Selective-correlation velocity analysis

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Summary

The need for increased resolution in velocity spectra is clear when one wishes to distinguish between neighboring primary events from reflectors with conflicting dip, or to identify primaries in the presence of multiples.

The transformation in velocity analysis from the offset and reflection-time domain to the stacking velocity and zero-offset-time domain can be achieved using any of several coherence measures based on the crosscorrelations between traces in a collection such as a common-midpoint (CMP) gather or common-image gather (CIG). Use of selected subsets of crosscorrelations, rather than all possible ones in a gather, however, can improve both the reliability and resolution of velocity analysis. In selective-correlation velocity analysis, we include in the summation only those crosscorrelations for whose pair of traces the relative differential moveout of reflections exceeds a chosen threshold value.

Comparisons of the performances on synthetic CMP gathers show that selective-correlation velocity analysis considerably enhances the resolving power of velocity spectra over that of conventional crosscorrelation sum (whether normalized or unnormalized) in the presence of closely interfering reflections, statics distortions and random noise, at no sacrifice in the quality of results, and does so at computational cost that is comparable to that for conventional velocity analysis.

Introduction

A conventional approach for estimating stacking velocities is to pick maxima in some coherence measure computed for a number of trial moveout velocities at fixed zero-offset reflection times (Taner and Koehler, 1969). A peak in the spectrum indicates the velocity corresponding to a hyperbolic moveout that fits the data relatively well at that zero-offset time. This procedure is repeated for different uniformly-incremented times, and the computed velocity spectrum is displayed as a function of zero-offset traveltime and trial velocity.

Stacking-velocity spectra provide maximum-likelihood estimates for stacking velocity of well-separated reflections in the presence of additive uncorrelated noise with Gaussian statistics, and they are relatively simple and computationally efficient. When, however, reflection events (perhaps one being a multiple) are too close to one another and have little moveout difference relative to the dominant period in the data, the velocity estimates can be highly erroneous.

Various methods have been proposed for improving the resolution of stacking velocity analysis (e.g., Kirling et al., 1984; de Vries and Berkhout, 1984; Toldi, 1989; Biondi and Kostov, 1989). They typically require specific information about the reflections and are computationally more intensive than is conventional velocity analysis. Here, we describe a method for increasing the resolution of stacking velocity analysis that retains the robustness of conventional velocity, doing so at comparable computational cost.

Approach

The approach here is a variation on the sum-of-crosscorrelations approach of Neidell and Taner (1971). While our method can be applied using either normalized or unnormalized coherence measures, here we consider the approach in terms of the unnormalized crosscorrelation measure (UC) given, as a function of trial velocity v_{trial} and two-way zero-offset traveltime t_0, by

$$UC(v_{trial}, t_c) = \sum_{w} \sum_{k=1}^{M-1} f_{k,t(k)} \sum_{j=k+1}^{M} f_{j,t(j)}, \qquad (1)$$

where M is the number of traces in the CMP gather or CIG, and $f_{j,t(j)}$ is the amplitude on the jth trace along a reflection-time trajectory $t(j)$, parallel to a specified time window w centered on the hyperbolic moveout curve governed by trial velocity v_{trial} and zero-offset time t_c.

In conventional velocity analysis, all possible crosscorrelations among the traces of a CMP gather are summed, with equal weight given to each contributing correlation, independent of the differential moveout between crosscorrelated traces. If the differential moveout is small, however, as occurs especially for short-offset traces, reflection events on the traces will be approximately in phase for a relatively wide range of velocities, giving a broad semblance response as a function of trial velocity. In contrast, crosscorrelation of a pair of traces with large differential moveout offers relatively large resolving power for the velocity estimation. The core idea underlying the approach here is thus to allow into the summation only those crosscorrelations whose pair of traces have a relatively large differential moveout.

To select which crosscorrelations to exclude from the computation of velocity spectra, we first assign a numerical *significance value* to each pair of crosscorrelated traces, using a parabolic trajectory as a convenient approximation of moveout. Given source-to-receiver offsets x_j and x_k for the jth and kth traces, with $j > k$, the parabolic

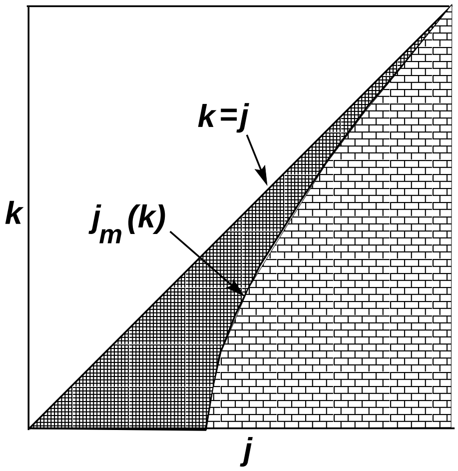

Fig. 1: Cartoon indicating those combinations of traces k and j whose crosscorrelations are used in the selective-correlation-sum method (shown as the brick pattern) and those combinations that are excluded from the sum (shown as the fine rectangular-grid pattern).

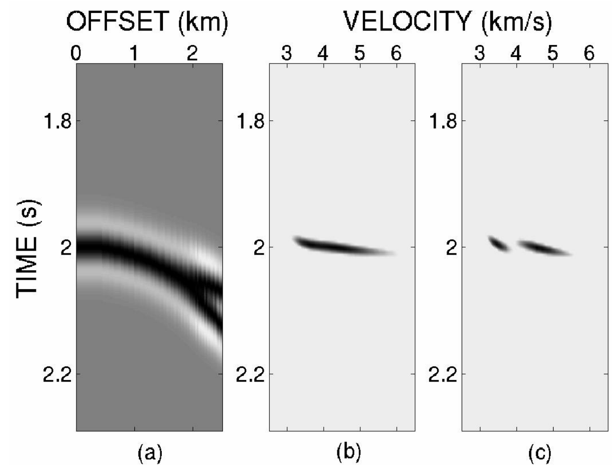

Fig. 2: (a) Synthetic CMP gather with two interfering reflections and velocity-analysis panels using (b) 100% and (c) just 25% of the crosscorrelations (dark shading indicates relatively high coherence).

approximation of the differential moveout Δt_{jk} is proportional to the difference of squared offsets, $\Delta t_{jk} \propto x_j^2 - x_k^2$, and the associated significance value, S_{jk}, satisfies

$$0 \leq S_{jk} \equiv \frac{x_j^2 - x_k^2}{x_{\max}^2 - x_0^2} \leq 1, \qquad (2)$$

where $x_{\max}$ is the maximum offset, and x_0 the minimum offset. Each possible crosscorrelation pair is thus assigned a significance value. We then discard from the computation all crosscorrelations with significance values below a specified threshold. One might choose, for instance, to include in the summation only a relatively small percentage (e.g., 30%) of all possible crosscorrelations — those with the most resolving power.

Figure 1 depicts the idea. Ignore the triangular region shown in white because we consider only $k < j$. The region shown by the brick pattern depicts those combinations of trace indices k and j for which crosscorrelations are included in the velocity-analysis computation. Thus, in the selected-correlation-sum approach, equation (1) is modified to

$$UC_{sc}(v_{trial}, t_0) = \sum_w \sum_{k=1}^{M-d_m} f_{k,t(k)} \sum_{j=j_m(k)}^{M} f_{j,t(j)}. \qquad (3)$$

The changes from equation (1) to equation (3) are solely in the lower limit, $j_m(k) \equiv k + d(k)$, for the sum over j, and in the upper limit for the sum over k. Here, $d(k)$ is the minimum difference $j - k$, which is a function of k, and d_m is the minimum of $d(k)$ for all k.

Synthetic gather with neighboring events

Any improvement in velocity resolution should aid in interpretation of closely interfering events, such as primaries and multiples. Figure 2a shows a noise-free synthetic CMP gather containing two reflections with the same zero-offset arrival time of 2 s, but with different stacking velocities of 4.5 km/s and 3.5 km/s. Figure 2b shows the velocity-analysis panel for these data, computed using the conventional crosscorrelation-sum method. It is impossible to distinguish the two events present in the data; the most probable pick would be around a velocity of 4 km/s. The selective-crosscorrelation sum allows separation of the two maxima, yielding good estimates of the velocity for each reflection (Figure 2c). The coherence curves (plots of coherence measure as a function of trial velocity v_{trial} for fixed zero-offset time) for zero-offset reflection time of 2 s, in Figure 3, reveal substantial improvement in resolution when just the 25% of the crosscorrelations with largest associated differential moveouts are used in the sum. Based on other tests, significant improvement is achieved for percentages of 50% or less.

A coherence measure commonly used in velocity analysis is the semblance coefficient, described by Neidell and Taner (1971). The coherence curve for semblance in Figure 3 shows relatively minor improvement in velocity resolution over that of the conventional crosscorrelation approach, in comparison with the improvement achieved by using the selective-correlation approach,

Noise- or statics-contaminated data

The sharpening of the peak in coherence curves does not itself mean a reduction in uncertainty in picking stacking velocity. Of comparable importance is the performance of any chosen coherency method in the presence of contaminating factors such as additive noise and static time anomalies. Either factor introduces erroneous shifts in

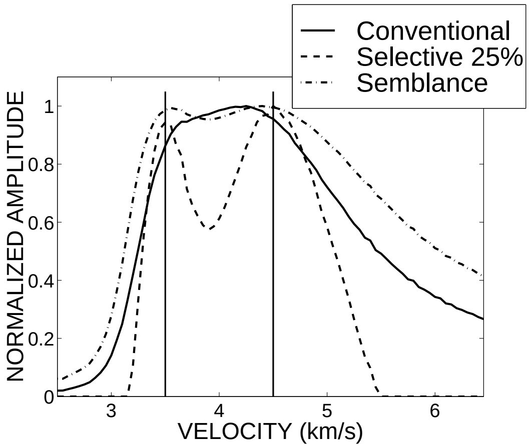

Fig. 3: Coherence curves for two interfering events using conventional crosscorrelation sum, selective-correlation sum (25%), and semblance measures. The vertical lines indicate the correct velocities for the two events.

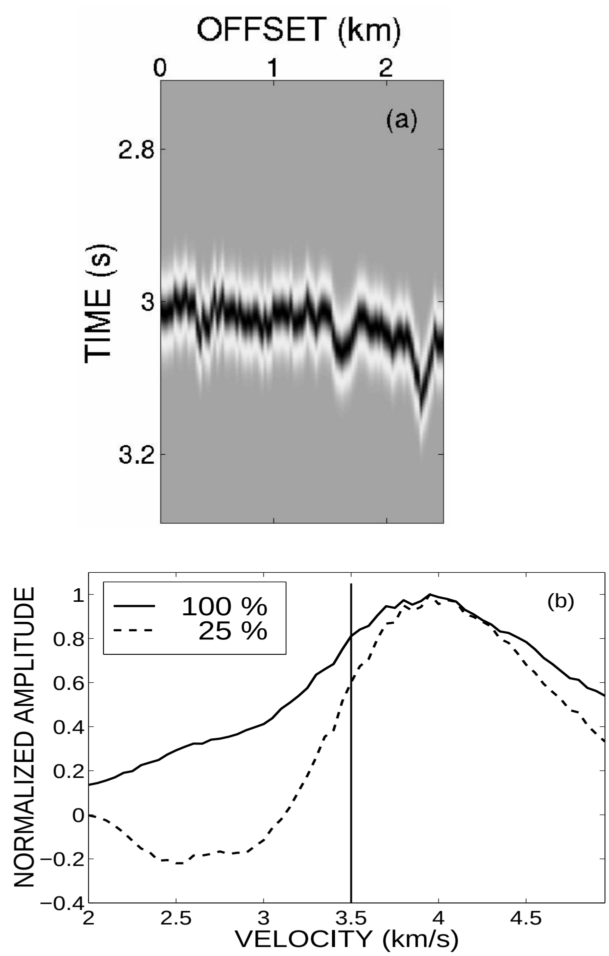

Fig. 4: (a) Synthetic CMP gather containing a reflection at $t_0 = 3$ s, with random static time distortions. (b) Coherence curves computed using conventional crosscorrelation sum (100%) and selective-correlation sum (25%).

the peaks of crosscorrelations away from the time shifts associated with the correct moveout.

We exemplify such errors with the synthetic CMP gather Figure 4a, which contains with a reflection event with laterally-smoothed, random static distortions. Figure 4b shows the coherence curves for the statics-distorted reflection, using conventional crosscorrelation sum (solid line), and selective-correlation sum for 25% of crosscorrelations (dashed line). Peaks in both coherence curves are biased toward velocities that, for this realization of statics, are about 500 m/s higher than the correct velocity. Note that the peaks of the coherence curves computed using both the conventional and selective-correlation method coincide, but at this wrong velocity value. Selective-correlation sum has improved velocity resolution over that of the conventional crosscorrelation sum, and has done so with comparable (in)accuracy. Results of other tests of synthetic data contaminated with either statics time distortions or additive random noise reveal that errors introduced by static time distortions are independent of the percentage used in the selective-correlation-sum method for percentages that exceed about 20%.

Synthetic CMP gather with many reflections

Bringing more realism into our synthetic data examples, we generated a series of 22 primary reflections and 22 multiples (both with Poisson distribution of arrival times) for the one-dimensional velocity model of Figure 5.

Figure 6a shows an 64-fold synthetic CMP gather with spreadlength of 3.15 km, trace spacing of 50 m, Ricker wavelet peak frequency of 18 Hz, and signal-to-noise ratio of about 2. The velocity analysis computed using conventional crosscorrelation sum is shown in Figure 6b, and that using the selective-correlation approach (25%) is shown in Figure 6c. Considerably higher resolution is achieved in the results of selective-correlation sum, allow-

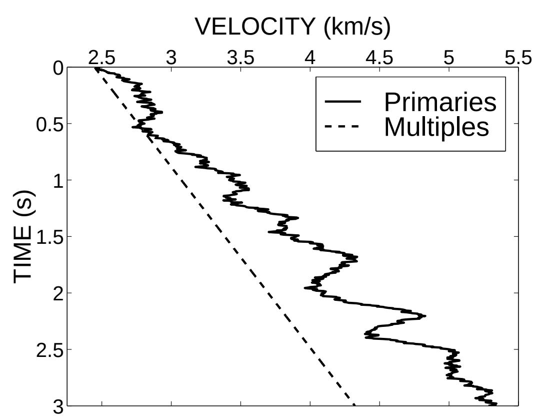

Fig. 5: Depth-varying interval-velocity model for primaries (solid line) and multiples (dashed line).

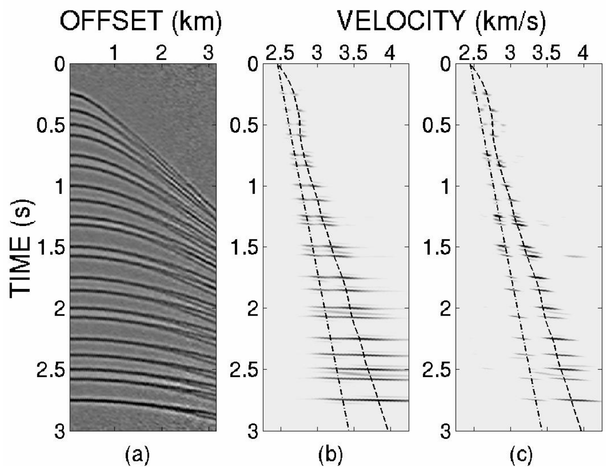

Fig. 6: (a) CMP gather with many reflections; (b) conventional velocity analysis; and (c) selective-correlation velocity analysis (25%). The dashed line represents the rms velocity of the primaries, and the dash-dot line that of the multiples.

ing better identification of the primary velocity function.

Discussion

In all our tests, for percentages of crosscorrelations 50% or less, selective-correlation sum yielded improved velocity resolution relative to that achieved by conventional velocity analysis and other methods. For data contaminated by multiples, interfering primaries, static distortions, and additive random noise, selective-correlation velocity analysis has accuracy for estimating the stacking velocity that is comparable to that of conventional crosscorrelation sum. The error that statics time distortions and random noise introduce in picked stacking velocity is quite independent of the percentage used in the selective-correlation method, for percentages from about 20% up to 100%. The locations of peaks in velocity spectra for both selective-correlation velocity analysis and conventional velocity analysis are determined largely by crosscorrelations of trace pairs with relatively large differential moveout.

The implementation of selective-correlation sum described here entails only a simple modification of conventional velocity analysis. For both approaches, the dependence of computational effort on the number of traces, M, in a gather is order M. The only added burden introduced by selectively deleting crosscorrelations is a small increase in required random-access memory.

Acknowledgments

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