The Midwater Stationary Cable (FreeCable) to solve today's offshore seismic acquisition paradox

Luc Haumonté[1*] presents a field-proven unmanned solution to address the industry's challenges.

Introduction

The world economy is demanding an increasing volume of oil and according to oil market specialists this trend is not expected to decrease in the next decades. The easy oil is gone and oil companies currently seek either increasing the existing production, which will last for some limited period of time, or continuing exploration for new discoveries. The fact that the easy oil has already been found practically means that the new exploration challenge is to look for complex reservoirs such as deep target, complicated geological environments, subsalt imaging, or hardly accessible sites. Generally speaking, solving this problem requires a high-end seismic acquisition technique able to provide full offset full azimuth coverage, broadband data and deep penetration. Indeed, zero offset traces are needed to build a reliable structural model and estimate velocity for deep imaging. Long offsets are required to illuminate salt body flanks and subsalt reservoirs. The low frequency content is necessary to image layer boundaries and obtain good penetration. The high frequency content is used for obtaining interface details and resolving thinner beds. Deep penetration is also obtained through low measurement noise and high fold leading to a great post-stack signal-to-noise ratio. Finally, full azimuth and full offset maximizes the target reservoir illumination and minimized the probability of shadow areas. Such a qualitative acquisition method is generally perceived to be very expensive. On the other hand, the economic downturn in the oil and gas industry and especially in the exploration market puts high pressure on expenditures and places traditional acquisition technologies in difficulty. Lots of seismic vessels are placed in cold stack and the ocean bottom cable time seems to be over. To solve this paradox the seismic industry is looking for new solutions providing better, cheaper, and faster acquisitions. Nodes are gaining momentum but do not completely respond to the three criteria. Robotic projects tend to flourish, but most of them are not yet industrial. In this article a field proven unmanned solution able to address the new industry challenges is presented. The patented technology developed by Kietta consists of controlling unmanned midwater stationary cables (MSCs).

Legacy offshore seismic acquisitions and their limitations

The existing methods can be grouped in two main categories as proposed by Haumonté et al. (2016): the towed streamer technique and the ocean bottom techniques (OBS, OBC, OBN). On the one hand, the towed streamer technique has been used for decades. It is a mature technology whose main advantage is to yield high productivity since both the source and the receivers are moving at 5 knots. However its productivity is reaching a limit since the spread width cannot be extended farther owing to the significant towing force needed to make the spread diverge – about 60 to 80 tonnes. Figure 1 displays the stalling trend of the streamer number vs. time curve with recently updated data.

More importantly, the offset and azimuth content obtained from the streamer technique is naturally narrow because the relative position of the source with respect to the receivers is fixed. This content can be enhanced by employing more streamer vessels or source vessels (WATS, shooting-over-the-spread), by repeating the number of sailing passes (MAZ), by sailing streamer vessels in loops (coil shooting), or by a combination of the aforementioned alternatives (RAZ, quad coil shooting). The enhancement is obtained through a substantial operating cost increase and finally does not provide a full offset full azimuth acquisition in an isotropic bin. Figure 2 shows the rose diagrams obtained from different variants of the towed streamer technique.

The streamer acquisition noise is dominated by three main factors: the flow noise, the swell noise and the mechanical noise. The flow noise is generated by the relative speed of the water with respect to the streamer, which is about 5 knots. Elboth et al. (2010) have shown that the noise level can be considered as proportional to the square of the speed. The mechanical noise can take several forms (e.g. tug noise, strumming noise) and is due to the high mechanical tensions at stake. Schoenberger and Mifsud (1974) found derived that the intensity of these phenomena is also proportional to the square of the water velocity. These vibrations

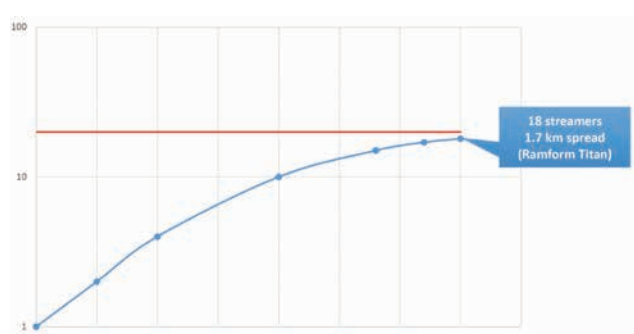

Figure 1 Maximum number of towed streamers behind a seismic vessel vs. time.

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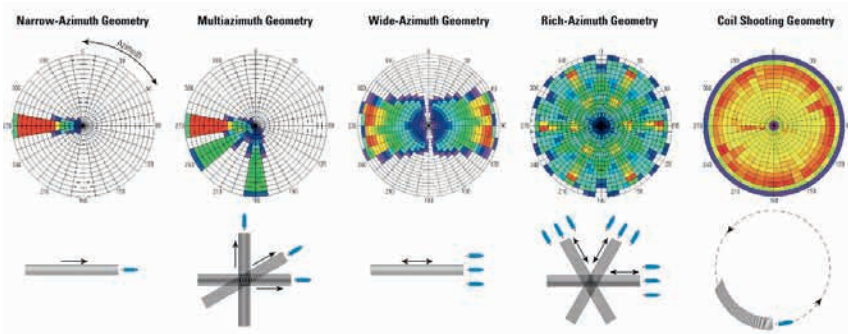

Figure 2 Rose diagrams obtained from different variants of streamer acquisition.

particularly affect the geophone signals. Finally the swell noise originates from the interface between the sea and the atmosphere and is owing to wave motion and wind effects (Elboth et al. 2009). The sea surface effects have an exponential decay with depth, as described in Haumonté and Manin (2017). Attempts at increasing towing depth remain limited because the low frequency noise of the geophones prevents the removal of the receiver ghost at large depths. Despite latest streamer evolutions (solid streamer, flush design, multi-component), digital group forming described by Savit et al. (1958) is still used today to attenuate measurement noise as much as possible, towing depth is limited owing to ghost notch frequency, and weather is still a cause of customer noise specifications not being met.

On the other hand, ocean bottom techniques do not suffer from the same limitations as the streamer. The receivers are stationary, placed away from sea surface, and are not subject to mechanical tensions. Hence the flow noise is limited to the sea current value and the swell noise is in principle reduced to its minimum since the seabed corresponds to the largest water depth. The source being independent of the receivers, the geometry is flexible and is capable of producing full azimuth and full offset acquisition. The acquisition is theoretically broadband since the combination of hydrophone and geophone signals yields a flat receiver spectrum through receiver deghosting. In practice, the reality is more complex and being on the seabed, which is the interface between water and the subsurface, creates lots of difficulties. First of all, the acquisition quality is impacted by a variety of surface related noise. The seabed is subject to specific waves whose physical description is given in Socco et al. 2010. The Scholte wave or mud roll is a well-known noise source for seabed acquisition (Kugler 2005: Le Meur 2010: Zheng 2013). It has a maximum intensity at the interface and decreases exponentially with distance. Shear waves are also complex, most of the time not desired for the processing and considered as noise (Paffenholz 2006). Shear noise strongly affects the geophone measurements especially the horizontal one. Being fixed on the seabed can create some flow noise owing to current, especially for OBCs which are subject to crossflow noise when the cable laying azimuth is not in line with the current. The seabed is also subject to environmental disturbances, such as those generated by pile driving which can be very strong and propagates easily on the sea floor (Duncan et al., 2010), or more infrequently by marine life randomly drumming the receivers.

Secondly, the coupling with the seabed is a complex problem. The receiver response is not isotropic since the receiver partially perceives the sea and partially perceives the sea bottom. The coupling to the seabed can hardly be considered as being perfect and might be of poor quality, especially in irregular seafloor conditions. Depending on whether it is coupled to a soft or to a hard part, and depending on the rock properties beneath, the impedance and the overall sensor response varies a lot (Parsons et al., 2011). As a consequence of the above characteristics the coupling is heterogeneous among all the receivers, the sensor responses are not accurately repeatable, and the deghosting, which requires impedance estimation, is made difficult and does not easily obtain a flat spectrum.

Thirdly the seabed interface exhibits a strong velocity contrast. Even though pressure and velocity waves are continuous, the velocity exhibits an abrupt step change at the interface: ground-type velocity below the seabed and underwater sound velocity above the seabed. The velocity contrast has important effects on the processing stage. Polarization or directional studies are difficult even for P-waves whose propagation angle is discontinuous at the sea bed.

Fourthly a non-flat seabed will require datuming in order to compensate for the fact that the receivers are not at the same elevation. Elevation correction is not an obvious task since it has to be done pre-stack and in 3D. The algorithms do not allow compensating depth perfectly nor cancelling out sea floor heterogeneities even with surface consistency metrics. The elevation correction introduces some distortion during the processing stage.

Finally, the major drawback of ocean bottom acquisition is its limited productivity because the stationary receivers need to be launched and recovered continuously. The deployment and the recovery are complex operations, require important operational means, and are time consuming. Some factors decrease the efficiency of ocean bottom acquisition even further. For some type of sea floors the technology is simply not suitable because it is too difficult or impossible to handle (e.g. corals, hilly seabed, pinnacles, well infrastructures). Water depth is linked to incremental overheads because of the operational methodology. And for OBN the absence of real-time QC increases the likelihood of infill shooting needs. Globally speaking, the overall costs are significant and the seabed acquisition is not efficient in terms of km^2/day/$.

MSC acquisition principle

Haumonté et al. 2016 recently introduced a new acquisition technique named MSC for midwater stationary cables that can be naively depicted as lifting OBC or stopping streamers. This technology employs unmanned vessels to control independent seismic cables. Each seismic cable contains 4C receivers and is maintained by a pair of autonomous vessels, one at each end. The unmanned vessels baptized Recording Autonomous Vessels (RAVs) are at the surface, maintain the seismic cables through lead-in cables and dynamically position them in the water. Since each cable is independent and autonomous, the number of cables is theoretically unlimited and the separation between the cables can be increased, usually between 100 m and 400 m. Hence it is possible to significantly increase the receiver area and to reduce the array displacement speed while still maintaining good productivity. Being stationary or pseudo-stationary brings two important advantages: the immersion depth can be increased to typical values between 50m and 100m, and it is possible to have independent source vessel(s) shooting orthogonal to the cables. The challenges of controlling the system at a low speed close to zero have been solved by using both RAVs simultaneously, by developing ballast units along the cable, and by designing smart control loop algorithms. The role of the ballast units is to ensure a neutral buoyancy along the cable in order to accurately control the depth with a fine precision – down to a few decimetres. The system is depicted on Figure 3.

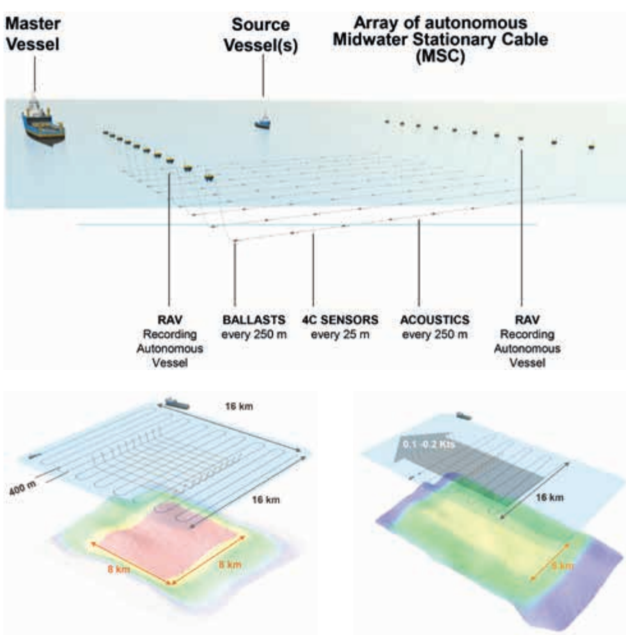

Figure 3 From top to bottom to bottom – Midwater Stationary Cable array and operating methods: patch shooting (left) and progressive shooting (right).

To cover a wide area, two main operating modes are possible. The patch mode consists of letting the array be stationary over a fixed location while the shooting is executed, and then moving to the next contiguous area once the patch shooting is completed. The progressive mode allows the array to slowly move while the shooting is done. The progression speed typically corresponds to the average source line interval change rate in the case of orthogonal shooting. In both the patch mode and the progressive mode, the productivity mainly depends on the number of cables, the shooting geometry, and the number of source vessels.

MSC advantages

The first advantage of the MSC geometry is to naturally produce a full azimuth and full offset distribution. The coverage and the distribution obtained with 20 8-km cables and orthogonal shooting lines spaced by 400 m are depicted in Figure 4. The isotropic distribution naturally comes from the fact that 2D space is equally sampled in both directions: the receiver spacing (25 m) provides inline sampling and the perpendicular shooting provides crossline sampling through shot point interval (25 m). The natural bin is perfectly square (12.5 m x 12.5 m) and the CMP coverage in patch mode reaches 400 in this example. Obviously, the coverage can be immediately increased by making the shots more dense. Comparing to the streamer case immediately attests the forward step brought by MSC acquisition: bringing long offset and full 360 degrees azimuth is essential to illuminate complex target reservoirs. With respect to ocean bottom techniques, MSC acquisition offers more zero and near offsets, which are precious for estimating velocity and building a reliable structural model. Zero offset is obtained only where the source vessel is vertical to the receivers. The seabed receiver spacing (e.g. 200 m x 200 m or 400 m x 400 m) is sparser than in the MSC acquisition (e.g. 25 m x 400 m or 25 m x 200 m) and therefore produces less zero offset spots. In both MSC and OBN cases the zero offset content can globally be related to the receiver density: the MSC receiver density is 8 to 16 times higher than the OBN with the above mentioned receiver geometries.

The second important advantage of the MSC is the acquisition quality obtained on the four components. The measurement noise level is reduced for several reasons. Since the spread is not moving or moving slowly, the water velocity of the cable is small and mainly driven by the sea current value. This significantly reduces the flow noise and the mechanical tensions. The square

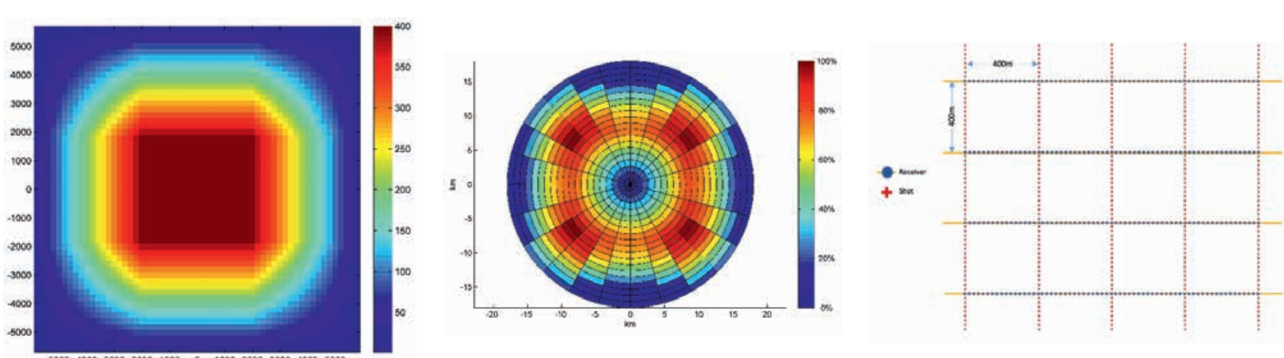

Figure 4 From top to bottom – seismic coverage, rose diagram and acquisition geometry zoom with Midwater Stationary Cable (20 8-km long cable spaced by 400 m; orthogonal shooting with 25-m shot point interval and 400 m).

law dependency of the noise with respect to the speed has been experimentally verified by Haumonté and Manin (2017): moving from the towed streamer speed of 5 knots to a 0.5 knot water speed for instance means an improvement of 40 dB in terms of noise reduction. In ocean bottom acquisition the water velocity is exactly equal to the current speed since the receivers are stationary. When the OBC azimuth is not aligned with the current direction, this creates some cross-flow noise. When the sea current has a time-varying direction, OBC or OBN receivers have a directional noise profile. Compared to the seabed acquisition, the MSC has the ability to adjust the cable heading in the direction of the average current. In other words, the MSC has the capability to minimize the cross flow noise. Given the fact that the current value at large depth is generally weaker, it means that the flow noise can be considered as being suppressed in the MSC deep water case. The other noise reduction factor concerns the mechanical noise which can take several forms (e.g. strumming noise, tug noise). The mechanical tensions at stake in the MSC are weak mainly because the system is not fighting against the crossflow. The towed streamer uses diverters to make the spread diverge: increasing the spread width corresponds to maximizing the mechanical tensions at the lead-in cable junction – typically several tens of tonnes. These mechanical tensions generate vibrations that are imperfectly damped by elastic sections, propagate along the cable, and particularly affect the geophones. Additionally, within the seismic cable the inline tension is proportional to the square of the speed: the 5-knot speed creates 40 dB more drag than it would be at 0.5 knot. In the OBC case, the lead-in cables endorse the crossflow on the entire water column and absorb the shocks created at the interface between the anchored cable and the freely moving vessel. In the MSC case, the crossflow phenomena are principally reduced to the lead-in cables between the sea surface and the cable depth. The tension in the seismic cables is in the order of a several hundreds of kgf and the tension at the RAV interface is a few tonnes. Since the seismic cables are not tethered to the seabed and both the RAVs and the seismic cable are freely moving in the water volume, there are no dynamic effects associated to the relative positioning and the vessel swell induced motion is damped by the catenary shape of the heavy lead-in cable. The residual vibrations are attenuated by stretcher sections. As a consequence, the level of vibrations, of tug noise and of strumming noise is largely reduced. The MSC

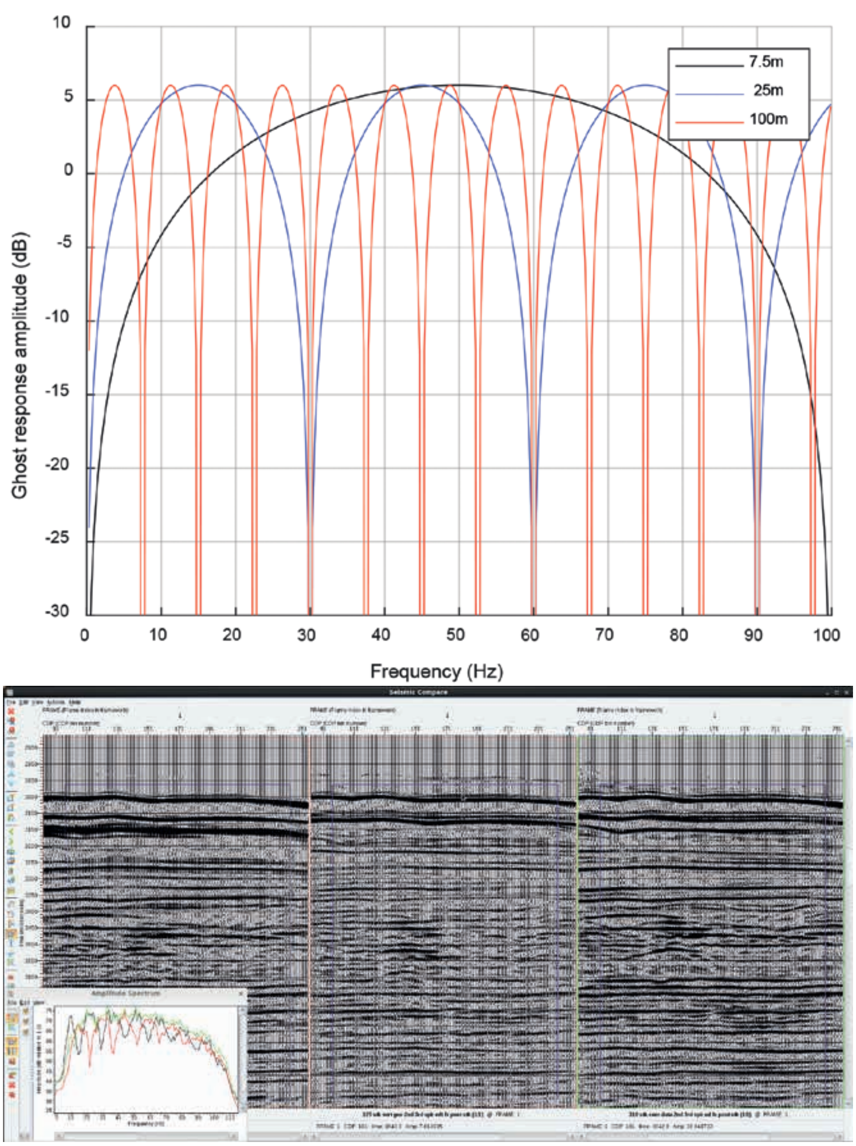

Figure 5 Deghosting through hydrophone and geophone combination. From top to left: theoretical ghost responses at several depths; experimental deghosting based on a hydrophone/geophone combination of MSC real data.

deployment methodology minimizes the environmental noise as well. By placing the seismic cables midwater, the 4C receivers are ideally positioned away from the sea surface and from the seabed surface. The baseline MSC cable depth is significantly larger than the usual towing depth, making it insensitive to swell. Haumonté and Manin (2017) recall the wave physic equations and compute for instance that the swell noise is in theory 33 dB lower at 100 m than at 7.5 m in the example of a 2.5-m half wave height having a 150-m wavelength. Conversely, not touching the sea bottom and staying in the water create a favourable environment to perform an unpolluted measurement. Indeed, the surface propagated waves are naturally filtered out. The Scholte wave in particular has an exponential decay with respect to the distance to the interface. And shear waves are not propagated since water is a purely acoustic medium.

In addition to reducing measurement acquisition noise, the MSC technology benefits from an excellent coupling with the water medium. Indeed the sensors are fully surrounded by water which is an isotropic and homogeneous medium. The hydrophones measure the sound pressure wave while the geophones capture the sound velocity wave: in the acoustic medium constituted by water they are simply related by the water acoustic impedance which is deterministically estimated from its density and the sound velocity. The temporal and spatial variations of the impedance are limited. The receivers are considered as perceiving the same impedance. Unlike sea bottom acquisition the receiver response for MSC is isotropic, homogenous and repeatable.

Consequently the MSC acquisition delivers high-quality data with low noise level and good signal on all four components as exposed by Haumonté and Wheizong (2017): hydrophone, vertical geophone, transverse geophone, and inline geophone are all capturing useful and clear signals in the seismic frequency band. The fact that this is especially true at low frequencies has an important impact: the deghosting is made possible at any cable depth since the low frequency content of the geophone fills in the notches of the hydrophone and vice versa (Figure 5). Moreover, the MSC naturally makes the deghosting process straightforward thanks to the favourable coupling characteristics discussed above. The deghosting can simply be performed by adding the hydrophone and the vertical geophone multiplied by a scalar value equal to the water impedance. This works almost perfectly in the presence of flat subsurface layers (Haumonté et al. 2016) and works acceptably in a more complex geology (Haumonté and Weizhong 2017). In the latter case angle-dependent deghosting which is made possible thanks to the unprecedented quality of the crossline and inline geophones would outperform the simple PZ sum by bringing additional useful signal content. The fact that all geophones record good signal opens the way to new possibilities in terms of multi-component vector processing. To summarize, the MSC acquisition method offers broadband seismic data thanks to its high quality multi-component data. Having a low frequency is essential to obtain a layer impedance response, and a high frequency is needed to provide details about the interface reflection responses.

It is interesting to highlight that low noise and increased depth are tightly correlated. The low noise acquisition is possible thanks to slow speed and large depth: this reduces flow noise, mechanical noise and sea surface noise. The increased depth is possible thanks to the low acquisition noise: good hydrophone and geophone signals are needed to obtain a flat spectrum after deghosting.

Figure 6 Real experimentation pictures with MSC in a complex environment. From top to bottom – hilly environment; presence of obstacles (shallow water, islands, platforms).

Finally the MSC acquisition geometry brings operational advantages. The survey design is flexible: the receiver geometry (number of cables, cable length, separation between the cables, cable depths), the source geometry (shooting pattern, shot point interval, source line length, separation between the source lines), the array progression speed, the number of shooting vessels give numerous degrees of freedom to match the survey requirements and to illuminate the geological target in the most efficient manner. The system is easily transportable and can be shipped to any location in the world (shallow water, deep water, landlocked seas, and lakes): the RAVs are road transportable, the seismic active sections are stored on reels, and the rest of the system is containerized. The system is capable of evolving in a challenging environment as seen from Figure 6. It can deal with shallow water thanks to its reduced draft and its ability to have a varying depth profile along the cable. It can cope with obstructed areas (islands, platforms) thanks to its agility to manoeuvre up to a few hundred metres of obstacles. Being midwater and stationary simplifies significantly the management of maritime traffic including fishery activities. The MSC has a light impact and a low footprint on the environment. It does not touch the seabed and can be used regardless of the seafloor type (corals, pinnacles, rocks, oil field infrastructures) and the water depth. The fuel consumption is reduced to its minimum level since the cross flow is not fought.

Conclusion

Offshore seismic acquisition is currently suffering from the economic situation but on the other hand the exploration needs to continue with ever more challenging geological targets to image. Hence oil companies are looking for better methods able to be more efficient in terms of cost, production rate, and quality. None of the legacy offshore techniques meet the three above criteria. The streamer type acquisition is productive but not good enough quality. Its quality can only be partially enhanced by significantly increasing the cost. The ocean bottom technique has a better quality than the streamer but is inefficient in terms of cost and production rate. Both techniques suffer from important limitations in terms of quality and productivity because on the one hand the streamer is moving too fast and is close to the sea surface, and on the other hand the ocean bottom techniques are tethered to the seabed and are impacted by the surface wave physical phenomena. The newly introduced midwater stationary technique is an extremely qualitative acquisition method that is faster and better than traditional methods. Recent surveys have confirmed its advantages with concrete in situ data. Operating deeper in the water without touching the seabed removes both the sea surface and seabed surface related problems. By being totally flexible, the MSC technology determines the right pace for the best quality and is able to evolve in any offshore environment. It is ideally suited to respond to the demanding challenges of today's seismic market.

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