Mathematics of Seismic Imaging Part II - addendum on Wave Equation Migration

William W. Symes

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Wave Equation Migration

Techniques for computing $F[v]^*$:

(i) Reverse time

(ii) Reverse depth

Reverse Time Migration, Zero Offset

Start with the zero-offset case - easier, but only if you replace it with the exploding reflector model, which replaces $F[v]$ by

$$\tilde{F}[v]r(\mathbf{x}_s,t) = w(\mathbf{x}_s,t),\ \ \mathbf{x}_s \in X_s, 0 \le t \le T$$

$$\left(\frac{4}{v^2}\frac{\partial^2}{\partial t^2} - \nabla^2\right) w = \delta(t)\frac{2r}{v^2},\ \ w \equiv 0,\ t < 0$$

To compute the adjoint, start with its definition: choose $d \in \mathcal{E}(X_s \times (0,T))$, so that

$$< \tilde{F}[v]^* d, r > = < d, \tilde{F}[v] r >$$

$$= \int_{X_s} dx_s \int_0^T dt\, d(\mathbf{x}_s,t) w(\mathbf{x}_s,t)$$

The only thing you know about w is that it solves a wave equation with r on the RHS. To get this fact into play, (i) rewrite the integral as a space-time integral:

$$= \int_{\mathbf{R}^3} dx \int_0^T dt \int_{X_s} dx_s \, d(\mathbf{x}_s, t)\delta(\mathbf{x} - \mathbf{x}_s)w(\mathbf{x}, t)$$

(ii) write the other factor in the integrand as the image of a field q under the (adjoint of the) wave operator (it's self-adjoint), that is,

$$\left(\frac{4}{v^2}\frac{\partial^2}{\partial t^2} - \nabla^2\right) q(\mathbf{x}, t) = \int_{X_s} dx_s \, d(\mathbf{x}_s, t)\delta(\mathbf{x} - \mathbf{x}_s)$$

so

$$= \int_{\mathbf{R}^3} dx \int_0^T dt \left[\left(\frac{4}{v^2(\mathbf{x})}\frac{\partial^2}{\partial t^2} - \nabla^2\right) q(\mathbf{x}, t)\right] w(\mathbf{x}, t)$$

(iii) integrate by parts

$$= \int_{\mathbf{R}^3} dx \int_0^T dt \left[\left(\frac{4}{v^2(\mathbf{x})} \frac{\partial^2}{\partial t^2} - \nabla^2 \right) w(\mathbf{x},t) \right] q(\mathbf{x},t)$$

which works if $q \equiv 0,\ t > T$ (*final value condition*); (iv) use the wave equation for w

$$= \int_{\mathbf{R}^3} dx \int_0^T dt \, \frac{2}{v(\mathbf{x})^2} r(\mathbf{x}) \delta(t) q(\mathbf{x},t)$$

(v) observe that you have computed the adjoint:

$$= \int_{\mathbf{R}^3} dx \, r(\mathbf{x}) \left[\frac{2}{v(\mathbf{x})^2} q(\mathbf{x},0) \right] =< r, \tilde{F}[v]^* d >$$

i.e.

$$\tilde{F}[v]^* d = \frac{2}{v(\mathbf{x})^2} q(\mathbf{x},0)$$

Summary of the computation, with the usual description:

- Use that data as sources, backpropagate in time - i.e. solve the final value ("reverse time") problem

$$\left(\frac{4}{v^2}\frac{\partial^2}{\partial t^2} - \nabla^2\right) q(\mathbf{x}, t) = \int_{X_s} dx_s\, d(\mathbf{x}_s, t)\delta(\mathbf{x} - \mathbf{x}_s), \;\; q \equiv 0, \; t > T$$

- read out the "image" (= adjoint output) at $t = 0$:

$$\tilde{F}[v]^* d = \frac{2}{v(\mathbf{x})^2} q(\mathbf{x}, 0)$$

Note: The adjoint (time-reversed) field q is *not* the physical field (δu) run backwards in time, contrary to some imputations in the literature.

Historical Remarks

- Known as "two way reverse time finite difference poststack migration" in geophysical literature (Whitmore, 1982)
- uses full (two way) wave equation, propagates adjoint field backwards in time, generally implemented using finite difference discretization.
- Same as "adjoint state method", Lions 1968, Chavent 1974 for control and inverse problems for PDEs - much earlier for control of ODEs - Lailly, Tarantola '80s.
- My buddy Tapia says: all you're doing is transposing a matrix! True (after discretization), but it's important that these matrices are triangular, so can be implemented by recursions - forward for simulation, backwards for adjoint.

Reverse Time Migration, Prestack

A slightly messier computation computes the adjoint of $F[v]$ (i.e. multioffset or *prestack* migration):

$$F[v]^*d(\mathbf{x}) = -\frac{2}{v(\mathbf{x})}\int dx_s \int_0^T dt \left(\frac{\partial q}{\partial t}\nabla^2 u\right)(\mathbf{x}, t; \mathbf{x}_s)$$

where *adjoint field* q satisfies $q \equiv 0$, $t \geq T$ and

$$\left(\frac{1}{v^2}\frac{\partial^2}{\partial t^2} - \nabla^2\right) q(\mathbf{x}, t; \mathbf{x}_s) = \int dx_r\, d(\mathbf{x}_r, t; \mathbf{x}_s)\delta(\mathbf{x} - \mathbf{x}_r)$$

Proof

$$< F[v]^*d, r > = < d, F[v]r >$$

$$= \int \int dx_s \, dx_r \int_0^T dt \, d(\mathbf{x}_r, t; \mathbf{x}_s) \frac{\partial \delta u}{\partial t}(\mathbf{x}_r, t; \mathbf{x}_s)$$

$$= \int dx_s \int dx \int_0^T dt \left\{ \int dx_r \, d(\mathbf{x}_r, t; \mathbf{x}_s) \delta(\mathbf{x} - \mathbf{x}_r) \right\} \frac{\partial \delta u}{\partial t}(\mathbf{x}, t; \mathbf{x}_s)$$

$$= \int dx_s \int dx \int_0^T dt \left[\left(\frac{1}{v^2} \frac{\partial^2}{\partial t^2} - \nabla^2 \right) q \right] \frac{\partial \delta u}{\partial t}(\mathbf{x}, t; \mathbf{x}_s)$$

$$= -\int dx_s \int dx \int_0^T dt \left[\left(\frac{1}{v^2}\frac{\partial^2}{\partial t^2} - \nabla^2 \right) \delta u \right] \frac{\partial q}{\partial t}(\mathbf{x}, t; \mathbf{x}_s)$$

(boundary terms in integration by parts vanish because (i) $\delta u \equiv 0,\ t << 0$; (ii) $q \equiv 0,\ t >> 0$; (iii) both vanish for large $\mathbf{x}$, at each t)

$$= -\int dx_s \int dx \int_0^T dt \left(\frac{2r}{v^2}\frac{\partial^2 u}{\partial t^2}\frac{\partial q}{\partial t} \right)(\mathbf{x}, t; \mathbf{x}_s)$$

$$= -\int dx_s \int dx\, r(\mathbf{x})\frac{2}{v^2(\mathbf{x})} \int_0^T dt \left(\frac{\partial^2 u}{\partial t^2}\frac{\partial q}{\partial t} \right)(\mathbf{x}, t; \mathbf{x}_s)$$

$$=< r, F[v]^* d >$$

q.e.d.

Implementation

Algorithm: finite difference or finite element discretization in $\mathbf{x}$, finite difference time stepping.

- For each $\mathbf{x}_s$, solve wave equation for u forward in t, record final (t=T) Cauchy data, also (for example) Dirichlet boundary data.
- Step u and q backwards in time together; at each time step, data serves as source for q (“backpropagate data”)
- During backwards time stepping, accumulate (approximations to)

$$Q(\mathbf{x}) += \frac{2}{v^2(\mathbf{x})} \int_0^T dt \, \left(\frac{\partial^2 u}{\partial t^2} \frac{\partial q}{\partial t} \right) (\mathbf{x}, t; \mathbf{x}_s)$$

  (“crosscorrelate reference and backpropagated field”).
- next $\mathbf{x}_s$ - after last $\mathbf{x}_s$, $F[v]^* d = Q$.

Reverse Depth Migration, Zero Offset

aka: depth extrapolation, downward continuation, or simply "wave equation migration".

Introduced by Claerbout, early 70's ("swimming pool equation"). Again, assume exploding reflector model:

$$\tilde{F}[v]r(\mathbf{x}_s, t) = w(\mathbf{x}_s, t),\ \mathbf{x}_s \in X_s, 0 \le t \le T$$

$$\left(\frac{4}{v^2}\frac{\partial^2}{\partial t^2} - \nabla^2\right) w = \delta(t)\frac{2r}{v^2},\ w \equiv 0,\ t < 0$$

Basic idea: 2nd order wave equation permits waves to move in all directions, but waves carrying reflected energy are (mostly) moving *up*. Should satisfy a 1st order equation for wave motion in one direction.

Coming up...

For the moment use 2D notation $\mathbf{x} = (x, z)$ etc. Write wave equation as evolution equation in z:

$$\frac{\partial^2 w}{\partial z^2} - \left(\frac{4}{v^2} \frac{\partial^2}{\partial t^2} - \frac{\partial^2}{\partial x^2} \right) w = -\delta(t) \frac{2r}{v^2}$$

Suppose that you could take the square root of the operator in parentheses - call it B. Then the LHS of the wave equation becomes

$$\left(\frac{\partial}{\partial z} - B \right) \left(\frac{\partial}{\partial z} + B \right) w = -\delta(t) \frac{2r}{v^2}$$

so setting $\tilde{w} = \left(\frac{\partial}{\partial z} + B \right) w$ you get

$$\left(\frac{\partial}{\partial z} - B \right) \tilde{w} = -\delta(t) \frac{2r}{v^2}$$

Some issues

This *might* be the required equation for upcoming waves.

Two major problems: (i) how the h–l do you take the square root of a PDO?

(ii) what guarantees that the equation just written governs upcoming waves?

Answers to be found in the theory of ΨDOs!

Classical ΨDOs

Important *subclass* of *classical* ΨDOs: those whose ("classical") symbols have asymptotic expansions:

$$p(\mathbf{x}, \boldsymbol{\xi}) \sim \sum_{j \leq m} p_j(\mathbf{x}, \boldsymbol{\xi}), \;\; |\boldsymbol{\xi}| \to \infty$$

in which p_j is *homogeneous in* $\boldsymbol{\xi}$ *of degree* j:

$$p_j(\mathbf{x}, \tau\boldsymbol{\xi}) = \tau^j p_j(\mathbf{x}, \tau\boldsymbol{\xi}), \;\; \tau, |\boldsymbol{\xi}| \geq 1$$

The *principal symbol* is the homogeneous term of highest degree, i.e. p_m above.

Products of ΨDOs are ΨDOs.

Classical ΨDOs have more complete *calculus*, including prescriptions for "computing" adjoints, products, and the like. From now on unless otherwise stated, all ΨDOs are classical.

Product rule for ΨDOs: if p^1, p^2 are classical,

$$p^1(\mathbf{x}, \boldsymbol{\xi}) = \sum_{j \le m^1} p^1_j(\mathbf{x}, \boldsymbol{\xi}),\ \ p^2(\mathbf{x}, \boldsymbol{\xi}) = \sum_{j \le m^2} p^2_j(\mathbf{x}, \boldsymbol{\xi})$$

then so is $p^1(\mathbf{x}, D)p^2(\mathbf{x}, D)$, and its principal symbol is $p^1_{m^1}(\mathbf{x}, \boldsymbol{\xi})p^2_{m^2}(\mathbf{x}, \boldsymbol{\xi})$, and there is an algorithm for computing the rest of the expansion.

In an open neighborhood $X \times \Xi$ of $(\mathbf{x}_0, \boldsymbol{\xi}_0)$, symbol of $p^1(\mathbf{x}, D)p^2(\mathbf{x}, D)$ depends only on symbols of p^1, p^2 in $X \times \Xi$.

Consequence: if $a(\mathbf{x}, D)$ has an asymptotic expansion and is of order $m \in \mathbf{R}$, and $a_m(\mathbf{x}_0, \boldsymbol{\xi}_0) > 0$ in $\mathcal{P} \subset \mathbf{R}^n \times \mathbf{R}^n - 0$, then there exists $b(\mathbf{x}, D)$ of order $m/2$ with asymptotic expansion for which

$$(a(\mathbf{x}, D) - b(\mathbf{x}, D)b(\mathbf{x}, D))u \in \mathcal{E}(\mathbf{R}^n)$$

for any $u \in \mathcal{E}'(\mathbf{R}^n)$ with $WF(u) \subset \mathcal{P}$.

Moreover, $b_{m/2}(\mathbf{x}, \boldsymbol{\xi}) = \sqrt{a_m(\mathbf{x}, \boldsymbol{\xi})},\ (\mathbf{x}, \boldsymbol{\xi}) \in \mathcal{P}$. Will call b a *microlocal square root* of a.

Similar construction: if $a(\mathbf{x}, \boldsymbol{\xi}) \neq 0$ in $\mathcal{P}$, then there is $c(\mathbf{x}, D)$ of order $-m$ so that

$$c(\mathbf{x}, D)a(\mathbf{x}, D)u - u,\ \ a(\mathbf{x}, D)c(\mathbf{x}, D)u - u \in \mathcal{E}(\mathbf{R}^n)$$

for any $u \in \mathcal{E}'(\mathbf{R}^n)$ with $WF(u) \subset \mathcal{P}$.

Moreover, $c_{-m}(\mathbf{x}, \boldsymbol{\xi}) = 1/a_m(\mathbf{x}, \boldsymbol{\xi}),\ (\mathbf{x}, \boldsymbol{\xi}) \in \mathcal{P}$. Will call b a *microlocal inverse* of a.

Application: the Square Root Operator

$$a(x,z,D_t,D_x) = \frac{\partial^2}{\partial x^2} - \frac{4}{v(x,z)^2}\frac{\partial^2}{\partial t^2} = \frac{4}{v(x,z)^2}D_t^2 - D_x^2$$

is

$$a(x,z,\tau,\xi) = \frac{4}{v(x,z)^2}\tau^2 - \xi^2$$

For $\delta > 0$, set

$$\mathcal{P}_\delta(z) = \left\{(x,t,\xi,\tau) : \frac{4}{v(x,z)^2}\tau^2 > (1+\delta)\xi^2\right\}$$

The SSR Operator

Then according to the last slide, there is an order 1 ΨDO-valued function of z, $b(x,z,D_t,D_x)$, with principal symbol

$$b_1(x,z,\tau,\xi) = \sqrt{\frac{4}{v(x,z)^2}\tau^2 - \xi^2} = \tau\sqrt{\frac{4}{v(x,z)^2} - \frac{\xi^2}{\tau^2}},\ (x,t,\xi,\tau) \in \mathcal{P}_\delta(z)$$

for which $a(x,z,D_t,D_x)u \simeq b(x,z,D_t,D_x)b(x,z,D_t,D_x)u$ if $WF(u) \subset \mathcal{P}_\delta(z)$.

b is the world-famous **single square root** ("SSR") operator - see Claerbout, IEI.

The SSR Assumption

To what extent has this construction factored the wave operator:

$$\left(\frac{\partial}{\partial z} - ib(x,z,D_x,D_t)\right)\left(\frac{\partial}{\partial z} + ib(x,z,D_x,D_t)\right)$$

$$= \frac{\partial^2}{\partial z^2} + b(x,z,D_x,D_t)b(x,z,D_x,D_t) + \frac{\partial b}{\partial z}(x,z,D_x,D_t)$$

SSR Assumption: For some $\delta > 0$, the wavefield w satisfies

$$(x,z,t,\xi,\zeta,\tau) \in WF(w) \Rightarrow (x,t,\xi,\tau) \in \mathcal{P}_\delta(z) \text{ and } \zeta\tau > 0$$

This statement has a ray-theoretic interpretation (which will eventually make sense): rays carrying significant energy are nowhere horizontal. Along any such ray, z decreases as t increases - *coming up!*

$$\tilde{w}(x,z,t) = \left(\frac{\partial}{\partial z} + ib(x,z,D_x,D_t)\right) w(x,z,t)$$

$$b(x,z,D_x,D_t)b(x,z,D_x,D_t)w \simeq \left(\frac{4}{v(x,z)^2}D_t^2 - D_x^2\right) w$$

with a smooth error, so

$$\left(\frac{\partial}{\partial z} - ib(x,z,D_x,D_t)\right) \tilde{w}(x,z,t) = -\frac{2r(x,z)}{v(x,z)^2}\delta(t)$$

$$+i\left(\frac{\partial}{\partial z}b(x,z,D_x,D_t)\right) w(x,z,t)$$

(since b depends on z, the z deriv. does not commute with b). So $\tilde{w} = \tilde{w}_0 + \tilde{w}_1$, where

$$\left(\frac{\partial}{\partial z} - ib(x,z,D_x,D_t)\right)\tilde{w}_0(x,z,t) = -\frac{2r(x,z)}{v(x,z)^2}\delta(t)$$

(this is the **SSR modeling equation**)

$$\left(\frac{\partial}{\partial z} - ib(x,z,D_x,D_t)\right)\tilde{w}_1(x,z,t) = i\left(\frac{\partial}{\partial z}b(x,z,D_x,D_t)\right)w(x,z,t)$$

Claim: $WF(\tilde{w}_1) \subset WF(w)$. Granted this $\Rightarrow WF(\tilde{w}_0) \subset WF(w)$ also.

Upshot: SSR modeling

$$\tilde{F}_0[v]r(x_s, z_s, t) = \tilde{w}_0(x_s, z_s, t)$$

produces the same singularities (i.e. the same waves) as exploding reflector modeling, so is as good a basis for migration.

SSR migration: assume that sources all lie on $z_s = 0$.

$$< \tilde{F}_0[v]^* d, r > = < d, \tilde{F}_0[v]r >$$

$$= \int dx_s \int dt\, d(x_s, t)\tilde{w}_0(x_s, 0, t)$$

$$= \int dx_s \int dt \int dz\, d(\bar{x}_s, t)\delta(z)\tilde{w}_0(x_s, z, t)$$

Define the adjoint field q by

$$\left(\frac{\partial}{\partial z} - b(x, z, D_x, D_t)\right) q(x, z, t) = d(x, t)\delta(z),\ \ q(x, z, t) \equiv 0,\ z < 0$$

which is equivalent to solving the initial value problem

$$\left(\frac{\partial}{\partial z} - ib(x, z, D_x, D_t)\right) q(x, z, t) = 0,\ z > 0;,\ \ q(x, 0, t) = d(x, t)$$

Insert in expression for inner product, integrate by parts, use self-adjointness of b, get

$$< d, \tilde{F}_0[v]r >= \int dx \int dz\, \frac{2r(x, z)}{v(x, z)^2} q(x, z, 0)$$

whence

$$\tilde{F}_0[v]^* d(x,z) = \frac{2}{v(x,z)^2} q(x,z,0)$$

Standard description of the SSR migration algorithm:

- downward continue data (i.e. solve for q)
- image at $t = 0$.

The art of SSR migration: computable approximations to $b(x, z, D_x, D_t)$ - swimming pool operator, many successors.

Proof of the Claim

Unfinished business: proof of claim

Depends on celebrated **Propagation of Singularities** theorem of Hörmander (1970).

Given symbol $p(\mathbf{x}, \boldsymbol{\xi})$, order m, with asymptotic expansion, define *bicharateristics* as solutions $(\mathbf{x}(t), \boldsymbol{\xi}(t))$ of Hamiltonian system

$$\frac{d\mathbf{x}}{dt} = \frac{\partial p}{\partial \boldsymbol{\xi}}(\mathbf{x}, \boldsymbol{\xi}), \;\; \frac{d\boldsymbol{\xi}}{dt} = -\frac{\partial p}{\partial \mathbf{x}}(\mathbf{x}, \boldsymbol{\xi})$$

with $p(\mathbf{x}(t), \boldsymbol{\xi}(t)) \equiv 0$.

Theorem: Suppose $p(\mathbf{x}, D)u = f$, and suppose that for $t_0 \leq t \leq t_1$, $(\mathbf{x}(t), \boldsymbol{\xi}(t)) \notin WF(f)$. Then either $\{(\mathbf{x}(t), \boldsymbol{\xi}(t)) : t_0 \leq t \leq t_1\} \subset WF(u)$ or $\{(\mathbf{x}(t), \boldsymbol{\xi}(t)) : t_0 \leq t \leq t_1\} \subset T^*(\mathbf{R}^n) - WF(u)$.

P of S has at least two distinct proofs:

- Nirenberg, 1972
- Hörmander, 1970 (in Taylor, 1981)

Proof of claim: check that bicharacteristics for SSR operator are just upcoming rays of geom. optics for wave equation. These pass into $t < 0$ where RHS is smooth, also initial condn at large z is smooth - so each ray has one “end” outside of $WF(\tilde{w}_1)$. If ray carries singularity, must pass of WF of w, but then it’s entirely contained by P of S applied to w. **q. e. d.**

Reverse Depth Migration, Prestack

Nonzero offset ("prestack"): starting point is integral representation of the scattered field

$$F[v]r(\mathbf{x}_r,t;\mathbf{x}_s) = \frac{\partial^2}{\partial t^2}\int\,dx\,\frac{2r(\mathbf{x})}{v(\mathbf{x})^2}\int\,ds\,G(\mathbf{x}_r,t-s;\mathbf{x})G(\mathbf{x}_s,s;\mathbf{x})$$

By analogy with zero offset case, would like to view this as "exploding reflectors in both directions": reflectors propagate energy upward to sources and to receivers.

However can't do this because reflection location is *same* for both.

The "survey sinking" idea

Bold stroke: introduce a new space variable $\mathbf{y}$ (a "sunken source", think of $\mathbf{x}$ as a "sunken receiver"), define

$$\tilde{F}[v]R(\mathbf{x}_r, t; \mathbf{x}_s) = \frac{\partial^2}{\partial t^2} \int \int dx\, dy\, R(\mathbf{x}, \mathbf{y}) \int ds\, G(\mathbf{x}_r, t - s; \mathbf{x}) G(\mathbf{x}_s, s; \mathbf{y})$$

and note that $\tilde{F}[v]R = F[v]r$ if

$$R(\mathbf{x}, \mathbf{y}) = \frac{2r}{v^2} \left(\frac{\mathbf{x} + \mathbf{y}}{2} \right) \delta(\mathbf{x} - \mathbf{y})$$

This trick decomposes $F[v]$ into *two* “exploding reflectors”:

$$\tilde{F}[v]R(\mathbf{x}_r,t;\mathbf{x}_s) = u(\mathbf{x},t;\mathbf{x}_s)|_{\mathbf{x}=\mathbf{x}_r}$$

where

$$\left(\frac{1}{v(\mathbf{x})^2}\frac{\partial^2}{\partial t^2} - \nabla^2_{\mathbf{x}}\right) u(\mathbf{x},t;\mathbf{x}_s) = \int dy\, R(\mathbf{x},\mathbf{y})G(\mathbf{x}_s,t;\mathbf{y})$$

$$\equiv w_s(\mathbf{x}_s,t;\mathbf{x})$$

(“upward continue the receivers”),

$$\left(\frac{1}{v(\mathbf{y})^2}\frac{\partial^2}{\partial t^2} - \nabla^2_{\mathbf{y}}\right) w_s(\mathbf{y},t;\mathbf{x}) = R(\mathbf{x},\mathbf{y})\delta(t)$$

(“upward continue the sources”).

This factorization of $F[v]$ ($r \mapsto R \mapsto \tilde{F}[v]R$) leads to a reverse time computation of adjoint $\tilde{F}[v]^*$ - will discuss this later.

It's equally possible to continue the receivers first, then the sources, which leads to

$$\left(\frac{1}{v(\mathbf{y})^2}\frac{\partial^2}{\partial t^2} - \nabla^2_{\mathbf{y}}\right) u(\mathbf{x}_r, t; \mathbf{y}) = \int dx\, R(\mathbf{x}, \mathbf{y}) G(\mathbf{x}_r, t; \mathbf{x})$$

$$\equiv w_r(\mathbf{x}_r, t; \mathbf{y})$$

("upward continue the sources"),

$$\left(\frac{1}{v(\mathbf{x})^2}\frac{\partial^2}{\partial t^2} - \nabla^2_{\mathbf{x}}\right) w_r(\mathbf{x}, t; \mathbf{y}) = R(\mathbf{x}, \mathbf{y})\delta(t)$$

("upward continue the receivers").

The DSR Assumption

Apply reverse depth concept: as before, go 2D temporarily, $\mathbf{x} = (x, z_r)$, $\mathbf{y} = (y, z_s)$, all sources and receivers on $z = 0$.

Double Square Root ("DSR") assumption: For some $\delta > 0$, the wavefield u satisfies

$$(x, z_r, t, y, z_s, \xi, \zeta_s, \tau, \eta, \zeta_r) \in WF(u) \ \Rightarrow$$

$$(x, t, \xi, \tau) \in \mathcal{P}_\delta(z_r), \ \ (y, t, \eta, \tau) \in \mathcal{P}_\delta(z_s), \ \text{and} \ \zeta_r\tau > 0, \ \ \zeta_s\tau > 0,$$

As for SSR, there is a ray-theoretic interpretation: rays from source and receiver to scattering point stay away from the vertical and decrease in z for increasing t, i.e. they are all upcoming.

Since z will be singled out (and eventually $R(\mathbf{x},\mathbf{y})$ will have a factor of $\delta(\mathbf{x},\mathbf{y})$), impose the constraint that

$$R(x,z,x,z_s)=\tilde{R}(x,y,z)\delta(z-z_s)$$

Define upcoming projections as for SSR:

$$\tilde{w}_s=\left(\frac{\partial}{\partial z_s}+ib(y,z_s,D_y,D_t)\right)w_s,$$

$$\tilde{w}_r=\left(\frac{\partial}{\partial z_r}+ib(x,z_r,D_x,D_t)\right)w_r,$$

$$\tilde{u}=\left(\frac{\partial}{\partial z_s}+ib(y,z_s,D_y,D_t)\right)\left(\frac{\partial}{\partial z_r}+ib(x,z_r,D_x,D_t)\right)u$$

Except for lower order commutators which we justify throwing away as before,

$$\left(\frac{\partial}{\partial z_s} - ib(y, z_s, D_y, D_t)\right)\tilde{w}_s = \tilde{R}\delta(z_r - z_s)\delta(t),$$

$$\left(\frac{\partial}{\partial z_r} - ib(x, z_r, D_x, D_t)\right)\tilde{w}_r = \tilde{R}\delta(z_r - z_s)\delta(t),$$

$$\left(\frac{\partial}{\partial z_r} - ib(x, z_r, D_x, D_t)\right)\tilde{u} = \tilde{w}_s$$

$$\left(\frac{\partial}{\partial z_s} - ib(y, z_s, D_y, D_t)\right)\tilde{u} = \tilde{w}_r$$

Initial (final) conditions are that $\tilde{w}_r, \tilde{w}_s$, and $\tilde{u}$ all vanish for large z - the equations are to be solve in decreasing z ("upward continuation").

Simultaneous upward continuation:

$$\frac{\partial}{\partial z}\tilde{u}(x,z,t;y,z) = \frac{\partial}{\partial z_r}\tilde{u}(x,z_r,t;y,z)|_{z=z_r} + \frac{\partial}{\partial z_r}\tilde{u}(x,z,t;y,z_s)|_{z=z_s}$$

$$= [ib(x,z_r,D_x,D_t)\tilde{u} + \tilde{w}_s + ib(y,z_s,D_y,D_t)\tilde{u} + \tilde{w}_r]_{z_r=z_s=z}$$

Since $\tilde{w}_s(y,z,t;x,z) = \tilde{w}_r(x,z,t;y,z) = \tilde{R}(x,y,z)\delta(t)$, $\tilde{u}$ is seen to satisfy the

DSR modeling equation:

$$\left(\frac{\partial}{\partial z} - ib(x,z,D_x,D_t) - ib(y,z,D_y,D_t)\right)\tilde{u}(x,z,t;y,z) = 2\tilde{R}(x,y,z)\delta(t)$$

$$\tilde{F}[v]\tilde{R}(x_r,t;x_s) = \tilde{u}(x_r,0,t;x_s,0)$$

DSR Migration

Computation of adjoint follows same pattern as for SSR, and leads to

DSR migration equation: solve

$$\left(\frac{\partial}{\partial z} - ib(x,z,D_x,D_t) - ib(y,z,D_y,D_t)\right)\tilde{q}(x,y,z,t) = 0$$

in *increasing* z with initial condition at $z=0$:

$$\tilde{q}(x_r,x_s,0,t) = d(x_r,x_s,t)$$

Then $\tilde{F}[v]^*d(x,y,z) = \tilde{q}(x,y,z,0)$

The physical DSR model has $\tilde{R}(x,y,z) = r(x,z)\delta(x-y)$, so final step in DSR computation of $F[v]^*$ is adjoint of $r \mapsto \tilde{R}$:

$$F[v]^*d(x,z) = \tilde{q}(x,x,z,0)$$

Standard description of DSR migration

(See Claerbout, IEI):

- downward continue sources and receivers (solve DSR migration equation)
- image at $t = 0$ and zero offset ($x = y$)

Another moniker: “survey sinking”: DSR field $\tilde{q}$ is (related to) the field that you would get by conducting the survey with sources and receivers at depth z. At any given depth, the zero-offset, time-zero part of the field is the instantaneous response to scatterers on which source = receiver is sitting, therefore constitutes an image.

As for SSR, the art of DSR migration is in the approximation of the DSR operator.

Remarks

Stolk and deHoop (2001) derived DSR modeling and migration via a more systematic argument than that used here, involving ΨDO matrix factorization of the wave equation written as a first order evolution system in z. This idea goes back to Taylor (1975) who used it to show that singularities propagating along bicharacteristics reflect as expected at boundaries.

Stolk (2003) has also carried out a very careful global construction of a family of SSR ΨDOs which are of non-classical type at near-horizontal directions ("nearly evanescent waves"). This construction should lead to more reliable discretizations.

The last part of the course will present the various apparently ad-hoc "prestack modeling" ideas within a unified framework.