The challenges of imaging beneath the complex salt canopies of the Gulf of Mexico and other areas of the world are well known. The complex wavefronts generated by the anisotropic velocity regimes and high reflection angles in these areas cause problems with illumination and also create complications in imaging. The absorption properties of the salt boundaries and heterogeneities within the salt mean that only the lowest frequencies penetrate to the structure beneath, causing a loss of resolution.

Impressive advances in illumination have been made by the rapid increase in the availability of wide-azimuth data, and advances in velocity modelling and imaging algorithms in recent years to handle complex arrivals and anisotropy have helped to clarify many subsurface structures. However, in some areas the subsalt is still not well-imaged and dim zones occur, both of which can be improved by increasing offset length and azimuthal illumination. In this article we will demonstrate how a full-azimuth, long-offset broadband acquisition using a staggered vessel configuration (StagSeis), provides enhanced illumination, velocity models, multiple attenuation, penetration and resolution.

Broadband for improved resolution

Extension of the frequency spectrum to lower frequencies, thanks to recent developments in broadband acquisition techniques, has been shown to improve the resolution of subsalt data. The curved variable-depth streamer broadband acquisition solution uses differences in receiver depths 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. The technique capitalizes on the extremely good signal-to-noise characteristics and low frequency response of solid streamers (Dowle, 2006) to provide the lowest-frequency recorded signal. The ghost notch diversity is exploited by proprietary deghosting and imaging techniques (Soubaras, 2010), to produce a wavelet with both high signal-to-noise ratio and maximum bandwidth.

The use of variable-depth streamers, combined with mirror migration and joint deconvolution was successful in improving penetration below the salt for a 2D line acquired over Alaminos Canyon (Figure 1). Mirror migration has the added benefit of providing double illumination of the subsurface and so increasing the data sampling. In areas with complex salt overburdens, high frequencies are easily absorbed, so that the only option for improving resolution, by increasing the number of octaves of signal recorded, is to broaden the spectrum at the low frequency end. The proprietary deghosting, that is an integral part of the curved variable-depth streamer solution, is performed in image space and so is fully 3D and therefore completely compatible with wide-azimuth acquisition; two proprietary broadband wide-azimuth surveys have already been completed using this technique.

The use of curved variable-depth streamers has been proven to provide optimal low frequencies, due to the increased depth of the streamers, so that frequencies down to 2.5 Hz are regularly recorded, without compromising the high frequencies. This is because the increased streamer depth provides improved low-frequency signal-to-noise ratios, while the receiver ghost notch diversity avoids loss of high frequencies. Although low frequencies are required for subsalt penetration, high frequencies provide the detail necessary for accurate velocity modelling in the near-surface and the resolution necessary for detecting shallow hazards, such as gas pockets and methane hydrates. The six octaves of bandwidth provided by variable-depth streamer acquisition produce sharp wavelets with minimal sidelobes, reducing interpretation confusion, enhancing the fine stratigraphic detail and clarifying impedance contrasts.

As well as increasing penetration, the extra low frequencies shape the larger-scale impedance variations, providing clear differentiation between sedimentary packages and increasing confidence in correlating interpretation across faults and other major structural features. The increased bandwidth and resolution provide a step-change in seismic stratigraphy allowing increased understanding of lithology and fluid effects in the data. The improved low frequencies also provide greater accuracy and stability for quantitative seismic inversion.
Figure 1 Comparison of a 2D conventional RTM saltflood image (20 Hz) over Alaminos Canyon in the Gulf of Mexico (left) and the improved image achieved with a variable-depth streamer broadband solution (images courtesy of CGG Data Library).

Figure 2 16-km offsets (right) provide improvement on the imaging compared to the 8km offsets model (left).
Long offsets and full azimuths for complex imaging

Longer offsets provide benefits for illumination as well as more accurate high-resolution velocity models, derived using full waveform inversion. Typically wide-azimuth acquisition provides up to 8 km offsets. Acoustic modelling using the SEG SEAM model of the Gulf of Mexico compared results using 16 km offsets with those using 8 km offsets. The longer offsets provide significant improvements to the definition of subsalt structures and continuity of events (Figure 2). By applying a 5% error to the exact model, it was shown that the use of longer offsets provided great improvements in sensitivity for velocity modelling. The subsalt velocity error is hardly visible on gathers with an 8 km offset, but is clearly seen on the gathers with 16 km offset (Figure 2). Long offsets may also be able to undershoot the complex salt geometry, so better illuminating the subsalt target area, and also help to provide better images for steeply dipping subsalt structures, such as the three- and four-way closures that are much sought in the Gulf of Mexico. In addition, long offsets help to reduce multiple contamination, which is recognized as a hindrance to providing clean subsalt images.

Modelling studies have shown that improved images can be obtained from data that have greater azimuthal coverage as well as longer-offset coverage (Cvetkovik et al., 2011). Poor illumination due to the complex geometry of the overlying salt canopies has always been an obstacle to the quality of subsalt imaging. Typical methods of improving the azimuthal coverage include shooting in precessing circles or combining multiple wide-azimuth acquisitions with different shooting directions, but these methods still tend to have limited offset ranges and generally produce irregular bin-fold with significant redundancy in near-offset coverage.

Other geophysical factors, such as dominant frequency and sampling, also play important roles in subsalt imaging. In addition, various operational issues for this type of long-offset, full-azimuth acquisition geometry need to be considered. It is necessary to determine the survey size, shape, line changes, run-in, run-out, cable noise, number of sources, etc. in order to optimize the cost while maximizing the sampling and data quality, and so make such an acquisition a viable proposition.

Staggered acquisition design

In the light of these factors, it was considered that an acquisition design combining improvements in azimuth distribution, offsets of at least 16 km and compatibility with variable-depth streamer broadband acquisition would provide a considerable enhancement to subsalt imaging in complex areas such as the Gulf of Mexico.

The acquisition design selected consists of a five-vessel configuration – two multi-streamer, single-source vessels and three additional source vessels (Figure 3), with the vessels being 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 acquisition is antiparallel and orthogonal, with the relative positions of the vessels being different for each sail line direction, providing a variety of azimuth directions in the super-shot gather, and allowing us to take advantage of the reciprocity principle to maximize the

![Figure 3](image-url)
Validation by modelling

Modelling comparisons to study the effect of this acquisition design on the illumination of deep targets under typical Gulf of Mexico salt structures were performed by using the SEAM model and ray-tracing by wavefront reconstruction. The results, shown in Figure 5, demonstrate the improvements in illumination achieved by the staggered configuration when compared with that achieved by orthogonal wide-azimuth acquisition (conventional wide-azimuth shot in two perpendicular directions).

Figure 6 compares the reverse time migration (RTM) images between the baseline conventional wide-azimuth and the staggered acquisition at a highly challenging location. The subsalt target inside the circled area is strongly contaminated by multiples, and the structure is barely visible in the baseline conventional WAZ image, whereas the image obtained with staggered acquisition is able to attenuate this noise and identify a potential prospect. The blue arrow indicates the crest of another structure whose image is improved by staggered acquisition.

The main challenge for the staggered acquisition design is turning the whole fleet at the end of each sail line in a safe and efficient manner. Compared with conventional wide-azimuth acquisition, the staggered acquisition technique has an advantage in that each vessel can start to turn in succession, as soon as they no longer contribute to the full fold area, while the vessels behind are still completing their production line. This allows acquisition in swaths without the lengthy turns required to maintain safe distances between vessels when they are aligned, and so improves efficiency when compared with conventional wide-azimuth. In the staggered acquisition that has been deployed in the Gulf of Mexico since June 2012, significant reductions in line change azimuth distribution. The maximum offset and azimuth distribution achievable is a function of the spread length and width.

For the first survey acquired using this technique, the Gulf of Mexico CGG multi-client IBALT (Integrated BroadSeis Acquisition and Long Tow) survey, each streamer vessel towed 10 x 9 km streamers at a separation of 120 m, providing an overall spread of 18 km x 6 km. The staggered geometry provides four axes of very long offsets, up to 18 km, and full-azimuth distribution (assuming source-receiver reciprocity) up to 9 km.

Regular fold, offset and azimuth coverage

Figure 4 shows different methods of representing the offset and azimuth distribution achieved with the staggered configuration. The rose plot shows the number of traces recorded in different offset bands within azimuth sectors, with and without applying the reciprocity principle. By reciprocity, a trace in the positive quadrant provides the same illumination as its symmetrical trace in the negative quadrant, so that shot and receiver locations for negative offset Y are swapped to positive offsets, restricting the azimuth to a range of 180°.

Although rose diagrams are a familiar way of looking at offset and azimuth distributions, they are of limited use, as they can be manipulated by changing the area covered and the azimuth sector size, and give little indication of the range of offsets and azimuths in any given processing bin. The map of the offset distribution in the 60 m x 60 m processing bins demonstrates the major benefit of this acquisition technique, in that there is regular and consistent fold, offset and azimuth distribution from bin to bin. This homogeneity of coverage between all bins favours efficient regularization during processing and avoids the irregular coverage and data redundancy created by some other patterns.

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times have been achieved compared to a conventional wide-azimuth survey, making the staggered design a cost-effective solution for such a large fleet.

The first survey to be acquired by this staggered acquisition technique, IBALT, covered 221 full fold GOM licence blocks over the Keathley Canyon area (Figure 7) and was acquired between July and December last year, with some initial fast-track processing results being available in November. About 10% of this survey still remains to be shot, as a drilling rig is currently in the area. When this rig has vacated, the remainder will be acquired. One of the advantages of the staggered acquisition technique is that it can easily be extended and infilled. The staggered acquisition configuration is fully compatible with continuous recording, so providing long record lengths with high shot density. It can also be combined with streamer fanning to counteract feathering and reduce infill requirements.

An advantage of the staggered technique is that it can be used in conjunction with all the recent acquisition developments for optimizing operations, as well as with variable-depth streamers for optimizing bandwidth (in this case the streamer depth varied from 10–50 m in a customized curve) and is easily repeatable for use in 4D.

**Processing**

The linear tow employed in the staggered acquisition configuration, combined with regular offset and azimuth coverage, facilitates efficient processing when compared with some other geometries. This means that full-azimuth data can be processed in a timely manner using standard wide-azimuth 3D algorithms, so reducing the overall timeframe (acquisition and processing) of the survey. Fast-track processed results of the IBALT survey will be available in July of this year, with the final products being available in 2014.

The fast-track processing sequence includes 3D SRME (surface-related multiple elimination) and TTI RTM (tilted transverse isotropy reverse time migration). The preliminary raw imaging results show improved low-frequency penetra-
tion, providing stronger amplitudes and greater continuity through the salt, as seen in Figure 8, as well as considerably better illumination (Figure 9) than was achieved by the previous Garden Banks wide-azimuth dataset. A depth slice at 2000 m shows a marked increase in the resolution and bandwidth of the top salt (Figure 10).

The long offsets and low frequencies provided by this broadband staggered acquisition technique are ideal for full waveform inversion (FWI) to derive detailed velocity models for improved imaging. The benefits of low frequencies for towed-streamer FWI have been demonstrated in the North Sea (Jupp et al., 2012). The benefits of full azimuths and long offsets for determining the velocities of the complex overburden in this area of the Gulf of Mexico area were investigated on the IBALT dataset. Tests showed that use of the longer offsets provided velocity updates that were more characteristic of the geology, and did not have the induced oscillation that was present when the offsets were limited to those typical of a conventional wide-azimuth spread (7.5 km inline and 4 km crossline). Comparing results using only the north-south shotlines with those from using both the north-south and the east-west shotlines (full-azimuth), it was observed that the velocity derived from the limited-azimuth spread suffered from an acquisition footprint that was not visible on the full-azimuth data. Comparing the FWI updated model using the full-azimuth data with the initial model after three iterations of tomographic updates shows spectacular correlation between the velocity and seismic data after FWI (Figure 11).

The full-azimuth information also enables detailed anisotropy analyses to be performed for use in tilted orthorhombic imaging algorithms, which have proved successful in enhancing subsalt imaging in the Green Canyon area (Thomas, Mothi, 2012). Figure 12 shows how the direction of fast velocity and azimuth anisotropic epsilon derived from the staggered acquisition data match the seismic amplitudes. Tilted orthorhombic model building and FWI will be considered for the final processing sequence.

**Conclusion**

The staggered acquisition technique combines all the recent advances in marine acquisition to provide full-azimuth, long-offset, broad-bandwidth data in an efficient manner. The improved azimuth distribution provides better illumination as well as improved noise and multiple attenuation. The extra-long offsets improve the imaging of steep dips and increase the accuracy of salt and subsalt velocity models. The penetration of low-frequency, long-offset energy provides stronger and more continuous subsalt reflectors. The broad bandwidth supplied by the variable streamer depth and deghosting algorithms allows the acquisition and processing of reliable low-frequency data down to 2.5 Hz with high signal-to-noise ratios and greater stability for seismic inversion. These low frequencies, combined with the long offsets and full azimuths, provide ideal data for FWI and advanced orthorhombic anisotropy imaging techniques.

The linear tow of the staggered acquisition design provides datasets with regular fold and consistent rich offset and azimuth distribution. It is a practical approach that means the data can be processed using existing wide-azimuth 3D algorithms for faster turnaround and delivery of results for important drilling and development decisions. These datasets are suitable for future development and 4D surveys as they can easily be repeated and/or interleaved to finer sail lines, making them a suitable baseline survey in complex areas.

As yet this acquisition technique has only been applied in the Gulf of Mexico, but it is being considered for other challenging geologic areas in other parts of the world, such
Figure 8 Comparison of existing Garden Banks wide-azimuth data with initial Fast-Track RTM of IBALT staggered acquisition, showing improved low-frequency penetration (images courtesy of CGG Data Library).

Figure 9 Comparison of existing Garden Banks wide-azimuth data with initial Fast-Track RTM of IBALT staggered acquisition, showing markedly improved sub-salt illumination (images courtesy of CGG Data Library).

Figure 10 Staggered acquisition shows a marked increase in the resolution and bandwidth at the top salt over previous wide-azimuth data (images courtesy of CGG Data Library).
as the subsalt plays off Brazil and Angola, the sub-basalt West of Shetlands and the Messinian Unconformity in the Mediterranean. Broad bandwidths, long offsets, and full azimuths will always benefit subsurface imaging; it is up to the geophysicists to convince the asset teams of the value of the accurate images obtained from this state-of-the-art seismic data for reservoir characterization, asset evaluation, and optimized production.

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