Practical, 3D Surface-related Multiple Prediction (SMP)

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Introduction

Prediction of surface multiples via 2D algorithms (e.g. SRME) is now routine in data processing, and is often effective in removing those multiples when combined with an adaptive subtraction. There are however many situations in which the 2D assumptions made on the geology and the acquisition geometry are invalid to the extent that the resultant errors in the predicted multiples are too large to allow those multiples to be effectively subtracted. A 3D prediction is theoretically possible and would eliminate these errors, but it requires data that are well sampled in all dimensions, and it can be very expensive. This paper covers the following aspects of 3D surface multiple prediction.

1. Determination of the timing errors associated with a 2D prediction, in order to determine the spatial locations where a 3D prediction is appropriate. This error analysis is model-based, and does not require the 2D prediction to be run.

2. Determination of the crossline aperture (maximum crossline component of the offset) that is required for the 3D prediction to be effective. The required aperture controls the cost of the 3D prediction, and may be space-variant.

3. 3D Surface-related Multiple Prediction (SMP) for typical marine acquisition geometries in which the crossline sampling and maximum crossline offset fall well short of the theoretical requirements.

4. QC of the results from both 2D and 3D predictions.

Data examples are used to demonstrate that a significant level of improvement in the accuracy of the predicted multipes is achievable using the 3D algorithm rather than the 2D algorithm, even for conventional geometries. In addition, the observed errors in the 2D predicted multiples are compared with the predicted errors to validate the usefulness of the error analysis.

2D multiple prediction and error analysis

The theory behind the surface multiple prediction (SMP) process (applicable in both two and three dimensions) is well known, and will not be repeated here. For more details, see for example Berkhout and Verschuur (1997) and Verschuur and Berkhout (1997). In essence, the process provides an accurate prediction of all surface multiples from the recorded data themselves, without requiring any knowledge of the subsurface.

Inadequate crossline sampling of recorded data has generally rendered direct application of the 3D algorithm impractical, and hence almost all the applications of the algorithm to real data have used a 2D prediction process. It should be noted that although the prediction process is 2D, the process may be applied to 3D data, e.g. on a subsurface line basis (Dragoset, 2000). This is not the same as a 3D prediction.

There are numerous examples in the literature of the successful application of 2D SMP to both 2D and 3D datasets. Almost invariably, the process is applied in two stages, namely multiple prediction and adaptive subtraction. An adaptive subtraction is necessary because the predicted multiples never match the recorded multiples sufficiently well that they may be subtracted without correcting for the differences. This correction is normally achieved via a least-squares matching filter approach. The errors are due mainly to 3D effects, notably crossline dip and cable feathering, both of which create timing errors in the predicted multiples. The first of these effects was studied by Ross (1999).

Kostov et al (2003) demonstrated that the timing errors depend on both crossline dip and feathering in a complex way. They used a newly developed software tool that is capable of predicting the timing errors associated with a 2D multiple prediction for a particular mode of multiple. The prediction process takes into account geological, data acquisition and data processing characteristics, and is both efficient and accurate.

There are many potential uses for such a tool. At the survey design stage, the error prediction may be used to optimise the survey orientation, and to place specifications on the maximum feathering that can accommodated, etc. During processing, the predicted errors are useful in determing optimum parameters for the adaptive subtraction, and also potentially in correcting the model for 3D effects. The predicted errors also provide a very useful QC of both the predicted multiples and the final results.

3D multiple prediction

Although the 2D SMP theory extends readily to 3D, there are two major practical impediments to its successful application on conventional, 3D marine seismic datasets.

1. The crossline sampling of both sources and receivers is inadequate and creates aliasing except at very low frequencies.

2. The maximum crossline offset of the recorded data is insufficient to predict surface multiples when the crossline dip is large.

The first of these issues can be addressed via interpolation, though this is often extremely expensive (Kleemeyer et al, 2003). In practice, it is necessary to use an interpolation scheme that is sufficiently accurate that the errors in the predicted multiples can be accommodated by the adaptive subtraction, whilst also maintaining practicality in terms of the cost involved and the requirements of any model (e.g. velocities) that the interpolation algorithm requires.

If the crossline dip is large, or the maximum crossline offset (i.e. the distance from source to outer cable) of the survey is small, then the multiple prediction will fail because it requires that the downward reflection points at the surface for the multiples lie within the aperture. The aperture is defined to be the region covered by receivers for each shot gather. If the aperture is too small, it is necessary to extrapolate offsets in the crossline direction, i.e. to simulate cables outside the furthest cables that were towed, in order to increase the crossline extent of the aperture. This can be a very difficult process.

It is clearly important that the crossline aperture is not too small. It is also important that the crossline aperture is not too large, because too large an aperture does not improve the accuracy of the model, but it increases both aliasing effects and the cost. The optimum crossline aperture is a function of crossline dip, and is therefore both offset- and space-variant. Given information about the crossline dip, it is possible to predict the required crossline aperture for each mode of multiple, and to incorporate this into the 3D prediction process. The prediction of the required aperture has been incorporated into the software tool that performs error analysis for a 2D prediction.

Data example

Figure 1 shows a plan view of the water depth below a narrow-tow, 3D survey. Also shown are the shot locations corresponding to one subsurface line. The line is above a canyon feature which is sufficiently deep that the first-arrival primaries and multiples reflect from the sides of the canyon, leading to significant 3D effects.

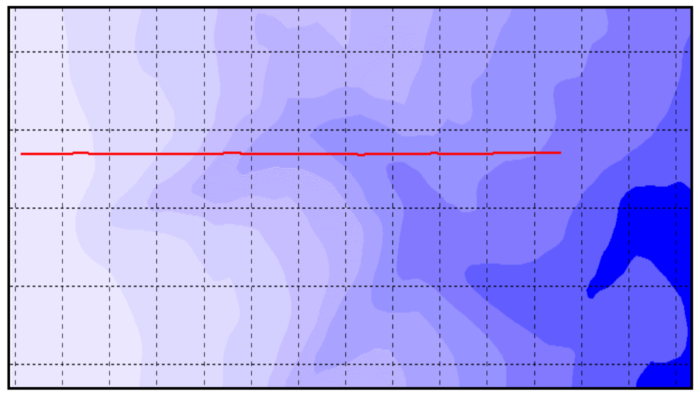

Figure 1: Water depth map. Depths range from 600 m (pale blue) to 1400 m (dark blue). The grid lines spacing is 1km. The shot locations follow the red line from right to left.

Figures 2a shows the 200 m offset plane from the input data, and figure 2b shows the surface multiples predicted using the 2D algorithm. The arrows indicate the timing errors in the multiple prediction for the first-arrival multiple, which is the first-order water bottom multiple. The timing errors reach 70 ms in the centre of the section where 3D effects are greatest.

Cross-correlations between the input data and the 2D predicted multiples are shown in figure 3, for three offset planes. The cross-correlations were computed in a short window containing the first-arrival multiple in order to show the timing errors for this multiple. The figure confirms the presence of timing errors of around 70 ms for some parts of the line. This magnitude of error is much more than could generally be accommodated by an adaptive subtraction algorithm.

Superimposed on the cross-correlations is the predicted timing error computed using the error analysis procedure. There is an excellent match between the predicted and observed errors, confirming the accuracy and usefulness of the error analysis.

Figure 4 shows the crossline aperture required to predict the first-arrival multiple as a function of shot location and offset. The magnitude of the required aperture exceeds 700 m for some parts of the line, which is many times larger than the maximum recorded crossline offset. In order to perform a 3D prediction and have any hope of success, it is therefore necessary to extrapolate the crossline offset range in order to provide input data to the prediction process, though it is not necessary to predict multiples for these extrapolated traces. The figure also indicates that in one area the aperture changes sign. This corresponds to the multiple's raypath flipping from one side of the canyon to the other.

The 3D predicted multiples are shown in figure 2c, and it is clear that the timing is greatly improved compared to the 2D prediction, with an almost perfect match for the first-arrival multiple. There are some aliasing artifacts evident as high-frequency ghost multiples that follow the real multiples and have a similar structure. These artifacts could be eliminated by interpolating the data to a finer crossline spacing.

Discussion

The main points from the preceding theory and example are as follows.

1. Multiple predictions using the 2D SMP algorithm suffer timing errors due to both crossline dip and cable feathering, and these effects interact in a complex way.

2. The timing errors associated with 2D SMP are predictable for a specific mode of multiple, given knowledge of the acquisition geometry and structure.

3. 3D prediction is possible, even when the recorded crossline sampling and aperture are insufficient. The requred aperture is predictable, and given a suitably interpolated and extrapolated dataset, the multiples can be accurately predicted using the 3D SMP algorithm.

In many ways, the example shown has addressed the problem from the wrong direction, since the acquistion had already taken place before the demultiple schemes were investigated. A more logical procedure would be as follows.

1. Use the error analysis to optimise the survey design, given some knowledge of the subsurface. Critical parameters include the acquisition direction and the maximum degree of feathering that can be accommodated.

2. Given the nominal (or real) acquisition geometry, predict the errors associated with a 2D prediction and determine the areas

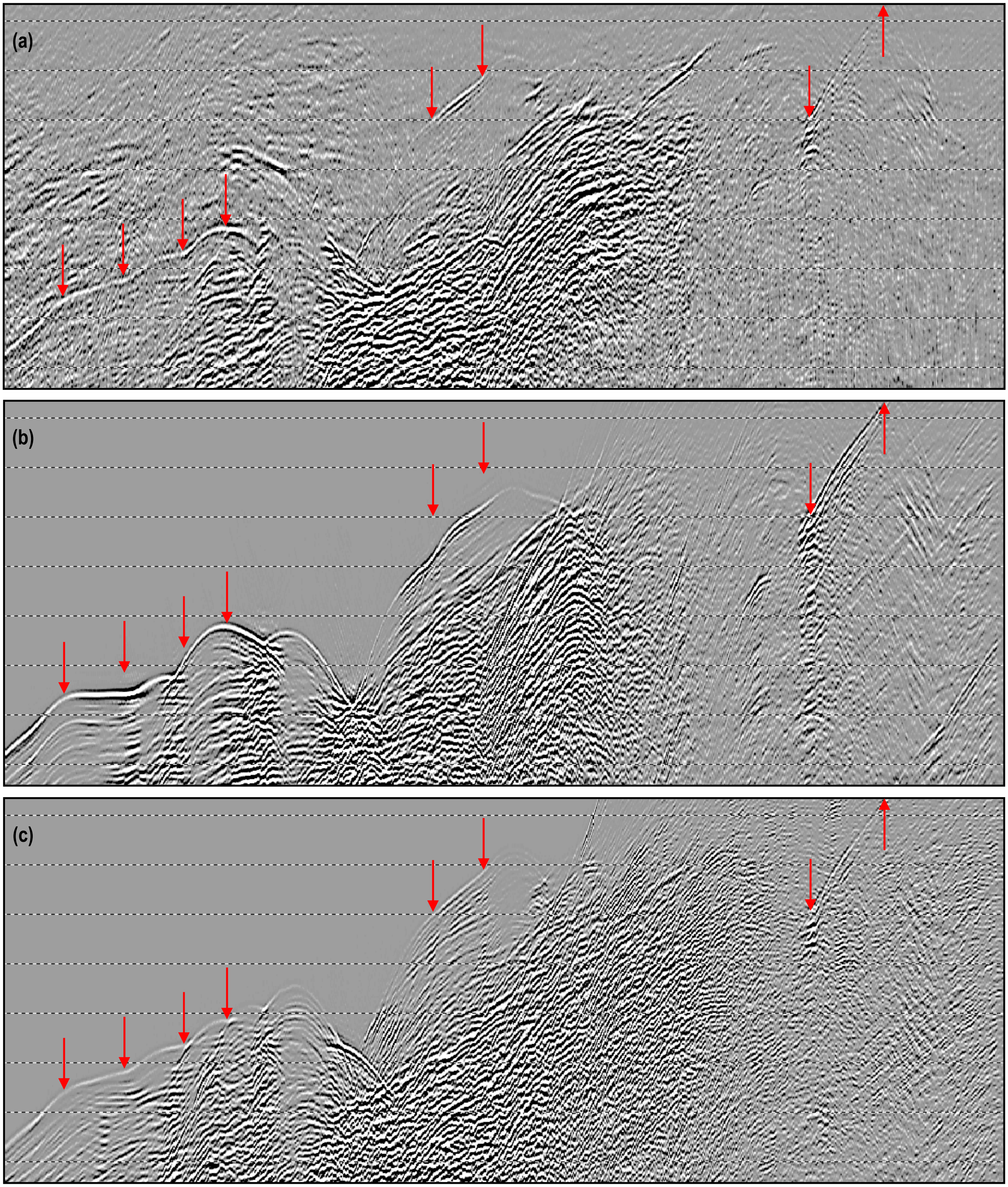

Figure 2: The 200 m offset plane at the level of the first-arrival multiple (arrowed) for (a) the input data, (b) 2D predicted multiples, and (c) 3D predicted multiples. Note that these plots are reversed with respect to figure 1, i.e. the sailing direction was from left to right.

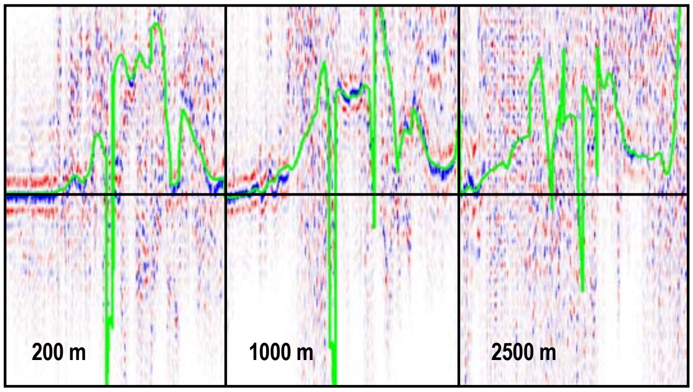

Figure 3: Cross-correlations between the input data and the 2D predicted multiples for 3 offset planes (as indicated), for a short window around the first-arrival multiple. The maximum lag is 100 ms. The green line indicates the predicted error from the error analysis.

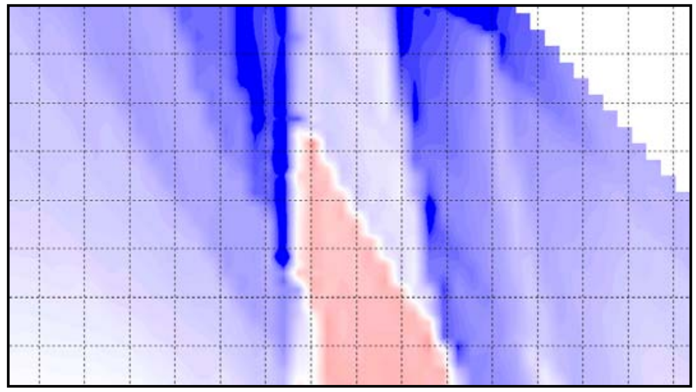

Figure 4: Crossline aperture as a function of shot location (horizontal axis) and offset (vertical axis). Deep red and deep blue correspond to –700 m and +700 m respectively.

where 2D multiple attenuation is likely to fail.

3. If necessary, determine the aperture required for a 3D prediction in these areas, potentially in a space- and offset-variant manner.
4. Predict the multiples using 2D or 3D SMP as appropriate, using no more aperture than is necessary.
5. Compare the observed errors in the 2D predicted multiples with the predicted errors, in order to provide a QC on the prediction process.

The survey design has a large impact on the potential success of both 2D and 3D SMP algorithms. Optimising the survey design may make the difference between success or failure of the process, and will almost invariably minimise the processing effort required.

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