Anti-aliasing multiple prediction beyond 2-D

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SUMMARY

Theoretically, the Delft approach of surface-related multiple elimination can be applied in three dimension, as long as the source and receiver coverage is dense enough. In reality, such a dense coverage is still far from reach, using the available multi-streamer acquisition system. One way to fill the gap is to massively interpolate the missing sources and receivers in the survey, which requires huge computational cost.

In this paper, I propose a more practical approach for the multi-streamer system. Instead of the large-volume missing-streamer interpolation, this approach tries to find the most reasonable proxy from the collected dataset for each missing trace needed in the multiple prediction. Although the missing-streamer interpolation is avoided, another problem pops up in the multi-streamer case, the aliasing noise caused by the sparse sampling in the cross-line direction. To solve this problem, I introduce a new concept, partially-stacked multiple contribution gather (PSMCG). Using the multi-scale PEF theory, this approach interpolates the PSMCG in the cross-line direction to remove the aliasing noise.

INTRODUCTION

The Delft approach of surface-related multiple elimination (Berkhout and Vershcuur, 1997; Vershcuur and Berkhout, 1997) formulated the demultiple process as a two-step inversion problem based on the Huygens' principle, that is, first predicting the multiple and then subtracting it from the original dataset.

The multiple prediction step, crucial for the success of the whole algorithm, involves one important assumption about the data acquisition geometry, that a source/receiver pair is needed wherever a multiple reflects. The Delft approach is quite successful in 2-D problem (Verschuur and Prein, 1999), since the assumption is relatively easily satisfied in the conventional 2-D acquisition geometry, which is not the case in 3-D.

Two different directions have been taken to resolve the conflict. One is to massively interpolate the trace at missing source and receiver positions to attain a dense coverage of the surface (van Dedem and Verschuur, 1998). However, the computational cost of this method is huge. The other is to predict the multiple based on the 2-D theory and then extend the subtraction step to handle incorrectly predicted multiples (Ross, 1997; Ross et al., 1997). The success of this approach is restricted to relatively simple 3-D cases.

This paper proposes an approach designed for the multi-streamer geometry. Two distinctive features make it more practical. First, this approach finds the most reasonable proxy from the collected dataset for any missing trace. There is no need to interpolate missing streamers and shotlines. Second, using a concept I call the partially-stacked multiple contribution gather (PSMCG) together with the multi-scale PEF theory (Claerbout, 1992), the proposed approach interpolates the PSMCG in the cross-line direction to get a densely-sampled multiple contribution from all possible Huygens' secondary sources before the summation step to remove aliasing noise.

Two numerical examples in the paper demonstrate how the approach works.

MULTIPLE PREDICTION BEYOND 2-D

First, I will list a summarization of the key points in this approach and then explain them in more details:

1. There are many missing traces in 3-D multiple prediction.

2. Instead of interpolating traces, this approach finds good proxies for the missing ones.

3. To be qualified as "good", a proxy must have the same offset and either a similar CMP location or a similar azimuth angle.

4. Using those proxies for the missing traces, we hope to predict multiples with first-order accuracy in multi-streamer geometry.

In order to better understand the approach, let's assume we have a multi-streamer acquisition system, as shown in Figure 1, with one shotline and seven streamers. Supposing that we want to predict the multiple from source S_0 to receiver R_4, we need to consider the contributions from all the possible multiple reflection points between S_0 and R_4 by cross-convolution. For instance, we need to collect all the traces with sources located at S_i $(i = 1, ..., 7)$ and receiver located at R_4. In Figure 1, the thin solid line represents the corresponding trace collected in the survey, and the thin dashed line stands for a missing trace in the survey. The challenge is to find appropriate proxies for such missing traces in the survey.

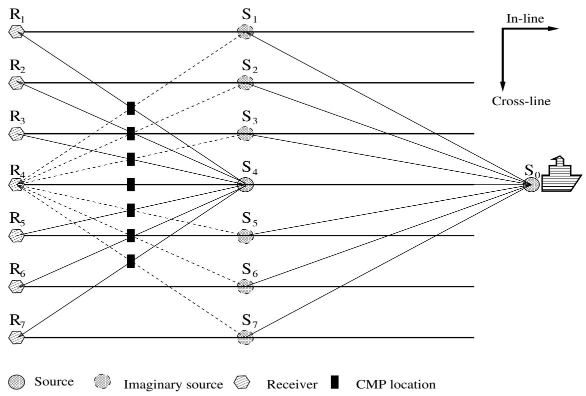

Figure 1: A typical multi-streamer geometry. The $\overrightarrow{S_4R_1}$ path is a good proxy for the absent out-of-plane shot $\overrightarrow{S_1R_4}$, since the two paths share the same midpoint and have the same offset. Similarly, $\overrightarrow{S_2R_4}$ is replaced by $\overrightarrow{S_4R_2}$, $\overrightarrow{S_3R_4}$ by $\overrightarrow{S_4R_3}$, $\overrightarrow{S_5R_4}$ by $\overrightarrow{S_4R_5}$, $\overrightarrow{S_6R_4}$ by $\overrightarrow{S_4R_6}$, and $\overrightarrow{S_7R_4}$ by $\overrightarrow{S_4R_7}$.

There is one well-known geophysical concept that can help us meet the challenge, common-midpoint (CMP), which assumes that traces with the same CMP location and the same offset contain the same information about one location in the earth. Although the common-midpoint assumption is a first-order approximation when the structure is not strictly flat, I will demonstrate that it is useful in our search for the substituting traces.

For example, we try to find the best proxy for $\overrightarrow{S_1R_4}$ from the collected dataset. Not surprisingly, we find that the real trace $\overrightarrow{S_4R_1}$ shares the same CMP location with the virtual trace $\overrightarrow{S_1R_4}$ and has the same offset as well. The only difference is the azimuth angle. Therefore, trace $\overrightarrow{S_4R_1}$ is a proxy for trace $\overrightarrow{S_1R_4}$ in the multiple prediction with first-order accuracy. Similarly, we find other substituting traces for other virtual traces.

The central streamer in Figure 1 is a special case, in which we can always find the substituting traces for the virtual ones with the same CMP location and offset. Working with other streamers (e.g. Figure

2), we cannot find proxies with the same CMP location and offset. However, we can relax the definition of a substitute trace by giving up the requirement that the proxy share the same CMP location. Then we can find another group of proxies for the missing traces, as shown in Figure 2. Since the cross-line spreading aperture is usually smaller than the in-line aperture, this extension might be acceptable in many real applications.

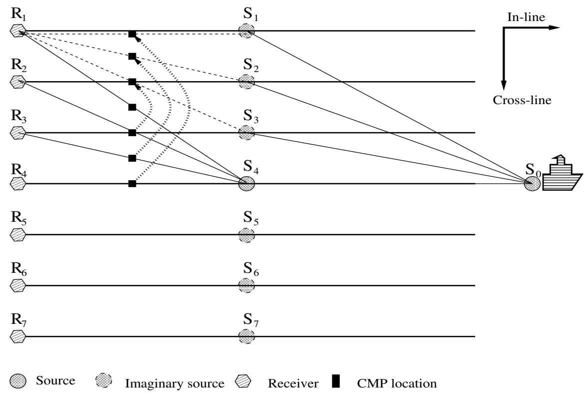

Figure 2: While working with other streamers, we have to give up the requirement that the proxy share the same CMP location, and find a group of proxies with reasonable accuracy. $\overrightarrow{S_1 R_1}$ can be replaced by $\overrightarrow{S_4 R_4}$, $\overrightarrow{S_2 R_1}$ by $\overrightarrow{S_4 R_3}$, and $\overrightarrow{S_3 R_1}$ by $\overrightarrow{S_4 R_2}$. Each pair shares the same offset and azimuth angle.

Figure 3 shows two types of 3-D multiples' geometries, $S_0\overrightarrow{M_1}R_1$ and $S_0\overrightarrow{M_2}R_2$, which are generated by different earth structures. For example, $S_0\overrightarrow{M_1}R_1$ is mainly caused by cross-line dip or scattering reflector and $S_0\overrightarrow{M_2}R_2$ by 1-D or in-line dip reflector. The difference between these two types is that the source, the multiple reflection, and the receiver locations are aligned in the second type, whereas they are not in the first one. The approach discussed here is fully applicable to the second type of 3-D multiple. There is no kinematic approximation at all. The approximation error happens only when we deal with the first type of 3-D multiple.

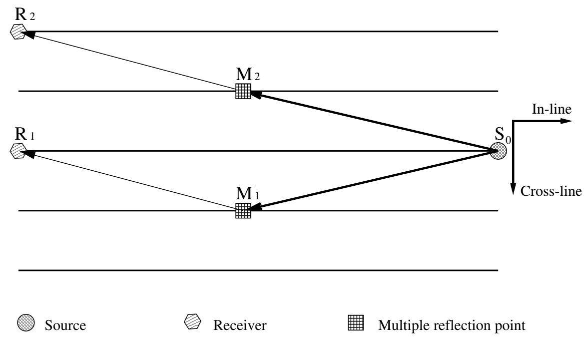

Figure 3: Two different types of 3-D multiple. Type one, the source S, the multiple reflection point M_1, and the receiver R_1 cannot be aligned by a single straight line, is probably caused by cross-line dip or scattering reflector. Type two, the source S, the multiple reflection point M_2, and the receiver R_2 are aligned by a single straight line $S_0\overrightarrow{M_2}R_2$, happens when the structure is approximately 1-D or in-line dip reflector. The approach discussed here has no approximation for the second type.

MULTIPLE CONTRIBUTION GATHER

The multiple prediction can be further divided into two sub-steps: trace cross-convolution and multiple contribution summation, which, in practice, people usually collapse into a single procedure. In order to gain more insight into the method, however, I consider them as two separate steps.

Figure 4 schematically demonstrates the 2-D multiple prediction. In order to predict the multiple from source S to receiver R, we need to cross-convolute all the possible contributing traces marked by M_i in the middle, since we do not know where exactly the multiple reflection occurs on the surface. Then the summation step locates the exact multiple reflection position as long as the contributing traces are densely sampled on the surface.

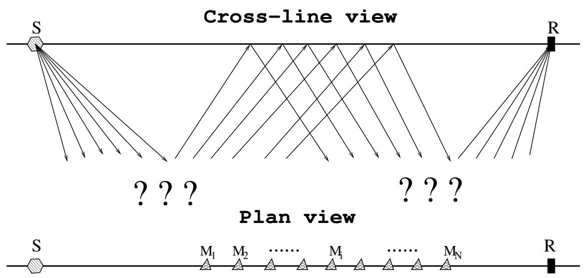

Figure 4: 2-D multiple prediction. All the contributing traces forms a 2-D MCG prior to summation.

Prior to summation, if we lay out the cross-convoluted traces from left to right, we get an intermediate result, a Multiple Contribution Gather (MCG). Figure 5 shows a 2-D multiple contribution gather and the corresponding summation result.

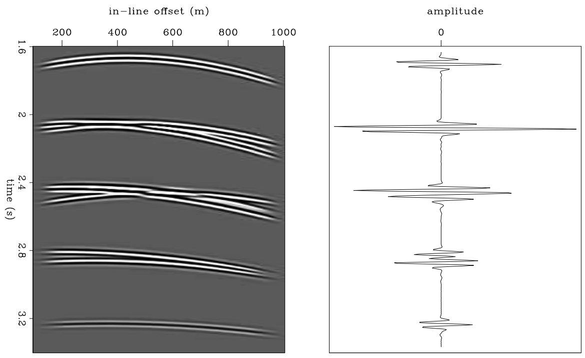

Figure 5: Left: a 2-D MCG. The amplitude has been tapered off to avoid edge effects. Crossing events imply that the multiples are split into different branches. Right: the stacking of the MCG. Notice the effect of the crossing events on the multiple prediction.

The MCG is a section in 2-D and a cube in 3-D. The restriction of the multi-streamer geometry makes the 3-D MCG cube densely sampled in the in-line direction and coarsely sampled in the cross-line direction. Therefore, we can safely apply the summation in the in-line direction first and get a partially-stacked MCG (PSMCG).

Figure 6 shows two PSMCGs with different sampling intervals and the stacked multiples. Unfortunately, a brutal summation in the sparsely-sampled cross-line direction introduces a large amount of aliasing noise into the predicted multiple. The next section describes a method of avoiding such noise.

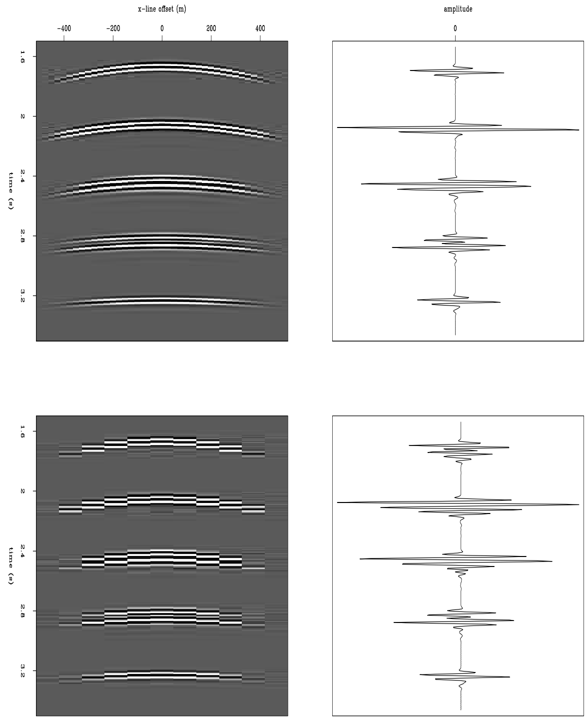

Figure 6: Top: a densely-sampled (Δ_{streamer}=25m) PSMCG and its stacking result. Bottom: a sparsely-sampled (Δ_{streamer}=100m) PSMCG and its stacking result. Stacking of the bottom PSMCG introduces aliasing noise to the multiple trace, especially to the top two wavelets in the plot.

ANTI-ALIASING IN THE MULTIPLE PREDICTION

The multiple prediction proposal discussed in the preceding section suggests that we can estimate 3-D multiples without trace interpolation. However, as Figure 6 shows, the other problem-aliasing noise-has to be dealt carefully if there is no missing-streamer interpolation. Like any other Kirchhoff-style operation, anti-aliasing is an important issue in the multiple prediction. This issue deserves even more attention in three dimension, since the cross-line sampling is more sparse than the in-line sampling.

The 3-D estimation of a multiple trace is achieved by stacking a 3-D MCG. As discussed in the preceding section, the 3-D MCG can be safely stacked into a 2-D PSMCG along the in-line direction. In the cross-line direction, the PSMCG has to be more densely sampled to avoid the aliasing noise. Therefore, we propose to interpolate the PSMCG directly and then stack it into a multiple trace.

We can interpolate the aliased data in either the F-X (Spitz, 1991) or the T-X domain (Claerbout, 1992). I have chosen the time-space domain multi-scale PEF theory discussed in Section 8.4 of Claerbout (1992) to interpolate the PSMCG. The basic idea embedded in the theory is that large objects often resemble small objects. Supposing that we have an input data with alternate missing traces, we can estimate a PEF with the following shape:

$$\begin{array}{ccccccccc} a & \cdot & b & \cdot & c & \cdot & d & \cdot & e \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & 1 & \cdot & \cdot & \cdot & \cdot \end{array} \qquad (1)$$

Then we can make the filter smaller by throwing away the zeros (represented by dots) in filter (1) to get

$$\begin{array}{ccccc} a & b & c & d & e \\ \cdot & \cdot & 1 & \cdot & \cdot \end{array} \qquad (2)$$

which has the same dip characteristics as filter (1).

Figure 7 shows two PSMCGs containing crossing events, before and after interpolating the alternative missing traces and the corresponding stacking results. The aliasing noise has been greatly reduced after trace interpolation.

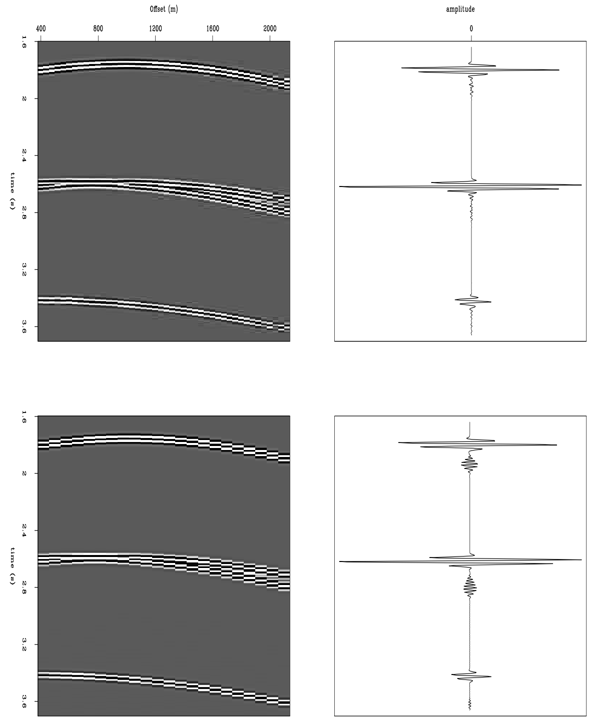

Figure 7: Top: a densely-sampled (Δ_{streamer}=25m) PSMCG and its stacking result. Bottom: a sparsely-sampled (Δ_{streamer}=50m) PSMCG and its stacking result. The aliasing noise has been greatly decreased after the trace interval is halved from 50m to 25m.

NUMERICAL EXAMPLES

Combining the multiple prediction and the PSMCG interpolation, we get a new, practical multiple prediction scheme beyond two dimension. In this section, two 3-D synthetic datasets with similar acquisition geometries are used to evaluate the new scheme. The corresponding model and acquisition parameters are given in Tables 1 and 2.

Model	In-line dip (°)	X-line dip (°)	Layer Velocity (km/s)
A	(0.0,5.0,10.0)	(0.0, 0.0, 0.0)	(1.5, 2.0, 2.5)
B	(0.0,5.0,10.0)	(0.0, -5.0, 5.0)	(1.5, 2.0, 2.5)

Table 1: Model parameters of Model A & B

Model	Δ_{source} (m)	Δ_{receiver} (m)	Δ_{streamer} (m)
A	20	20	100
B	20	20	50

Table 2: Acquisition parameters of Model A & B

Model A is designed so that the shotline and streamers are deployed along the in-line dip direction. Therefore, there is no approximation error in our approach. With 11 streamers covering from $-500m$ to $+500m$ and $100m$ streamer interval in the cross-line direction, this is a wide azimuth survey. For a given shot location, the ideal multiple gather and the predicted one are shown in Figure 8. Each 3-D MCG cube in this example is first stacked along the in-line direction into a 2-D PSMCG containing at most 11 traces of $100m$ sampling interval. The 2-D PSMCG is then interpolated in the cross-line direction to be sampled at $25m$ interval. The interpolated PSMCG is further stacked into a trace.

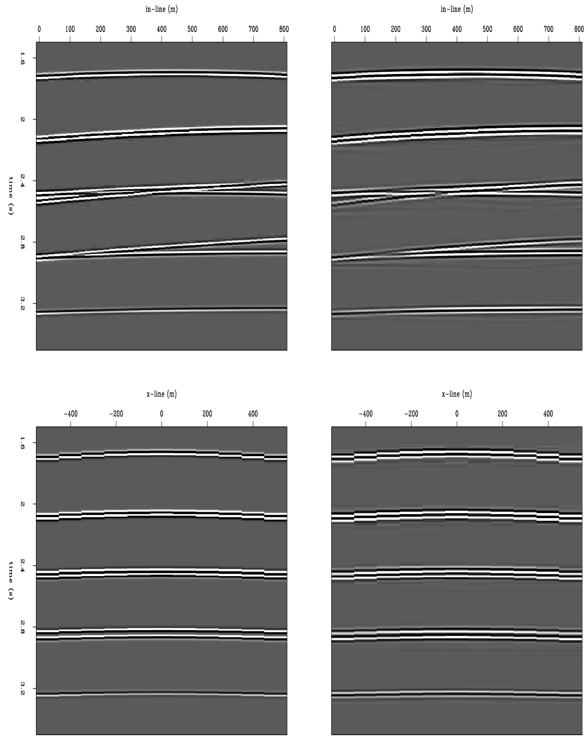

Figure 8: In-line dip model. Left: ideal multiple reflection. Right: estimated multiple reflection.

Model B is a relatively narrow azimuth survey with still 11 streamers covering from $-250m$ to $+250m$ and $50m$ streamer interval in the cross-line direction. The bottom two reflectors in the model have the opposite cross-line angles, which, inevitably, introduce the approximation error in the estimation. However, as shown in Figure 9, as long as the cross-line dips have no dominant direction, the error is usually tolerable and can possibly be handled in the subtraction step.

CONCLUSIONS AND FUTURE WORK

This paper has proposed a method of predicting 3-D multiples in multi-streamer geometry that does not require massive missing-streamer interpolation. Two numerical examples suggest that this approach can be used in the multi-streamer survey if the cross-line dip is mild. I am now working on the subtraction step and will show final demultiple results at the meeting. My future work will focus on evaluating and improving this approach with real data.

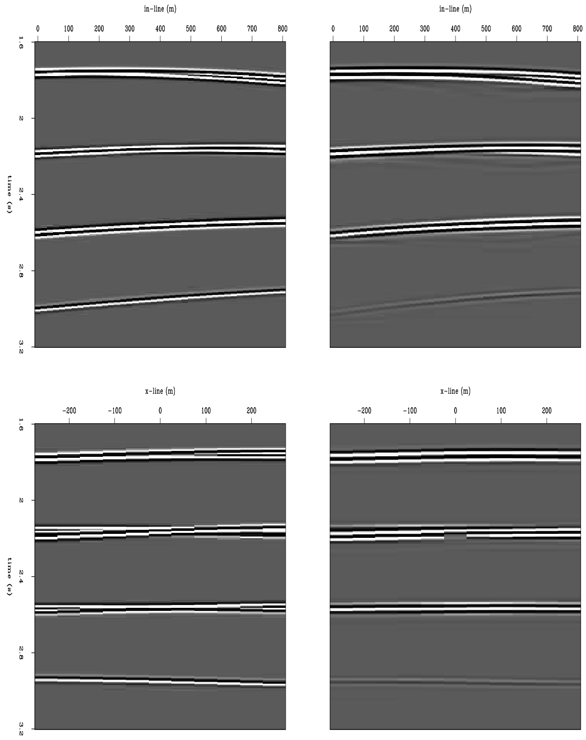

Figure 9: Mixing dip model. Left: ideal multiple reflection. Right: estimated multiple reflection.

REFERENCES

Berkhout, A. J., and Vershcuur, D. J., September-October 1997, Estimation of multiple scattering by iterative inversion, Part I: Theoretical considerations and examples: Geophysics, **62**, no. 5, 1586–1611.

Claerbout, J. F., 1992, Earth Soundings Analysis: Processing Versus Inversion: Blackwell Scientific Publications.

Ross, W. S., Yu, Y., and Gasparotto, F. A., 1997, Mulitple suppression: Beyond 2-D. Part II: Application to subsalt multiples: 67th Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, 1391–1394.

Ross, W. S., 1997, Mulitple suppression: Beyond 2-D. Part I: Theory: 67th Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, 1387–1390.

Spitz, S., 1991, Seismic trace interpolation in the f-x domain: Geophysics, **56**, no. 6, 785–794.

van Dedem, E. J., and Verschuur, D. J., 1998, 3-D surface-related mulitple elimination and interpolation: 68th Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, 1321–1324.

Verschuur, D. J., and Prein, R. J., 1999, Multiple removal results from Delft University: The Leading Edge, **18**, no. 1, 86–91.

Vershcuur, D. J., and Berkhout, A. J., September-October 1997, Estimation of multiple scattering by iterative inversion, Part II: Practical aspects and examples: Geophysics, **62**, no. 5, 1596–1611.