Optimized wave propagation for geophysics

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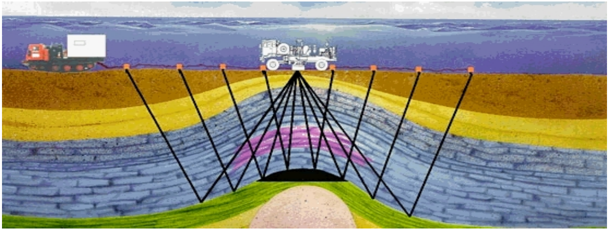
Outline

Context

Geophysics:

- Hydrocarbons detection: petroleum or natural gas
- Earth medium: seismic waves, heterogeneous complex domain



Simulation:

- Seismic imaging: find the subsurface layers
- Equations: elastic/acoustic wave in 2D/3D

Reverse Time Migration (RTM)

Iterative method based on multiple wave equation resolutions

TOTAL code

RTM for seismic imaging:

TOTAL code (Fortran2003)

DIVA: Depth Imaging Velocity Analysis / DIP

- acoustic/elastic waves
- 2D/3D domains
- heterogeneous complex media

Huge volume of data

Classical benchmark:

- 2D: 10^5 to 10^6 elements in hundreds of processors
- 3D: 10^7 to 10^8 elements in thousands of processors

$\Rightarrow$ needs to be massively-parallel

Outline

Elastic wave equation

Let us consider $\mathbf{x} \in \Omega$ and $t \in [0, T]$, the space and time variables

Velocity-stress formulation

$$\begin{cases} \rho(\mathbf{x})\partial_t v(\mathbf{x}, t) & = & \nabla.\underline{\underline{\sigma}}(\mathbf{x}, t) \\ \partial_t \underline{\underline{\sigma}}(\mathbf{x}, t) & = & \underline{\underline{C}}(\mathbf{x}) : \underline{\underline{\epsilon}}(v(\mathbf{x}, t)) \end{cases} \quad (1)$$

- $v \in \mathbf{H}^1(\Omega \times [0, T])$, the unknown velocity field
- $\underline{\underline{\sigma}} \in \underline{\underline{H}}_{div}(\Omega \times [0, T])$, the stress tensor

$\underline{\underline{C}}$, the stiffness tensor: contains elasticity & anisotropy

$$C = \begin{bmatrix} C_{11} & C_{12} & C_{13} \\ & C_{22} & C_{23} \\ & & C_{33} \end{bmatrix} \quad (2)$$

TTI: Tilted Transverse Isotropy

- Isotropic: sparse stiffness tensor $\underline{\underline{C}}$
- VTI: same non-zero values (two TI parameters)
- TTI: rotation of VTI $\Rightarrow$ dense tensor!

Geophysics anisotropy

Earth's crust (geological layers of rocks) is assumed to be locally polar anisotropic, also called transversely isotropic (TI).

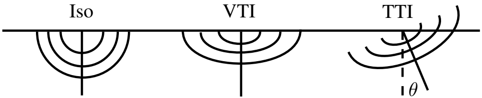
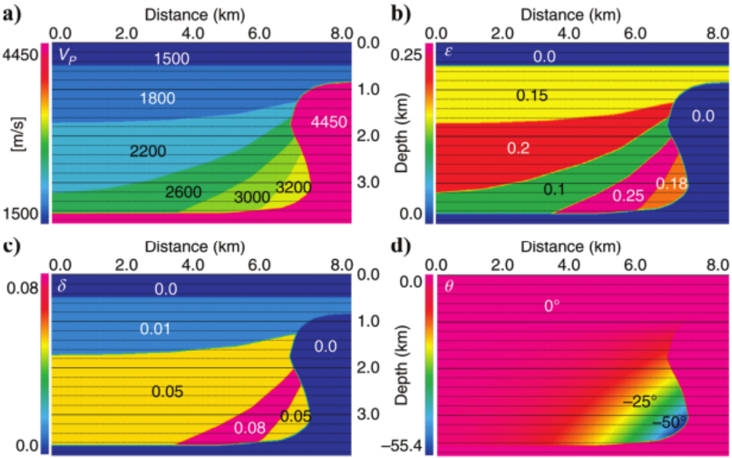


Figure: Wavefronts for isotropy and transverse isotropy (vertical and tilted)

TTI example

Synthetic realistic case: [Duveneck & Bakker 2011]



TTI example

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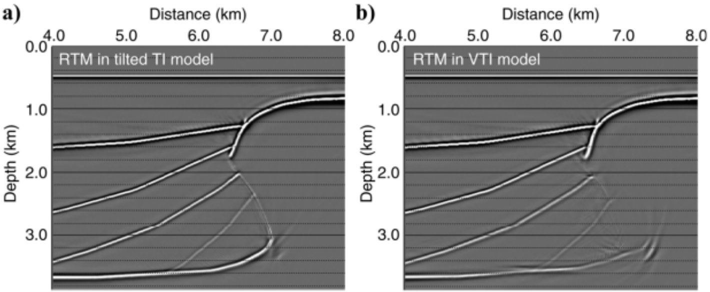


⇒ complex domains require to be more realistic!

Outline

PMLs vs ABCs

Infinite geophysical domains compared to the wavelengths:

- Reduction of the computational domain to a box (source & receivers)
- Design of efficient boundary conditions (attenuate the reflections)

Two common ways:

Perfectly Matched Layers (PMLs), [Bérenger 1994, 1996]

Equation for a layer all around the problem domain
$\rightarrow$ easy to implement, instabilities may appear (anisotropy)

Absorbing Boundary Conditions (ABCs), [Enquist-Majda 1977, 1979]

Equation for the boundary of the problem domain
$\rightarrow$ stable, low-order easy to implement but not very accurate

RTM framework: spurious reflections considered as noise!

Hypothesis: elliptic anisotropy $\boxed{\delta = \varepsilon}$

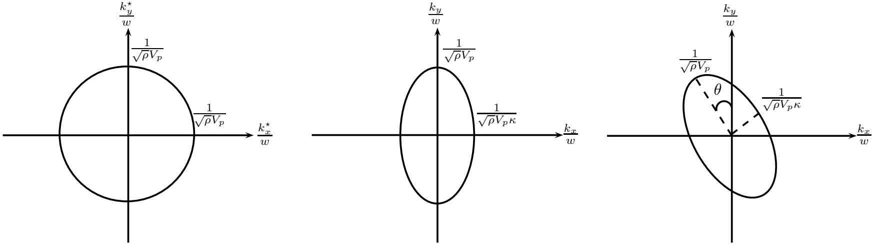


Figure: P-waves **slowness curves** of isotropic, VTI and TTI cases

Geometric way

- find a change of coordinate between slowness curve equations
- apply replacement on the isotropic ABCs to form TTI ABCs

Outline

1. Context and TOTAL framework
2. Anisotropic elastodynamics
   - Absorbing Boundary Conditions
   - Numerical results
3. Runtime
4. Conclusion and perspectives

2D test case

- $[10km \times 10km]$ – 200.000 cells
- Homogeneous medium
- P-waves source
- $V_p = 2500m.s^{-1}, \ V_s = 1250m.s^{-1}$
- VTI: $\varepsilon = 0.24, \ \delta = 0.01$
- TTI: $\theta = 30^{\circ}$

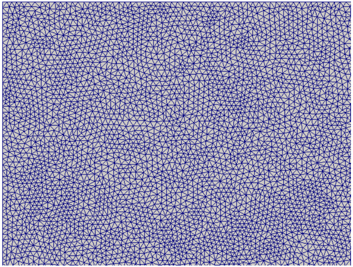


Figure: zoom on the mesh

Isotropic results

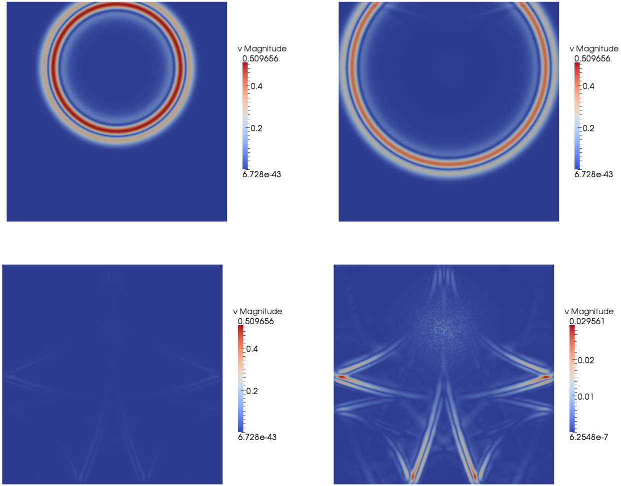


Figure: Velocity magnitude at different time steps of the simulation

TTI results

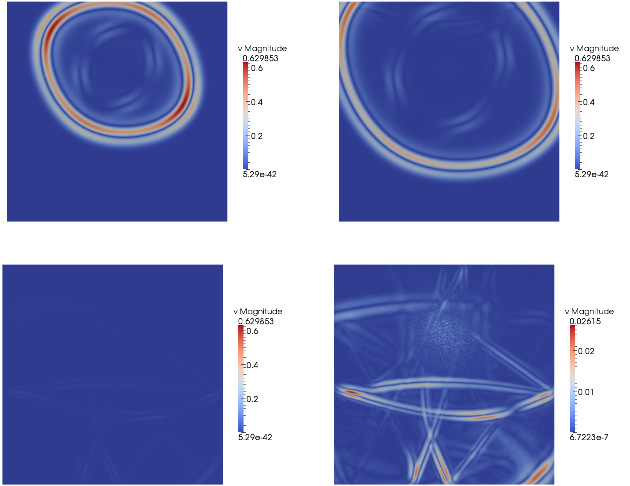


Figure: Velocity magnitude at different time steps of the simulation

TTI ABC versus simple ABCs

TTI medium only, with different kind of ABCs:

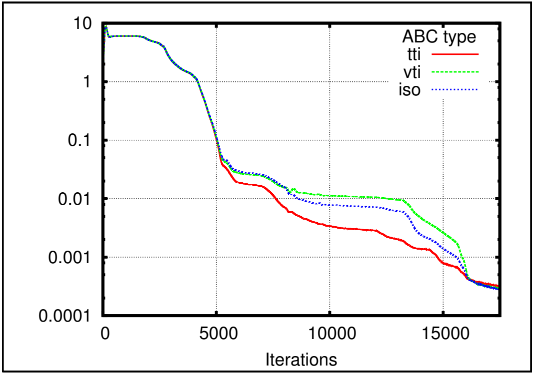
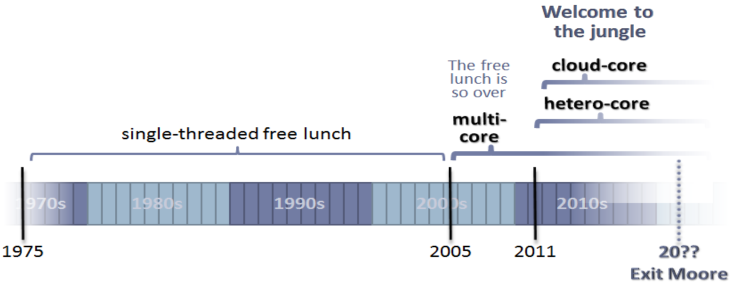


Figure: TTI ABC versus simple ABCs

⇒ TTI ABC is better than isotropic or VTI ABCs!

Outline

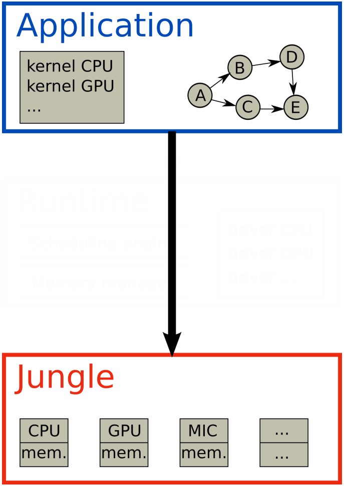
"*Welcome to the jungle*", Herb SUTTER, 2012



The jungle, a definition:

- Architectures: Xeon, Cell, MIC, KALRAY, GPU, FPGA, . . .
- Memories: RAM, caches, (cc)NUMA, . . .
- HowToDo (mainly): MPI, CUDA/OpenCL, OpenACC, . . .

Basic scheme



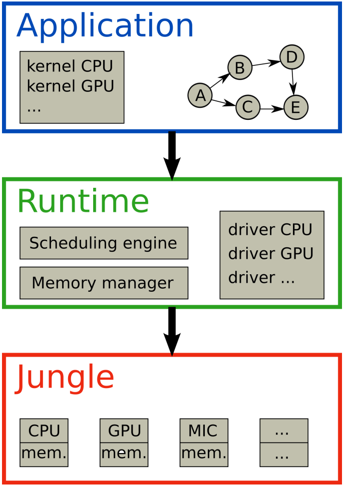
Classical approach:

- MPI over CPUs
- CUDA over GPUs

implies:

- big programming effort
- difficult to maintain
- hardware-dependent

Basic scheme



Runtime:

- abstraction layer
- hiding heterogeneity

Scheduler:

- where to execute
- when to execute

Memory:

- does the transfert
- guarantees consistency

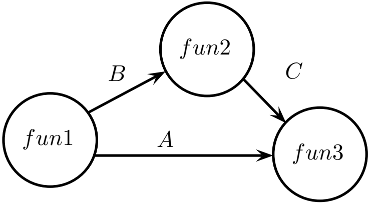
How to use runtimes?

fun1(A: inout, B: out)
fun2(B: in, C:out)
fun3(A: inout, C: in)

Task-based

- Describe the functions as tasks
- Form the dataflow: specify dependencies

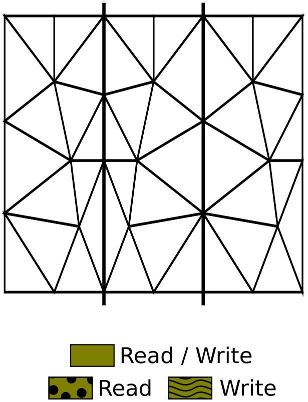
⇒ creation of the DAG (Direct Acyclic Graph)



Outline

Multidomain DAG

Basic COMPUTE and EXCHANGE model:



Multidomain DAG

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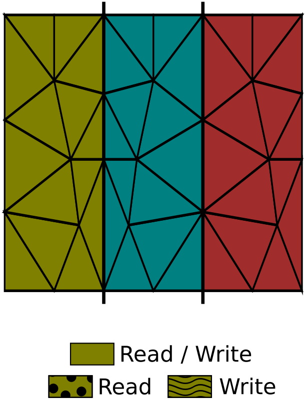

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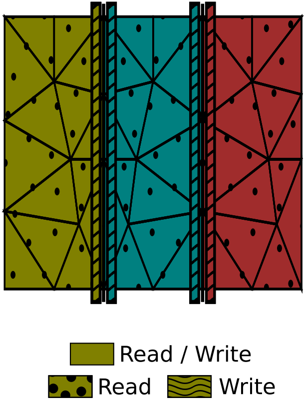

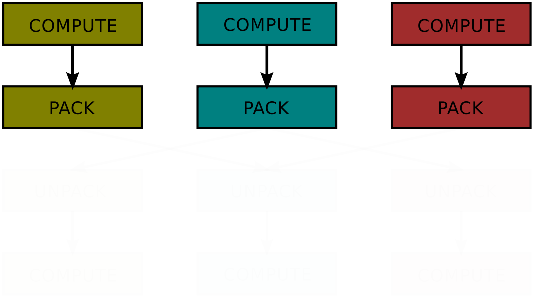

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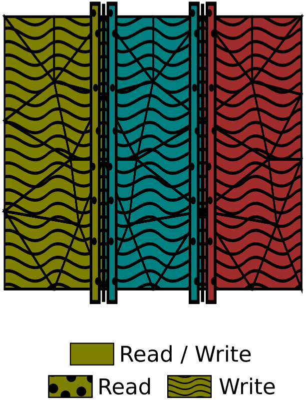

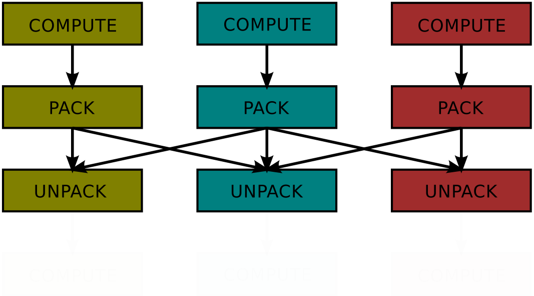

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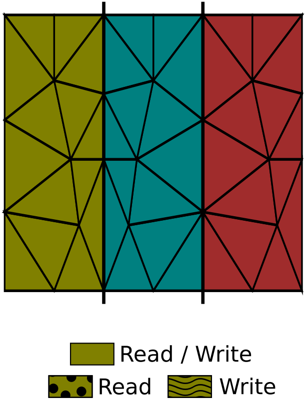
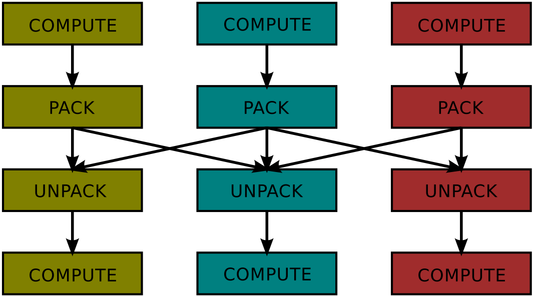
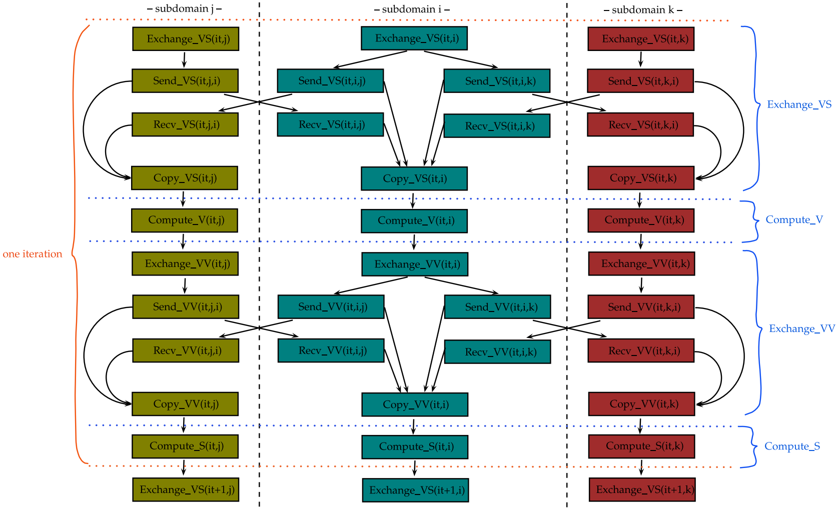




DAG of tasks for runtime



Outline

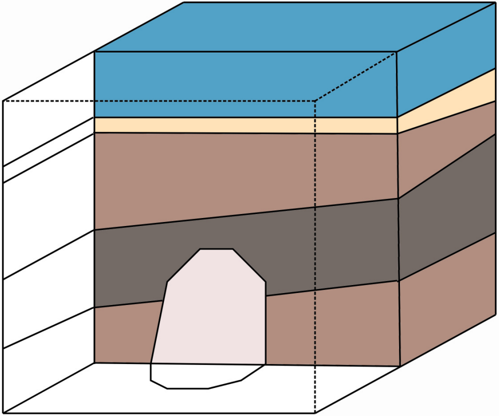
Geophysics test case

Realistic test case:

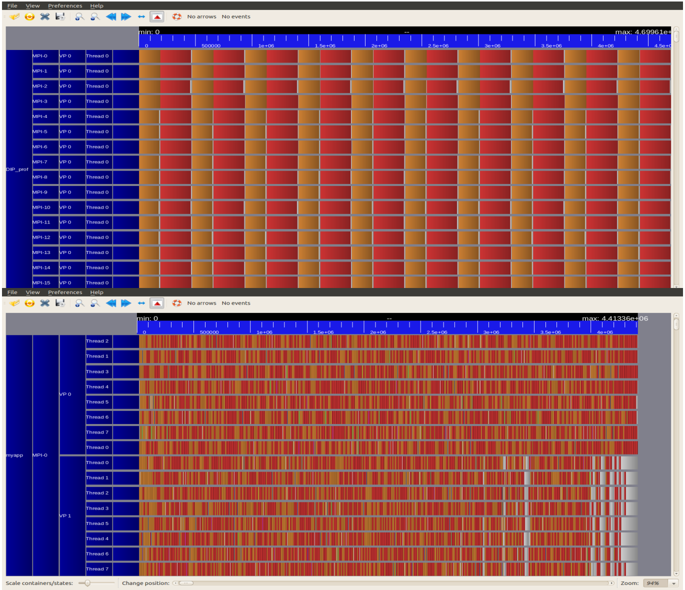
- 3D elastic
- TTI (anisotropy)
- multi-layers

Hybrid discretization:

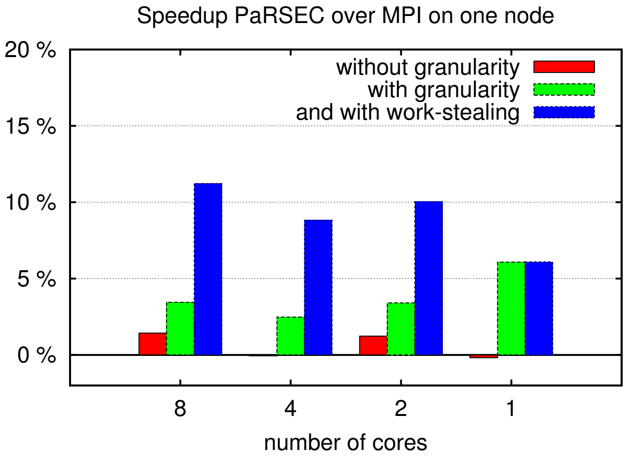
- unstructured tetrahedra
- P1-P2-P3 orders
- boundary conditions



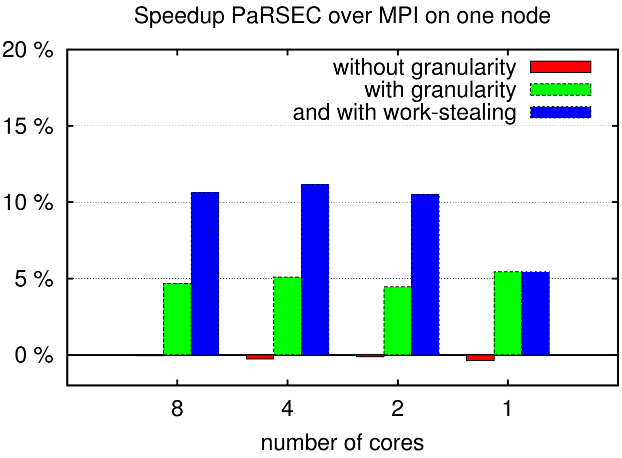
Trace on one node – 16 cores



Speedup


Speedup PaRSEC over MPI on one node
20 %
15 %
10 %
5 %
0 %
without granularity
with granularity
and with work-stealing
8
4
2
1
number of cores

Speedup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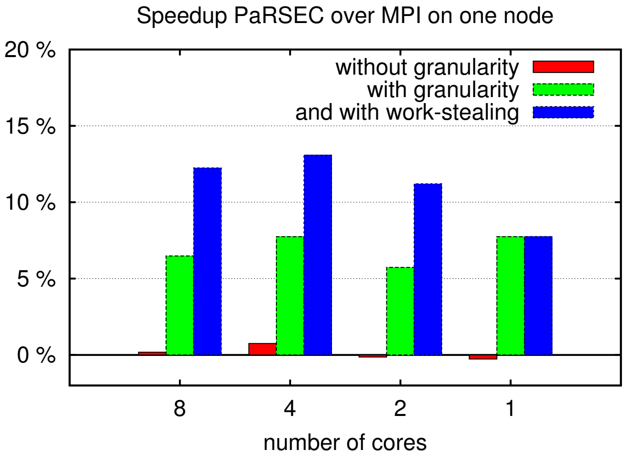
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Outline

Conclusion and perspectives

First-order elastic wave equation

Conclusion:

- new 2D elliptic-TTI ABC
- runtime plugged in DIVA code

Perspectives:

- 3D TTI ABC, following the same technique
- Coprocessors Intel Xeon Phi (MIC)

Support by INRIA-TOTAL strategic action DIP (`http://dip.inria.fr`)