Receiver static corrections from passive seismic data

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ABSTRACT

A stack power optimization method is used to compute receiver station statics using data from a passive seismic survey. The method relies on the presence of vertically incident plane wave energy in the data. The computed statics are those time shifts that would best align such vertically incident events. Two problems that affect this algorithm are the effect of random noise (and coherent but not vertically incident energy) on the crosscorrelation procedure that is central to the processing, and the inability to distinguish between true statics and arrival time differences caused by energy that is not vertically incident. Using more data in the crosscorrelation helps to overcome the noise problem somewhat. To determine the effectiveness of the method, I process passive data recorded during two different recording periods independently. The results show that there is some agreement between the two statics solutions obtained, but not enough that either the problem of interfering noise or of non-vertical incidence is completely overcome. The results suggest that multichannel filtering to enhance vertically incident energy relative to the incoherent and coherent noise is necessary if the method is to be able to "see" through the noise better.

INTRODUCTION

The determination of receiver station corrections or receiver statics, the time shifts that correct for surface topography and near-surface velocity variations and improve the coherency of recorded signals across a receiver array, is a well-known problem that has been studied in the contexts of both earthquake and exploration seismology. Aki and Richards (1980) examined the problem of determining the station corrections that align teleseismic events incident on a receiver array. Following their discussion, a plane wave moving with an apparent surface velocity c and arriving from a direction specified by an azimuthal angle ϕ arrives at the i–th station at a time given by:

$$t_i = t_0 + \frac{\cos\phi}{c}(x_i - x_0) + \frac{\sin\phi}{c}(y_i - y_0) + \tau_i$$

where (x_i, y_i) are the coordinates of the receiver, t_0 is the arrival time of the wave at a reference point (x_0, y_0), and τ_i is the station residual. The station correction is then $-\tau_i$.

Once the traveltime at each receiver t_i has been picked, then, the following system of equations can be set up:

$$\begin{pmatrix} 1 & x_1 - x_0 & y_1 - y_0 \\ 1 & x_2 - x_0 & y_2 - y_0 \\ \vdots & \vdots & \vdots \\ 1 & x_n - x_0 & y_n - y_0 \end{pmatrix} \begin{pmatrix} t_0 \\ \frac{\cos\phi}{c} \\ \frac{\sin\phi}{c} \end{pmatrix} = \begin{pmatrix} t_1 \\ t_2 \\ \vdots \\ t_n \end{pmatrix}$$

and solved to obtain t_0, ϕ, and c using least squares or other inversion techniques, with the constraint that the sum of the squares of the station corrections $\Sigma{\tau_i}^2$ is minimized. Then the station corrections can be obtained by solving for τ_i at each receiver.

Wiggins et al., (1975) describe a method for determining shot and receiver station static corrections for a seismic reflection survey. The picked traveltime for a given reflection event T_{ij} is written as a sum of four terms:

$$T_{ij} = S_i + R_j + G_k + M_k X_{ij}^2$$

where i is the receiver position index, j is the source position index, k is the midpoint index (which is equal to $(i + j)/2$), S_i is the traveltime from the source to some common datum plane, R_j is the traveltime from the datum plane to the receiver, G_k is the two-way traveltime from the datum plane to the reflector, M_k is the residual normal moveout coefficient at the kth CDP position, and X_{ij} is the distance between receiver j and shot i. Then a system of equations can be set up with the form:

$$Ap = t$$

where:

$$p^T = (\, S_1 \ \ \ldots \ \ S_n \ \ R_1 \ \ \ldots \ \ R_m \ \ G_1 \ \ \ldots \ \ G_l \ \ M_1 \ \ \ldots \ \ M_l \,)$$

and:

$$t^T = (\, T_{11} \ \ T_{12} \ \ \ldots \ \ T_{mn} \,)$$

and the matrix A contains only three ones and an RNMO coefficient on each row of the matrix, in columns that indicate the source, receiver, and midpoint positions for the traveltime in the corresponding row of the vector t.

The key similarity between these two methods is that travel times for an incident signal must be picked and then represented as a linear sum of several components, each of which depends on some physical parameter, such as apparent velocity of the wave or travel time from source to the datum plane. Representing the problem in this linear fashion allows the components (and the physical parameters upon which they depend) to be computed using least squares or other inversion techniques.

Event picking is not practical when dealing with passive seismic data. Random noise is very strong relative to coherent energy, and tracking an event reliably for more than a few adjacent stations is difficult. Ronen and Claerbout (1985) and Rothman (1985) described statics algorithms that do not require traveltime picking. These methods iteratively determine static corrections that best improve the final stack, without the need of identifying specific reflections. The methods of Ronen and Claerbout and of Rothman proceed as follows. The traces are stacked with no static corrections, or perhaps field static corrections based on elevations. Then each trace is crosscorrelated with the stacked trace (minus its own contribution to the stack). The crosscorrelation lag that gives the maximum correlation coefficient is the static shift for that receiver that would best improve the stack power. A correction is computed for each trace in turn, and the procedure iterates until the statics solution has converged.

The difference between the two methods lies in their optimization strategies. In the method of Ronen and Claerbout, the new static that best improves the stack is always chosen. Thus their method goes to the local maximum of stack power that is nearest the starting position. For this reason, it is best applied to the problem of residual statics estimation, where the nearest local maximum is likely to be the desired stopping place. Rothman's simulated annealing method is able to handle very large statics, even if cycle skips or conflicting events are present. In this work, I have coded and used the optimization method of Ronen and Claerbout. Because of the possibility of conflicting events and the large amount of random noise, there may be advantages to using a global optimization method such as simulated annealing, but because of the size of the passive seismic dataset the computational cost would be extremely large.

RESULTS

The passive dataset I have used contains 1023 sign-bit channels, from which 120 32 second records of data have been recorded. A portion of one record is shown in Figure 1. I have independently obtained statics solutions for the first 20 records of the dataset and the last 20 records. The independent processing of the two recording intervals will serve as a check on the reliability of the method. If the two solutions agree well, then it is reasonable to assume that we have obtained true statics corrections.

The method proceeds as follows. The 1023 traces in a record are summed with no shifts applied to produce a single stacked trace. Then each trace in turn is crosscorrelated with the stacked trace (minus its own contribution). The crosscorrelation

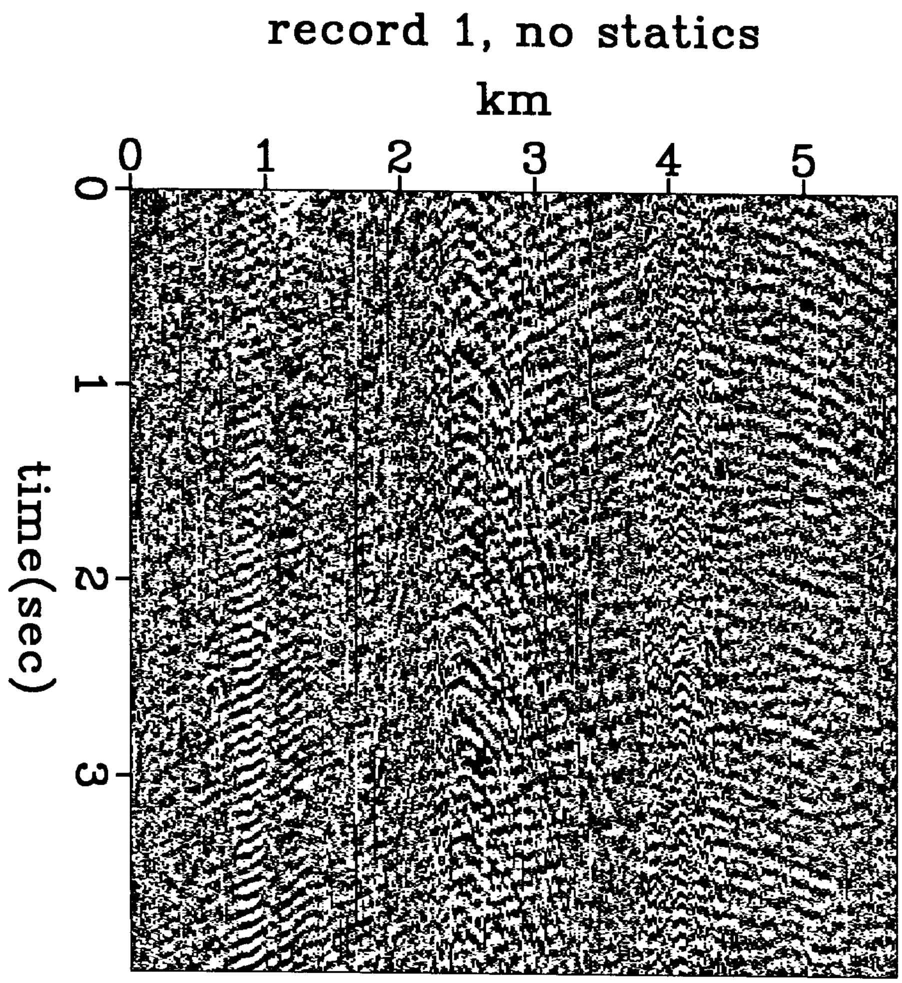


FIG. 1. A portion of a passive seismic record.

value for a particular lag is the stacked trace power that would result if that lag were selected as the new static value.

These crosscorrelations are computed for each of the twenty records being studied, and then the twenty crosscorrelation functions for each receiver are averaged to produce a single crosscorrelation. Averaging the crosscorrelations gives us the same result as if all twenty records were concatenated to form one record that is 640 seconds long. This large amount of data redundancy is important. Because of the small amount of vertically incident energy and the large amount of noise contamination, increased data redundancy increases the contribution of vertically incident energy to the crosscorrelation, since all vertically incident energy should correlate at a lag corresponding to the static solution, while noise will affect all lags.

From the averaged crosscorrelations, new static values are chosen by selecting for each receiver the crosscorrelation lag that gives the maximum stack power. The algorithm can then be iterated, with the stack being formed by taking into account the static corrections obtained in the previous iteration.

If the statics solutions for the two recording intervals are in close agreement, then we can assume that we have obtained the true statics solution. If there are discrepancies, these are most likely due to the effect of noise contamination on the statics algorithm. There are two ways in which noise can affect the processing. First, coherent noise can affect the crosscorrelations. Second, coherent energy that is not vertically incident can be mistaken for vertically incident energy with "statics" corresponding to the differing arrival times due to non-vertical incidence.

Figure 2 shows the crosscorrelation functions obtained by correlating each of the traces in the first record of the passive seismic dataset with the stack of all 1023 traces, along with the same results from the first record in the last part of the survey, record 101. We could pick statics from these crosscorrelations, but more reliable picks are made if the repeat the procedure for all twenty records and then average. Figure 3 shows the crosscorrelation functions resulting from averaging the correlations from the first twenty records of the survey, as well as from the last twenty records of the survey. The difference is just barely noticeable at this stage, but will be more apparent when averaging is used for later iterations.

From the crosscorrelation functions in Figure 3, station statics are picked. The results are shown in Figure 4 for the two parts of the survey. The two static solutions have some gross similarities, but are very different. This implies that the crosscorrelations were contaminated by noise, and therefore the resulting picks do not represent the true statics solution.

When applying this method iteratively, I found that the crosscorrelation functions improve noticeably for a few iterations, and then that additional iterations produce insignificant amounts of improvement. Figure 5 shows the crosscorrelation functions obtained for a single record from the beginning and end of the survey (the same two records as in Figure 2), and Figure 6 shows the twenty-record average for

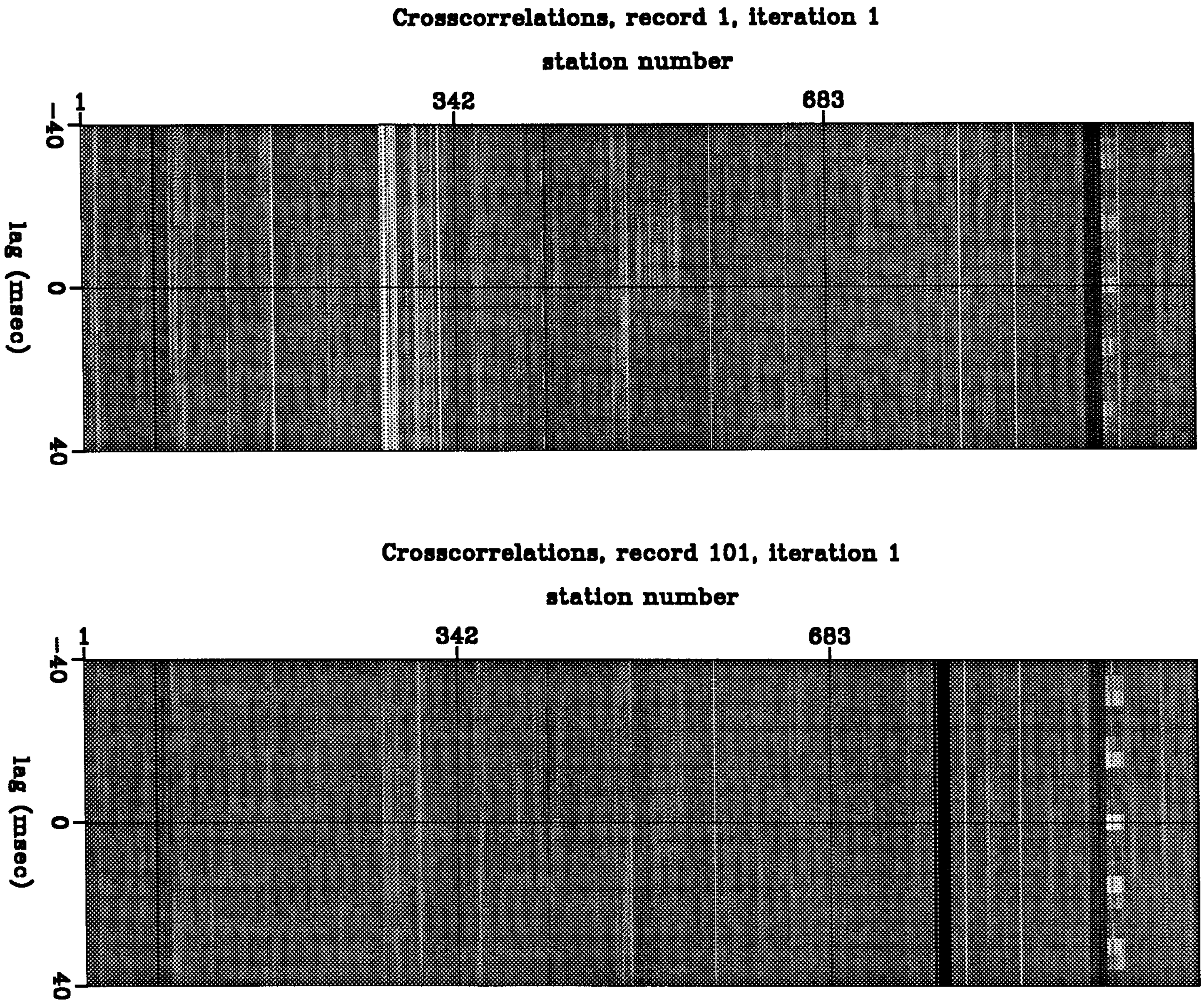


FIG. 2. Top, crosscorrelation functions computed by correlating every trace in one record with the stack. Bottom, same result using a record from a second recording interval. White indicates positive correlation, black negative correlation. Several bad traces are evident.

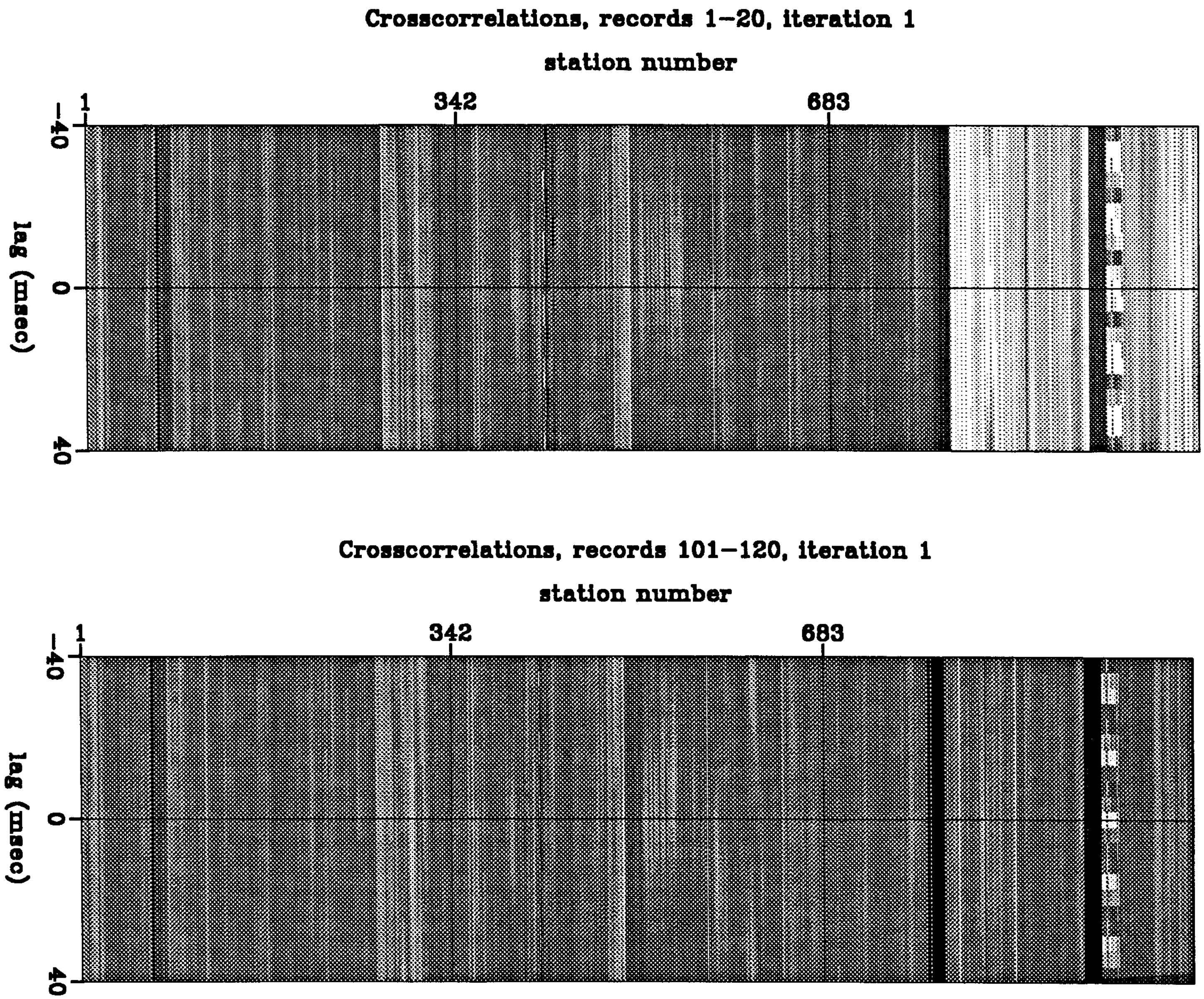


FIG. 3. Same as Figure 2 only crosscorrelations are averaged over twenty records. Top, first twenty records of the survey are used. Bottom, last twenty records are used. While averaging has made modest improvements, its benefits are more apparent in later iterations.

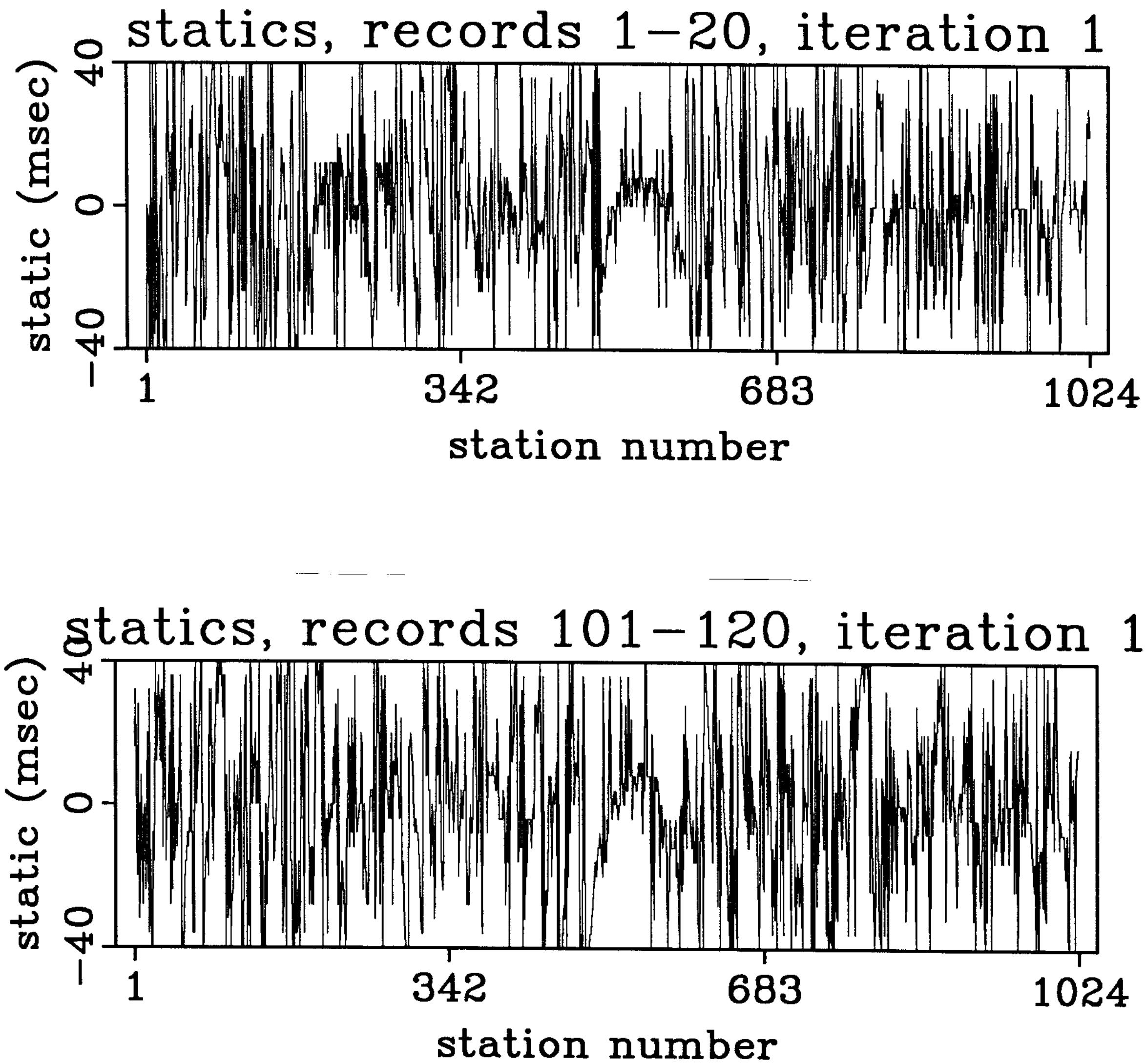


FIG. 4. Receiver station statics picked from the crosscorrelation functions of Figure 3. Top, for first twenty records of the survey. Bottom, for last twenty records of the survey. While there are some similarities, large differences suggest that noise contamination has hindered the method.

the two parts of the survey after three iterations. Here the benefits of averaging are more noticeable, as is the improvement gained by running several iterations of the statics algorithm. The correlation functions from the two parts of the survey have been sharpened by the application of statics in computing the stack. The corelation functions from the two parts of the survey have some obvious similarities, suggesting that, to some extent at least, we are seeing the effects of differing arrival times at the various receivers that would be corrected by application of statics.

Figure 7 shows the statics that are picked from the crosscorrelation functions of Figure 6. Though the correlation functions from the two different parts of the survey have many similarities, the statics obtained from the two are still quite different. In fact, a quick statistical analysis implies that the agreement between the two sets of static picks was better after the first iteration. If we subtract one set of statics from the other and look at the standard deviation of the difference (a measure of how dissimilar the two solutions are) it is actually slightly smaller after the first iteration than after the third iteration.

Figure 8 shows the same portion of the passive dataset as Figure 1 with static corrections from Figure 7 (for the first recording interval) applied. There is obviously an increased amount of lateral coherency in the data after statics application. The stack power for this record has in fact been almost doubled by the application of statics. However, hyperbolic events visible in Figure 1 have been removed by the application of statics. This points to a problem that was alluded to earlier, that the differing arrival times of an event that is not a vertically incident plane wave can be mistaken for static shifts superimposed on an otherwise vertically incident event. This ambiguity has a serious effect on the method, since these apparent statics cause correlations that may mask correlations due to true statics. For the method to be successful, I need to come up with a way of suppressing energy that is not vertically incident that works better than stacking. This problem was addressed by Burg (1964), for the problem of extracting mantle P-waves in the presence of ambient noise. He used the properties of the noise to design a frequency-dependent filter for each trace, with the result that vertically incident energy is enhanced relative to noise. I plan to determine whether a similar approach can also overcome the noise problems that have affected these statics solutions.

CONCLUSIONS

The statics algorithm is partially successful at seeing a consistent set of receiver station statics for the passive seismic data, but is hindered by noise in two ways. First, noise affects the quality of the crosscorrelations from which statics are picked. Second, the differing arrival times of events that are not vertically incident can be misinterpreted as static shifts on an otherwise flat event. Stacking is not effective at dealing with either of these problems and enhancing energy that is truly vertically

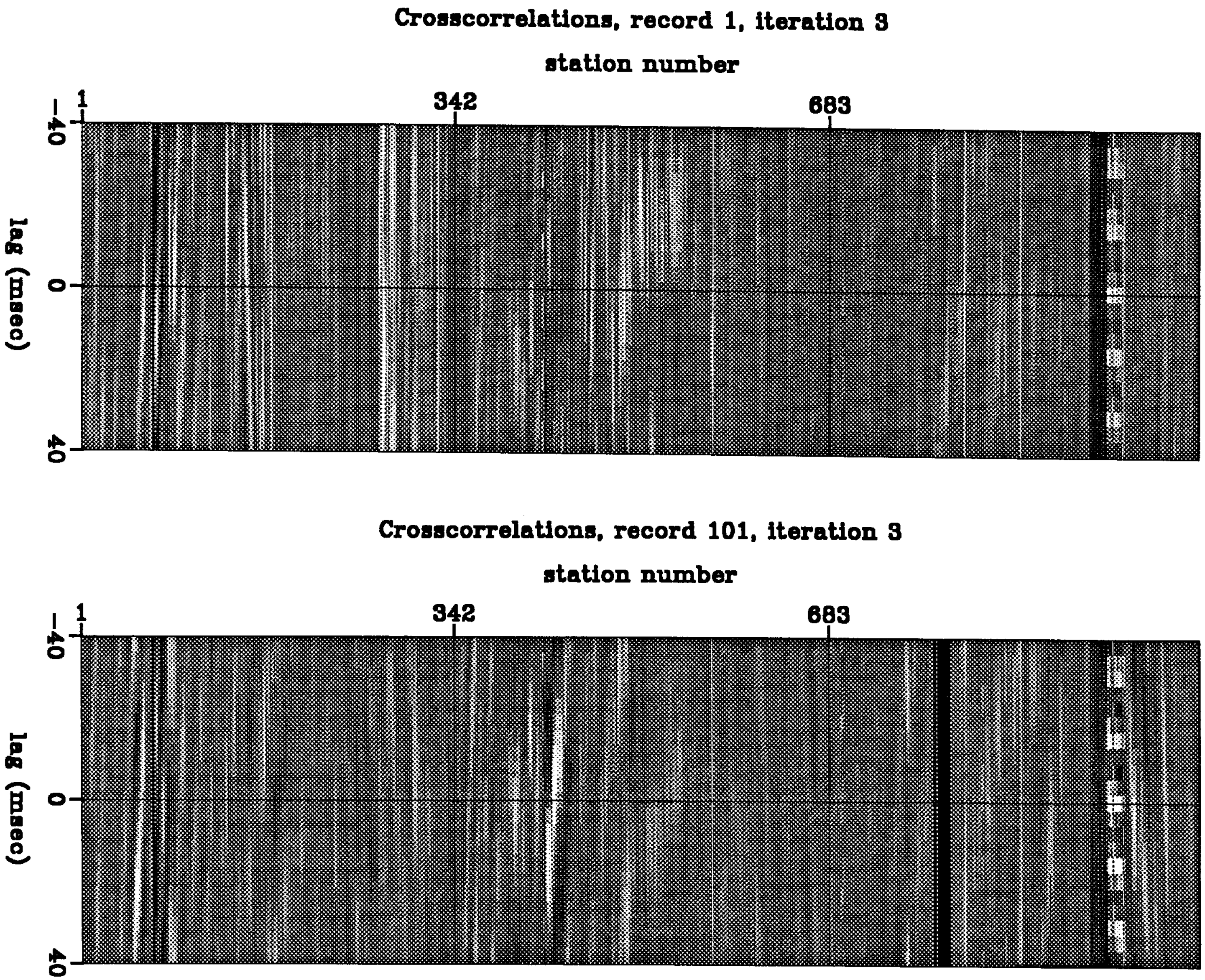
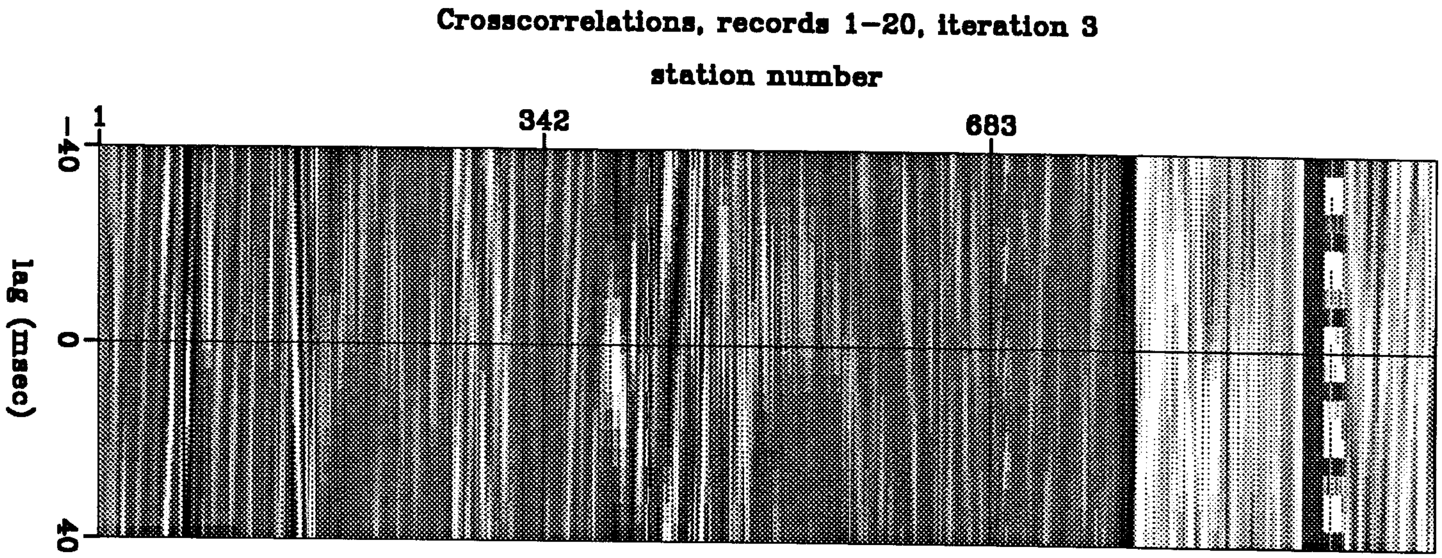


FIG. 5. Crosscorrelation functions for a single record after three iterations of the statics algorithm. The records are the same ones used in Figure 2. Top, the record is from the first recording interval. Bottom, from the second recording interval.



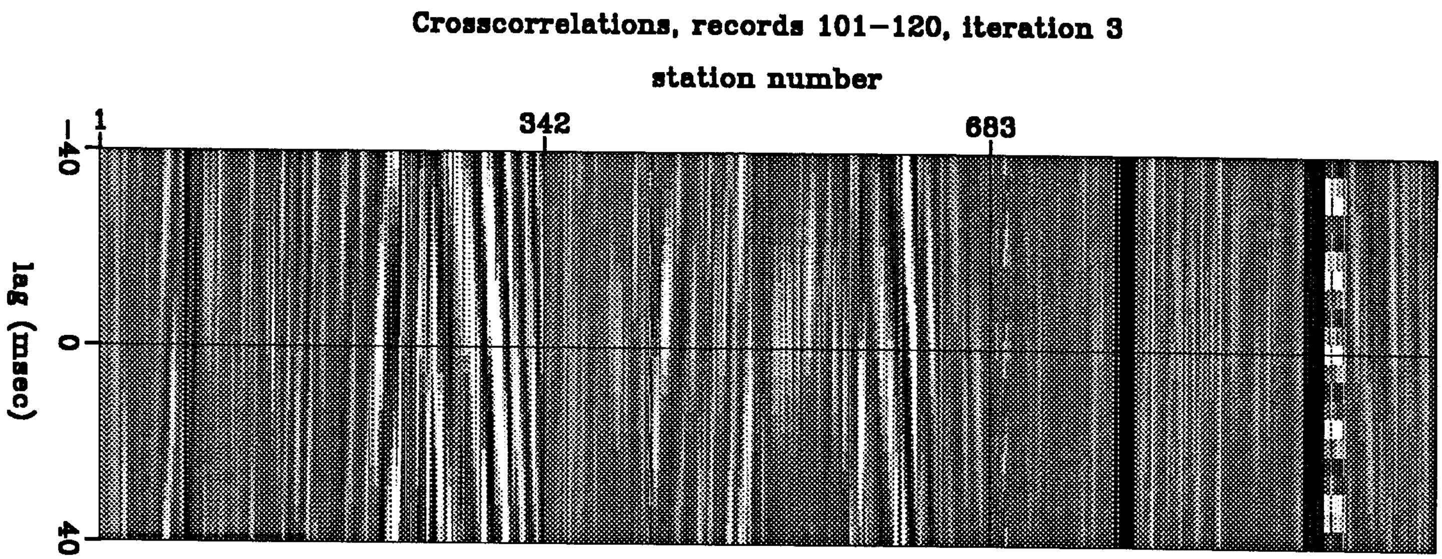
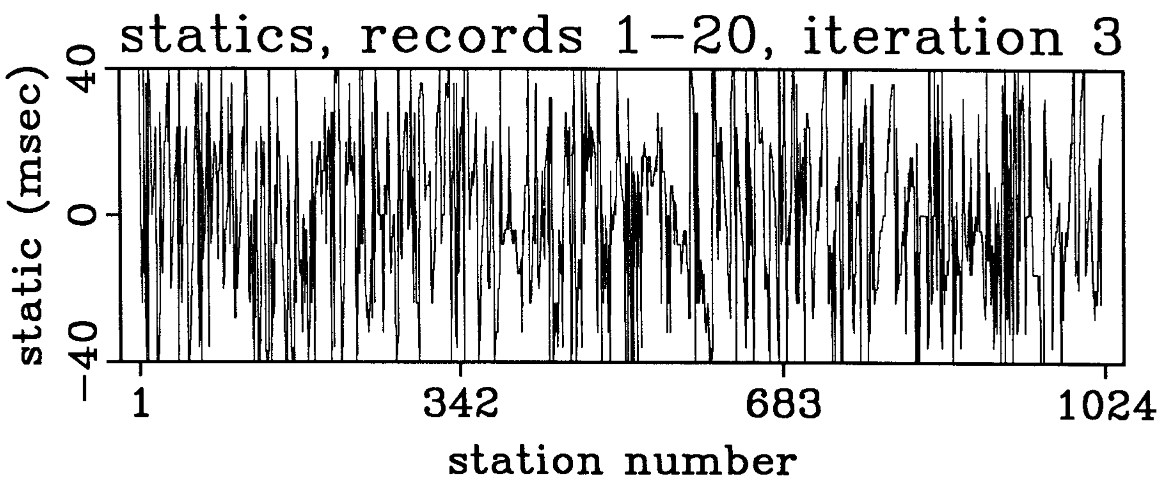


FIG. 6. Crosscorrelation functions computed by twenty-record averaging after three iterations of the statics algorithm. Top figure is average over first twenty records of the survey, bottom is average over the last twenty records. Crosscorrelations are much sharper than after the first iteration because of the application of statics derived in previous iterations. Note the benefits of averaging over a number of records by comparing with Figure 5.



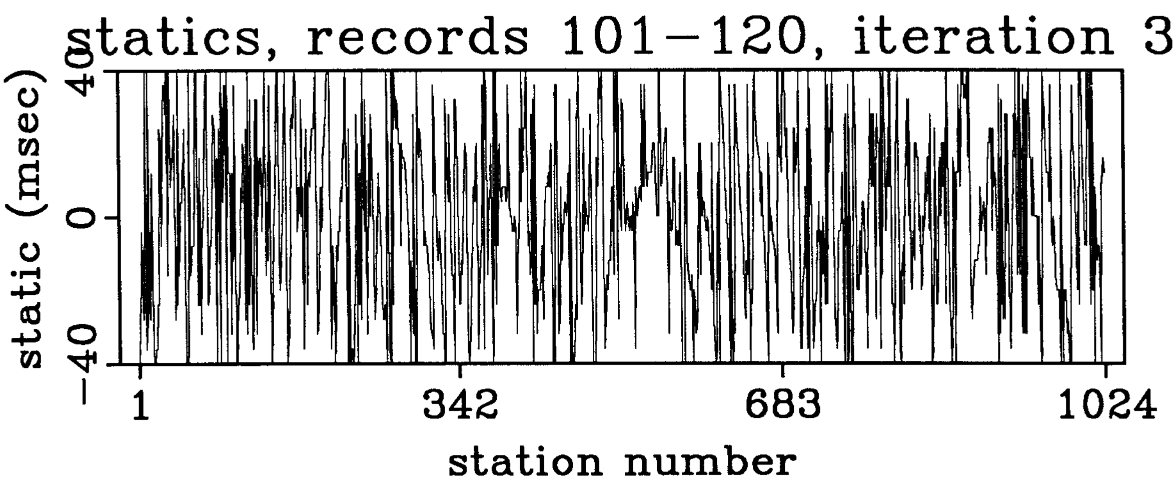


FIG. 7. Statics solutions obtained after three iterations for the two different recording intervals. These are picked from the crosscorrelations of Figure 6. While the crosscorrelations show a fair amount of agreement, the statics are still very different, suggesting that the problem of noise contamination has not been completely overcome.

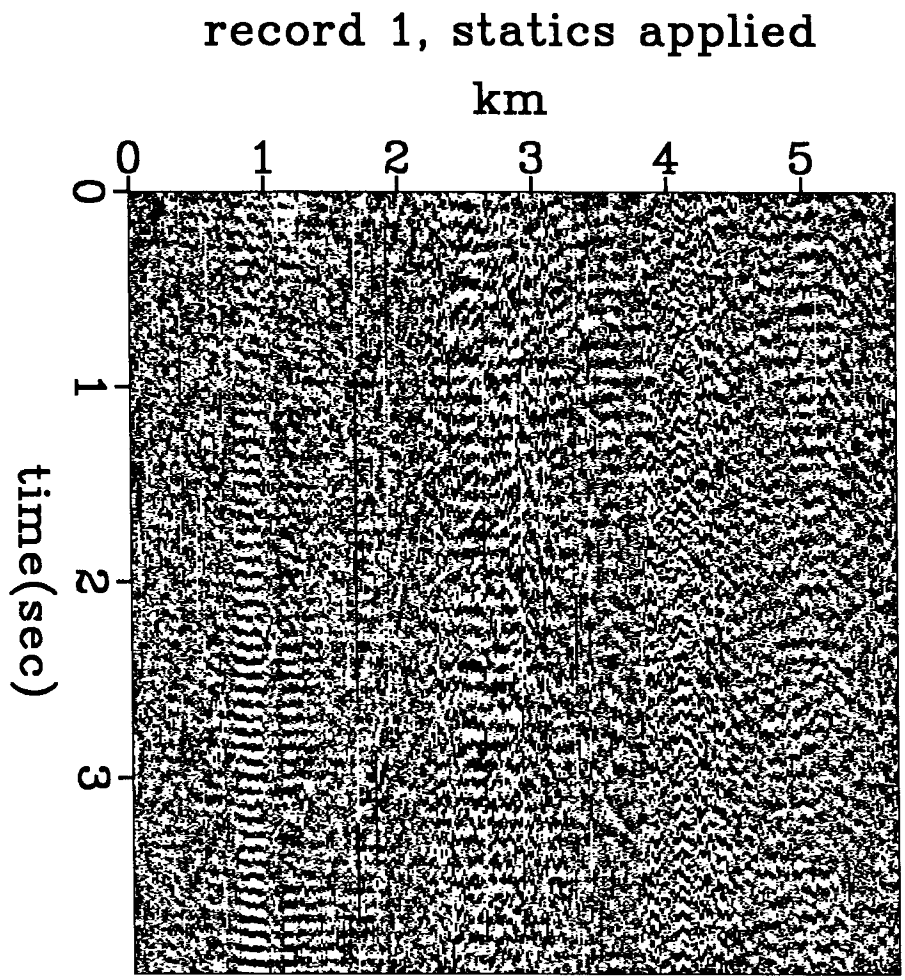


FIG. 8. Same portion of a passive seismic record displayed in Figure 1, but with static corrections applied. While lateral continuity is improved, some moveout has been interpreted as statics and removed.

incident. A multichannel filtering scheme that enhances vertically incident energy better than stacking would probably enable this algorithm to do a much better job.

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