High resolution seismic imaging

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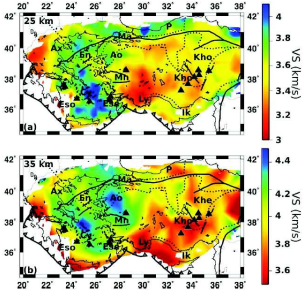
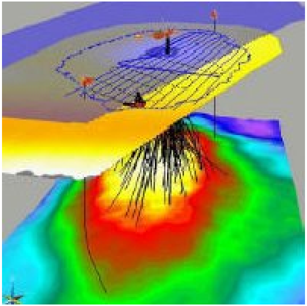
Outline

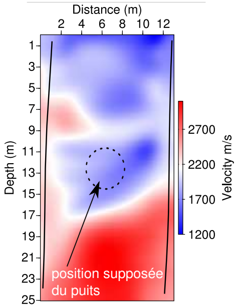
1. Introduction
2. Algorithm
3. Example on the Valhall Oil & Gas field
4. Perspectives and challenges on the HPC side

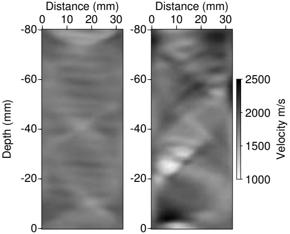
Outline

Multi-scale challenges of geophysical imaging





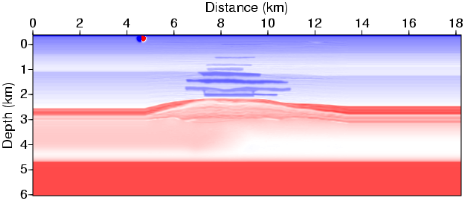




Seismic imaging of the Earth

- Imaging/tomography : reconstruction of Earth subsurface properties from indirect measurements of seismic waves

$$\frac{\partial U}{\partial t} + \Lambda \frac{\partial U}{\partial x_i} = F_0 \qquad (1)$$



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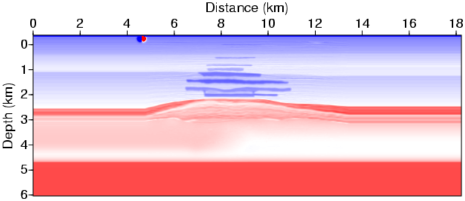
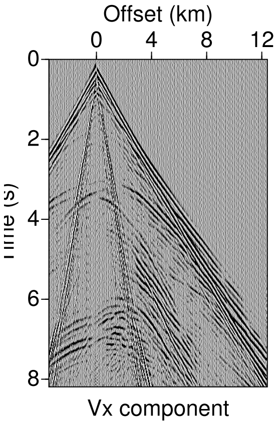
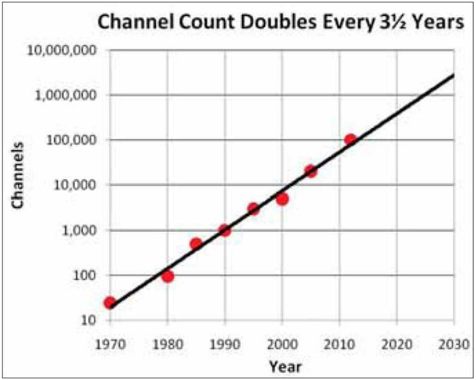




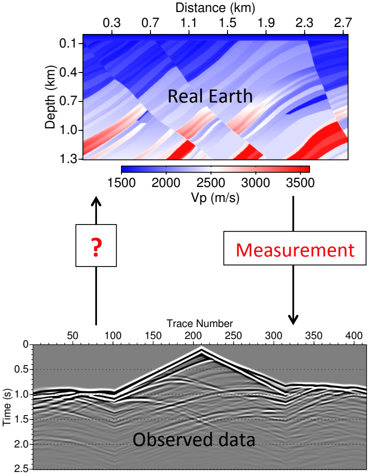
Difficulties for Oil & Gas industry

- "Easy" reservoirs are already discovered
  - Improvement of the acquisition : number of channels and frequency band (Moore law)
  - Improvement of the imaging algorithms to handle complex geology (and high number of channels...)



Keho & Kelamis, 2012

Full waveform inversion : principle



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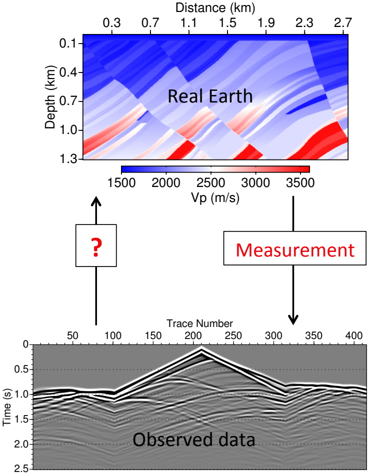

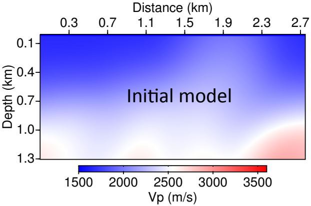

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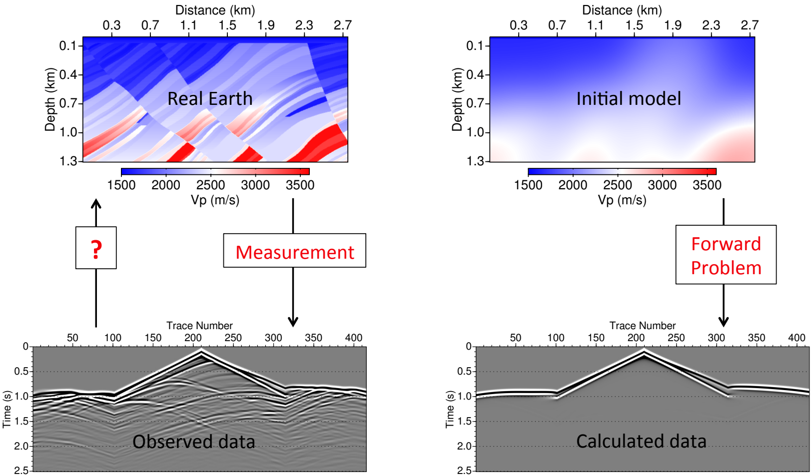
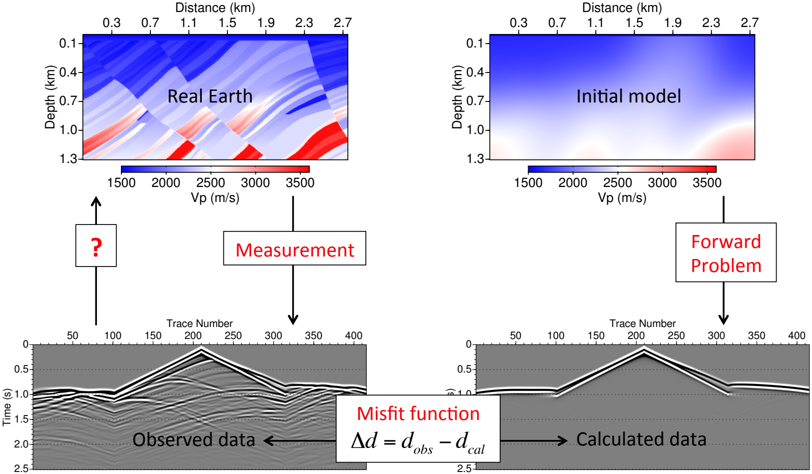
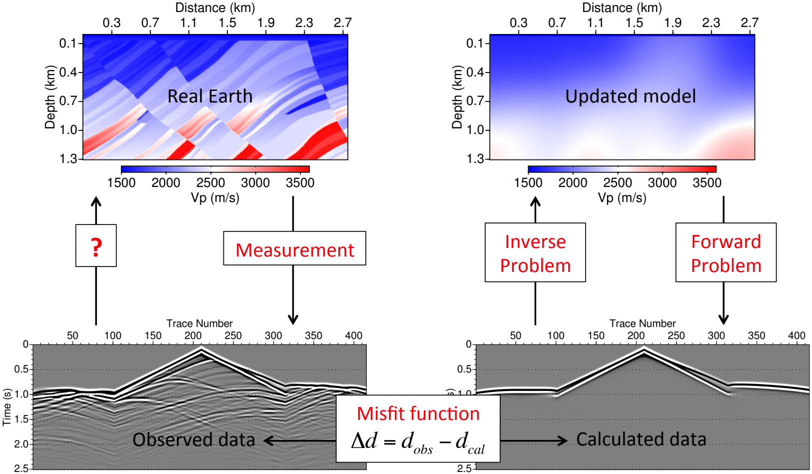


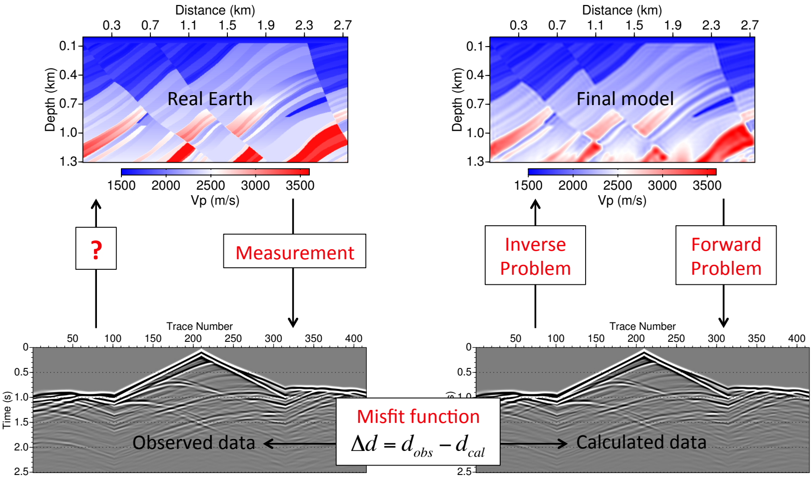
Full waveform inversion : principle



Full waveform inversion : principle



Full waveform inversion : principle



Initial velocity model
m_0

Forward modeling
Wave equation
- *Finite differences*
- *Finite elements*

Synthetic data
d_{cal}

Observed data
d_{obs}

Calculate misfit

$$\Delta d(m) = d_{obs} - d_{cal}(m)$$

$$C(m) = \frac{1}{2}\|\Delta d(m)\|^2$$ *(minimize L2 norm of difference)*

Calculate Gradient and Hessian

$$C'(m) = g$$

$$C''(m) = H$$ *(approx.)*

Solved with adjoint method

Calculate model update

$$H\Delta m = -g$$

Inverse problem solved implicitly

Updated velocity model

$$m = m_0 + \Delta m$$

Iterative approach

Full waveform inversion : issues

FWI is a difficult problem that requires expertise in many fields

- Physics and Geophysics : understanding of physics of seismic waves
- Applied Mathematics : PDE, optimization and inverse problem
- Signal Processing
- HPC : efficient implementation of numerical method of modern HPC platforms and managing of large data volumes

Outline

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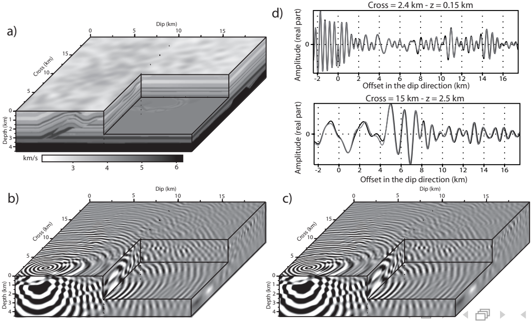
Frequency-domain PDE solver

- Helmholtz equation for discretized with optimal finite-difference

$$\frac{\omega^2}{\kappa(\mathbf{x})} p(\mathbf{x},\omega) + \frac{\partial}{\partial x} b(\mathbf{x}) \frac{\partial p(\mathbf{x},\omega)}{\partial x} + \frac{\partial}{\partial y} b(\mathbf{x}) \frac{\partial p(\mathbf{x},\omega)}{\partial y} + \frac{\partial}{\partial z} b(\mathbf{x}) \frac{\partial p(\mathbf{x},\omega)}{\partial z} = s(\mathbf{x},\omega) \quad (2)$$

- Leads to large sparse linear systems $Ax = b$ with many $(10^2 - 10^4)$ RHS
  $\rightarrow$ requires plateforms with lots of core-memory

F (Hz)	h(m)	n_u (10^6)	M_{LU} (Gb)	T_{LU} (s)	T_s (s)	N_p
7	75	6.2	260	1822	0.97	64 (32*2)



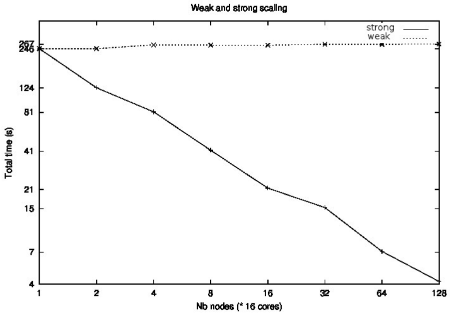
Outline

Time-domain PDE solver

- Wave equation visco-acoustic media discretized with finite-difference

$$\frac{1}{\kappa(\mathbf{x})}\frac{\partial^2 p(\mathbf{x},t)}{\partial t^2}+\frac{\partial}{\partial x}b(\mathbf{x})\frac{\partial p(\mathbf{x},t)}{\partial x}+\frac{\partial}{\partial y}b(\mathbf{x})\frac{\partial p(\mathbf{x},t)}{\partial y}+\frac{\partial}{\partial z}b(\mathbf{x})\frac{\partial p(\mathbf{x},t)}{\partial z}=s(\mathbf{x},t) \quad (3)$$

- Explicit time-marching algorithms with high scalability
  $\longrightarrow$ number of cores is the crutial point

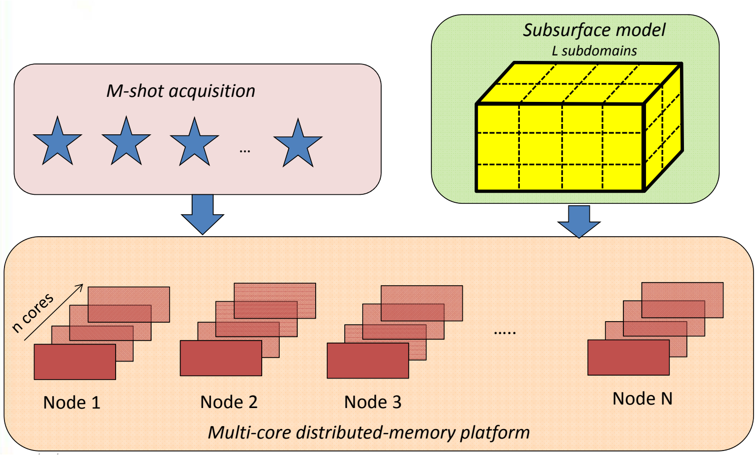


weak and strong scaling done on the Freeride slot on Froggy

- strong scaling : grid $512 \times 1024 \times 1024$
- weak scaling : $512 \times 1024 \times 1024$ points on 16 cores to $2048 \times 4096 \times 4096$ points on 2048 cores

Time-domain PDE solver

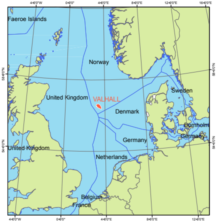
How to optimally distribute sources and computational mesh over MPI processes ?
2 levels of parallelism

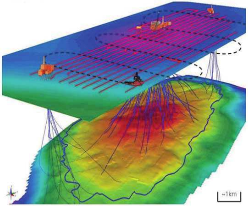


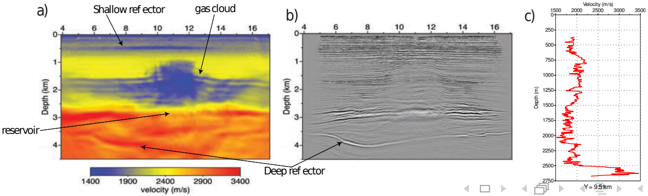
Outline

The Valhall field environment and data

- Valhall field : off-shore shallow-water in the North Sea. Over-pressured, under-saturated, Upper Cretaceous chalk reservoir (exploited since 1982)
- Shale at shallow depth : strong inprint of anisotropy in the seismic data
- 3D seismic : ≈ 50000 shots, 2414 permanent 4C sensors on the sea bed (OBC)

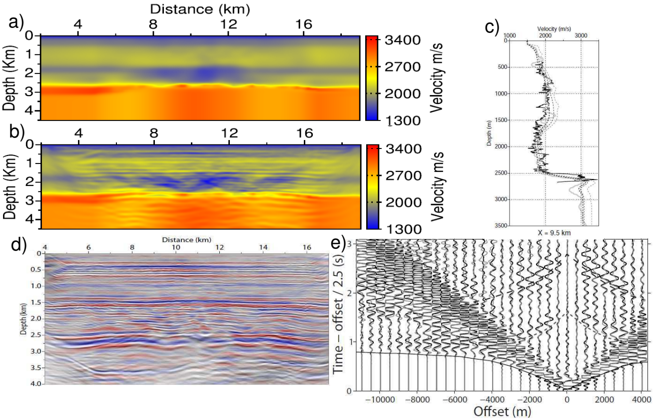






2D Acoustic anisotropic inversion

from Prieux et al, 2011, GJI



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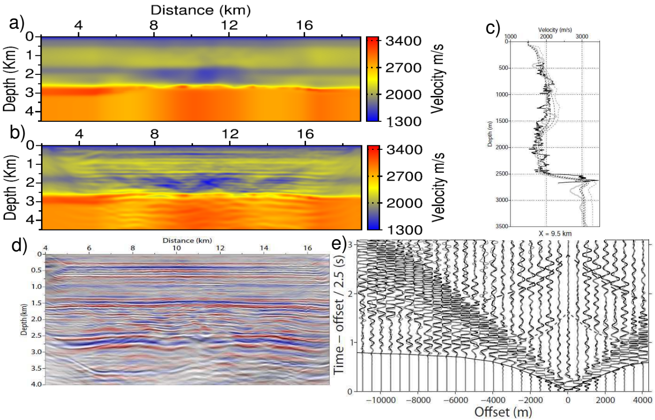
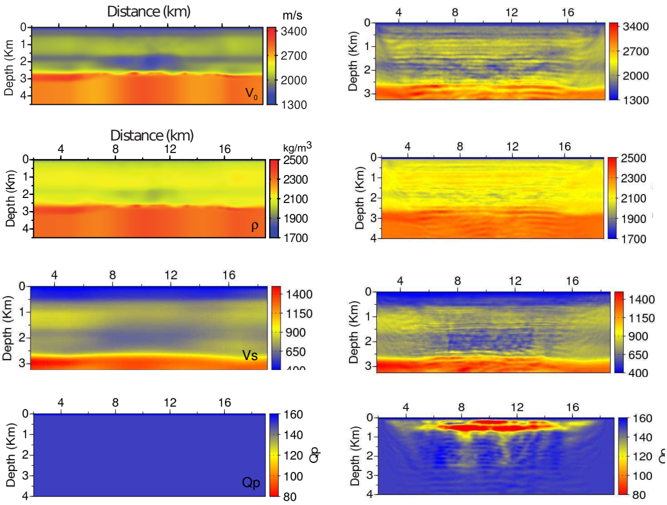


→ **Jade/CINES, 52 h, 32 procs, 55 Gb of RAM**

2D Elastic anisotropic inversion

from Prieux et al, 2013, GJI



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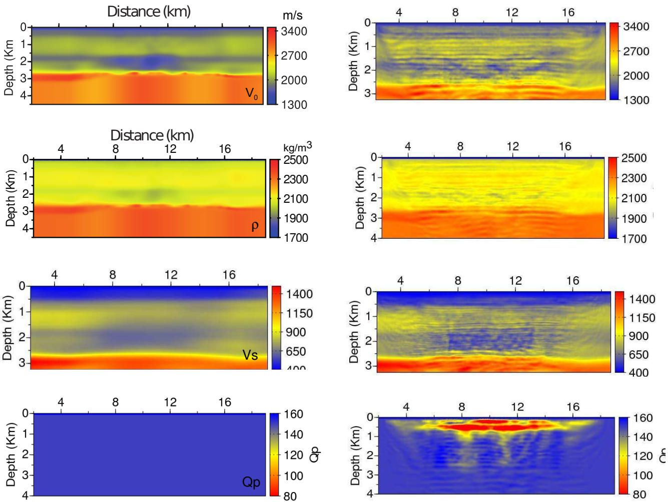
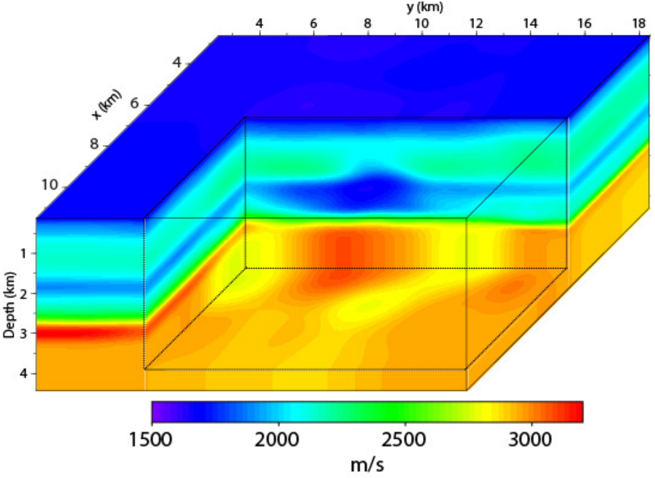


→ **Jade/CINES, 42 h, 240 procs, 322 Go of RAM**

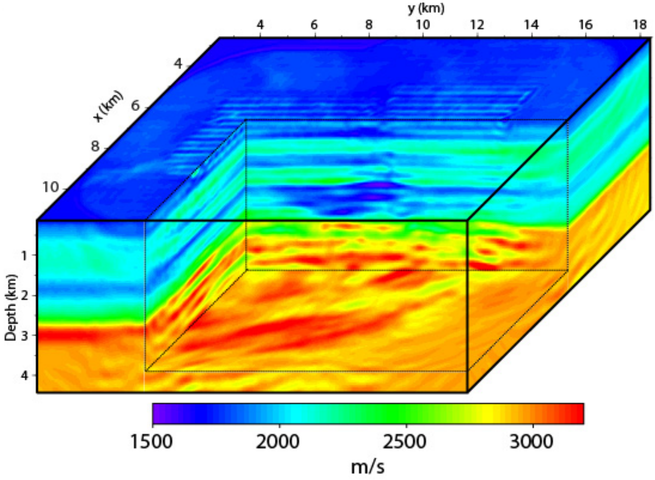
3D Acoustic inversion

Starting model from reflection tomography



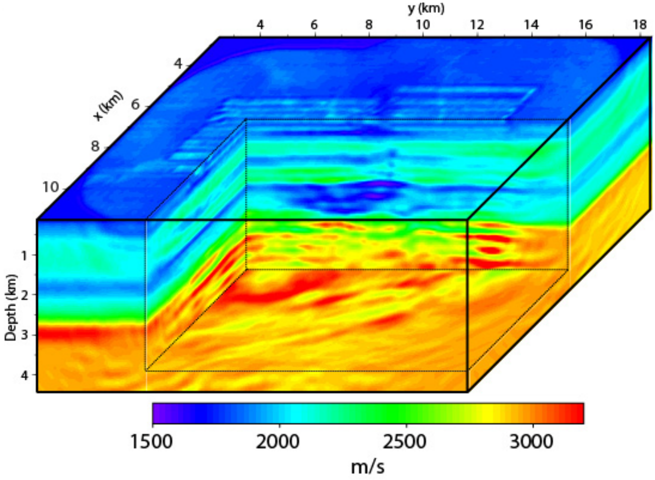
3D Acoustic inversion

FWI : [3.5,4] Hz



3D Acoustic inversion

FWI : [4,5] Hz



3D Acoustic inversion : Performances

Code	*TOY3DAC*	*GeoInv3D*
archi.	Gofree Intel cluster	IBM Blue Gene
nb cores	72	2048
time/it. (h)	1.33	2.30
tot. time/it. (h)	96	4710
theo. pic flop/it	3.1E15	5.8E16
tot memory	$\approx$ 500Gb	$\approx$ 500Gb

- Gofree Intel Cluster
  - Intel Westmere nodes
  - 2 proc. $\times$ 6 cores per node 2.26 Ghz
  - 72 Gb of memory per node
  - Mellanox QDR 40 Gb/s Infiniband network
- IBM Blue Gene P (IDRIS) center
  - Power PC 450 nodes
  - 1 proc. $\times$ 4 cores per node 850 MHz
  - 2 Gb of memory per node

Outline

Perspectives and challenges on the HPC side

- Speed up : data "compression" and local optimization performances
- code efficiency : third parallelism level based on shared memory threads (OpenMP)
- Improve our physics : more complex PDE, but more expensive
- Tackle bigger problems
  - larger size targets : $\approx 50 \times 50 \times 10$ km
  - higher frequencies : $\approx$ 15-20 Hz
  - denser acquisition : $\approx 10^5$ channels $\times$ 10^4 sources