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Normalization of Kirchhoff imaging for variable fold

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ABSTRACT

For multichannel recording, abundance of data traces represents a key element in the processing stage and the quality of the final image. Therefore, seismic acquisition geometries are often designed to optimize the fold coverage in the survey. However, this often neglects a crucial processing requirement: a good distribution of offset and azimuth in the CMP bins. The processing of seismic data for amplitude inversion requires both accuracy of algorithms and proper handling of irregular geometry. Sampling irregularities in the form of varying fold may introduce noise, cause amplitude distortions, and even structural distortions when wave equation processes such as DMO, AMO, and prestack migration are applied to the data. In the context of amplitude-preserving processing, we present a new development in our true-amplitude sequence for processing wide-azimuth 3D surveys. We extend the concept of multiplicity to wave equation processes and explore a normalization procedure to correct for the variations in fold distribution. Given a common-offset common-azimuth 3D subset, we correct for the fold variations by normalizing each input trace according to the local fold of its corresponding bin. The normalization corrects for data trace redundancy but does not account for missing traces or for the spatial distribution within local bins. Results of the application of integral migration and integral AMO as summation over the preconditioned data have proved to correct and equalize the imaging processes for the effects of fold variations.

INTRODUCTION

3D acquisition geometry can have a tremendous impact on the quality of the final image. Detailed exploration objectives such as detection of fracture density and orientation from P-wave surface seismic data have pushed 3D seismic surveys to be carefully designed carefully. Many important and sometimes conflicting issues influ-

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ence 3D survey design; we need to be concerned about adequate midpoint sampling, azimuth and offset distribution and high fold for best quality images. Conventional 3D seismic survey design software is based on CMP analysis of these bin attributes. However, with current recording geometries it is impossible to sample the five dimensional wavefield completely. Vermeer (1994) has proposed a criterion for the sampling of the prestack wavefield based on an extension of the 2-D cryteria for symmetric sampling. He presented sampling principles for two major classes of geometries: the patch geometries and line geometries. The spatial continuity of symmetric sampling would then be well preserved in the shot or receiver domain. Figure 1 shows an example of a Button-Patch geometry for a real 3D survey which we use in our simulations. It is characterized by a dense areal arrangement of receiver stations and sparse sampling of shots.

For 3D data, obstructions, cable feathering, environmental objectives, economic constraints, and many other factors cause seismic data to be sampled in sparse and irregular fashion. These irregularities are always observed in the form of variations in fold coverage, which can manifest itself as an acquisition foot-imprint on prestack data or even the stacked image. If not accounted for, irregular sampling can affect prestack data analyses and may introduce noise, cause amplitude distortions, and even structural distortions when 3D wave equation processes are applied to the data (Black and Schleicher, 1989; Gardner and Canning, 1994; Beasley, 1994). Many techniques with varying accuracy and effective cost have been proposed for processing irregularly sampled data; among them equalized DMO (Beasley and Klotz, 1992), geometrically calibrated DMO (Ronen et al., 1995) and spatial dealiasing (Ronen and Liner, 1987).

Chemingui and Biondi (1996) have demonstrated that the effects of irregularly-sampled data on seismic amplitudes can be substantial and have proposed a method for processing wide-azimuth 3D surveys that can largely overcome these problems. The technique is based on applying the AMO transformation (Biondi and Chemingui, 1994) in order to organize the data into common-azimuth common-offset cubes and, therefore, to allow interpolation to a regular grid before imaging. In this paper, we propose a new development in our technique to compensate for the effects of irregular fold distributions. The method extends the multiplicity concept to wave equation processes and uses a normalization procedure to correct and equalize for the effects of irregular coverage.

IRREGULAR SPATIAL SAMPLING

Most of the solutions for handling irregularly-sampled data address the issue of missing data traces, and irregular spatial distribution within bins. Variable fold in the form of trace redundancy has received much less attention and is more often treated as harmless to the processing operation. We first explain the problem as we discuss it in the scope of processing wide-azimuth surveys, then we present our new development to account for the fold variations in the implementation of the algorithms, finally, we demonstrate our improved results on a synthetic reflectivity model.

Variations in fold coverage

It is difficult to acquire seismic data that is adequately distributed in azimuth and offset. Moreover, it is impossible to extract an adequately sampled 3D subset representing a single common-azimuth common-offset realization from the 5D prestack volume. An alternative solution is to consider a subset over a small range of azimuths and offsets for prestack processing. An example of such a subset from a 3D wide-azimuth data volume is shown in Figure 2. Traces whose source-receiver offset is between 7000 and 9000 ft and azimuth between -30^o and 30^o were extracted from a true 3D land survey acquired with Button-Patch geometry and we plotted the surface locations of their common mid-points. There is a fundamental problem with this subset. At a nominal bin size spacing, variations in fold between different bins may vary substantially. Figure 3 shows the fold distribution for this subset binned at nominal CMP spacing of 80 ft. The fold coverage varies from 0 to 5 with arithmetic average of about 1.5.

Normalization for variable fold

"Mathematical derivations of integral operators assume that physical quantities such as time, source-receiver midpoint, azimuth and offset are continuous. In practice, the resulting algorithms are simply then applied to the discretely sampled seismic field data" (Beasley and Klotz, 1992). However, a fundamental problem exists in the implementation of integrals as discrete summations; the integrands must be regularly and adequately sampled. A way of thinking that can be very helpful takes us back to the definition of definite 3D integrals, and their volume approximations. This suggests that we should consider a multiplicity concept to avoid summing over redundant traces within bin elements. A straightforward extension of the NMO-Stack compensation for variable fold, based on dividing the summed data by a function of the multiplicity, cannot be used for our application since traces within local bins may have different azimuths and offsets. The summed trace will then suffer severe amplitude and phase distortions.

What we propose as a new development in our imaging sequence is a normalization procedure which includes all the traces within each CMP bin in the discrete summation while it normalizes each input trace by the local fold of its corresponding bin. This solution is accurate for the case in which all the traces within the CMP bin share the same offset and azimuth and provides a good approximation for the case of small variations in offset and azimuth. Application of this normalization procedure leads to an approximation of the survey subdivision by a single-fold 3D subset that is better suited for prestack processing when the wave equation operator is implemented as a discrete integral summation.

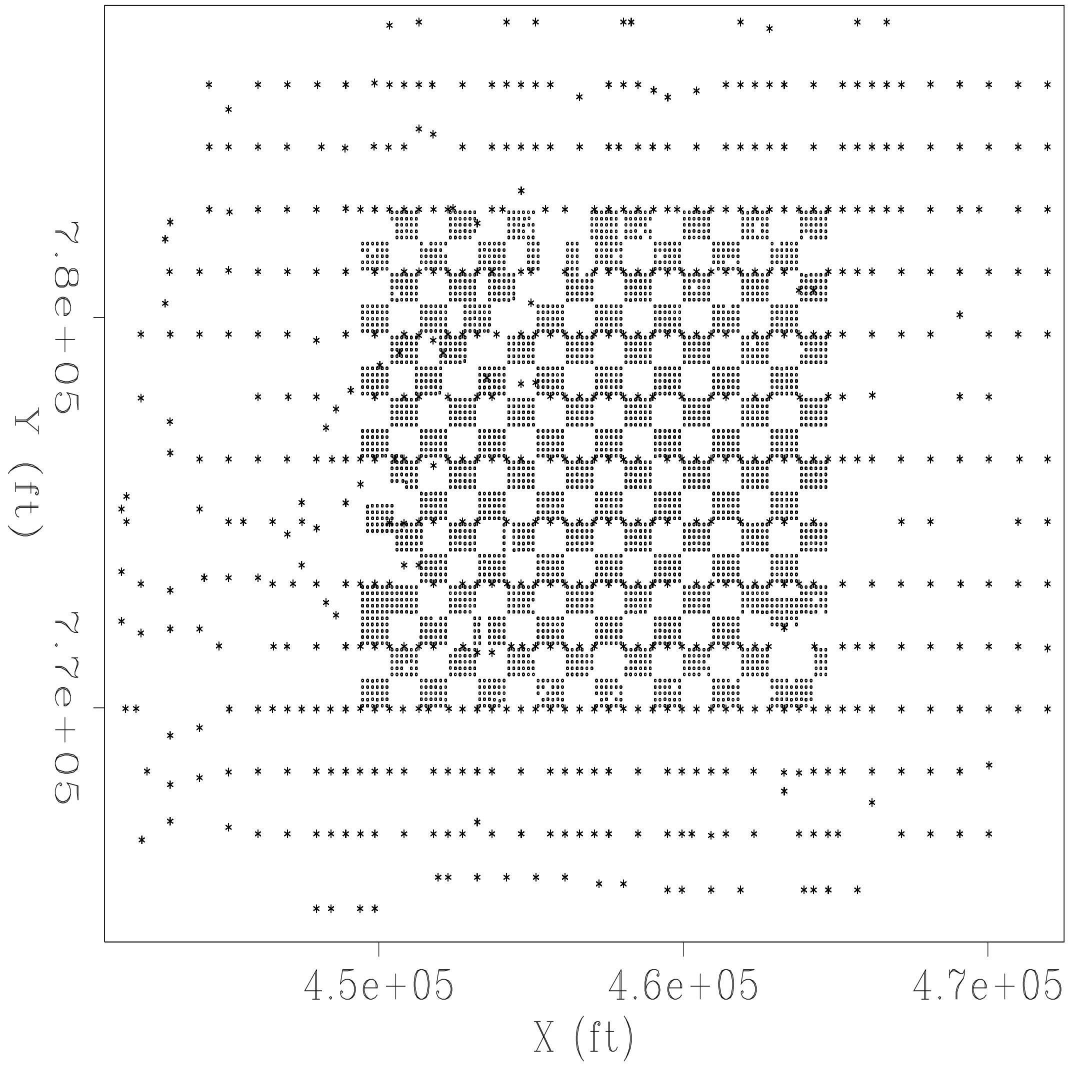

Figure 1: Layout of the sources and receivers in the 3D land survey designed with a Button-Patch geometry; the dots and stars indicate receiver and source locations respectively. nizar1-survey [ER]

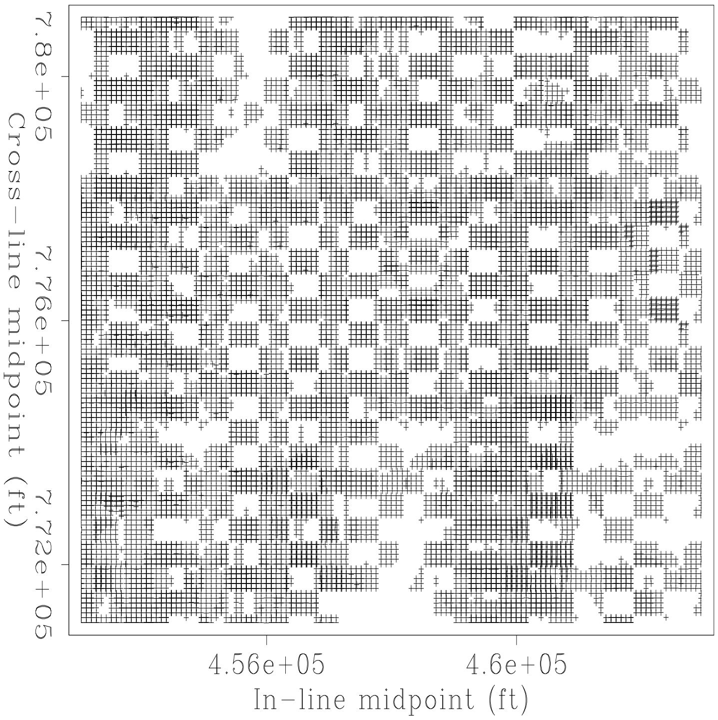

Figure 2: CMP geometry of a subset from a wide azimuth 3D land survey. The corresponding traces have source-receiver azimuth between -30 and 30 dgrees and offset between 7000 and 9000 ft. nizar1-irregular [ER]

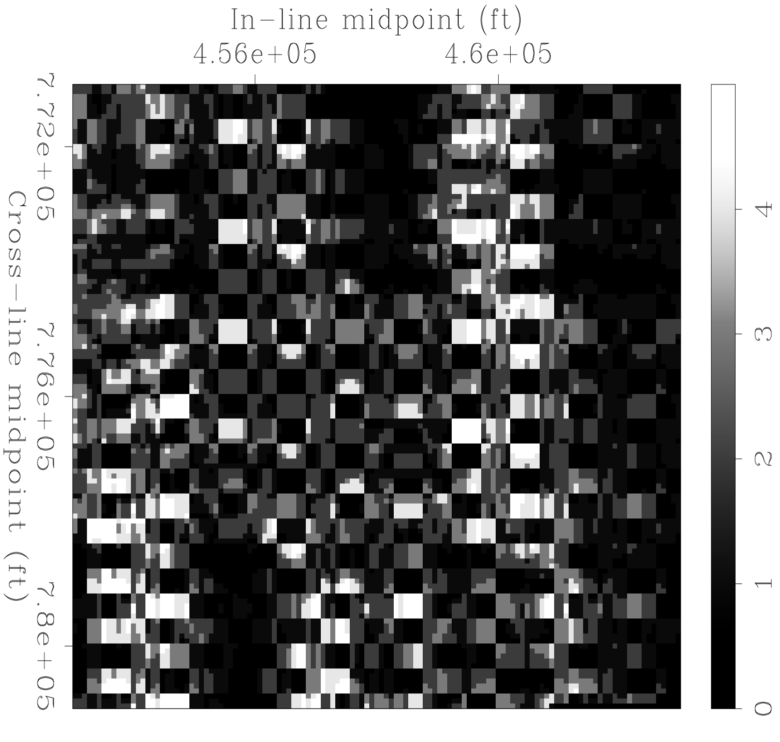

Figure 3: Fold diagram for the 3-D subset binned at nominal CMP spacing of 80 ft. nizar1-Fold [CR]

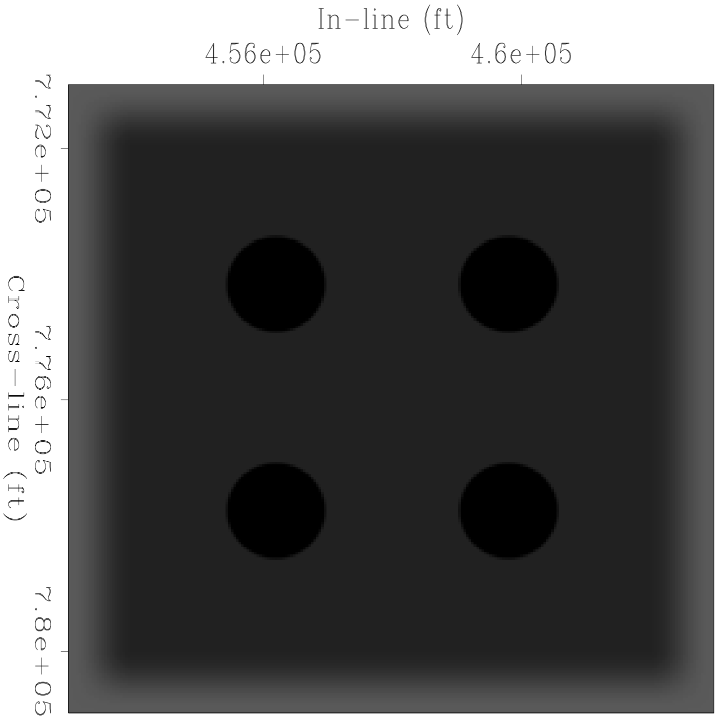

Figure 4: Synthetic reflectivity model of a flat reflector. The white circles are zones of high reflection coefficient of 2.5 in a constant background of unit reflectivity. nizar1-model [ER]

SYNTHETIC EXPERIMENT

To examine the effects of fold variations on wave equation processes, namely AMO and migration, we tested our normalization technique on the synthetic reflectivity model used by Chemingui and Biondi (1996) to prove their proposed true amplitude sequence for processing wide-azimuth 3D surveys. The model is 10,000 by 10,000 feet wide and simulates a flat reflector with amplitude anomalies along its surface. The anomaly zones take the form of circles of high reflectivity. Figure 4 shows a cross section of the synthetic model taken at the top of the flat reflector. The edges of the model are tapered to avoid numerical diffractions from the modeling algorithm. For the sake of simplicity, we consider a medium with a constant velocity of 10,000 ft/sec. The Button Patch geometry of the survey is discussed in Chemingui and Biondi (1996). A 3D subset containing 24,000 traces with source-receiver azimuth between -30^o and 30^o and an absolute offset range from 7000 to 9000 ft was extracted from the 5D prestack volume. The nominal CMP spacing is 80 ft in both x and y directions. The new simulations use a high frequency source wavelet to better resolve the details of the reflectivity images. The results are also plotted with high resolution to distinguish the anomalous zones in the constant background.

In a first experiment, we migrated the data using a true-amplitude Kirchhoff algorithm without accounting for fold variations. Figure 5 shows the results of the direct migration. The reflectivity map has a poor resolution and suffers amplitude distortions scattered along the entire flat reflector. Figure 6 shows the results of the normalized migration; the image is now smoother, it shows more continuity and better resolution than the unconditioned migration result. The equalization for fold coverage during migration eliminated most of the amplitude distortions along the horizontal reflector and helped image the location of the anomalies.

Next, we applied the AMO transformation to regularize the geometry and reconstruct the data as a zero-azimuth cube with 8000 ft effective offset and constant mid-point spacing of 80 ft. The CA/CO cube is then migrated using the 3D prestack depth migration algorithm. Figures 7 and 8 show the results of this processing sequence. Figure 7 is generated with an AMO algorithm that does not account for the variations in the fold coverage. This is the previous result presented in (Chemingui and Biondi, 1996b) regenerated and displayed at better resolution. We compare this result to the new image obtained by including the normalization procedure in the integral AMO algorithm. The output of the AMO transformation is a regularly gridded single-fold CA/CO cube well suited for prestack migration. Figure 8 shows that the normalization procedure improved the quality of the reflectivity map and eliminated the foot imprint of the geometry.

The results of the normalized migration and normalized AMO are very similar. The advantage of applying the correction procedure during the AMO transformation is the resulting reduction in the the size of the prestack volume and the regularization of the data into CA/CO cubes for prestack migration. This allows for more reliable amplitude analysis as a function of offset and azimuth.

Figure 9 shows the difference in the reflectivity maps between the unconditioned migration and the normalized migration, whereas Figure 10 shows the difference between the migrated images of the unconditioned AMO and the normalized AMO. The residual maps are very similar and show direct correlation with the fold distribution as displayed on the fold diagram (Figure 3).

We conclude that the normalization of the Kirchhoff operator in its discrete summation implementation helps eliminate the effects of fold variations. It is important to note that this approximate solution for equalization cannot compensate for missing traces or varying spatial distribution of traces within CMP bins. The latter aspect was not a major concern since most redundant traces shared the same spatial coordinates. This is related to the fact that, in land acquisition, Button-Patch geometry in this case, the receiver locations are fixed and geophones are only deployed after the recording of an entire patch.

CONCLUSIONS

We have presented an approximate solution to the problem of varying fold in 3D subsets extracted from 5D prestack volumes. The solution is based on a multiplicity

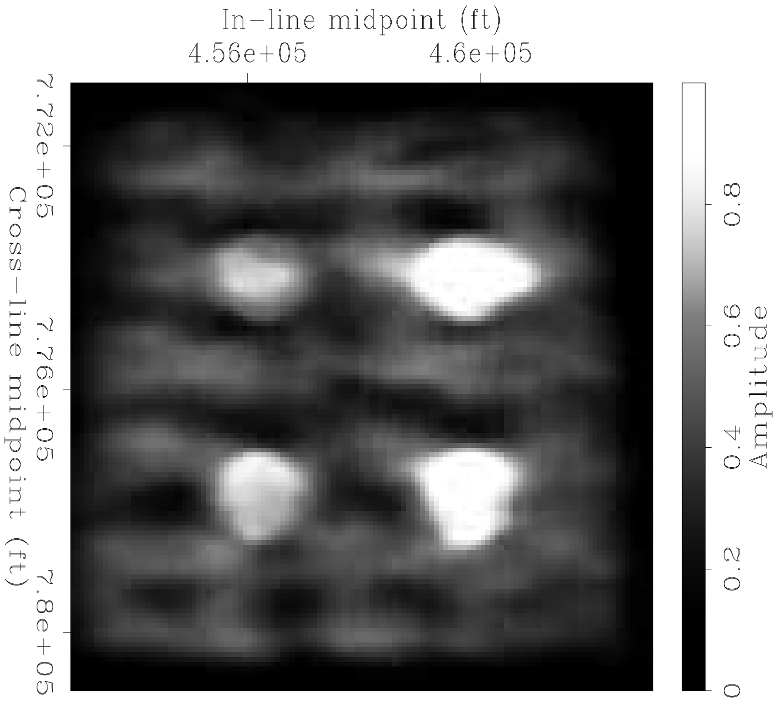

Figure 5: Reflectivity map obtained by direct Kirchhoff migration without normalization. nizar1-mig-neq [CR]

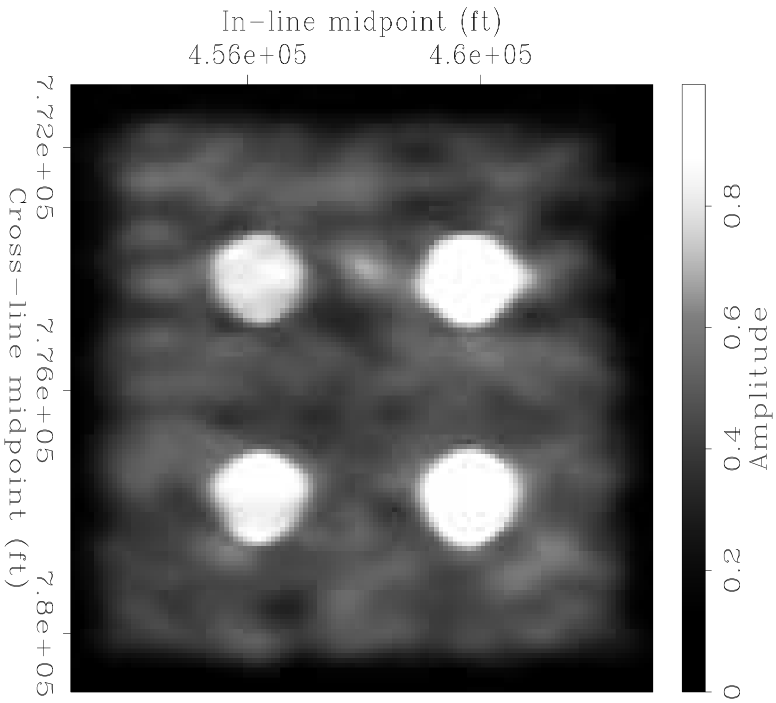

Figure 6: Reflectivity map obtained by normalized migration. nizar1-mig-equ [CR]

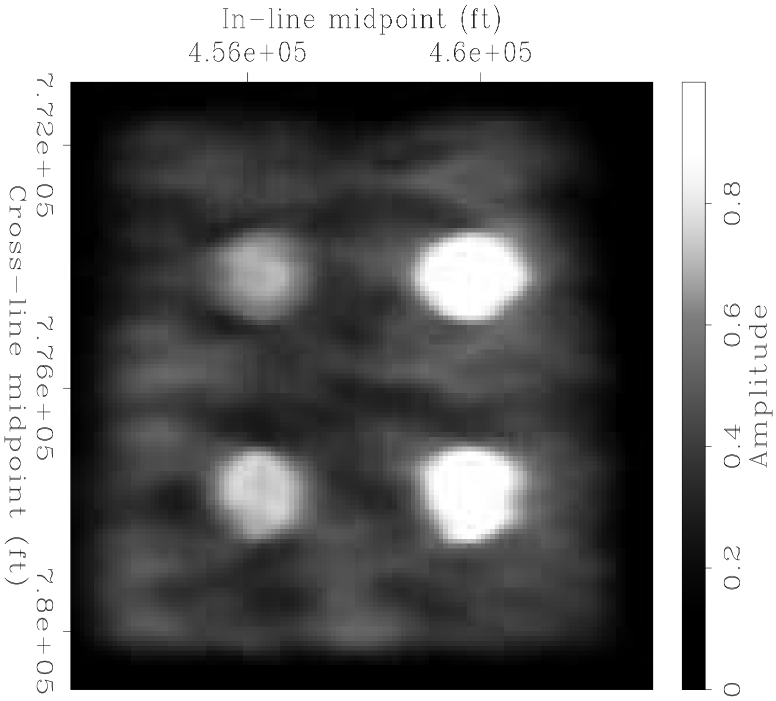

Figure 7: Reflectivity map obtained by migrating the data after applying the AMO transformation to an effective zero-azimuth and a constant offset of 8000 ft without normalization of AMO. nizar1-amo-neq [CR]

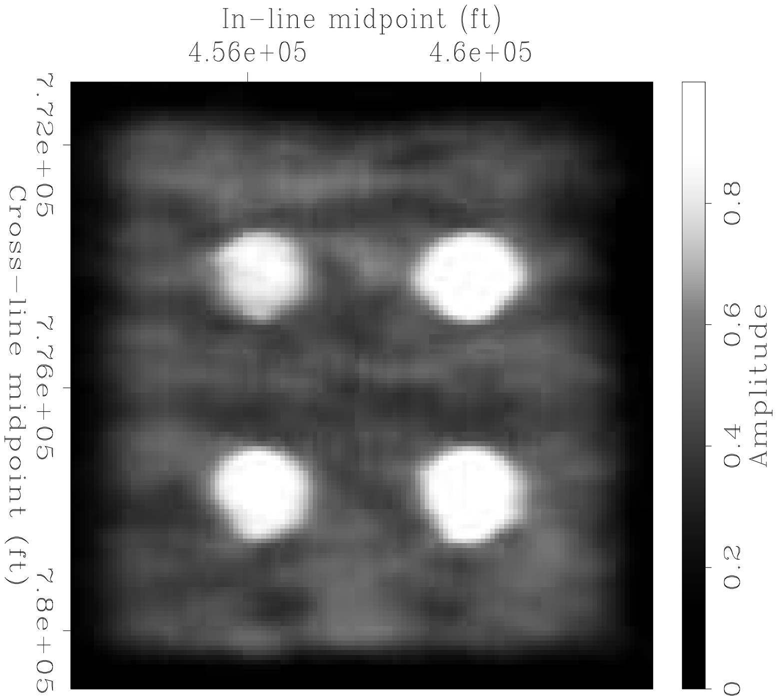

Figure 8: Reflectivity map obtained by migrating the data after applying a normalized AMO transformation to zero azimuth and constant offset of 8000 ft. nizar1-amo-equ [CR]

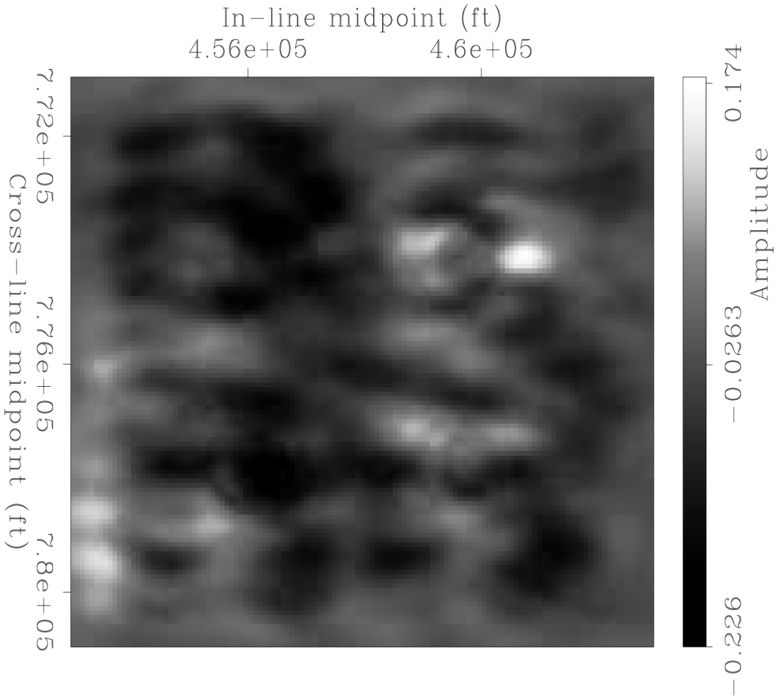

Figure 9: Difference in reflectivity maps between the unconditioned migration and the normalized migration. nizar1-diff-mig [CR]

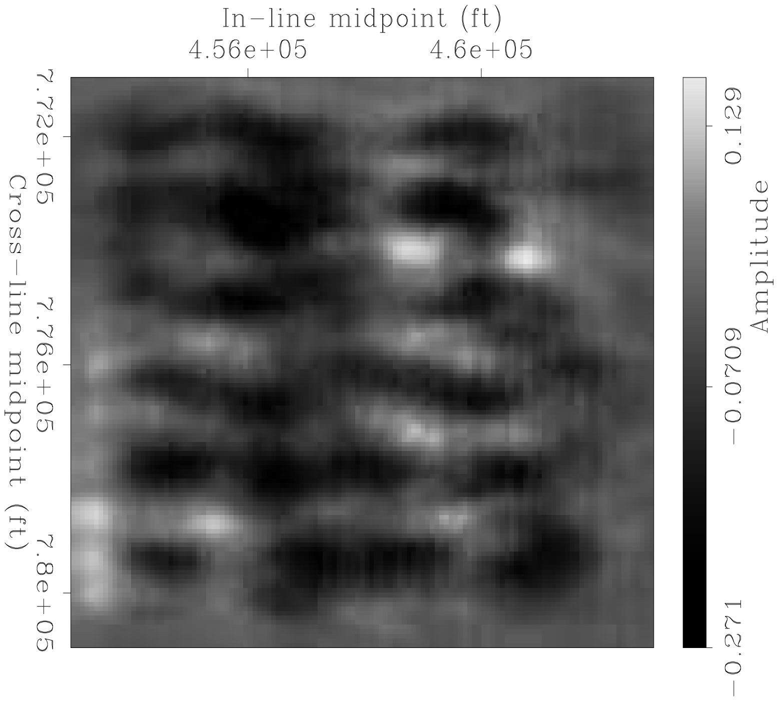

Figure 10: Difference in migrated images between the unconditioned AMO and the normalized AMO. nizar1-diff-amo [CR]

concept that normalizes each input trace by the local fold of its corresponding bin. The technique represents a new development in our proposed strategy for processing wide-azimuth surveys for amplitude inversion. Results of the application of integral migration and integral AMO as discrete summations over the preconditioned data have proved to correct and equalize the imaging process for the effects of irregular fold. The advantage of applying the normalization procedure at the AMO stage is threefold: (1) reduction of the size of prestack data subsets (2) interpolation to a regular grid before imaging (3) common-azimuth common-offset processing of the 3D survey. Moreover, if we consider processing to be the inverse of modeling irregular data from a regularly-sampled model, AMO can be used to formulate a general inversion scheme for 3D models from irregularly sampled data. The limited small aperture of AMO enables inexpensive implementation of the inversion algorithm. The equalization technique could be used for preconditioning the inversion by column scaling under the assumption of small variations in azimuth and offset. This is the subject of continuing work and a full algebraic description of the solution will be presented in subsequent reports.

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REFERENCES

Beasley, C. J., and Klotz, R., 1992, Equalization of DMO for irregular spatial sampling: 62nd Annual Internat. Mtg., Soc. Expl. Geophys., Expanded Abstract s, 970–973.

Beasley, C. J., 1994, Acquisition geometry related amplitude artifacts: 64th Ann. Internat. Meeting, Procedings of the SEG Post-convention Workshop, Prestack Amplitude Preservation.

Biondi, B., and Chemingui, N., 1994, Transformation of 3-D prestack data by Azimuth Moveout: 64th Ann. Internat. Meeting, Soc. Expl. Geophys., Expanded Abstracts, 1541–1544.

Black, J. L., and Schleicher, K., 1989, Effect of irregular sampling on prestack DMO: 59th Annual Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, 1144.

Chemingui, N., and Biondi, B., 1996a, Handling irregular geometry in wide azimuth surveys: SEP–**92**, 13–28.

Chemingui, N., and Biondi, B., 1996b, Handling the irregular geometry in wide-azimuth surveys: 66th Ann. Internat. Meeting, Soc. Expl. Geophys., Expanded Abstracts, 32–35.

Gardner, G. H. F., and Canning, A. J., 1994, Effects of irregular sampling on 3-D prestack migration: 64th Annual Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, 1553–1556.

Ronen, J., and Liner, C., 1987, Theory of spatial antialiasing of log-stretched multichannel reflection data: 57th Annual Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, Session:S14.5.

Ronen, S., Nichols, D., Bale, R., and Ferber, R., 1995, Dealiasing DMO: Good-pass, bad-pass, and uncostrained: 65th Ann. Internat. Meeting, Soc. Expl. Geophys., Expanded Abstracts, 743–746.

Vermeer, G. J. O., 1994, 3-D symmetric sampling: 64th Ann. Internat. Meeting, Soc. Expl. Geophys., Expanded Abstracts, 906–909.