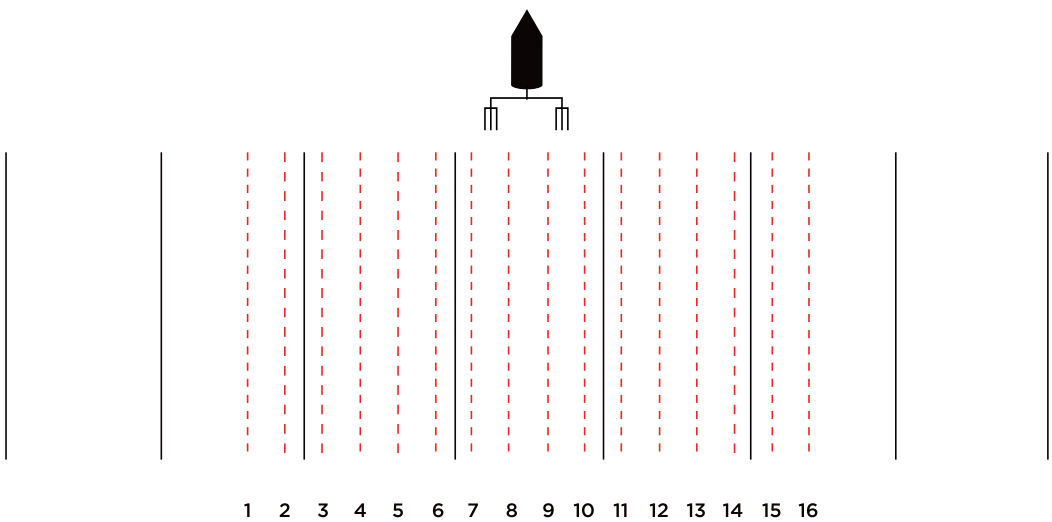


Figure 9 – schematic diagram of an 8-streamer, dual-source operation *(credit: Chris Walker)*

The solid lines represent the streamers and the dashed lines represent the loci of points where the reflections originate in the subsurface. If this were a single source operation, the width of the subsurface covered would be half the total distance between the two outside streamers. Because dual sources are used, the subsurface width covered is ${}^{4}/_{7}$ of the total distance between the outside streamers.

hydrophone receivers positioned along any one of the streamers. These are the theoretical reflection points between the source and the streamers, and their theoretical locations will not be too far from the actual reflection points if the geologic structure is flat or not too complicated. If the structure is complicated, then more advanced processing is required to obtain an accurate picture of the subsurface. When the port source energy is released, CMP lines 1, 3, 5, 7, 9, 11, 13 and 15 are produced from the streamers. Similarly the starboard source produces CMP lines 2, 4, 6, 8, 10, 12, 14 and 16. The number of CMP lines achieved in a single vessel pass is a measure of the efficiency of a particular survey towing configuration.

Multi-streamer operations require a significant amount of in-sea equipment – the 16-streamer operation referred to above entailed 72 kilometres of cable being towed behind the vessel. – Consequently,the back deck of the vessel becomes very busy due to the activity involved in handling equipment including streamers, sources and the related control devices. Organising and operating such a set-up in a safe and efficient manner requires a very high level of knowledge and skill.

3.3.2 Undershooting

One of the more common problems associated with seismic data acquisition is the location of surface obstructions in the survey area. These are usually man-made, such as drilling rigs or production facilities In addition, natural obstacles such as sandbanks also present quite serious impediments to the survey process. A more specialised problem arises where there are complex subsurface geological structures such as salt domes. Because of the way the seismic energy travels into the rock layers and back to the surface, in the vicinity of these complicated features reflected energy can be missed using 'normal' towed seismic geometries as the receivers are not in the right position to detect the returning energy. Some deep geological interfaces under complex structures may end up being poorly sampled or not sampled at all. Undershooting is the technique used to image the sub-surface beneath obstructions, and is one of the techniques used to better image in areas of complex geology.

Figure 10 illustrates a two-vessel operation. One vessel acts as the streamer and recording vessel and the other provides the source energy from two independent units. Note that the streamers are long, 3 to 12 kilometres in length. The deployment of the sources from a separate vessel gives greater versatility when it comes to avoiding obstructions. Typically, the recording vessel will sail on one side of the obstacle and the source vessel the other. The subsurface CMP lines will lie between the two vessels and under the obstructed area, hence the name 'undershooting'. In theory, the vessels can be separated by a long distance, but in practice, the separations are kept as short as possible in such situations. The reason for this is that if the source and receivers are too far apart, there will be very few short offsets (offset is the individual source-to-receiver distance) in the CMP offset distribution and this results in a poor sampling of the shallow subsurface interfaces. This set-up is not only used for avoiding obstructions, but also to achieve an optimum distribution of offsets. With careful planning, it can just as easily be employed to avoid the salt dome sampling problems mentioned earlier. Note that where there is more than one streamer towing vessel, the separation between the streamers and sources has to be controlled very precisely to maintain regular surface offsets between all the stations recorded for each shotthereby providing the accurate subsurface coverage that is required.

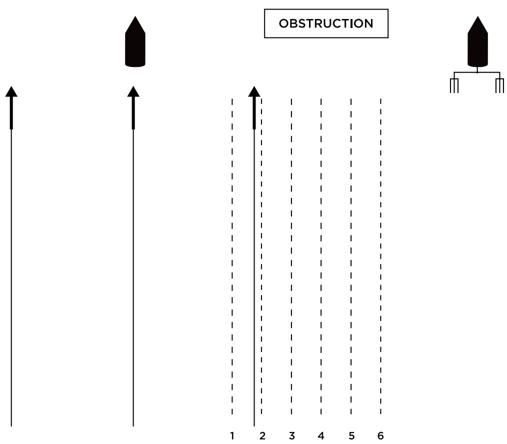


Figure 10 – Triple streamer, dual source undershoot geometry *(credit: Chris Walker)*

The solid lines indicate the streamers and the dashed lines indicate the CMP lines. Towing long streamers (up to 8km) around obstructions requires skill and experience from both the maritime crew and the seismic crew on board the vessel. This is true whether it's a one- or two-vessel situation.

3.3.3 3D seismic survey vessel

The key elements or areas of a typical marine 3D seismic survey vessel (shown in Figure 11) are outlined below.

Figure 11 – Two currently operated seismic vessels (credit: CGGVertias and Western Geco)

The lines coming off the stern of each vessel are associated with the towing equipment for the streamers. The deck just below the deck from where the streamer towing equipment eminates is the gun deck. The yellow circle with the 'H' in the centre is the helipad, used for ferrying the crew and other personnel to and from the vessel when it is at sea.

Instrument room

This is where the main seismic instrumentation is located and operated. The position of the instrument room varies from vessel to vessel but is normally located centrally, somewhere below the bridge and forward of the back deck. It contains the main seismic instruments for recording seismic data and controlling the seismic streamer(s) and activating the energy source. The electronics associated with the main navigation system is also here with its links to satellite, radio systems, compasses and the various positioning control and monitoring systems. There is usually a working area for instrument testing and repair. Computers used for the onboard seismic and positioning data quality checking and processing are also located in this area.

Back deck

Although ship to ship designs will vary, the back deck is used for storage, deployment and retrieval of the towed seismic equipment. The seismic streamers are stored here on large reels and when acquisition is in progress, the streamers are deployed from the back of the vessel and towed directly behind and/or to the sides of the vessel. The number of streamers varies depending on the vessel design and capability. All the wiring from the streamers is fed through watertight connections to the instrument room. Most vessels have a small streamer repair area on the back deck. The seismic streamers are under control of the observer department of the seismic crew.

The back deck is also the location of the energy source equipment. The energy source usually comprises a number of source elements called air guns, which are supplied with high-pressure air. A marine seismic source is made up of an array of many different sized source elements, linked together with special harnesses, air supply lines and electronic control cables. When not in use, these cables are stored on reels usually at the forward and of the back deck. During deployment, they enter the sea through a slipway at the rear of the deck. The air feed from the vessel compressors to the arrays is monitored from a control panel housed in a small work shack where gun repairs can also be done.

The towing equipment is a complex, carefully designed arrangement of specialised equipment that enables the multiple streamers and source arrays to be positioned accurately behind the vessel, and depending on the survey design, allows for different source and streamer separation distances. The crossline streamer separation is the distance between streamers, perpendicular to the direction of movement of the vessel, which results in tremendous pulling forces which the towing system must withstand in variable weather conditions. It can take several hours or days to deploy or retrieve all the equipment. Maintenance of the source and towing equipment systems are the main responsibilities of the mechanical department of the seismic crew.

Finally, the navigation or positioning in-sea hardware equipment is also stored on the back deck. This usually involves buoy systems containing navigation instruments. Tail buoys are attached to the 'tail' end of each of the streamers furthest from the vessel. Additional navigation buoys are sometimes attached to the source arrays (flotation buoys are attached to the front ends of the streamers). In complex multi-streamer/source vessel arrangements, the navigators need a great deal of other control and monitoring systems on sources, streamers and any other vessels.

Compressor room

This contains the compressor engines and compressors, which supply high pressure air to the source arrays. The compressors are capable of recharging the individual source elements rapidly and repeatedly, which enables the source array to be activated, typically every ten seconds or so during acquisition of data and for periods of up to 12 hours or more, depending on the length of the sail line. This room is under the control of the mechanics and is usually situated near the back deck.

3.3.4 Operations

The basics

The first stage of normal operations (commonly called mobilisation) is supplying the ship being with all necessary fuel, water, food, seismic equipment and crew. It will then sail to the designated survey area. The vessel will have been provided in advance with all necessary details regarding the survey layout and design, and what and how much equipment will be deployed. The navigators will have information, specifying where each data acquisition sail line must start and finish, and the location of each source or shot point. This information will have been fed into the onboard integrated navigation system. On the bridge, the captain will ensure that while the ship is under normal manual control, he will be navigating as agreed to the first line-start position. He and the seismic crew (party) manager will be closely monitoring wind, weather conditions and any incoming reports.

As the survey area is approached, the observers will deploy the streamers, attaching depth monitoring and control devices (birds) at regular spacings as they go. As sea water temperature and salinity vary by location, considerable care is taken to ensure that the streamers are correctly "ballasted", to be neutrally buoyant for the chosen operating depth for the specific survey area. Ballasting is accomplished by ensuring that the upward lift of the positively buoyant streamer is exactly counterbalanced by the weight of the streamer electronic module, stress members, external devices and, if necessary, externally attached weights. The mechanics will start the compressors and prepare and check the source arrays, which are deployed after the streamers, but can later be recovered and re-deployed when necessary. The navigators will work with the mechanics and observers to attach the necessary buoys for positioning.

In the instrument room, positioning of all in-sea equipment will be verified and all equipment will be powered up, tested and checked for trouble free operation. Test records for background noise will be made. The streamer, source and buoy links will all be tested, and the whole system confirmed ready for use. As the ship approaches the start of a pre-defined sail line, it is said to be on the run-in. This is the stage where it is very close to the agreed start position, the vessel has the correct heading and the streamers are as much in line behind the vessel as conditions will allow. Now the ship is steered according to the input from the navigation system. Around the vessel, all involved crew members will be monitoring the ship's position from information screens in their respective areas. The navigator monitors the approach to start of line in terms of distance to go, heading and speed to ensure that no positioning problems arise at the last moment. The mechanics will be closely watching the compressor monitors and will make a last minute visual inspection of the source equipment that can be seen from the vessel. The observers will take any final test records for future reference, and will check the source control system.

Depending on the country of operations and the area-specific environmental controls in place, a visual watch for marine mammals from the vessel may be ongoing for at least 30 to 60 minutes before the source is first activated. On some surveys, dedicated acoustic monitoring methods may additionally be utilised to identify the presence of marine mammals within the vicinity of the source array. It is only when the crew has been informed that no marine mammals are present that the source can be activated and data acquisition can proceed.

The source is activated at the first predetermined position and data acquisition commences recorded. This process is repeated at successive regularly spaced distance intervals, (with the source firing every 10 to 12 seconds)depending on vessel speed as determined by the navigation system. This process is repeated until the vessel has reached the pre-defined end of the sail line. Throughout the recording period, all personnel involved perform detailed prescribed tasks. The navigator monitors the positioning system output, checking for any discrepancies, and completes the end of line paperwork and prepares plans for the line change (relocating of vessel to the next sail line). The mechanic monitors the compressor performance, checks the backdeck towing systems, and is ready to deal with any 'mechnical' problems. The observer monitors the data recording system operation, changes recording media (typically high density tape decks), and fills in the line log as the line progresses.

When the line is complete, all systems stop recording. The ship is now in line-change mode. The navigator has planned how the vessel should manoeuvre to start the run-in for the next line. The line-change time varies according to the layout of the survey and the configuration of the equipment, but is usually between one and three hours. During the changeover period, all of the crew involved work quickly to resolve any problems and make modifications or repairs in readiness for the next line. The run-in is then started, all equipment is readied, the sources activated, and the activity cycle is repeated. Infrequently, technical failures occur and line-starts are delayed or lines are terminated early. Operations may also be affected by weather, and oceanographic conditions or adjacent shipping.

Weather

In general, seismic surveys are planned to be acquired in calm weather, to minimise the amount of extraneous noise recorded along with the primary signals. This noise increases with increasing sea state and most companies specify how much measured noise is acceptable during the acquisition of the data. If the prevailing conditions lead to this level being exceeded, the acquisition is stopped. If conditions become excessive, then the streamers and source arrays may have to be recovered. The vessel will 'ride out the storm' on location or move to more sheltered waters, whichever is the safer and better operational option; the vessel crew's safety being the overriding concern.

Shipping

If the survey is in an area of high shipping activity, seismic operations can be difficult. A seismic survey vessel is limited in its manoeuvrability because of the long streamers (generally several kilometres, with a maximum length currently of approximately 12 kilometres) deployed from the stern. The main vessel itself is in little danger, but with many vessels in close proximity, the streamers may be fouled or cut. Aside from the large financial loss from the value of the streamers themselves, this can mean reduced revenues through disrupted operations. In difficult areas, chase or guard boats are employed. These are smaller vessels, usually ex-fishing boats, which contact potentially threatening shipping traffic and direct them away from possible contact with the streamers.

Currents, water depth and obstructions

The survey vessel is sometimes required to operate in areas of strong currents; shallow water such as over sandbanks, or in the vicinity of obstructions such as oil platforms. These may, in many cases, cause problems and affect the rate or quality of data acquisition due to the limited manoeuvring ability of the vessel. Careful planning can mitigate these problems to some extent in some areas, but the ability of the survey vessel to acquire data efficiently will be severely hampered.

4 Advanced acquisition techniques

Increasingly complex acquisition geometries have recently been employed to acquire 3D towed-streamer data in areas where the data quality obtained from conventional towed streamer acquisition has been insufficient for cost-effective field development. The methods, summarised below, provide an increased range of horizontal directions, or azimuths, from which data are acquired which ,when combined, provide an improved signal-to-noise ratio of the resulting seismic data. This is analogous to taking a photograph of an object from different directions to image all sides of the object.

4.1 Multi-azimuth

In a Multi-AZimuth (MAZ) survey, the increase in azimuth range is achieved by acquiring 3D data over the same subsurface area with multiple orientations, *ie* the survey is acquired a number of times in different directions. In a conventional towed streamer survey, the data are essentially acquired along a single azimuth so that it can be considered a 'narrow azimuth' survey. MAZ obtains a wider range of azimuths by acquiring overlapping conventional surveys at various azimuths, typically 3 – 6. It is a single vessel, multi-pass technique. The net result of adding the different orientated 3D data together is an improved combined image of the subsurface.

4.2 Wide azimuth

In this case the increase in azimuthal range is accomplished by acquiring the data over the same subsurface area using multiple towed streamer/recording and source vessel configuration. Multiple passes are acquired with increasing lateral separation between the streamer and source vessels to build up the range of offsets and azimuths. Figure 12 shows a wide-azimuth towed streamer (WATS) survey example operating four source vessels. By making successive passes over the target, increasing the offset between the streamers and the source vessels by the width of the streamer spread each time, a wider range of azimuths and offsets are obtained. WATS is a multi-vessel, multi-pass technique.

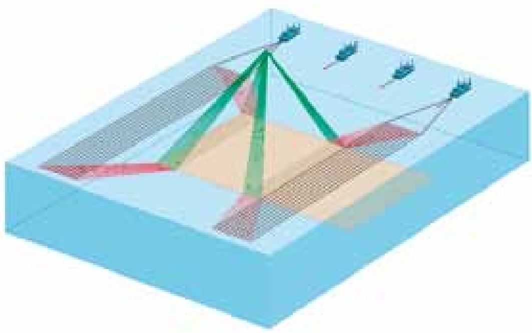


Figure 12 – Wide-azimuth towed streamer geometry *(credit: WesternGeco)*

Schematic illustrating a wide-azimuth configuration using 4 source vessels (left). A photograph of 4 source vessels conducting a wide-azimuth survey (right). This technique provides better offset (distance between the source and each sensor position in the streamers) distribution as well as a broader range of azumiths. This geometry delivers an improved subsurface geomerty.

5 Ocean bottom seismic techniques

There are three principal types of seabed recording systems used in marine seismic: Ocean Bottom Seismometers (OBS), Two-Component (2C), and Four-Component (4C). Two-component and four-component data are generally recorded using cables laid on the seabed, although there are systems which use Remotely Operated Vehicles (ROVs) to deploy and recover sensor nodes (which may or may not be connected by cables) placed on the seafloor. A geophone measures the velocity of the particle displacement, an accelerometer, as its name implies, detects the acceleration of the particle displacement, and a hydrophone detects changes in pressure.

2C data are acquired using a ground motion sensor – historically a geophone, but more recently an accelerometer – and a hydrophone at each receiver location. 4C uses a three-component ground motion sensor in addition to a hydrophone. The use of three-component sensors, which detect particle motion along three mutually perpendicular axes, allows the geophysicist to infer more information concerning the subsurface geological layers from which the reflections, and mode conversions, occur. To date, this has been more useful in producing reservoirs, rather than exploration, where multi-component techniques have the potential to enhance hydrocarbon recovery. OBS systems historically have been used by university research groups to provide large-scale information for crustal studies and lithospheric investigation.

5.1 Four-Component (4C) data acquisition

The 4C technique is illustrated in Figure 13. In this instance, the four-component sensors are usually electrically connected to a recording vessel by means of a cable, which provides power, instrument command and control, and data telemetry of the sensor data to the recording equipment on the vessel. Several cables are commonly employed to improve operational efficiency, similar to towed streamer operations. Cable length varies according to survey requirements, but is typically on the order of 5-6 kilometres per cable, with a 4C sensor usually located every 25 or 50 metres. The recording vessel is equipped with dynamic positioning thrusters to facilitate accurate cable placement and ease of recovery. Multi-cable operations are generally used for 3D (and 4D) surveys, whilst a single cable configuration is used for 2D surveys. Recently a buoy-based system has been introduced into commercial operations: this eliminates the need for a recording vessel. In this system, each 4C cable is connected to a radio-controlled remote recording buoy.

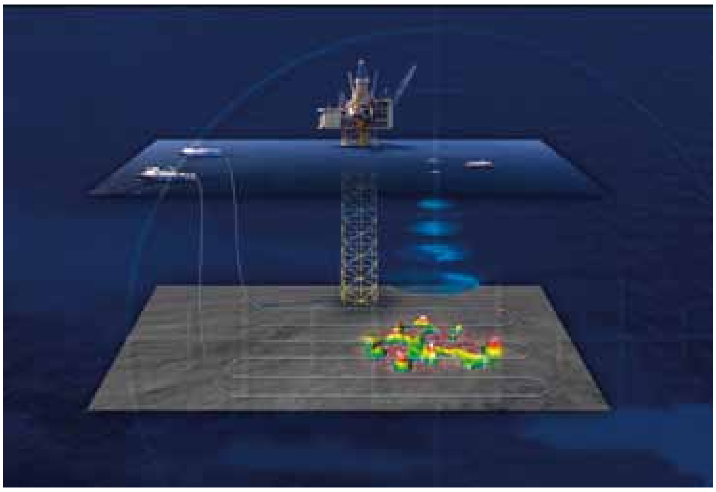


Figure 13 *(credit: Western Geco)*
Example of an ocean bottom cable operation. The bottom cables contain either 2- or 4-component sensors.

A separate source vessel is used for deployment and operation of the seismic sources, which clearly increases the cost of 4C surveys compared to towed streamer. There are two principal objectives for 4C surveys: improved imaging of the subsurface and/or increased understanding of reservoir lithologies, both of which rely on the recording of P-waves and mode-converted shear waves (S-waves) by the geophones on the seabed. Figure 3 illustrates the mode-conversion concept. Energy propagates down to the target horizon as P-waves and back up to the detector on the seabed as S-waves.

The physical separation of sources and receivers allows two alternative geometries to be operationally employed: 'swath' where the source-lines are parallel to the receiver lines akin to towed streamer surveys, or 'patch' surveys where the source-lines are orthogonal to the receiver lines.

5.2 Two-Component (2C) data acquisition

By using particle motion sensors that measure the particle motion in the vertical axis, and hydrophones in combination, it is possible to remove the frequency limiting effects of the sea surface ghost. This is possible because the particle motion sensor response to upward and downward travelling reflections has the same polarity, unlike that of a hydrophone. The two component (2C) technique utilises both particle motion sensors and hydrophones in a combined cable that is deployed from a cable/recording vessel down to the seabed, just like the 4C technique. Historically, equipment design limited the depth to which these systems could be deployed to less than 200m, but the more recent generation of cables are being used in much deeper waters. The techniques employed for 2C and 4C are broadly the same, although because the 2C method utilises P-wave data rather than P- and S-wave, less source effort is required due to the asymmetric nature of the PS-wave ray path (see Figure 3) and shorter record lengths are needed as the P-wave energy travels at roughly twice the speed of the S-wave.

The 2C technique provides higher resolution than a conventional towed streamer operation due to the elimination of the ghost notch, but the need to deploy and recover cables to and from the seabed provides less areal efficiency than modern multi-towed streamer vessels. This has historically limited the use of the technique to areas where of shallow water depth or there are obstructions such as platforms, or where the use of a deep-water marine vessel is prohibited. However, increasingly in certain areas like the Middle East, the 2C technique has been extensively used to image specific subsurface geological features which are poorly imaged using conventional towed-marine data.

5.3 Autonomous nodes

The use of autonomous nodes for recording data on the sea floor has recently been used commercially. Remotely Operated Vehicles (ROVs) are used to deploy and recover the sensor nodes. There are two types of node systems: those that are connected by cables to each other; and connected to a recording vessel; and those that have data recording capability built into each node. The cabled systems have power supplied to each node along the cable and data returned to the recording vessel along the cable (or perhaps use radio telemetry for data downloading). These systems can stay deployed for extended periods of time, when the cables (or pigtails to the cables) are attached to a buoy or platform at the surface. The self-contained nodes have a limited power supply, which needs to be replaced periodically, and the current maximum time the self-contained nodes can operate before having to be brought to the surface for data downloading and power supply refreshment is 60 days, now sufficient for most surveys. The nodes are placed on the seabed in a fairly coarse X-Y grid – typically 400 metres apart – and a conventional source vessel is used to obtain 3D subsurface coverage (Figure 14).

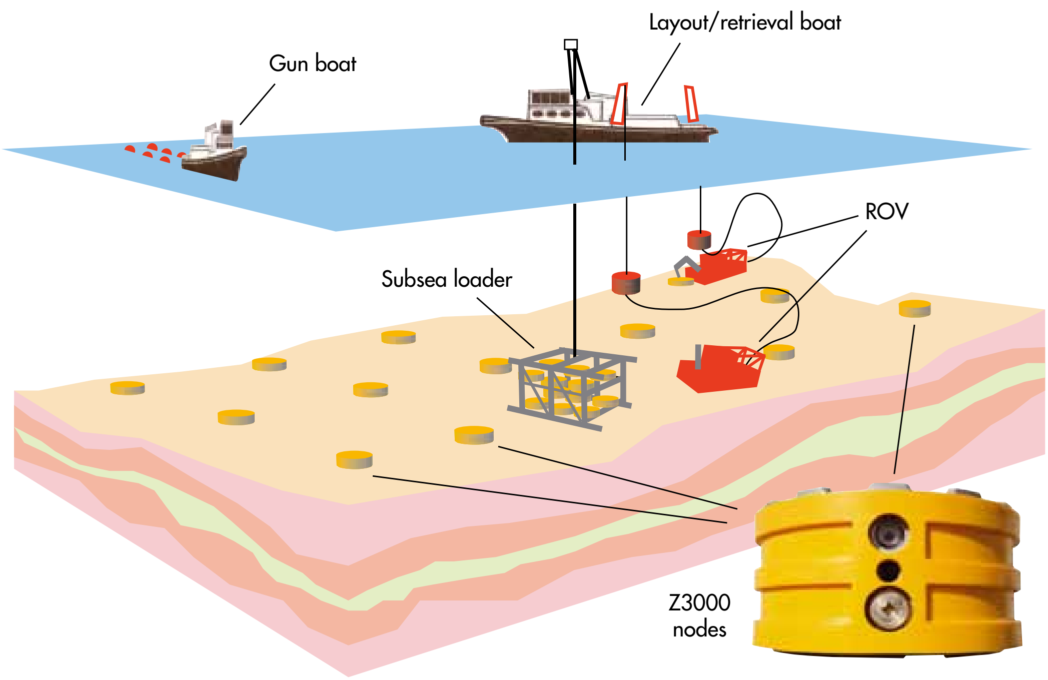


Figure 14 – Ocean bottom node acquisition *(credit: FairfieldNodal)*

5.4 Permanent seismic installations

A very small number of producing fields has been equipped with permanent seismic systems (figure 15), typically trenched into the first metre or so of the seabed. These are often referred to as Life of Field Seismic (LoFS) and are used for multiple 4D or timelapse measurements, often at fairly short (several months) time intervals. One advantage of these permanently installed sensors is that the cost of the repeat surveys is limited to that of the source vessel only. One disadvantage is the relatively high initial cost of the permanently installed system. By having a dedicated source vessel, usually an upgraded oilfield service vessel equipped with a mobile containerised seismic source, the 4D monitor surveys can be conducted very rapidly.

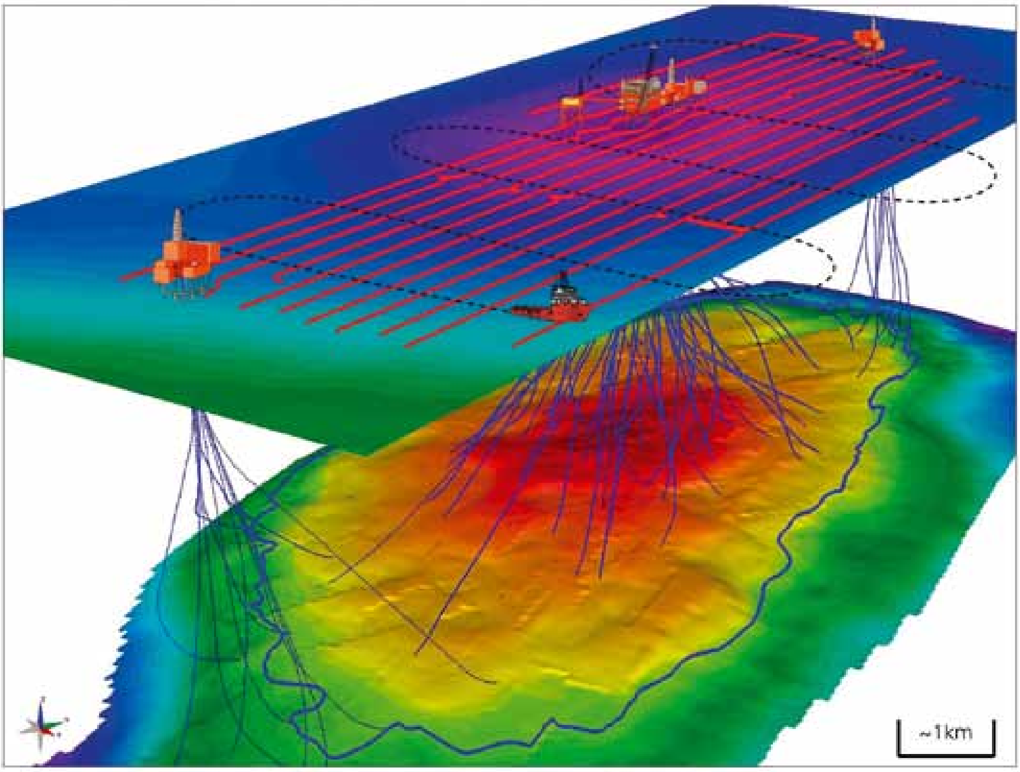


Figure 15 *(credit: BP; van Gestel et al. 2008. Continuous seismic surveillance of Valhall Field. TLE 27; 1616-1621)*

Example of a permanent seismic installation. The receiver system is permanently emplaced in the ocean bottom and tied back to the platform for power, control and data transmission.

6 Vertical Seismic Profiling (VSP)

In vertical seismic profiling (VSP), a number of geophones is lowered into a well hole and used to record data from a seismic source, which can be deployed in a number of ways:

- zero offset VSP – source is deployed from the well platform itself
- offset VSP – source vessel is stationed at a fixed location some distance from the platform
- walkaway VSP – source vessel traverses one or more lines away from the platform, generating a VSPfor each line traverse.

The main advantage of this technique is that the sound energy only has to travel one way through the earth. The reflected signal only has to travel a short way from the reflector to reach the down-hole geophones. This results in higher frequency bandwidth data being recorded, since there is less absorption of the higher frequency energy due to the shorter ray path lengths, and only one time through the near-surface, which is where the highest attenuating material is located.

As detailed knowledge of the geological layers penetrated by the well are available from analysing drill cuttings and down hole logging data. The combination of the higher resolution and the co-location of the VSP with the well allows the geophysical interpreter to make a very good correlation between the geology and its corresponding seismic data. Sound source volumes are generally smaller than for conventional data but larger than for site surveys. The duration of these surveys is typically short: one or two days at most.

There have been a number of 3D VSPs recorded but these are relatively expensive to acquire. Much like the dragged array multi-component system, they require many passes of the source vessel to achieve complete 3D coverage and are therefore relatively expensive, especially when the cost of the well time is included.

7 Shallow water/Transition Zone (TZ) acquisition

Shallow water or transition zone (SW / TZ) acquisition is by far the most complex and challenging area of seismic acquisition. Such areas are, by definition, almost bound to be either highly variable in their geography or provide some particular operational difficulty for acquiring data. Shallow shelving waters are the most common problem as they often require small, shallow draft, specialised vessels to move cables, sources, people,and equipment. The rough surf conditions commonly associated with such areas present some difficult challenges for deployment, retrieval and operation of equipment in the flat-bottomed boat required in such circumstances.

One safety aspect of SW/TZ operation is the use of dynamite as one of the source types employed. Shallow holes are typically drilled into the seabed, lined with lightweight casing, and loaded with explosive charges for subsequent detonation. Small airgun arrays are also employed, and it is common for multiple source types to be employed across an area. Where water is deep enough, it may be possible to deploy an airgun source from the back of a barge, for example, but where it is shallow, the use of buried explosives may be required. Providing reliable recording sensors is also problematic.

Marine hydrophone receivers may be used if water depth allows them to operate properly, however such an operation may not be most efficient in areas prone to tidal water depth variations. An additional problem involves placing the cable at a reasonable depth in the deeper water. In these environments, the streamer is not being pulled through the water with depth controlling devices. Personnel are often required to weight the cable to the sea bottom with chains and anchor blocks. With active surf or current conditions, it is likely that the cables will move and then subsequently have to be manhandled back into position. An alternative cable that can be used very successfully in transition areas is called a bay cable. It is essentially a very well sealed land cable with geophones on gimbals so that they remain upright. Some variants of these cables can contain hydrophones as well. This cable is lighter and easier to handle than a marine type of cable, but it is still not either straightforward or effortless to use.

Another method of recording data in these zones is to integrate the sensors with data recording electronics, creating rugged sensor stations that radio transmit the received earth signal back to an instrument position, either continuously or on command from the observer. In some areas this is often the only equipment that can be effectively used, but these units still need to be positioned and anchored appropriately and this is seldom easy. Positioning of the equipment can be complicated. Close inshore areas are usually less problematic, but the highly variable mid-zone, complete with fast currents, drifting cables, varying source effort locations, large tidal ranges, intertidal mud flats can make boat work extremely challenging.

8 The seismic source

Airgun arrays used during 2D, 3D and 4D surveys are almost always made up of sub-arrays or single strings of multiple airguns. There are a few main underlying concepts about airguns (and airgun source arrays) to keep in mind:

1. The output of an airgun is directly proportional to the operating pressure of the airgun (the norm in the industry is between 2,000 and 2,500 pounds per square inch [psi]).
2. The output of an airgun increases as the cube root of the volume (and less than that for an array, due to the array effect).
3. The output of an airgun array is generally directly proportional to the number of airguns in the array,
4. Airgun arrays are not point sources, they typically have dimensions of 15 – 30 metres in-line by 15 – 20 metres cross-line.
5. For a source array, the actual maximum sound output is less than the modeled, or 'back-calculated', value, typically some 15 to 25 dB less. This discrepancy in values is commonly referred to as the 'array effect'.
6. The array effect is not a simple one to visualise because the arrays are arranged in a horizontal plane, so the asymmetry of the array means that the pattern of the pressures moving horizontally out from the array will be different compared to the pattern of pressures moving vertically up and down from the array. Because the distribution of airgun sizes in the array is not uniform, the pattern of the pressure values moving away from the array is complicated further.
7. As presented in another chapter, There is a range of ways of expressing sound pressure in numerical terms. These include zero-to-peak (0-Peak or 0-P, or just 'peak') Sound Pressure Level (SPL) – the excursion in amplitude from zero to the maximum value, peak-to-peak (P-P) SPL – the excursion in amplitude from the maximum value to the minimum value, or some other calculated value such as the root mean square (RMS) amplitude. These measures ared described in OGP 2008 In the discussions in this chapter, zero-to-peak (0-Peak) will be used, unless otherwise stated.

Number (2) is contrary to a popular misconception that a large volume array has a much higher output than a small volume array. For almost all 3D surveys, arrays will be between 1,000 and 8,000 cubic inches in volume. That volume ratio is 8, the cube root of which is 2. Hence, the 8,000 cubic inch array has a maximum of twice the output of the 1,000 cubic inch array, a 6dB difference. The reason that it is a maximum difference is because the array effect will diminish that difference, if the two arrays have the same number of guns.

Number (3) means that doubling the number of airguns in an array will have a larger effect than doubling, and, more than likely, trebling, the total volume of the array. This item is the reason that cluster airgun configurations are used: if a 150 cubic inch airgun has a peak output of 2.8 bar-metres (see below), then a 300 cubic-inch airgun has a peak output of 3.5 bar-metres (an increase equal to ~26%, equal to the cube root of 2 [300/150]). If two 150-cubic-inch airguns are placed within a metre of each other, then their output will be ≤5.6 bar-metres, or close to double the output of a single 150 cubic-inch airgun. This is why it is actually more important to know the number of guns in an array than it is to know the volume of the array, if one wants to obtain an idea about the maximum output of the array (as indicated above with respect to the volume of arrays used in the industry, if one knows nothing about a second array, one knows that it can not have a maximum output greater than 2 times the output of whatever the reference array is, if one is dealing with conventional 3D seismic arrays). If one array has more than twice as many airguns as another array, then one has to do a bit more analysis to determine the difference in peak outputs between the two arrays. Although most conventional 3D arrays used by industry will involve no less than 15 and no more than 48 guns.

Table 1 is provided for ease of reference for this section on sources (see OGP report № 406) for a fuller description of acoustic measurement units). Besides the note at the bottom of the table, that will be discussed again in a few paragraphs, it is important to glean from the table that a factor of 2=6dB, a factor of 10=20dB, a factor of 100=40dB, and a factor of 1000=60dB. Note also that this table just lists the zero-to-peak output value of the sources listed, that the sources are towed at a depth of 5 or 6 metres and that the total frequency band is a maximum of 0 – 900 Hertz.

Table 1

Source	Measured (broadband) 0-Peak Bar-Metres	dB re 1µPa 0-Peak	Source	Back-calculated (0-900Hz) 0-Peak Bar-Metres	dB re 1µPa 0-Peak
	0.00001	120		40.0	252
	0.01	180	3959 in^3 array (17 guns)	47.4	254
Single 10 in^3 gun	1.1	221	5400 in^3 array (18 guns)	55.1	255
	2.0	226		60.0	256
3090 in^3 array (28 guns)	2.7	229	3090 in^3 array (28 guns)	57.0	255
Single 150 in^3 gun	2.8	229		80.0	258
	4.0	232			
4450in^3 array (24 guns)	8.3	238	4450 in^3 array (24 guns)	83.0	258
	10.0	240			
3797 in^3 array (24 guns)	10.7	241	3797 in^3 array (24 guns)	50.9	254
	12.0	242		100.0	260
	15.0	244		110.0	261
	20.0	246		120.0	262

The measured values and the back-calculated values are for source depths of either 5 or 6 meters. There are two different source columns, one with measured values and one with 'back-calculated' values. Three sources are repeated in the two columns – the 3090, 4450 and 3397 arrays. Note that for these three cases, there is a measured and a back-calculated value, and the back-calculated value is 13-24dB larger than the actual measured value. The bar-meters values generally increase in this table, first going down the left 'source' column side and then down the right 'source' column side. By looking at both of these sides of the table, the relationship between bar-meters and dB may be seen. In particular, the largest value in the table is 12 million times larger than the smallest value, which is equal to a difference of 142dB (262dB-120dB).

8.1 Basic operation of an airgun seismic source

One type of airgun is shown schematically in Figure 16. In its 'charged' or 'ready-to-operate' state, the high pressure air chambers are sealed by a triggering piston and a firing piston, mounted on a common shank forming a shuttle. High pressure air, typically at 2,000 or 2,500psi, is supplied to the return chamber from the compressor onboard the seismic vessel via an air hose and 'bleeds' into the main chamber through a small orifice in the shank of the shuttle. The airgun is sealed because the area of the left triggering piston is larger than that of the right firing piston. This results in a net 'holding' force. The source is activated by sending an electrical pulse to the solenoid valve which opens, allowing high pressure air to flow to the left side of the triggering piston, into the triggering chamber. This forces the triggering piston to move away from its rest position and as the firing piston, which is physically connected to the triggering piston by the shuttle, follows, the high pressure air in the main chamber is discharged into the surrounding water through the ports. The air from these ports forms a bubble which oscillates. The period and characteristics of the oscillation beingdepend on the operating pressure, the depth of operation, the temperature and the volume of air vented into the surrounding water. The shuttle is forced back down to its original position by the high-pressure air in the control chamber, so that once the main chamber is fully charged with high-pressure air, the source can then be activated again. The shuttle opens very rapidly (in only a few milliseconds). This allows the high-pressure air to be discharged very rapidly. One variation in the design of airguns is the sleeve-gun (Figure 17), which, by nature of its design, has a 360° port or sleeve in place of air exhaust ports, so that air is expelled uniformly from the source.

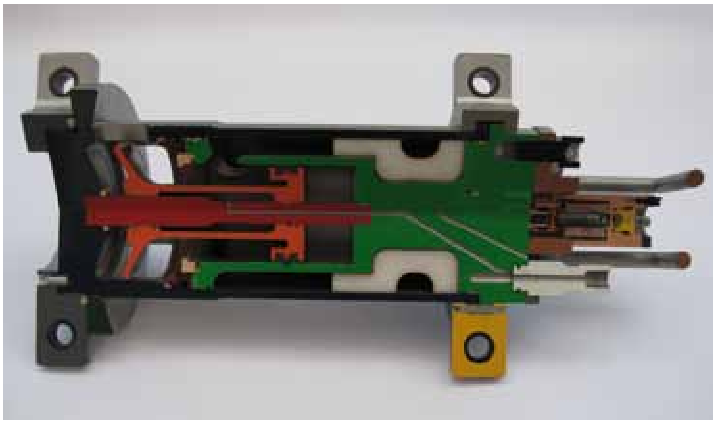


Figure 16 *(credit: Sercel)*
Photograph of a G Gun (left). Cutaway of an airgun (right).

Figure 17 *(credit: ION Geophysical)*
Photograph of a variety of different size sleeve guns.

Figure 18a shows an amplitude versus time plot for a single airgun output. This is known as its source signature. A typical seismic source array is made up of a number of airguns with an assortment of volumes. This is done to cancel the variation in signal generated by a single airgun (Figure 18a & b) due to each individual bubble oscillation. The use of many airguns causes the bubble pulses to interfere destructively with each other, as shown in Figure 19a & b, creating a 'clean' impulsive array source signature. The primary output of an airgun source typically has most of the energy in the frequency bandwidth between 10 and 200 Hz, which is the frequency bandwidth of most interest in seismic surveying. In some specialised surveys, this bandwidth can be increased, for example when looking at the shallow surface geology in preparation for siting platforms.

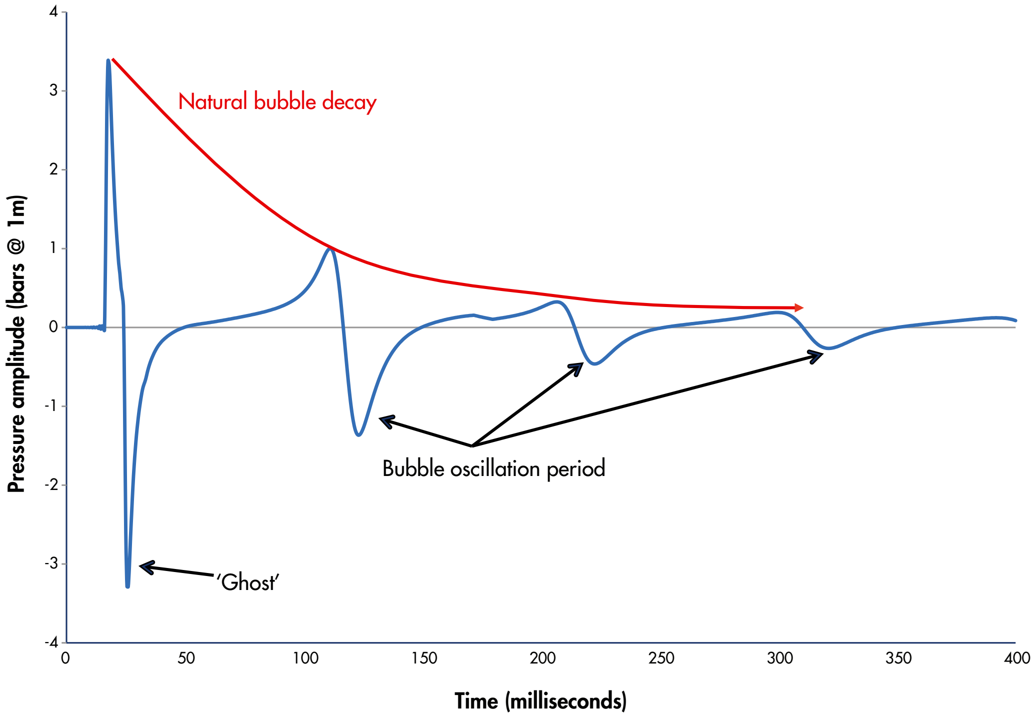


Figure 18a – Source signature of a single airgun *(credit: Polarcus)*

Source signature of a single 150 in³ airgun. The pressure amplitude is given in bars at 1m. The total time duration of the signal shown is ~400ms. The source signature is the time series (pressure amplitude versus time) view of the airgun output.

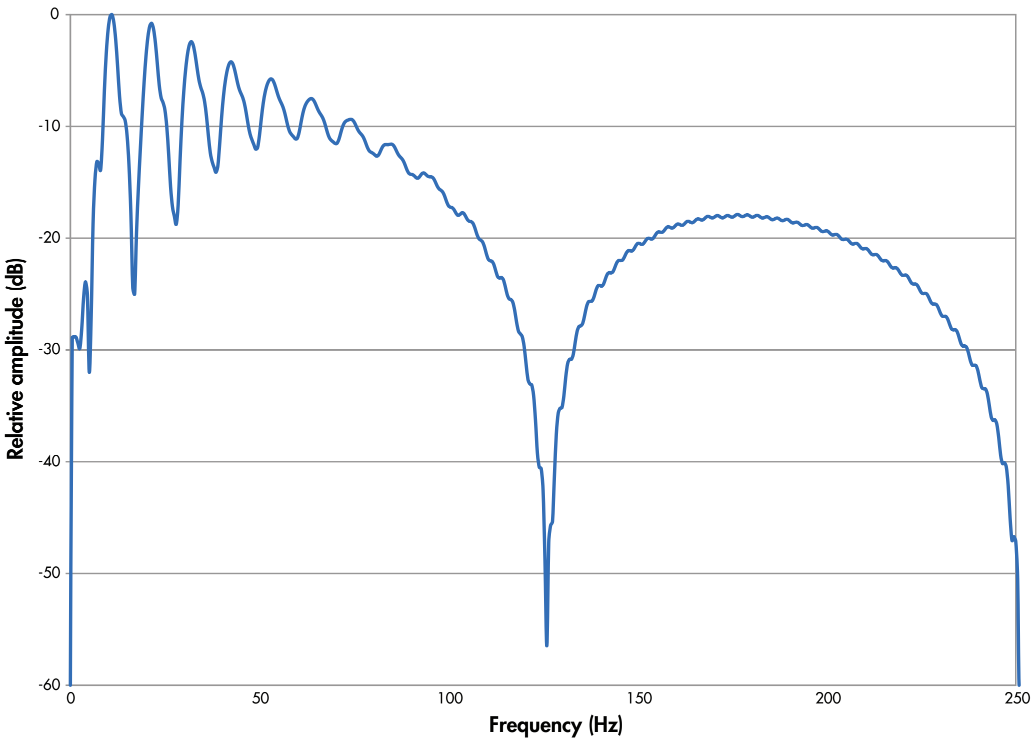


Figure 18b – Amplitude spectrum of a single airgun *(credit: Polarcus)*

Amplitude spectrum of single 150 in³ airgun. Amplitude is shown in negative dB down from the peak at 0 dB which occurs at about 10Hz. The amplitude spectrum displays the amplitude (or relative amplitude as in this case) versus frequency.

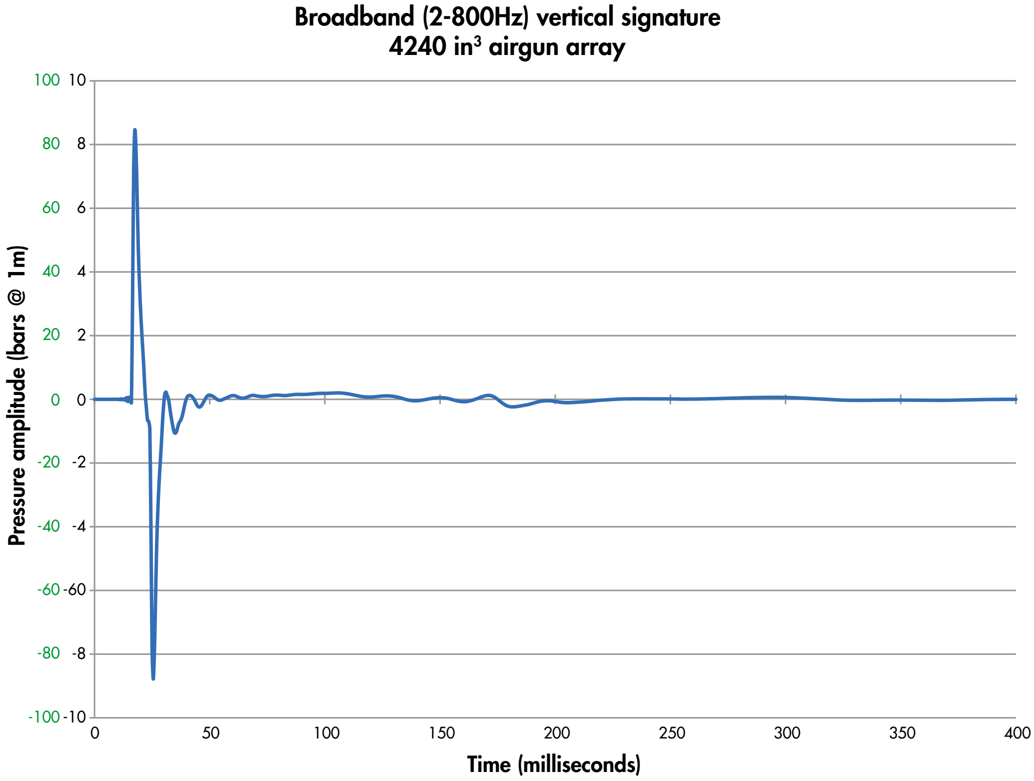


Figure 19a *(credit: Polarcus)*

This shows the time-series (amplitude versus time) display of an airgun signal from a 4450 in³ array that has 33 active guns. The green numbers are the theoretical back-calculated values for this array if one could measure the full output at 1m from the center, thus the units bars at 1m. The black numbers are the actual maximum values in bar-meters that one would measure given the array dimensions of about 14m by 14m.

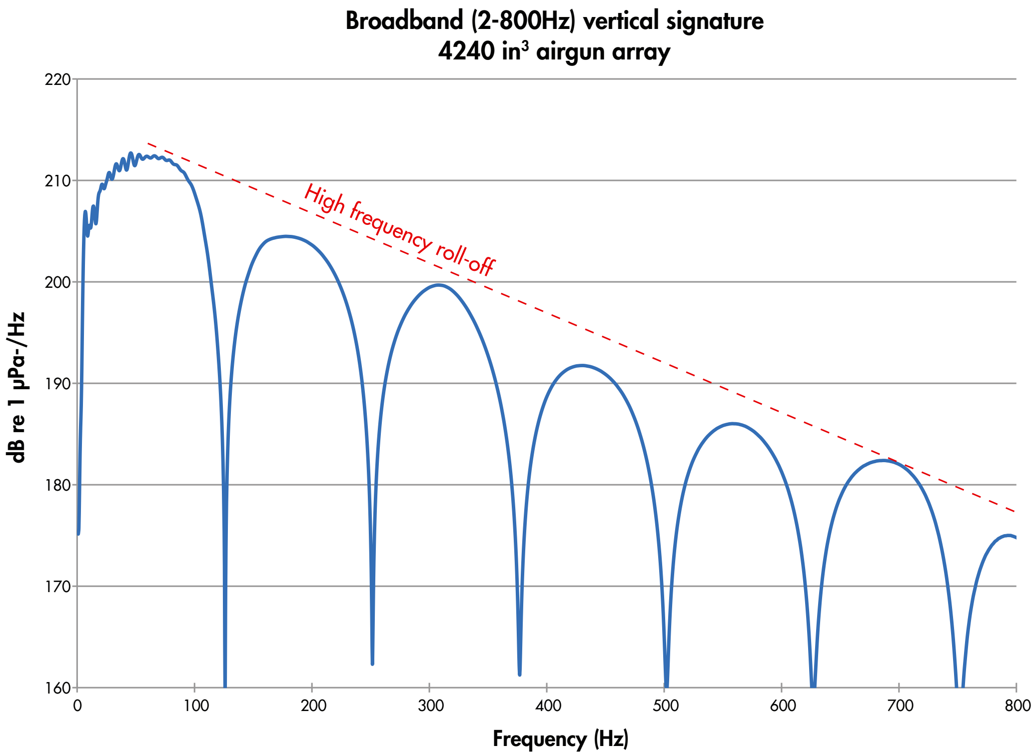


Figure 19b *(credit: Polarcus)*

This shows the amplitude versus frequency (amplitude spectrum) display of an airgun signal from a 4450 cubic-inch array that has 24 active guns. The very low values that occur every 125Hz are caused by the 'ghost' notch, due to the array being towed at 6m depth.

Total energy source volumes vary from survey to survey and are designed to provide sufficient seismic energy to illuminate the geological objective of the survey. The number of airguns in the array, their size and distribution are selected to reduce the effects of the bubble oscillations and to provide source directivity.

An airgun array is commonly made up of sub-arrays or 'strings', which are suspended from floatation devices to maintain the specified operating depth. The layout of a three-string array is shown in Figure 20. Array dimensions are usually on the order of 15-25 metres wide by 15-20 metres long. A typical sub-array is illustrated in Figure 21a and a photo of single airgun suspended from a float is shown in Figure 21.

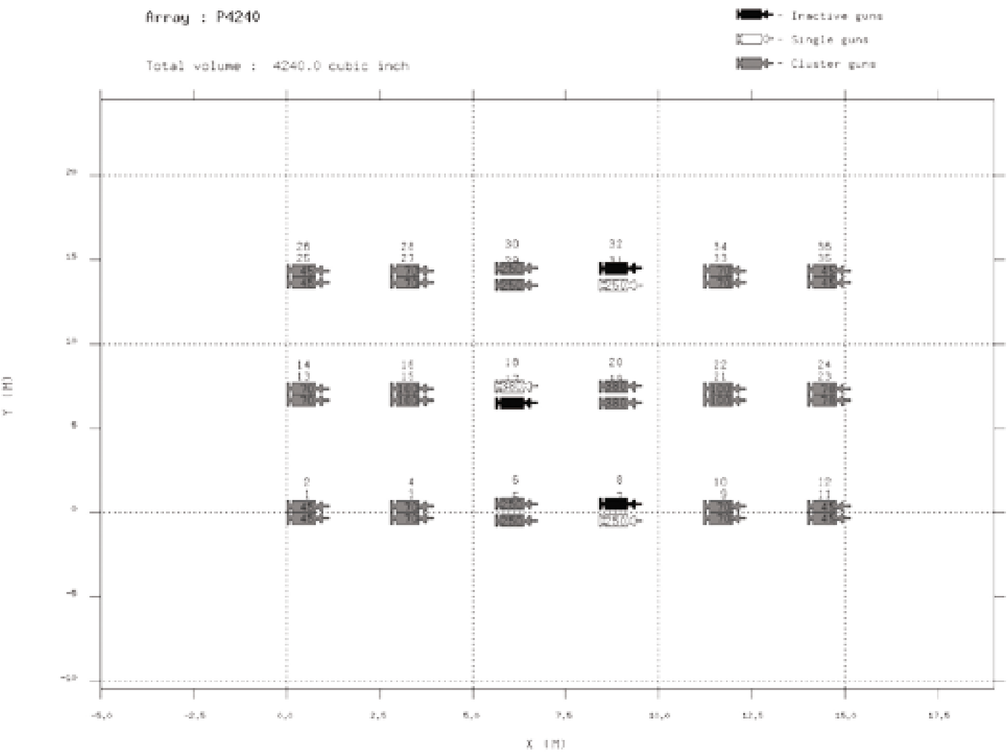


Figure 20 – airgun array geometry *(credit: Polarcus)*

4240 in^3 airgun array geometry. There are 3 sub-arrays: each of the 3 left-to-right lines of guns. Black guns are inactive (spare) guns, gray guns are cluster guns (2 guns so close together that they act as a single gun) and white guns are single guns. The number listed on each gun indicates the cubic inches for that individual gun (for the cluster guns, both guns will have the same cubic-inch value).

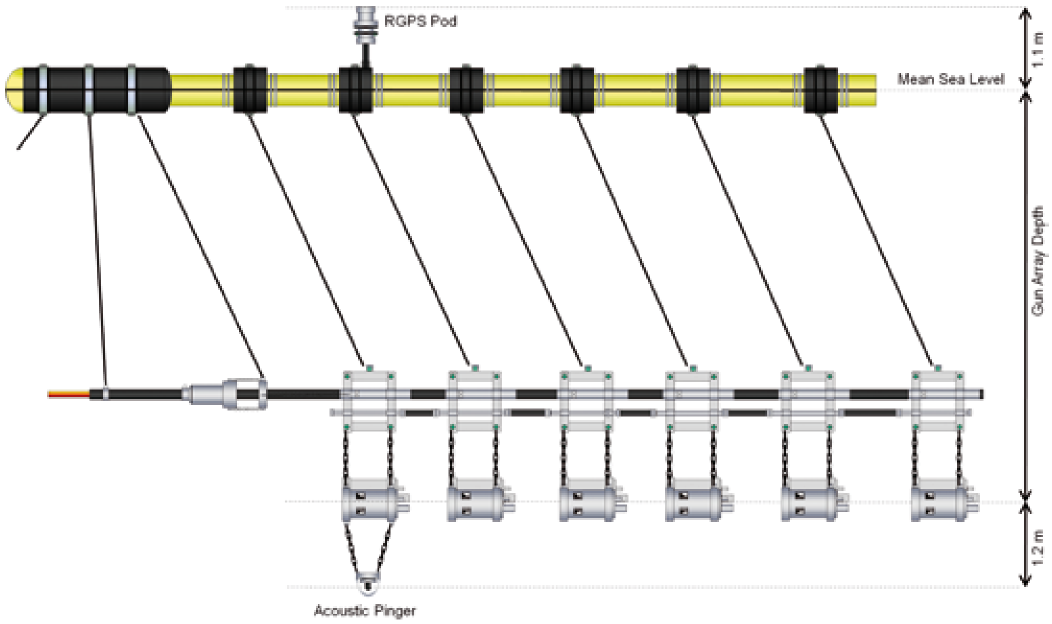


Figure 21a – Side view diagram of a sub-array *(credit: Polarcus)*

Side-view diagram of a sub-array from the 3 sub-array 4240 in^3 array. There are 12 guns arranged in pairs (2-gun clusters) in this sub-array. The yellow tube at the top provides floatation and the guns are hung below at the desired depth below the water surface. Also note the position of an rGPS beacon on top of the float and an acoustic transponder below the guns. These provide precise positioning information of the guns relative to the vessel and the seismic signal receivers (streamers).

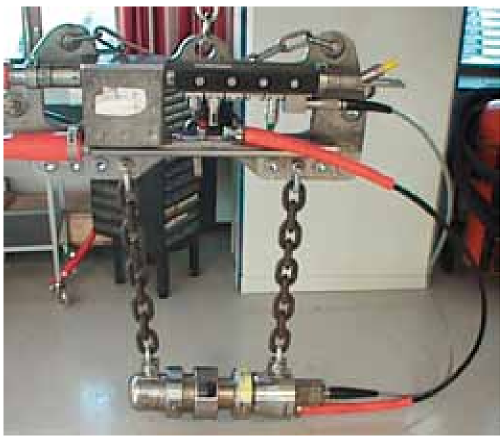


Figure 21b *(credit: Western Geco)*

Single airgun suspended

The output characteristics of typical marine seismic source array are commonly presented in terms of a nominal peak source level or sound pressure level (SPL) in dB re 1 µPa @ 1m. It should be noted that this SPL represents the so-called 'back calculated' SPL, which is the pressure level that would be achieved if all the elements in the source were concentrated into a single point (with zero dimensions!). The actual sound pressure level in the vicinity of the source array is lower, where the maximum SPL is some 15 to 20dB – 10 times smaller than the nominal output of the array.

Figures 22a and22b are necessarily somewhat involved graphics indicating the radiation pattern, or directivity plots representing the pressure pattern from a seismic source array. The pressure is released in all directions, but not in a symmetrical and uniform way. The non-uniformity is caused by

i. the overall dimensions of the array;
ii. fact that all of the airguns are basically tied together in a horizontal plane, and are not also distributed in a vertical one;
iii. non-uniform distribution of airgun volume sizes (as shown in Figure 20); and
iv. non-uniform properties (velocity, density, temperature, salinity) of the volume of water surrounding the array, including also the variable roughness of the sea surface.

Figures 22a & b demonstrates the far-field pressure pattern, for a constant frequency of 60Hz, for the 4240in^3 airgun array. The three dimensional pressure field can be conceptually viewed as a hemispherical shell with the pressure field impinging on about 2/3rds of the shell.. Vertically down is in the very centre, and the peak pressure occurs there at a relative level of 0dB. The first (smallest) concentric circle out from the centre intersects the shell at 10° up from vertical, and the pressure level is still the same. The 3rd concentric circle intersects the shell 30° up from vertical and looking at an azimuth of 0 and 180 (in line with the vessel), the pressure level is still well within the dark orange zone. However, looking at an azimuth of +90 and −90 (that is side-on), the pressure level is right on the boundary between the dark orange, and the lighter orange, or 6dB down. The next-to-last concentric circle intersects the shell at 50° up from vertical, and, in line with the vessel, the pressure is still within 6dB of the maximum, but in a direction of port-to-starboard, the level is in the green to white region, depending on whether the view is to port or to starboard. White is 24dB down from the maximum, and the first green is 30dB down.

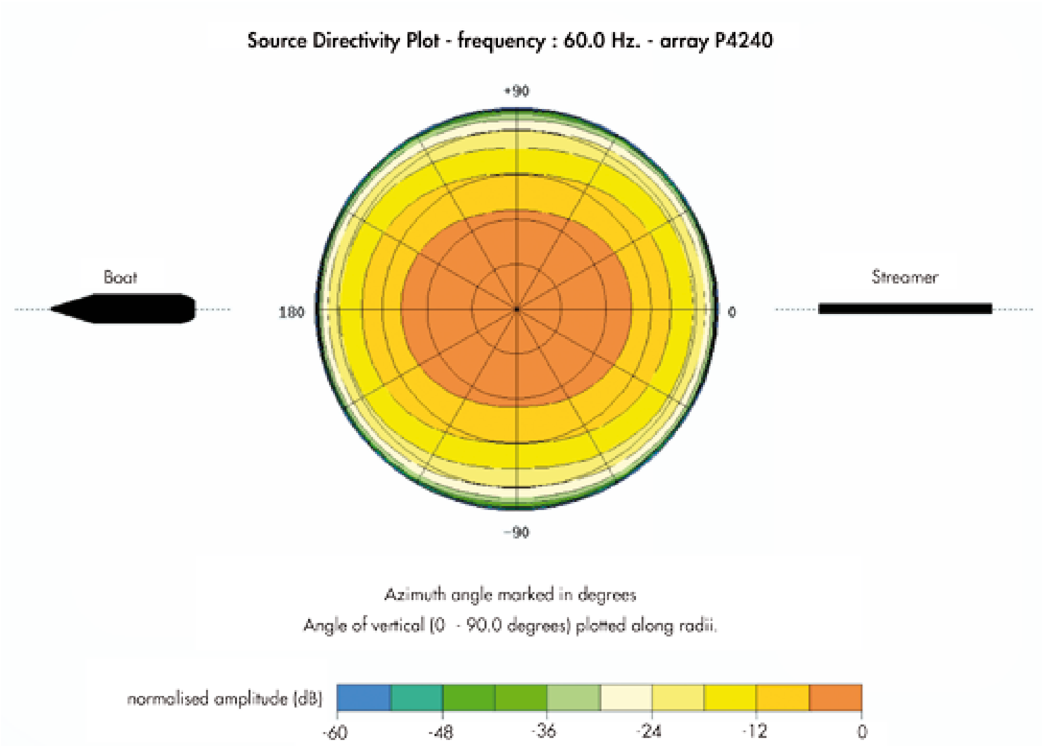


Figure 22a *(credit: Polarcus)*

This is a constant frequency (60Hz) acoustic radiation response for the 4240in^3 airgun array. Colours indicate relative pressure levels: orange is the highest and the dark blue is 60dB down ($^1/_{1000}$th) down from the orange level. The angles (0, 180, +90, -90) indicate looking to stern, to bow, to starboard, and to port respectively. The center of the diagram is vertically down and each inner concentric circle represents 20° of elevation from the vertical. The outside edge is 90° from the vertical and shows propagation levels in the horizontal directions. For example: 60° up from the vertical in the starboard direction has a relative pressure level that is on the edge of pale orange and yellow which is between 12 & 18dB lower (¼ to ⅛) than the maximum.

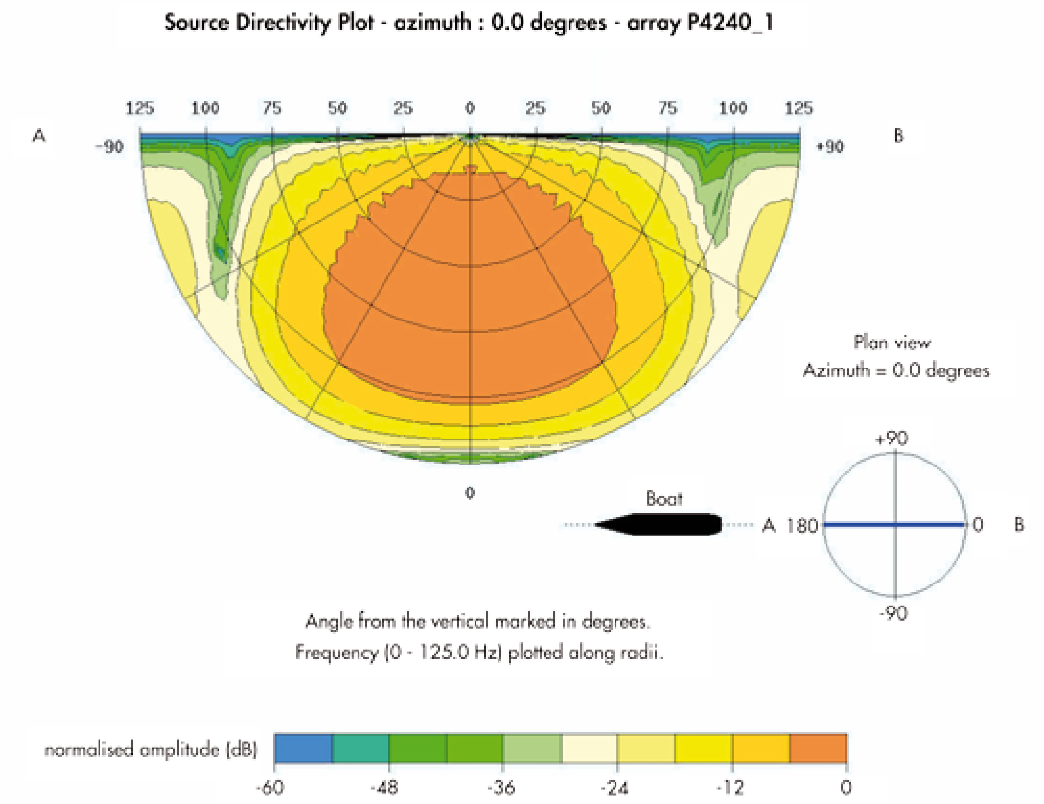


Figure 22b *(credit: Polarcus)*

This is the in-line acoustic radiation response for the 4240 in^3 airgun array. Colours indicate relative pressure levels: orange is the highest and the dark blue is 60dB down ($^1/_{1000}$th) down from the orange level. The angles (+90, 0, and -90) indicate looking to bow, vertically down, and to stern respectively. The concentric circles indicate frequency from 0 to 125Hz (the annotations are split on each side only for visual clarity). For example, ~60° up from the in the stern direction, at 100Hz, the relative pressure level is white, which is between 24 & 30dB lower ($^1/_{16}$ to $^1/_{32}$) lower than the maximum.

Figure 22b shows a vertical section view, in line with the vessel. The radial lines are vertically down, 30° up from vertical, and 60° up from vertical. The pressure level does not drop anywhere in the region from vertically down until an angle greater than 30° up from vertical is reached, except in the region of the smallest concentric circle. This circle represents frequencies less than 10Hz. The next concentric circle represents frequencies between 10 and 20Hz, and so forth. The graphic here presents what the pressure field looks like in the vertical planar section in line with the vessel, so in only two dimensions, but shows how that field varies with frequency. The pressure levels can change radically with frequency, particularly near the surface. The main point to be taken from Figures 22a & b is that the radiation pattern in detail can be complex, but overall is focused as a conical volume with the long axis in line with the vessel, and the focusing strength about a factor of two greater within 40° or so of vertical.

Figure 23a maps the modeled sound pressure 12.5 metres below a typical source array.

Figure 23b is dealing with the same array that is treated in Figure 23a. The plot represents a 'view' in a vertical plane (looking from one side of the source array) aligned along the position of the middle of the three sub-arrays comprising the full array. This plot shows the peak pressure along this plane, so the pressure field is close to circular in shape below the middle of the array.

Source arrays are designed to focus energy downward into the subsurface as illustrated in Figures 22b & 23b. The depth of the source effectively controls the high frequency output of the source. The signatures previously shown are for sources operating at a depth of 5-8m, which is typical for many seismic surveys . The amplitude reduction at 125Hz is known as the 'ghost notch' (see Figures 19a & b). This is caused by destructive interference between the energy travelling directly from the source and that reflected from the sea surface, which is delayed by the additional time taken to travel the 12 metres up to the sea surface and back down again (Figure 19a & b).

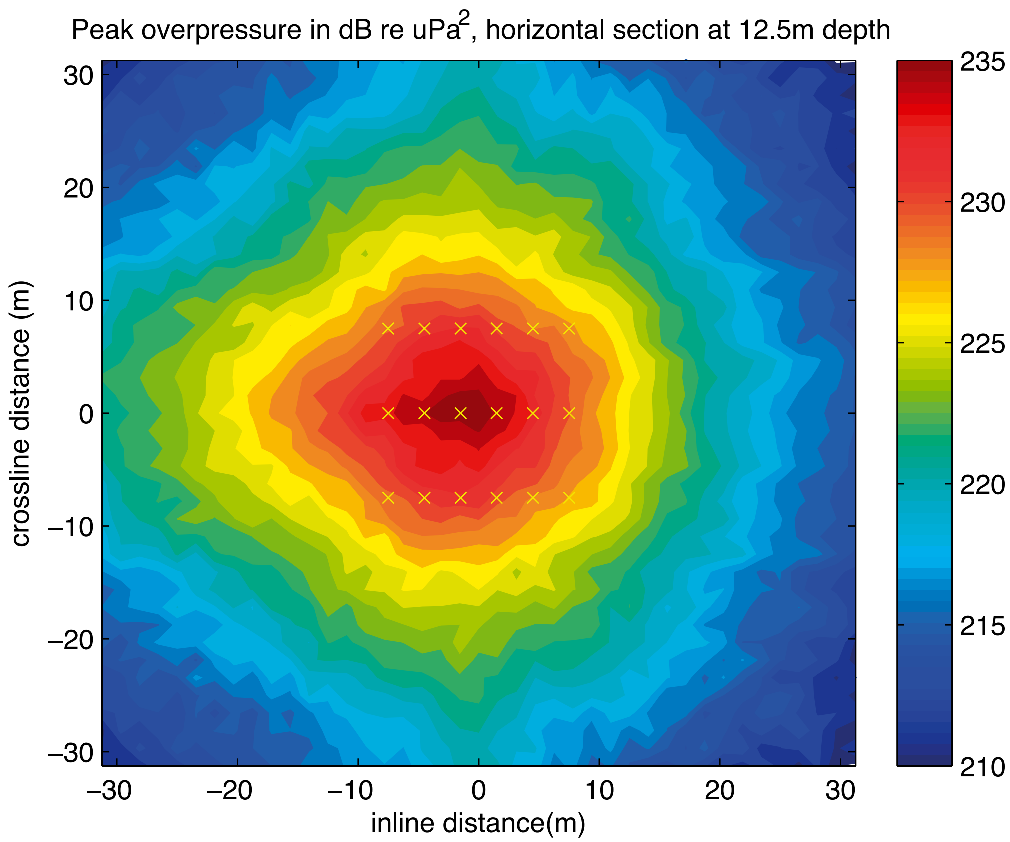


Figure 23a *(courtesy IAGC)*

This shows the modeled sound pressure (zero-to-peak) on a horizontal slice at a depth of 12.5 metres. The depth of the array is 7.5 metres, and the total frequency band used is 0-400 Hz. It has 18 elements arranged in three subarrays each 15 metres long and separated by 7.5 metres. It has a total volume of 5205 cubic inches and is charged to 2000 psi. The elements at the front (left) of the array are larger and this accounts for the inline asymmetry. The yellow crosses indicate positions of the source elements. Contours are shown from 210dB re μPa^2 upwards.

The pressure levels emitted from a source array decay with distance and generally decay more quickly with distance for high frequencies than for low frequencies (Figures 24a & b). The pressure levels in a given high frequency band are also lower than are emitted in a comparably wide low frequency band, once the frequencies of consideration are above about 100Hz. SPL's are lower at higher frequencies than at lower frequencies, and longer source-to-receiver ranges have lower SPL's than shorter source-to-receiver ranges. Figure 25 deals with energy rather than pressure (amplitude) levels, so that the partitioning by frequency can be more clearly seen. The primary point of this figure is to show that 99.9% of the energy (the blue curve is the cumulative energy, and its scale is the right-hand vertical axis) from an airgun source array is contained in frequencies between about 2Hz and 305Hz.

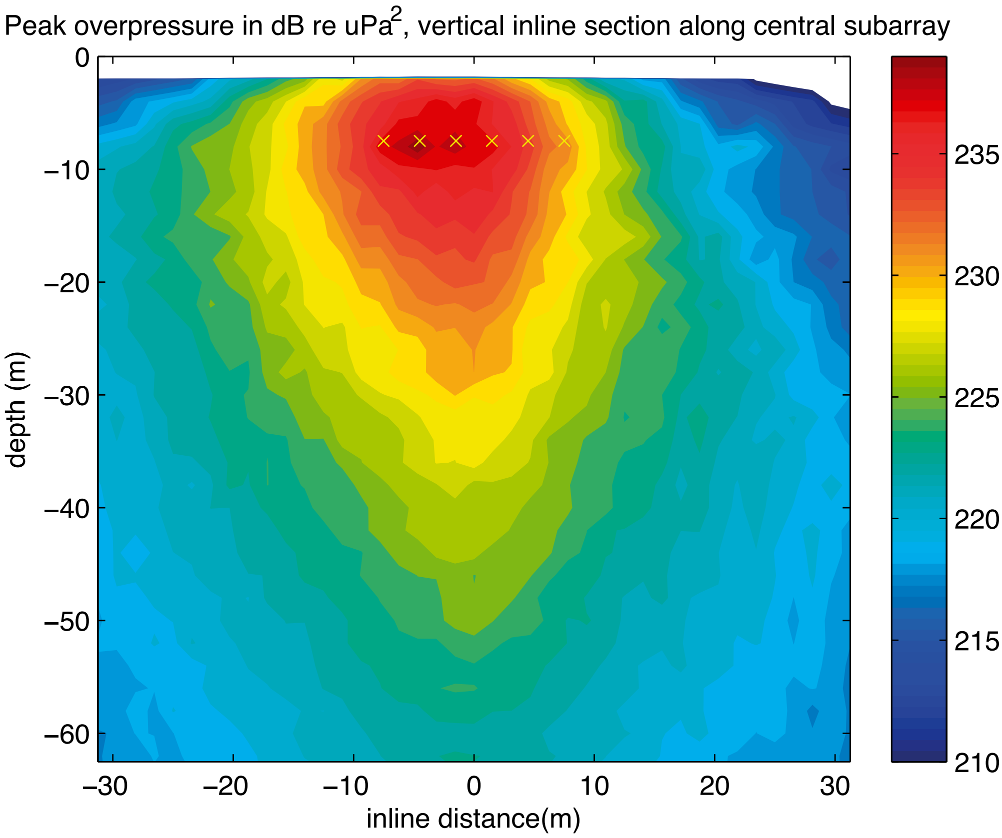


Figure 23b *(courtesy IAGC)*

This shows the modeled sound pressure (zero-to-peak) on an inline vertical slice through the centre of the array. The depth of the array is 7.5 metres, and the total frequency band used is 0-400 Hz. It has 18 elements arranged in three subarrays each 15 metres long and separated by 7.5 metres. It has a total volume of 5205 cubic inches and is charged to 2000 psi. The elements at the front (left) of the array are larger and this accounts for the inline asymmetry. The yellow crosses indicate positions of the source elements. Contours are shown from 210dB re μPa^2 upwards.

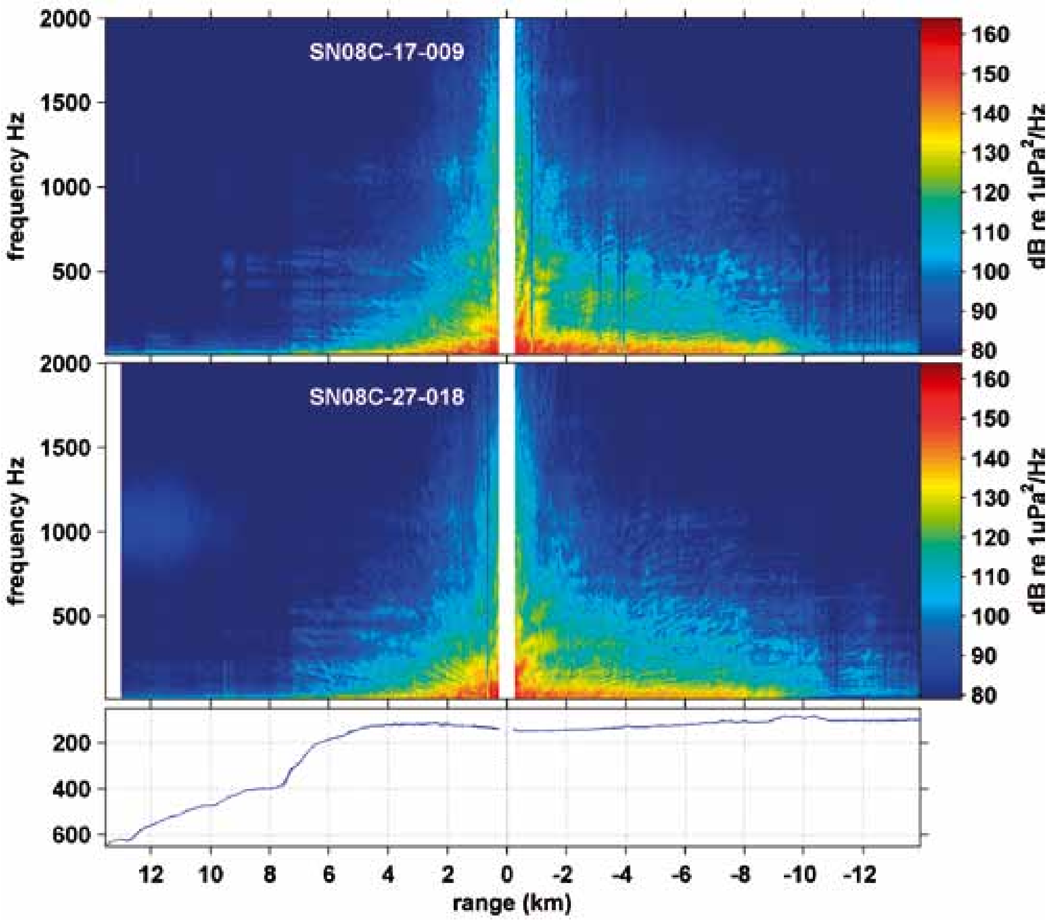


Figure 24a *(credit: Rob McCauley, Curtin University for Santos Ltd.)*

The top two panels show the frequency content with range of seismic air gun arrays operated along the bathymetry path shown on the lower panel (where the y axis is water depth in metres). The top panel shows signals from a 3040 in3 airgun array source while the lower panel shows signals from a 2130 in3 source run along the same survey line with as best as possible each shot of the two arrays fired at the same location. The range has been arbitrarily assigned as negative for signals to the east of the receiver location. The two survey lines started at the eastern (negative range) end and ran to the west. The survey line was approximately perpendicular to the continental shelf edge. The receivers were located on the sea floor at 152 m depth.

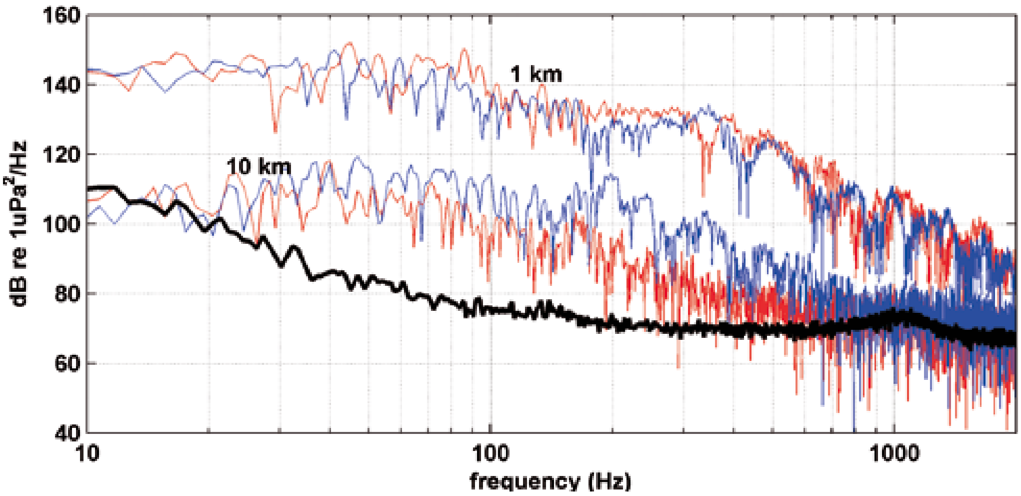


Figure 24b *(credit: Rob McCauley, Curtin University for Santos Ltd.)*

Spectral content of two approaching air gun arrays at 1 and 10 km (red is 3040 in3 source, blue 2130 in3). The black line is the average low ambient noise conditions at the site.

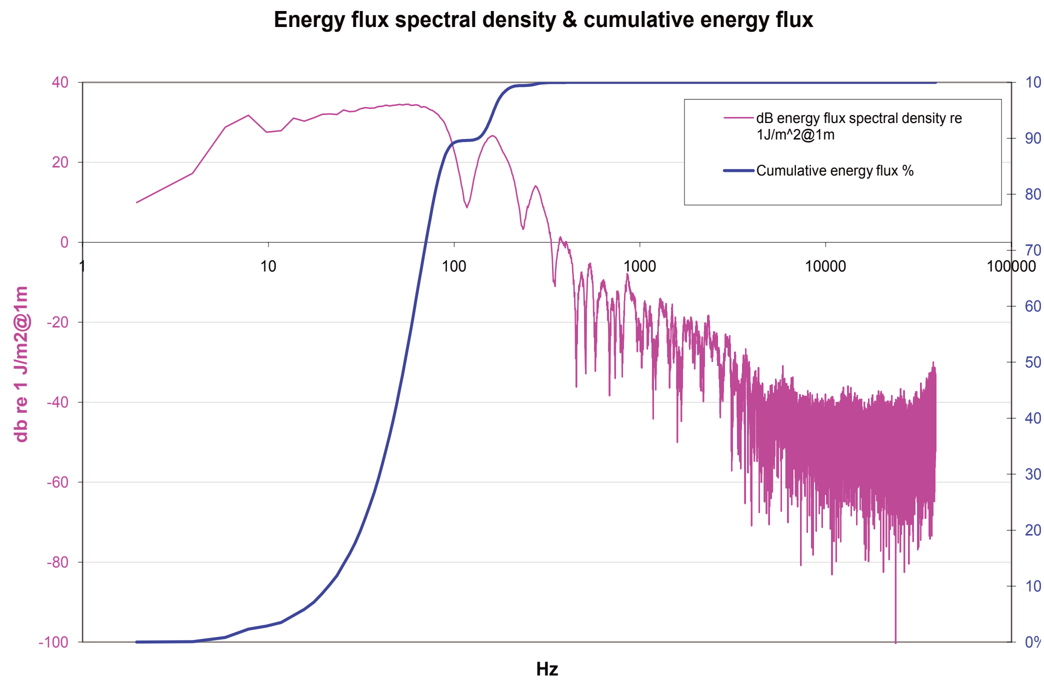


Figure 25 *(credit: Gary Hampson, Chevron)*

Broadband spectrum of the energy flux (proportional to the square of the amplitude) indicated by the vertical axis on the right. The main point from this figure is that 99.9% of the energy is contained in frequencies below 305Hz. These data are for the 3397 cubic-inch array that has 24 guns.

8.2 Marine vibrators

A marine vibrator (Figure 26) operates by using either hydraulic or electrical power to drive an actuating plate in a controlled, oscillatory manner. The advantage of this is that a very precise signal can be projected into the subsurface. The signal usually employed is a group, or sweep, of frequencies, for example 10-80Hz, over a 10-second interval. Thus the instantaneous sound pressure level is much lower than that from an airgun. The recorded data are then correlated against the input sweep to recover the reflection record. Control of these devices is however, very complex, due to non-linear feedback in the internal mechanisms in the case of hydraulic vibrators. The output from a single vibrator, even after correlation, is comparable to that from an airgun sub-array but suffers the disadvantage that its low frequency response has historically been poor. Thus,the likelihood of imaging deep geologic targets is reduced. Whilst the geophysical concept of marine vibrators is understood and offers great promise, further investment and development will be required in order to improve operational efficiency and data imaging capability that is comparable with airgun source arrays.

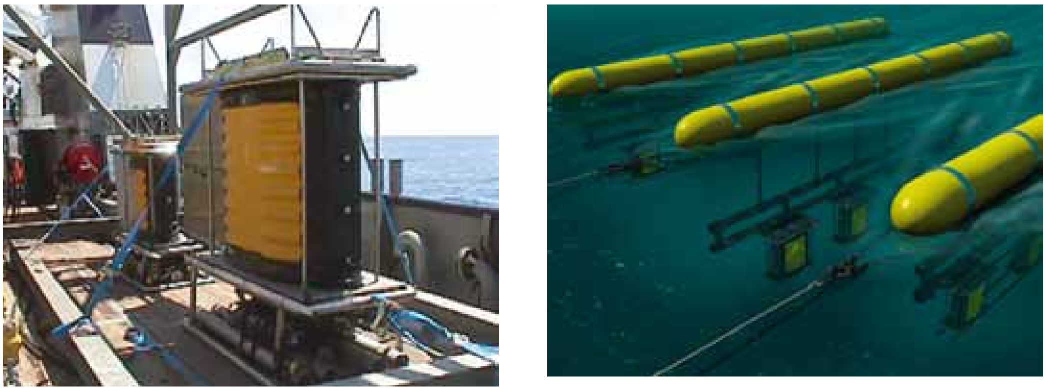


Figure 26 – marine vibrator *(credit: Petroleum Geo-Services)*

Marine vibrator source (left). Illustration of a marine vibrator source array underwater (right)

These factors have resulted in only very limited use of vibrators in the offshore industry, with no commercial surveys having been conducted for several years. Vibrators have been used for Vertical Seismic Profiling which is briefly described in Section 6. Clearly, as the energy of the vibrator source is spread out over a much longer time than that from an airgun array – tens of seconds rather than a few hundred milliseconds – the radiated sound pressure level is correspondingly lower. Additionally, as a controlled source, where the upper and lower frequencies of vibration are user defined (apart from the inevitably generated harmonics) the broadband output of a vibrator source is considerably less than that from an airgun array. No broadband measurements have been taken at this time so it is not possible at the present to quantify the relative broadband signal levels between the different sources. Development work continues.

9 The seismic streamer

The seismic cable or streamer (Figure 27) detects the very low level of reflected energy that travels from the seismic source, through the water layer, down through the earth and back up to the surface, using pressure sensitive devices called hydrophones. These convert the reflected pressure signals into electrical signals, which are digitised and transmitted along the seismic streamer to the recording system on board the vessel where the data are stored onto tape or disc. Normal noise levels in calm weather conditions are of the order of 2-3 microbars root mean square (RMS) and it is quite common for streamers to remain operating in the water for months at a time.

The streamer itself is made up of five principal components:

1. hydrophones, usually spaced almost 1 metre apart, but electrically coupled in groups 12.5 or 25 metres in length
2. electronic modules, which digitise and transmit the seismic data
3. stress members, steel or kevlar,that provide the physical strength required, allowing the streamer to be towed in the roughest of weather
4. an electrical transmission system, for power to the streamer electronic modules and peripheral devices, and for data telemetry
5. the skin of the streamer in which all the above are housed.

The groups in the streamer are combined into sections, each 50-100 metres in length, to allow modular replacement of damaged sections. Each section is terminated with a connector unit, and is filled with electrical isolating fluid, with a specific gravity of less than one, to make the overall streamer neutrally buoyant. , Historically, this fluid has been an organic compound such as kerosene, used primarily since it would evaporate in the event of a spill. (for a variety of reasons it has been kerosene, one of which was so it would evaporate quickly in the event of spills). More recently a purely synthetic material has been used.

Recent advances in cable technology have led to a new generation of seismic streamer, moving away from the traditional fluid-filled cable to a solid cable, constructed of extruded foam, where the requirement for fluid is minimised or removed entirely. This generation of streamer has many advantages in that it is more robust and resistant to damage, does not leak streamer ballast fluid when damaged either on the vessel or in the sea and is less sensitive to weather and wave noise. This has been achieved without reducing the sensitivity of the cable to the reflected signal. Another variation has been the introduction of gel-filled cables which combine some of the advantages of fluid-filled cables – ease of component replacement and manufacturing with those of solid cables – no fluid leakage and reduced levels of energy propagating inside the cables themselves. A further development has been the introduction of single sensor recording where the output of each individual hydrophone is recorded. This system is designed to improve the resolution of the recorded data.

Figure 27 *(credit: ION Geophysical)*

Photograph of a streamer entering the water (left). Photograph of a solid-fill streamer stored on a reel (right).

Streamer lengths have increased over time with improving technology. The streamer length depends on the depth and type of the geological target for a given survey. For instance, streamer lengths employed in the North Sea are typically shorter than those used in the Gulf of Mexico, or offshore West Africa. Recent surveys in the North Sea have seen streamer lengths that were typically 3,000 metres now 5,000-6,000 metres. Whereas in the Gulf of Mexico and offshore West Africa some surveys are using streamers up to 12,000 metres in length. This increase in length, coupled with the increasing number of deployed streamers, has resulted in a marked increase in the quantity of streamers in the water, with survey vessels regularly deploying 40-50 km of streamer.

Streamer tow depths are a compromise between the requirement to operate these sensitive devices away from the weather and wave noise, which limits the usability of the recorded data, and the ghost notch mentioned earlier, which affects the streamer in exactly the same way as the source. The deeper the tow depth;the greater the immunity to weather noise, but also the narrower the bandwidth of the data. As for most operationalparameters, the specific survey objectives will dictate the precise streamer depth required. Typically the range of operating depths varies from 4-5 metres for shallow, high resolution surveys in relatively good weather areas like the southern North Sea, to 6 metres in probably a majority of areas around the world, to 8-10 metres for deeper penetration, lower frequency targets in locations such as the European Atlantic Margin.

In addition to the internal components, there are different types of external devices, which are sometimes attached to the streamer, such as depth control units or birds (Figure 28), lateral-control birds (Figure 29), magnetic compasses (often integrated within depth control units), and acoustic positioning units. Power for these systems is provided both through the streamer itself, inductively coupled, and by batteries in each external device. In addition, a tailbuoy (Figure 30) is connected to the end of each streamer to provide hazard warning of the submerged towed streamer, especially important at night, positional information from a GPS receiver and tension for the tail of the streamer.

Depth control units or birds (Figure 28) are used to control the depth of the streamer to an accuracy of typically +/– 1 metre. The wings on the bird are electronically controlled to pivot in response to the hydrostatic pressure (depth) measured by a pressure transducer inside each bird. If the streamer is too deep, the wing is rotated up to provide lift; if too shallow, the opposite occurs. As the streamer is weighted to be neutrally buoyant, the birds are used to counteract depth variations in the streamers introduced by vessel pitching moments in heavy weather or when different currents are experienced, with corresponding fluctuations in density and/or temperature. These units are normally spaced approximately 300 metres apart on each streamer.

Figure 28 *(credit: ION Geophysical)*

Example of one type of depth-control bird.

Figure 29 *(credit: ION Geophysical)*

On the left is an example of one type of 'lateral-control bird.' These are used to control horizontal cable movement in the water and keep the streamers in a certain location relative to one another. On the right is a photograph of the lateral-control bird attached to the streamer before entering the water.

As previously mentioned, it is critically important for the success of a 3D survey to know very precisely the location of sources and receivers, so a variety of hardware is used to achieve this. The shape that the streamer adopts as it is being towed through the water is usually determined using compasses, which measure the deviation of the streamer relative to magnetic North. A computer algorithm is used to derive the shape of the streamer from these individual compass measurements, which are taken roughly once every 300 metres. In addition to the compasses, acoustic ranging units are used to provide additional positional information. These are attached to the hull of the vessel, the source floats, the streamers themselves, and the tailbuoys. The travel times between a variety of acoustic node locations are measured and solved, together with the streamer shape information from the compasses, to provide a better positional solution. The acoustic units operate at moderate to high acoustic frequencies, 10 to 100 kiloHertz, with a maximum output SPL of approximately 195 dB re 1 microPascal at 1metre (most systems operate at levels below this). They provide range information up to approximately 1 kilometre, after which distance the received sound pressure levels of these signals are attenuated to background levels.

The tailbuoy (Figure 30) is used to house Differential Global Positioning System (DGPS) receivers that are used in the positioning solution for the hydrophone groups in the streamers. It has been mentioned several times that one of the critical elements in the 3D seismic method is the positioning of the in-sea equipment. These devices all contribute to the location accuracy of 3-8 metres absolute, with which seismic surveys are normally conducted. Differential Global Positioning System (DGPS) is the standard system used for positioning the vessel itself and Relative DGPS is used to position both source floats and tailbuoys. Compasses and acoustics are used to position the subsea equipment relative to these. Recently, depth control bird technology has been developed to provide a limited degree of lateral streamer positioning control – so called 'streamer steering'. In this technology, the bird wings operate in both the cross-line and vertical planes to compensate for approximately 3-4 degrees of streamer feathering, which is beneficial for 4D surveys.

Figure 30 *(credit: Fugro-Geoteam)*

Photographs of tailbuoys on deck (left). Photograph of tailbuoys deployed in the water (right).

10 Ancillary equipment

In addition to the in-sea equipment described above, there are a number of other devices used in seismic exploration. As the search for offshore oil and gas goes into ever deeper waters, the effectiveness of surface mounted sensors is reduced because power at the high frequencies necessary to provide the high resolution definition of the near seabed is lost in the water column. Also, the effectiveness of deep towed systems is lost because they, and, therefore, the data they acquire, cannot be positioned accurately. Moreover, line turn times are greatly increased when the survey vessel is towing a negatively buoyant cable several kilometres long. To mitigate this situation, Autonomous Underwater Vehicles (AUV's) (Figure 31) have been developed which are equipped with multi-beam echo sounders, sidescan sonars and chirp sub-bottom profilers. They are truly autonomous, being capable of travelling to the seabed, up to 4,500 metres down and surveying a prescribed grid of lines, and acquiring the data sets described earlier in this section (except airgun/sparker data). In water depths greater than approximately 300 metres, the following benefits accrue:

- The data are very high quality because the AUV flies at the optimum height above the seabed at the optimum speed and in an extremely stable attitude.
- The data are very tightly coupled to the seabed and therefore the location of the features on it and under it is accurate.
- The survey is completed sooner because far less time is spent making line turns.

Doppler sonar current metres are devices used to measure the magnitude and direction of subsurface currents by measuring the Doppler shifts that affect acoustic signals that are reflected due to the variations in temperature and density of the water in different current layers. The operating frequency is inversely proportional to the range and can vary from 600 kHz (50 metres) to 2 MHz (10 metres). Output source pressure levels are typically 160 to 210dB re 1 µPascal at 1 metre. Echo sounders are more sophisticated versions of the systems that are installed on every marine vessel. Typical operating frequencies range from 12kHz to 200kHz. The sound source pressure levels are 180 to 230dB re 1 µPascal at 1 metre.

Figure 31 *(credit: Fugro Survey)*
Autonomous Underwater Vehicle (AUV) being launched from its support vehicle.

11 Operational performance

The rate of progress during a seismic survey depends on a number of factors, but the most dominant is usually the weather. Other issues that affect the duration of a specific survey are:

- Survey location
- Time of year
- Survey size, particularly sail line length
- Technical acquisition parameterss
- Vessel configuration
- Line orientation and prevailing current direction
- Fishing and shipping activity in the survey area
- Other seismic operations
- Marine mammal activity
- Drilling and subsea equipment maintenance
- Technical equipment downtime

The net effect of all of these factors is to limit the time actually spent acquiring seismic data to just 35 - 40% of the available time.

The reason the weather is so important is that the signal levels that are recorded by the seismic streamer are very small. Because there is a requirement to record data with as wide a frequency bandwidth as possible, to improve the resolution with which geologic features in the subsurface can be identified and mapped, the streamers are towed at quite shallow depths to avoid problems with the ghost notch. Thus any wave action, which is directly proportional to weather conditions, causes noise that degrades the quality of the recorded data. The location, timing and duration of a survey is dictated by the weather environment for the survey, as does the time of year the survey is being conducted. Offshore West Africa, for example, the weather is much better than in the North Sea. Thus, two identically sized surveys in these two regions could have significantly different durations.

A survey vessel typically operates at a tow speed of between 4.5 and 5.0 knots (approximately 9 kilometres/hour). At this rate, the survey vessel could conceivably cover some 216 kilometres in a day and almost 6,500 kilometres m in one month. As survey dimensions are not usually as great as 200 kilometres, the vessel must turn at the end of each line before starting the next, the 3D 'racetrack' shown in Figure 8. With seismic streamers as long as 8,000 metres (and in some cases even longer) being towed behind the vessel, and with as many as 16 streamers being towed simultaneously, the time taken to change direction or line change time, may be up to three hours or more for the largest streamer configuration, which is significant. For a survey with a 45-kilometre line length, which is fairly long even by today's standards, the line acquisition time of 5 hours is then followed by a line change of 3 hours or 60% of the acquisition time. It thus follows that when a vessel acquires more than 100 traverse kilometres in a single day, it is considered very productive.

The specific technical acquisition parameters for a given survey also influence productivity. For a survey with a shallow depth of target, the need to record higher frequencies, up to 100 Hertz, necessitates the use of shallow tow depths for the streamer. This increases the effect of wave noise, thus rendering the operation more prone to weather downtime. If the survey objective were deeper, then deeper streamer depths could be used and the productivity of the operation would improve. As discussed, the configuration of the deployed equipment, that is the number of sources and streamers utilised, dictates the number of subsurface CMP lines that will be generated for each vessel sail line as shown previously. Thus a vessel towing eight streamers will acquire approximately twice as much data per pass as a vessel towing four streamers using the same source effort. For a 1,000 square kilometre survey (40 kilometres x 25 kilometres), a four-streamer vessel would require 125 sail lines to cover the area assuming perfect coverage. The eight streamer vessel would logically require only half this number, 62.5, and thus would acquire the data in just over half the time. The incremental time to deploy the additional in-sea equipment, and the extra line change time, are among the reasons why the time is not precisely halved, but overall these 'extra' times are small.

The relative orientation of the survey to the prevailing current and tides has an impact on survey efficiency, since the feathering of the streamers is dictated by these conditions. If the survey is oriented so that the main currents are in the direction of sail line, changes in these currents and tides will have little impact on the feathering of the streamers. If these currents are across the sail line and they vary, the feathering of the streamers will correspondingly change, causing irregularities in the location of the subsurface data being collected. These irregularities result in data holes or gaps, which need to be 'infilled', a term used to describe the additional sail lines required during a 3D survey to acquire data for those areas of irregularities in subsurface coverage caused by the feathering of the streamers. In areas with very severe current variation, infill can amount to as much as 40 - 50% of the total survey area, which has a very dramatic impact on the time taken to complete the survey. Typically infill is between 10 and 20% but increases with increasing streamer length.

The presence of shipping in the survey area can restrict vessel operations due to physical access constraints such as proximity to harbours, data acquisition in shipping lane areas such as the English Channel, or due to excessive noise contamination from other vessels. The effect of such vessel noise can require portions of the recorded data to be re-recorded, which necessitates the vessel repeating asail line. Although seismic vessels are flagged to indicate that they are towing equipment in the water, and employ guard vessels to try to ensure that other vessel traffic does not sail across the submerged streamers, other vessels do not always respond and the depth control birds have to be used to effect an 'emergency dive' to lower the streamers below the keel depth of the transgressing vessel when this happens. This results in data acquisition having to be aborted and the vessel having to circle to re-acquire the line, starting some distance back from where the incident occurred to ensure proper overlap of subsurface data coverage. Container vessels and oil tankers, which often prove difficult to contact, provide a particular hazard to survey operations due to their size and limited speed of manoeuvring capabilities.

In a similar manner, fishing activity can restrict vessel operations, either by the presence of fixed gear, which has to be systematically removed, or by long lines, which become entangled in the streamers. Disruption to fishing activity by a seismic survey can lead to physical confrontation offshore, unless proper notification and communication of the impending survey has been undertaken.

The source energy from one seismic survey being detected by other seismic vessels in the vicinity of the same survey area can also reduce productivity. This is known as seismic interference (SI), and the severity of the problem is highly dependent on a number of factors, including the direction from which the interference is from, water depth in the survey area, the source volumes used, the nature of the sea bed and any layering (temperature, salinity) in the water column itself. The impact radius can be significant, but there have been significant efforts in recent years to try to improve data processing methods to allow data to be acquired in the presence of SI.

If surveys are being conducted in close proximity to drilling rigs or production platforms, there can also be delays. Since the reflected seismic data is of very low amplitude, local noise from both the motors and various other equipment running on the rig, in addition to downhole noise from the drill bit itself, can degrade the recording, necessitating re-shoots in extreme cases. Supply vessel movements and general traffic restrictions in producing fields can limit seismic vessel access. Seismic operations are also prohibited within 1,500 metres of any diving activity, a frequent occurrence around platforms and in the maintenance of subsea equipment, including pipelines.

The performance of the survey equipment, both onboard and deployed from the survey vessel, also has a strong impact on survey duration. However, it is worth noting that overall seismic vessel efficiency has improved in recent years at the same time as the volume, number, and length of streamers has dramatically increased. Just as the last two decades have seen much improvement in efficiency, that time period has seen other issues come to the fore, so that they just become another piece of the operational puzzle. Mitigation measures for the protection of marine mammals is one such issue, and they are handled on a case-by-case basis in a straight-forward way. Local restrictions and requirements are observed, and operational procedures are set up and executed to meet those conditions.

It is impossible to define the duration of a typical seismic survey, as there are simply too many factors that have to be included. For a specific size of survey, in a given location at a particular time of year, using a defined configuration, with no seismic or shipping/fishing interference, to be acquired with established acquisition parameters, a survey duration can be estimated.

About IAGC

The International Association of Geophysical Contractors (IAGC) is the international trade association representing the industry that provides geophysical services (geophysical data acquisition, seismic data ownership and licensing, geophysical data processing and interpretation, and associated service and product providers) to the oil and gas industry.

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