Analysis of a dip-dependent operator relating migration velocities and interval velocities

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ABSTRACT

In previous papers in SEP-44 and SEP-48 I derived a linear operator that relates perturbations in interval slownesses to the resultant changes in the slownesses used for prestack time migration. This operator is suitable only for point diffractors; the migration slowness change for a continuous reflector will not in general be the same as the migration slowness change for a point diffractor. In this paper I show how to decompose the point-diffractor operator into dip components and from this, how to derive an operator suitable for continuous beds of any specified dip. This dip-specific operator, like the all-dip point-diffractor operator, is derived using a two-step procedure of first tomographically estimating traveltime perturbations, and then finding a least-squares fit for a diffraction pyramid to the perturbed traveltimes. This fitting now uses not the whole pyramid, but only that part of it illuminated by a family of rays symmetric around the normal-incidence ray. For flat beds, the dipping-bed migration- slowness operator reduces to Toldi's flat-bed stacking-slowness operator.

INTRODUCTION

Building on ideas of Fabio Rocca's, Loinger (1983) and Toldi (1985) analyzed the relations between stacking velocities and interval velocities. For regions with significant geological structure, prestack time-migration velocities are easier to use than stacking velocities for velocity analysis, because they are much less sensitive to the effects of structure. These time-migration velocities can be derived easily by multiple constant-velocity prestack Stolt migration (Shurtleff, 1984), or by applying DMO and migration to constant-velocity stacks (Fowler, 1984). In previous papers (Fowler, 1985,1986), I have described how one might extend Toldi's algorithms to apply to migration velocities.

In this previous work, I derived a linear operator relating perturbations in interval slowness to the changes they cause in migration slowness. I also discussed how such an operator could be used in an automatic velocity-analysis algorithm. Numerical experimentation has convinced me that the theory I derived for the linear operator needs refinement. In this paper I re-examine the derivation of the operator, and show how to convert it into one more suitable for implementation. I do not discuss further here how to use this operator for velocity analysis; for that I refer the reader to Toldi's dissertation and to my previous papers.

The operator I previously derived treated each point in the Earth as an isolated diffractor, as is done in deriving migration operators. The problem I encountered is that I am, in effect, back-projecting traveltime residuals, not wave fields. The point-diffractor model works for waves because of constructive and destructive interference. For traveltime computations, one wants to back-project only along those rays that represent significant energy propagation, where the wave interference is constructive. One way of thinking about this is to visualize a point-diffraction traveltime pyramid at each point in the earth; only those parts of each pyramid are really "illuminated" by the seismic experiment that contribute to building up the continuous-bed traveltime curves actually visible in data. For a constant-velocity medium, the migration velocities measured from point diffractors would be the same as from any structure. However, if the velocity is perturbed, the change in migration velocity one measures is not structure independent. Thus the theory for the linear operator relating these changes must explicitly contain the local dip.

In what follows I derive such a dip-dependent operator. To do so, I first review the derivation of the all-dip point-diffractor operator, slightly modified. I then show how to decompose it into dip components to get a dip-dependent operator.

DERIVING THE ALL-DIP OPERATOR (ONE MORE TIME!)

Write the migration slowness $\mathbf{w}$ as a function of midpoint y and zero-offset time τ, and the interval slowness $\mathbf{m}$ as a function of lateral position x and depth z. What I want to find is an expression for $\partial w_d / \partial m_a$, relating a change in interval slowness at a particular model anomaly point $\mathbf{a}=(x_a, z_a)$ to the resulting change in observed migration slowness at some point $\mathbf{d}=(y_d, \tau_d)$ in the data space.

Relating traveltime perturbations to diffraction pyramids

Consider first a single point diffractor at (x_d, z_d) in a medium of constant slowness w. If one runs a seismic survey passing over this point, the kinematics of the pre-stack point diffractor are described by the pyramid equation

$$t = w \sqrt{z_d^2+(y-h-x_d)^2} + w \sqrt{z_d^2+(y+h-x_d)^2} \tag{1}$$

where t is the traveltime and h the half-offset. Suppose now that the slowness model is perturbed. The travel-time data for the point diffractor is now a set $\{t_{ik}, y_i, h_k\}$ which no longer satisfies equation (1) exactly. However, if the perturbations are not too large, it is possible to define a slowness W, a zero-offset time T, and a location Y for which an equation of the form

$$t = \sqrt{T^2/4 + W^2(y-h-Y)^2} + \sqrt{T^2/4 + W^2(y+h-Y)^2} \tag{2}$$

best fits the data points in a least-squares sense.

Note that it is necessary to consider the changes in T and Y as well as W, since all three may change. I want to consider not just perturbations away from constant slowness, for which the initial pyramid is an exact fit, but also from variable slowness case, where one has a previous estimate of the best fitting pyramid and perturbs it in turn. For variable slowness it is not in general true that $T = Wz_d$ and $Y = x_d$ as they would be for the constant slowness background of the starting model.

The pyramid equation (2) does not lend itself to a t^2–x^2 linearizing parametrization such as Toldi used for least-squares analysis of stacking slownesses. Instead, I solve the problem of fitting a pyramid through the data points $\{t_{ik}, y_i, h_k\}$ by linearizing around an initial value of $(\hat{W}, \hat{T}, \hat{Y})$. Then the set of equations to solve are given by

$$t_{ik} \approx t(\hat{W}, \hat{T}, \hat{Y}) + \frac{\partial t}{\partial W}\Delta W + \frac{\partial t}{\partial T}\Delta T + \frac{\partial t}{\partial Y}\Delta Y \tag{3}$$

where all the partial derivatives are evaluated at $(\hat{W}, \hat{T}, \hat{Y}, y_i, h_k)$. To make the notation more compact, denote the partial derivatives by subscripts: $\partial t/\partial W \equiv t_W$, etc. Explicitly,

$$\begin{bmatrix} t_W \\ t_T \\ t_Y \end{bmatrix} = \frac{1}{\sqrt{T^2/4 + W^2(y-h-Y)^2}} \begin{bmatrix} W(y-h-Y)^2 \\ T/4 \\ W^2(Y-y+h) \end{bmatrix} + \frac{1}{\sqrt{T^2/4 + W^2(y+h-Y)^2}} \begin{bmatrix} W(y+h-Y)^2 \\ T/4 \\ W^2(Y-y-h) \end{bmatrix}. \tag{4}$$

Let boldface denote vectors, so $\mathbf{t_W} = \{(t_W)_{ik}\}$, etc. For generality, let α_{ik} be a set of weights for the least squares fitting. Write the weighted inner product as, e.g.,:

$$\mathbf{t_W} \cdot \mathbf{t_T} = \sum_{i,k} \alpha_{ik} (t_W)_{ik} (t_T)_{ik} . \tag{5}$$

One then needs to solve the following system of normal equations for $(\Delta W, \Delta T, \Delta Y)$:

$$\begin{bmatrix} \mathbf{t_W}\cdot\Delta\mathbf{t} \\ \mathbf{t_T}\cdot\Delta\mathbf{t} \\ \mathbf{t_Y}\cdot\Delta\mathbf{t} \end{bmatrix} = \begin{bmatrix} \mathbf{t_W}\cdot\mathbf{t_W} & \mathbf{t_T}\cdot\mathbf{t_W} & \mathbf{t_Y}\cdot\mathbf{t_W} \\ \mathbf{t_W}\cdot\mathbf{t_T} & \mathbf{t_T}\cdot\mathbf{t_T} & \mathbf{t_Y}\cdot\mathbf{t_T} \\ \mathbf{t_W}\cdot\mathbf{t_Y} & \mathbf{t_T}\cdot\mathbf{t_Y} & \mathbf{t_Y}\cdot\mathbf{t_Y} \end{bmatrix} \begin{bmatrix} \Delta W \\ \Delta T \\ \Delta Y \end{bmatrix}. \tag{6}$$

This matrix equation has the solution

$$\begin{bmatrix} \Delta W \\ \Delta T \\ \Delta Y \end{bmatrix} = \frac{1}{D} \begin{bmatrix} \mathbf{A}\cdot\Delta\mathbf{t} \\ \mathbf{B}\cdot\Delta\mathbf{t} \\ \mathbf{C}\cdot\Delta\mathbf{t} \end{bmatrix} . \tag{7}$$

where

$$\mathbf{A} = a_1 \mathbf{t_W} + a_2 \mathbf{t_T} + a_3 \mathbf{t_Y} \tag{8}$$

$$\mathbf{B} = b_1 \mathbf{t_W} + b_2 \mathbf{t_T} + b_3 \mathbf{t_Y} \tag{9}$$

and

$$\mathbf{C} = b_1 \mathbf{t_W} + b_2 \mathbf{t_T} + b_3 \mathbf{t_Y} \ . \tag{10}$$

The scalars a_1, a_2, etc., as well as D, are all functions of various combinations of inner products of the form $\mathbf{t_W} \cdot \mathbf{t_T}$, etc., and can be found by Cramer's rule.

I have tried without success to find closed form solutions or approximations expressing these many inner products as simple functions of the upper and lower bounds. Toldi was able to approximate his analogous, but much simpler, sums by integrals that could be solved explicitly. Unfortunately, the integrals become too messy here. In practice, the closed form solutions are not too useful, anyway. It is better to evaluate this generalized matrix inversion numerically, as it can be numerically unstable; I use singular value decomposition for implementation, zeroing small singular values. One can either invert the normal equation matrix in equation (6) and have a set of coefficients for equations (8-10), or invert the original equations (3) and interpolate the coefficients to calculate the operator anywhere other than at the original h and y sampling points. These coefficients A_{ik}, B_{ik}, C_{ik}, and D are all functions of W, T, and Y, as well as depending on the geometry of the seismic experiment.

Relating interval slowness perturbations to traveltimes

These equations (7) describe how the W, T, and Y arising from a single point diffractor change when the traveltimes are perturbed, I intend, as the notation suggests, to identify (W, T, Y) with $(w(y, \tau), \tau, y)$. To complete the linearization, I need a relation between Δt_{ik} and Δm_a telling how the traveltimes change when the interval-slowness model is changed.

Consider the family of rays from the surface to the point diffractor. A perturbation in m affects not just one midpoint and offset, but many of them, since the same ray may be followed for many different combinations of midpoints and offsets. Let the subscript i index midpoint and k offsets, and let the subscript a denote the anomaly coordinates. For a given ray S_{ik} one has

$$t_{ik} = \int_{S_{ik}} dS_{ik}\, m(x_a, z_a) \ . \tag{11}$$

Invoking Fermat's principle, one can perturb the model and calculate the changes in traveltimes integrating the slowness perturbations along the *unperturbed* ray S_{ik}:

$$\Delta t_{ik} = \int_{S_{ik}} dS_{ik}\, \Delta m(x_a, z_a) \ . \tag{12}$$

This last calculation is valid for a general model, but to apply it directly requires tracing many rays at every iteration. I hope it proves adequate to evaluate these derivatives only once at the start. If a simple enough starting model is used (constant velocity, or only depth variable), it may be possible to evaluate them analytically; I consider the constant velocity case in detail. Otherwise one needs to trace rays from all diffracting points to all surface points, something that is not computationally too dreadful if done once, but could become prohibitive if repeated too often. This means using approximate values in place of the more accurate values that would be calculated by ray tracing using an iteratively updated model, but I do not think this approximation will prove to be too bad.

Figure 1 shows the geometry of the ray path for a particular diffractor point, midpoint, and offset in an arbitrary velocity model. Let the subscript d refer to the coordinates of a particular diffractor point (x_d, z_d), and let the subscript a refer to the location of a slowness anomaly (x_a, z_a), that is, a particular element of the model $\mathbf{m}$. Such an anomaly at a depth z_a can effect the diffraction pyramid if it is at either of two positions x_a, since it can be intercepted by either the ray going down or the one coming back up. Using the notation of Figure 1, equation (12) becomes

$$\Delta t_{ik} = \int_{x_a} dx_a \int_{z_a} dz_a \, \Delta m(x_a, z_a) \left(\frac{\delta_1}{\cos\psi_{ik}(z_a)} + \frac{\delta_2}{\cos\phi_{ik}(z_a)} \right) \tag{13}$$

where

$$\delta_1 \equiv \delta[x_a - y'_i(z_a) + \mu_{ik}(z_a)] \tag{14}$$

and

$$\delta_2 \equiv \delta[x_a - y'_i(z_a) - \nu_{ik}(z_a)] \; . \tag{15}$$

Now assume that a rule is known associating a diffracting point (x_d, z_d) with the point (y_d, τ_d) where it appears in the data. Rewrite equation (7) as

$$\Delta W(Y,T) = \frac{1}{D} \sum_i \sum_k \alpha_{ik} A_{ik} \Delta t_{ik} \tag{16}$$

and substitute from eq (15) for ΔT to yield

$$\Delta W(Y,T) = \frac{1}{D} \sum_i \sum_k \alpha_{ik} A_{ik} \int_{x_a} dx_a \int_{z_a} dz_a \, \Delta m(x_a, z_a) \times \left(\frac{\delta_1}{\cos\psi_{ik}(z_a)} + \frac{\delta_2}{\cos\phi_{ik}(z_a)} \right) . \tag{17}$$

Pull the integrals outside the sums and make the identification of $W(Y,T)$ with $w(y_d, \tau_d)$ to get

$$\Delta w(\mathbf{d}) = \int_{x_a} dx_a \int_{z_a} dz_a \, G_W(\mathbf{d},\mathbf{a}) \Delta m(x_a, z_a) \tag{18}$$

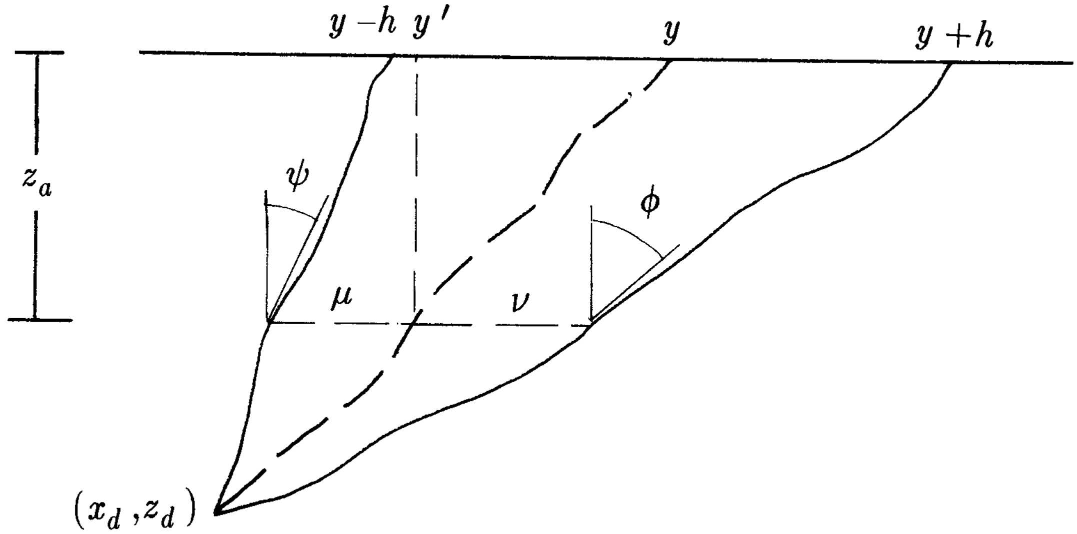

FIG. 1. Geometry of rays for a single diffractor point and a variable background slowness. The rays for a single trace with midpoint y and offset h are shown, along with the zero-offset ray (dashed). The diffractor is at (x_d, z_d). The point in the model at which the slowness is perturbed is denoted by (x_a, z_a). The quantities ϕ, ψ, μ, and y' are used in calculating the effect on the travel-time of perturbing the slowness.

where

$$G_W(\mathbf{d},\mathbf{a}) = \sum_{i=1}^{N_y} \sum_{k=1}^{N_h} \frac{\alpha_{ik} A_{ik}}{D} \left(\frac{\delta_1}{\cos\psi_{ik}(z_a)} + \frac{\delta_2}{\cos\phi_{ik}(z_a)} \right) . \tag{19}$$

This Green function $G_W(\mathbf{d},\mathbf{a})$ can be identified with $\partial w_d / \partial m_a$; they both represent the change in $w(y, \tau)$ caused by a perturbation in $m(x, z)$. One can also write similar Green function representations for $G_T(\mathbf{d},\mathbf{a}) = \partial \tau_d / \partial m_a$ and for $G_Y(\mathbf{d},\mathbf{a}) = \partial y_d / \partial m_a$ simply by substituting B or C in place of A in equation (19).

Evaluation of the Green function G_W in a form suitable for implementation involves substituting for the trigonometric terms in equation (19) and using the delta functions to eliminate one sum. To do this evaluation against a general background velocity model, one needs to trace the rays to find, for each diffractor and each midpoint y and offset h, the values of $y'(z_a)$, $\mu(z_a)$, $\phi(z_a)$, and $\psi(z_a)$. This computation is greatly simplified for a laterally invariant background, since the computation is then identical for all midpoints and need only be done once. Note also that a rule for finding (y_d, τ_d) as a function of (x_d, z_d) is also needed, and that this rule is also greatly simplified for a laterally invariant background. The whole computation of G_W is even easier for a constant background, and may be done analytically in that simple case.

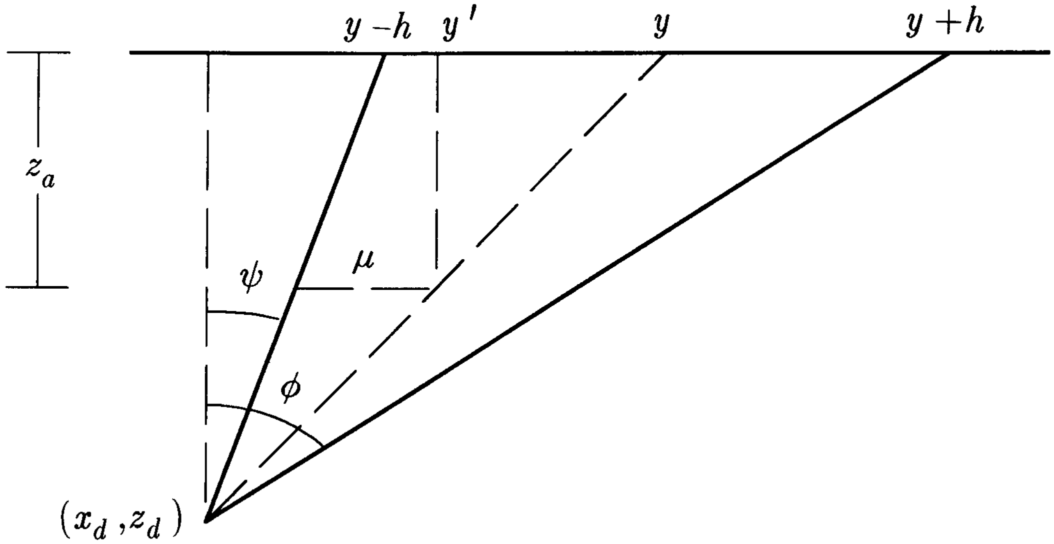

FIG. 2. Geometry of rays for a single diffractor point and a constant background slowness. The rays for a single trace with midpoint y and offset h are shown, along with the zero-offset ray (dashed). The diffractor is at (x_d, z_d). The point in the model at which the slowness is perturbed is (x_a, z_a). The quantities ϕ, ψ, μ, and y' are used in calculating the effect on the travel-time of perturbing the slowness.

ALL-DIP OPERATOR FOR CONSTANT SLOWNESS BACKGROUND

If the background velocity model is constant the rays are straight, as shown in Figure 2, and ϕ and ψ become independent of z_a. Consider first the sum containing δ_1,

$$(G_W)_1(\mathbf{d},\mathbf{a}) = \sum_{i=1}^{N_y}\sum_{k=1}^{N_h} \alpha_{ik} \frac{A(y_i, h_k)\delta_1}{D\cos\psi} . \tag{20}$$

Substitute

$$\cos\psi = z_d \left[z_d^2 + (y - h - x_d)^2 \right]^{-1/2} \tag{21}$$

$$\gamma = \frac{z_d}{z_d - z_a} \tag{22}$$

$$y' = x_d + \frac{y - x_d}{\gamma} \tag{23}$$

and

$$\mu = \frac{h}{\gamma} \tag{24}$$

to get

$$\delta_1 = \delta\,[\, x_a - y' + \mu(z_a)\,] \tag{25}$$

$$= \delta\left[\, x_a \;-\; x_d \;-\; \frac{(y - x_d - h\,)}{\gamma}\,\right] \tag{26}$$

$$= \gamma\,\delta\,[\,\gamma\,(x_a - x_d\,) - (y - x_d - h\,)\,] \tag{27}$$

and then

$$(G_W\,)_1(\mathbf{d},\mathbf{a}) = \sum_{i=1}^{N_y}\sum_{k=1}^{N_h} \frac{\alpha(y\,,h_k\,)A\,(y_i\,,h_k\,)\,\left[z_d^{\,2} + (y_i - h_k - x_d\,)^2\right]^{1/2}}{(z_d - z_a\,)D} \times \tag{28}$$

$$\delta[\,\gamma(x_a - x_d\,) - (y_i - x_d - h_k\,)]$$

The double sum thus contains non-zero terms only when $y_i - h_k - x_d = \gamma(x_a - x_d\,)$. This relation can be used to eliminate either of the sums. I choose to approximate the sum over h_k as an integral and eliminate it using the delta function. Let $h' = y_i - x_d - \gamma(x_a - x_d\,)$. Equation (28) then reduces to

$$(G_W\,)_1(\mathbf{d},\mathbf{a}) \approx \frac{1}{D\,(z_d - z_a\,)\Delta h} \times \tag{29}$$

$$\sum_{i=1}^{N_y} \int_0^{L/2} dh\;\; \alpha(y_i\,,h\,)A\,(y_i\,,h\,)\left[z_d^{\,2} + (y_i - h - x_d\,)^2\right]^{1/2} \delta(h - h'\,)$$

$$\approx \frac{\gamma}{z_d\,D\,\Delta h}\left[z_d^{\,2} + \gamma^2(x_a - x_d\,)^2\right]^{1/2} \sum_{i=1}^{N_y} \alpha(y_i\,,h = h'\,)\;A\,(y_i\,,h = h'\,) \tag{30}$$

where Δh is the survey offset spacing, and L is the cable length. I have assumed that the innermost offset is approximately zero. By a derivation similar to that of equation (30), the sum in equation (19) containing δ_2 becomes

$$(G_W\,)_2(\mathbf{d},\mathbf{a}) = \frac{\gamma}{z_d\,D\,\Delta h}\left[z_d^{\,2} + \gamma^2(x_a - x_d\,)^2\right]^{1/2} \sum_{i=1}^{N_y} \alpha(y_i\,,h = -h'\,)\;A\,(y_i\,,h = -h'\,) \tag{31}$$

so

$$G_W(\mathbf{d},\mathbf{a}) = \frac{\gamma}{z_d\, D\, \Delta h} \left[z_d^{\,2} + \gamma^2 (x_a - x_d)^2 \right]^{1/2} \times \tag{32}$$

$$\sum_{i=1}^{N_y} \left[\alpha(y_i, h = h') \, A\,(y_i, h = h') + \alpha(y_i, h = -h') \, A\,(y_i, h = -h') \right] .$$

But only positive values of h really have much meaning here; including the reciprocal experiments only gives us a constant factor of 2, since $A\,(y, h) = A\,(y, -h)$. So, if the weights α also are an even function in h, one can reduce equation (33) to

$$G_W(\mathbf{d},\mathbf{a}) = \frac{\gamma}{z_d\, D\, \Delta h} \left[z_d^{\,2} + \gamma^2 (x_a - x_d)^2 \right]^{1/2} \times \tag{33}$$

$$\sum_{i=1}^{N_y} \left[\alpha(y_i, h = \mid h' \mid) \, A\,(y_i, h = \mid h' \mid) \right] .$$

Note that one could have used the delta function to eliminate the sum over y instead. Doing this, and letting $y' = \gamma(x_a - x_d) + x_d$, one gets

$$G_W(\mathbf{d},\mathbf{a}) = \frac{\gamma}{z_d\, D\, \Delta y} \left[z_d^{\,2} + \gamma^2 (x_a - x_d)^2 \right]^{1/2} \times \tag{34}$$

$$\sum_{k=1}^{N_h} \left[\alpha(y = y' + h_k, h_k) A\,(y = y' + h_k, h_k) + \alpha(y = y' - h_k, h_k) A\,(y = y' - h_k, h_k) \right] .$$

The y and h in the above equations will now usually not fall on grid points, but A can be calculated for any y or h numerically. In all these computations against a constant-slowness background, one can use $(\tau_d, y_d) = (2wz_d, x_d)$ if an explicit relation between $\Delta w\,(y_d, \tau_d)$ and $\Delta w\,(x_d, z_d)$ is needed.

Equations (33) or (34) may be understood graphically using Figure 3, which shows a bird's-eye view of a traveltime pyramid. Superimposed on the pyramid is the V-shaped track of a single anomaly. This V will always be a right angle, and will always be at 45 degrees to the y and h axes. For each non-zero offset, two midpoint values contribute to the sum in equation (34); these correspond to the two legs of the V pattern. Only half the pyramid is drawn; this corresponds to the restriction to positive h in equation (33).

DIP-DECOMPOSING THE TRAVELTIME PYRAMID

So far I have derived an expression for $\partial w / \partial m$ for a point diffractor. In a constant velocity medium the migration slowness observed for a point diffractor is the same as that observed for any structure. This does not guarantee, however, that $\partial w / \partial m$ will be the same independent of the actual structure present; in fact it will depend on what dips are present. A point diffractor may be thought of as equal parts of all dips. I now show how to decompose the traveltime pyramid into dip components to find $\partial w / \partial m$ for a particular dip θ.

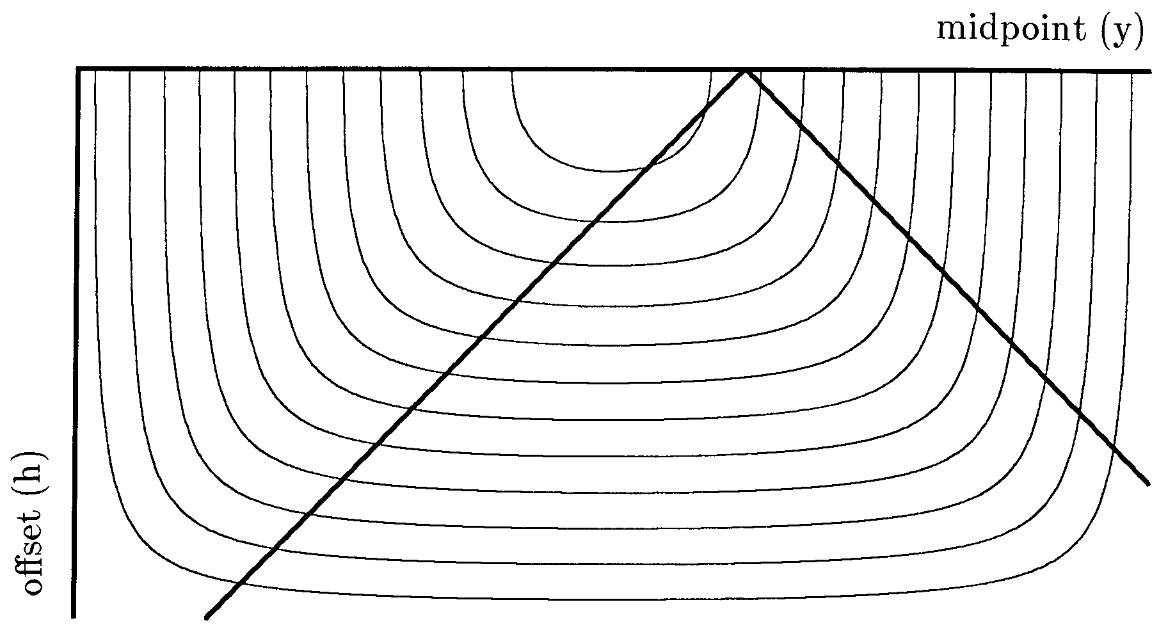

FIG. 3. Bird's-eye view of a point diffractor traveltime pyramid. Contours are equal traveltime curves. Also shown is the V-shaped pattern of all midpoint-offset combinations that represent rays passing through a particular anomaly point.

Suppose the reflecting point (x_d, z_d) lies on a bed a bed with dip θ. Figure 4 shows the geometry of rays reflecting off such a dipping bed. Unlike the rays used for stacking-velocity analysis, the rays for migration-velocity analysis have a common reflection point, and do not cross each other. The ray picture for migration-velocity analysis is like that for flat-bed stacking-velocity analysis, but rotated by the dip angle so that the rays remain symmetric around the normal incidence ray.

Let x be the point where the normal ray intersects the surface; in general x will not coincide with the midpoint y. From the law of sines one has

$$\frac{x-s}{\sin\varsigma} = \frac{t_1}{\sin(\pi/2-\theta)} \tag{35}$$

and

$$\frac{g-s}{\sin\varsigma} = \frac{t_2}{\sin(\pi/2+\theta)} \tag{36}$$

where $s=y-h$ is the shot location and $g=y+h$ is the geophone location, and ς is the incident angle of the rays at the bed, measured from the normal. But $\sin(\pi/2-\theta)=\sin(\pi/2+\theta)=\cos\theta$, so equations (33) and (34) yield

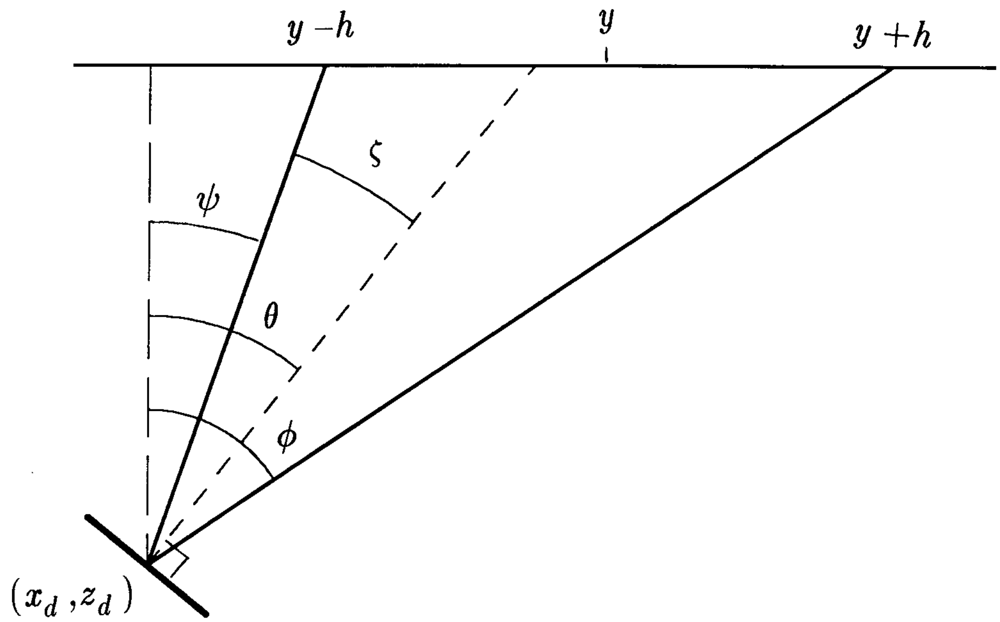

FIG. 4. Geometry of rays for a dipping bed and a constant background slowness. The rays for a single trace with midpoint y and offset h are shown, along with the normal ray (dashed). The reflecting point is at (x_d, z_d). Note that the normal ray does not go through y.

$$\frac{x-s}{t_1} = \frac{g-x}{t_2} . \tag{37}$$

It follows that

$$x = \frac{gt_1 + st_2}{t_1 + t_2} \tag{38}$$

and

$$\tan\theta = \frac{x}{z_d} = \frac{g\sqrt{s^2+z_d^2} + s\sqrt{g^2+z_d^2}}{z_d\left(\sqrt{s^2+z_d^2} + \sqrt{g^2+z_d^2}\right)} . \tag{39}$$

Substituting $y=(g+s)/2$ and $h=(g-s)/2$ gives a relation for θ, but it is awkward to solve for y or h. A simpler relation can be found using double angles.

Referring to Figure 4 again, one has

$$\varsigma = \theta - \psi = \phi - \theta \tag{40}$$

so

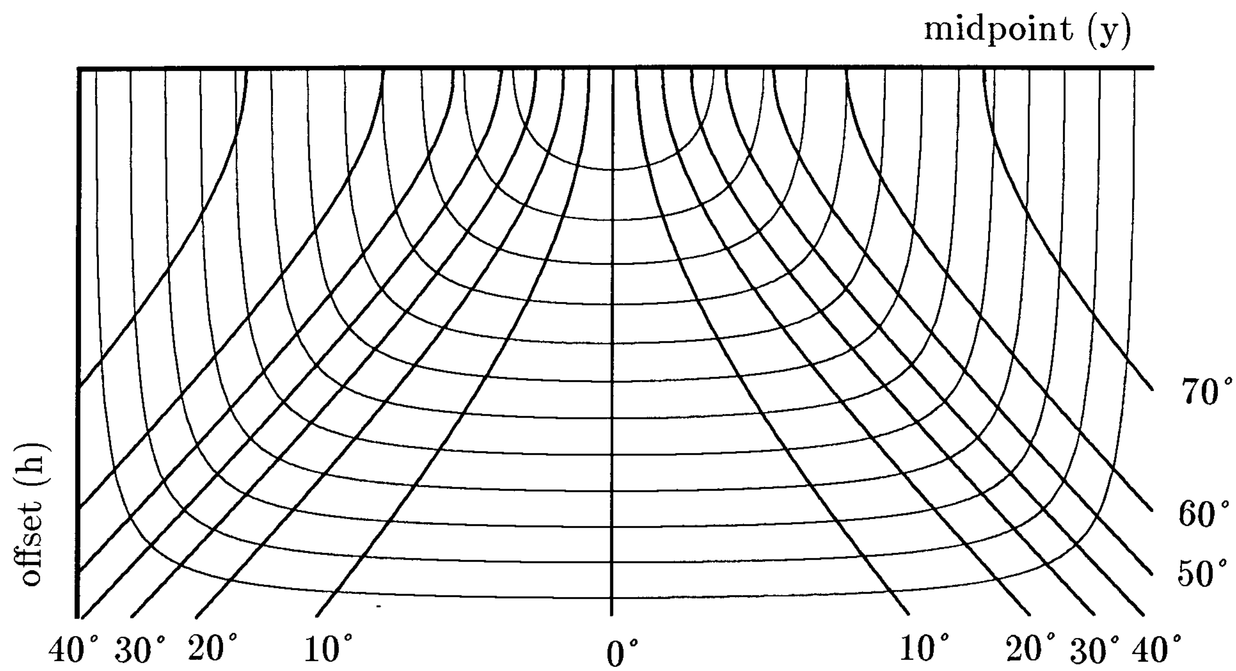

FIG. 5. Bird's-eye view of a point diffractor traveltime pyramid. Contours are equal traveltime curves. Also shown are lines representing constant-dip components, in increments of 10 degrees.

$$\theta = \frac{1}{2} (\psi + \phi) \tag{41}$$

and

$$\tan(2\theta) = \tan(\psi + \phi) \tag{42}$$

$$= \frac{\tan\psi + \tan\phi}{1 - \tan\psi \tan\phi} . \tag{43}$$

Substituting

$$\tan\psi = \frac{y - x_d - h}{z_d} \tag{44}$$

and

$$\tan\phi = \frac{y - x_d + h}{z_d} \tag{45}$$

gives

$$\tan(2\theta) = \frac{2 z_d (y - x_d)}{{z_d}^2 - (y - x_d)^2 + h^2} . \tag{46}$$

This last equation tells which y and h have rays reflected off the dipping bed at the particular point (x_d, z_d). This is the desired decomposition of the pyramid into contributions from different dips. Figure 5 shows a bird's-eye view of the traveltime pyramid of equation (1), contoured in equal traveltime increments. Superimposed on this are curves from equation (46) that represent 10 degree dip increments.

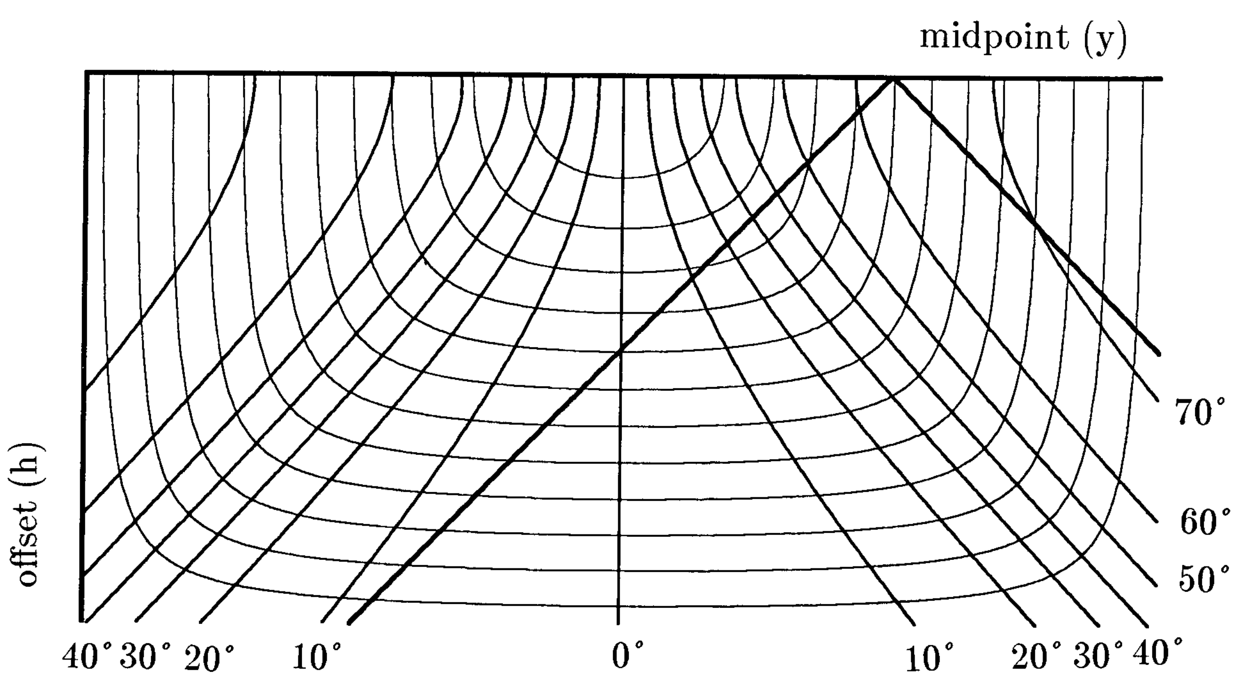

FIG. 6. Bird's-eye view of a point diffractor traveltime pyramid. Contours are equal traveltime curves. Also shown are lines representing constant dip contributions, in increments of 10 degrees, and the V-shaped track of a point anomaly. This Figure combines Figures 3 and 4.

WEIGHTING DIPS SELECTIVELY: THE DIP-DEPENDENT OPERATOR

So far I have derived an expression for $\partial w / \partial m$ for a point diffractor. In a constant velocity earth the migration slowness observed for a point diffractor is the same as that observed for any structure whatsoever. This does not guarantee, however, that $\partial w / \partial m$ will be the same independent of the actual structure present. Each point diffractor can be treated as made up equally of all dips; the component for a given θ is given by equation (46). Figure 6 shows that the V-shaped track of an anomaly intersects a constant dip contour only at one point. Limiting the point diffractor Green function to a single dip component thus has the effect of zeroing out all but a particular (y, h)

point in the sum of equation (19) or equation (33).

To find the intersection point, rewrite equation (46) as

$$\frac{(y-x_d+z_d\cot 2\theta)^2}{z_d^2\csc^2 2\theta} - \frac{h^2}{z_d^2\csc^2 2\theta} = 1 \ . \tag{47}$$

This can be recognized as the equation for a hyperbola with asymptotes

$$\pm h = y-x_d+\cot 2\theta \tag{48}$$

and foci

$$(h,y) = (\,0,\ x_d+z_d(\cot 2\theta \pm \sqrt{2}\csc 2\theta)\,)\ . \tag{49}$$

One can solve equation (47) for h in terms of y and θ to get

$$\begin{aligned} h^2 &= (y-x_d+z_d\cot 2\theta)^2 - z_d^2\csc^2 2\theta \\ &= (y-x_d)^2 + 2z_d(y-x_d)\cot 2\theta - z_d^2\ . \end{aligned} \tag{50}$$

One could as well solve for y to get

$$y_\theta(h) = x_d-z_d\cot 2\theta \pm \sqrt{h^2+z_d^2\csc^2 2\theta} \tag{51}$$

where the choice of sign will depend on whether $\theta>0$ or $\theta<0$. Note that $\theta=0$ must be considered separately; h may then take on any value, but y must always equal x_d; the two branches of the hyperbola have collapsed to one straight line. The delta functions in equation (19) also give relations between allowable values of y and h, as represented by the legs of the V pattern in Figure 6. Solving equation (50) and the appropriate one of these equations simultaneously will give the needed intersection point. For the constant velocity case one has

$$h = |\ y-x_d-\gamma(x_a-x_d)\ | \tag{52}$$

and so

$$h^2 = (y-x_d)^2 - 2\gamma(x_a-x_d)(y-x_d) + \gamma^2(x_a-x_d)^2\ . \tag{53}$$

From this and equation (50) one gets

$$2z_d(y-x_d)\cot 2\theta - z_d^2 = -2\gamma(x_a-x_d)(y-x_d) + \gamma^2(x_a-x_d)^2\ . \tag{54}$$

Solving for y gives

$$y = x_d + \frac{z_d^2+\gamma^2(x_a-x_d)^2}{2[z_d\cot 2\theta+\gamma(x_a-x_d)]}\ . \tag{55}$$

(Note that $\theta=0$ is treated correctly as the limiting case of equation (55).) This gives y, and h can then be found from equation (52):

$$h = \left|\frac{z_d^2+\gamma^2(x_a-x_d)^2}{2[z_d\cot 2\theta+\gamma(x_a-x_d)]} - \gamma(x_a-x_d)\right|\ . \tag{56}$$

Write these values of the intersection point coordinates as h_θ and y_θ. Equation (33) then becomes

$$(G_W)_\theta(\mathbf{d},\mathbf{a}) = \frac{\gamma}{z_d\, D\, \Delta h} \left[z_d^{\,2} + \gamma^2 (x_a - x_d)^2 \right]^{1/2} \times \tag{57}$$

$$\alpha \left[y_\theta(\mathbf{d},\mathbf{a}), h_\theta(\mathbf{d},\mathbf{a}) \right] A \left[y_\theta(\mathbf{d},\mathbf{a}), h_\theta(\mathbf{d},\mathbf{a}) \right]$$

I note that the values of h , y , and θ which can be used in these equations are restricted. Both legs of the travel time path must be above the horizontal and must have equal incident angles; from this limitation one can show that, for positive θ, one must have $\cot 2\theta > (x_d - x_a)/(z_d - z_a)$ and for negative θ, $\cot 2\theta < (x_d - x_a)/(z_d - z_a)$

This single dip operator could also be derived from scratch, fitting only over the appropriate hyperbolic curve using a sum over h only, then replacing the sum by an integral and using the delta function to eliminate the integral; the result is again equation (57). A subtle, but important, point to notice here is that A and D in the preceding equations should really be written as A_θ and D_θ. The factors of $\mathbf{t_W}\cdot\mathbf{t_T}$ and such like that occur in the coefficients in equation (6) will in fact be different for each dip. The inner products must also be taken over the appropriate hyperbola, which will differ for each dip, rather than over the whole pyramid.

What does this mean in practice? It suggests that the operator should be weighted to reflect the actual dips present in the data at each point. For the case of a single dip component, these weights are just delta functions that pick out the contour representing a given dip, and would be zero elsewhere. In practice, one might want to weight by an estimate of the dips in the data, allowing for multiple dips and inaccurate knowledge of the dips. Reasonable dip estimates should be obtainable from the prestack time migrated image, perhaps by local slant stacks. The G_W operator could then be weighted by this estimated dip spectrum. Like the ray tracing, the dip spectrum decomposition is probably something one would want to do once at the start, and accept the small inaccuracies that arise by not refining it often as one iterates toward a better answer.

One can combine the operators for all dips are combined and write

$$G_W(\mathbf{d},\mathbf{a}) = \int d\theta \, (G_W)_\theta(\mathbf{d},\mathbf{a}) \tag{58}$$

$$= \int dy \left| \frac{d\theta}{dy} \right| (G_W)_\theta(\mathbf{d},\mathbf{a}) \,. \tag{59}$$

The value of this jacobian can be found via implicit differentiation of equation (46) to be

$$\frac{\partial \theta}{\partial y} = \frac{z_d \; (z_d^{\,2} + (y - x_d)^2 + h^2)}{[\, z_d^{\,2} - (y - x_d)^2 + h^2 \,]^2 + 4 z_d^{\,2} (y - x_d)^2} \tag{60}$$

$$= \frac{z_d \; (z_d^{\,2} + (y - x_d)^2 + h^2)}{[\, z_d^{\,2} + (y - x_d)^2 + h^2 \,]^2 - 4 (y - x_d)^2 h^2} \,. \tag{61}$$

This suggests that the integral over a spectrum of dips should either be explicitly taken over θ, or if it is evaluated in terms of an integral over y, the integral should be weighted by $d\theta/dy$ as given in equation (60) or (61). Doing this recovers equation (33), with the previous warning about the dip dependence of the A and D factors remembered.

One set of weights has been suggested to pick out the contributions that correspond to the dips present in the data, and another to weight these contributions. This still leaves freedom to weight the contributions from different offsets h as one chooses while computing A and G_W in equation (57).

ZERO-DIP OPERATOR

I now look in detail at the special case of $\theta=0$. This operator should behave like Toldi's stacking operator, since for flat beds and laterally invariant velocities, prestack migration reduces to stacking. All gathers will be symmetric, so $y_\theta = x_d$ and $h_\theta = |\gamma(x_a - x_d)|$. In terms of equation (4) this means that

$$\begin{bmatrix} t_W \\ t_T \\ t_Y \end{bmatrix} = \frac{1}{\sqrt{T^2/4 + W^2h^2}} \begin{bmatrix} 2Wh^2 \\ T/2 \\ 0 \end{bmatrix} . \tag{62}$$

So $t_Y=0$, as one might expect (flat beds don't migrate laterally), and equation (6) reduces to

$$\begin{bmatrix} \mathbf{t_W}\cdot\Delta\mathbf{t} \\ \mathbf{t_T}\cdot\Delta\mathbf{t} \end{bmatrix} = \begin{bmatrix} \mathbf{t_W}\cdot\mathbf{t_W} & \mathbf{t_T}\cdot\mathbf{t_W} \\ \mathbf{t_W}\cdot\mathbf{t_T} & \mathbf{t_T}\cdot\mathbf{t_T} \end{bmatrix} \begin{bmatrix} \Delta W \\ \Delta T \end{bmatrix} \tag{63}$$

from which one gets

$$\begin{bmatrix} \Delta W \\ \Delta T \end{bmatrix} = \frac{1}{D} \begin{bmatrix} \mathbf{A}\cdot\Delta\mathbf{t} \\ \mathbf{B}\cdot\Delta\mathbf{t} \end{bmatrix} \tag{64}$$

where

$$\mathbf{A} = (\mathbf{t_T}\cdot\mathbf{t_T})\,\mathbf{t_W} - (\mathbf{t_W}\cdot\mathbf{t_T})\,\mathbf{t_T} \tag{65}$$

$$\mathbf{B} = -(\mathbf{t_W}\cdot\mathbf{t_T})\,\mathbf{t_W} + (\mathbf{t_W}\cdot\mathbf{t_W})\,\mathbf{t_T} \tag{66}$$

and

$$D = (\mathbf{t_W}\cdot\mathbf{t_W})\,(\mathbf{t_T}\cdot\mathbf{t_T}) - (\mathbf{t_W}\cdot\mathbf{t_T})^2 . \tag{67}$$

Because these inner products are all weighted for flat dips only, they reduce to a sum over offset h for $y=Y$. Now assume a laterally invariant background and set $Y=x_d$, $W=w$, and $T=2wz_d$. Then

$$\mathbf{t_W}\cdot\mathbf{t_T} = \sum_h \alpha(y=x_d, h)\; t_W(y=x_d, h)\; t_T(y=x_d, h) \tag{68}$$

$$= \sum_h \alpha(y=x_d, h) \frac{2wh^2}{\sqrt{w^2 z_d^2 + w^2 h^2}} \frac{w z_d}{\sqrt{w^2 z_d^2 + w^2 h^2}} \tag{69}$$

$$= \sum_h \alpha(y=x_d, h) \frac{2h^2 z_d}{z_d^2 + h^2} \tag{70}$$

$$\approx \frac{1}{\Delta h} \int_0^{L/2} dh \;\; \alpha(y=x_d, h) \frac{2h^2 z_d}{z_d^2 + h^2} \tag{71}$$

$$\approx \frac{4 z_d N_h}{L} \int_0^{L/2} dh \;\; \alpha(y=x_d, h) \frac{h^2}{z_d^2 + h^2} \tag{72}$$

where L is the recording cable length, and N_h is the number of offsets used; I assume for simplicity that the innermost offset is small enough to be taken as zero.

The evaluation of this integral is particularly simple if one takes $\alpha_{\theta=0}(y=x_d, h) = z_d^2 + h^2$. This choice of weight is not completely coincidental; it can be shown that this is exactly the weighting needed to convert the linearized least squares solution I have used here into the x^2–t^2 parametrization that Toldi used. Using this substitution one gets

$$\mathbf{t_W}\cdot\mathbf{t_T} \approx \frac{4 z_d N_h}{L} \int_0^{L/2} dh \;\; h^2 \tag{73}$$

$$\approx \frac{N_h L^2 z_d}{6} \;. \tag{74}$$

Similarly one gets

$$\mathbf{t_W}\cdot\mathbf{t_W} \approx \frac{8 N_h}{L} \int_0^{L/2} dh \;\; h^4 \tag{75}$$

$$\approx \frac{N_h L^4}{20} \tag{76}$$

and

$$\mathbf{t_T}\cdot\mathbf{t_T} \approx \frac{2 N_h z_d^2}{L} \int_0^{L/2} dh \tag{77}$$

$$\approx N_h z_d^2 \tag{78}$$

and then

$$D \approx \frac{N_h^2 L^4 z_d^2}{45} . \tag{79}$$

One also has

$$t_W(y_\theta, h_\theta) = \frac{2\gamma^2 (x_a - x_d)^2}{\sqrt{z_d^2 + \gamma^2 (x_a - x_d)^2}} \tag{80}$$

and

$$t_T(y_\theta, h_\theta) = \frac{z_d}{\sqrt{z_d^2 + \gamma^2 (x_a - x_d)^2}} . \tag{81}$$

Thus

$$A(y_\theta, h_\theta) = \frac{z_d^2 N_h \left[12\gamma^2 (x_a - x_d)^2 - L^2\right]}{6\sqrt{z_d^2 + \gamma^2 (x_a - x_d)^2}} \tag{82}$$

and

$$B(y_\theta, h_\theta) = \frac{z_d N_h L^2 \left[3L^2 - 20\gamma^2 (x_a - x_d)^2\right]}{60\sqrt{z_d^2 + \gamma^2 (x_a - x_d)^2}} . \tag{83}$$

If these are substituted into equation (57) with $\alpha(y_\theta, h_\theta) = z_d^2 + \gamma^2 (x_a - x_d)^2$ the result is that

$$(G_W)_{\theta=0}(\mathbf{d},\mathbf{a}) = \frac{2N_h \gamma}{z_d DL} \left[z_d^2 + \gamma^2 (x_a - x_d)^2\right]^{3/2} A\left[y_\theta(\mathbf{d},\mathbf{a}), h_\theta(\mathbf{d},\mathbf{a})\right] \tag{84}$$

$$= \frac{15\gamma}{z_d L^5} \left[z_d^2 + \gamma^2 (x_a - x_d)^2\right] \left[12\gamma^2 (x_a - x_d)^2 - L^2\right] . \tag{85}$$

Letting $L' = L/\gamma$ and shuffling terms around a bit yields

$$(G_W)_{\theta=0}(\mathbf{d},\mathbf{a}) = \frac{15 z_d}{L^2 L'} \left[3\left(\frac{2(x_a - x_d)}{L'}\right)^2 - 1\right] \left[1 + \frac{L^2}{4z_d^2}\left(\frac{2(x_a - x_d)}{L'}\right)^2\right] \tag{86}$$

which is just equation (4.18) of Toldi's dissertation (p. 77) with minor notational changes.

The similar expression for G_T becomes

$$(G_T)_{\theta=0}(\mathbf{d},\mathbf{a}) = \frac{2N_h \gamma}{z_d DL} \left[z_d^2 + \gamma^2 (x_a - x_d)^2\right]^{3/2} B\left[y_\theta(\mathbf{d},\mathbf{a}), h_\theta(\mathbf{d},\mathbf{a})\right] \tag{87}$$

$$= \frac{3\gamma}{2z_d^2 L^3} \left[z_d^2 + \gamma^2 (x_a - x_d)^2\right] \left[3L^2 - 20\gamma^2 (x_a - x_d)^2\right] \tag{88}$$

$$= \frac{3}{2L'} \left[3 - 5\left(\frac{2(x_a - x_d)}{L'}\right)^2\right] \left[1 + \frac{L^2}{4z_d^2}\left(\frac{2(x_a - x_d)}{L'}\right)^2\right] . \tag{89}$$

Toldi did not present this result, but following through the same line of analysis he used to derive G_W yields exactly equation (89). I note that for $L << z$ this almost reduces to Loinger's (1983) result, but has a leading factor of $3/2L'$ where he had $3/4$. I believe that this result is correct and that Loinger's equation has a minor error.

For zero dip, the choice of a good weighting function made it possible to approximate all the inner product sums by simple integrals and to re-derive the simple, closed form algebraic expressions found by Toldi. Is such a simplification also possible for the non-zero case? Alas, the answer appears to be no; at least I have not been able to find one. This is not a problem for implementation, since the inner-product sums used in evaluating A , etc., are straightforward to evaluate numerically. What is lost is perhaps some degree of insight provided by analyzing the form of an explicit solution.

WEIGHTING REVISITED

The choice of weights to use can be constrained. For the constant-slowness background, one can incorporate some knowledge of how the interval slowness and migration slowness should be related. Specifically, if $\Delta m(\mathbf{a})$ equals some constant K everywhere, one can expect that $\Delta w(\mathbf{d})$ will also equal K everywhere. This implies that

$$\int dz_a \int dx_a \; G_W(\mathbf{d},\mathbf{a}) = 1 \; . \tag{90}$$

Similarly

$$\int dz_a \int dx_a \; G_T(\mathbf{d},\mathbf{a}) = 2z_d \tag{91}$$

and

$$\int dz_a \int dx_a \; G_Y(\mathbf{d},\mathbf{a}) = 0 \; . \tag{92}$$

These normalization conditions should be met by the G operators for any dip range, and put some limits on what weights can be used.

I note first that Toldi's operator, as given by equations (87) and (88) meets these criteria, since

$$\int_0^{z_d} dz_a \int_{x_d-L'/2}^{x_d+L'/2} dx_a \; G_W(\mathbf{d},\mathbf{a}) = \int_0^{z_d} \frac{dz_a}{z_d} = 1 \tag{93}$$

and

$$\int_0^{z_d} dz_a \int_{x_d-L'/2}^{x_d+L'/2} dx_a \; G_T(\mathbf{d},\mathbf{a}) = \int_0^{z_d} 2dz_a = 2z_d \tag{94}$$

so equations (90) and (91) are satisfied. The constraint on G_T is trivial here. Thus, the weights $\alpha = h^2 + z^2$ are good ones to use for the flat bed case, and whatever the general weighting formula is, it should reduce to this for θ=0. Note that scaling the weights has no effect, and that the units associated with the weights always cancel out and hence are irrelevant.

For numerical experiments I have been using a weighting scheme with α proportional to the traveltime, as given in equation 1. This is an obvious generalization of the weights used for zero-offset, but I have not yet proven or disproven either analytically or numerically whether these weights satisfy equations (90) to (92).

WORK LEFT TO DO

I have begun testing this theory numerically, but I do not present any results here because I cannot present a good intuitive explanation for the physical significance of some of the operator behavior I have seen in these tests, and cannot yet eliminate with confidence the possibility that I am just seeing errors in theory or in programming. My operator does numerically duplicate Toldi's for flat beds (except for a constant scaling factor that I have not yet tracked down).

When I trust my code more, I will need to test how well this operator makes reasonable predictions. To do this I will generate simple synthetic data, introduce an interval-slowness anomaly, measure the migration-slowness response, and see how well it agrees with that predicted by the operator. When the forward modeling works satisfactorily, I will attempt inversion of synthetic data examples. Doing this inversion by singular value decomposition on the operator will allow me to examine the singular value structure and the model and data resolution matrices to gain a better understanding of what can and cannot be resolved. Eventually, of course, I want to use the linear operator to find a gradient direction for an iterative inversion that would allow me to move away from the assumption of constant background slowness.

There remain two final points I want to mention. The Green functions derived above will in general not be convolutional over either x_a or z_a. However, it is not difficult to verify that for a laterally invariant background slowness, equation (19) is a convolution over x_a. This is intuitively reasonable; if nothing in the medium varies laterally, the effect of an anomaly on a diffractor should not depend on where along the line they are. In saying this, I assume that the weights α depend only on $x_d - x_a$ and that the operator is either the all-dip diffraction version or that the dip weights are laterally invariant (constant structure along the line). This last assumption may not be too useful in practice, but it makes possible examination of the transfer functions associated with these Green functions. So one of the things for me to do is to Fourier transform the operator over x and examine the transfer functions.

I mentioned earlier that the matrix inversion used to derive the operator (equation (7)) can be unstable. This is particularly a problem for steep dips and for very small dips. One possible reason for this trouble is that W, T, and Y are not really a good set of parameters to use in describing the traveltime pyramid; they are not independent enough. That is, because changes in these parameters tend to be well correlated, the resulting matrix for inversion is nearly singular. A related problem is that W, T, and Y have different physical units, so a change in measurement units from say, km to m, scales the three parameters differently, and can change the condition number of the matrix one wishes to invert. One way out of this problem is to scale the parameters so that they have the same units and are of similar magnitude. Sherwood et al. (1986), for example, scaled both depth and slowness to have units of traveltime in their inversion scheme. One such scaling that appears natural to me here is to scale to units of slowness, replacing T by $T/2z_d$ and Y by $WY/2z_d$. I need to experiment to find out whether such scaling helps, and whether this choice would be a good one.

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Photo by N. Volodko.

Without Leaving the Beach

No, no matter what people may say, the romantic tribe is not about to die out in our rational age.

One romantic voluntarily took over a lagging collective farm and made it into a leader. Another volunteered to turn the desert into a flowering garden. A third, not retreating in the face of difficulties, is successfully fighting against certain negative phenomena in our lives. And who but romantics could get up one fine day and change their place of residence en masse and without ceremony, taking off from the South for the North, for example, just like that? And not for the mists and the scent of the taiga that you hear about in songs, but to make a real contribution of their own and take a place in the vanguard.

You want facts? Why, certainly, here you are.

Once upon a time on the fertile land of the Kuban, there lived a research institute—the Scientific Research Institute of Marine Geophysics of the *Soyuzmorgeo* (All-Union Marine Geophysics) Association. Its numerous employees did not collect their pay for nothing; they tilled the rich soil of science in the sweat of their brows and even reaped some fruits. Otherwise, the USSR Ministry of the Gas Industry would never have given the institute the responsible assignment of developing and testing a prototype of a linear pneumatic source for seismic work in oil and gas exploration way up on the continental shelf in the Arctic seas.

"We'll be happy to try!" chorused the Kuban scientists. "We won't let you down. However, we must point out that the geophysical problems involved aren't simple. It seems to us that it would be more convenient to tackle them not amid the mellowing influence of the citrus groves on the Black Sea coast of the Caucasus, but up where the blizzards blow, the hummocks pile up in the ice fields, and the storm waves roar, that is, right up there above the Arctic Circle. Therefore we request that our institute, and the whole *Soyuzmorgeo* Association along with it, be relocated from our native Krasnodar Territory to the distant (and none too comfortable for us southerners) Murmansk Province."

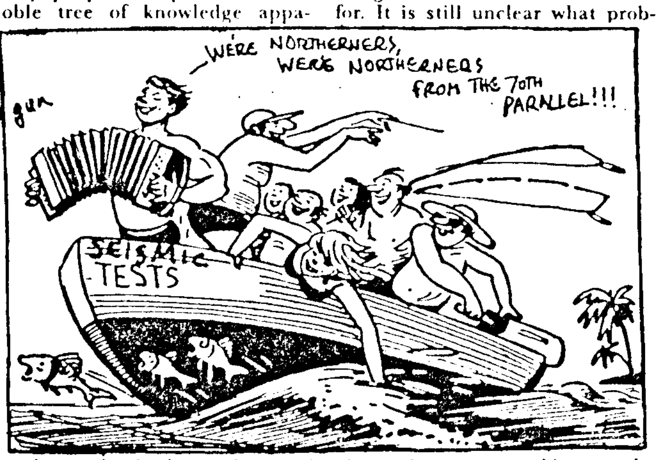
"A logical, bold, and in some way even romantic proposal," the higher-ups said in approval.

And soon, huddling up against the cold north wind and rubbing their instantly numbed ears with their mittens, the fledgling far northerners from the Kuban ran briskly down the ladder of the plane that had landed them on the Kola Peninsula.

Then the work got going, but because of the low temperature of the surroundings, it didn't get going any too fast. Oh no, you mustn't think the romantics lost their enthusiasm. It was just transformed somewhat, to use a scientific term. Evidently, under the influence of those same unfavorable local weather conditions.

Here is what was written in the document headed "Program of Research and Development Work," approved back in 1983 by the general director of *Soyuzmorgeo*, Ya. Malovitsky: "...Preliminary testing of the prototype (this refers to the above-mentioned pneumatic source—G. Ya.) will be carried out at the Arctic test site, and final testing is to be done in the fourth quarter of 1985 on the continental shelf in Pechorskaya Bay or in the waters of the Barents Sea. . ."

As we can see, everything was in order; the work was specified and a deadline was set. After some time, however, it turned out to many people's surprise that the noble tree of knowledge apparently growing in the northern soil was a flourishing fake. Let us quote the conclusion of the experts: "The main task of the scientific research and experimental design work—to develop a linear pneumatic source for carrying out seismic exploration on the Arctic continental shelf—was not carried out by the institute. The report contains no results of any scientific research directed at accomplishing the main task."



I foresee the reader's question: so it turns out that the northern settlers from the Kuban blew the plan, to put it bluntly?

I answer, not at all. They're not such simpletons as that. The institute's report was approved by General Director Ya. Malovitsky, but his deputy V. Utnasin issued a fake certificate of completion of the project. Glibly reporting to the higher-ups that the work had been done with high quality and on schedule, the northerners in return got warm congratulations on their labor victory. And that, as the reader can guess, portended a bonus. It did indeed materialize. A nice, round sum migrated from the state treasury to the pockets of our heroes.

However, it's not without reason that people say, "The truth will out." A commission descended on the institute and immediately discerned, with the naked eye, glaring deficiences both in the work itself and in matters concerning personnel and finances. Representatives of the RSFSR People's Control Committee and auditors from the republic's finance ministry ascertained that the scientists had failed to cope with their assigned task, but that the laboratory staff included ten more design engineers and four more "just plain designers" than the staff list called for. It is still unclear what problems they were working on, but about 20,000 rubles were spent for their upkeep.

As for the piece of equipment with which we are by now familiar, alas, the outlined program of preliminary testing was less than half completed. But what of that? The tenderhearted chairman of the commission, Chief Engineer Ya. Protas of *Soyuzmorgeo*, and a representative of the USSR Ministry of the Gas Industry, B. Sidorov, both amiably scrawled their names on documents accepting the work as completed. Thus they gave their blessing to the unlawful expenditure of state budget funds amounting to 355,000 rubles and the payment of almost 10,000 rubles in bonuses to the scientists at the marine geophysics research institute. That's not counting the thousands spent by the clever polar expedition members on renting a helicopter for trips to nearby fishing lakes.

However, our real, heroic polar expedition members will hardly be pleased to hear us apply this name that is dear to our hearts to a group of common, garden-variety frauds. And therefore let us remove the last veil of romanticism from their brand-new fur hats and sheepskin coats. There were no tests either in Pechorskaya Bay or on the continental shelf in the Barents Sea. While receiving the high supplementary pay for people working in the far north, those who were supposed to be doing the testing sat for weeks in Krasnodar and sunny Gelendzhik. They forged boldly ahead, one might say, in highly comfortable conditions and without leaving the beach.

"Well, what's the big deal? There's sea up there and there's sea down here. Ice hummocks? What do ice hummocks have to do with anything? You say we went swimming and lay around sunning ourselves? Well, you know, that still remains to be proved. It's true, there were certain flaws and omissions. We realize that, and we'll correct the situation. We'll finish the tests. No, not in the Barents Sea (b-r-r-r!), but not in the Black Sea either—see how conscientious we are? We'll move to the Azov or the Caspian. By the way, it wasn't a bad idea to haul our imported transport platform down there from Murmansk, to the waters around ancient Khazar. We shelled out half a million for it. It's a wonderful gizmo—goes like crazy on land and water both. But we didn't get it all the way to the Caspian Sea; we stopped off at the Black Sea, at Gelendzhik, out of habit. So that's where it is now, poor thing. Let's hope it doesn't get pulled to pieces."

Calm down, dear scientists. Go easy on your nerves. Go swimming and boating to your hearts' content in Anapa or Sochi or Makhachkala or wherever you want. But just don't do it on work time and at government expense.

G. YASTREBTSOV.

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