The SEAMX Modeling Framework and Process Development for SEAM QC

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The Rice Inversion Project

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Agenda

Overview

Design concept for QC

SEAMX: An Acoustic Modeling Code

Numerical Issues

Qualification Results: First Pass QC

SEAMX Status, Lessons Learned, and Plans

TRIP, SEAM, and SEAMX

Phase I press releases

- SEAM Corporation announces Simulation Award
  10 February 2009

Phase I participants

The SEAM Phase I consortium consists of 24 companies from the hydrocarbon and geophysical exploration industries. Each Participant is represented on the SEAM Phase I Management Committee.

Additional industry participants are encouraged and welcome. To request a model contract, please contact SEAM.

Thank you for visiting the SEAM Phase I page!

TRIP, SEAM, and SEAMX

The question posed by SEAM:

- how accurate are seismic simulations, anyway?

Irresistable!

TRIP interaction with SEAM:

- develop new modeling framework to
  - support all of TRIP's inversion research
  - provide benchmark for SEAM
- develop QC process for use by SEAM and the rest of the seismic research community

Upshot: SEAMX = new modeling package, some surprising lessons, and new research directions.

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Requirements for reliable multi-vendor modeling

Require that vendor traces differ by *an acceptable amount* from benchmark data. Inference: then data from various vendors can be used interchangeably for all purposes.

Implications:

- construction of *benchmark modeling code*, verification;
- spot checks of vendor shot gathers against output of benchmark code.

Proposal for Verification of Benchmark Code

For benchmark-based QC to function as intended, benchmark code *must be trusted*.

- open source;
- accuracy, repeatability trump speed;
- comparison with analytical solutions (homogeneous medium);
- Richardson extrapolation: *a posteriori* estimation of error *without knowing the exact solution*. Assume that computed data $D(\Delta t)$ differs from exact data $\bar{D}$ by $E(\Delta t) = C\Delta t^p + O(\Delta t^{p+1})$, then

  $$E(\Delta t) \simeq \frac{D(2\Delta t) - D(\Delta t)}{2^p - 1}.$$

  A little more work: can estimate p from $D(\Delta t), D(2\Delta t), D(4\Delta t)$.

Upshot: conservative code, basic verification against analytic solutions, estimation of "typical error bars" by Richardson extrapolation using target model.

Agenda

Model problem and method

- Pressure-velocity formulation of the acoustic wave equation:

$$
\begin{aligned}
\frac{1}{\kappa(\mathbf{x})}\frac{\partial p(\mathbf{x},t)}{\partial t} &= -\nabla \cdot \mathbf{v}(\mathbf{x},t) + f(t,\mathbf{x}), \\
\rho(\mathbf{x})\frac{\partial \mathbf{v}(\mathbf{x},t)}{\partial t} &= -\nabla p(\mathbf{x},t),
\end{aligned}
$$

  κ = bulk modulus, ρ = material density, f = source of acoustic energy (constitutive law defect).

- Numerical method: staggered FD scheme on rectangular grid
- Requirements:
  - accommodate 3D models, modern survey geometry with reasonable sample rates, respect physics
  - modular design, extensible, portable, public release

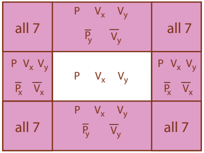
SEAMX Features

- staggered leapfrog scheme, 2nd order in time, 2k-th order in space, k=1,...,7 (Virieux 1986, Levander 1988, many others)
- PML or zero-pressure boundary conditions on any side
- model input: gridded 1D, 2D, or 3D RSF/SEP file structure, any sensible combination of velocity, bulk modulus, density, bouyancy, any axis order, scale, native/XDR floats
- data output: SU (SEGY without reel header)
- arbitrary source/receiver positions, sample rate (interpolation from comp. grid), flexible source representation
- parallelization via domain decomposition, MPI, also loop level via OpenMP
- domain decomposition *computed* from stencil, # of processes on each axis - easy extension to other models
- parallelization over shots via subclustering
- ISO C99, self-contained
- SU-style self-doc, html man pages via doxygen

RICE

Nearly PML (NPML) for 2D acoustic equation

- Cummer 2003, Habashy et al. 2007
- 2D: 9 domains, 7 (4) variables
- 3D: 27 domains, 10 (6) variables



$$
\begin{aligned}
\frac{1}{\kappa}\frac{\partial p}{\partial t} + \frac{\partial \bar{v}_x}{\partial x} + \frac{\partial \bar{v}_y}{\partial x} &= 0, \\
\rho\frac{\partial v_x}{\partial t} + \frac{\partial \bar{p}_x}{\partial x} &= 0, \\
\rho\frac{\partial v_y}{\partial t} + \frac{\partial \bar{p}_y}{\partial y} &= 0,
\end{aligned}
$$

$$
\begin{aligned}
\frac{\partial \bar{p}_x}{\partial t} + \sigma(x)\bar{p}_x &= \frac{\partial p}{\partial t}, \\
\frac{\partial \bar{p}_y}{\partial t} + \sigma(y)\bar{p}_y &= \frac{\partial p}{\partial t}, \\
\frac{\partial \bar{v}_x}{\partial t} + \sigma(x)\bar{v}_x &= \frac{\partial v_x}{\partial t}, \\
\frac{\partial \bar{v}_y}{\partial t} + \sigma(y)\bar{v}_y &= \frac{\partial v_y}{\partial t}.
\end{aligned}
$$

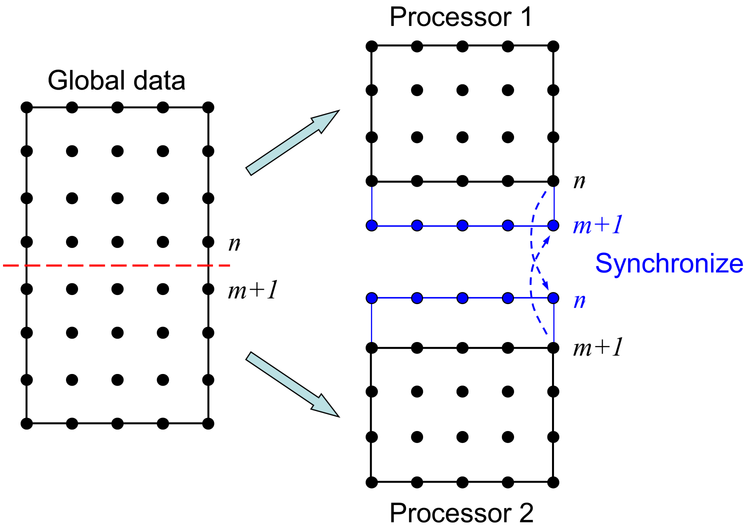
Nearly PML (NPML) for 2D acoustic equation

Numerical Example: 3D homogeneous unbounded domain

play

Parallelization via Domain Decomposition

SEAMX *computes* allocation of exchange buffers, necessary exchange ops - addition of new stencil requires no new MPI code.

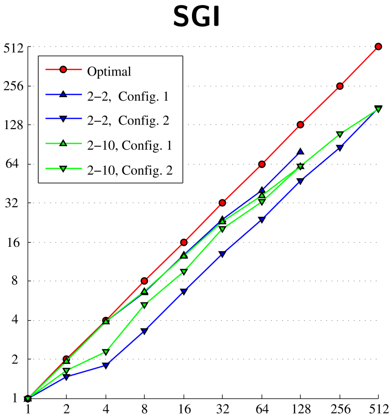


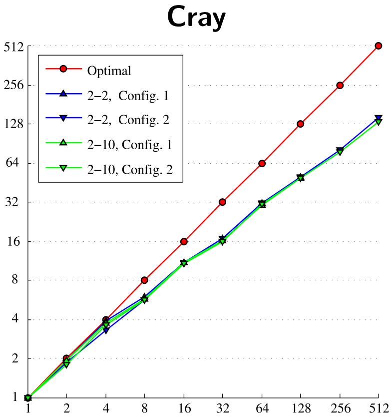
Parallelization via Domain Decomposition

Timing Studies: Strong Scaling

- Test Problem;
  - three-dimensional problem
  - 2-2 and 2-10 staggered schemes
  - $480 \times 480 \times 390$ grid points and 500 time steps
- **Hardware:**
  - SGI Altix, 384 Dual-core Intel Itanium 2 Montvale 9130M processors with 8 GB RAM per node
  - Cray XD-1, 316 Dual-core AMD Opteron 275 (2.2GHz) processors with 8 GB RAM per node
- **Processor Configuration**
  - one processor per node, i.e, # of processors = # of nodes
  - one processor per core, i.e,. 4 processors per node

Parallelization via Domain Decomposition





Agenda

Source Representation

Point source: $f(t, \mathbf{x}) = w(t)\delta(\mathbf{x} - \mathbf{x}_s)$.

Adjust w to produce a given pulse $g(t)$ at appropriate delay in homogeneous medium with velocity c_0 at offset r_0:

$$w(t) = 4\pi c_0^2 r_0 \int_{-\infty}^{t} d\tau \, g(\tau).$$

Simple representation of $\delta(\mathbf{x} - \mathbf{x}_s)$: “discrete delta”.

- for $\mathbf{x}_s$ on gridpoint, assign $1/$(cell volume) to that point, zero elsewhere.
- otherwise, use adjoint linear interpolation.

Source Representation

Theory: FD field produced by "discrete delta" source is *weakly* convergent - averages over fixed (grid-independent) volumes converge - and at optimal order of scheme ($\simeq 2$).

Practice: point values (traces) appear to converge, but slowly.

Example: 2D homogeneous square with free boundaries, comparison quasi-analytic solution courtesy T. Hagstrom.

Δx	abserr	relerr
10.00	1740	0.201
5.00	911	0.109
2.50	581	0.067
1.25	340	0.039

Upshot: suboptimal convergence of traces, but probably OK because of next item...

FD: Homogeneous/smooth vs. Heterogeneous Media

- **Homogeneous or smooth models:** regular mesh FD solutions converge to analytical solutions as space and time steps tend to zero in fixed proportion.
- Rate of convergence is determined by truncation error.
- Staggered finite differences of order 2 in time and $2k$ in space:
  - the error is eventually proportional to Δt^2,
  - spatial order controls numerical dispersion on coarser grids.

FD: Homogeneous/smooth vs. Heterogeneous Media

Brown '84, Gustafsson & Mossberg '04, Gustafsson & Wahlund '04

- **Discontinuous models** (interfaces or worse):

$$\text{Error} = \text{component 1} + \text{component 2}$$

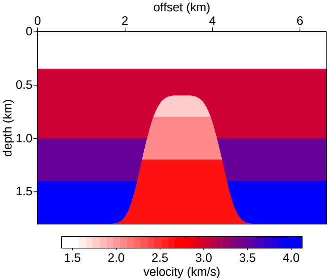
- **Component 1:**
  - corresponds to the truncation error of homogeneous problem
  - is responsible for numerical "grid" dispersion
  - can be controlled by application of higher order methods
- **Component 2:**
  - stems from misalignment of grid and material interfaces
  - is of the first order and insensitive to scheme order
  - related concept: stairstep diffraction

Once the dispersion error (component 1) is controlled, interface misalignment error (component 2) remains and becomes dominant.

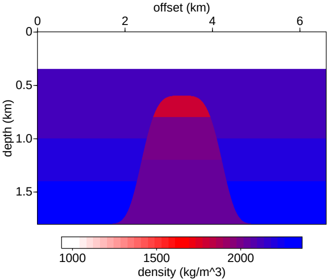
Interface Error: Dome Model

- Sampled in 3D from analytical specs
- 2nd order in time, 10th order in space staggered grid Taylor series stencil, $0.2\Delta t_{max}$
- Point source calibrated to produce unit amplitude Ricker pulse at specificed distance; position: near the center of the model, 40 m depth
- 301 traces at 20 m group interval, 20 m depth, 3 s.

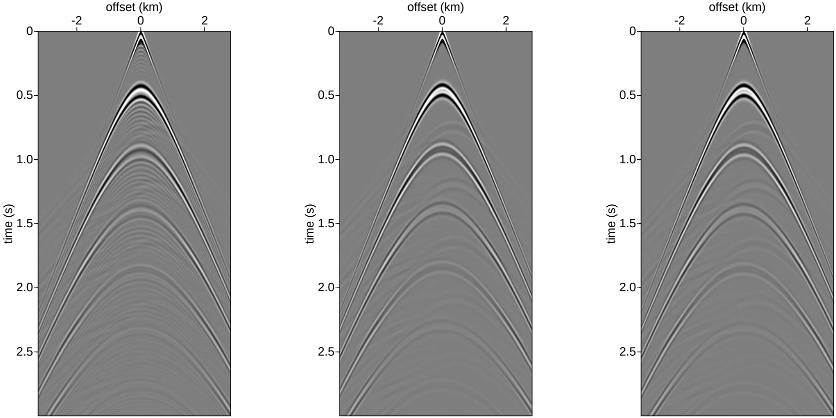
Velocity field



Density field



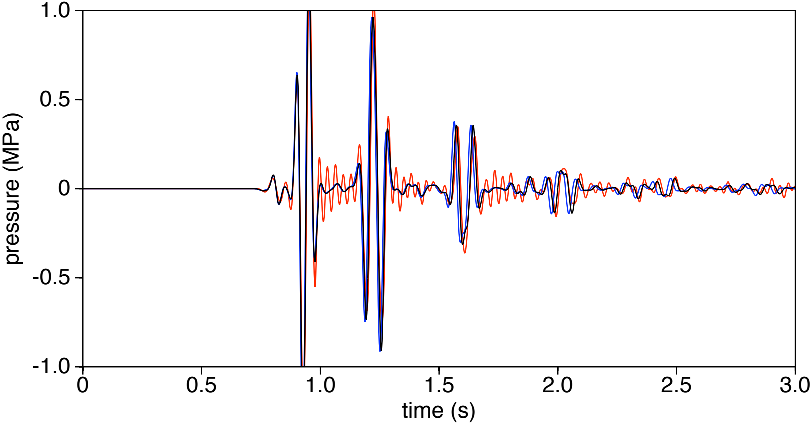
Interface Error: Dome Model



Shot gathers: 20m, 10m, and 5m grids.

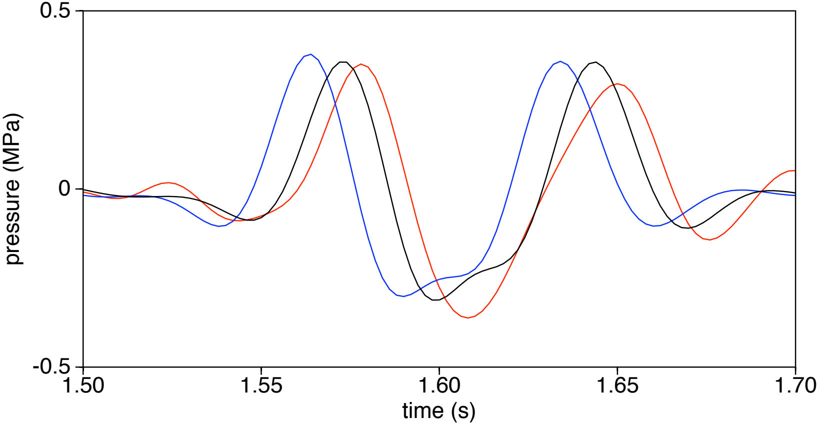
Trace 100 (offset 280 m), $\Delta x = 5$m (black), 10m (blue), 20m (red)

Interface Error: Dome Model



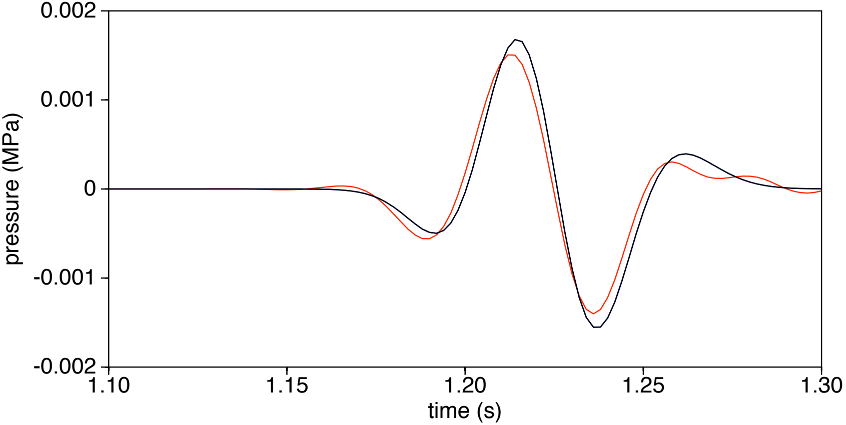
Trace 100 (offset 280 m), $\Delta x = 5$m (black), 10m (blue), 20m (red)

Interface Error: Dome Model



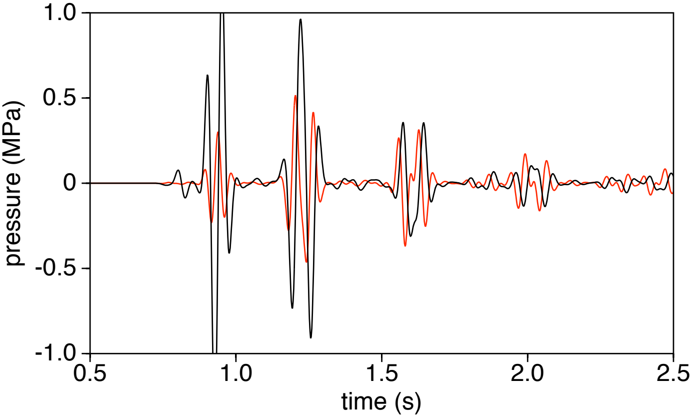
Trace 100 (offset 280 m), $\Delta x = 5$m (black), 10m (blue), 20m (red)

Interface Error: Dome Model



Homogeneous case! Trace 100 (offset 280 m), $\Delta x = 5$m (black), 10m (blue), 20m (red)

Effect on Richardson Extrapolation



Trace 100 (offset 280 m) for $\Delta x = 5$m (black) vs. error estimated from $\Delta x =$5m, 10m (red). Note that after 1.5 s, error appears to be 100%!

Effect on Richardson Extrapolation

Richardson estimates of relative RMS errors in various windows:

- 0.7-1.1 s: 20%
- 1.1-1.3 s: 51%
- 1.5-1.7 s: 88%
- 1.9-2.1 s: 120% (!)

Conclusion: interface location error accumulates as wave passes through interface; after encountering a few interfaces, computed wave may be 100% in error!

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Homogenous medium test

Target pulse *shape* specified, but not amplitude.

Error assessment: scale each trace to best RMS fit normalized free space solution.

Compute max and average RMS errors.

Because traces scaled individually to maximize fit, this is an *underestimate* of actual error.

Homogenous medium test

Maximum relative RMS errors over all traces:

Vendor	Max RMS Err
1	1.100
2	0.047
3	0.046
4	0.047
5	0.047
6	0.475
7	1.606
8	0.052

Vendors 2-5 and 8 passed this test (so did we).

Half Model Experiments

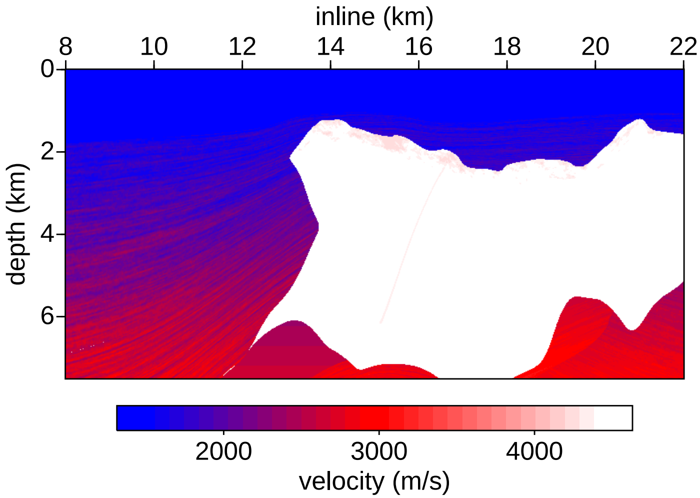
Half model: 14 km $\times$ 14 km $\times$ 7.5 km subcube of SEAM model, centered at source (x,y). Extracted by window (and subsample, for 20m) by SU::subset from SEAM 07/08 data files (.vodat). Output 12 km $\times$ 12 km $\times$ 8 s subset of SEAM shot1 traces, centered at shot1 source (sx=15km, sy=17km), also inline and crossline through source position sampled at 20 m group interval. Source: SEAM 05/08 wavelet.

10 m grid: run on TACC-Ranger, $8\times8\times4$ domains, 7 hrs.

20 m grid: run on CAAM-Obelix $2\times2\times2$ domains, 13 hrs.

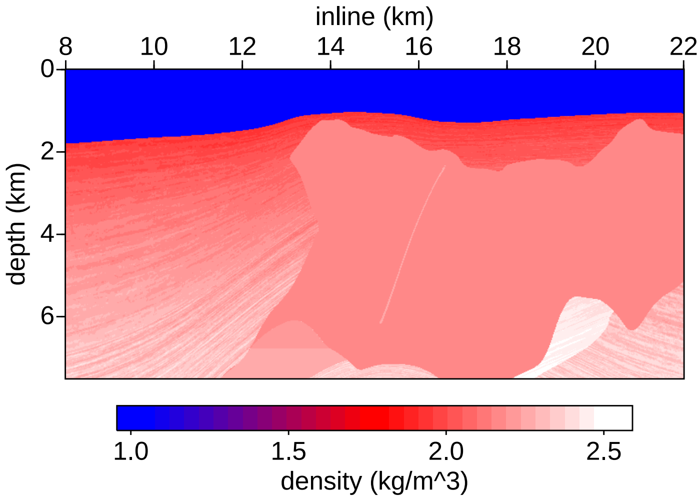
Half Model Experiments

Velocity (x,z) slice y=17km



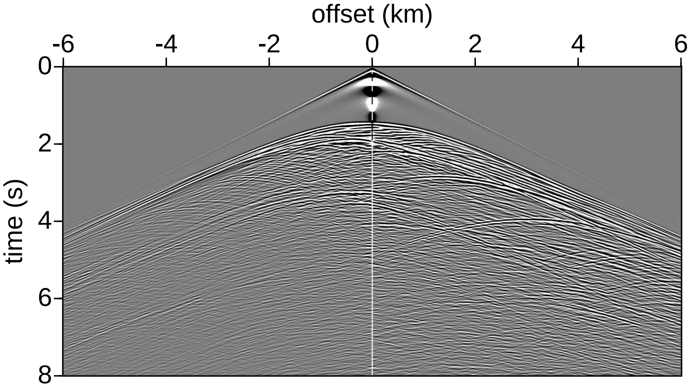
Half Model Experiments

Density (x,z) slice y=17km



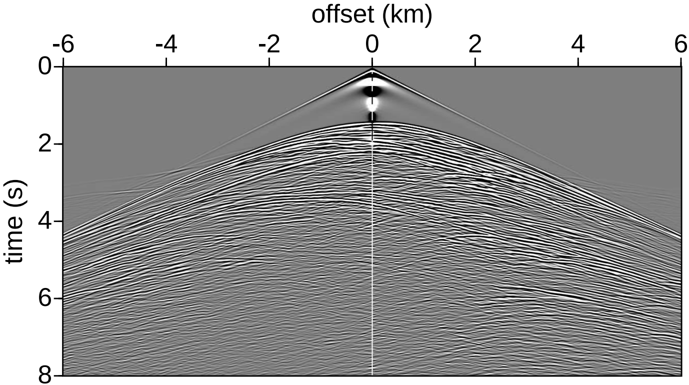
Half Model Experiments

Inline gy=17km, dgx=20m

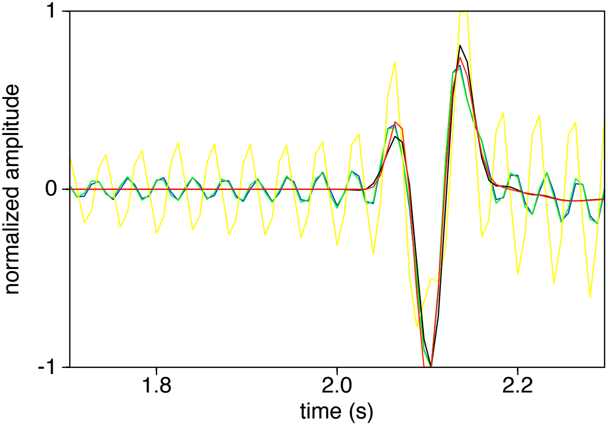


Half Model Experiments

Crossline gx=15km, dgy=20m

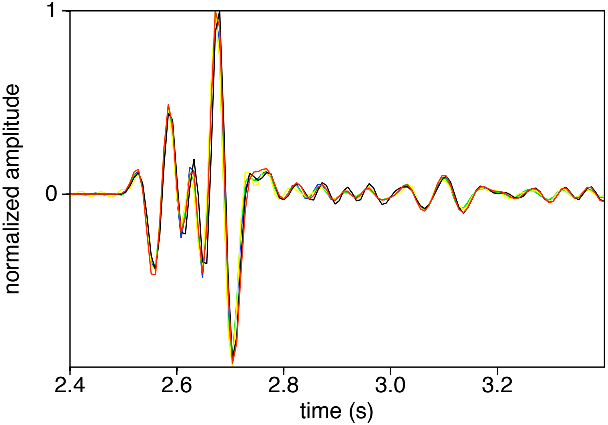


Half Model Experiments



Trace at (12km,17km) - Vendors 3 (blue), 4 (green), 5 (yellow), 8 (black), SEAMX (red).

Half Model Experiments



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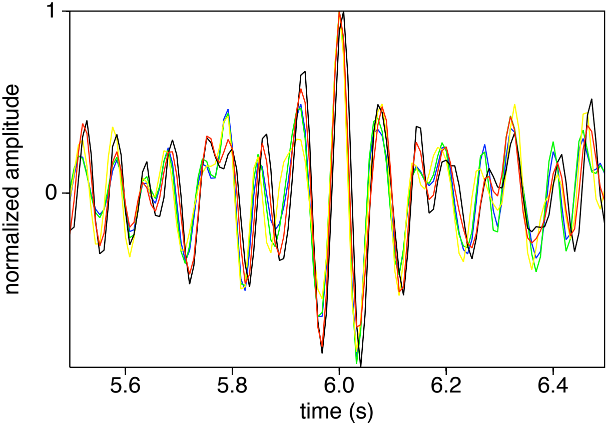

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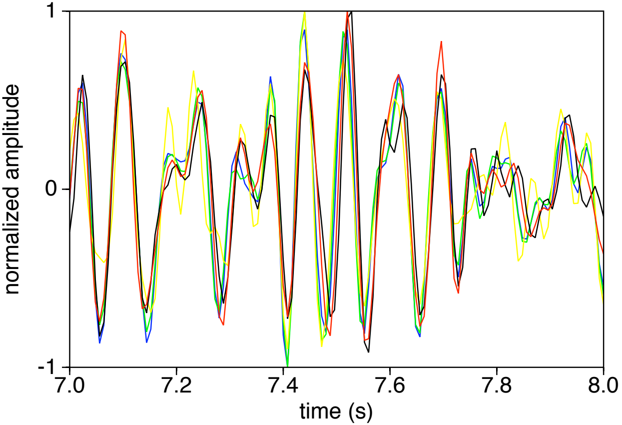


Trace at (12km,17km) - Vendors 3 (blue), 4 (green), 5 (yellow), 8 (black), SEAMX (red).

Half Model Experiments

Relative RMS Errors in each window vs. Vendor 5 trace, compared with Richardson error estimates from 20 m and 10 m SEAMX runs, assuming 1st order convergence:

window	1.7-2.3 s	2.4-3.4 s	5.5-6.5 s	7.0-8.0 s
Vendor 3	0.79	0.16	0.38	0.47
Vendor 4	0.79	0.10	0.35	0.42
Vendor 8	0.77	0.44	0.80	0.77
SEAMX	0.77	0.30	0.55	0.63
Rich. Err	0.06	0.31	0.61	0.62

Upshot: variance between results roughly $\simeq$ predicted error in SEAMX 10 m trace.

Full Model Experiments

10 m grid version of full SEAM model, full SEAM qualification geometry, 05/08 wavelet.

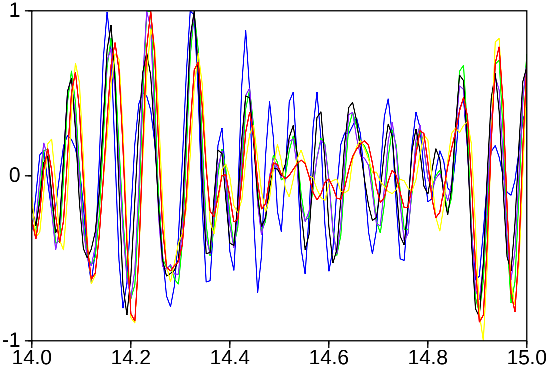
Grid volume: nx=2800 $\times$ ny=2800 $\times$ nz=1500 *times* nt=20000.

40 hrs on 900 PEs.

Analysis in progress.

Thanks: Scott Morton

Full Model Experiments



Trace at (12km,17km) - Vendors 2 (blue), 3purple, 4 (green), 5 (black), 8 (yellow), SEAMX (red).

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Current projects

- i/o server to replace serial disk accesses with message-passing - partially tested
- portable performance tuning, vector/SSE instr. in inner loops - prelim tests promising
- bandwidth-optimized stencil coefficients - appears to be straightforward
- finish documentation - is it ever finished?
- complete test suite - exists, but needs grooming and regression harness

Release acoustic app under GPL, article to *Geophysics* software section - Q2 09?

What We Have Learned

- Quantitative assessment of large-scale complex simulations appears to be feasible.
- Basic FD not very accurate (interface misalignment effect, 1st order error) - cf. other talks this AM.
- Simple “discrete delta” source modeling not very accurate. With homog. zone around source, can use *time tube* construction - optimal order convergence for point sources (prototype demo’d by TWV in spring 08). Without homog. near-source, other ideas needed (grid refinement?)
- Current package attains most design goals.

Where We Go From Here

- implement checkpointing design [needed both for fault-tolerance and for RTM, inversion apps]
- validate framework design by adding new models, schemes: other acoustic methods, *elastic* modeling
- investigate accuracy enhancement methods based on FEM (other talks this AM)
- coupling to inversion framework via TSOpt package, described in PM - RTM, WI, DS