3D pre-processing techniques for marine VHR seismic data

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Introduction

In VHR3D data, the positions of the source and receivers are required to decimetre accuracy in all three directions to ensure the correct processing of the data. However, current acquisition technology does not permit this level of accuracy in a cost-effective way. Any available instrumentation for the real-time measurement of source and receiver position is both very costly and designed for conventional seismics.

During acquisition, movement of the boat and the streamers away from the nominal geometry can affect the recorded data and the quality of the processed results. In conventional seismic acquisition, these variations are small compared to the dimensions of the system and are generally not considered a major problem. In very high-resolution data however, where frequencies above 800 Hz and bin sizes of 1–2 m are common (Table 1), they can severely affect the results. Wave motion and tidal variations can produce degradation of the signal by destructive interference in the stack. Variations in x and y, if

Table 1 Typical VHR3D acquisition specifications.

Survey area	1000–1500 square m
Target depth	75–100 m
Source	Multi-tip sparker
Frequency bandwidth	200–1500 Hz
Source depth	At or near surface
Record length	100–200 ms
Sample interval	0.250 ms.
No. of streamers	4
Streamer separation	4 m
Streamer depth	At or near surface
Streamer length	12 m (10 m active)
No. of channels per streamer	6
Channel Interval	2 m
Shot point interval	1 metre
In-line offset	4–14 m
Minimum offset	4–14 m
Maximum offset	16–25 m

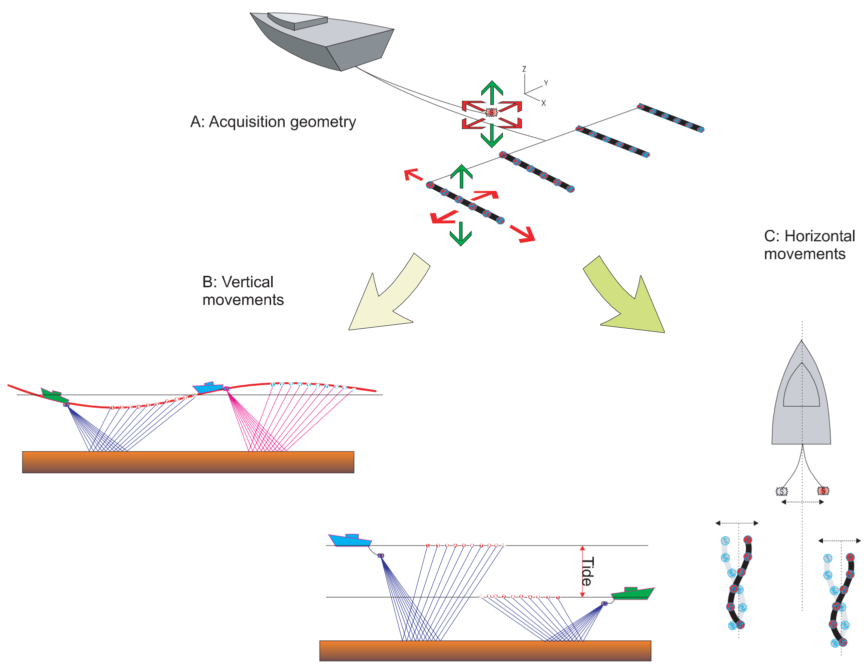

Figure 1 A typical VHR3D acquisition system and the various horizontal and vertical movements that can effect the system.

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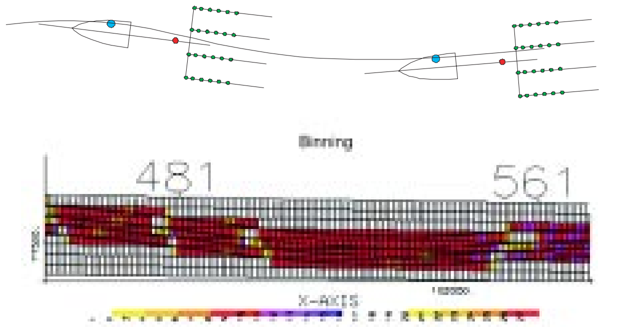


Figure 2 The reconstructed positioning for a portion of a seismic line (top) and the resultant 3D-binning. The distribution of the traces from different cables along the same in-lines is clearly seen.

uncorrected, can cause traces to have an erroneous source-to-receiver offset distance or to be included in the wrong 3D bins.

A schematic diagram of the possible movements that the acquisition system can be subjected to is shown in Fig. 1. The three main movements that are identified produce variations in the theoretical x, y and z positions and require different corrections in processing. Vertical variations due to wave motion and swell require static corrections (or time-shifts). Lateral variations, due to currents and changes in the ship's heading, require dynamic corrections since they change the source-to-receiver offset. Tidal variations, on the other hand, require time shifts but at zero-offset, i.e. after application of NMO.

The vertical variations are analogous to the near-surface problems in land data which require the application of residual static corrections. Algorithms exist in most processing packages to derive these residual static corrections using various correlation techniques. These are generally surface consistent with each shot and receiver having a consistent static. In the marine case, consistency is maintained for the shots but not for the receivers, since they move with the streamer. CDP consistent algorithms can be used to correct these problems and to improve the quality of the final stack section. However, they cannot take into account variations in the sea floor or provide reliable information for the relative positions of shot and receivers if pre-stack imaging or reflection tomography is envisaged.

Methodology

To overcome this problem, methodologies have been developed to derive these corrections from the data themselves using the redundancy of information contained in the first break arrival times. The basic concept is to analyse the data contained in these first breaks statistically to verify the available field information. Where discrepancies occur, corrections can be computed both in time and in offset distance that make the two sets of information more compatible. Obviously, care is taken not to force the fit but to make the different sets of information converge without imposing unreal conditions.

The picking of the first break times can be a time consuming and laborious process since the final results depend upon the accuracy of these picks. Some miss-picks may not seriously effect the statistical process, but obviously, the better the starting data, the better the result. Various automatic picking methods were studied; the most effective one was a simple threshold value in a sliding window. The water bottom is a strong reflection, and, assuming that there is not too much noise on the traces, can be identified fairly easily.

Absolute positioning

Usually in VHR3D acquisition, the x/y positions of source and receivers are not recorded in the field. Where the co-ordi-

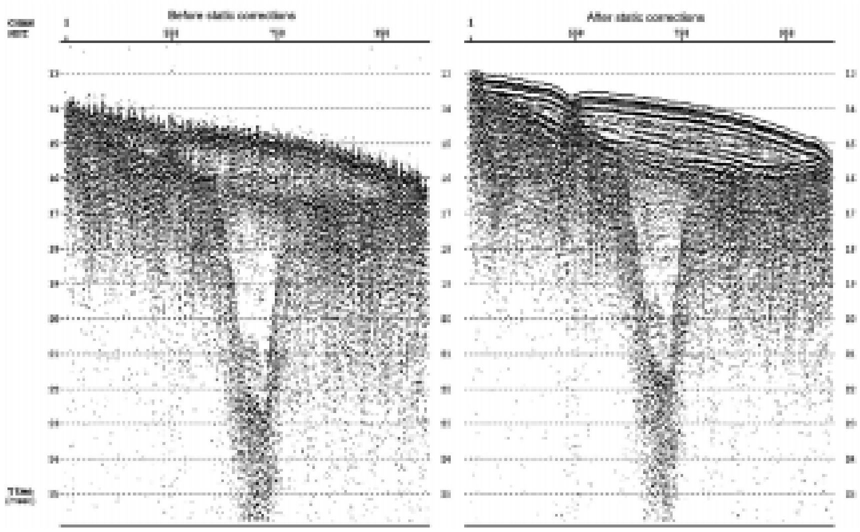
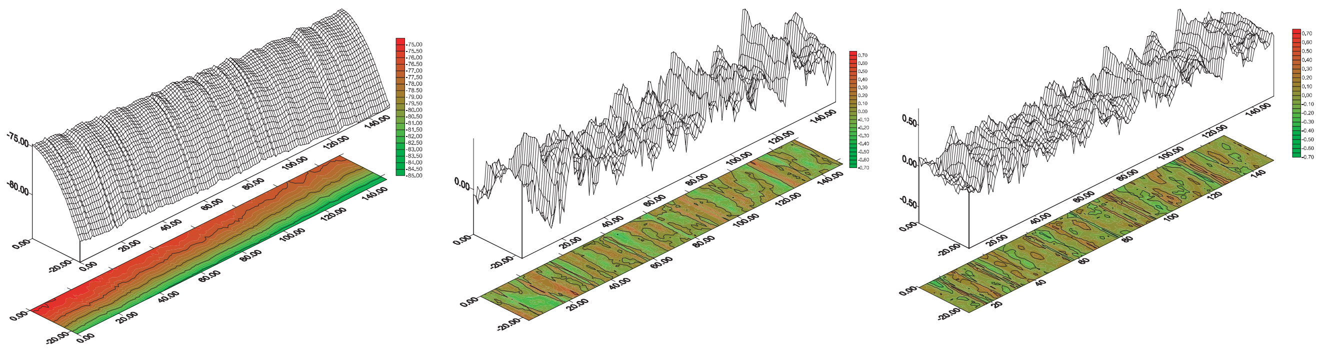


Figure 3 Static corrections applied to single channel boomer data to correct for wave motion effects.



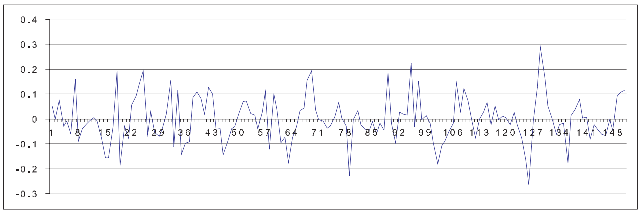


Figure 4 2D static corrections using common offset spatial averaging (COSA). The upper figures, from left to right, show the original pick surface, after common offset averaging, and after removal of the CDP component. The lower figure shows the derived static corrections for each shot.

nates are available, these data are used to calculate the geometry and to sort the shot lines into the 3D volume. Where this information is not available, coordinates have to be calculated from the available information, usually the antenna position and the nominal source and streamer positions.

Since no exact physical relationship exists between the recorded antenna position and the acquisition system itself, a simple navigation model based on a least squares projection of the ship's course can be used to map the positions of the source and receivers (Fig. 2). Any corrections to this basic model are left to the offset correction phase, later in the preprocessing sequence.

Shot static corrections

In Very High Resolution marine data, swell or wave motion can introduce time variations in the acquired seismic traces, which if not corrected can lower the quality of the final stack sections. In single channel acquisition, this wave motion can be removed during actual recording by the application of a swell filter. In the processing phase, this could be performed using a smoothing function or spatial filter on the water bottom times. Figure 3 shows an example of this operation on single channel boomer data. This operation, however, can tend to smooth the water bottom and flatten small structures or irregularities on the seabed which are smaller than the length of the spatial filter. This would not be acceptable in VHR3D processing since it could cause distortion of the data beneath the water-bottom.

A methodology is proposed that, by identifying and separating the various components, produces acceptable corrections without modifying the original data or creating artefacts that could alter the geological interpretation. The method is analogous to the statistical analysis used to calculate refraction statics on land data. Picked arrival times from a target horizon, normally the water bottom, are manipulated statistically to identify anomalous values that can be used to correct the data.

A 3D surface is created by plotting these picks as a function of shot number and offset (or channel number). To derive the swell or wave motion statistically, seen as striations on the 3D surface (Fig. 4), it is first necessary to eliminate the velocity and the morphology of the water bottom, two factors that make the values incomparable.

The first factor can be removed using NMO corrections, but this could introduce errors due to inaccuracies in the velocity determination (Wardell *et al.* 2000). A better approach consists of applying a spatial averaging function to the first break picks for each common offset. Using this Common Offset Spatial Averaging (COSA), a normal horizon, i.e. one without any static problems, can be defined for each offset. Deviations of the original data from this normal horizon represent variations from a smooth, regular acquisition.

Based on the assumption that a CDP is a gather of traces related to the same point on the water bottom, it can be considered to contain all the information pertaining to the morphology of the water bottom. Sorting the data into the CDP domain and filtering the mean value of the residuals effectively removes this CDP consistent component.

After the derivation of the residuals using COSA and the removal of the CDP component, a matrix of comparable values is obtained that can be used to calculate a mean value for each shot gather. This represents the cumulative effect of the swell on the system. The methodology, with the original and

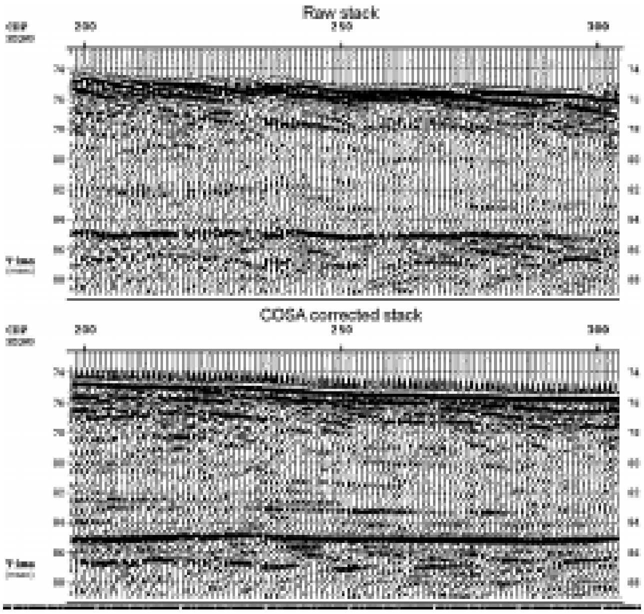


Figure 5 2-D stack sections before and after COSA computed static corrections.

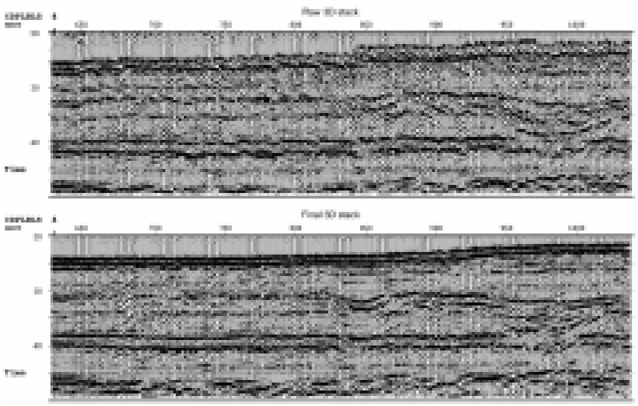


Figure 6 In-line stack sections before and after geometry regularization. The discontinuities in the top section caused by erroneous geometry of traces from different cables have been corrected, in the lower section, by geometry regularization.

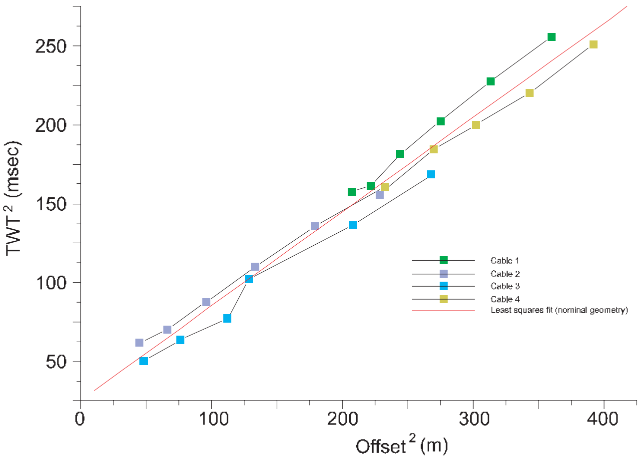


Figure 7 A plot of the first break picks of a single shot plotted as TWT² against Offset² showing the variations between the four cables. The theoretically correct positions are shown by the line from the least squares fit.

residual matrices and the derived shot component is shown in Fig. 4. Corrections of the order of tenths of milliseconds have been obtained, which, when subtracted from the data as a static time shift, improves the continuity of the stacked section (Fig. 5).

Geometry processing

When acquiring very high-resolution 3D data using a multistreamer configuration, it is almost impossible to maintain the ship on an exact straight course or to keep the streamers parallel behind the boat. If the exact positions of the source and receivers are known, then accurate processing of the navigational data can ensure that the traces are assigned their correct geometry within the 3D bins. Unfortunately, current navigation technology does not allow a cost-effective real-time positioning of the source and receiver cables to the level of accuracy required by very high resolution seismics.

The application of theoretical multicable acquisition geometry, projected onto the ship's course, can produce offsets that may be incompatible with the recorded two-way times of the seismic records. Within a single cable, the NMO errors due to incorrect offsets, can be consistent and may not be noticeable. However, if, after 3D binning (Fig. 2), contiguous bins contain traces from different cables, the errors can produce unacceptable shifts in the summed zero-offset stacked traces. The results on an in-line stack are shown in the upper section in Fig. 6 where the jumps in the stack correspond to different cables.

A methodology was devised to regularize the shot-receiver offsets within each shot using the first-break arrival times and an averaged water velocity. This methodology was based on one of the earliest procedures, proposed by Green in 1938, for determining the velocities from seismic reflection data. This procedure involved plotting the square of the travel time T, to and from a reflector at depth z, vs. the square of the offset distance x, using the relation:

$$T^2 = \frac{4}{V^2} z^2 + \frac{1}{V^2} x^2$$

For a constant water velocity V, a plot of T^2 against x^2

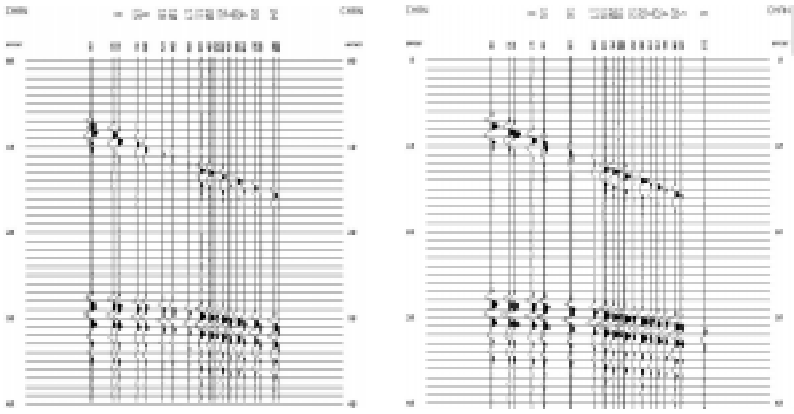


Figure 8 A shot record plotted with trace spacing proportional to offset distance before (left) and after regularization.

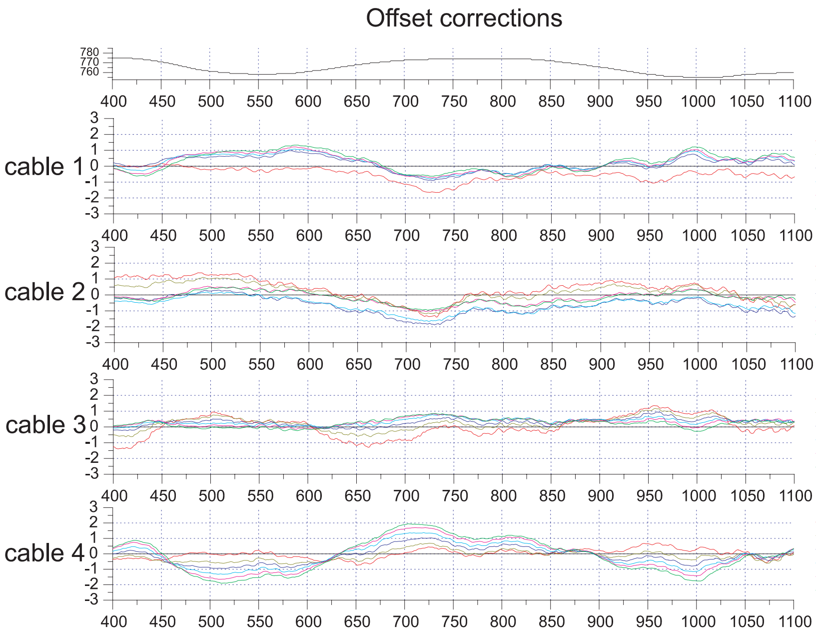


Figure 9 A plot of the corrections in offset calculated for each trace on the four cables showing the consistency within each cable and between cables. The ship's track is shown above the plot; variations in the ship's track are reflected in the computed offset corrections.

gives a straight line with a slope of $1/V^2$.

Plotting the first break times from a typical VHR3D shot in this manner, variations from the 'straight line' can be clearly seen (Fig. 7). Since the static correction for the wave motion has already been applied, these variations are primarily due to the lateral movement of the source and streamers. Using an average water velocity, calculated using the least squares method on the squared values of T and x for all shots, the offsets for each shot can be regularized. This regularization involves iteratively computing the best line fit for the first break time/offset values and correcting the distance of the farthest point from the line onto the best fit. Since any lateral movement of the source or of the cables in water can, by nature, be considered 'fluid', common offset spatial averaging was used on the picked first-break arrival times to eliminate spurious picks and to filter out any high frequency 'noise' and maintain this fluidity.

The one assumption is that the water bottom within each shot was relatively flat. Considering the small footprint of the acquisition system, this assumption is acceptable. The results produce offset errors of less than 2 m and are compatible with the scale of the acquisition system. A 2 m difference in offset represents a 1 m difference in the subsurface. Plotting single shots with a horizontal scale proportional to offset, the effects of this regularization can be clearly seen (Fig. 8).

Figure 9 shows a plot of the calculated offset corrections by channel and by cable, which demonstrates the consistent behavioural pattern of the cables. The outer cables vary more than the inner cables and the farther traces drift more than the nearer traces. After the application of the offset correction, the revised stack sections show greater continuity, not only at the water-bottom, but also in the deeper part of the section (Fig. 6).

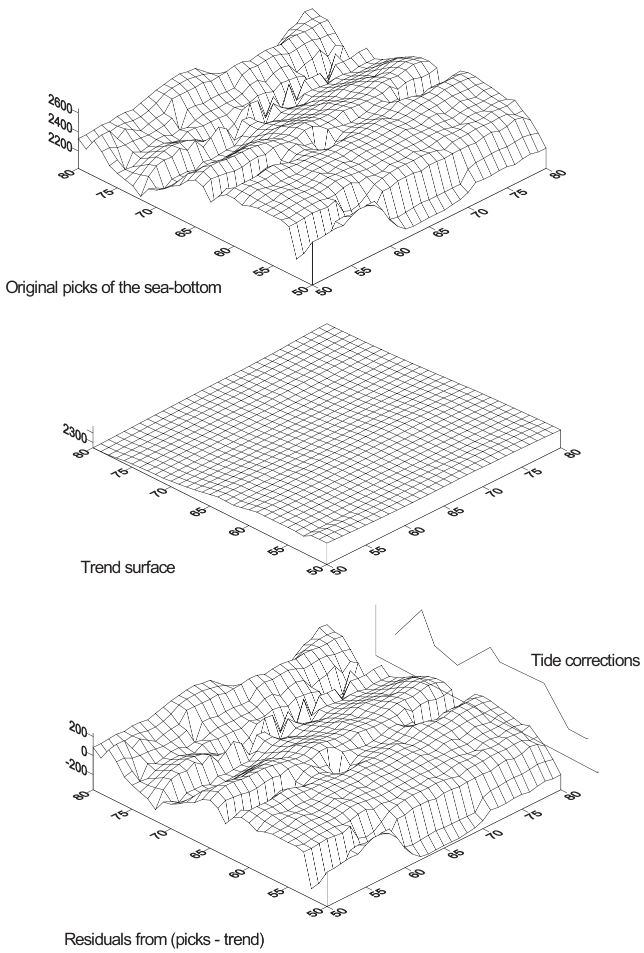


Figure 10 The steps in the calculation of the major tidal components. The original picks are shown in the upper surface, the derived trend surface in the centre, and the residual surface from which the tidal components can be calculated at the bottom.

Tidal corrections

Whereas on a single 2D line, tidal variations are not critical, lines recorded at different times in a 3D survey can have different tidal components. In VHR3D data, these tidal differences can be critical to the coherency of the final data volume. Where tidal information is available, the first break picks are corrected with this information prior to the application of the methodology.

If the tidal information is not available, a statistical method using picked first break times can be applied to isolate these tidal differences from the wave motion and the morphology of the seafloor. Within the recording of a single seismic line, the tidal elevation is considered constant. However, deriving the relative tidal differences between lines using the mean of the picks from a common offset can be influenced by variations in the seafloor. A 3D-trend surface is therefore computed for the water bottom by a spatial averaging of first break times of a single common offset. The spatial averaging function in this case is purposefully chosen to excessively smooth the surface and leave only a trend and not the detail. This trend surface can be subtracted from the original picks to simulate a flat water-bottom. Having removed the influence of variations in the seafloor, relative tidal values can be computed from the mean of the picks from a common offset for each line. Corrections can then be applied to the original picks to compensate for the major part of the tidal variations. Certain residual tidal variations will be left in the picks; these will be included in the shot component of the 3D solution for the wave motion.

The methodology for the removal of the trend surface and the computation of the tidal component is shown in Fig. 10. The picks from a single common offset are shown as a 3D sur-

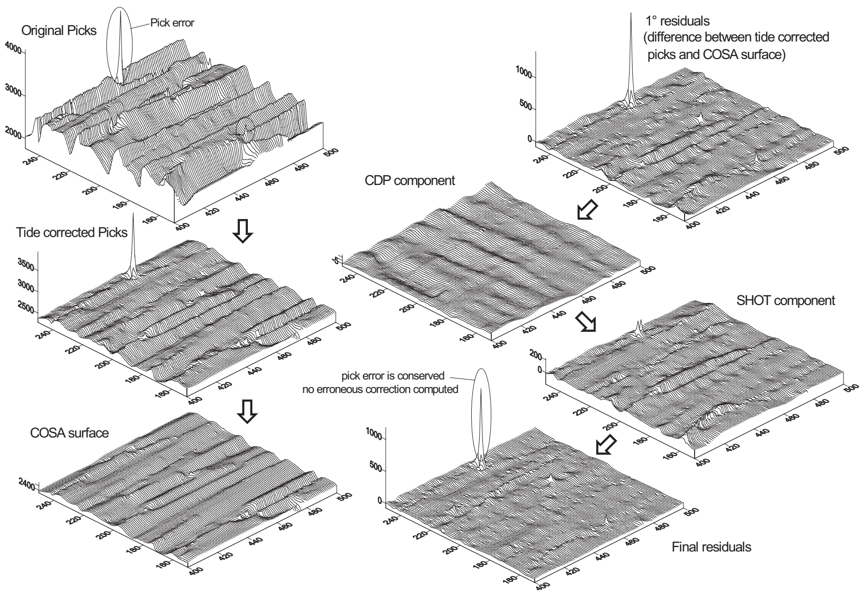


Figure 11 The principal steps in the Common Offset Spatial Averaging (COSA) methodology.

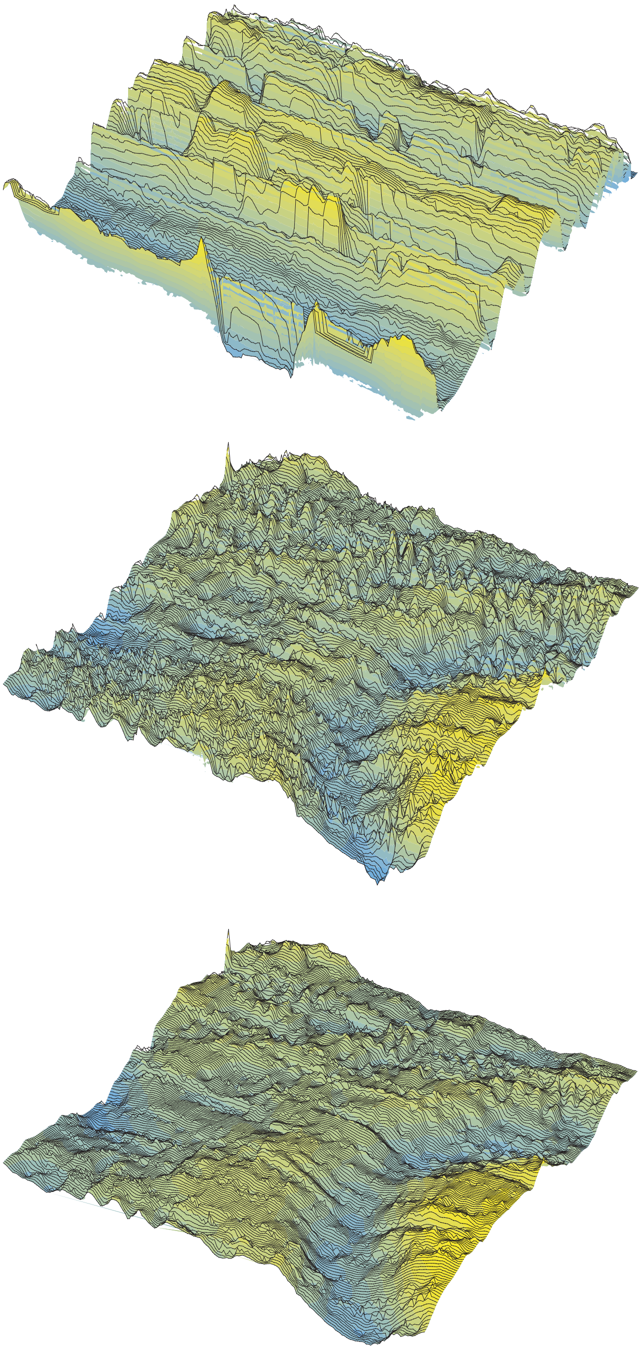


Figure 12 A single offset surface from a 3D survey before corrections (top), after computed tidal corrections (centre) and after tidal and shot corrections (bottom).

face (top); in the trend surface (centre) a dip to the left is clearly seen; the tidal component can then be computed from the residual surface (bottom).

3D static corrections

A static solution for VHR3D data should also be able to identify and correct for time variations that can exist between lines during acquisition. In extending the methodology to 3D, a similar methodology was used as for 2D. Using the times of the picked first break arrivals, a three-dimensional surface is computed for each common offset using a 3D spatial averaging function. The original first break picks are then subtracted from these surfaces to obtain a matrix of difference times. This matrix contains two main components: a shot component common to all the traces of the same shot, and a CDP (or bin) component from all traces in the same bin.

Previous work had shown that the CDP component is a function of the spatial averaging parameters and the residual of the water-bottom morphology; its removal allows a consistent shot component to be calculated. In 2D, where all the shots are assumed to be in-line with no lateral variations in shots or receivers, a high fold (and hence statistic) is obtained in each (in-line) CDP. However, in 3D, where the actual *x/y* positions of shots and receivers are used, the distribution of the traces in the bins is less regular. This is especially true in the cross-line direction, when the distance between streamers is generally not of the same order of magnitude as the in-line receiver spacing. Empty or single trace bins can be common. The CDP component calculated from a single CDP is not, in this situation, statistically valid and the shot component thus calculated can be unstable. If any residual of the tidal correction is present, this could be included in the CDP component, and hence erroneously removed before computation of the shot component.

To take into account these tidal residuals and the uneven fold distribution, the CDP component is calculated using extended CDP bins. The width of this extended bin is designed to cover more than one shot-line to ensure sufficient statistics to identify any residual tidal component. However, such an extended bin size in the in-line direction would cause an excessive smoothing of the CDP component, causing elements of the water bottom morphology to be left in the shot component. To avoid this problem, a rectangular extended bin is employed, wide in the cross-line direction and short in the in-line direction.

Figure 11 shows a sequence of 3D surfaces demonstrating the methodology applied to a 3D dataset. On the left the sequence shows the removal of the tidal component and the common offset spatial averaging (COSA) on the resultant matrix. The sequence on the right shows the residual's surface, the derivation of the CDP component and the resultant shot component. The final residual surface after removal of the shot component shows that an erroneous pick is still preserved and did not contribute to the calculated shot component.

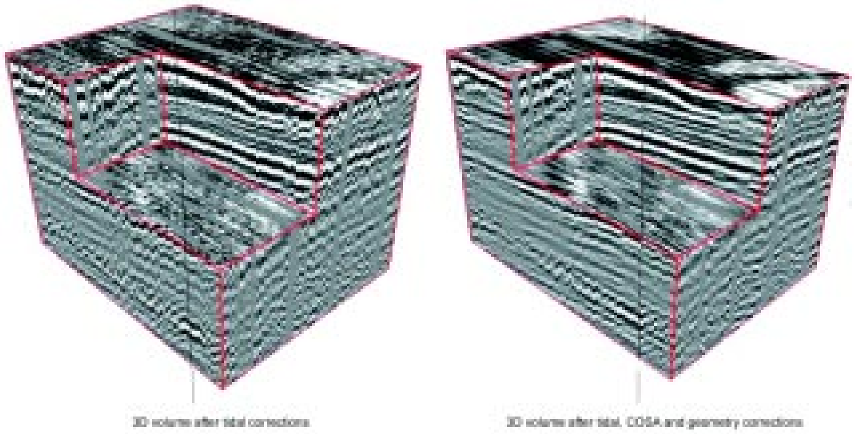


Figure 13 A 3D volume after computed tidal corrections (left) and after tidal, COSA and geometry corrections (right).

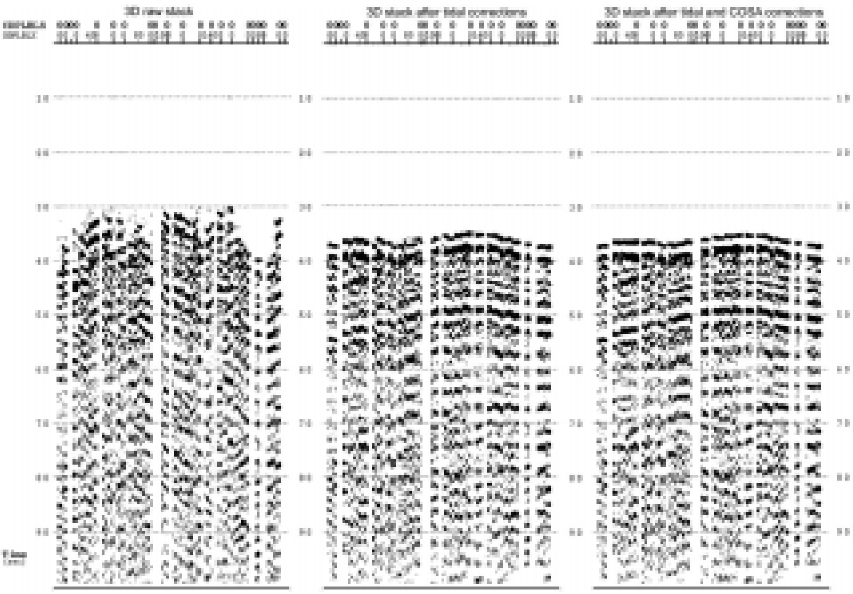


Figure 14 A cross-line through a 3D cube showing the efficacy of the methodology. The raw section is shown on the left, after tidal corrections in the centre and after COSA derived shot statics on the right.

Application to 3D datasets

The 3D methodology was first applied on a survey where the fold was uniform, but due to the acquisition practice of abutting and not overlapping the shot-lines, many areas contain zero fold, even with a 2 m bin size. The application of 3D COSA is shown in Fig. 12. The upper surface is the original picks for a single common offset, the middle after removal of the computed tidal component, and the lower after removal of the shot component. The improvement in continuity of the surface is clearly seen. The morphology of the water bottom is maintained with a crescent-shaped shallow feature being much more evident after the preprocessing sequence.

The final stack 3D volume with and without the corrections is shown in Fig. 13. Again, the greater continuity is clearly evident. The crescent shaped feature mentioned before is well delineated, both on the surface and extending below it. The interaction between the dipping horizons and the more recent superficial sediments is more clearly seen.

Figure 14 shows a cross-line from the 3D cube, before and after corrections. Tidal variations and wave motion on the individual lines produce a chaotic effect in the cross-line direction. After correction, the improvement throughout the section demonstrates the efficacy of the preprocessing methodology in 3D.

In a second 3D survey, calculation of the source and receiver *x*/*y* coordinates resulted in offset distances for each channel varying along the line and between lines. Some lines, recorded on different days, had also different initial geometry. A regularization of offsets was necessary prior to the common offset spatial averaging. The offsets varied from 4 to 20 m but were concentrated between 9 and 16 m.

Processing the data with a 1-m bin interval meant that there were many bins with zero or single-fold, necessitating

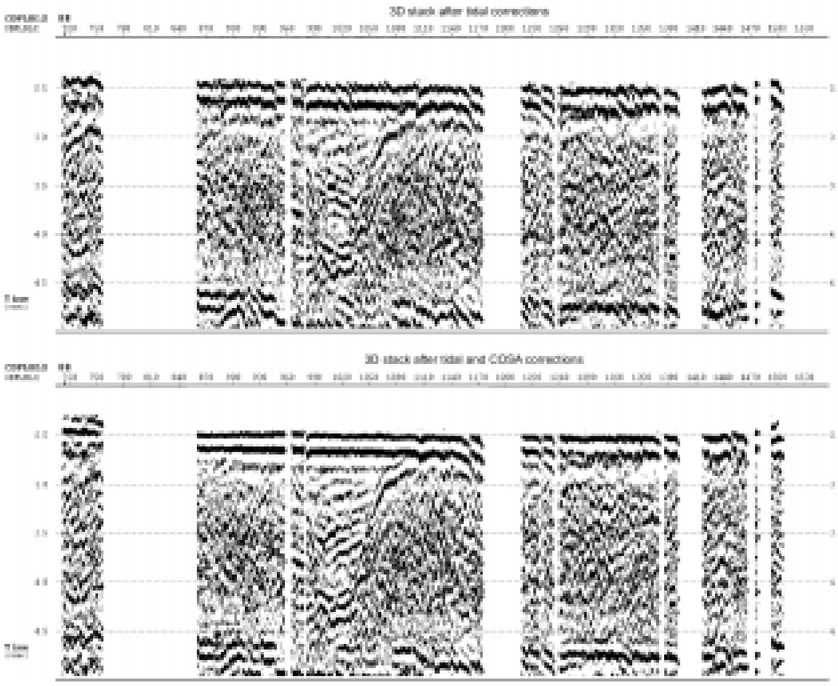


Figure 15 An in-line section from a 3D volume after tidal corrections (top) and after the full preprocessing methodology showing the improved detail inside the channel. Gaps in the sections are due to zero fold resulting from noncomplete coverage in the acquisition and a 1 m bin size.

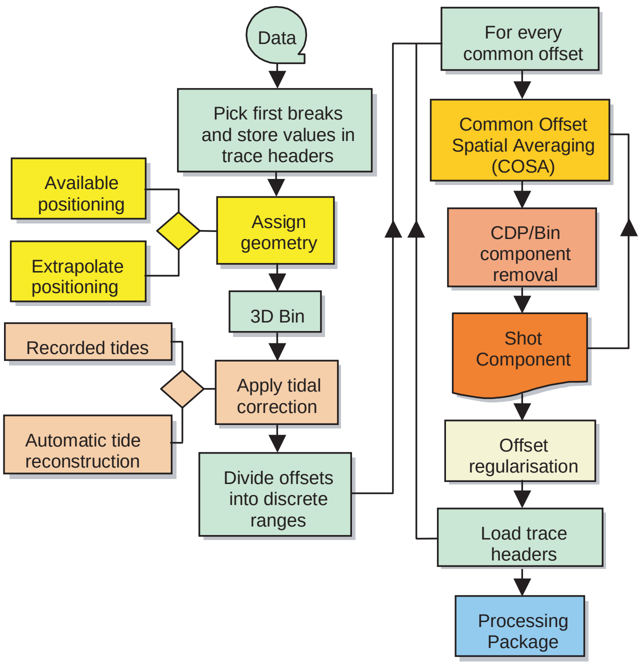


Figure 16 A schematic flowchart outlining the steps in the preprocessing methodology.

extending the bin size for the computation of the CDP component to maintain statistics. In Fig. 15, a section through a channel shows that these preprocessing corrections can also help the interpretation. The channel in-fill on the lower, corrected section is coherent with a pronounced dip. In the top section, corrected only for the tidal component, it is confused, and, if any dip is identifiable, it is in the opposite direction.

Conclusions

A methodology has been developed which can effectively derive corrections in both time and offset to compensate for variations from the recorded or computed positional data. It uses the redundancy of information contained in the times from the first breaks to statistically compute corrections to match the recorded data. As with refraction statics on land data, the calculated values are relative values. In areas of greatly varying tides, corrections would be required to an agreed datum. Application to 3D data has demonstrated the efficacy of the methodology which is summarized in the flow chart in Fig. 16.

Common Offset Spatial Averaging (COSA) is the key to the methodology. For good statistics, regular geometry and consistent fold data are preferred. However, irregular data can also be handled with the appropriate choice of parameters. Where the acquisition parameters permit, an individual cable component can be computed for each cable rather than a total shot component. After correcting the original picks for the shot component, the process can be run iteratively to fine-tune the results.

Although the methodology was developed on Very High Resolution 3D marine data where small variations can be critical to the results, it is envisaged that it could have applications to resolve specific problems in conventional seismic surveys. Compensating for the presence of a long wavelength swell in a 3D survey, or matching 3D surveys shot at different times and in different conditions, in a 4D or time-lapse study, could be two such applications.

Acknowledgements

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