Simultaneous statics and velocity estimation for data from structurally complex areas

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ABSTRACT

Where subsurface structure is complex, reflection data from land seismic surveys often suffer triply — from statics variations, the presence of various types of noise, and imperfect moveout correction due to crossing events and rapidly varying non-hyperbolic moveout. For such data, velocity analysis, already difficult due to the non-hyperbolic moveout and crossing events, is further complicated by anomalies due to variations in the near-surface. Conversely, accurate statics estimation requires some accuracy in the velocity model. Because the velocity and statics problems are intertwined for data from structurally complex areas, it is appropriate to treat the two problems as one.

Modern practice for data from structurally complex areas is to base velocity analysis on iterative use of prestack depth migration in conjunction with some process such as depth-focussing analysis. The hope is that the iterations will converge to an acceptable velocity model. We propose to incorporate into this iterative velocity analysis a statics-estimation procedure that also utilizes prestack migration. When applied to statics-contaminated data, the prestack depth migration will correct the data for non-hyperbolic moveout, dipping, and crossing events, provided that the velocity model is sufficiently accurate. These prestack-migrated data are then stacked, and the stacked traces are input to a multi-offset modeling that generates an unmigrated reference trace for each of the traces in the unstacked data. Cross-correlation of each data trace with its associated reference trace gives a time shift for that data trace. The derived shifts are then used in a conventional statics-estimation procedure under the familiar assumption of surface-consistency.

Tests with statics-contaminated Marmousi model data show that even where the initial velocity model is poorly known, the migration-based method produces acceptable initial-stage statics estimates. After applying the method iteratively in conjunction with a migration velocity analysis, alternating between statics and velocity estimation, both velocity and statics solutions are improved, producing a good statics solution in the Marmousi data after just two iterations. Further iterations can then be directed solely towards improvement of the velocity model.
INTRODUCTION

Tjan et al. (1994) showed that the compounding of problems due to random noise, large static time-distortions, and complex moveout can cause conventional statics-estimation methods to fail. A major source of error for conventional statics-estimation methods is the imperfect moveout correction. Typically, these methods apply a normal-moveout (NMO) correction to the data, followed by a common-midpoint (CMP) stack. The stacked trace acts as a reference trace for the traces in the CMP gather. Clearly, when the data contain crossing events and non-hyperbolic moveout, simple NMO correction does not suffice and large errors can be introduced in the statics-estimation procedure. Tjan et al. (1994) proposed introducing prestack depth migration into the statics-estimation process to align events in common-reflection-point (CRP) gathers. The prestack migration will do necessary correction for non-hyperbolic moveout, as well as remove the dependence of moveout velocity on dip, provided that the velocity model used for the migration is accurate.

In their approach, Tjan et al. obtain a separate reference trace for each individual data trace from the survey by using the stacked, prestack-migrated trace for each CRP gather as input to multi-offset modeling. Cross-correlation of each original statics-distorted data trace with its associated reference trace gives the time shift for that data trace. With the derived shifts, static corrections can then be estimated by a Gauss-Seidel approach (Taner, et al., 1974) or a power-stacking method (Ronen and Claerbout, 1986), both under the conventional assumption of surface-consistency.

Tests of this method applied to synthetic traces from a complex structural model, the Marmousi model (Versteeg and Grau, 1991), contaminated by added surface-consistent statics and bandlimited random noise, have demonstrated the superiority of this approach over conventional methods, as long as the correct velocity structure is used in the process (Tjan et al., 1994). Unfortunately, knowledge of the true subsurface velocity structure is a luxury available solely in the synthetic environment.

Where subsurface is complex but data are not complicated by near-surface time anomalies, iterative methods have been developed for estimation of velocity (Faye et al., 1986). At the heart of the iteration process is the costly step of prestack depth migration. Where near-surface time anomalies are present as well, we suggest incorporating statics estimation into the iteration process. Starting with an initial guess for the velocity, which typically contains large errors, we update alternatively the statics estimation and the velocity model with the goal of converging to an accurate statics solution and velocity model.

Tests of this iterative approach on statics- and noise-contaminated data show that the process is capable of yielding a good statics and velocity solution in only two or three iterations. The superiority of the migration-based approach over conventional methods based on NMO correction is heightened in the presence of noise.
MIGRATION BASED STATICS ESTIMATION WITH AN IMPERFECT VELOCITY MODEL

Tjan et al. (1994) showed, with examples of statics-contaminated data from the Marmousi model, that a statics-estimation method based on prestack migration and multi-offset modeling yields accurate estimates of surface-consistent static time shifts in data from complex subsurface structures, provided that the exact velocity model is used in both the migration and modeling.

Unfortunately, for field data we do not know the velocity model accurately in the early stages of the processing. Consequently we inevitably choose an initial velocity model that contains velocity errors, often large ones. These velocity errors translate into large moveout errors, which will cause errors in the statics solution. Therefore, in the migration-based statics-estimation method, the first iteration of the statics solution will certainly be inaccurate.

In general, we obtain an initial model for the interval (i.e. migration) velocities from stacking velocities obtained from a conventional velocity analysis. Unfortunately, conventional velocity analysis for data that are severely contaminated with near-surface time distortions is not trivial. Often, however, we do not need to rely solely on the seismic data for a guess of the subsurface velocities. A priori information such as well-log data can give a reasonable idea of the velocities in the subsurface. With the Marmousi data set, also, data from two “wells” —at midpoint locations 1504 and 9004 m of the model (see Figure 1)— were provided. From these well data Audebert (1991) obtained parameters for a simple, constant-gradient velocity model,

\[ v(z) = 1623 + 0.7z \text{ m/s}. \]  \hspace{1cm} \text{(1)}

Marmousi data uncontaminated by statics problems

Let us use this velocity model in a migration-based statics estimation applied to the original, non-statics contaminated Marmousi data (one of the 96 common-offset sections is shown in Figure 2). Ideally the statics corrections would be zero since the data are free of imposed static time shifts. Figure 3 shows the prestack depth-migrated image of these data. It shows well-focussed reflectors toward the sides of the model, where the constant-gradient velocity model used is close to the correct one. In the complex part of the model, however, poor focussing results from errors in the velocity model. Multi-offset modeling (the next step in the statics-estimation procedure) with the same velocity model will inevitably result in erroneous reference traces and therefore in errors in the statics solution. As a result, Figure 4 shows estimated statics where none exist in the data. One reason is that since the near-surface is not well modeled, the structural complexity yields dynamic corrections that show up as statics problems. Given that a similar test (not shown here) with a conventional statics method based on NMO correction yielded larger statics estimates, again where none exist, we judge that a larger part is due to poor moveout correction.
FIG. 1. The Marmousi velocity model. Darker shading indicates higher velocity.

FIG. 2. Shortest-offset (200 m) time section from the original Marmousi data.
Fig. 3. Prestack depth-migrated image of the original Marmousi data. The migration velocity has a constant gradient in depth. The first shot location is at midpoint position 3 km, and the 2575 m off-end cable lies to the left of each shot.

Statics-contaminated Marmousi data

Now let us contaminate the Marmousi data with random, zero-mean, surface-consistent source and receiver static time shifts uniformly distributed between $-20$ ms and $+20$ ms (Figure 5). With no loss in generality, we have made the source statics and receiver statics identical. Figure 6 shows the migrated stack of these statics-contaminated data, migrated with the constant-gradient velocity. Now the migrated image suffers from a compounding of the problems of an erroneous migration velocity and the imposed statics. Note especially the loss of high-frequency content compared with the migration result for the original Marmousi data (Figure 3). This high-cut filtering action is typical when misaligned reflections are averaged. Despite shortcomings of this image, remodeling of the data from this image, using the constant-gradient velocity, produces reference traces that can be used for statics estimation.

Figure 7 shows the error in the source and receiver static corrections when we use these reference traces in the statics-estimation procedure. Compare these errors with those when a conventional statics-estimation method (i.e., one based on NMO correction) is used (Figure 8). The conventional method is based on cross-correlation of NMO-corrected traces with a reference trace that is the CMP stack of those NMO-corrected traces. Even though the initial velocity model for the migration and modeling is simple, the estimated statics corrections are considerably more accurate than those estimated with a conventional method. Prestack depth migra-
FIG. 4. Source and receiver statics corrections estimated in the original Marmousi data, which actually have no additive statics. The migration-based method was used with a constant-gradient velocity model. Ideally, the derived statics corrections would be zero for this test.

FIG. 5. Randomly generated source and receiver static time shifts, as a function of station position. The time shifts are uniformly distributed between -20 ms and +20 ms.
tion alleviates the problems due to crossing events even though the velocity model is incorrect. Prestack depth migration with this constant-gradient velocity model, however, does not treat non-hyperbolic moveout correctly and thus introduces errors in the complex part of the model between 4.5 and 6.7 km, where not only crossing events but also non-hyperbolic moveout complicate the data. Especially around station position 6.3 km, an anomalous spike exists in the statics error. This feature is at the location where a large fault in the model cuts the free surface (Figure 1). In this region, reflections terminate against the fault, and, since the velocity model is not correct, cycle skipping is likely.

![Midpoint (km)](image)

**Fig. 6.** Prestack depth-migrated image of statics-contaminated Marmousi data. The migration velocity has a constant gradient in depth.

**SIMULTANEOUS VELOCITY AND STATICS ESTIMATION**

Although migration-based statics estimation with the constant-gradient velocity model has reduced the static contamination, the errors are still too large for accurate imaging in the complex part of the model. The initial velocity model is simply not good enough. Clearly we need to pursue two simultaneous goals here — improvements of both the statics and velocity estimation. Our approach will be to alternate between velocity and statics estimation.

For areas with subsurface structure as complex as that in the Marmousi model, iterative use of prestack depth migration, in conjunction with some process such as depth-focussing analysis (Faye et al., 1986) or the perturbation method described by
**Fig. 7.** Difference between the imposed random static time shifts and the migration-based estimated source and receiver corrections. The prestack depth migration and multi-offset modeling were done with the constant-gradient velocity model.
FIG. 8. Difference between the imposed and conventionally estimated source and receiver statics corrections.
Liu and Bleistein (1994) have been successful in obtaining accurate velocity models after a few iterations — in the absence of statics problems. Here we will follow the method described by Stork (1992) to do the velocity analysis. He uses reflection tomography in the postmigration domain to update the velocity model by flattening CRP gathers.

**Iterative sequence**

One can envision any of several iterative approaches that combine migration velocity analysis with migration-based statics estimation in a bootstrapping effort to improve both. Here, we implement the following straightforward iterative process, in which prestack migration is exercised repeatedly for the dual purpose of converging on an acceptable statics solution as well as on an acceptable velocity structure.

1. Given an initial guess for the velocity model (e.g., from conventional velocity analysis or well-log data), prestack depth migrate the data and exercise the prestack-migration-based, statics-estimation procedure mentioned above. Specifically, stack the migrated data and perform multi-offset modeling to obtain the reference traces for use in conventional surface-consistent statics estimation.

2. Using the data corrected with the above-derived statics estimates, perform prestack depth migration with the initial velocity model. With these migrated data, follow the approach of Stork (1992) to obtain an updated velocity model.

3. Return to step 1, but now use the updated velocity model in the prestack depth migration of data and in the multi-offset modeling. Repeat steps 1 through 3, as necessary.

Within this iterative sequence, we consider two different options. These options pertain to the return to step 1 with the updated velocity model. In option \textit{cum}, the statics estimates are cumulative. The updated velocity model is used in prestack migration of data that have had the statics corrections from the previous iteration applied. In this variation, the reference traces generated by multi-offset modeling are cross-correlated with the data, again after having had statics corrections previously applied. The statics estimates computed during the iteration are added to previously accumulated statics corrections. In option \textit{fresh}, full statics estimates are freshly computed during the iteration. The original statics-contaminated data are used in building the reference traces (i.e., in the migration, stacking and multi-offset modeling) and are correlated with those reference traces.

Each of these variations has its advantages and disadvantages for the iterative processing. To achieve some desired purpose, the two variations can be used interchangeably from one iteration to the next.

Conventionally, several iterations of prestack depth migration are required to obtain an acceptable velocity model where the subsurface is complex. When statics
estimation is incorporated into the process, an additional prestack depth migration and multi-offset modeling, which is as costly as a prestack migration, are required for each cycle through the three-step iteration sequence. This, in itself, still does not add much relative cost to that for the iterative velocity-modeling process, which requires several iterations of partial migration or tomographic inversion and intensive interactive interpretation for each cycle through the three-step sequence.

We judge that large statics distortions in data make analysis of complex moveout particularly difficult. We therefore use only coarse velocity information as input to the statics-estimation procedure as the first step in this approach, hopefully reducing the statics contaminations to a level that allows more refined velocity analysis in a subsequent step. For this first iteration of statics estimation, we can choose either a conventional method and the migration-based method. In the previous section however, we saw that the migration-based method produces better statics estimates than does a conventional method even with an imperfect initial velocity model. Moreover, as Tjan et al. (1994) have shown, in data from areas with complex subsurface structure but with little or no near-surface time distortions, conventional methods may introduce errors that are much larger than those introduced by the migration-based method seen in (Figure 4).

Implementation on the Marmousi data

Let us return to the Marmousi data that have static time shifts imposed on them, and follow the above processing sequence. The first step was done in the previous section, with the constant-gradient velocity model as initial velocity model, and Figure 7 showed the error in the statics solution.

After correction of the statics-contaminated Marmousi data with the statics corrections estimated in the first iteration, we apply Stork's migration velocity analysis method in an attempt to improve the velocity model (step 2). The resulting velocity model (let us call it the "first-update velocity model"), shown in Figure 9, is then used in the second iteration of the migration-based statics estimation (step 1, second iteration).

Figure 10 shows the image of the corrected Marmousi data, prestack migrated with the updated velocity model of Figure 9. Note the large increase in frequency bandwidth compared with the migration shown in Figure 6. Because a large portion of the statics contaminations have been resolved in the first iteration of statics estimation, the high-cut filtering action of stacking misaligned events has been reduced significantly. The improved bandwidth in Figure 10 offers the prospect that the next iteration of the statics-estimation procedure will have the benefit of improved reference traces. At the same time, the poor focussing of many reflectors in Figure 10 indicates that this first-update velocity model still contains large errors.

Figure 11 shows the difference between the cumulative source and receiver statics estimated from the first two iterations of statics estimation and the imposed statics.
Fig. 9. Velocity model after one iteration of migration-velocity analysis (i.e., first-update velocity model). Darker shading indicates higher velocity.

Fig. 10. Prestack depth-migrated image of the Marmousi data corrected with statics corrections obtained in the first iteration of statics estimation. The migration velocity model is shown in Figure 9.
FIG. 11. Difference between the imposed random static time-shifts and the cumulative migration-based estimated source and receiver corrections after two iterations (with option *cum* used in the second iteration).
Likely because of the broader bandwidth in Figure 10 as compared with that in Figure 6 (and, consequently, the better reference traces) the statics errors in Figure 11 have reduced somewhat across the entire section (compare with Figure 7). The large errors in the more complex part of the model (specifically the large peak at station position 6.3 km), however, remain. Apparently the second statics-estimation iteration, with the more accurate velocity model, could not recover from the cycle skip introduced in the first iteration. Perhaps it would be better to compute statics corrections afresh from the uncorrected data (i.e., follow option \textit{fresh} with the updated velocity model).

As a test of this possibility, let us interrupt our process for a moment and insert a velocity model that is believed to be good into the second iteration of the migration-based statics-estimation procedure. Performing his velocity-analysis approach on the original Marmousi data, Liu (1995) has obtained a velocity model (Figure 12) that produces an excellent image of the subsurface. Let us, therefore, try a second iteration of our processing sequence with Liu's high-quality velocity model. Figure 13 shows the prestack-migrated Marmousi data, corrected with the statics solution of the first statics-estimation iteration (in which the constant-gradient velocity model was used) but migrated with Liu's good velocity model.

Figure 14 shows the difference between the cumulative source and receiver statics of the first two iterations of statics estimation and the imposed statics when Liu's velocity model was used in the second iteration (option \textit{cum}). With use of this high-quality velocity model, the statics errors overall are much reduced. Even with the use of a good velocity model, the migration-based method, however, still cannot correct for the introduced cycle skip at about 6.3 km, so the large peak at that location remains.

For comparison, Figure 15 shows the errors in estimated statics obtained with Liu's velocity model, but in this instance total statics have been computed from the original data (option \textit{fresh}) rather than add-on statics computed from data corrected with statics estimates from the first iteration. Now, the cycle-skip problem, is much reduced. Note, however, that the general statics solution has larger errors than those in Figure 14. Apparently, although use of the improved velocity model in option \textit{fresh} helps to overcome the cycle-skip problem, option \textit{cum} has merit in generally improving portions of the solution that are not plagued by cycle-skipping. We will return to this point below.

Based on the result with Liu's velocity model, let us return to our iterative solution of the Marmousi data. Instead of following option \textit{cum} as we did in generating Figure 11, let us exercise option \textit{fresh}. That is, let us return to our statics and velocity iterations, but use the original, statics-contaminated data for a statics-estimation iteration with the first-update velocity model shown in Figure 9. Figure 16 shows the migration of the original, statics-contaminated data with this first-update velocity model. Again, note the high-cut filtering action attributable to the statics contamination, but now the reflectors are more accurately positioned compared with the
**Fig. 12.** Velocity model obtained by Liu (1995) after velocity analysis in the original Marmousi data.

**Fig. 13.** Migrated image of the statics-contaminated Marmousi data with statics corrections obtained from one iteration of the migration-based approach. Liu's velocity model, shown in Figure 12, was used for this migration.
Fig. 14. Difference between the imposed random static time-shifts and the cumulative migration-based estimated source and receiver corrections after two iterations. Here Liu's velocity model was used in option *cum* during the second iteration of the processing sequence.
FIG. 15. Difference between the imposed random static time shifts and the migration-based estimated source and receiver corrections. Here Liu’s velocity model was used in option *fresh* during the second iteration of the processing sequence.
migration based on the constant-gradient velocity (Figure 6).

Figure 17 shows the error for a statics estimation with the first-update velocity model, obtained after a first iteration (Figure 9), but now done on the original statics-contaminated data. The peak at the fault is still present but has reduced considerably, as have errors elsewhere, compared with the statics estimates from the constant-gradient velocity model (Figure 7).

Fig. 16. Stack of prestack migration of the original, statics-contaminated data. The migration was done with the first-update velocity model (Figure 9).

Finally, let us add one more iteration of the three-step velocity and statics estimation sequence. An updated velocity model (Figure 18) is obtained from a migration velocity analysis on data corrected with the newly estimated statics shifts (option \textit{cum}). This second-update velocity model is used in the next iteration of statics estimation. Figure 19 shows the stack of statics-corrected Marmousi data, prestack migrated with the second-update velocity model, shown in Figure 18. Correction was done with the estimated statics of Figure 17. Note the reduced high-cut filtering action compared with the image after the first iteration, shown in Figure 16.

Figure 20 shows the error in the cumulative estimated statics corrections after (1) an initial iteration of statics estimation based on the constant-gradient velocity model, (2) an iteration of statics estimation (option \textit{fresh}) with the first-update velocity model (Figure 9), and (3) a final iteration of statics estimation (option \textit{cum}), with the second-update velocity model (Figure 18).

Now the errors in the statics solution have reduced to an acceptable level, i.e.,
FIG. 17. Difference between the imposed random static time-shifts and the migration-based estimated source and receiver corrections after statics-estimation (option fresh) with the first-update velocity model, shown in Figure 9.

FIG. 18. Velocity model after two iterations of migration-velocity analysis (i.e., second-update velocity model).
Fig. 19. Stack of prestack migration of the statics-corrected data. The migration was done with the second-update velocity model of Figure 18 applied to data corrected with statics estimates obtained from the second iteration of the processing sequence.

Errors do not exceed 1-1/2 samples (the sampling interval here is 4 ms). We have arrived at this result after just three iterations of statics estimation, alternated with two iterations of migration velocity analysis. The estimated statics corrections may now be good enough that further iterations to improve the imaging of the subsurface can now be directed solely to improving the velocity model, as is conventionally done in the absence of statics problems.

We have obtained the quite good statics solution suggested in Figure 20 through the choice of option *fresh* in the second iteration and option *cum* in the third one. This sequence of option choices was aimed at first overcoming the cycle skipping and then refining the statics solution over less troublesome portions of the data.

Let us review the progress toward a statics solution in this sequence of tests with the Marmousi data. Figure 21 collects results for receiver-statics solutions at various stages of the sequence. The statics errors (i.e., unresolved statics problem in the data) after application of a conventional method based on NMO correction (Figure 21a) are large, approaching the size of the statics problem that was imposed on the Marmousi data. One iteration of the migration-based statics approach (Figure 21b), in which a simple linear $v(z)$ model was used for the prestack migration and modeling, was sufficient to reduce the statics errors substantially, although the solution was poorest over the most complex portion of the Marmousi model. In particular, cycle skips near 6.3 km left a large statics anomaly in that region.
Fig. 20. Difference between the imposed random static time-shifts and the cumulative migration-based estimated source and receiver corrections after three iterations.
Figure 21c shows the residual statics errors after a second iteration of statics estimation using the upgraded velocity model (the first-update velocity model) and option cum. While this iteration yields an improved solution over most of the line, it is unable to overcome the cycle-skip problem, near 6.3 km, that arose in the previous iteration.

An alternative second iteration of statics estimation again used the first-update velocity model, but this time with option fresh. This option was chosen (with success, as seen in Figure 21d) for the purpose of suppressing the cycle-skip problem near 6.3 km. Use of option fresh at this stage, however, yielded a poorer statics solution over other portions of the data than was achieved with option cum (Figure 21c). A third iteration, this time with the second-update velocity model and option cum (Figure 21e) gives further improvement in the statics solution over the entire model.

If further iterations of the sequence are deemed desirable (we do not believe the effort is justified here), option cum will be the preferred choice since the residual statics errors in Figure 21e appear to be free of large errors such as those that result from cycle skipping. In comparing the residual statics problems remaining after the various iterations, as seen in Figure 21, we see that, with the exception of the problems near 6.3 km, the solution in Figure 21c (after just two iterations) is quite good. The alternative solution in Figure 21d, followed by the third iteration to yield the result in Figure 21e, primarily improves just the problems over the complex portion of the model.

STATICS ESTIMATION FOR DATA CONTAMINATED WITH INCOHERENT NOISE

In all the tests shown above, the data are noise-free. Tjan et al. (1994) emphasized the problems that conventional method have when the data suffer from the compounding of problems due to static time distortion, noise, and complex subsurface structure. Let us now treat data that suffer from all these problems. Figure 22 shows the near-offset traces of the Marmousi data contaminated by noise as well as statics. The noise is bandlimited to the same general frequency band as that of the signal, and the root-mean-square amplitude of the noise is 1/2 the peak signal amplitude, multiplied by .707. For this definition, we shall say that the signal-to-noise (SNR) ratio is 2. Comparing Figure 22 with the near-offset traces of the original Marmousi data in Figure 2 shows the significant contamination caused by the noise. Let us use these data as input to the migration-based method, starting as before with the constant-gradient velocity model.

Figure 23 is the migrated image obtained from these data. The image has deteriorated compared to the image of the noise-free data (Figure 6), but the high-amplitude (but highly-bandlimited) events still focus reasonably well. Noise is still present in the data, but the SNR, particularly at the dominant lower frequencies, has been improved significantly by the stacking. This noise reduction makes it possible to again obtain acceptable reference traces, despite the high-cut nature of the stacked migration.
Fig. 21. Collected residual receiver statics errors, from previous figures, after various stages of the iterative migration-based statics estimation. The five sets of residual statics errors are described in the text.
FIG. 22. Shortest-offset (200 m) time section from the Marmousi data contaminated by the imposed source and receiver statics and random amplitude noise. Compare with the uncontaminated section in Figure 2.

FIG. 23. Prestack migrated image of the noise and statics-contaminated data. The migration was done with the constant-gradient velocity model.
Figure 24 shows the error in the estimated statics in these statics-contaminated, noisy data. Notably, the error has not increased much in comparison with the error obtained in the noiseless case (Figure 7). Apparently, the migration-based method was able to generate reference traces of sufficient quality that the problems due to the noise are minimized. Given the quality of the solution after this first iteration of statics estimation, in subsequent iterations we might expect success similar to that found for the noiseless data. One source of uncertainty in that expectation, however, is difficulty that may arise in interpreting velocity analyses in the presence of noise.

![Error in source statics](image)

![Error in receiver statics](image)

Fig. 24. Difference between the applied random static time shifts and the migration-based estimated source and receiver corrections in statics- and noise-contaminated data. The constant-gradient velocity model was used in both the migration and modeling.

Now consider the residual statics error when a conventional method is applied to the noise-contaminated data (Figure 25). In contrast to the result for the migration-based approach, statics estimates here have deteriorated considerably compared with the conventionally estimated statics in noise-free data (Figure 8). Apparently, the compounding of statics, noise, and poor moveout corrections, in the conventional approach has accentuated difficulties in statics estimation. From these results, we can expect that the benefits of the migration-based approach over the conventional NMO-based approach to statics estimation for noiseless data will be even larger for noise-contaminated data.
**Error in source statics**

**Error in receiver statics**

**FIG. 25.** Difference between the applied random static time shifts and the conventionally estimated source and receiver corrections in statics- and noise-contaminated data.
CONCLUSION

The treatment of statics- and noise-contaminated data from structurally complex areas presents a chicken-and-egg problem: statics correction, velocity estimation, suppression of noise, and imaging are all intertwined. In conventional processing, the answer has been to iterate the various processes: get a first estimate of the stacking velocity; attempt statics estimation and correction; with the obtained statics solution, attempt to improve the estimate of stacking velocity; and so on. Given the mixture of problems in complex areas, we must also be prepared to iterate several times with the migration-based statics-estimation procedure. Such an effort would entail considerable cost, but, even in the absence of statics problems, we presently iterate between velocity estimation and migration in complex areas. As we have implemented our process here, the added cost compared with such an iterative velocity analysis is an additional prestack depth migration and a multi-offset modeling for each iteration. These computer-intensive steps, however, likely introduce only modest additional cost and effort relative to the intensive interactive interpretation required for the velocity modeling.

Once we are satisfied with the obtained solution (such as after three iterations in our tests with the Marmousi data), we can direct all attention to iterative improvement of the velocity model alone. Then, after having converged on an acceptable velocity model, we can revisit the migration-based method for one final effort at statics estimation.

The examples shown here were all done with the Marmousi synthetic data set, with surface-consistent static time distortions imposed on the traces. Although we have shown that the migration-based method can work well for such data, even when the initial velocity model is far from correct, field seismic data are not so ideal. Noise, both random and coherent, may contaminate the data, and time distortions may be neither surface consistent nor static. Therefore, further tests on field data need to be done to assess the migration-based method under more realistic conditions. Of course, conventional methods would encounter the same additional problems with field data. Our expectation is that the degradation that reality imposes on the migration-based approach is less severe than that on the conventional approach by virtue of the opportunity to reduce moveout problems from the combination of so many compounded problems.

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