Efficient Approach to 3-D Prestack Redatuming

POS 2.2

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Summary.

To make 3–D pre–stack migration feasible on current supercomputers it is sensible to invert correctly for only a small part of the subsurface, the so called target zone.
One of the steps in such a target oriented scheme is the redatuming of the shot records to the upper boundary of the target zone. With this redatuming step, shot records measured at the surface are converted into 'genuine' zero offset data, as if it was measured at the upper boundary of the target zone. By applying an efficient ray tracing scheme to calculate the extrapolation operators, this scheme is very well suited for use on current supercomputers within reasonable computation times.
The output of the redatuming is zero offset data of a far better quality than can be obtained with conventional CMP stacking at the surface. In our target oriented scheme, this zero offset data will be input for a 3–D zero offset migration scheme to obtain a depth image of the target zone.

Introduction.

In recent years much attention has been paid to the migration of 3–D seismic data. Full 3–D migration is presently only possible for post–stack data. Full pre–stack migration schemes are too much time consuming to be of practical use in 3–D seismic migration today.
However, 3–D pre–stack migration is feasible when only for a small part of the subsurface the imaging is performed, the so called target zone.

The three main parts of such a target oriented migration scheme are:

- Estimation of the macro subsurface model, i.e. the model containing the major geological boundaries and interval velocities. This macro model describes the propagation properties of the subsurface.
- Full 3–D redatuming of the shot records to the upper boundary of the target zone. With this step, from shot records at the surface 'genuine' zero–offset data are constructed at the upper boundary of the target zone.
- Full 3–D depth migration of the genuine zero–offset data, thus giving a high quality image of the target zone.

This paper will focus on the second stage in this scheme, namely the redatuming of the shot records.

Theory.

The principle of pre–stack redatuming has been treated by many authors, e.g. Berryhill (1984). From pre–stack surface data, pre-stack data is generated for shots and receivers located on a new datum. Using the matrix notation (Berkhout ,1982) for the full pre-stack redatuming:

Inverse extrapolation of the upgoing detected wave field:

$$P^-(z_N) = F^-(z_N,z_0)\,P^-(z_0) \qquad (1a)$$

Forward extrapolation of the downgoing source wave field:

$$S^+(z_N) = W^+(z_N,z_0)\,S^+(z_0) \qquad (1b)$$

and "deconvolving" the detected wave field for the illuminating source wave field at z_N:

$$\langle X(z_N)\rangle = P^-(z_N)\,[\,S^+(z_N)\,]^{-1} \qquad (1c)$$

The matrix notation describes a space variant convolution in the x and y directions.
The columns of $\langle X(z_N)\rangle$ describe the (monochromatic) common shot gathers that would be measured at the upper boundary of the target zone. In the same way the rows of matrix $\langle X(z_N)\rangle$ describe common receivers gathers. Hence the diagonal elements of $\langle X(z_N)\rangle$ give 'genuine' zero offset data as would be measured at the upper boundary of the target zone.

For the use of redatuming in a 3–D migration scheme the method is preferably applied per shot record (Berkhout ,1982), giving a better efficiency with respect to data handling.
To do this, the monochromatic shot records, measured at the surface are downward extrapolated to the upper boundary of the target zone:

$$\vec{P}_j^-(z_N) = F^-(z_N,z_0)\,\vec{P}_j^-(z_0) \qquad (2a)$$

and

$$[\,\vec{Z}_j^+(z_N)\,]^T = \frac{[\,\vec{S}_j^+(z_N)\,]^{*T}}{\|S(\omega)\|^2}\,F^+(z_0,z_N) \qquad (2b)$$

where $[\vec{Z}_j^{+}(z_N)]^T$ represent the rows of inverse matrix

$$[S^{+}(z_N)]^{-1} .$$

z_0 and z_N denote the surface and the new datum respectively

$\vec{S}_j^{+}$ and $\vec{P}_j^{-}$ are the downgoing source wave and the upgoing reflected waves, related to shot j.
F^{-} and F^{+} are the inverse wave field extrapolation operators for the up– and downgoing waves respectively.

For a description of equations (1) and (2) one is referred to Wapenaar and Berkhout (1987).
The redatumed wave field at the upper boundary of the target zone is obtained from:

$$< X(z_N) >_j = \vec{P}_j^{-}(z_N)\,[\vec{Z}_j^{+}(z_N)]^T \tag{3}$$

Equation (3) inverts the upgoing reflected waves for the downgoing source waves at the new datum and thus it gives the single fold redatumed section (related to one shot only) at the upper boundary of the target zone.
The full multi-fold pre-stack redatumed wave field is obtained by stacking the single fold wave fields $<X(z_N)>_j$ over all shots:

$$< X(z_N) > = \sum_j < X(z_N) >_j \tag{4}$$

Notice that this multi-fold redatumed wave field is exactly the same as would have been obtained with a full pre-stack redatumign scheme as described by relation (1c).
By restricting the output to the 'genuine' zero offset data (i.e. the diagonal elements of $<X(z_N)>$), the number of computations is reduced considerably. The quality of this ZO data is much better than can be reached by conventional CMP stacking at the surface.

From the Kirchhoff integral for inhomogeneous media, it follows, that for the calculation of the extrapolation operators one needs the Green's functions, describing the response at the surface of a point source placed at the upper boundary of the target zone. An accurate way to calculate the Green's functions is by finite differences. However for 3-D applications this method is not practical, because of the large computer requirements. So instead of finite differences we use a 3-D ray tracing algorithm to calculate these Green's functions. A ray tracing is performed for each point at the upper boundary of the target zone to a coarse grid of points at the surface.
After this ray tracing the operator travel times and amplitudes are calculated for the (irregularly spaced) acquisition points by an interpolation scheme.

Results.

To show the results of this method we first present a 2-D example. In figure 1 the model that is used is shown. For this model pre-stack data at the surface is generated using finite differences. Figure 2 shows a some shot records, for which the sources were located at 1000 m, 1500 m and 2000 m respectively.
The result after redatuming to the level depicted in figure 1 gives the result as shown in figure 3. Clearly the reflection from the interface at a depth of 800 m lines up correctly. It is clear that the propagation effects of the overburden are eliminated with this redatuming method and 'genuine' zero–offset data is generated.

The reflections of the layers in the overburden itself are positioned after redatuming at negative times and can thus be separated from the response of the target zone.

In Figure 4 the model is displayed of a 3–D subsurface. To demonstrate the 3–D inverse wave field extrapolation, data were generated at the surface using an exploding reflector model for a rectangular reflector at z=1000 m. In Figure 5 a some cross sections through this data set are shown.
Using a 3–D operator generated by ray tracing these data were inversely extrapolated. In Figure 6 the result of this extrapolation is shown. We see here one cross sections for x= 1270 m and one for the line y= 1000 m. at a depth of 1000 m.
The data are aligned around t=0 and also the lateral positioning is correct.

This shows that the extrapolation method works also good for 3–D extrapolation.
A full 3–D redatuming example will be discussed during the presentation.

Conclusions.

With a simple 2-D example we showed that redatuming per shot record is possible. Even for strong lateral velocity variations the redatuming inverts for the propagation effects of the overburden correctly. Genuine zero-offset data is generated at the upper boundary of the target zone.

By using a 3-D instead of a 2-D ray tracing algorithm an algorithm is obtained for 3-D pre-stack redatuming that is feasible on present vector computers.

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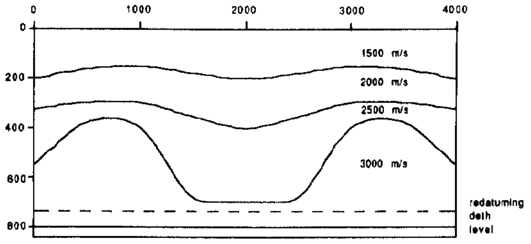

FIG. 1. Subsurface model used for 2-D redatuming example.

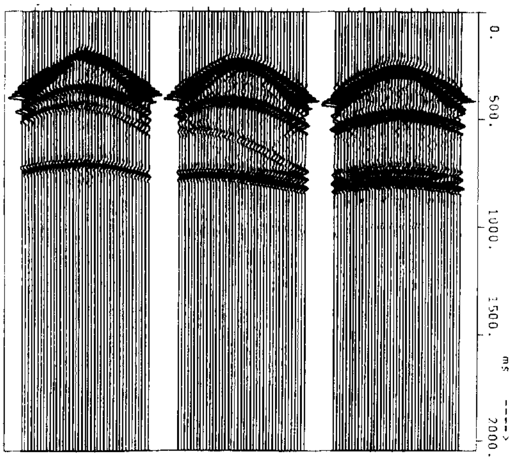

FIG. 2. 3 shot records at x = 1000 m, 1500 m, and 2000 m in model of Figure 1.

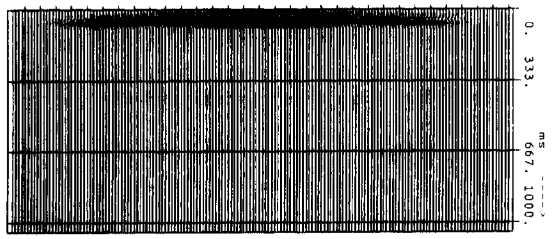

FIG. 3. Result after 2-D shot record redatuming.

References:

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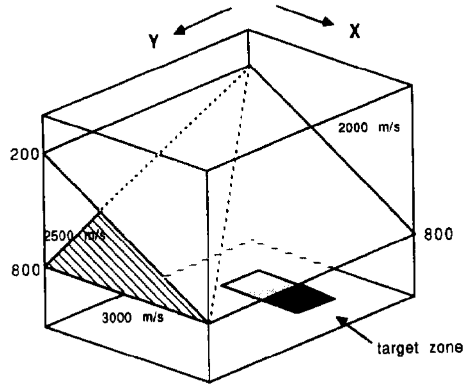

FIG. 4. 3-D subsurface model.

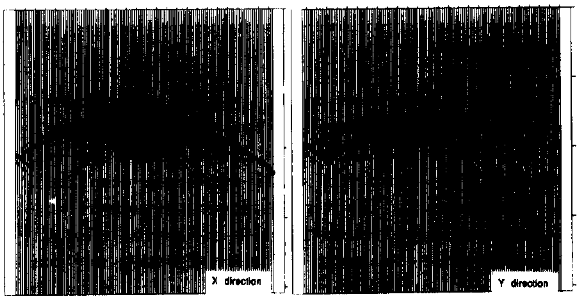

FIG. 5. Cross-sections through data at x = 1280 m and y = 1280 m.

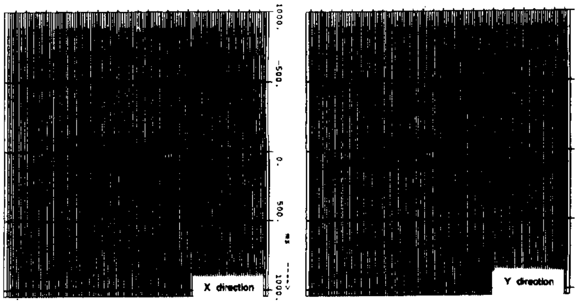

FIG. 6. Cross-section through result after 3-D inverse extrapolation at x = 1270 m and y = 1000 m.