Stacking and velocity estimation for 3-D surveys

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Abstract

The standard approach to stacking and velocity estimation for 3-D seismic reflection surveys is to organise the data by CMP bins and then apply techniques originally developed for 2-D surveys. The benefit of conventional binning is primarily in the display of the 3-D data volume.

Velocity estimation can be carried out directly with 3-D data provided the geometry of the survey is readily available. To minimise the effects of dip it is still desirable to restrict the location of the CMP's to lie in a restricted region without the requirement of bins of fixed size. Since the stacking velocities are azimuthally dependent, the trace gathers for velocity estimation over a narrow azimuth window should be chosen for that purpose rather than be based on stacking bins. Once the elliptic variation of stacking velocity with azimuth has been estimated, the seismic traces can be simultaneously stacked and interpolated onto a regular grid. The interpolation procedure is of most significance for short reflection times. The regular array of traces is particularly beneficial for the development of 3-D self-consistent statics procedures exploiting recent developments in large scale inverse problems.

Key words: 3-D surveys, stacking, velocity estimation, binning

Introduction

The majority of processing schemes for 3-D seismic data have evolved directly from their 2-D counterparts. Indeed in many cases the handling of 3-D data is so arranged that 2-D techniques, which are oriented to information along a line, are applied directly. However, for 3-D land surveys at least, the data collection procedure is not equivalent to a set of 2-D swaths. The data processing techniques employed should therefore be developed to take full account of the characteristics of 3-D survey geometries.

In particular, much 3-D processing involves combining traces for which the midpoint between source and receiver lie in a designated zone (a 'bin'). The purpose of this procedure is to produce regularly spaced data in the horizontal directions which are suitable for display or for the application of 2-D processing techniques. The traces within a bin are frequently stacked on the assumption that all traces effectively lie at the centre of the bin, and velocity analysis is conducted based on the same binning pattern.

Stacking with azimuth dependent velocities

In the presence of dip, lateral velocity variations or anisotropy, the appropriate stacking velocity for 3-D data requires azimuthal dependence. To a good approximation, this azimuthal variation is elliptical (Lehmann and Houba 1985) so that the stacking velocity along azimuth can be represented as

(1) $\quad v_{ST}(\theta) = v/(1 - e^2 \cos^2(\theta-\theta_o))^{1/2},$

where e is the eccentricity of the ellipse and ϕo is the azimuth of its major axis (Figure 1). For a single dipping plane with a uniform, isotropic, overburden v is the medium velocity, θ_o is the dip direction and $e = \sin\phi$, where ϕ is the dip angle (Levin, 1971). However, in general with multilayering or curved interfaces, there is no simple relations between e, θ_o and geologic parameters. Nevertheless, we have to take account of the azimuthal variation of the optimum stacking velocity when constructing stacked sections. In order to estimate this angular dependence, any stacking velocity estimate must be generated from a relatively narrow range of shot-receiver azimuths. With an even coverage of an azimuth window, a span of more than 60° can give errors in the stacking velocity estimates for the centre of the window of 5 per cent or more, which tend to be enhanced by an uneven distribution of azimuths (Figure 1). Practically, 60° should be regarded as the largest azimuth window which is likely to give useful stacking velocity estimates.

The affect of a range of azimuths is akin to the presence of a further class of offset-dependent static errors; the time shifts are larger for traces with larger offset. Monte-Carlo simulations including statics errors and varying noise levels have shown

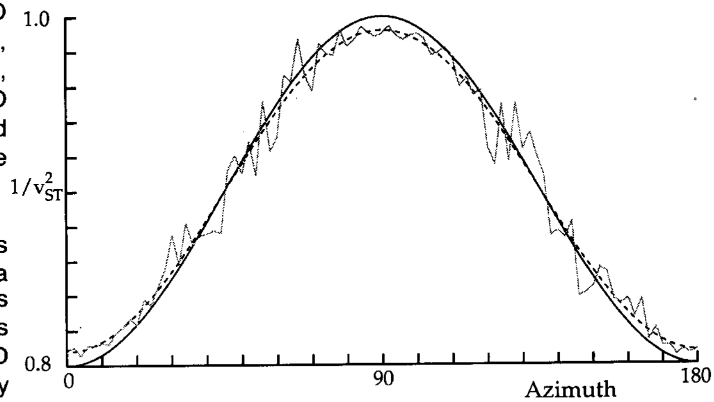

FIGURE 1
Variation of stacking parameter ($1/v_{ST}$) with azimuth. The solid curve represents the variation from equation (1) with eccentricity $e^2 = 0.2$. The dashed curve shows the result of averaging the stacking parameter over a 40° window about the selected azimuth. The grey curve simulates the effect of uneven coverage in an azimuth window by combining 10 randomly chosen directions within a 40° azimuth window and allowing 1 percent error in each estimation. Note that the error is largest near 45° where uniform coverage gives the best fit to the true curve.

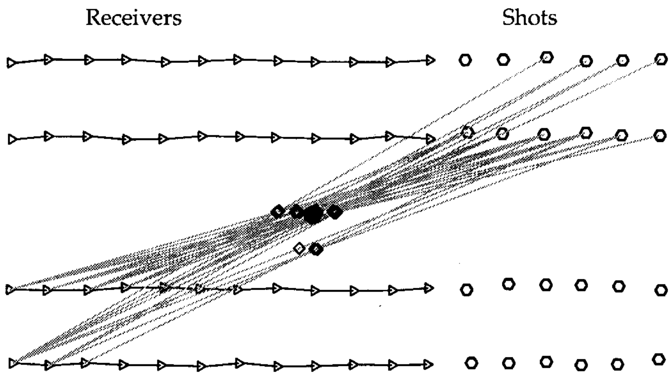

FIGURE 2
Selection of traces for a narrow azimuth window on a swath shooting geometry. The illustrated paths fall within a 30° azimuth window and their midpoints within a receiver spacing of the target point (shown as a solid symbol). The fold of coverage for velocity analysis can be markedly improved by using a velocity bin extended parallel to the receiver lines.

that an azimuth window 40° wide can give good estimates of the stacking velocity for the centre of the window. Even so there will be a tendency to overestimate the smallest stacking velocity and to underestimate the largest stacking velocity. In order to get a reliable estimate of the three parameters v,e,θ_0 appearing in (1) via least squares fitting we need at least 5 independent estimates of stacking velocities in narrow azimuthal windows.

In order to get sufficient fold of coverage for azimuthally varying estimates of stacking velocity centred on a particular point we must separate the concept of bins for velocity estimation and stacking. We have to assume that the stacking velocity ellipse varies only slowly on the scale of a few stacking bins. The optimum choice of 'velocity bin' for a particular survey will depend on the geometry. If, for example, the shots are deployed perpendicular to lines of receivers an effective way of increasing fold of coverage is to extend the bin oblique to the target azimuth as shown in Figure 2. To reduce systematic time errors from traces with CMP's well displaced from the intended point it can be advantageous to apply spatial weighting across the bin. When a number of azimuth windows are used, the resulting azimuth dependence will be derived for the region which is the intersection of all the velocity bins.

Once we have determined the angular variation of the stacking velocity with reflection time, we can combine the traces within a stacking bin by simultaneous stack and interpolation to the grid location required for the bin trace. The use of azimuthally dependent velocities in stacking will help to preserve the high frequencies and this can be enhanced by correcting all the traces to the same location. If the displacement of the CMP from the required grid point for the bin Δr (Figure 3) is small compared with the source-receiver offset, the interpolation procedure can be achieved during normal moveout correction by a small correction to the NMO time

(2) $$\Delta t_{NMO} = -4\,(\Delta r)^2/v^2(\Theta)\; t_{NMO}$$

for source-receiver azimuth Θ. This correction decreases with increasing tNMO and is in general quite small, but can be significant for high resolution surveys. In general the time correction for midpoint location will prove sufficiently accurate for arrivals left after mute. This procedure of relocating the stack traces will give a regularly spaced grid of traces for subsequent analysis.

The trace interpolation cannot accommodate large displacements from the grid location for the bin, but does allow some flexibility in choice of traces and thus the shape of the bin which is used to generate the composite trace. The centre of the bin should not depart very far from the grid point.

3-D statics corrections

Even when the main object of 3-D processing is a migrated data volume, the construction of an optimally stacked section has an important role in the estimation of static corrections. Field statics derived from uphole data or refraction surveys are valuable but rarely take full account of the complexity of the near surface region. In order to improve the statics corrections a further set of assumptions has to be made. A common choice is the surface consistent residual statics model of Taner et al (1974) which assumes that the corrections are time shifts which depend only on source and receiver position and not on the propagation path through the Earth. Although somewhat simplified, this model works well in practice: for the *h* th reflection horizon, the time correction for the *j* th shot recorded at the *i* th receiver can be approximated as

(3) $$t_{ijh} = s_j + r_i + G_{kh} + M_{kh}x_{ij}^2$$

where s_j is the source static, r_i the receiver static, G_{kh} is the time correction for the trace at the gridpoint k corresponding to the CMP, and $M_{kh}x_{ij}^2$ is a residual moveout term to correct for velocity errors (x_{ij} is the offset term for the source and receiver via the grid point). The time corrections thus depend on 4 different sets of parameters with distinct physical character.

Once estimates of the t_{ijh} have been generated we wish to extract the statics field and the horizon corrections. Under the assumption that the errors in the t_{ijh} have a Gaussian distribution we can attempt to minimise

(4) $$s = \sum_{ijh} (t_{ijh}^{obs} - t_{ijh})^2 + \text{Reg},$$

with respect to the required parameters S_j, r_i etc. To remove ill-conditioning we have imposed a regularisation term e.g.

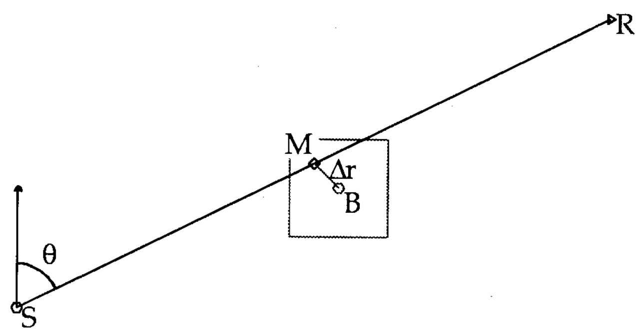

FIGURE 3
Mapping of the midpoint M between source and receiver onto a fixed grid point B within a bin by displacement through Δr.

that the horizon corrections be smooth. The set of linear equations resulting from this minimisation have been solved by Wiggins et al (1976) using a Gauss-Siedel method. For a full 3-D survey the number of equations is too large for direct attack. The conventional approach is to adopt line oriented 2-D schemes and then to patch together cross-line consistency. A better approach is to treat the problem using recently developed techniques in inverse problems. A suitable candidate is the subspace approach of Kennett et al (1988) which is designed to deal with parameters of different physical types and dimensions. This approach is iterative and the central computation requires the solution of a small matrix (no larger than 40x40) at each step. Convergence is rapid and the method is easily adapted to other measures of data fit than (4).

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