Seismic marine acquisition with autonomous marine vehicles: potential for offshore exploration in Brazil

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Abstract

The use of autonomous systems in marine environment in recent years has increased and covers activities from oceanographic studies, environmental awareness, maritime surveillance, defense, and oil and gas. For oil and gas, the current applications are related to meteorological and oceanographic monitoring, hydrocarbon detection and mapping, subsea communication by means of acoustic modems, and localized real-time geomagnetic surveys. Herein, we discuss an application related to seismic exploration and the potential for Brazil offshore exploration.

Introduction

The autonomous marine vehicle that we use is a Wave Glider™, invented by Liquid Robotics Inc., that harvests waves and solar energy (Moldoveanu *et al.,* 2014). A diagram of the Wave Glider is presented in Figure 1.

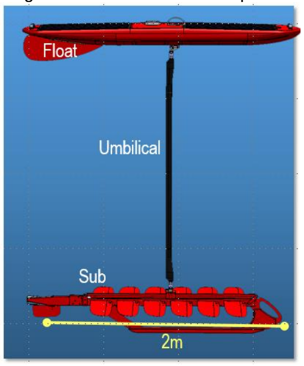

Figure 1 *- Wave Glider components: float, umbilical, and sub; wave energy is converted into a forward thrust.*

The wave motion moves the Wave Glider up and down and this movement is converted into forward propulsion by the submersible wings. Solar power is stored in rechargeable batteries and it is used to power the computer placed inside the float with different sensors used for different applications. For seismic applications, we built a mini-acquisition system and a three-dimensional multimeasurement sensor array (3DSA) that is attached to the Wave Glider sub by means of a decoupling cable (Figure 2).

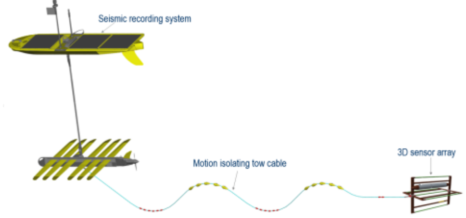

Figure 2 - *The 3D multimeasurement sensor array is connected to the Wave Glider by means of a motion isolating cable; seismic data are transmited to the mini-acquisition system.*

A detailed view of the 3DSA is presented in Figure 3. It consists of a rigid frame that has five arms (green color) placed in a horizontal and a vertical frame. In each arm there are three hydrophones spaced at 50 cm. The gray tube in the vertical plane contains a buoyancy engine and inertial motion sensors to measure array orientation: three-axis accelerometers, three-axis gyroscope, three-axis magnetic sensor, and a depth sensor. The yaw, roll, and pitch are measured every second and transmitted to the acquisition system located in the Wave Glider float. Seismic data are continuously recorded.

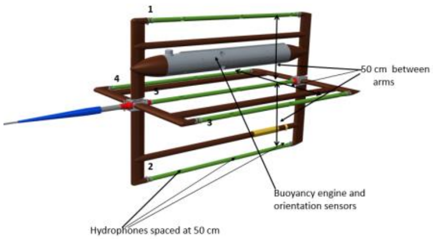

Figure 3 - *Three-dimensional hydrophone sensor array with 15 hydrophones spaced at 15 cm in X, Y, and Z directions.*

The 15 hydrophones and the 3D array geometry allow us to calculate the first and second derivative of the pressure; these multimeasurements can be used in data processing for different applications.

3D sensor array positioning is based on the GPS receiver positioning of the float and on the orientation and depth measurements.

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We performed field experiments that allowed us to evaluate seismic data quality acquired with 3D sensor arrays towed by Wave Gliders vs. conventional streamers and ocean-bottom cable (OBC) data.

Field experiments with Wave Gliders towing 3D sensor arrays

The comparison with OBC data was performed with a limited number of Wave Gliders during three OBC surveys performed in three different geographical areas: the Arabian Gulf (2015), the North Sea (2016) and the southern Gulf of Mexico (2017).

The experiment in the Arabian Gulf was done during an OBC survey acquired in a shallow-water, 20- to 25-m water depth, and with a hard water bottom. It was an orthogonal acquisition geometry with eight receiver lines, 10,000-m receiver line length, 400-m interval between receiver lines, 25-m receiver station interval, 10,800-m source line length, and 100-m source line interval (Figure 4a). Two source vessels were used, each with a dual source array, and 50-m crossline separation. The shot interval was 25 m (flip-flop). Three Wave Gliders equipped with 3D sensor arrays were deployed inside the source patch, on top of the OBC receivers. The 3D sensor arrays were separated by 400 m in both directions (Figure 4b). The data were acquired while shooting two source patches for six days. The Wave Gliders were programmed to hold station by moving in a small circle around the station location. The blue dots in Figure 4b represent the locations of the Wave Gliders during seven acquisition days. The average circle radius around each preplot receiver station for each Wave Glider was 27.1 m, 18.0 m, and 17.1 m (shown in red). The desired depth for the 3DSA was 10 m and the average depth achieved was 9.93 m.

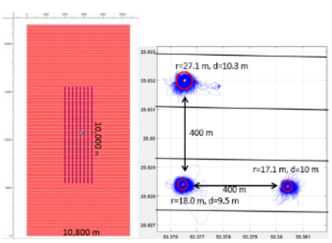


Figure 4 *- (a) OBC source patch (red) and receiver patch (blue); (b) Deployement of three Wave Gliders on top of the OBC receiver patch.*

The data quality evaluation was performed by comparing common receiver gathers from OBC and 3D sensor arrays recorded at the same locations, and limited offset 3D stacks. The comparison with OBC is only for the hydrophone data.

Each shot recorded in a 3D sensor array has 15 traces, corresponding to 15 hydrophones. Most of the processing steps are performed in common-receiver gathers (CRG), similar to OBN processing. A CRG is generated for each hydrophone and contains the shots from a single source line. In Figure 5, we show 3D unprocessed sensor array data from a CRG corresponding to one hydrophone and one shot line. The typical swell noise dominates the record, as the 3D sensor array is deployed at a 10-m depth. In Figure 6, we show a comparison between an OBC CRG with a 2-Hz low-cut filter applied in the acquisition system and 3D sensor array CRG after swell noise was removed. A singular-value decomposition-type algorithm was used to evaluate the swell noise and subtract it from the data (Moldoveanu, 2011). Scholte wave energy is quite strong on the OBC CRG because it propagates along the water-bottom interface. Evanescent Scholte waves propagate through the water layer with exponentially decaying amplitude and are recorded at the 3D sensor array hydrophones with weaker amplitudes. Direct arrivals, refracted waves, and seismic interferences from the far source are visible on both CRG gathers.

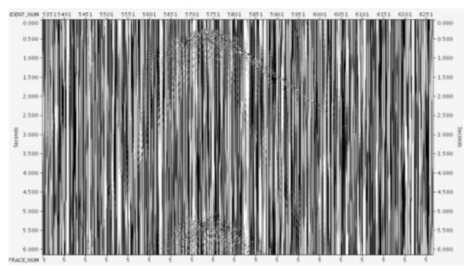
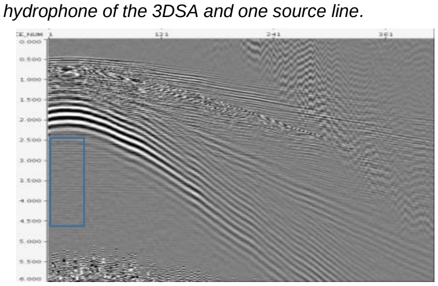
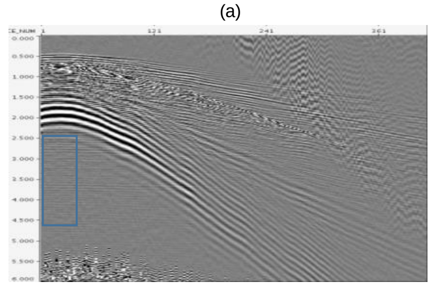


Figure 5 *- Raw (unprocessed) CRG gather for one hydrophone of the 3DSA and one source line.*



(a)



(b)

Figure 6 - *Comparison of OBC CRG (a) vs. 3DSA CRG (b), after swell noise was removed from 3DSA data.*

The experiment in the North Sea was conducted during an OBC survey in a 152-m water depth. A single Wave Glider towing a 3D sensor array was deployed on top of the OBC receiver spread and a full shot patch was acquired (Figure 7).

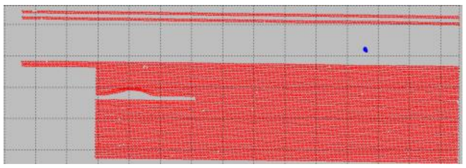
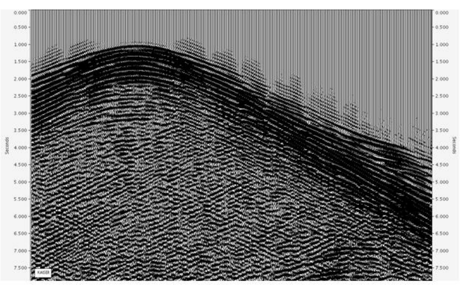
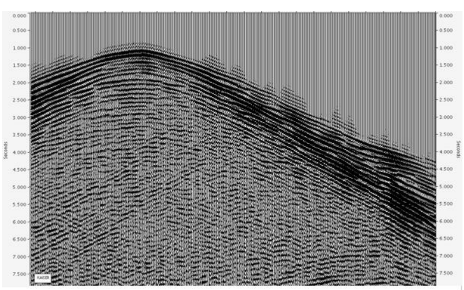


Figure 7 *- The Wave Glider location (blue) and shot locations (red); the Wave Glider was above the OBC receiver.*

A comparison of the common-receiver gather from the OBC survey and from the common-receiver gather generated from Wave Glider data for the same shot line is shown in Figure 8, for a 3- to 10-Hz seismic bandwidth. As the OBC receiver is laid on the ocean floor, the noise related to seafloor conditions in an active oil field is higher than on 3DSA data that was deployed 12 m below the sea surface.



(a)



(b)

Figure 8 *- CRG from OBC data (a), and CRG from 3DSA data (b), for 3- to 10-Hz bandwith: similar signal energy but less ambiental noise related to seafloor infrastructure on 3DSA data.*

Both experiments proved the following:

- Data quality acquired with 3D sensor arrays and OBC were comparable in terms of signal-to-noise ratio and frequency content.
- Field operations were successful in terms of deployement and retreival, holding station, and moving the Wave Gliders from one point to another when this was required.

The comparison with towed streamer was conducted with 20 Wave Gliders deployed along a 2D line and a streamer vessel towing two streamers, 2 km in length. The interval between Wave Gliders was 300 m. The streamer vessel sailed paralell with the Wave Glider line at a 100-m crossline distance (Figure 9). The total length of the streamer line was 22 km. The shots generated by the source on the streamer vessel were recorded by 3D sensor arrays and the streamers.

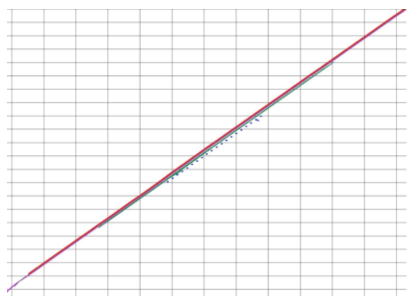


Figure 9 - *20 Wave Gliders (blue dots) deployed at a 300-m interval; the streamer vessel towing two streamers 2 km in length sailed parallel with the Wave Glider line.*

A comparison between the stack sections from streamer data and 3DSA data is shown in Figure 10. The stacks were generated from the same offset ranges and the same number of recievers.

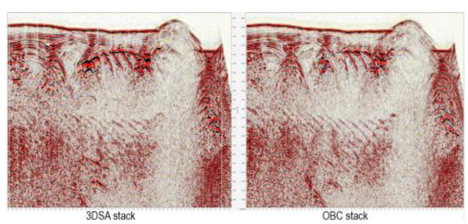


Figure 10 - *Stack comparison of data acquired with 3DSA (left) and towed streamer (right).*

This experiment proved that data quality acquired with 3DSA towed by Wave Gliders is comparable with streamer data in terms of frequency content and signal-to-noise ratio.

Processing aspects of 3D sensor array data towed by Wave Gliders

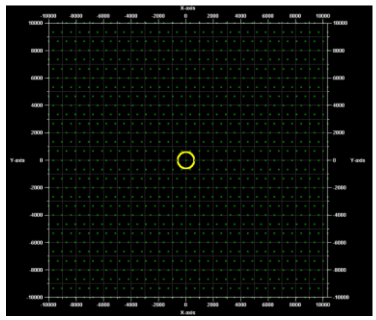
Processing data recorded with the 3D sensor array is performed in the CRG, as is typically done for node surveys. A typical processing sequence could include harvesting the shot data from continuous data, merging the shot positions into 3DSA data, positioning QC based on pressure gradient estimations, sorting the data in common receiver gathers, swell noise attenuation, source signature shaping, sorting the data in shot domain, receiver deghosting based on pressure gradients, summing of the 15 hydrophones to improve the signal-to-noise ratio, data sorting to CRG, source deghosting, surface-related multiple attenuation, velocity model building, and depth or time imaging.

One distinct difference between node acquisition and 3DSA towed by Wave Glider acquisition is that the node location is fixed for the duration of the acquisition, while for the Wave Glider, we do not have a fixed location because the Wave Glider moves in a small circle around the station, if so desired. Knowing the location of the 3DSA at any time, it may be possible during the processing to relocate the 3DSA data to the desired location using the pressure gradients derived in X, Y, and Z directions. This processing capability addresses the issue of receiver repeatability for 4D studies.

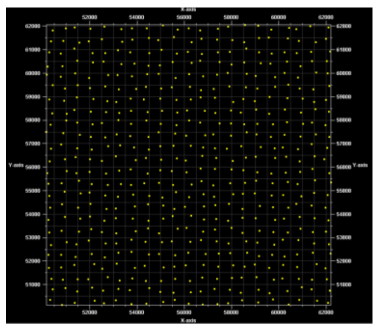
Survey design aspects for 3DSA towed by Wave Glider acquisition

Seismic acquisition with 3D sensor arrays towed by Wave Gliders opens new possibilities for marine acquisition due to Wave Glider capabilities to navigate, at a slow speed, in a circle around a defined "holding" station and to move along a predefined path. Based on these features, different acquisition geometries can be implemented. Ocean-bottom node-type geometry implemented with 3DSA towed by Wave Gliders has the main benefit that it does not require a remote operating vehicle for node deployment and retrieval. Once all the shots are acquired for a given source patch, the Wave Glider (receiver) patch will move to a new patch location. This has the potential to significantly reduce the operational cost.

A novel type of geometry can be defined by considering a patch of Wave Gliders towing 3D sensor arrays that could be stationary at one location, recording data for a period of time and, after that, moving to the next location along a predefined path. (Muyzert, 2013). The sources can be in the center of the receiver patch distributed in a circle, and both the dimension of the receiver patch and the receiver sampling inside the patch are calculated based on the required fold and maximum offset. A source patch must be defined to cover the subsurface target area where we plan to acquire full-azimuth data with the required maximum offset. The number of centers of the source circles and the interval between circles are determined based on the required fold. Examples of the receiver patch and the source circle in the center of the patch are shown in Figure 11a, and the centers of the source circles, for the entire survey area, are displayed in Figure 11b. The receiver patch will move from center to center to cover the entire source patch. The main benefits of this type of survey design vs. a regular node-type survey design are more uniformity in offset and azimuth distribution and reduced operational cost.



(a)



(b)

Figure 11 *- (a) Receiver patch (green dots) and source circle (yellow), (b) centers of the source circles (yellow dots). The receiver patch will move from center to center and record the data generated along the source circles.*

Potential of Wave Glider seismic acquisition for offshore exploration in Brazil

Acquisition with 3D sensor arrays towed by Wave Gliders could have applications in areas where seismic data quality acquired with OBN or OBC systems is not adequate due to the seafloor conditions or in very deep waters where the ocean-bottom systems cannot be deployed. Another potential application is to complement towed-streamer acquisition by efficiently acquiring seismic data around obstructions, and long and ultra-long offsets.

Acquiring data under an obstruction during towed-streamer surveys requires an additional source vessel. This could be costly and also there are limitations in the minimum near offsets that can be acquired due to restricted streamer vessel access around platforms. The Wave Gliders can be deployed much closer to the platforms and this could be very beneficial for acquiring data under the platforms, particularly for 4D surveys. Joint processing of towed-streamer data and 3DSA data is straight forward, as both systems are based on hydrophone measurements.

Another very useful application could be to acquire 3DSA data during a 3D vertical seismic profile (VSP) or a walkaway survey. We performed a 3D finite-difference seismic modeling and reverse time migration (RTM) imaging study to simulate acquisition with Wave Gliders towing 3D sensor arrays during a 3D VSP survey. A patch of 42 Wave Gliders was placed around the well where the 3D VSP tool was deployed and recorded the shots distributed along a spiral (Figure 12). The 3D RTM image is presented in Figure 13. This could complement very well the VSP image that is typically confined below the VSP tool, and it can be used to calibrate surface seismic data with borehole data in terms of amplitudes and travel times.

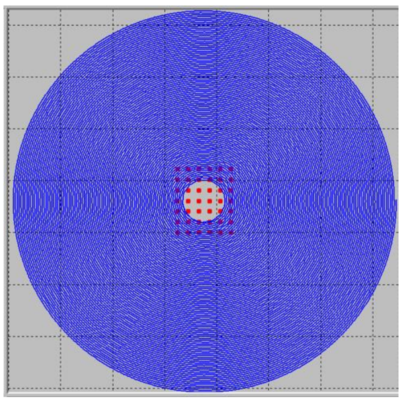


Figure 12 - *The Wave Glider patch (red) is deployed around the well in the midle of the spiral.*

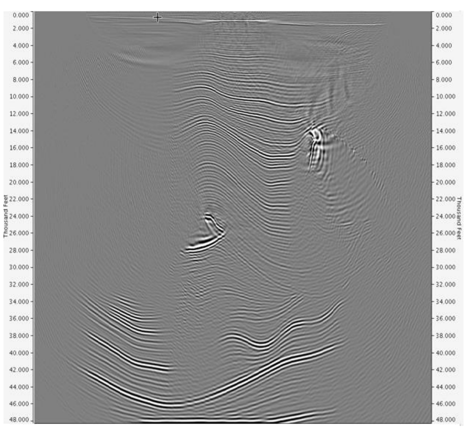


Figure 13 - *3D RTM depth image of the Wave Glider data acquired during the 3D VSP survey.*

Discussions and conclusions

We demonstrated, using field experiments, that acquiring data with 3D multimeasurment sensor arrays towed by Wave Gliders is operationally feasible and data quality is comparable with OBC and towed-streamer data. We learned that current Wave Glider technology has limitations, particularly in areas where marine currents are strong or where the wave and solar energy is not enough to propel the vehicle and to power the hardware. Operational planing is required to determine the optimum environmental conditions at the survey location. Thus far, we operated a limited number of Wave Gliders. Certain commercial applications of this technology can be performed with a limited number of Wave Gliders. However, for future commercial applications where hundreds of Wave Gliders could potentially be used, we have to consider how the Wave Gliders communicate with each other and with a master vessel, and how the data can be downloaded in a minimum time without affecting production.

The multihydrophone measurements open new possibilities in signal processing and in imaging 3DSA data, such as receiver deghosting, detecting the direction of the seismic arrivals, QC of the positioning based on seismic data, wavefield interpolation or extrapolation, and vector acoustic imaging (Vasconselos, 2013).

Acknowledgements

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