Implications of multiple suppression for AVO analysis and CMP-stacked data

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Introduction

Multiples are seismic energy that has bounced more than once before their recording at the surface of the earth. The successful suppression of multiples is often a difficult task and imperfect results are obtained in all but the most unusual circumstances. Propossed methods for multiple supression rely on either their periodicity (predictive deconvolution in t-x and τ-p domain) or their distinct moveout when compared with the primaries (F-K and τ-p filtering approaches). The level of multiple suppression, measured as the inprovement in primary/multiple amplitude ratio, strongly depends on the hability of the chosen transform (F-K or τ-p) to map the primaries and the multiples to different regions in those domains. This, in turn, depends on the moveout difference between the primaries and the multiples.

Primary/multiple amplitude ratio inprovement, however, is not the only consideration, and, in some cases, may not even be the most important one. The effect of the multiple suppression algorithm on the variations of amplitudes with offset can be a critical factor to consider.

Three moveout-based approaches are compared in this paper in light of both considerations. These approaches are: F-K filtering, τ-p filtering (Hampson, 1986) and a hybrid method combining Hampson's with a statistical method to discrimate focused energy (that is, energy "concentrated" to a small region of the τ-p domain), from defocused energy (that is, energy smeared out in the τ-p domain). This statistical method was devised by Harlan in 1984 for velocity analysis.

Model data

In order to compare the performance of the three methods mentioned above, four models, simulating NMO-corrected CDP gathers, were created, the first of which is shown in Figure 1. In this model, there are four primaries and four undercorrected multiples. The relative amplitude of all events is the same and no amplitude variation with offset exists, other than that due to NMO-stretch mute. The multiple/primary amplitude ratio es 4:1. Two of the multiples are zero-offest time-coincident with primaries and the other two are not. The first ones are intended to test the AVO issue and the other two the primary/multiple amplitude ratio inprovement. Model 2 is the same as that in Figure 1, except that the multiple/primary amplitude ratio is 1:1.

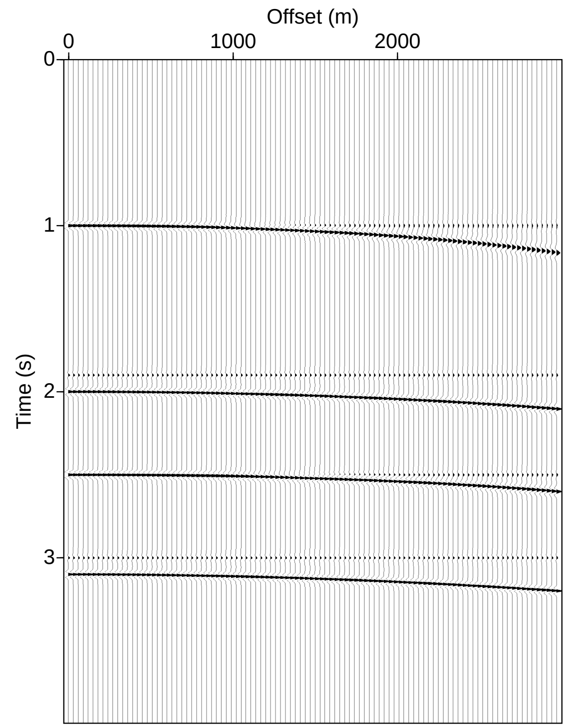

Figure 1. NMO-corrected modeled test dataset 5a. The amplitude of the multiples is four-times that of the primaries. Neither signal nor multiple has any trace-to-trace amplitude variation.

Model 3 is the same as model 1, with a linear decrease of amplitude with offset introduced to both the primaries and the multiples, such that the amplitudes on the last trace are only 0.5 of those on the first trace. Model 4 introduces an even stronger decrease of amplitudes with offset, such that the amplitudes on the last trace are −0.5 those on the first trace, thus introducing a polarity reversal. Polarity reversals are likely to occur in practice when the elastic parameters of the layers change strongly across an interface (Rüger, 1995), although the situation in model 4 is a extreme case devised to test the algorithms under the harshest of situations.

Description of the methods

The F-K filtering approach to multiples supression is simple enough: the NMO-corrected data is F-K transformed such that the primaries, being flat, are mapped to the vertical axis (infinite apparent velocity), whereas the multiples, exhibiting residual moveout, are mapped away from the vertical axis. A suitable mute is then applied that will keep the primary energy while removing the multiple energy. A taper should be applied, so that the no hard zeros are introduced, preventing Gibb's effects from appearing when the data are inversely transformed back to the t-x domain.

Hampson's method (Hampson, 1986), works similarly. The data are first τ-p transformed so that the primaries are mapped to the zero slope line and the multiples are mapped away from that line. Again, a suitable mute is applied and the data are inversely transformed to the t-x domain.

The hybrid approach also begins by τ-p transforming the data and applying a mute to suppress the most identifiable multiple energy. In most cases, residual multiple energy is likely to be mapped to the same region as the primaries. In this method, Harlan's statistical S/N separation algorithm is then applied to identify and suppress the residual, unfocussed, multiple energy, leaving only the primary energy. As before, an inverse τ-p transform is applied to bring the data back to the t-x domain. Detailed descriptions of Harlan's method can be found in Harlan et al. 1984, Harlan 1988 and Alvarez 1995, and of the hybrid method on Alvarez, 1995.

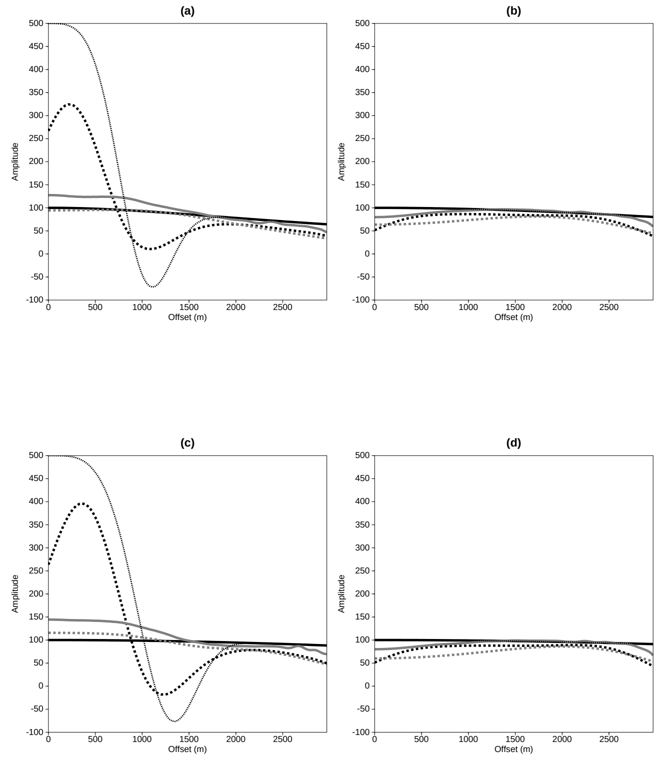

Figure 2. Amplitude variation with offset of extracted primaries in model1. a) through d) represent the primaries from the shallowest to the deepest. The solid black line is the input (in the absence of multiples), the thinly dotted line the input (in the presence of multiples) and the dashed black, solid gray and dashed gray lines the extracted primary with FK, Hampson's and hybrid approaches respectively. The dashed vertical black line represents offset equal to the depth of the reflector.

AVO implications of multiple suppression

In order to quantitatively compare the performance of the three algorithms for multiple suppression from the standpoint of their AVO response, let us plot the amplitude of each of the extracted primary reflections as a function of offset for every model and every multiple removal method. The amplitudes are measured as the peak of the wavelet at the two-way traveltime corresponding to each primary (which, at times, may be contaminated by residual multiple). In the plots in Figure 2, a solid black line indicates the amplitude of a primary (in the absence of multiples) in the input data in Figure 1. Any departure from this curve for the extracted primaries, indicates amplitude variation with offset introduced by the multiple-suppression algorithm. That variation could be a combination of the amplitude variation of the extracted primary and contamination from residual multiples. A finely dotted line indicates the amplitude of the primary in the input data including the presence of the multiples. For primaries not coincident with multiples, the two curves are the same. A dashed black line represents the primary extracted with the FK filtering algorithm, a solid gray line the primary extracted with Hampson's approach, and a dashed gray line the primary extracted with the hybrid approach. A dashed vertical line indicates the offset that equals the depth of the reflector. This line is relevant because normally offsets approaching the depth of a reflector are not included in AVO analysis.

Figure 2 shows the four sets of curves described above, corresponding to each of the four primaries in model1 (Figure 1). Where primaries are contaminated by multiples (plots a and c), the contamination is so severe that AVO analysis would be hopeless. Because the FK filtering algorithm (dashed black line) has not suppressed the strong multiples sufficiently for the smaller offsets of the primaries that are contaminated by multiples, those primaries show insufficient improvement of measured amplitude on the small-offset traces and thus are again useless for AVO study. For those primaries that are not coincident with multiples (Figures 2b and 2d), the extracted primary amplitudes are closer to the ideal behavior but are distorted at the very short and long offsets, due to edge effects. Thus, in any case, the

FK algorithm is unsatisfactory when the goal is to analyze AVO behavior.

Hampson's approach (solid gray line) performed well for intermediate offsets for all primaries, but showed departures for long- and, of more importance, short-offsets. Although not as severe as the departures when the FK filter approach was used, the amplitude variations will distort AVO analysis. For the third primary, for example, the departure from the true amplitude is almost 50% in Figure 2c. More important, a strong, roughly linear amplitude variation with offset is present for offsets between about 800 to 1600 m. The results in Figures 2b and 2d indicate that the near-offset primary amplitudes were reduced in the process of suppressing the multiples, and that the increase in amplitude for short offsets for the other two reflections is due to the presence of the residual multiples. For AVO analysis, however, the results are good for a large range of the shorter offsets.

The hybrid approach performed the best for the short offsets of the primaries contaminated by the multiples because the level of residual multiple present is much smaller than that for the other two methods. For those primaries not coincident with the multiples, use of the algorithm resulted in a general loss of amplitudes, which, however, seems to have been more or less uniform for all offsets compared with Hampson's results (which makes the curves from this two methods roughly parallel). Since AVO analysis depends more on the relative variation of amplitudes with offsets than on the actual amplitude values, the result of the method in terms of AVO can be considered at least equal to that of Hampson's. The algorithm did not do very well for the far offsets, for which the departure from the true amplitudes varied rapidly to values as high as 50% in Figure 2c, probably due to an edge effect. Such large-offset data, however, are not used in AVO analysis.

Similar results were obtained for the other three datasets, indicating that the F-K filtering approach, despite its conceptual simplicity and low computational cost, is not the right method to use for multiple suppression, unless there is no zero-offset time-coincidence between primaries and multiples and provided edge effects, particularly at short offsets, can be minimized. Hampson's and the hybrid approach seem to perform about the same, giving good results, except when the variation of amplitudes with offset in the data is so severe that a polarity inversion occurs. In this situation, some other method has to be used, such as that of Lumley, 1995, which is specifically tailored to AVO preservation and that could perhaps give a better result, although that remains to be seen.

Table 1. Comparison between the different methods for multiple suppression presented in this paper in terms of primary-to-multiple amplitude ratio in a CMP stacked trace. The numbers correspond to peak-to-peak amplitude ratio between primaries and multiples.

Model	**Input**	**Stack**	**FK**	**Hampson**	**Hybrid**
Model1	0.25	1.0	1.0	5.5	10.2
Model2	1.0	4.0	4.3	18.0	40.0
Model3	0.25	0.8	0.85	3.9	4.4
Model4	0.25	0.31	0.33	0.9	0.87

Influence of the multiple extraction on the quality of the CMP stack

Having compared the relative performance of the three methods for multiple suppression for use in AVO analysis, let us now compare their performance in terms of the improvement in primary-to-multiple amplitude ratio in a stacked trace. For this, and for each of the four test models, let us stack the NMO-corrected data, the NMO-corrected input primaries-only and the NMO-corrected input primaries extracted with each of the methods. The stacked traces are plotted side-by-side for comparison such that the first is the stacked trace of the input data, the second is the stacked primary-only input data (ideal) and the next three are the extracted primaries with the FK filtering method, Hampson's method and the hybrid method.

Figure 3 shows the stacked traces for model1. From this figure, and similar ones for the other models, we measured the primary-to-multiple amplitude ratio (P/M) for the stacked traces after the application of each of the multiple suppression methods. The P/M was computed as the quotient of the amplitude of the extracted primary divided by the amplitude of the residual multiple. For primaries coincident with multiples, the amplitude of the residual multiple was estimated as the difference of the amplitude of the primary (which has a contribution from the multiple) and the amplitude of an adjacent primary with no contribution from multiples.

The results of these P/M computations appear in Table 1. Analysis of the results in Table 1 shows that the CMP stack itself was able to provide a P/M ratio improvement of up to 4.0, except for model1 (polarity reversal) for which its improvement was marginal.

The FK filtering approach yielded only marginal P/M ratio improvement over and above what the CMP

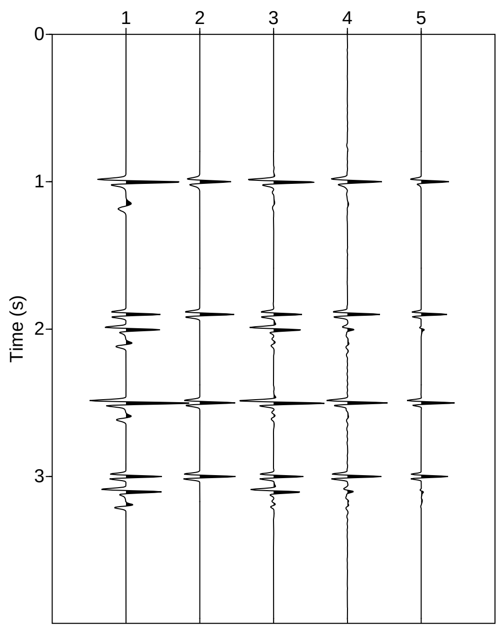

Figure 3. CMP stacked traces for model 1. The first trace corresponds to the stack of the NMO-corrected input data, the second the stack of the NMO-corrected primary-only input data and the last three traces the extracted primaries with FK filtering, Hampson's and the hybrid method.

stack itself did. Since it was shown before that it also performed poorly in terms of AVO preservation, this method is not adequate for the type of differential moveouts and primary-to-multiple amplitude ratios tested in this paper.

Hampson's method yielded an improvement in P/M ratio over the CMP stack that ranged from about 3:1 for model 4 to more than 5:1 for model 1. In general, for all the datasets, the improvement in P/M ratio was significant.

The hybrid approach, as expected, yielded further improvement of P/M ratio for the first and second datasets (those for which the trace-to-trace amplitudes were constant). For the fourth dataset, for which the polarity reversal reduced the focusing of the primaries and increased the smearing of multiple energy in the τ-p domain to a point that the algorithm could not discriminate between the primaries and the residual multiples, the result of the hybrid method was actually poorer than that of Hampson's method.

In summary, then, from this quantitative analysis carried out with the four datasets, we consider that if improvement in P/M ratio is the overriding factor, then the extra cost of the hybrid approach compared with Hampson's (about 50%), is justified except for model 4 (polarity reversal with offset), for which none of the methods was able to produce the level of multiple rejection achieved with the other model datasets. As with the AVO issue, perhaps another method should be sought, that could produce a larger P/M ratio.

Conclusions

Hampson's approach works well in preserving AVO as long as the primary-multiple moveout separation is sufficiently large and the multiple-to-primary amplitude ratio is not very large, so that not much residual multiple energy can be expected in the extracted primaries. If this is not the case, however, the residual multiple energy will tend to increase or decrease the amplitudes of the short offsets of the extracted primaries, depending on the relative polarity of the two. The hybrid approach, on the other hand, can provide increased multiple suppression but can decrease the amplitude of the extracted primaries in the process. Details of the trade off govern whether or not this approach to multiple suppression will result in data that are appropriate for AVO analysis.

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