Improving multiple prediction in image space using ADCIGs for limited-offset recordings

Madhav Vyas, Stanford Exploration Project (SEP), Stanford University*

SUMMARY

Convolution of the recorded data with itself is a convenient way of generating multiple models and is the basis for Surface Related Multiple Prediction (SRMP/SRME). The completeness of the multiple model however relies on recording all the primary paths leading to multiple generation. In practice, with limited offset recordings and in areas of complex subsurface geometries (especially steep dips) we might only record the multiple path and not the primary, leading to incomplete multiple models. In image space, this translates to modeling multiples at fewer opening angles than are actually present. In this article, I show that the Angle Domain Common Image Gathers (ADCIGs) of multiple models provide useful angular information which may be used to infill or extrapolate missing angles and make up for the missing multiples in the model generated using SRMP.

INTRODUCTION

Kinematics of surface-related multiples can be predicted by convolution of recorded data with itself (Anstey and Newman, 1966). However, due to discrepancies between modeled and observed multiples in terms of their amplitudes and frequency content, direct subtraction is not possible. Various iterative and adaptive subtraction schemes have been proposed in the past to address this issue. The problem of multiple removal can also be attacked in image space instead of in the data domain.

Artman and Matson (2006) extended the SRMP approach through commutability of wavefield extrapolation and convolution to predict multiples in image space during shot profile migration. However, since SRMP is based on convolving recorded data with itself it yields perfect multiple prediction only when we record all the primary paths that lead to multiple generation. This is true when either our recording geometry is infinite or the subsurface structure is flat. In practice, neither of the aforesaid conditions are likely; in addition, there are situations when the primary escapes the recording geometry, but the corresponding multiple after hitting some steeply dipping reflector bounces back in and gets recorded. Figure 1 shows the ray path for one such possibility. It is not possible to predict the multiple depicted in Figure 1 using SRMP since we do not record the primaries that contribute towards that particular multiple.

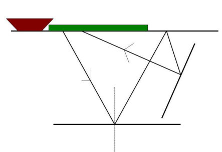

Figure 1: A ray path illustrating the situation where the primary escapes the recording geometry but the multiple bounces back and gets recorded.

It is difficult to model such multiples; however, image space gives us a better chance to handle them. We can make use of the redundancy present in the image space to address this problem. Multiple events in the data space migrate to a single point in image space (if perfect multiple velocity) but with different opening angles and a missing event in data space translates to a missing angle in image space. If we can spread the information consistently from one opening angle to another we may be able to reconstruct the missing part of the multiple model. When the migration velocity is perfect events in the image space will appear flat in the angle domain and we can easily infill the missing angles to reconstruct the multiple models. But in general, multiples have very different velocities than the primaries recorded at similar times and hence they show curvature in the angle domain (when migrated with the true velocity). The task of infilling is thus not as straightforward as it is for flat gathers. There are two ways to approach this: either, we can migrate with the multiple velocity do infilling and then demigrate, or alternatively, we can use radon style transforms to infill gathers with curvature.

In this article I first demonstrate the problem using a simple synthetic example and then illustrate a possible corrective approach. I give a second example using the Sigsbee model, which is a more realistic case.

SYNTHETIC DATA

I generate a synthetic data set using finite-difference modeling for the velocity model given in Figure 2. The velocity model is a combination of a flat and a dipping layer, with the dipping layer having a dip of about 30 degrees. The simulation is done with a free surface condition to model multiple events as well. I modeled about 225 shots with offsets ranging from -8000 to 8000 and shot spacing of 40. The data has primaries and both first- and second-order multiples. We observe primaries coming from the flat as well as the dipping reflector. There are also different types of first-order multiples having varied trajectories, including multiple bounces on the flat layer, multiple bounces on the dipping layer and one bounce each on the flat and dipping layers. Finally, there are second-order multiple events which have higher degrees of freedom in terms of possible ray combinations and have further complicated trajectories. Most of the multiple analysis carried out henceforth focuses on first order multiples.

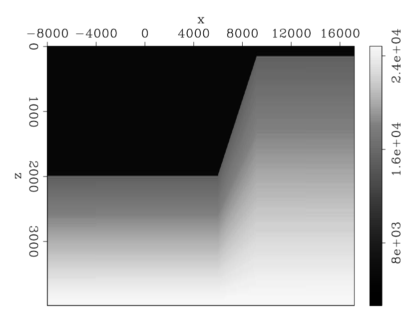

Figure 2: Velocity model used for modeling the synthetic data

Surface Related Multiple Prediction

In an ideal world where we record all the offsets, SRMP can perfectly model surface-related multiples. In this section I test how the SRMP algorithm performs when we do not have access to far offsets. To simulate this situation, I throw away half the modeled offsets, keeping only the offsets from -4000 to 4000 instead of -8000 to 8000. We would expect SRMP to fail for events which bounce back into the recording geometry, as previously shown in Figure 1. For the given synthetic example, first-order multiples that have either one or both bounces on the dipping surface bounce back in to the recording geometry. In the subsequent analysis we focus on the multiple which gets back into the recording geometry after bouncing twice on the dipping surface, though the same may apply to other kinds of multiple events as well.

To estimate first-order multiples using SRMP, we need to record two primary paths that contribute to the multiple. In Figure 3, I draw a cross-plot where on X axis is the offset at which the multiple is actually recorded, and on the Y axis is the offset of primaries which contribute to this multiple. This plot is for a particular first-order multiple that bounces twice on the dipping layer and corresponds to a shot at a surface location of 5000. Note that for multiples recorded at offsets of about -4000, the corresponding primaries come from much farther offsets, about -6000. When we limit the maximum recording offset to -4000, we will not be able to model any portion of this multiple event that has a contribution from a primary recorded at more than -4000. This will limit us to be only able to model the multiple events recorded at offsets of -2000 or less.

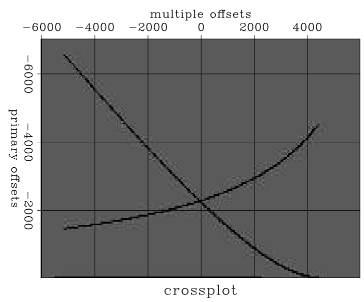

Figure 3: Cross-plot between offsets of recorded multiples and primaries contributing to those multiples

Figure 4 shows the shot gather, the multiple model created using SRMP, and the gather after adaptively subtracting the multiple model. Notice that the tail of the particular multiple event (two bounces on the dipping surface) is not modeled between offsets of -2000 to -4000, as predicted by the cross-plot in Figure 3.

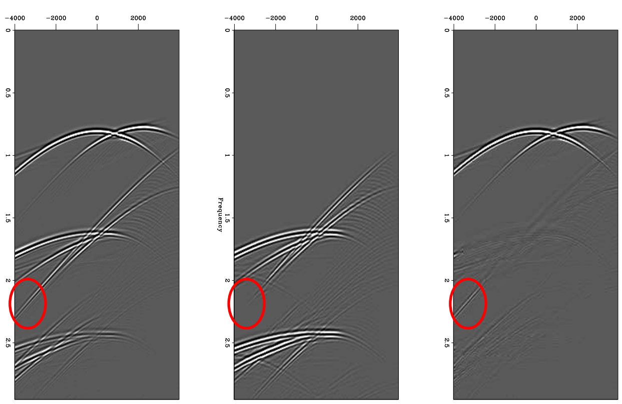

Figure 4: The (a) shot gather, (b) the multiple model and (c) the gather after subtracting the multiple model

Once we migrate the data after subtracting the multiple model obtained using SRMP we expect to see some remains of the multiples in the image space, since we were not able to completely model all the multiple events. Figure 5 compares the two images obtained by migrations carried out on the data with and without multiple subtraction. The image obtained from the data after removing the multiple model is devoid of the flat portion of the first-order multiple, but some portion corresponding to the dipping layer remains. This dipping multiple in the image space corresponds to the same event in data space that has two bounces on the dipping layer; we were not able to model this perfectly due to limited-offset recording. Some multiple energy also remains in the bottom portion of the image, corresponding to the second-order multiples, but here I limit the analysis to the first order multiple events.

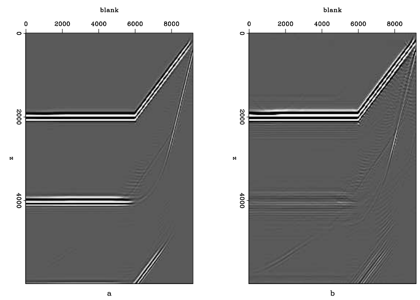

Figure 5: Image obtained by migrating the data (a) before multiple removal and (b) after multiple removal

Use of ADCIGs

There are many events in data space that migrate to the same point in image space (if perfect velocity) with different opening angles. In the class of events discussed above, because of limited recording geometries, we do not expect to model all those angles. However, if we can capture some subset of angles, we can make use of ADCIGs to infill these missing angles and generate a more complete multiple model. When migration velocity is same as the multiple velocity this reduces to simple extrapolation, since events will be perfectly flat in the ADCIGs. In cases of imperfect velocity, radon-style transforms can be used to accomplish the same goal.

To illustrate the point, I extract an ADCIG corresponding to a surface location of 8000 (where the dipping multiple persists). Figure 6 (a) is the ADCIG of the recorded data and shows angles at which the multiple is actually illuminated. Figure 6 (b) displays the illumination range of the modeled multiple. It should be noticed that for the modeled multiple most of the energy is concentrated close to zero opening angle and is missing at high angles, where the recorded multiple exists. This indicates that SRMP in this case was unable to effectively model the multiple at large opening angles. Figure 6 (c) is the ADCIG for the data obtained after removing the multiple model generated using SRMP in data domain. Again, we were able to get rid of multiple energy close to zero angle (since we could model it), but we still have multiple energy at large opening angles (where we were unable to model the multiple using SRMP). The process of multiple removal could have been equivalently carried out in image domain.

For a given velocity model, we can compute analytically the angles up to which we will be able to model a particular multiple, and the angles up to which it will be actually recorded. The multiple event having two bounces on the dipping surface (the one discussed above) maps as a dipping reflector with twice the dip in image space. ADCIGs above also show the angular illumination for this multiple event. Figure 7 shows a plot between illumination angle and offsets for an image point located at the multiple event, with twice the dip of the original and having an X position of 8000. The plot shows the relation between surface offsets and the illumination angles for this multiple event along with the two primaries that contribute towards it. It can be noticed from the plot that if we limit our recording from -4000 to 4000, the multiple will be illuminated from -10^o to $+10^o$. To model this multiple we need to record both the primaries that contribute towards it. The plot shows that for limited offsets we record both primaries only in an angular range of -5^o to $+5^o$. This would be the the range in which we

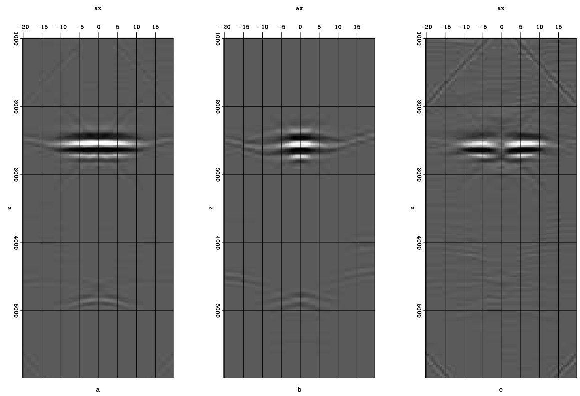

Figure 6: ADCIG for (a) complete data (b) multiple model and (c) data after removing the multiple model

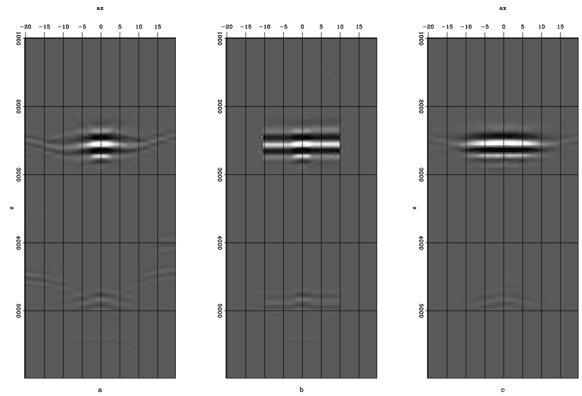

Figure 8: ADCIG for (a) multiple model and reconstructed multiple model using (b) stack and spray and (c) adaptive approach

will be able to model the multiple and it reiterates the incapability of SRMP to model multiples at large opening angles, with such geometries and limited offsets.

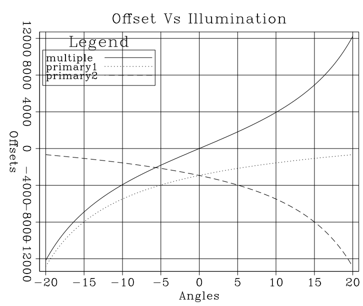

Figure 7: The relation between recording offsets and opening angles for the multiple event with several bounces on the dipping layer, and the primaries that contribute to it, for an image point corresponding to the *X* position of 8000.

Reconstructing missing angles

The advantage of working with image-space SRMP is that we have access to information in angle domain, which can be used to infill the missing angles in the multiple model. When the velocity used for migration is perfect, angle gathers look flat, and extrapolating farther angles is fairly straightforward. A simplistic approach like stacking along angles and then spraying can work in the case of perfectly flat gathers.

Alvarez and Guitton (2006) show the use of matching filters and adaptive subtraction as a tool for removing multiples. I use the same algorithm to match the modeled multiples with the recorded ones in angle domain. Since the algorithm tries to match the two, it tries to make up for the amplitudes as well as the missing angles. Results of reconstruction using the adaptive scheme look good for this example even without the use of stack and spray approach.

In Figure 8, I compare angle gathers for the original multiple model, the reconstructed multiple model generated using a stack-and-spray approach, and the one reconstructed using the adaptive matching algorithm. Once we reconstruct the missing angles, we can carry out the process of subtraction.

Finally, let us compare the ADCIGs extracted from the image cube: one created by multiple removal in data domain followed by migration (Figure 9(a)) and the other created in the image space using adaptive subtraction working on one ADCIG at a time(Figure 9(b)). Notice remaining multiple energy at higher angles in Figure 9 (a) which could be removed almost totally in Figure 9 (b).

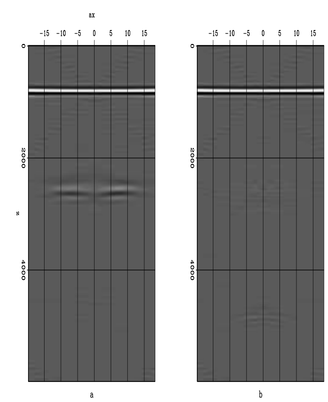

Figure 9: ADCIGs corresponding to (a) data space multiple removal followed by migration and (b) image space multiple removal

SIGSBEE

Moving to a more realistic and complex subsurface geometry, in this section I discuss the application of SRMP on the Sigsbee data set. Figure 10 displays a window from the zero offset image on the top and the multiple model created using image space SRMP on the bottom. Free surface multiples corresponding to even an almost flat water bottom image in a very complicated fashion due to the presence of complex subsurface and the salt body. It is difficult to identify these multiples that image underneath the salt body. Our goal here is to analyze multiples modeled by SRMP and improve our estimate if we have some missing parts in our model. Ideally, we would like to look at multiples in a domain where they can be easily identified and understood. To accomplish this I use water velocity as the migration velocity for further analysis. Not all multiples travel at the water velocity, but many that emanate from shallow layers almost do that.

The Sigsbee data set has offsets of about 30000 ft. To illustrate the limitations of SRMP in the case of small-offset recordings, I retain only very small offsets (5000 ft) to model the multiples. To demonstrate the possible use of angle gathers in SRMP, I focus on the dipping part of the first-order water-bottom multiple. The

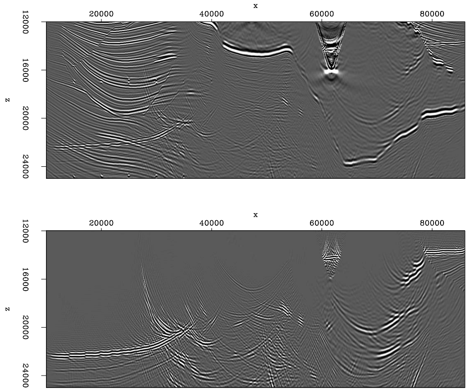

Figure 10: A window from the zero offset image (top) of the Sigsbee data and the corresponding multiple model generated using image-space SRMP (bottom).

dip of the water bottom around that part is about 10^o. Figure 11 (a) shows the ADCIG drawn from the image around the location of the dipping water bottom. Figure 11 (b) is the ADCIG of the multiple model at the same location. The first-order water-bottom multiple (at about a depth of 15000) is illuminated at a wider range of angles than it is actually modeled. This is not very apparent from the figure but most of the energy is concentrated close to zero angle. If we subtract the multiples in the data space and then migrate the resulting data set, our image has some remnants of the multiple (marked), which is understandable, since we did not model all the multiples that we recorded. Figure 11 (c) is the ADCIG from the same location, but corresponding to the data for which we subtract modeled multiples in the data space. For the specific water-bottom multiple, the energy is removed close to the zero opening angle but is present at higher opening angles. This observation is similar to the one in the simple synthetic example discussed in the previous section.

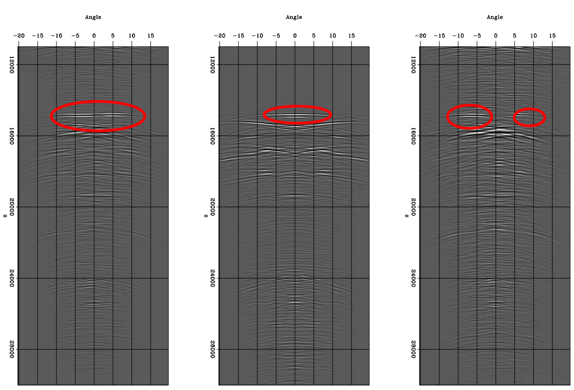

Figure 11: ADCIG for (a)the image, (b) the multiple model and (c) the image after multiple removal in the data domain

As in the simple synthetic example, if instead of applying adaptive subtraction in the data domain we now do that in image domain on one ADCIG at a time, we have a better chance of removing this class of multiples. This is because in the angle space, multiples appear flat when migrated with the perfect velocity, and it is relatively straightforward for the matching filters to adaptively match the pattern of recorded multiples. When the velocity is not perfect, and multiples show curvature, it may be better to use radon transforms going back and forth to reconstruct missing multiples at higher opening angles. To draw a comparison for the given example, I plot in Figures 12 (a), (b) and (c) the ADCIG for the modeled multiple, the reconstructed multiple using the matching filter, and the multiple-free gather after subtraction in image space. The angle gather looks relatively cleaner after subtraction in the image domain.

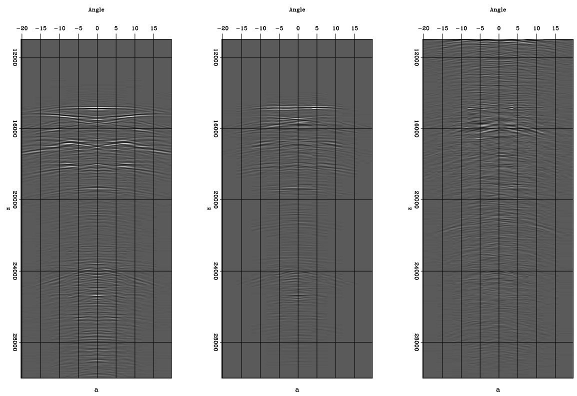

Figure 12: ADCIG for (a) the multiple model, (b) the reconstructed multiple model and (c) the image after multiple removal in image domain

CONCLUSIONS

Surface related multiple prediction works well for kinematically predicting the multiples associated with the free surface, but as shown through a series of tests and examples, it fails for certain ray paths when the subsurface geometry is complicated, and we have access to only small offsets. Though data-space and image-space SRMP are mathematically equivalent, image-space subtraction gives us a better chance to reconstruct the missing parts of the multiple model because of some redundancy associated with the image space. In the present analysis we used angle gathers as a preferred domain of reconstruction.

To illustrate these points, in the examples above I retain only very small offsets, which might appear unrealistic for the inline direction. However, there is a trade off between the offsets and dip of the structure; for instance, if dip is very high SRMP can fail even for large recording offsets. Furthermore, in 3D surveys, along with many limitations of SRMP, extremely limited crossline offsets might be a concern for even gently dipping water bottom. The heuristic extension of the idea discussed here would be that in 3D, a multiple event might be perfectly modeled for some azimuths, but not all. In that case we may spread information across azimuths to reconstruct the multiple model, like we did across aperture angles in the 2D case.

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EDITED REFERENCES

Note: This reference list is a copy-edited version of the reference list submitted by the author. Reference lists for the 2007 SEG Technical Program Expanded Abstracts have been copy edited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

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