Optimal stacking for multi-azimuth pre-stack seismic data

Barry Hung
CGGVeritas
Singapore
barry.hung@cggveritas.com

Yanling Yin
CGGVeritas
Singapore
yanling.yin@cggveritas.com

SUMMARY

Offshore exploration for hydrocarbons in increasingly challenging environments often requires more advanced acquisition methods than conventional 3D narrow-azimuth towed streamer to better image the sub-surface for AVO analysis and reservoir characterization. Multi-Azimuth (MAZ), Wide-Azimuth (WAZ) or Full-Azimuth (FAZ) seismic acquisition overcomes the limitations of the conventional acquisition in better illuminating the sub-surface, suppressing the multiple and enhancing signal to noise (S/N) ratio. Nevertheless, to realize the added value of multi-azimuth data, the data need to be combined in a way that will overcome the issues such as time-shift and amplitude difference due to varied illumination between the surveys.

This paper describes a method that can be used for combining MAZ pre-stack data to generate AVO-preserving common image gathers (CIGs) in the presence of poor illumination. Based on the concept of cross-correlation, MAZ CIGs are first flattened to account for any inaccuracy in the velocity model and imaging process so as to align the events to a pilot. Repeating the cross-correlation process, weights are then derived from the correlation coefficients and applied to individual offsets that take into account the AVO behaviour. With this post-migration processing, any anomaly in AVO resulted from poor illumination can be mitigated. Applying it on MAZ post-stack data, the method can also provide optimal stacking for obtaining higher S/N images.

We demonstrate, through synthetic and real data examples, that clearer images with high AVO fidelity can be obtained from MAZ data using our optimal stacking method.

Key words: Multi-azimuth, stacking.

INTRODUCTION

Conventional narrow-azimuth marine acquisition is known to have difficulties in illuminating sub-surface targets in the presence of complex overburdens such as salt and faults. The ray-bending effect resulting from these velocity overburdens may cause the target illumination to vary significantly with shooting direction. Poor illumination can be detrimental in revealing and characterising hydrocarbon reservoirs. Hence, to improve target illumination, multi-azimuth (MAZ), wide-azimuth (WAZ) and full-azimuth (FAZ) acquisitions have been suggested and demonstrated to be a viable solution (Barley and Summers, 2007).

In addition to improved illumination, marine seismic data acquired with more azimuths can benefit from just stacking the data with higher fold to enhance signal-to-noise (S/N) ratio and multiple attenuation (Keggin *et al.*, 2006). Nevertheless, to maximise the benefits of MAZ data, conventional stacking methods may not be effective because, as mentioned by Manning *et al*. (2008), in the presence of strong noise it is better to exclude noisy samples rather than including in the stack. Moreover, since stacking requires events to be flat across offset in the common image gathers (CIGs), it is important to obtain an accurate velocity model. In the presence of azimuthal anisotropy, the estimation of the velocity model can be a challenging task (Hung *et al*. 2006).

In this paper, we describe a processing workflow for optimally stacking MAZ data by taking into account the inaccuracy of velocity model that is manifested as time statics in the image gathers. We also present a way of preserving the AVO behaviour in the gathers that is not explicitly mentioned in the work of Manning *et al* . (2008). We then demonstrate, with synthetic and a real data example acquired with three azimuths, how our workflow can obtain clearer images with high AVO fidelity for MAZ data.

METHOD

Our approach, summarised in Figure 1, is based on calculating appropriate weights for each azimuth of a MAZ survey that has been migrated (time or depth) before summing the data. The weights are determined by a cross-correlation process between a pilot and each input and the process can be applied on post-migrated stack or pre-stack data. For pre-stack data, it is important to first flatten the image gathers because, at a given image location, gathers from different azimuths can exhibit different residual and non-hyperbolic moveout. Traces from different azimuths of the same image point are interleaved to form a supergather so that the same travel-time will be referenced. The trim statics procedure similar to the one that is described by Hung *et al*. (2006) can be followed which has the capability of handling azimuthal anisotropy.

With the flattened CIGs, the weights for stacking can then be calculated. This is done by computing the cross-correlation coefficients between the pilot, which can be the average sum of all the azimuths or a user input dataset, and each individual azimuth (denote by the subscript *i* in the following) with these equations:

$$a(t) = \sum_i w_i(t)\, a_i(t) \qquad (1)$$

$$w_i(t) = \frac{c_i}{\sum_i c_i} \frac{a_i(t)}{\sum_i a_i(t)} \quad (2)$$

where $w_i(t)$ is the stacking weight for each azimuth at time t, c_i is the maximum cross-correlation coefficient obtained in a time window centred at time t and $a_i(t)$ is the input normalised amplitude. The cross-correlation process is done in a sliding-window fashion in time. As can be seen from Equation (2), there are two components in the determination of the summing weights. The first component is responsible for achieving the best S/N ratio from the MAZ stack; whereas, the second term is to compensate for poor illumination by giving more weight to data that have better illumination. Hence, Equation (2) presents a trade-off between obtaining enhanced S/N ratio and improved illumination in generating an optimal stack for MAZ data. If all the individual azimuths have reasonable S/N ratio, the illumination component of the stacking weights will allow the amplitudes to be better preserved than simply averaging the amplitudes in conventional stack. In fact, if one chooses a suitable pilot in the cross-correlation process, the AVO (amplitude variation with offset) behaviour can be better preserved.

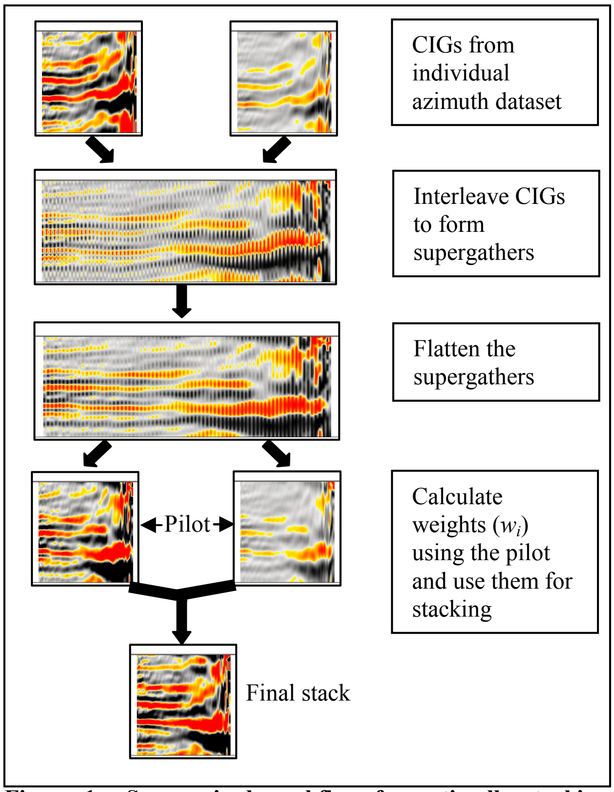

Figure 1. Summarised workflow for optimally stacking MAZ data.

EXAMPLES

We first carried out a synthetic test to verify our approach. Figure 2 displays the 3D velocity model that was used in the test. Four dipping events and a flat event (the bottom event) are present in the model with a localized velocity perturbation in the shape of rhombus situated above the flat event. The amplitude of each event is constant. The variation in velocity is spatial invariant in the crossline direction. The velocity perturbation is meant to create an azimuthal variation in illuminating the flat event.

Two acquisition configurations were simulated – one shooting along the inline direction (dip direction) which we denote as azimuth A and the other along the crossline direction (strike direction) which we denote as azimuth B. As can be seen from the modelled seismic data in Figure 3(a) where we plotted an amplitude map of the bottom event for azimuth A, the velocity anomalous body causes the event to be illuminated differently at different locations resulting in a non-uniform amplitude pattern recorded by the receivers. However, for azimuth B acquisition, the event is fairly evenly illuminated because the change in velocity is spatially invariant in this direction; hence, the recorded amplitude is largely uniform as depicted in Figure 3 (b).

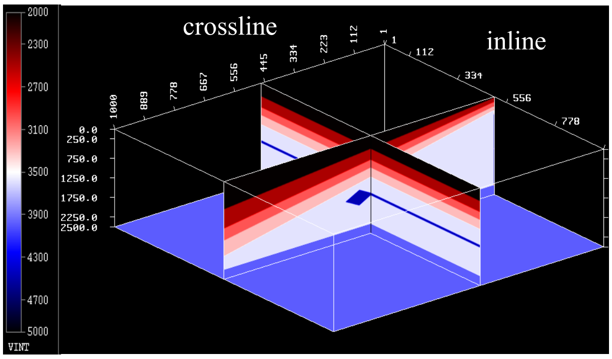

Figure 2. Velocity model for the synthetic test.

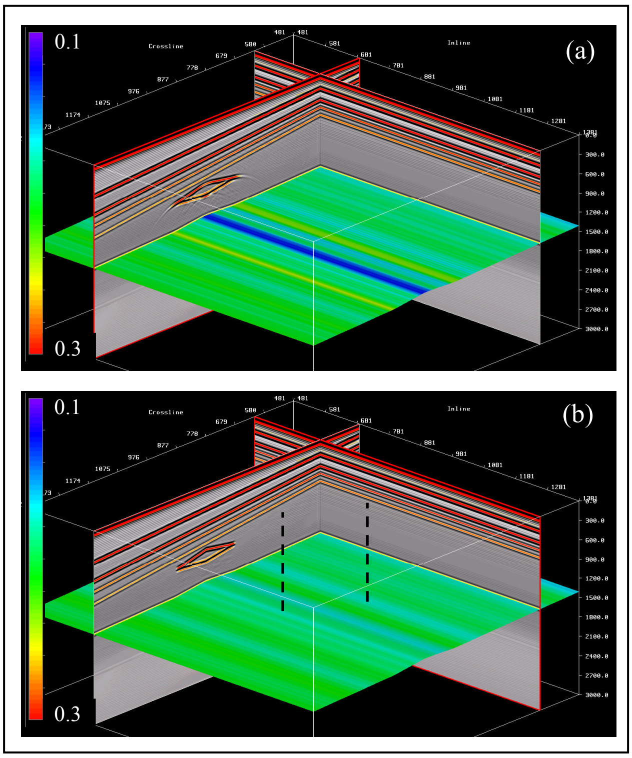

Figure 3. Modelled seismic data from shooting direction along (a) the inline direction, and (b) the crossline direction. The amplitude maps are extracted from the bottom event.

The data were then depth migrated with an amplitude preserved algorithm. Figure 4 dsiplays the CIGs at two image points whose locations are indicated by the dotted lines in Figure 3(b). The amplitudes of the bottom events are plotted on top of Figure 4. It can be observed from Figure 4(a) that the illumination on the event is not only azimuth dependent but also offset dependent. However, for azimuth B data, the amplitudes of the event are fairly constant across offset as expected. Applying our workflow for stacking the two sets of data, we obtained an optimal stacked result (MAzStack) in which the AVO is well preserved with better S/N as shown in Figure 4.

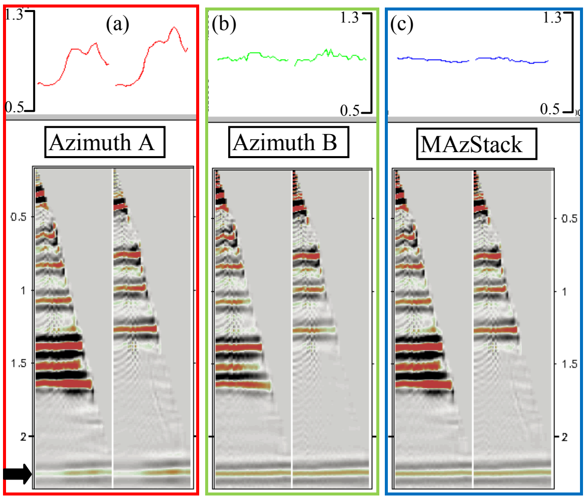

Figure 4. Common image gathers of (a) azimuth A; (b) azimuth B; and (c) MAzStack result.

The real data example comes from three offshore 3D surveys that were acquired separately at different time but covering a common subsurface area of about 100 km^2. Figure 5 displays the offset-azimuth distribution for the acquired data and Table 1 shows some of the acquisition parameters for each survey.

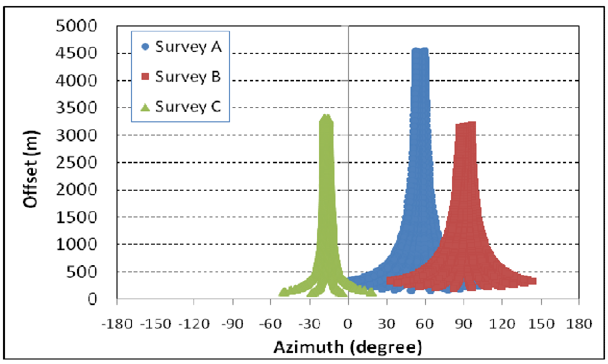

Figure 5. Offset-azimuth distribution of the three surveys.

Survey	A	B	C
Shooting azimuth	60	90	-27
Number of streamers	8	6	2
Number of channels per streamer	352	240	240

Table 1. Some of the acquisition parameters for the three surveys.

We processed each survey separately using the same sequence until pre-stack depth migration. The data was then binned onto a common 25×25m grid for migration. Missing traces were filled in by interpolation. To accurately image the faults in the sub-surface and maintain amplitude fidelity for inversion, amplitude preserved Control Beam Migration (Zhou *et al.*, 2011) was applied in the anisotropic depth imaging process. Eight iterations were performed to update the anisotropy parameters in the velocity model building process through tomography. As a result, we obtained fairly flat CIP gathers from migrating the three datasets, as depicted in Figure 6(a) which shows two supergathers formed by interleaving the corresponding CIGs from the three migrated datasets. This made the trim statics process rather straightforward. Figure 6(b) shows the time-shift values required for flattening the gathers. All of them are within two samples (sampling rate is 4 ms). Nevertheless, as can be seen from the stacks of an inline (zero degree orientation) in Figure 7, variation in sub-surface illumination with respect to acquisition azimuth is evident, with Survey C whose azimuth is the closest to the dip direction of the faults exhibits the poorest illumination beneath the faults.

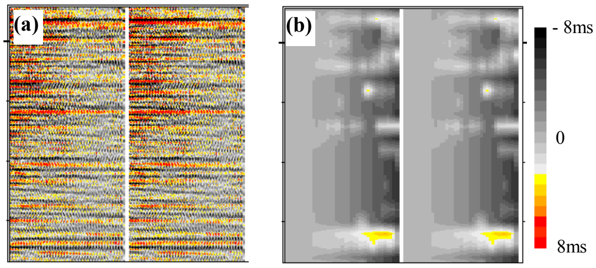

Figure 6. (a) Supergathers formed by interleaving the migrated gathers of the three surveys. (b) Corresponding time-shift required for flattening the gathers.

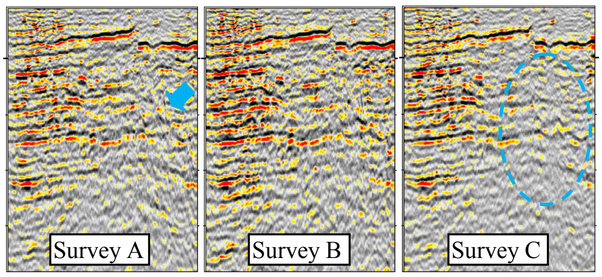

Figure 7. Stack section of an inline.

We applied our workflow to optimally stack the three datasets. Figure 8 displays the results obtained on post stack volumes. Comparing with the average stack which simply assigns equal weights to the three datasets, the MAzStack result clearly shows that our workflow can enhance the S/N ratio while at the same time compensating the azimuthal variation in illumination. The effect on the post stack volumes can be illustrated further by examining the amplitude at a depth level where the target zone is as shown in Figure 9. By enhancing the amplitude through giving more weights to the surveys that have better illumination, MAzStack reveals more structural details with enhanced continuity.

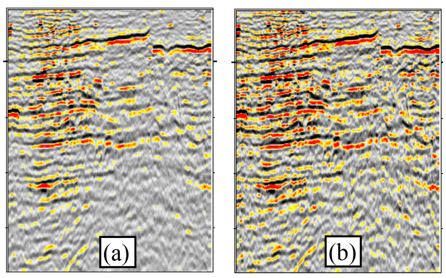

Figure 8. Inline section. (a) Average stack result. (b) MAzStack result.

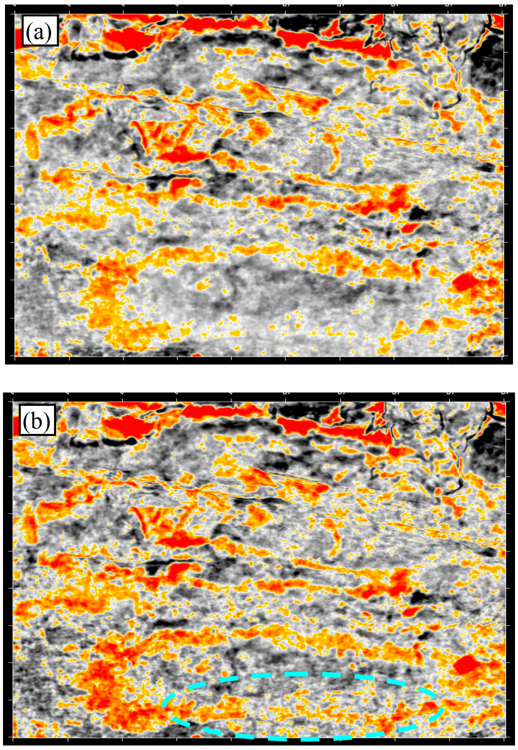

Figure 9. Depth slice of a target zone. (a) Average stack result. (b) MAzStack result.

We also observed that illumination not only varies with azimuth but also with offset in these datasets. Figure 10 displays the gathers of the same image point obtained from the three surveys. The amplitude of a target event, indicated by the arrow, was tracked and is plotted on top of each CIG. It is clear that the AVO behaviour is very different for different azimuths with Survey B which was acquired in the strike direction showing that the event was most illuminated. This poses a challenge for AVO analysis. By applying our stacking method on pre-stack gathers whereby common offsets from the three surveys were stacked, the AVO is well preserved in the MAzStack result in comparison with the conventional stack as depicted in Figure 10. Moreover, the pre-stack MAzStack result has higher S/N ratio as indicated by the blue coloured arrows.

CONCLUSIONS

We have described a workflow based on adaptively balancing the two factors of S/N ratio and illumination for optimally stacking MAZ prestack data. Our synthetic and real data examples show that, with a proper choice of pilot for stacking, our workflow provide a means of obtaining clearer images with high AVO fidelity from MAZ data, thereby compensating any anomaly caused by azimuthal variation in illumination. For geological structures that exhibit amplitude variation with offset and azimuth (AVOAz), our method, however, cannot preserve the amplitude variation but is useful for imaging enhancements for geological structural studies.

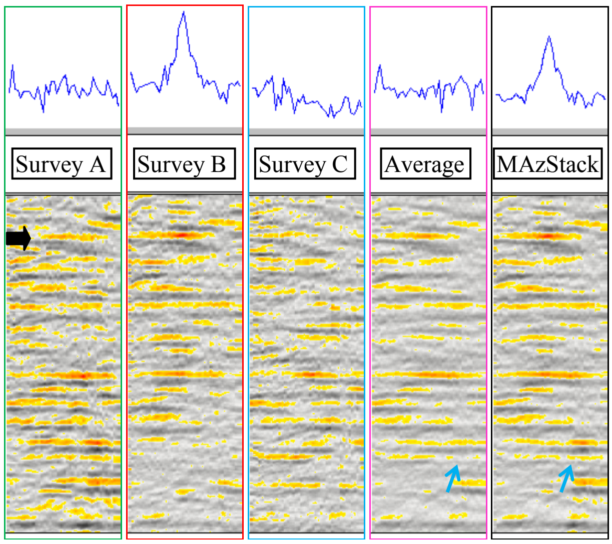

Figure 10. CIG of one particular location. The graphs on top show the amplitude of the event (across offset) indicated by the arrow. The fourth panel is a result obtained by averaging the three surveys.

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