Staggered marine acquisition design for complex imaging.

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Summary

We present a new staggered acquisition geometry aimed at providing improvements to complex imaging of the subsurface, such as subsalt in the Gulf of Mexico. The proposed design is a linear acquisition geometry that improves offset and azimuth distribution compared to pre-existing wide azimuth acquisition techniques and generates extra-long offset of up to 18 km. It also includes a broadband solution, by towing streamers with variable depth shape, to provide significant imaging resolution uplift.

Introduction

Areas with complex structure, such as subsalt in the Gulf of Mexico, require new-generation acquisition.

The WAZ acquisition geometry and evolution of processing techniques have allowed us to significantly improve the quality of imaging in such areas.

Figure 1 shows the evolution of subsalt imaging by just increasing the crossline offsets, from narrow azimuth to wide azimuth acquisitions, combined with the improvements of imaging technics from one-way wave equation to reverse time migration algorithms.

However, on the right side of the left images in Figure 1, dipping sediments are not well-imaged and create a dim zone at the same location in both images. The imaging resolution of those complex areas can be improved by increasing azimuthal illumination, as proposed, for example, with Orthogonal WAZ (Baldock 2011) and Rich Azimuth Acquisition (Howard 2007).

In this paper we present a new staggered acquisition design, improving spatial and temporal resolution of subsalt imaging, thanks to wider azimuth distribution, extra-long offsets, and a broadband dataset.

Broadband for complex imaging

Complex areas, such as subsalt in the Gulf of Mexico, require enhanced low-frequency content, which are less affected by the attenuation and penetrate deeper. The richness of low frequencies allows greater accuracy and stability for seismic inversion.

Conventional marine streamer acquisition lacks sufficient signal-to-noise ratio in the 2–7 Hz bandwidth due to the

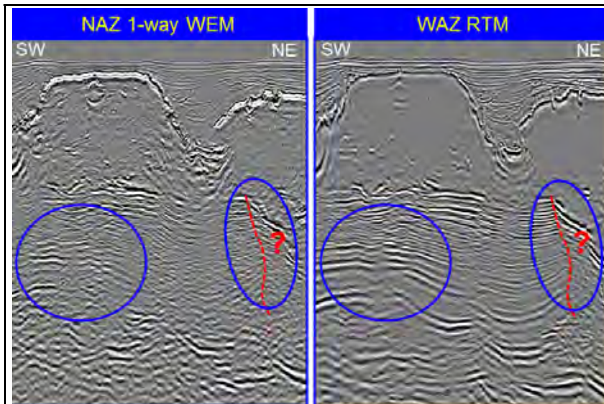

Figure 1: Evolution of subsalt imaging. On the left, a NAZ 2006 dataset and on the right, a WAZ 2009 dataset over the same area. WAZ and RTM significantly improve the quality of imaging. However, some areas are still not well-imaged and require further improvement.

streamer depth, streamer tow noise, source array configuration, source depth, and source bubble.

Variable-depth streamer broadband solution uses variations of the receiver depth to produce receiver ghost notch diversity, allowing the streamer to be towed deeper to improve the low-frequency signal-to-noise ratio without compromising the high frequencies. This ghost notch diversity is exploited to produce a wavelet with both a high signal-to-noise ratio and maximum bandwidth (Soubaras 2010). With this technique, signals can be recovered down to 2.5 Hz, providing three octaves of data below 20 Hz.

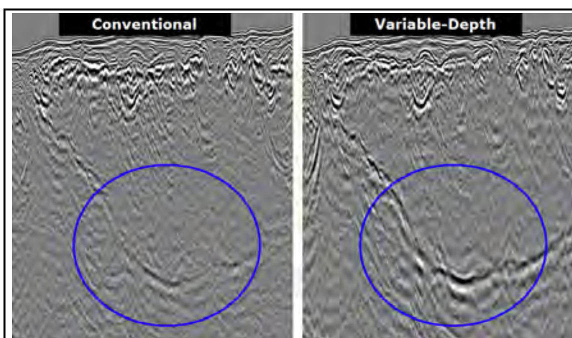

Figure 2: On the left, conventional marine streamer acquisition RTM Saltflood image (20 Hz) over Alaminos Canyon in Gulf of Mexico. On the right, improvement achieved with a variable-depth streamer broadband solution.

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A 2D line was acquired over Alaminos Canyon in the Gulf of Mexico. The data (in Figure 2) shows significant improvement over the conventional marine streamer acquisition.

In consequence, the staggered acquisition we propose is designed to be compatible with variable depth broadband technique.

Long offsets for complex imaging

Typical WAZ acquisition provides up to 10-km offsets. Longer offsets are expected to provide benefits for illumination as well as more accurate high-resolution velocity models with full waveform inversion.

An acoustic modeling exercise done using SEG SEAM model of Gulf of Mexico (Figure 3) compares results using 8-km offsets (on the left) versus 16-km offsets (on the right). The longer offset bring improvements in the definition of subsalt structures and continuity of the events.

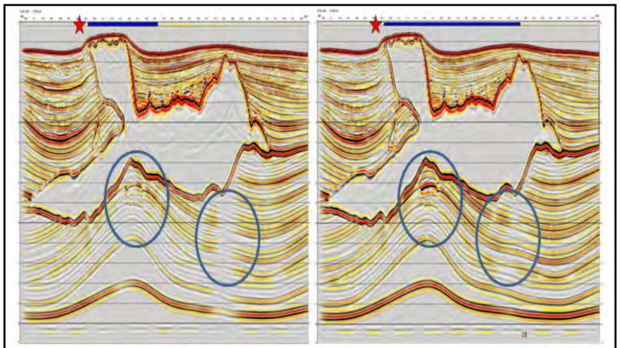

Figure 3: 16-km offsets (right) provide improvement on the imaging compared to the 8km offsets model (left).

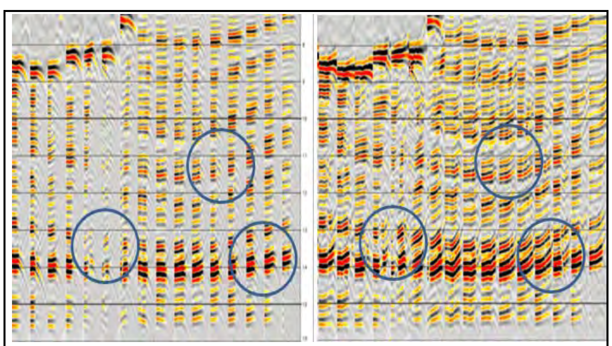

Figure 4: Modeling using SEAM model with a 5% velocity error. The subsalt velocity error is clearly seen on gathers with 16-km offsets (right), while difficult to notice on the gathers with 8-km offsets (left).

To evaluate the improvement brought by long offsets in velocity modeling, we apply a 5% error to the exact model. We can then evaluate how this error affects gathers with a 8-km versus 16-km offset. Figure 4 shows gathers with 5% error with 8-km (on the left) and 16-km (on the right) offsets. The subsalt velocity error is clearly seen on gathers with 16-km offsets, while the error is hardly visible on the gather with 8-km offsets.

A design that provides extra-long offsets will help for both illumination as well as accurate velocity model building.

Staggered acquisition design

Following the above analysis, a new acquisition design must provide improvement in azimuth distribution, longer offsets of up to a minimum of 16 km, and compatibility with the variable depth broadband technique.

The design proposed consists of a 5-vessel configuration: 2 streamer/source vessels and 3 source vessels (Figure 5). The vessels are staggered in the inline direction.
The position of each vessel and the overall size of the pattern is a function of the spread width and length. The values indicated are representative of a configuration of 10 x 120 m x 9 km spread, providing an overall pattern of 18 km x 6 km.

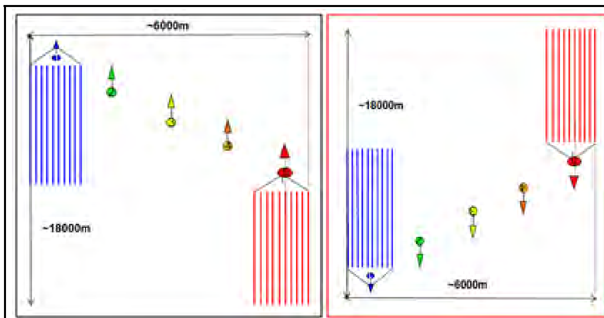

Figure 5: Acquisition is antiparallel and orthogonal.

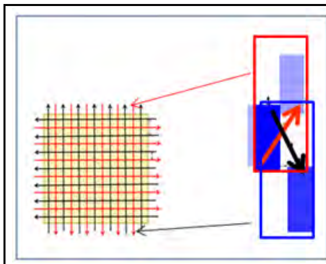

Figure 6: Staggered vessel configuration in each direction.

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The acquisition is antiparallel and orthogonal as shown Figure 6. The relative position of the vessels is different for each sail line direction, with the port vessel in front of the spread in one direction at the tail of the spread in the other direction. This provides a variety of azimuth distributions in the super shot gather and allows us to take advantage of the reciprocity principle (symmetry provided by the reciprocity of sources and receivers).

The maximum offset achievable and the azimuth distribution will be a function of the spread length and width.

Considering a 10 x 120 m x 9 km spread, the staggered geometry provides 4 axes of very long offsets of up to ~18 km and a full azimuth distribution up to ~9 km (assuming source-receiver reciprocity).

Figure 7 represents offset and azimuth for a super shot gather (1,200 m x 1,200 m in this case) achieved with the staggered configuration. The color level represents a relative number of traces in each quadrant. Figure 7a) shows the offset and azimuth distribution for a sail line acquired in the North-South direction and a sail line acquired in the East-West direction. Figure 7b) shows the distribution when combined with the antiparallel acquisition. Figure 7c) includes the reciprocity principle. By reciprocity, a trace in the positive quadrant provides the same illumination as its symmetrical trace in the negative quadrant. In Figure 7c), shot and receiver locations for negative offset Y are swapped to positive offsets, restricting the azimuth to a range of 180°.

In terms of data processing, an important aspect of this design is the uniformity of the coverage and regularity of the offset and azimuth distributions. Acquisition based on straight navigation lines has an intrinsic homogenous spatial distribution of bin coverage. Figures 8 and 9 show the map of offset distribution per bin. The homogeneity between all bins favors an efficient regularization during processing.

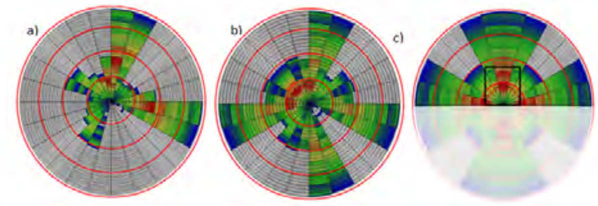

Figure 7: Azimuth and offset distribution for a) North-South lines, b) East-West lines, and c) combination. The red circles represent 5 km, 10 km, 15 km and 20 km offsets. Figure 7c) includes the reciprocity principle. The black rectangle represents what would be covered by a conventional WAZ geometry.

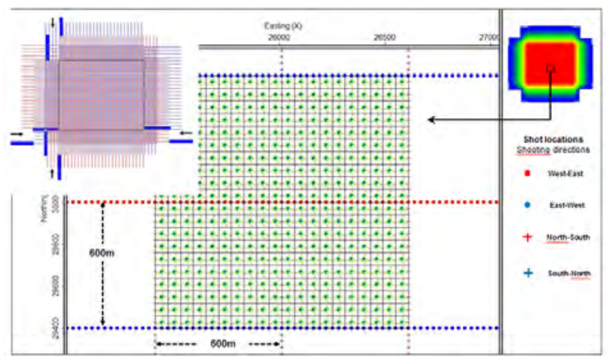

Figure 8: Map of offset distribution per 60 m x 60 m bin.

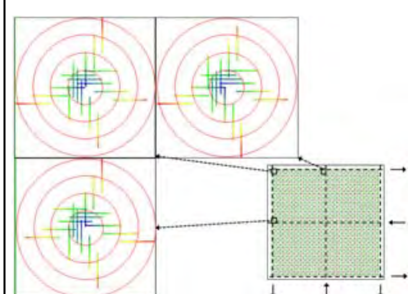

Figure 9: Offset distribution in selected 60 m x 60 m bins.

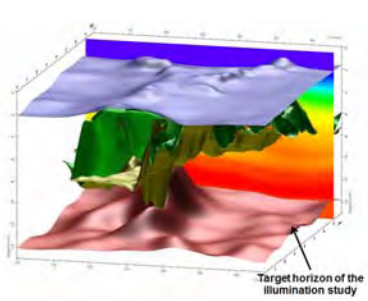

Figure 10: Model used for ray tracing.

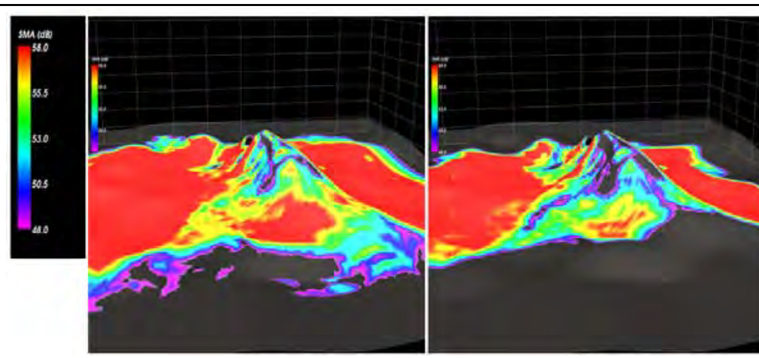

Figure 11: Illumination map with staggered configuration (left) and orthogonal WAZ (right).

To validate the design, a first study of the illumination on deep targets under typical GoM salt domes was done using the SEAM model and ray tracing by wavefront reconstruction. The results (as shown in Figure 10) were compared between the staggered configuration and an orthogonal WAZ (i.e., a conventional WAZ shot in two perpendicular directions).

Further acoustic modeling confirmed that the proposed design enabled improvement of complex subsalt imaging (p.c. Beng S. Ong, C.O. Ting 2013). An acquisition with staggered setup is currently underway in the Gulf of Mexico, and the first results of FWI illustrate the benefits of this broadband staggered acquisition (Sabaresan 2013).

Operational challenges

The main challenge for the staggered acquisition design is to turn the whole fleet at the end of a sail line in a safe manner and efficiently optimize production time.

In conventional WAZ, line changes were usually performed in a “cloverleaf” shape such that vessels are moving to an adjacent sail line. Acquiring conventional WAZ acquisition in swath mode significantly lengthens turns: since all vessels are aligned, significant safety distances must be maintained to avoid risk of collision.

The staggered acquisition design has the advantage that each vessel can start her turn one after the other, allowing acquisition in swaths and improving efficiency of the turns compared to conventional WAZ.

When the vessel in front has completed her run-out, i.e., the distance beyond the survey boundary where the vessel’s source still contributes to full-fold, she can start turning while other vessels are completing their production line. Subsequent vessels also start turning when they no longer contribute to the full-fold area, increasing the distance between vessels and the margin of safety.

This provides flexibility in the way the line changes can be performed. To optimize acquisition time, various line change scenarios were pre-defined as a function of the turn direction (port or starboard) and in anticipation of the effect of currents and feather.

These line changes require very clear communication within the fleet as deviation from the plan from any vessel would necessitate extension of line change and loss of productivity.

An acquisition with a staggered setup has been in progress in the Gulf of Mexico since 2012. Results show a significant reduction of line change time compared to a standard WAZ. This makes the staggered design a cost-efficient solution.

Conclusions

The proposed acquisition geometry with staggered vessels provides additional offsets and azimuths, combined with the variable depth broadband acquisition.

The improved azimuth distribution provides better illumination and multiple attenuation. The extra-long offsets improve the imaging of steep dips and increase the accuracy of subsalt velocity allowing the estimation of a more accurate salt model. The penetration of long offset energy also provides stronger and continuous subsalt reflectors.
In addition, the introduction of a broadband solution with variable streamer depth into the staggered design allows the acquisition and processing of reliable low-frequency data down to 2.5 Hz with high signal-to-noise ratio and greater stability for seismic inversion.

The straight navigation lines of the staggered design allow regular fold and provide rich offset and azimuth distribution. This proposal benefits the compatibility with existing WAZ processing algorithms for better turnaround and makes it suitable for future development and 4D surveys: it can easily be repeated and interleaved to finer sail lines.

From an operational point of view, the proposed acquisition scheme, compatible with existing techniques of continuous recording and streamer fanning, is also suitable for future developments such as simultaneous sources. In addition, this design offers optimized line change downtime.

Acknowledgments

We thank CGG for permission to publish these results.
We also acknowledge Mike Meech, Bill Skinner, Thomas Mensch, Damien Grenier, Jean-Pierre Dégez, Corinne Sagary, and Robert Soubaras for their input and contribution to this work.

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Paper to be submitted at SEG 2013
3D modeling of a staggered ultra-long offset and full-azimuth acquisition
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