Fully Autonomous Marine Seismic Acquisition Systems for Reservoir Monitoring

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Abstract

We present a vision for fully autonomous marine seismic acquisition systems where all activity takes places on the seabed, with no reliance on costly surface vessels. This system would be most suitable to enable low-cost, on-demand reservoir monitoring in deepwater fields, for example, those in the Brazilian pre-salt province. The sensor components of the system are developed or under development (i.e., permanent or semi-permanent sensors on the seabed or in wells). For the source components we propose mobile impulsive or vibratory sources which are towed by an AUV close to the seabed or carried by a RAUV on the seabed. Such a system would be naturally distant from environmental concerns and interference with surface operations, would support simultaneous source operations to increase survey efficiency, and would be resilient against water velocity variations which limit 4D seismic resolution. We consider reflection geometries and long-offset target-oriented refraction geometries, to reduce the load on the source system (much fewer source points). We also discuss the requirements for AUV endurance.

Introduction

Seismic acquisition requirements in deepwater and the technologies to fulfill them depend critically on the desired business objectives. For exploration, one requires coarse images over large areas at relatively low cost, such as provided by towed streamer narrow azimuth seismic. Where feasible, this technology has evolved into Wide Azimuth (WAZ) seismic, which uses multiple vessels. For field development planning the areas are smaller, but the quality and resolution need to be better. In complex geological settings the use of Ocean Bottom Nodes (OBN) is becoming widespread, especially in areas such as the pre-salt in the Brazilian Santos Basin where multiple simultaneous vessels have not been permitted (precluding the use of WAZ). For reservoir monitoring the requirements become yet stricter with the need for very good data repeatability and frequent or on-demand surveys. Permanent or semi-permanent ocean bottom or in-well sensor systems become preferable in that case.

In all cases seismic acquisition faces challenges in terms of cost, ability to execute on demand, interference with other operations, and environmental restrictions. In this paper we focus on solving these problems in the area where they are most acute, namely seismic monitoring, by considering fully autonomous marine acquisition. To this end we discuss existing autonomous seismic sensors and sources and propose new ones. A realistic solution also requires new, fit-for-purpose acquisition geometries. Ultimately, we envision a situation where all activity takes place autonomously on or near the seabed.

Such fully autonomous marine acquisition systems would be a very welcome technology solution to monitor the Brazilian pre-salt fields (Lopez, Cox, Hatchell, & Wang, 2017). Indeed, the prolific carbonate reservoirs are being exploited using a combination of water, gas, and water-alternating-gas injection schemes. Due to limitations on the capacity of the FPSO systems to separate gas from the produced liquids, gas cycling (i.e., injected gas that finds its way to the producers sooner than models predict) needs to be avoided, otherwise liquids production will need to be curtailed and oil production will drop. Similar issues occur with injected water. Seismic monitoring could provide information about the distribution of gas and water in the reservoir and prompt actions to avoid them reaching the producers when not wanted. Seismic monitoring would also add value in its traditional use to identify by-passed oil and enable better placement of infill wells. Due to the recent increase in licensing rounds and in the diversity of operators, the opportunity for deployment of automated acquisition systems to monitor the pre-salt is growing.

Seabed autonomous acquisition systems would enable cost reductions by removing dependence on costly surface vessels, facilitate on-demand data acquisition, and be distant from environmental concerns and interference with surface operations. In the Brazilian pre-salt it would be 2km away from surface activities and 2km closer to the reservoir. Such location should allow operation of multiple seabed sources and render their likely small power more effective. By-passing the entire water column would make the system resilient to water velocity variations between or during 4D seismic surveys, which ultimately limit the 4D seismic resolution (Theriot, Yin, & Lopez, 2017), especially important where the 4D signals are expected to be small.

Autonomous Marine Acquisition – Sensors

We consider permanent or semi-permanent sensors as possible elements for an autonomous acquisition system. These may be deployed on the seabed or in wells. (Retrievable sensors that "fly" to the seabed and position and retrieve themselves autonomously could also be considered, if they would not rely on surface vessels.)

Permanent Reservoir Monitoring (PRM) systems comprise ocean bottom cables permanently installed on the seabed containing sensors, typically at 100m spacing along the cable, with the cables themselves arranged to cover the area of interest, and the whole system connected to a surface vessel, such as a FPSO. PRM systems installed in deepwater in the Brazilian Campos Basin at O-North (Ebaid, Wang, Seixas, Kumar, & et al., 2017) and Jubarte (Thedy & et al., 2015) have provided very high quality 4D seismic data. Here we consider fiber-optic systems, which are expected to be more reliable in the long term.

Technology	Description	CAPEX	OPEX	Limitations	4D Quality	Reliability	Mobilization	Market	Maturity
OBN	Retrievable seabed nodes	None	Node vessel	Impacted by weather	Depends on node re-positioning	High	Node vessel	Growing	High
PRM	Fiber optic cables on the seabed	High	Interrogation units (IUs)	Resilient	High	Long-term reliability unproven	IUs are permanent	Stagnant	High
DAS VSP	Fiber optic cables in a well	Low	Interrogation units (IUs)	Targeted areas	Impacted by well flow & geometry	Mitigate issues with spare fibers	IUs if not permanent	Growing	Low for subsea wells
OD OBN	Semi-permanent seabed nodes	Scalable	Resident AUV	Recording 500 days in 5 years	Impacted after 5 years	Replace nodes if they fail	Resident AUV	Available 2021	Integration is key risk
Conventional sources	Sources towed by surface vessels	None	Source vessel	Impacted by weather	Depends on source re-positioning	Maintained by onboard personnel	Source vessel	Stable	High
RAM4D	Small source towed by USV	None	Unproven low day rate	Small sources	Unproven	Unproven	Depends on USV market	Immature	Needs testing in deepwater
Flying seabed	Seabed source towed by AUV	Low	Low with resident AUV	Endurance	Depends on source used	R&D	Resident AUV	Immature	Conceptual
Roving seabed	Seabed source carried by RAUV	R&D	R&D	Endurance & navigation	Depends on source used	R&D	R&D	Immature	Conceptual
Fixed seabed	Sparse seabed sources	High	Permanent	No seismic images	Only time shifts	Long-term risk	Permanent	Immature	Conceptual

Figure 1: Comparison of options for sensors and sources to enable a fully autonomous marine seismic acquisition system for reservoir monitoring. OBN and Conventional sources are shown for reference to traditional acquisition systems. Colors indicate: desirable or manageable (green), limitation or risk (yellow), undesirable (red), and immature (blue).

Fiber-optic cable systems can also be installed in wells, using Distributed Acoustic Sensing (DAS) to record VSP data along the borehole where the cable is installed, with the DAS interrogator units located on the topsides or at the seafloor. This application has been matured for reservoir monitoring (Mateeva, et al., 2017) and is available for wells with direct vertical access from the platform. Deployment in the more numerous subsea wells (e.g., all the ones in pre-salt Brazil) is expected in the next few years.

Finally, semi-permanent nodes, which can stay on the seabed for years and record seismic data on demand, have been developing using ROVs (Magseis Fairfield, 2015) or AUVs (Lopez, Cox, Hatchell, & Wang, 2017) for node communication and data harvesting. The nodes that use a subsea resident AUV (aka On-Demand OBN) would qualify as autonomous, as they do not depend on surface vessels; these are under development with a specification of 500 days of data recording in 5 years before refurbishing (Lopez, Chalenski, & Grandi, 2018).

The options for sensors discussed above and the options for sources to be discussed below are listed in Figure 1 and compared across a number of dimensions: cost (CAPEX and OPEX), system limitations, impact on quality of 4D seismic acquired by the system, reliability in the field, ease of mobilization, status of the market, and level of maturity. The colors are meant to guide the eye for ease of comparison of advantages and disadvantages.

Autonomous Marine Acquisition – Sources

Autonomous seismic sources that operate similarly as conventional sources have been introduced and tested, for example in the embodiment called Rapid Autonomous Marine 4D (RAM4D) (Chalenski, Hatchell, Lopez, & Ross, 2017) (Patent No. US 2018/0164456). RAM4D uses an Unmanned Surface Vessel (USV) to tow a small airgun array and conduct seismic surveys ‘over the horizon’, although with some degree of supervision (Anderson, 2018). The system is restricted to small sources (e.g., 500 ci) due to the limited space available for the airgun compressor in the typically small USV (vessels up to 12m long have been tested) (Chalenski, Lopez, Hatchell, & Grandi, 2018). Nonetheless, airgun sources of that volume have been shown to be useful in many instances, even to great depths and in reservoir monitoring applications (Chalenski, Wang, Lopez, & Hatchell, 2016). This system uses surface vessels and does not address the issue of interference with surface operations and only partially the issue of environmental restrictions (by using small airgun sources, although marine vibrators could also be towed).

Moving the source to or near the seabed has been considered and tested by several authors, when towed by surface or submarine vessels or when activated at fixed locations. Recently Watts (Watts, 2019) has proposed using fixed seabed sources for reservoir monitoring. The main drawback of that concept is the sparsity of source locations, which coupled with a typically sparse set of seabed receivers, makes conventional 3D imaging unfeasible. Reservoir monitoring may still be possible by observing time-shifts on raw data.

Here we propose to use mobile seabed seismic sources that are transported in vehicles that navigate near the seabed or roam on the seabed. The “flying” sources could be carried by a special-purpose AUV, while the “roving” sources would be transported on Roving Autonomous Underwater Vehicles (RAUV) conceptually analogous to a Mars Rover or to the seafloor roaming Benthic Rover (Monterry Bay Aquarium Research Institute, n.d.). A survey of the literature shows several options for seabed sources, including impulsive and vibratory ones. Dorman and Sauter (2006) have developed and tested a reusable implosive seismic source that relies on high-pressure water influx, Gresillon and Forgues (Patent No. WO 2015/177631, 2015) have proposed a seafloor version of the piezoelectric SeisMovie source, Clark has proposed a seabed seismoacoustic source (Patent No. US 7,710,820) and Meldhal (Patent No. WO2015/082010 A1) suggested using submarines carrying or towing both a seismic and an EM source (the latter for EM data acquisition). As seismic sources in our vision, one may also consider accelerated weight drops, marine sparkers, and EM sources.

The mobile seabed seismic source systems face many engineering challenges, such as replenishable seabed power, source position and signature repeatability, autonomous endurance, achievable speed, and obstacle avoidance. For example, for the implosive source from Dorman and Sauter, once the chamber is filled with water, it needs to be brought to surface to empty, before it can be fired again. From all these challenges, access to power on the seabed is probably the least problematic, as for example seabed resident AUVs (Zagatti, Juliano, Doak, & Mimoso Souza, 2018) can recharge subsea and all-purpose subsea power stations are available commercially (Deep C Solutions AS, s.d.)

From the point of view of seismic quality, seabed sources will generate shear waves (Drijkoningen, Dieulangard, Kjos, & Holicki, 2015) which may or may not be desirable. Despite these challenges, however, should these sources become viable, the advantages would be numerous, including on-demand availability, resilience to sea surface weather, minimization of disturbance to environment and marine life, potential to deploy multiple sources simultaneously, and more effective use of the source energy being much closer to the reservoir (thus compensating for potentially small sources).

Having the source under the water column will remove the impact of water velocity variations on 4D resolution. For example, a common 0.2% variation in water velocity (3 m/s) would give an uncertainty of 2.6 ms in one-way travel time in 2km of water, which is large enough to obscure the expected 4D signals in the pre-salt reservoirs.

Autonomous Marine Acquisition – Systems

Given the discussion above, we propose an autonomous marine acquisition system based on autonomous sensors and autonomous sources, operating near or at the seabed carried by AUVs or RAUVs (see Figure 2). Both sensors and sources would need to be autonomous to remove dependency on surface vessels and to allow for a possibly slower pace of autonomous seismic operations. There could be synergies between the source and receiver systems, for example the AUV could also be used to communicate with the nodes before the survey starts and harvest their data afterwards, and in principle also to recharge the node batteries. The RAUV would be a less synergistic concept in this sense.

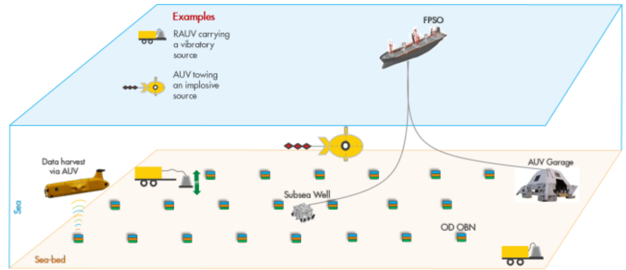

Figure 2: Vision for fully autonomous marine seismic acquisition systems, using semi-permanent ocean bottom nodes and mobile seabed sources (either flying or roving). Other sensors are possible, such as permanent fiber-optic cables on the seabed (PRM) or in wells (DAS VSP).

Autonomous Marine Acquisition – Reflection Surveys

Typical 4D seismic survey geometries utilize reflections from the subsurface, requiring a dense grid of source points to compensate for the sparse set of seabed receiver locations. For reference we consider a 10km x 10km = 100 km^2 sensor area of PRM or semi-PRM receivers, over which we would shoot a grid of source points at 50m spacing with a "rind" typically of 4km in all directions. The shooting square would then be 18km x 18km, traversed by 18km/50m = 360 shot lines, covering a total distance of 360 x 18km = 6480 km (see Figure 3). With a conventional dual-source vessel, we would shoot 180 sail lines (360 shot lines) covering 3240 km. At 100km/day production shooting, this survey would take 32 days to acquire. With a single (slower) towed seabed source, it would take much longer: 130 days with an AUV endurance of 50km/day. This is clearly unworkable, especially for On-Demand OBN systems with limited battery life.

In the present context, the term **endurance** is meant to capture the number of kilometers of AUV activity before a recharge is needed. This distance could include activities with lower or higher power demand such as travelling to location or shooting the seismic source, which may occur at higher or lower speeds.

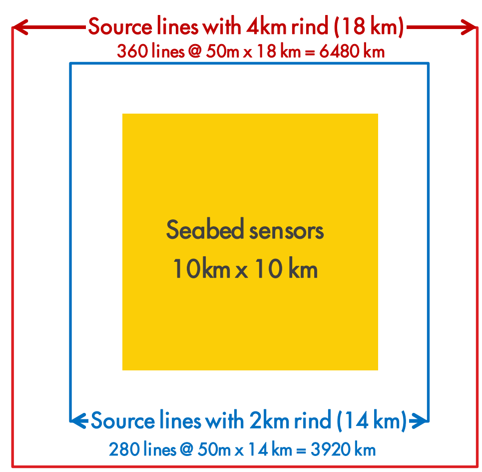

Figure 3: Outline of source positions for a reflection survey over a 100 km^2 area of seabed sensors. The rind of the source polygon may be decreased for sources located on the seabed. The total line distance is computed in each case.

One may envision an improvement to this situation, with an AUV endurance increased to 100km/day in next generation systems and with a smaller shot rind as the sources are now at the seabed (say 2km instead of 4km). With these adjustments the shot square would be 14km x 14km, comprising 280 shot lines covering a total distance of 3920 km (see Figure 3) in 39 days, so only a bit longer than with the conventional source vessel. However, the source effort would be massive for such an immature source: 78,400 source points (3920 km @ 50m).

The calculations above would also apply to a DAS VSP receiver system, if we assume the same shot grid. In practice we may shoot smaller source areas, unless multiple wells were being recorded simultaneously.

Autonomous Marine Acquisition – Refraction Surveys
The seismic reflection surveys require a dense grid of source points to compensate for the sparse set of seabed receiver locations. An alternative geometry consists of using refractions or diving waves generated by source locations distant from the reservoir. If the subsurface conditions are favorable, a “ring” of source points would be enough for target-oriented monitoring of a reservoir at a known depth using 4D Full Waveform Inversion (FWI) methods. This type of monitoring survey has been demonstrated in a steam injection operation onshore for both surface (Hansteen & Wills, Time-lapse refraction seismic monitoring, 2010) and in-well receivers (Wills & De Meersman, 2013), (Patent No. US 8,077,546) (Figure 4).

This geometry should be feasible for the pre-salt carbonate reservoirs, and with lower 4D noise, as offshore sources are more repeatable than onshore sources. However, these methods are not well developed, and, in the pre-salt would have to deal with the strong transmission effects at the top of salt, likely requiring an elastic 4D FWI approach. Nonetheless, for an immature seabed source, the fewer the number of source point locations the better.

A refraction survey could be acquired over a ring of shots circumscribing the 10km x 10km sensor area, which for discussion we consider having a 25km radius (see Figure 5). The circumference of this circle would be 157km. With the same 100km/day operational endurance for the AUV, we can imagine the AUV traversing a quadrant of this circle in each mission (25+39+25=89km) of one day duration. Repeating four times would complete the full circle in four days. The total source effort would be quite modest: 1,570 source points (157km @ 100m). A similar estimate would apply to the case of a DAS VSP array.

For such a small number of source points, a conventional source vessel would not be sensible, as the two-day operation would not justify mobilization. This situation is analogous to when a small airgun source is needed, which would be reasonable to deploy with an autonomous vessel (RAM4D), but not with a conventional source vessel.

Conclusions & Outlook
The development of seabed autonomous acquisition systems would enable cost reductions by removing dependence on costly surface vessels, facilitate on-demand data acquisition, be naturally distant from environmental concerns and interference with surface operations, and be resilient to water velocity variations that limit 4D seismic resolution. In the Brazilian pre-salt these advantages would be very welcome.

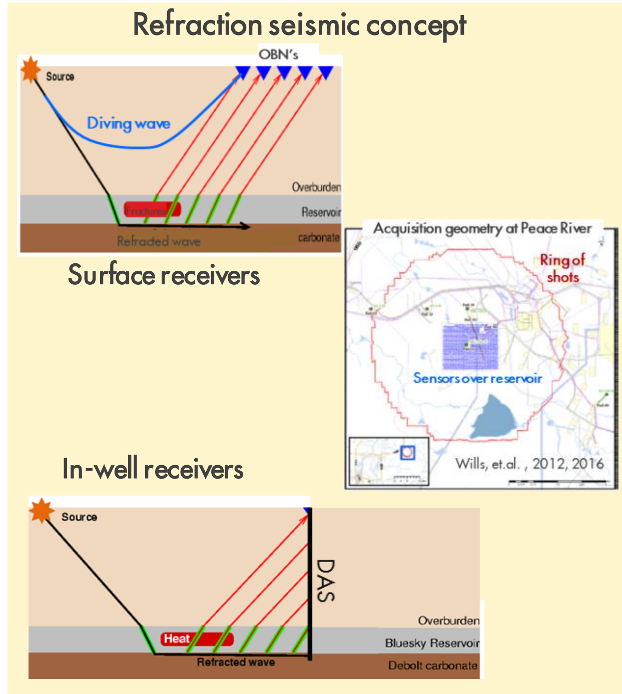

Figure 4: Target oriented refraction seismic geometries from a steam injection project **(Hansteen & Wills, Time-lapse refraction seismic monitoring, 2010)**. Receivers may be placed on the surface or in a well. In our marine application surface receivers would be located on the seabed.

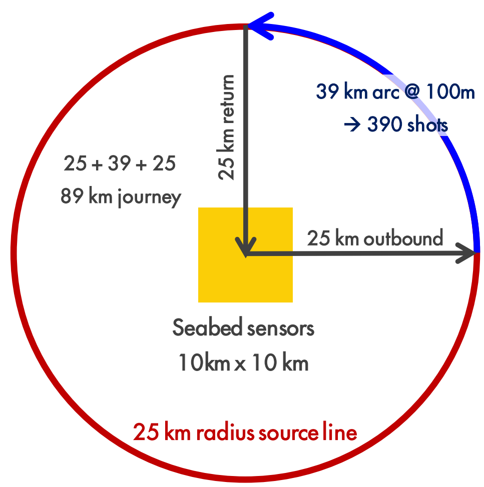

Figure 5: Notional long-offset refraction seismic geometry for targeted-oriented monitoring under a 100 km^2 area of seabed receivers. The survey could be acquired in four subsets with an AUV with 100km/day operational endurance.

The sensor component of the autonomous acquisition systems is developed or being developed. Application to autonomous acquisition may provide new options for deployment. The source component is immature. For seabed source surveys to be feasible, the endurance of the AUV needs to be improved significantly, to at least 100km/day (travelling or shooting), including the time to recharge the AUV and the additional power required to energize the source. A conventional reflection geometry would become possible, but a refraction geometry seems more realistic given the much smaller number of source points required (1,570 vs. 78,400 in our scenarios).

An implementation using an RAUV would face similar issues, compounded by the slower speed of the RAUV and its additional terrain and seabed infrastructure avoiding challenges. The advantages of the seismic source coupled directly to the seabed may motivate this concept further.

In all cases one may consider simultaneous sources to speed up the acquisition, as they would be environmentally friendly, and could operate in “flip-flop” mode during the “move up” time or using coded sequences for deblending.

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