

Моделирование распространения динамических волновых возмущений в гетерогенных средах на высокопроизводительных вычислительных системах.

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Numerical Methods and Models

- Media models:
 - Linear elasticity, viscoelastic
 - Linear acoustic
- Numerical methods:
 - Grid-characteristic
 - FDTD
 - TVD, WENO finite-volumes
- Features:
 - Explicit cracks setting
 - Explicit layers borders setting
 - High-order numerical schemes, monotonicity
 - HPCs oriented

Mathematical model

Relation between velocity and deformation

$$\left\{ \begin{array}{ll} \rho \dot{\vec{v}} = \nabla \cdot \mathbf{T} & \text{Motion equation} \\ \dot{\mathbf{T}} = \lambda(\nabla \cdot \vec{v})\mathbf{I} + \mu(\nabla \otimes \vec{v} + \vec{v} \otimes \nabla) & \text{Hooke's law} \end{array} \right.$$

ρ – density

λ, μ – Lamé elastic parameters

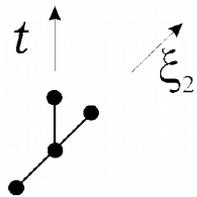
\vec{v} – velocity

\mathbf{T} – stress tensor

Grid-characteristic method

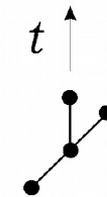
Split directions

$$u = (v_x, v_y, \sigma_{xx}, \sigma_{xy}, \sigma_{yy})$$



$$\frac{\partial \vec{u}}{\partial t} + \mathbf{A}_1 \frac{\partial \vec{u}}{\partial \xi_1} = 0$$

$$\vec{u}' = \vec{u}^n - \tau \mathbf{A}_1 \Delta_1 \vec{u}^n$$



$$\frac{\partial \vec{u}}{\partial t} + \mathbf{A}_2 \frac{\partial \vec{u}}{\partial \xi_2} = 0$$

$$\vec{u}^{n+1} = \vec{u}' - \tau \mathbf{A}_2 \Delta_2 \vec{u}'$$

$$\vec{u}^{n+1} = \vec{u}^n - \tau (\mathbf{A}_1 \Delta_1 + \mathbf{A}_2 \Delta_2) \vec{u}^n + O(\tau^2)$$

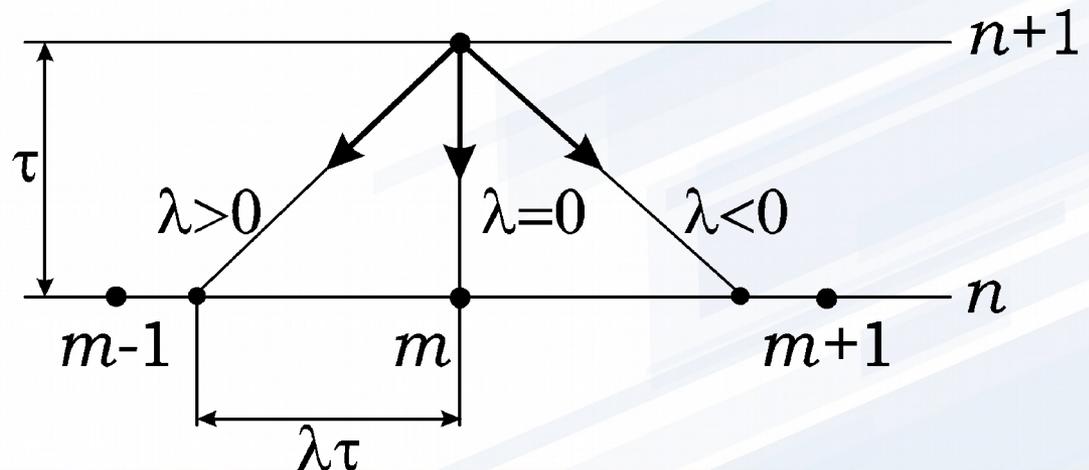
Hyperbolic problem

$$\mathbf{A} = \Omega^{-1} \mathbf{\Lambda} \Omega$$

$$\frac{\partial \vec{u}}{\partial t} + \Omega^{-1} \mathbf{\Lambda} \Omega \frac{\partial \vec{u}}{\partial \xi} = 0$$

$$\frac{\partial \vec{v}}{\partial t} + \mathbf{\Lambda} \frac{\partial \vec{v}}{\partial \xi} = 0 \quad (\vec{v} \equiv \Omega \vec{u})$$

$$v^{n+1}(\xi) = v^n(\xi - \lambda \tau)$$



Research Software

- **Structural mesh**

- Grid-characteristic, finite-volume, FDTD methods 1-4 order of accuracy
- Block structural meshes, curved meshes
- Large mesh sizes (over 1 billion nodes)
- Parallelized to MPI / OpenMP / CUDA / OpenCL

- **Features:**

- VTK-based visualization (ParaView, VisIt, Mayavi)
- Seismogram format - segy
- Elastic / acoustic media, explicit separation of contacts and heterogeneities

Вычислительный модуль

Блочные структурные сетки,
иерархические сетки
2D/3D

Неструктурные сетки,
адаптивные сетки
2D/3D

Препроцессинг

Встроенная система
конфигурационных
файлов

Открытые CAD
пакеты,
RSF, segy

Постпроцессинг

На основе
VTK, segy

Research Software Features

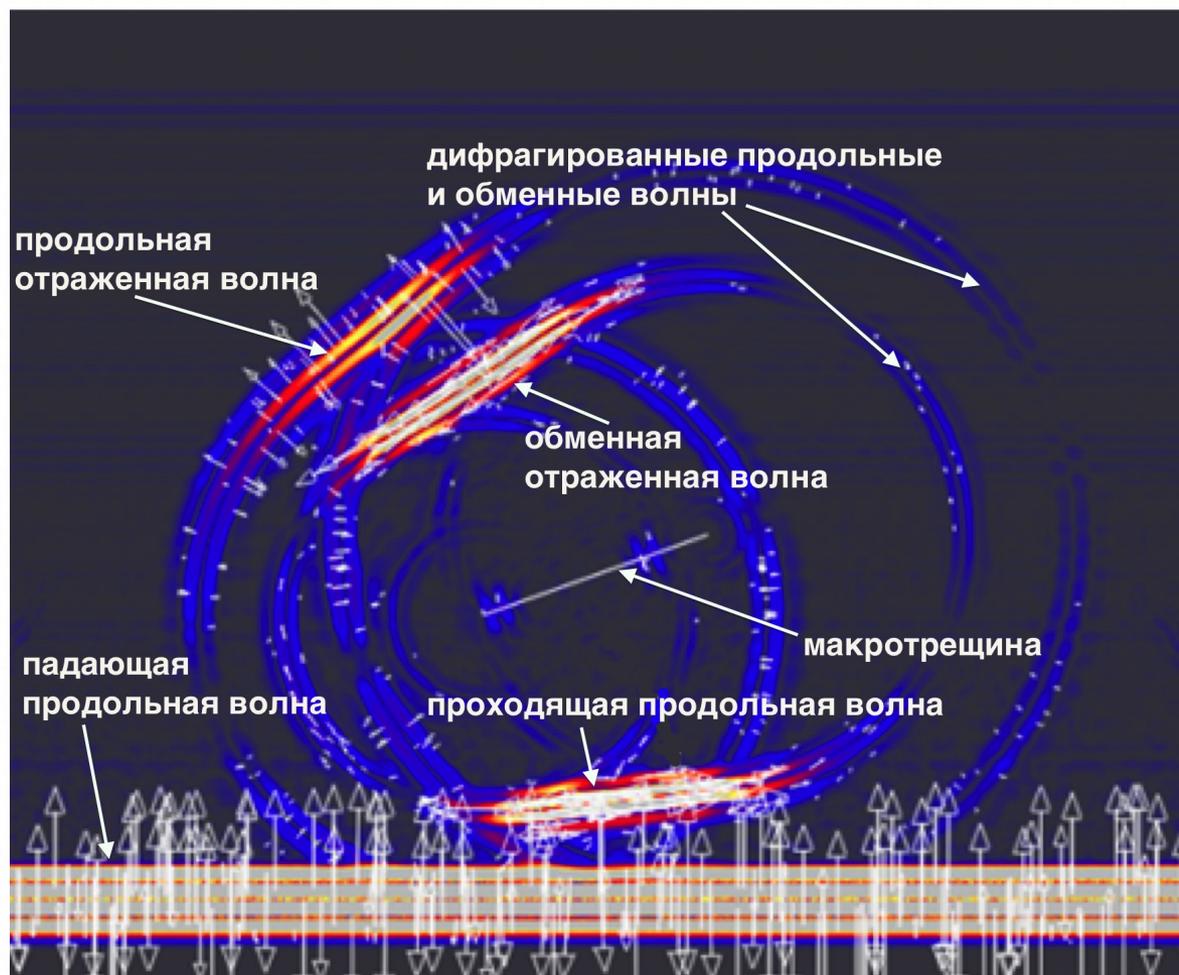
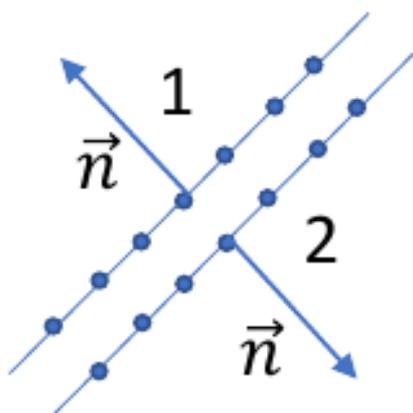
- Linux console intensive usage
- MPI and OpenMP technologies utilization, remote access to hardware
- No external dependencies, pure C++
- Oriented on C++ 98 (currently porting to C++11) to eliminate compile problems on old hardware

Моделирование геологических неоднородностей

- Трещиноватые неоднородности
- Выделение топографии поверхности
- Явное выделение раздела контактных поверхностей

Модель бесконечно тонкой трещины (БТТ)

- Явное выделение границ трещины



Подходы к моделированию

- Структурные сетки
 - Задание трещины между узлами сетки (в ячейке)
 - Дублирование узлов в области трещины
 - Искривление сетки в области трещины
 - Наложенные (Химерные) сетки
- Неструктурные сетки
 - Дублирование узлов в области трещины

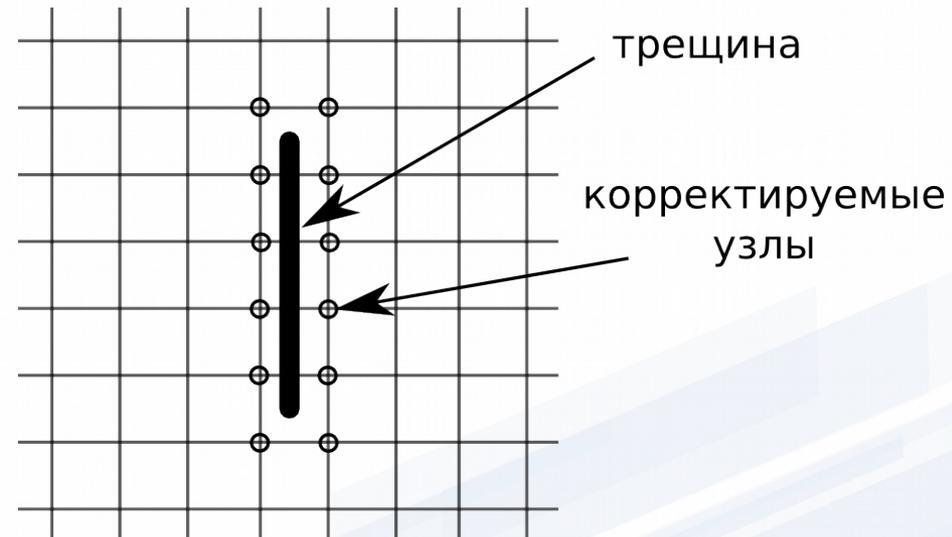
Задание трещины между узлами сетки (в ячейке)

- **Преимущества**

- простота алгоритма, не затрагивает распараллеливание
- нет необходимости менять сетку
- скорость расчета

- **Недостатки**

- фиксированная ошибка $O(h)$ (кинематическая)
- невозможно задать трудные конфигурации трещин



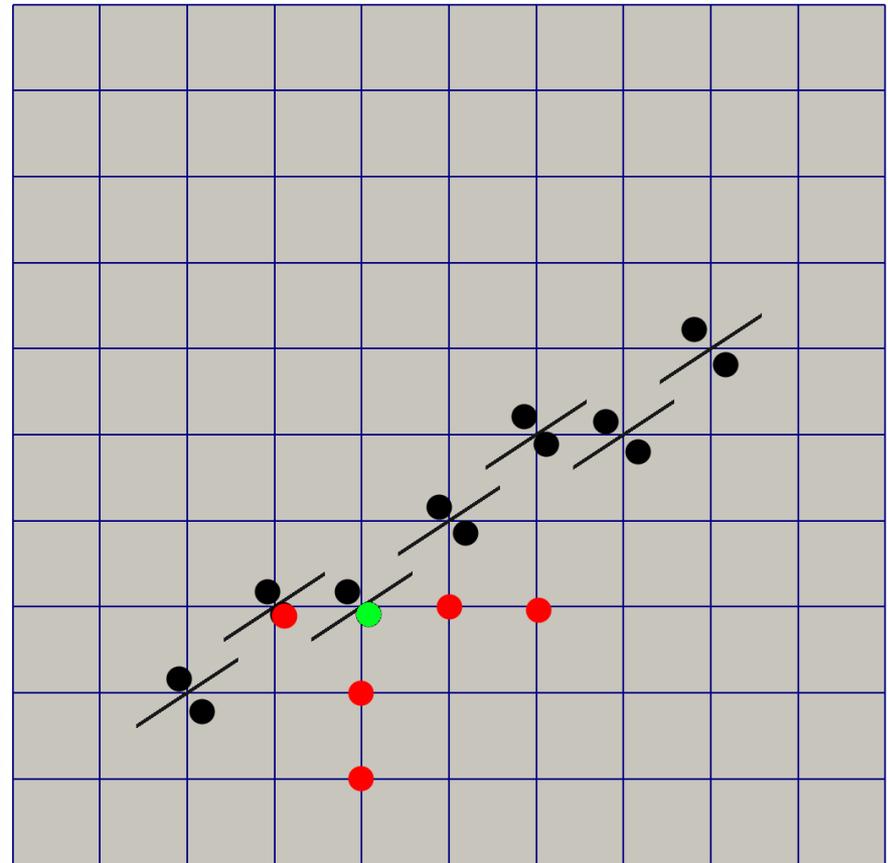
Дублирование узлов в области трещины

- **Преимущества**

- для трещин, сонаправленных с ячейками нет ошибки
- относительная простота алгоритма
- Произвольные конфигурации трещин
- скорость расчета

- **Недостатки**

- фиксированная ошибка $O(h)$ (кинематическая) в случае наклонных трещин
- требуется доработка алгоритмов распараллеливания
- Анизотропия ошибки от угла падения волны



Искривление сетки в области трещины

- **Преимущества**

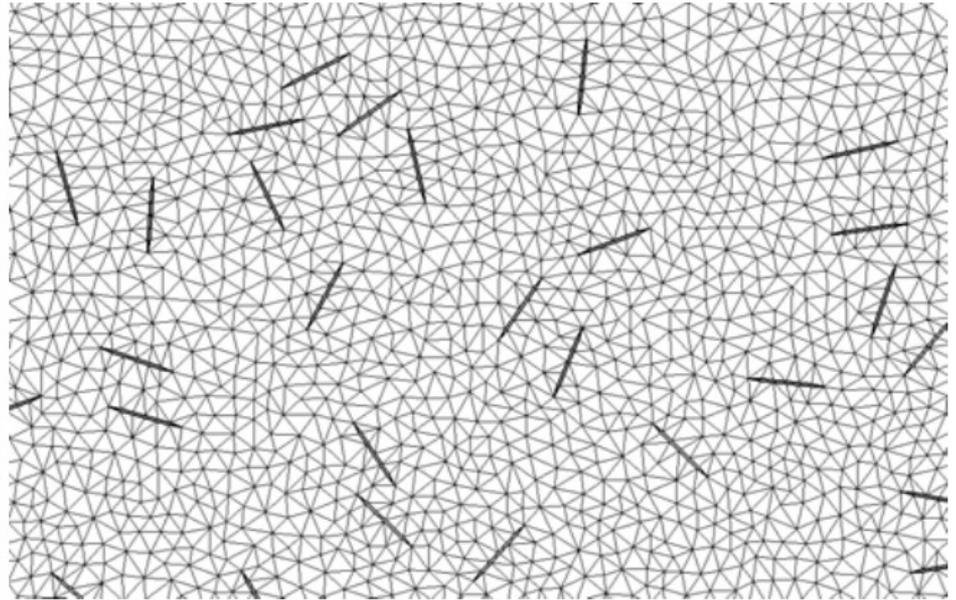
- Возможность использования любого из алгоритмов для обсчета трещины
- Задание наклонный трещин

- **Недостатки**

- Сложность построения сеток
- Уменьшение числа Куранта
- Увеличение времени счета
- Невозможность задания сложных конфигурация

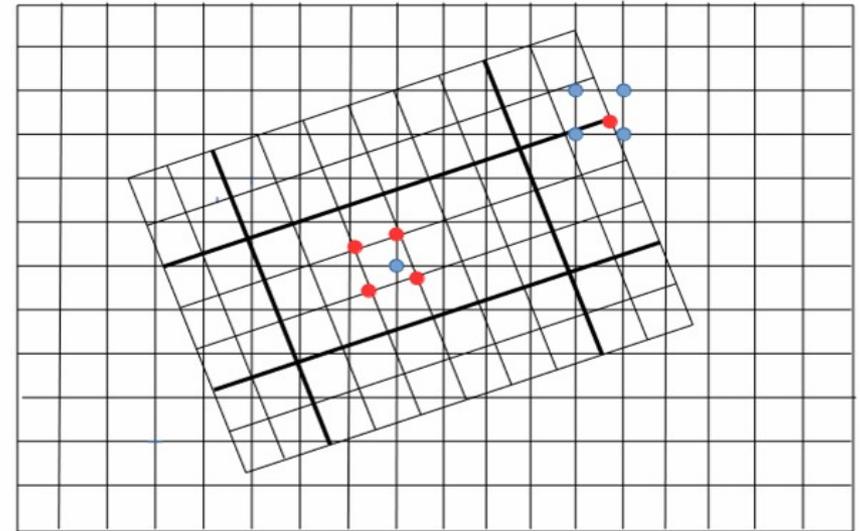
Неструктурные сетки

- **Преимущества**
 - Произвольные конфигурации трещин
 - нет ошибки при наклонных трещинах
- **Недостатки**
 - сложность реализации
 - построение сеток
 - время расчета



Наложенные (Химерные) сетки

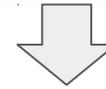
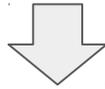
- **Преимущества**
 - Произвольные конфигурации трещин
 - нет ошибки при наклонных трещинах
 - время расчета
 - нет необходимости криволинейных сеток
- **Недостатки**
 - относительная сложность реализации



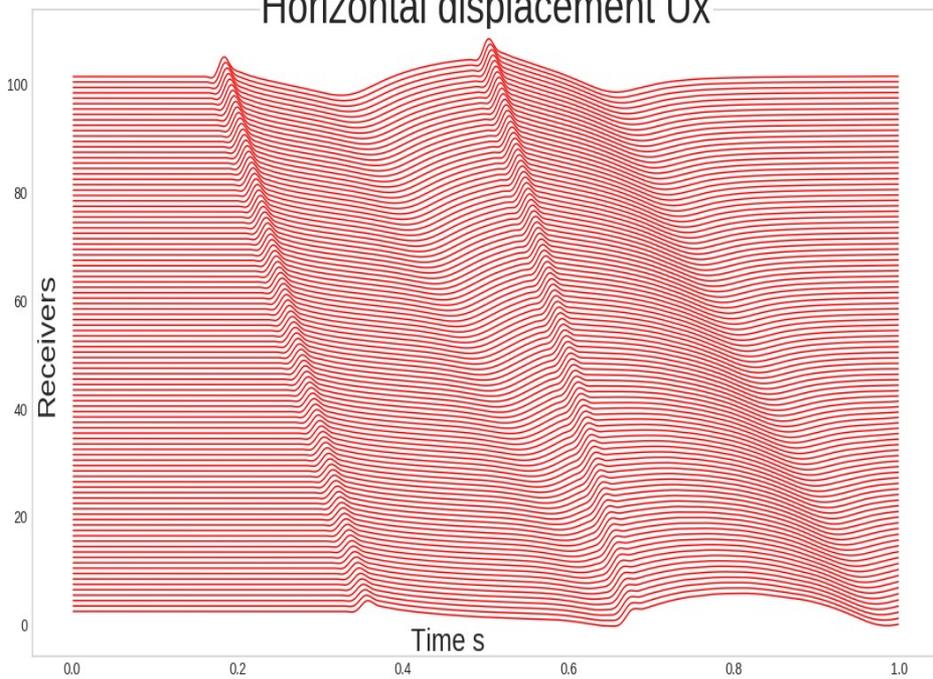
Сравнение подходов

	Трещина между узлами	Дублирование узлов	Криволинейные сетки	Неструктурные сетки	Химерные сетки
Простота алгоритма	+	+/-	+/-	+/-	+/-
Построение сеток	+	+	-	-	+
Скорость расчета	+	+	-	-	+
Дополнительная ошибка	-	+/-	+	+	+
Сложные конфигурации трещин	-	+/-	-	+	+/-

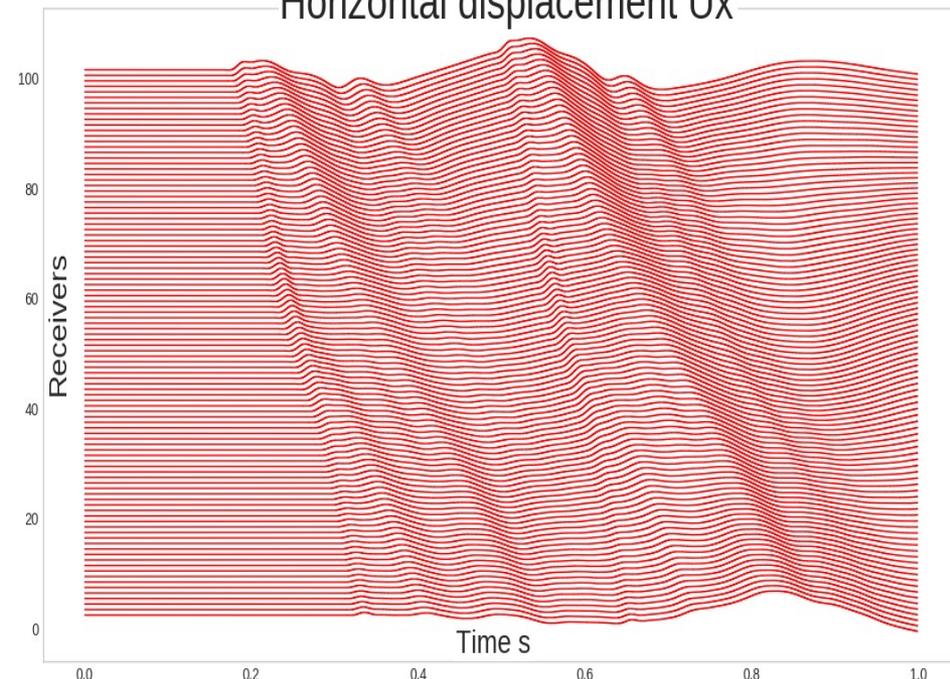
Выделение топографии поверхности



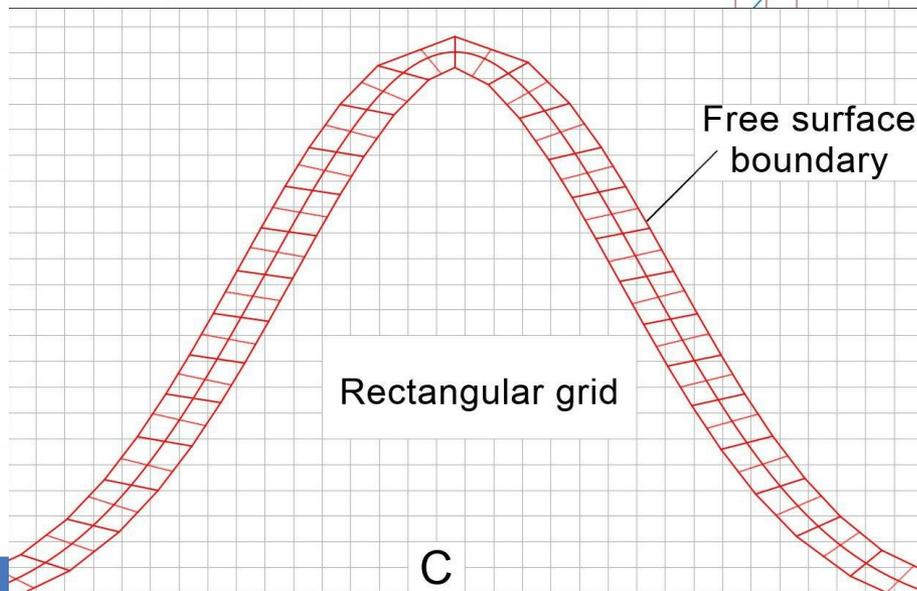
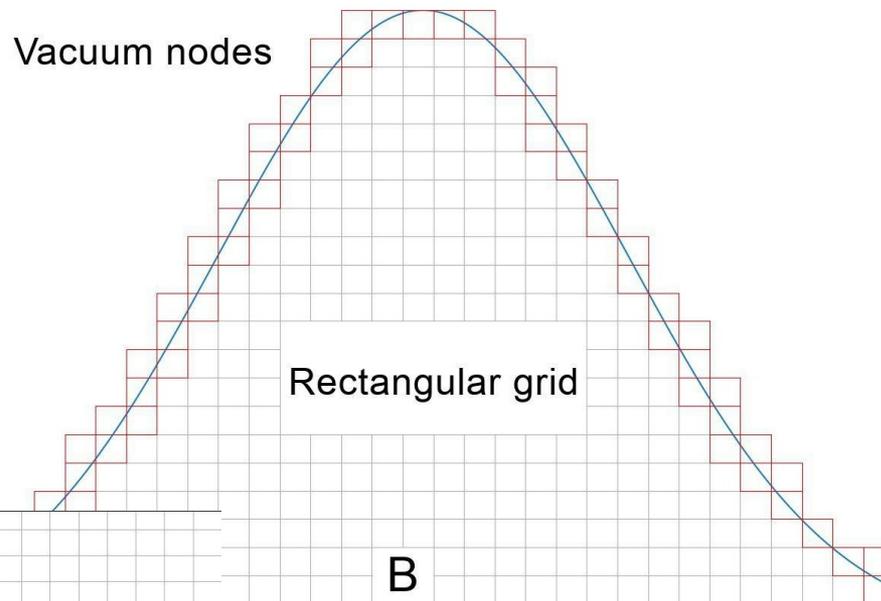
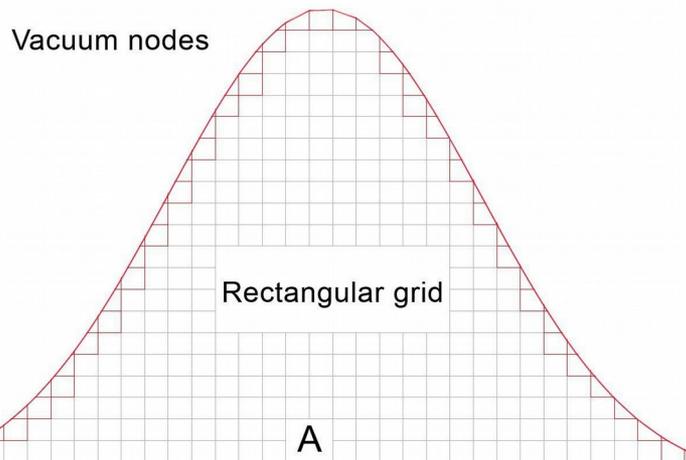
Horizontal displacement U_x



Horizontal displacement U_x

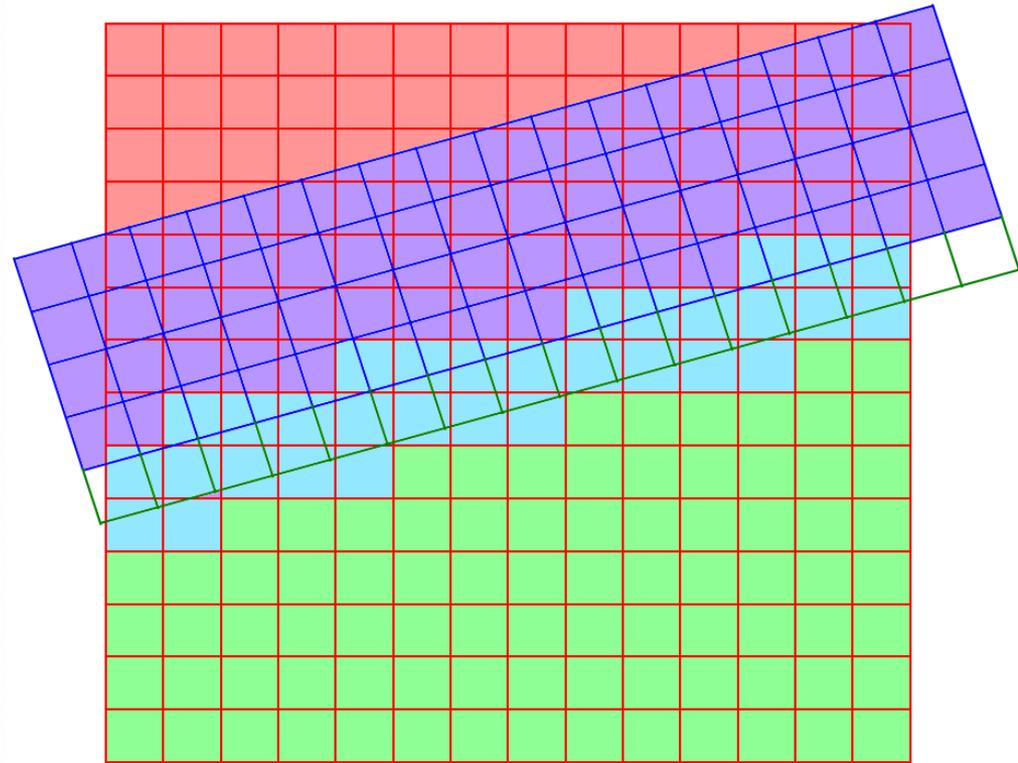


Подходы к моделированию



Наложенные сетки на границе

- Наложённая сетка: интерполяция в приграничные узлы
- Основная сетка: интерполяция из основных узлов наложенной сетки
- Игнорирование всего что выходит за границу



Верификация

Wave reflection from flat free surface.

Green square – source

Yellow square – receiver

Displacement first derivatives at receiver during simulation are compared.

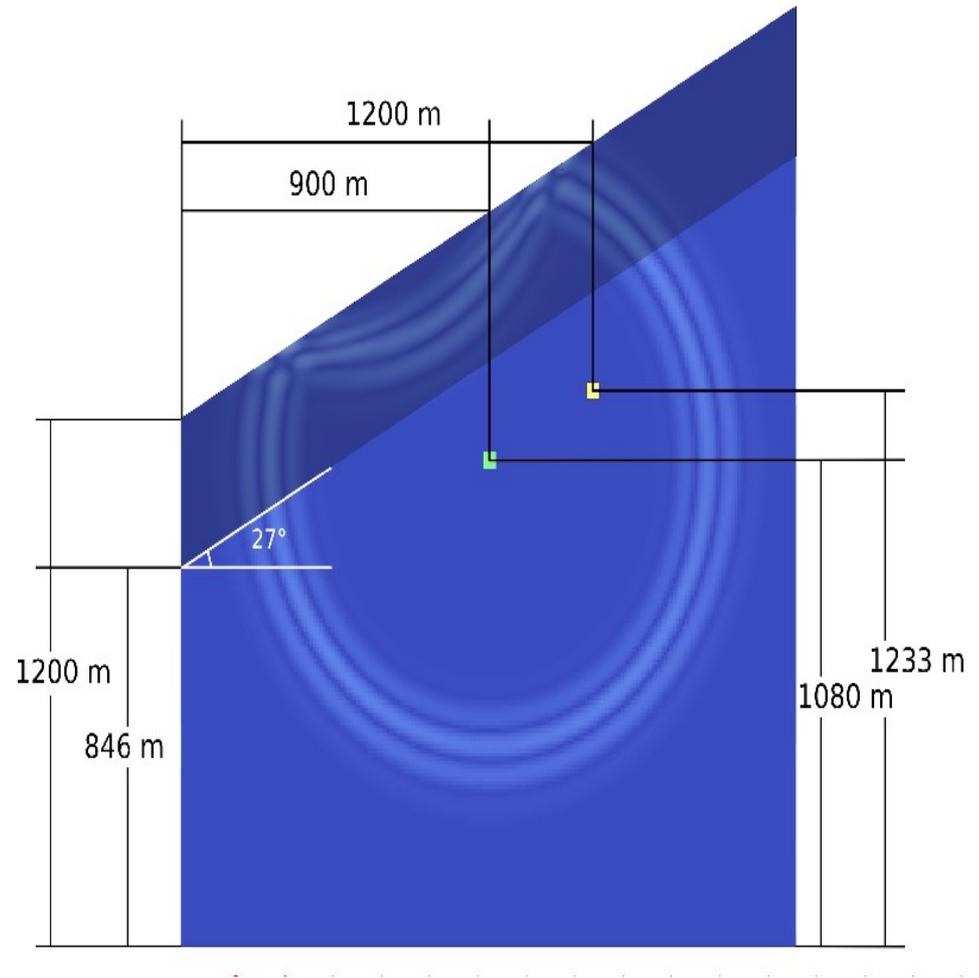
$$C_s = 2500 \text{ m/s}$$

$$C_p = 1558 \text{ m/s}$$

$$\rho = 1500 \text{ kg / m}^3$$

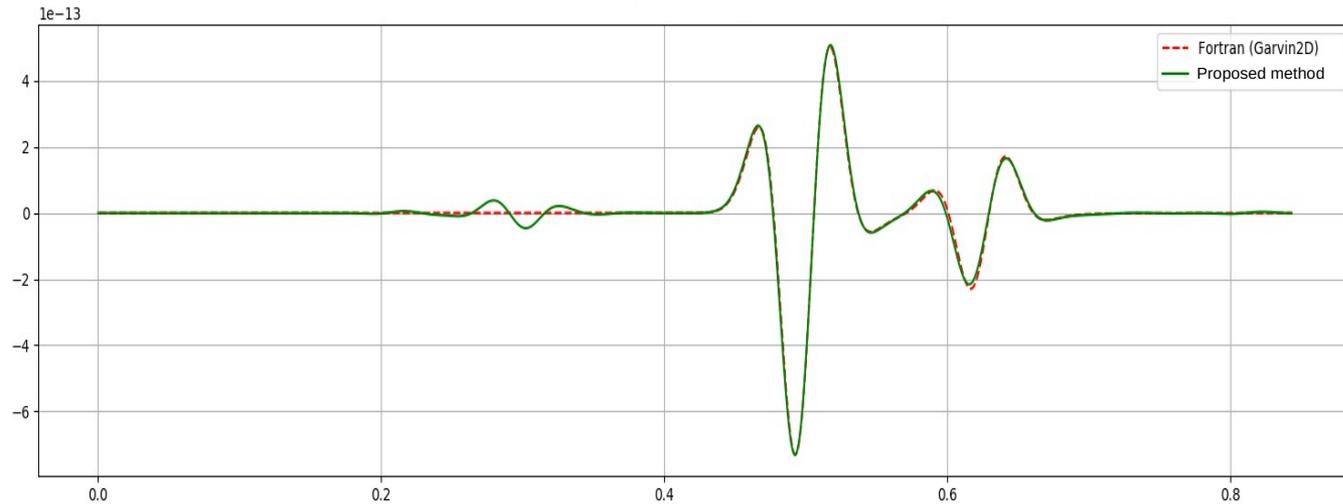
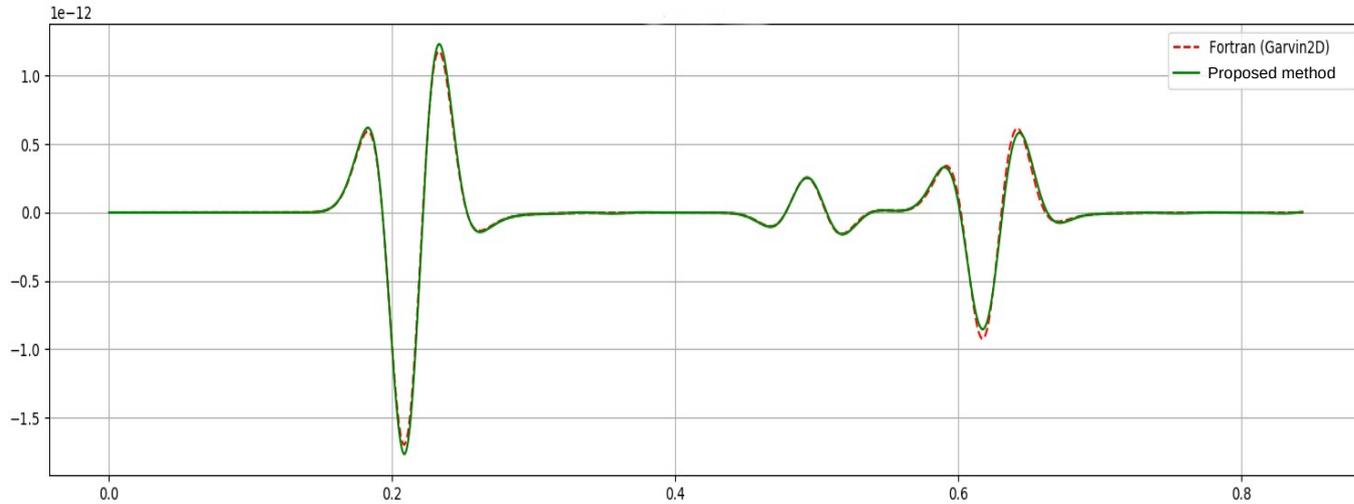
$$\Delta t = 200 \text{ ms}$$

$$\Delta x = 3 \text{ m}$$



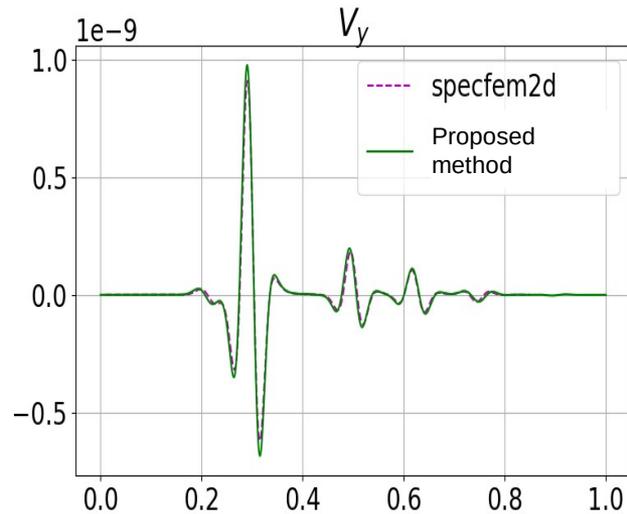
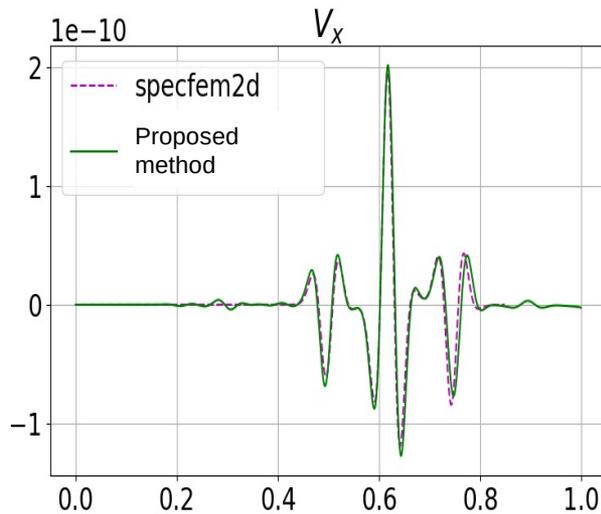
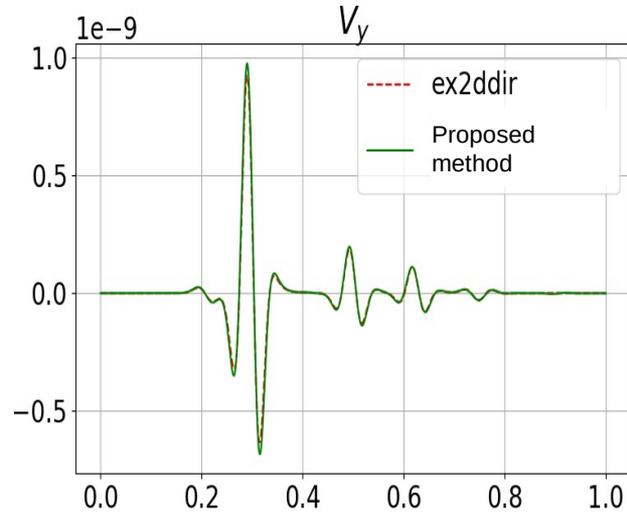
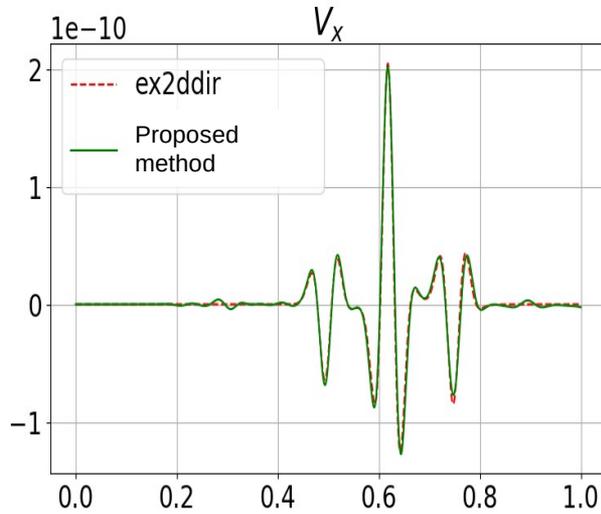
Верификация: Garvin problem

Receiver value comparison



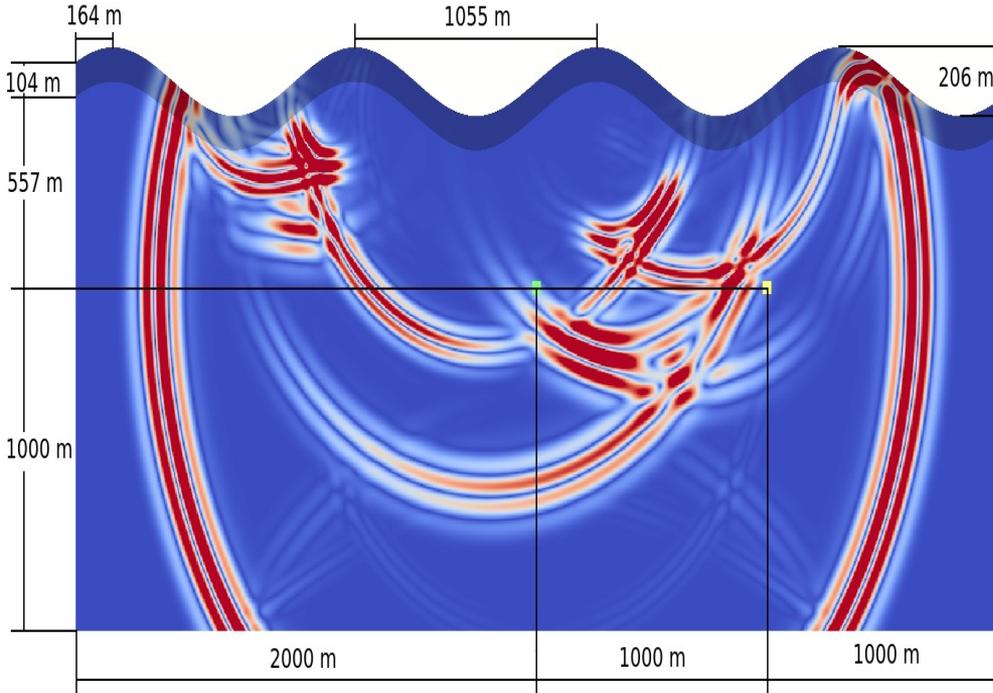
Верификация: Lamb problem

Receiver value comparison



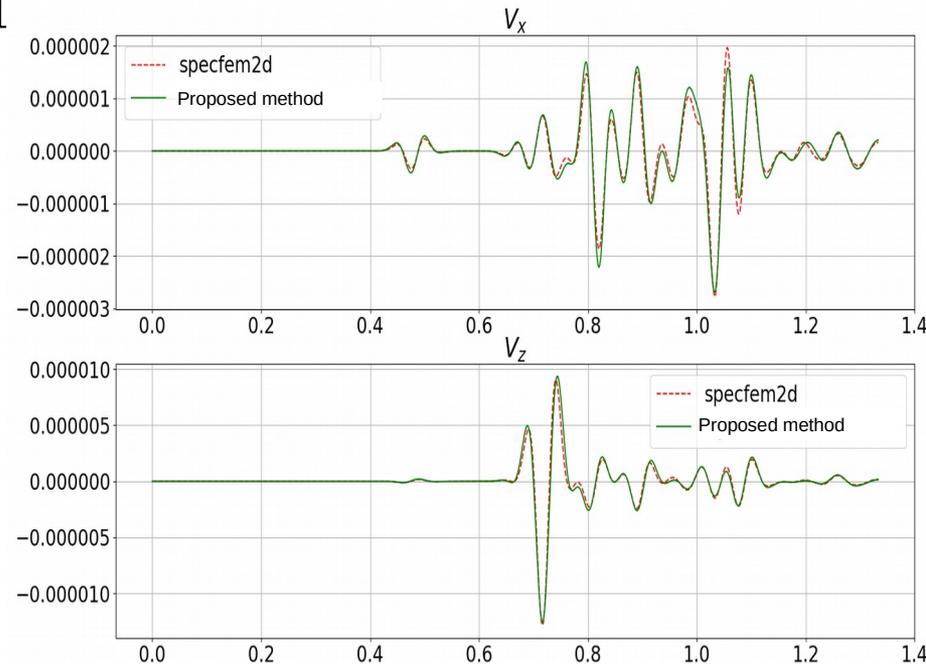
Верификация: curved surface

- Illustration of the "wavy surface" problem statement and wave field
- Green square – source
- Yellow square – receiver.



Comparison of the horizontal and vertical displacement derivatives (as in problems before)

Receiver value comparison



Распареллеливание

- CPU, низкоуровневая оптимизация
- GPU
- OpenMP
- MPI

GPU parallelization

- CPU
 - Compilers: icc
 - Compiler Options :
 - -mavx
 - -fopenmp (auto vectorization)
 - -O2
- GPU
 - Compilers: nvcc, gcc
 - Compiler Options:
 - -O2
 - -use_fast_math

CPU properties: Intel Xeon E5-2697 2.7 GHz

GPU properties:

GPU	CUDA cores (streaming processors)	Clock rate, MHz	GFLOPS - single precision	SP:DP	GFLOPS - double precision
GeForce GT 640	384	900	691	24	29
GeForce GTX 480	480	1401	1345	8	168
GeForce GTX 680	1536	1006	3090	24	129
GeForce GTX 760	1152	980	2258	24	94
GeForce GTX 780	2304	863	3977	24	166
GeForce GTX 780 Ti	2880	876	5046	24	210
GeForce GTX 980	2048	1126	4612	32	144
Tesla M2070	448	1150	1030	2	515
Tesla K40m	2880	745	4291	3	1430
Tesla K80	2496	562	2806	1.5	1870
Radeon HD 7950	1792	800	2867	4	717
Radeon R9 290	2560	947	4849	8	606

Test program

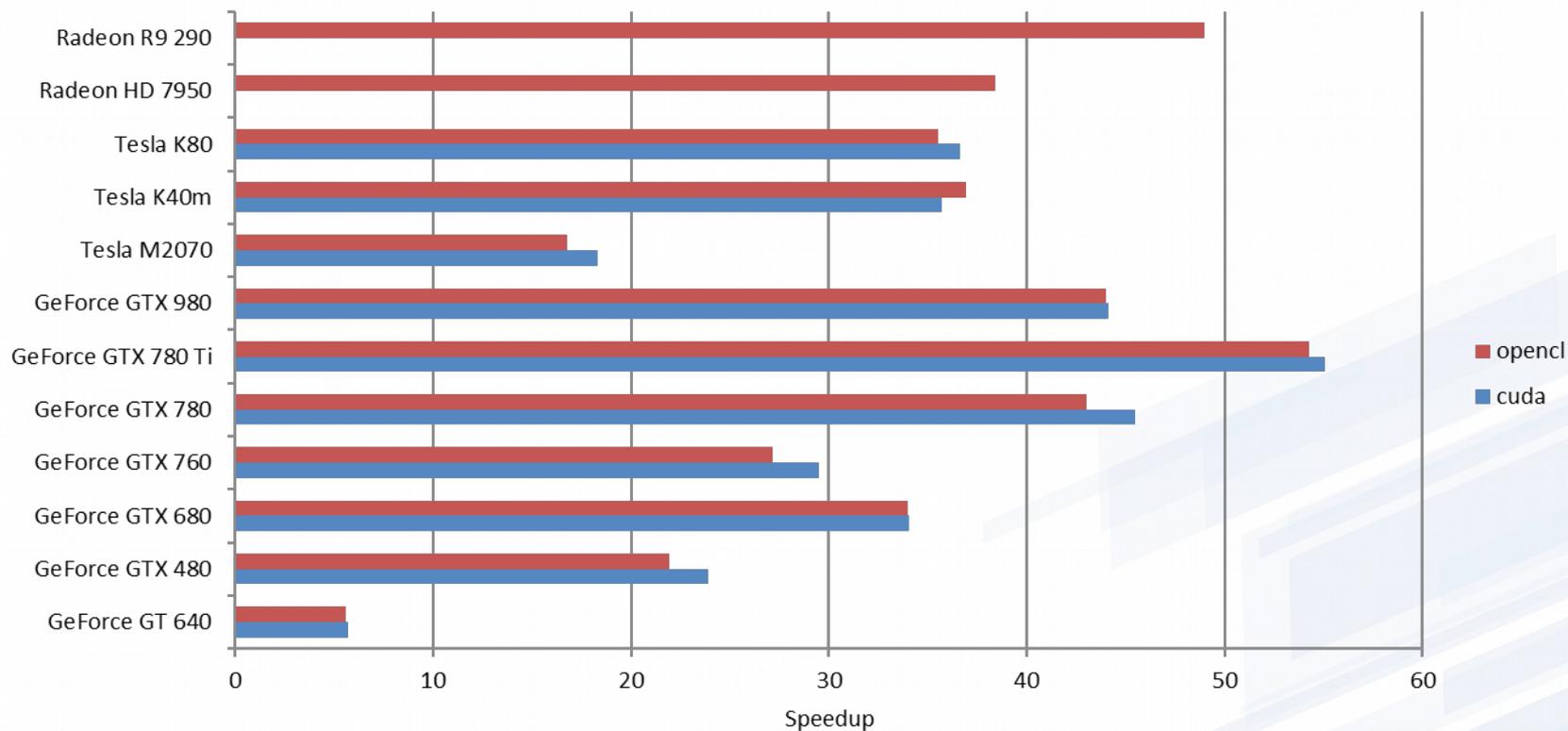
- Grid size: 4096x4096
- Time steps: 6500
- Data type: float, double
- Grid node: 5 float (double)
- Occupied memory:
 - 320 MB (float)
 - 640 MB (double)

CPU version

- Single-precision and double-precision
- 190 FLOPS to recalculate one node in grid
- Program consumes 18.8 TFLOPS
- Single-thread, single CPU core
- AVX instructions – vectorization

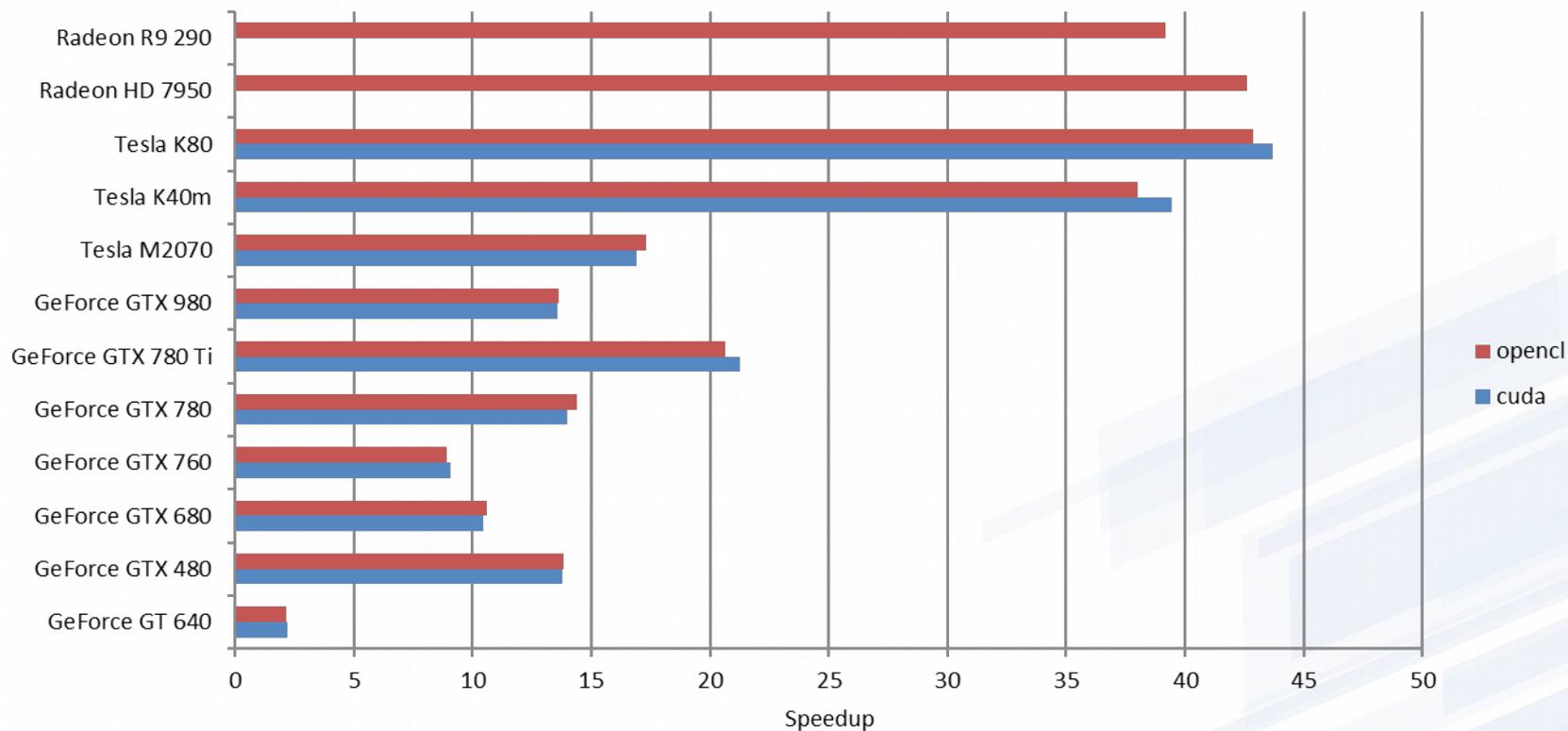
Speedup of GPU implementation compared to CPU

compare with cpu Intel Xeon E5-2697 - float + fast math



Speedup of GPU implementation compared to CPU

compare with cpu Intel Xeon E5-2697 - double

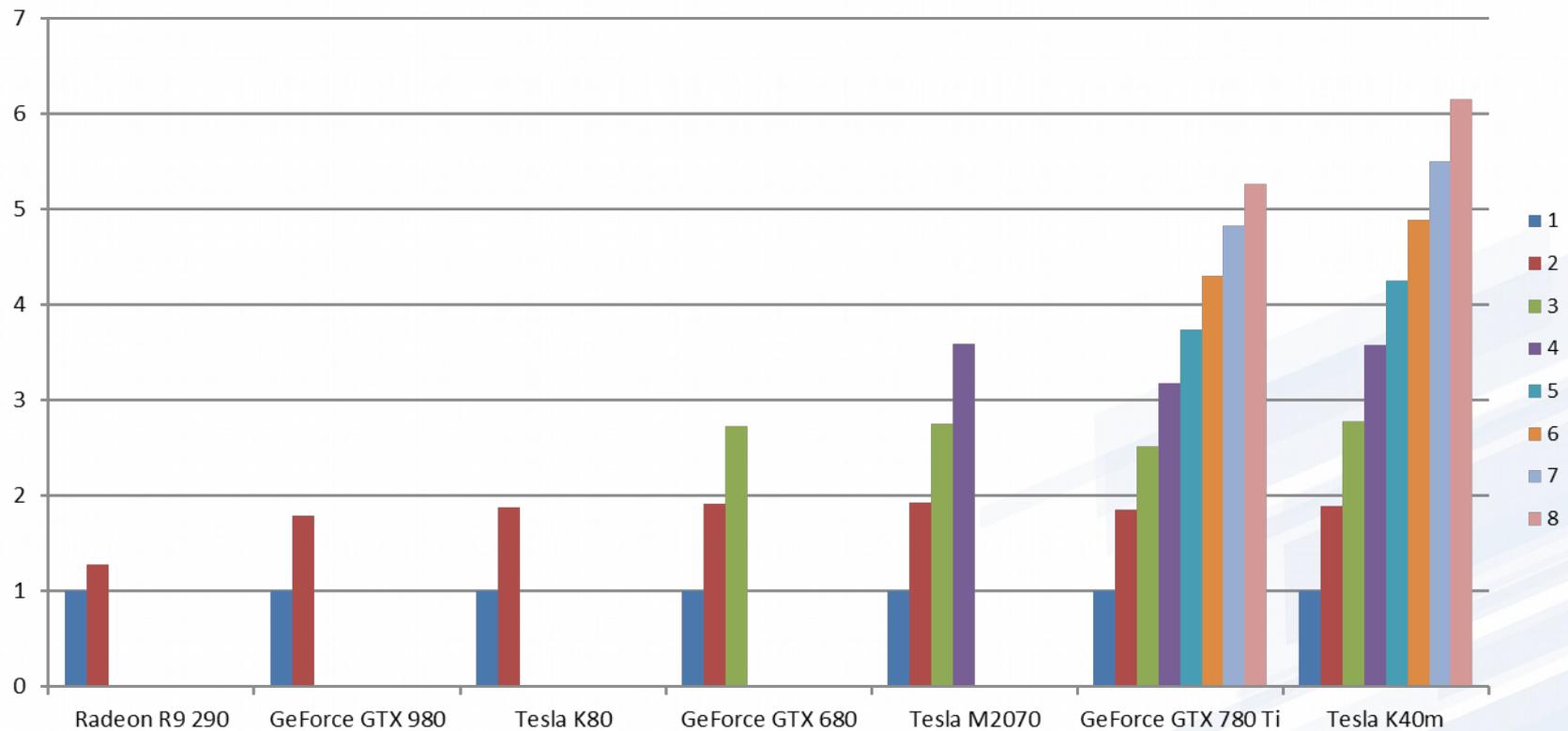


GPU parallelization

- Multiple GPUs
- Divide grid along axis Y
- Data exchanges between GPUs by adjacent grid nodes
- GPUDirect (only in CUDA) – exchange data by PCI Express bypassing CPU

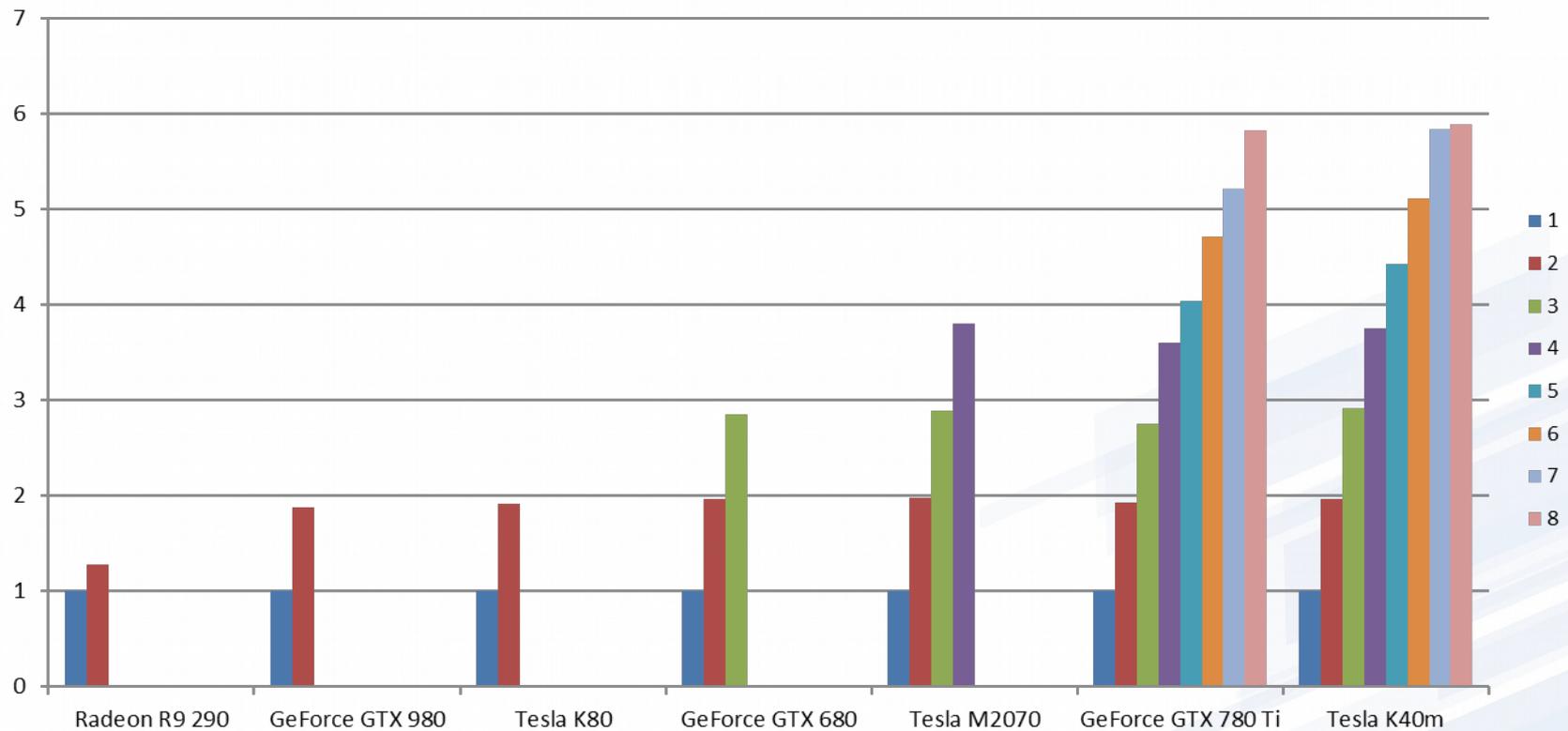
Speedup (number of GPUs)

Speedup, float

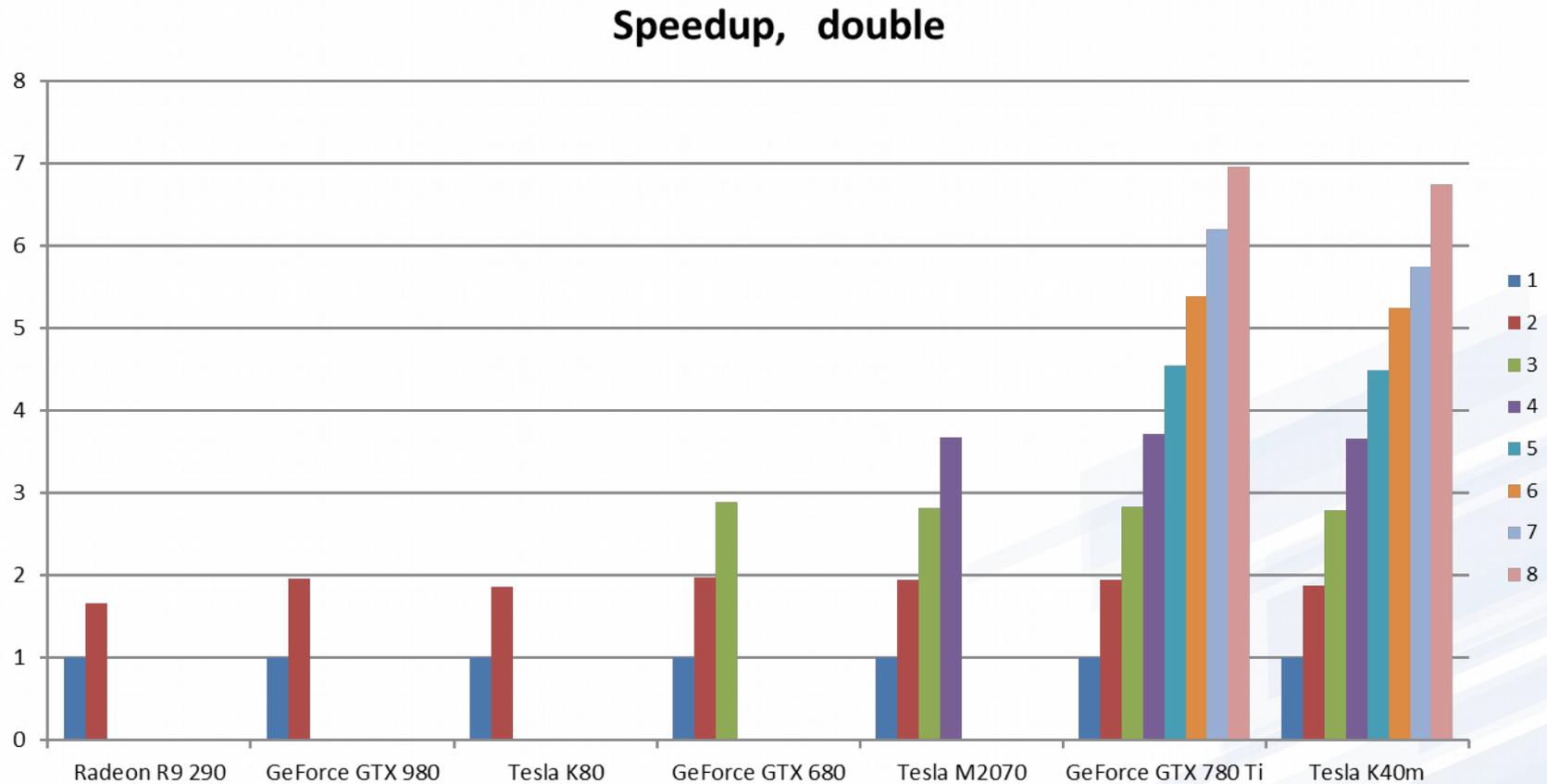


GPUDirect (except Radeon R9 290)

GPUDirect, float

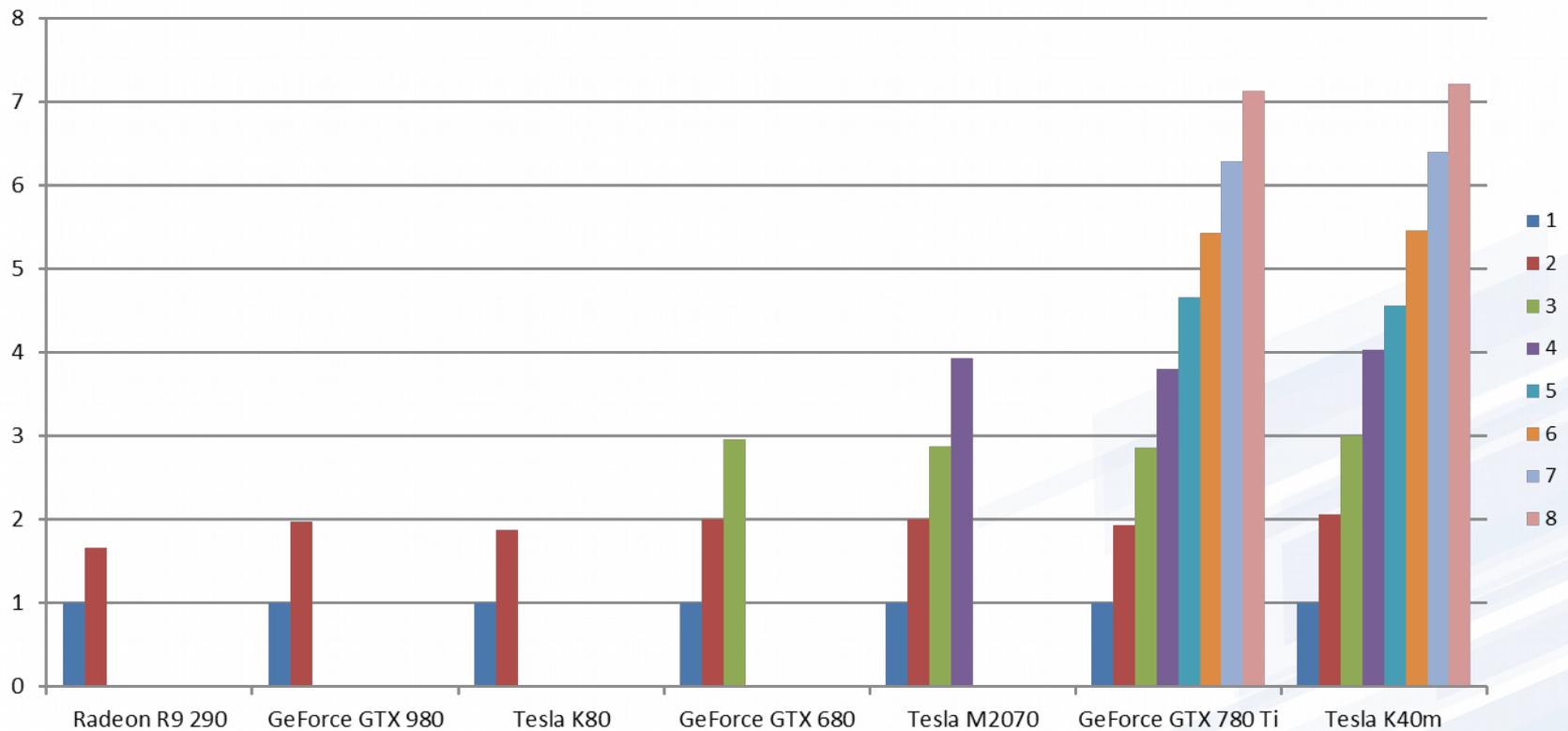


Speedup (number of GPUs)



GPUDirect (except Radeon R9 290)

GPUDirect, double



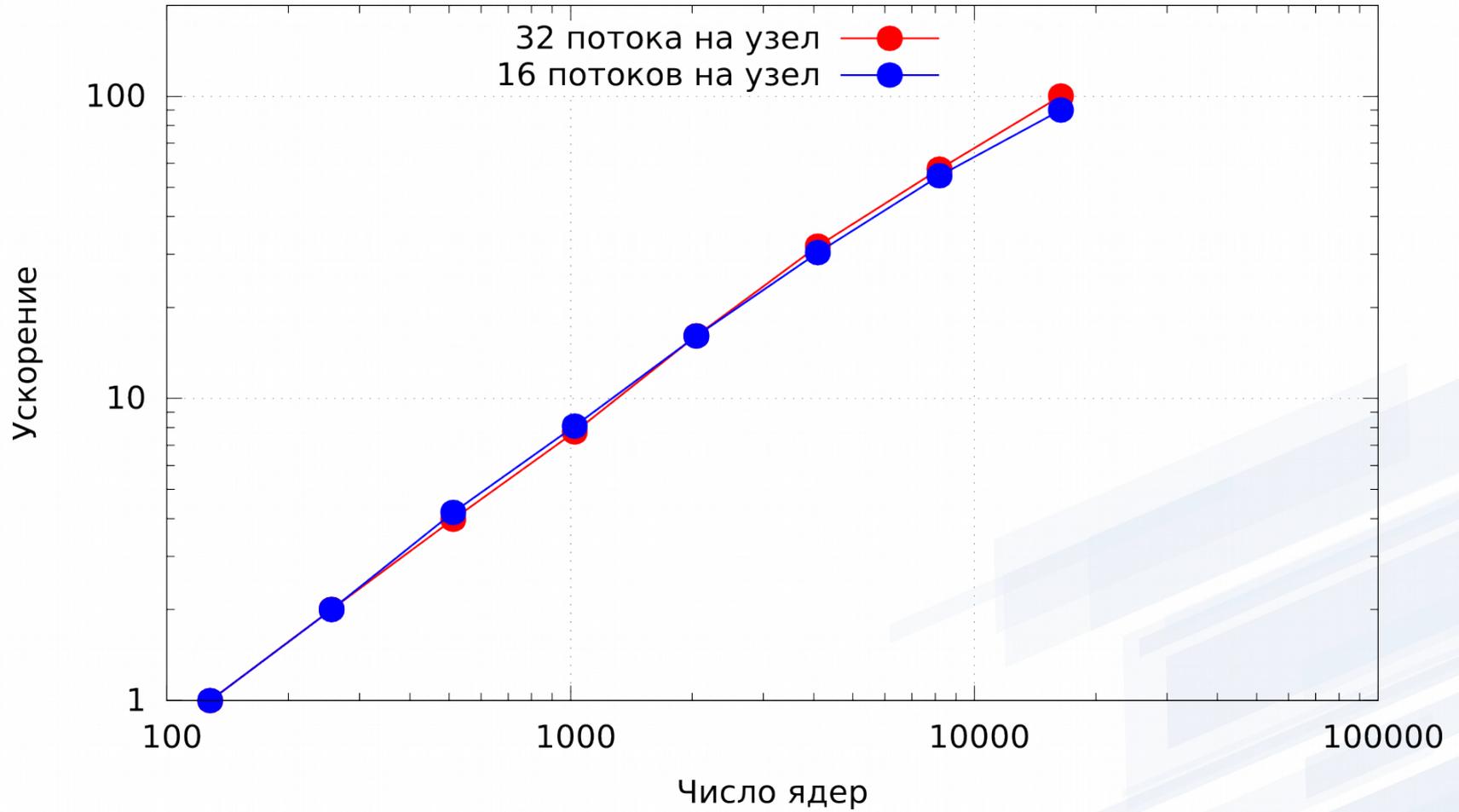
Conclusion

- Speedup (single GPU compared with CPU):
 - Single-precision - up to **55** times (**GeForce GTX 780 Ti**)
 - Double-precision - up to **44** times (**Tesla K80**)
- Performance (single GPU):
 - Single-precision - up to **460** GFLOPS (**GeForce GTX 780 Ti**)
 - Double-precision - up to **138** GFLOPS (**Tesla K80**)
- Speedup (multiple GPU compared with single GPU):
 - Single-precision - up to **6.1** times (**Tesla K40m**)
 - Double-precision - up to **7.1** times (**GeForce GTX 780 Ti**)
- Increase in speedup with GPUDirect
 - Single-precision - **10%** on 8 **GeForce GTX 780 Ti**
 - Double-precision - **2.4%** on 8 **GeForce GTX 780 Ti**

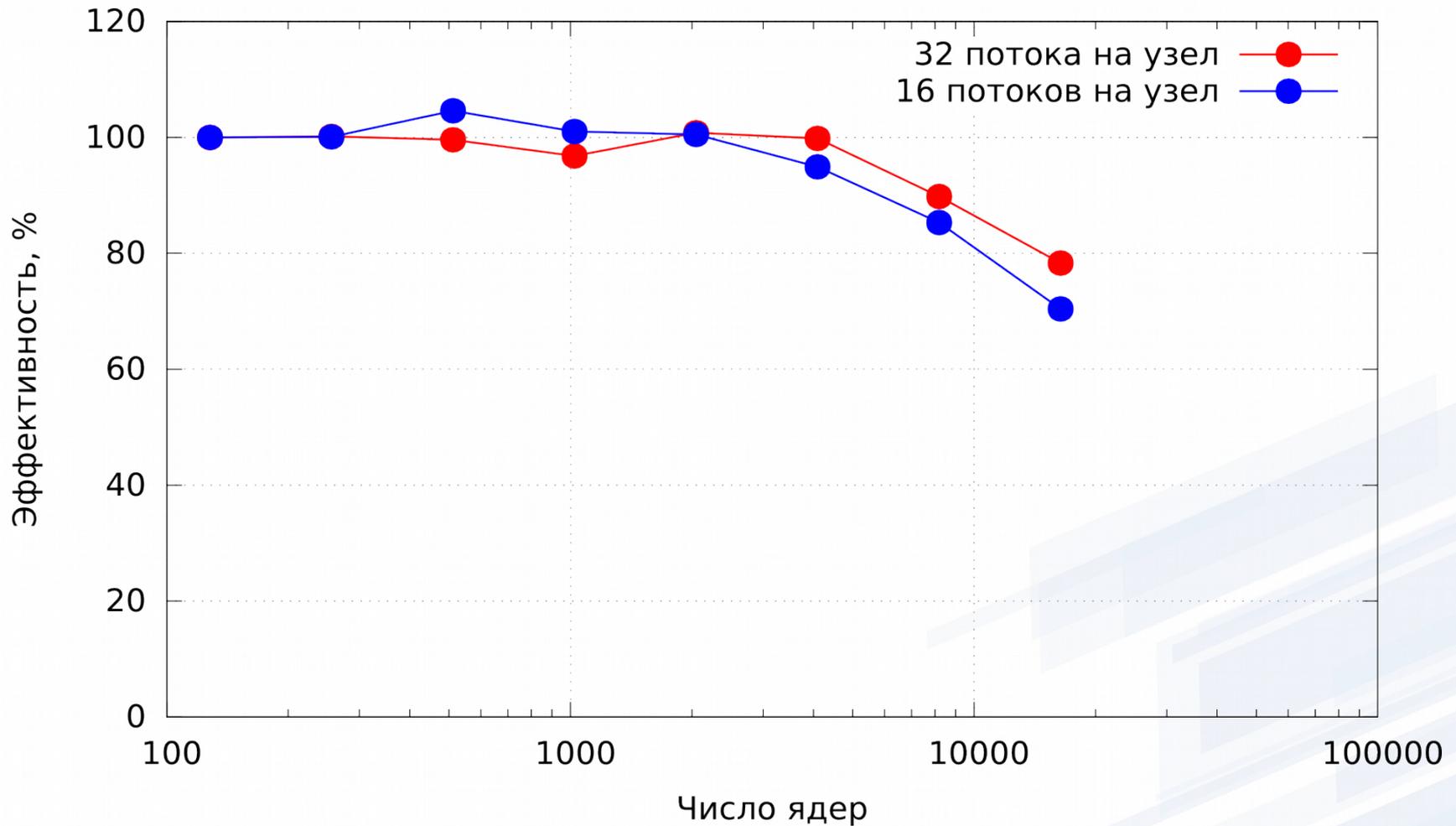
MPI: cluster HECToR

- ~90 000 cores
 - 1 GB memory per core
 - 32 cores per node
-
- Test on a grid 1000x1000x1000 - 1 billion nodes
 - The number of cores from 128 to 16 thousand
 - The number of threads per node - 16 and 32
 - Measurement only of the general operating time of the program
 - Acceleration - 100 and 90 times
 - Efficiency - 78 and 70%

MPI: strong scalability



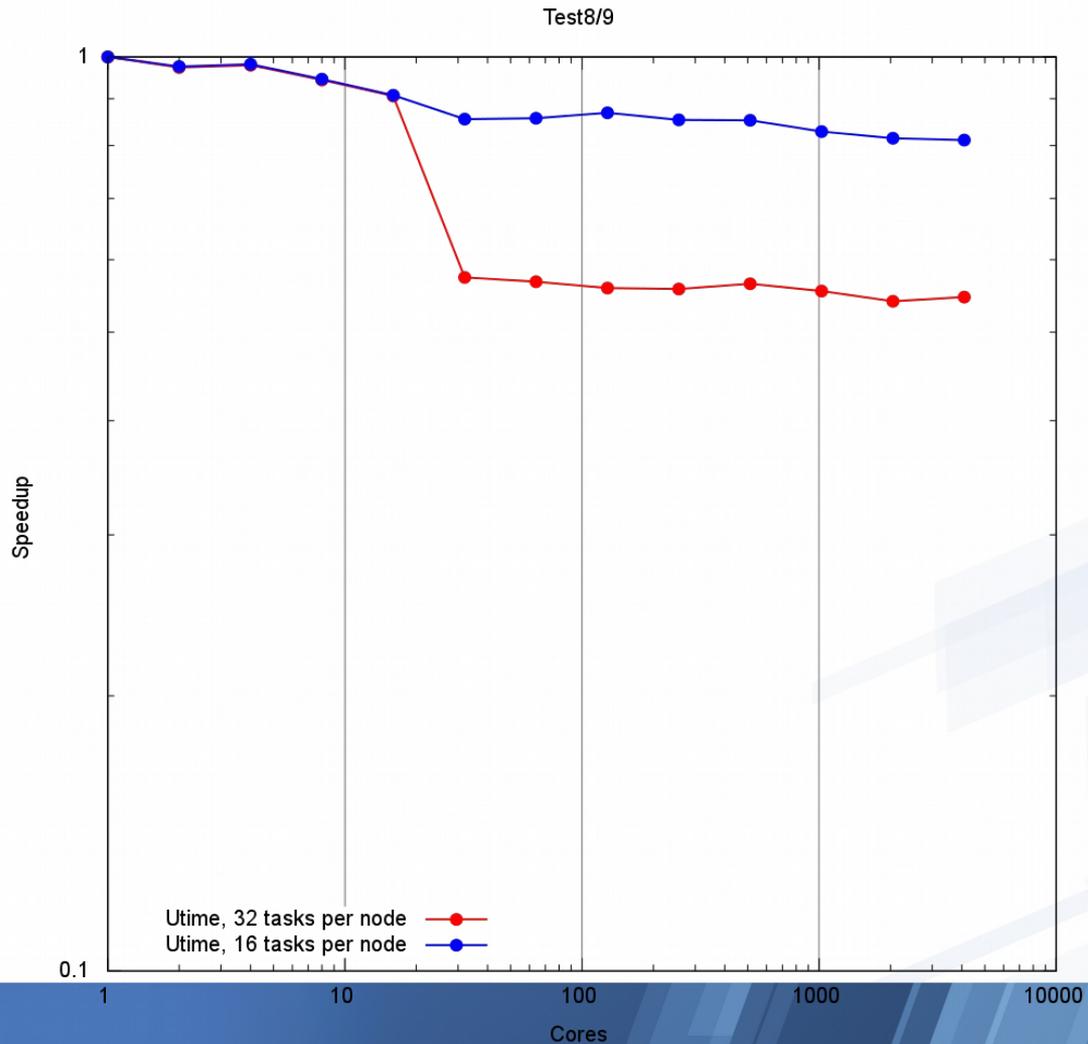
MPI: efficiency



Weak scalability

- The number of grid nodes per core - 16 million
- Maximum grid size - 62 billion nodes
- Good performance
- Difference in calculations for 16 and 32 threads per node
- Acceleration - 0.8 and 0.55 respectively

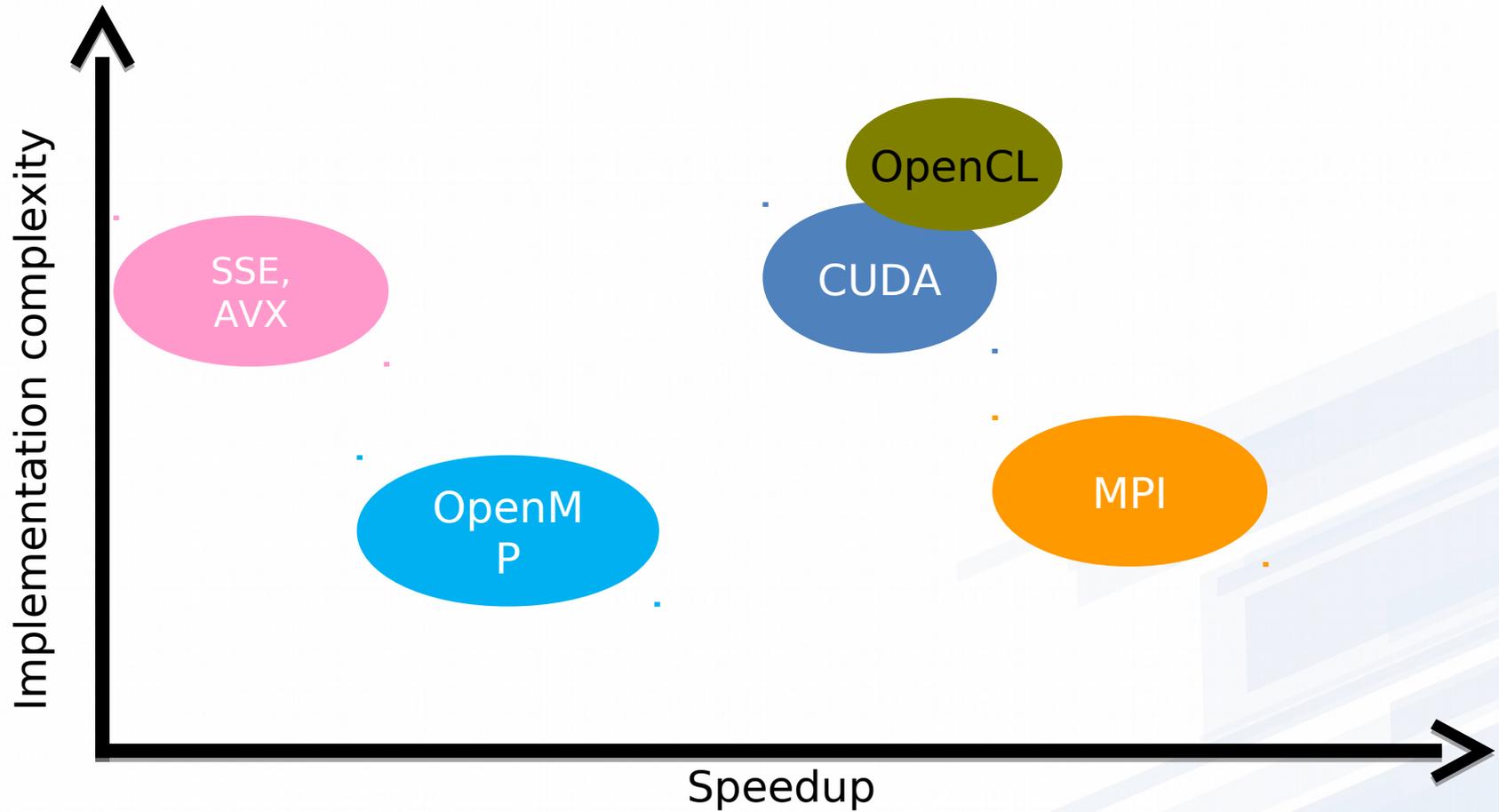
Weak scalability



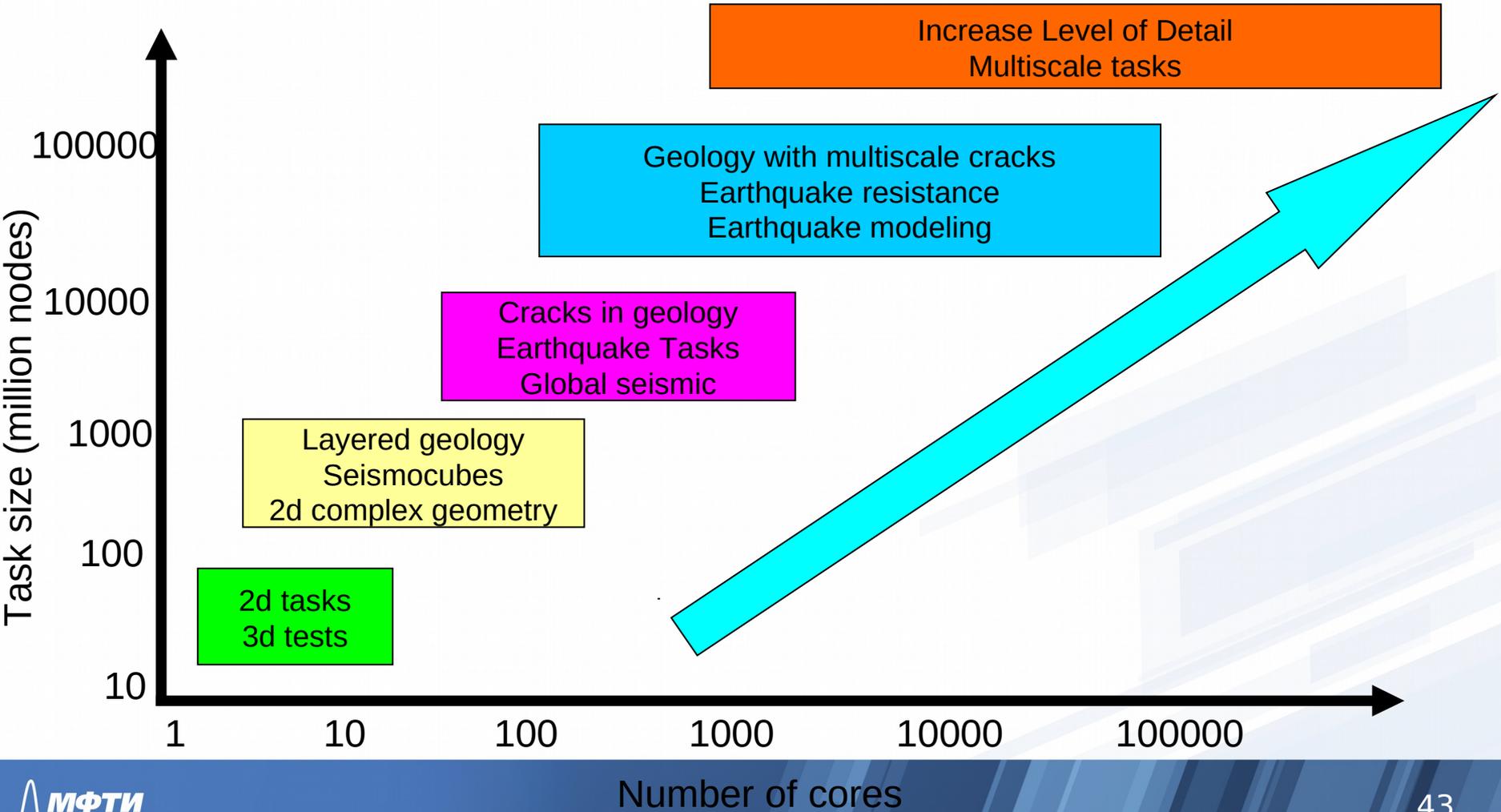
OpenMP parallelization

- The highest performance of the serial version is 22% of the peak for float and 17% for double with optimization and using avx instructions
- Acceleration on AMD Opteron 6272 - 37 times on 64 cores
- Acceleration on AMD Opteron 8431 - 25 times on 48 cores
- Acceleration on Intel Xeon E5-2697 - 17 times on 24 cores

Implementation complexity



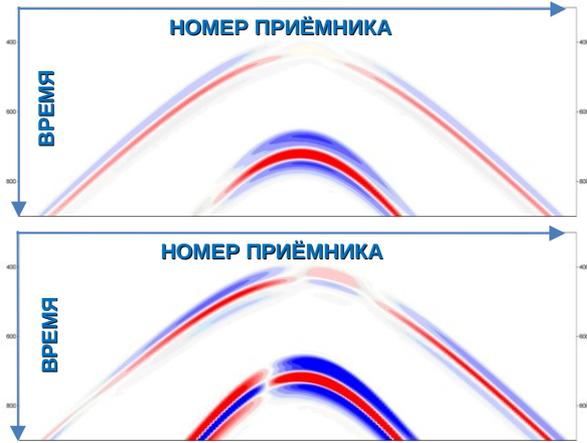
Task size



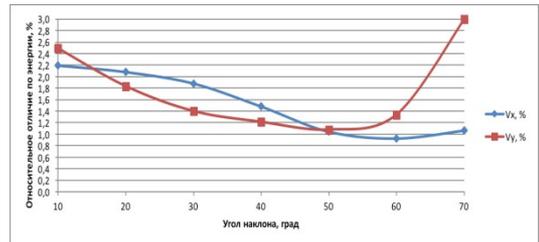
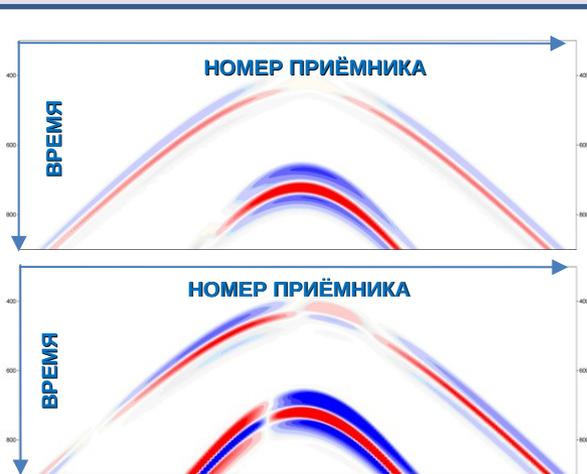
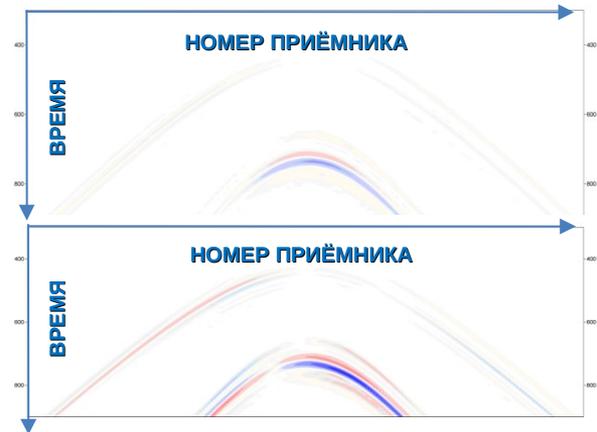
Seismic modeling

Fracture model

РАСКРЫТИЕ 1:1000



РАЗНИЦА СЕЙСМОГРАММ

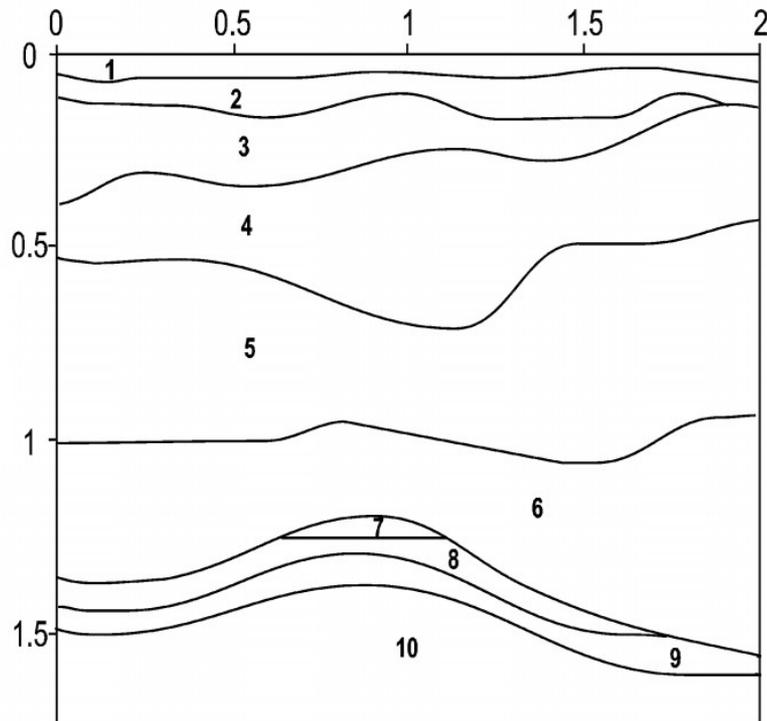


АНАЛИЗ, РАЗНИЦА <3%

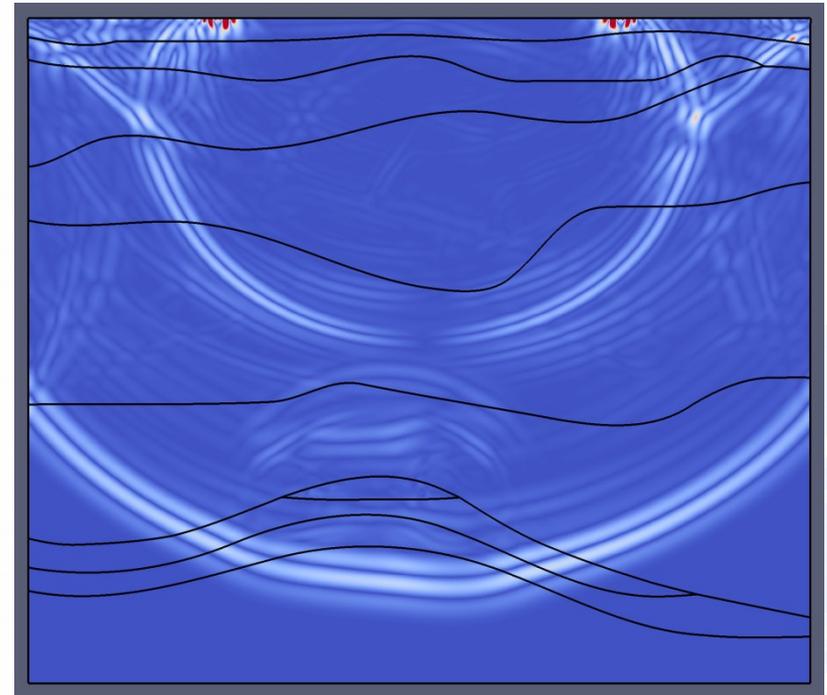
МОДЕЛЬ ТРЕЩИН БТТ

**МОЖНО ИСПОЛЬЗОВАТЬ
МОДЕЛЬ БТТ**

Example problem



Geological model of anticlinal trap

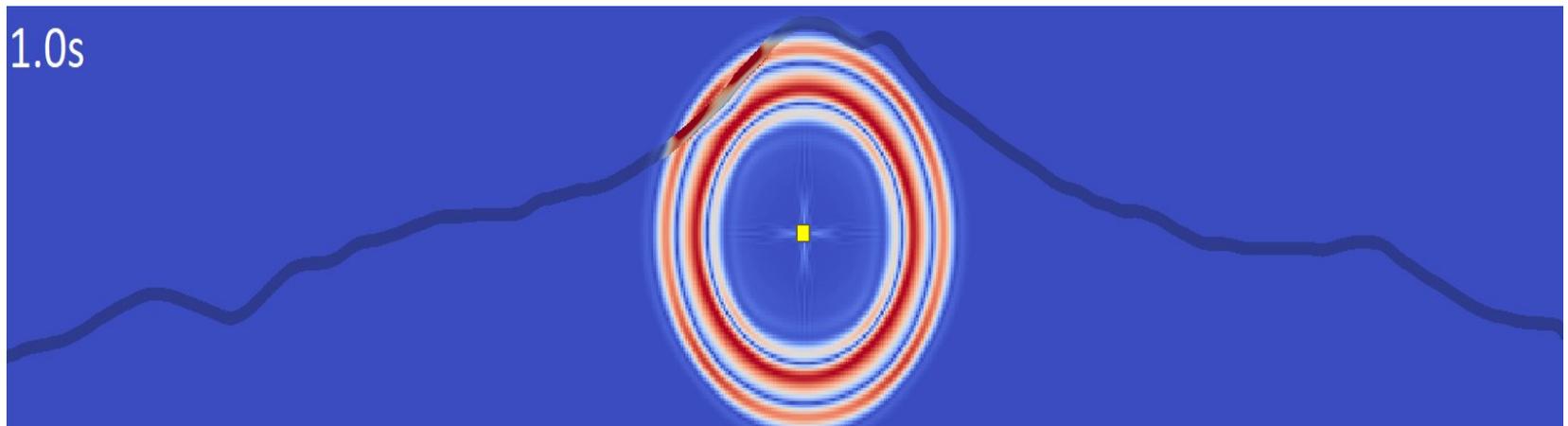


The calculation result is the wave field at time moment $t = 0.38$ s

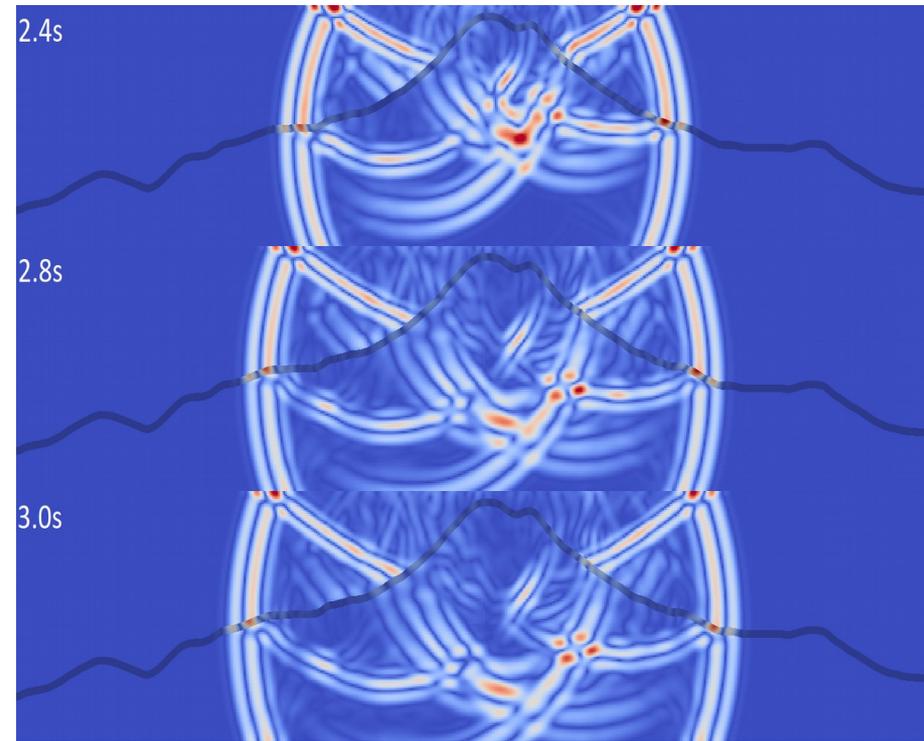
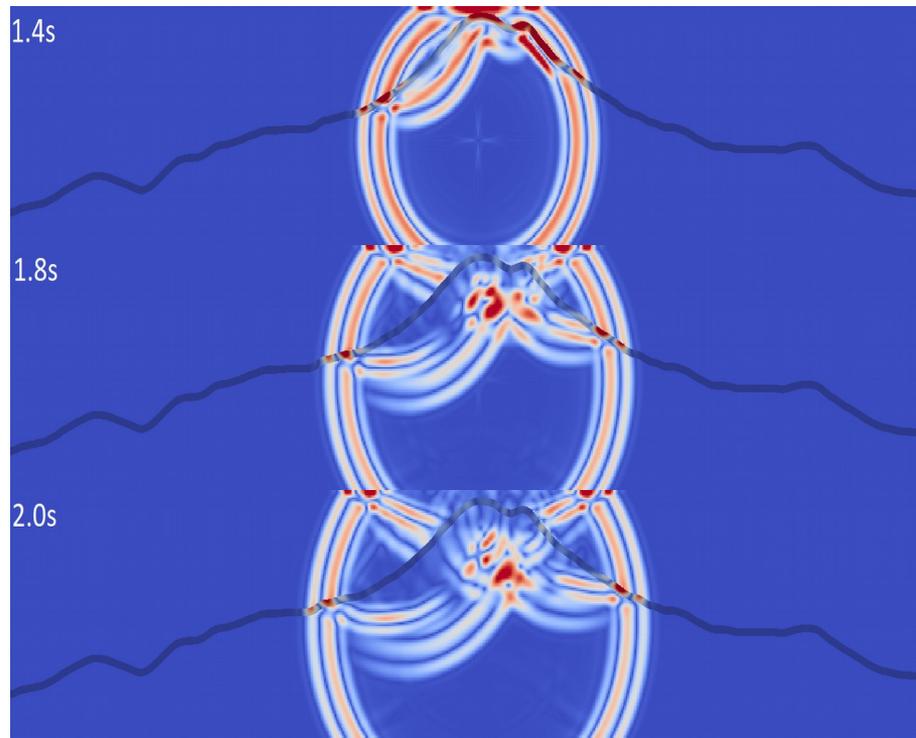
Вулкан

Two dimensional model of Ricker explosion reflection from hillsides free surfaces

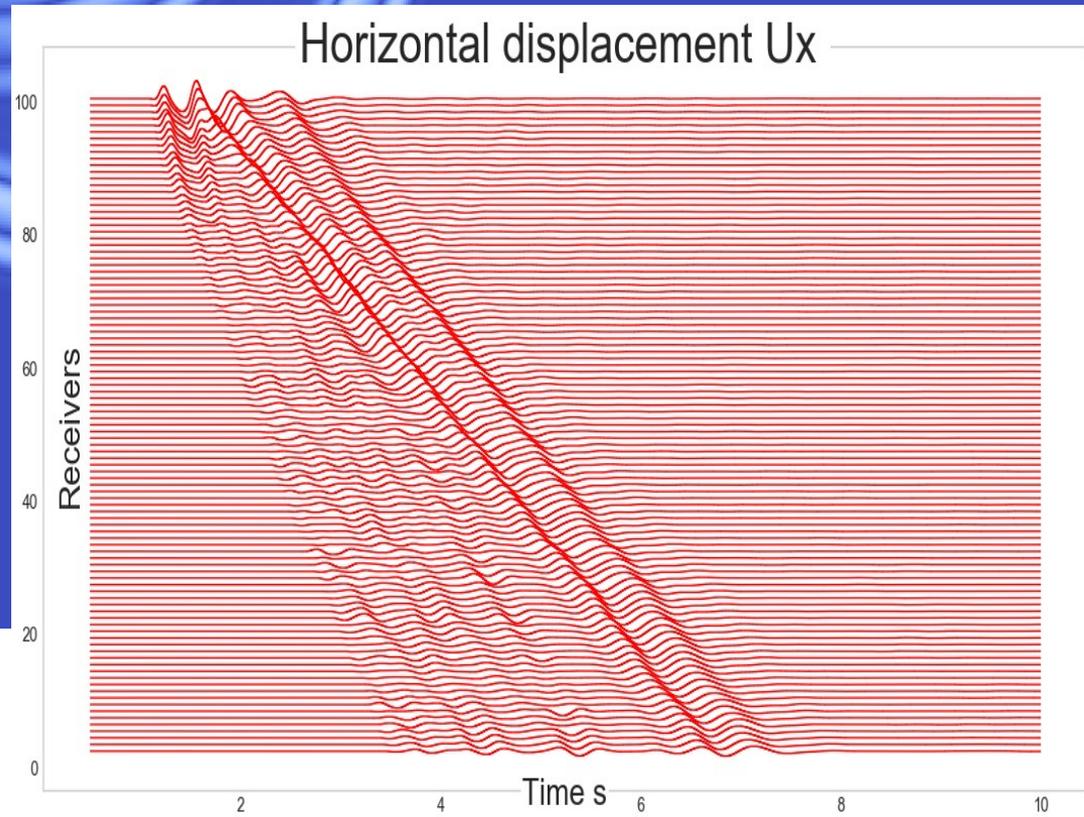
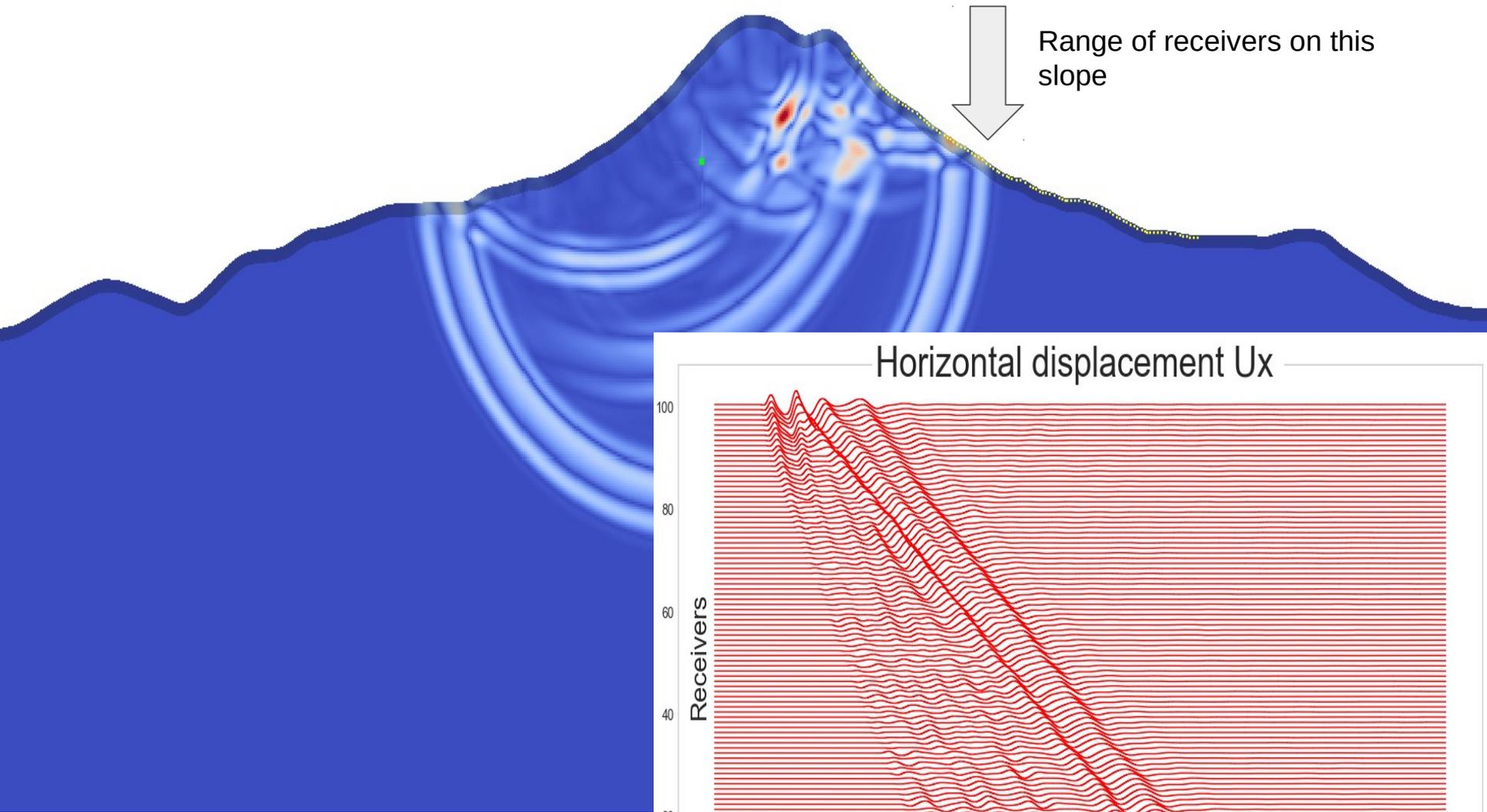
- $C_s = 2850 \text{ m / s}$
- $C_p = 1650 \text{ m / s}$
- $\rho = 2500 \text{ kg / m}^3$
- Region 6 x 36 km
- $\Delta t = 0.02 \text{ second}$
- Main grid – 680 x 120 nodes, 50 x 50 m
- Curved grid – 873 x 5 nodes, typical cell size 50 m



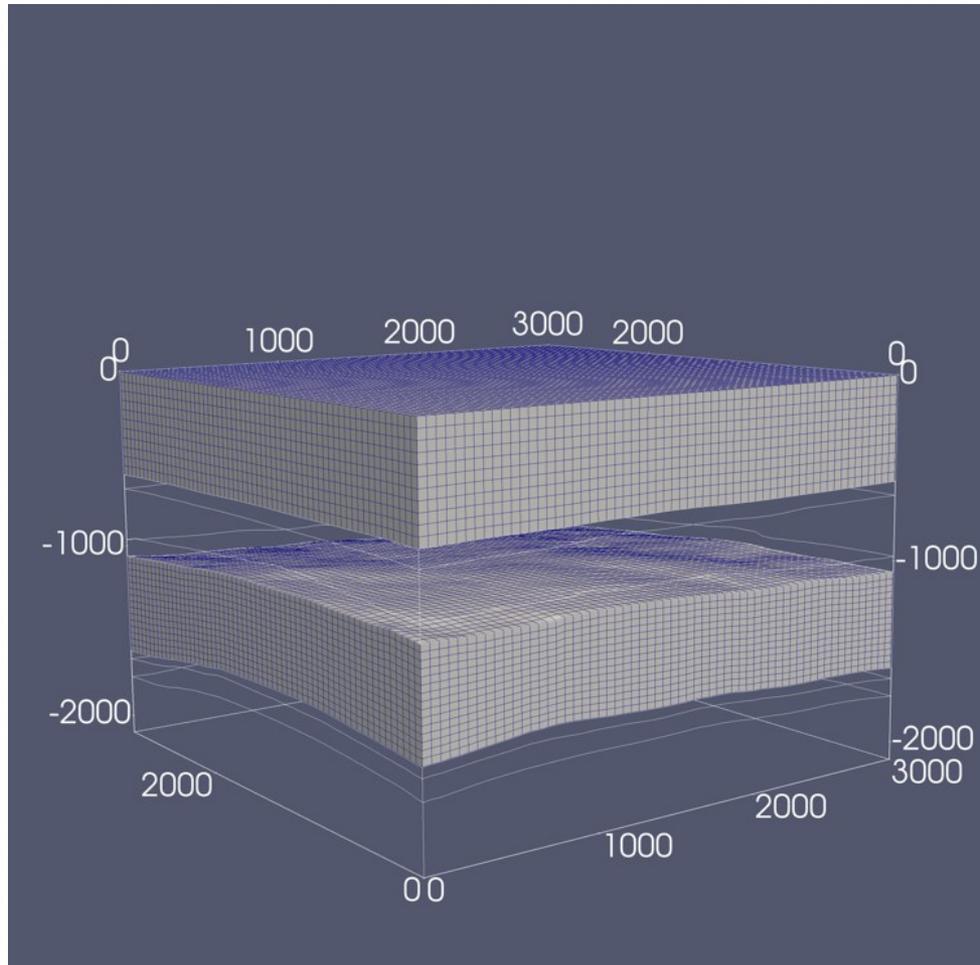
Вулкан



Вулкан

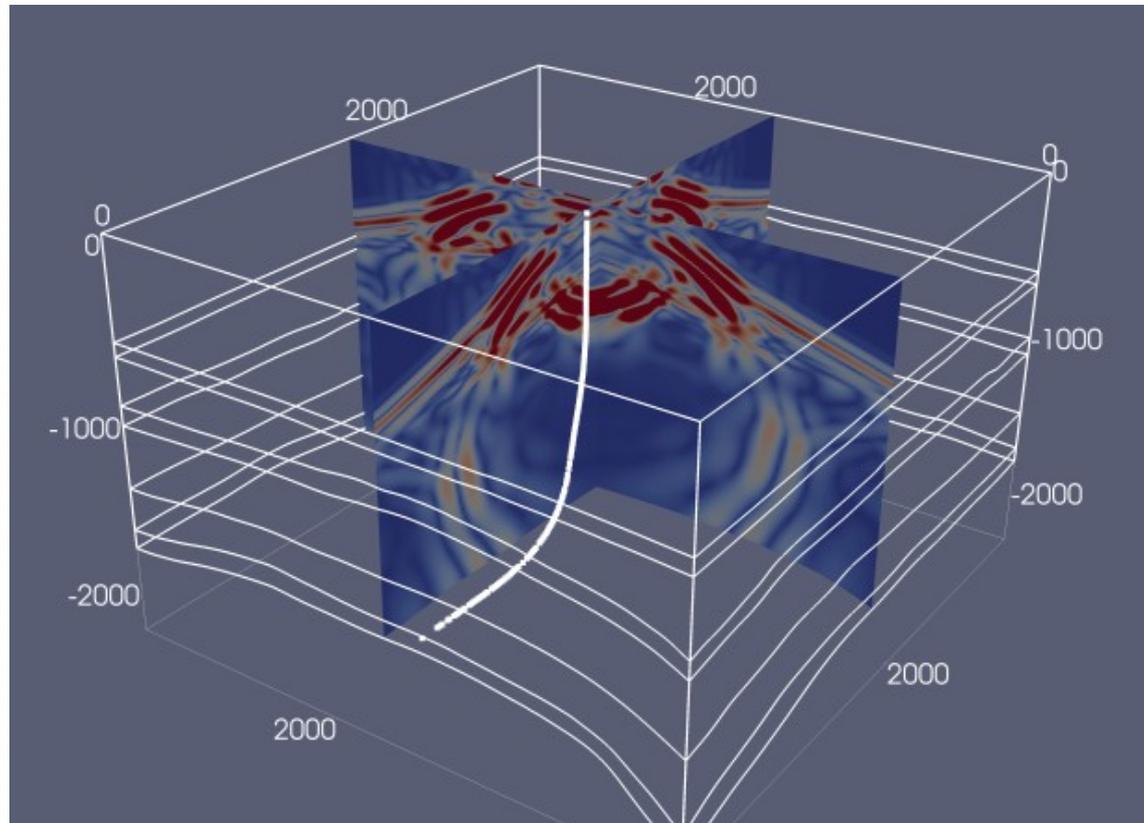


Explicit Curvilinear Borders Benefits



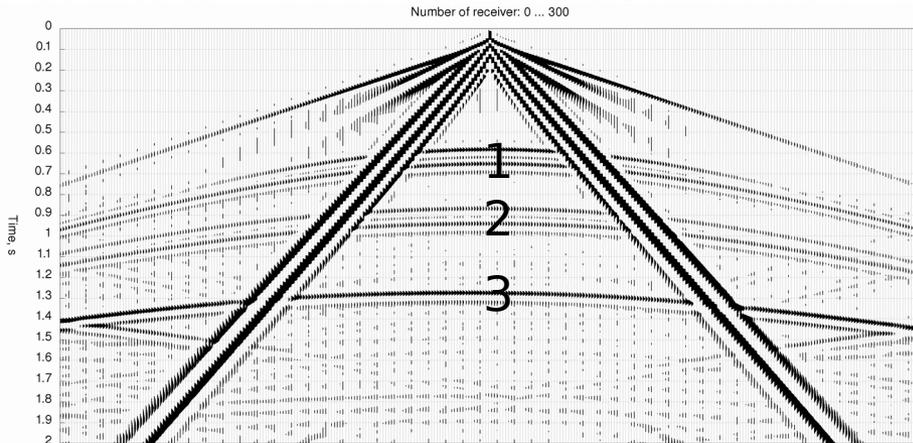
Based on the real data

3D Wave Field

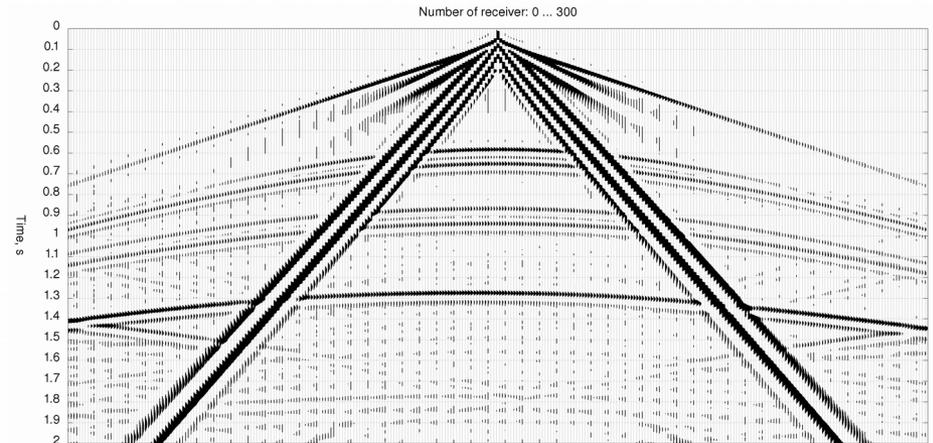


Seismograms

Explicit Borders Setting



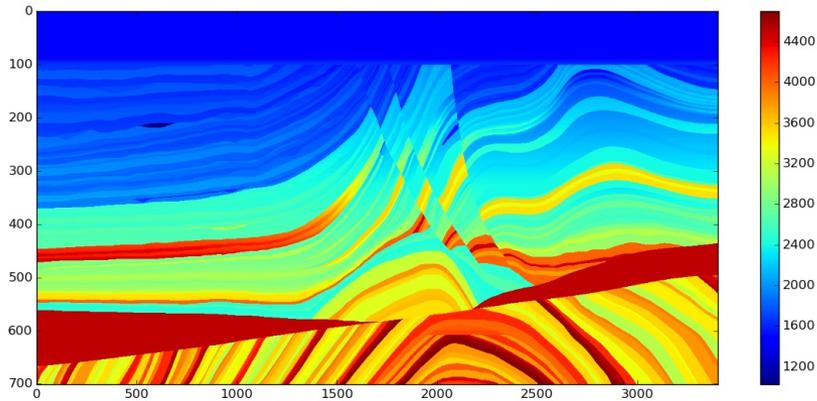
Implicit Borders Setting



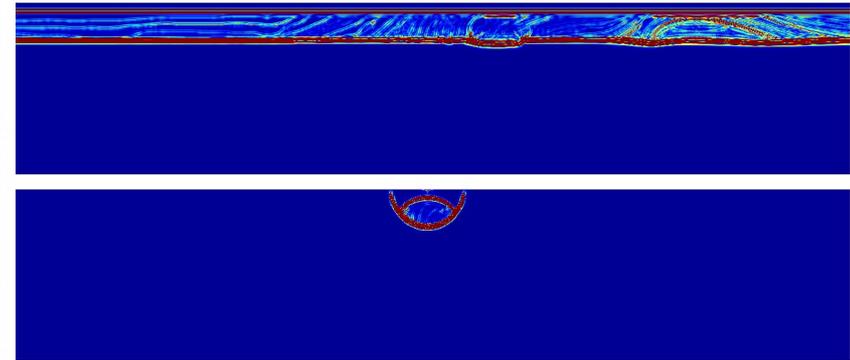
	Implicit	Explicit
Time (2 000 cores), s	815	7415
RAM, Gb	21,7	47,5
Amplitude 1		22 %
Amplitude 2		26 %
Amplitude 3		30 %

Difference up to 30 %!

Geological model «Marmousi2»

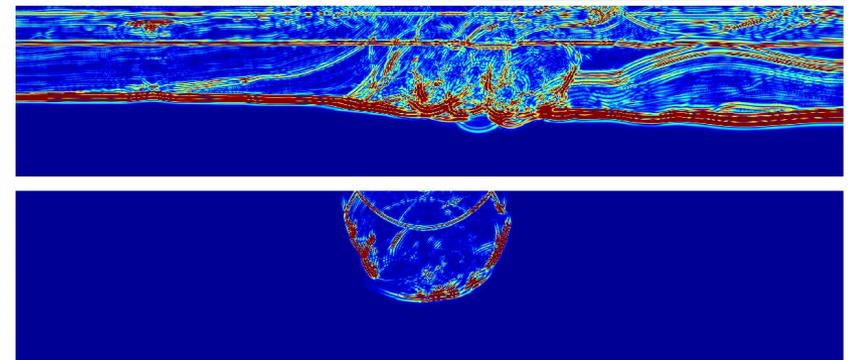
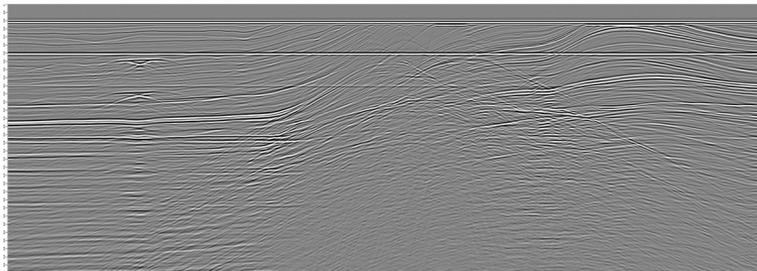


Geological model

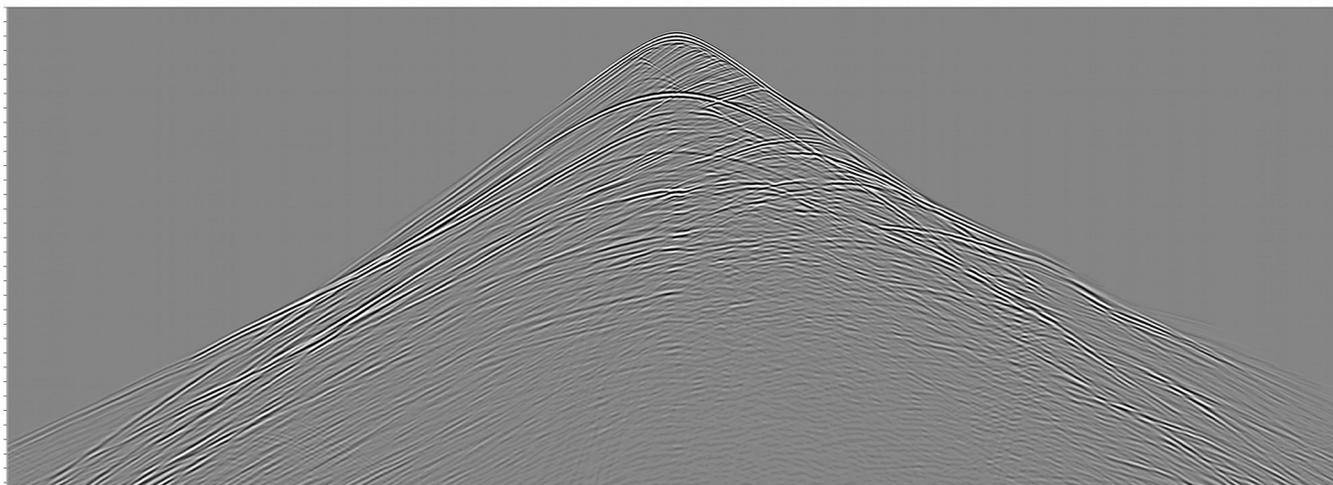
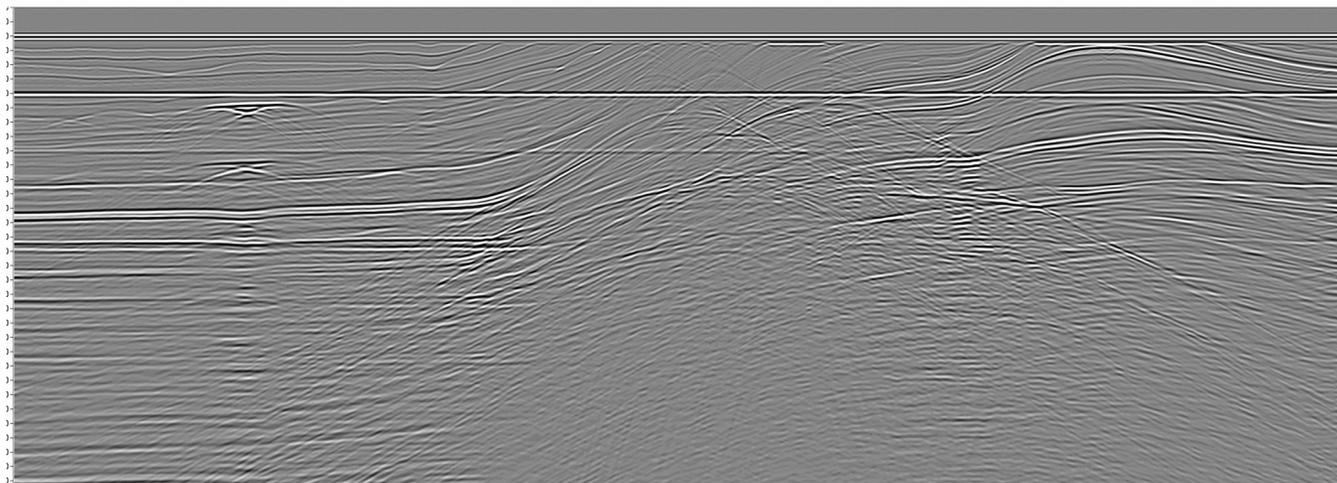


DIFFERENT TYPES OF SOURCES

- ❖ ПЛОСКАЯ ВОЛНА (СВЕРХУ)
- ❖ ТОЧЕЧНЫЙ ИСТОЧНИК (СНИЗУ)

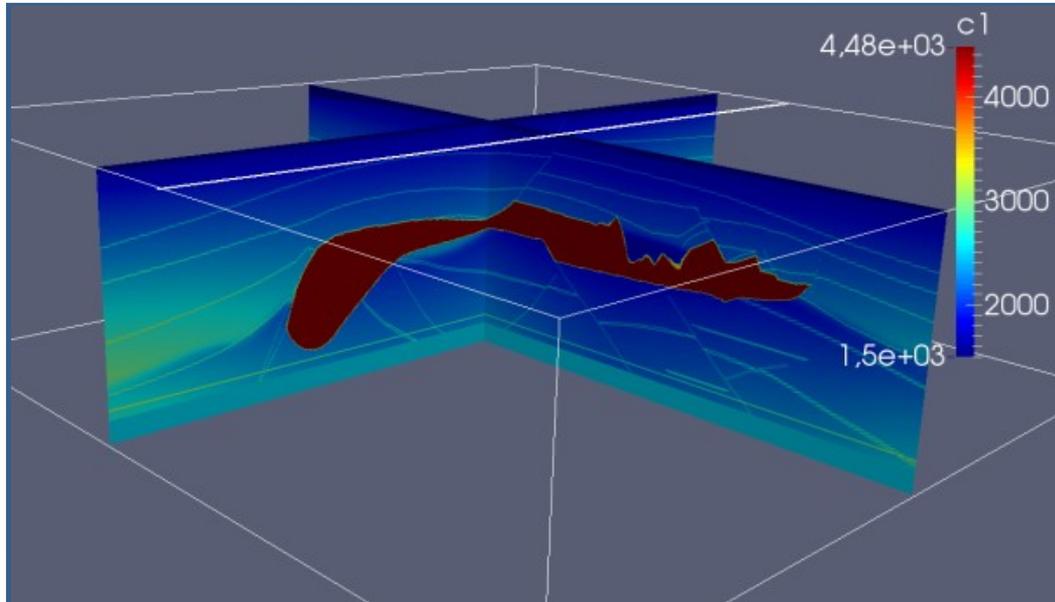


Geological model «Marmousi2»



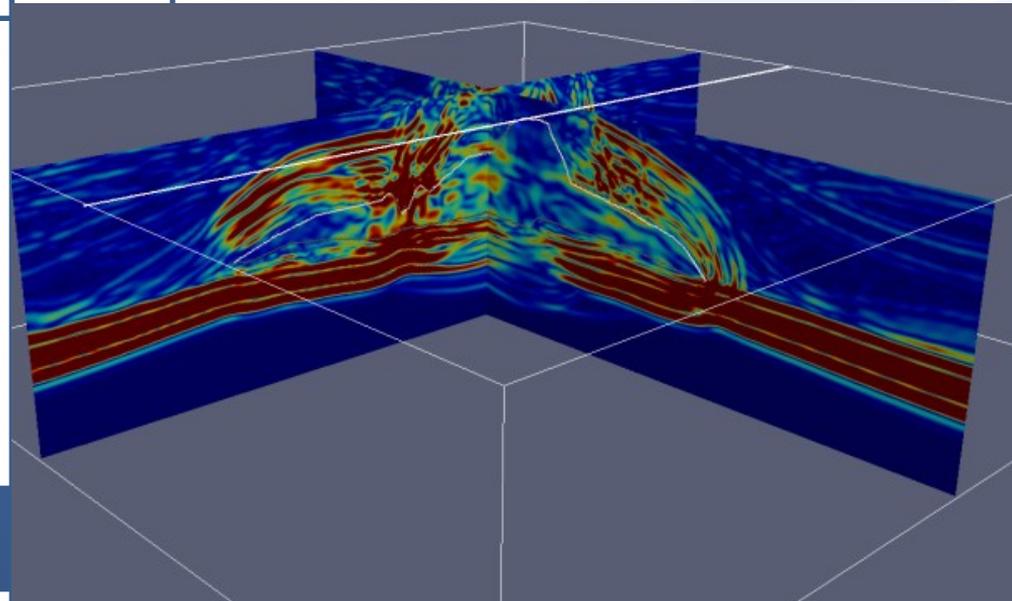
СЕЙСМОГРАММЫ: ПЛОСКАЯ ВОЛНА (СВЕРХУ) И ТОЧЕЧНЫЙ ИСТОЧНИК (СНИЗУ)

«SEG C3 NA»



3D MODEL

3D WAVE FIELDS



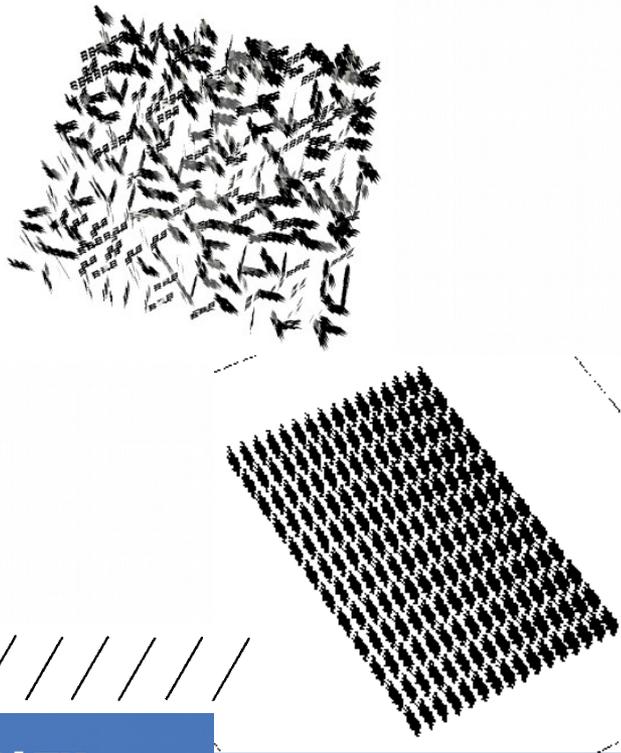
Моделирование трещиноватых сред

Были построены следующие 3D модели:

1. однородное полупространство,
2. трёхслойная горизонтально-слоистая среда,
3. включение с вертикальными одинаково ориентированными трещинами,
4. включение с наклонными (30°) одинаково ориентированными трещинами,
5. включение с вертикальными хаотично ориентированными трещинами:
 - А. азимут от -30 до $+30$ градусов,
 - В. азимут от -180 до $+180$ градусов.

Моделирование трещиноватых сред

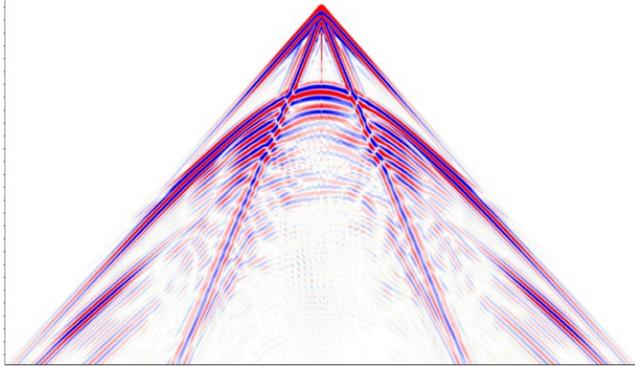
Примеры структуры трещиноватой среды



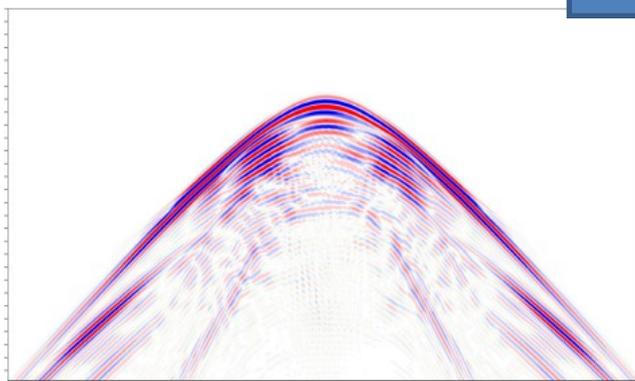
Характеристики моделей:

- ❖ параллелепипед 10 x 10 x 3,9 км;
- ❖ плотность среды 2500 кг/м³;
- ❖ толщина 1 слоя 550 м, C_p – 4500 м/с, C_s – 2250 м/с;
- ❖ толщина 2 слоя 200 м, C_p – 6000 м/с, C_s – 3000 м/с;
- ❖ толщина 3 слоя 3150 м, C_p – 4500 м/с, C_s – 2250 м/с;
- ❖ глубина залегания трещин 600 м;
- ❖ горизонтальная протяжённость кластера 2,4 км;
- ❖ длина трещины 100 м;
- ❖ расстояние между трещинами 50-150 м.

Методика и анализ данных (V_z)



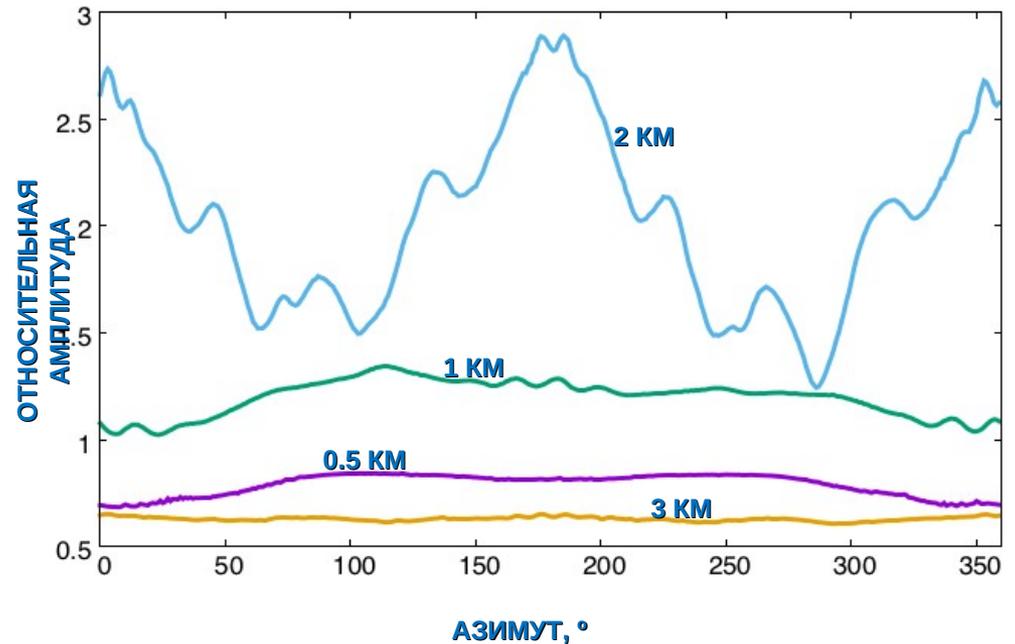
**3D ТРЕЩИНОВАТАЯ
ГЕОЛОГИЧЕСКАЯ
МОДЕЛЬ**



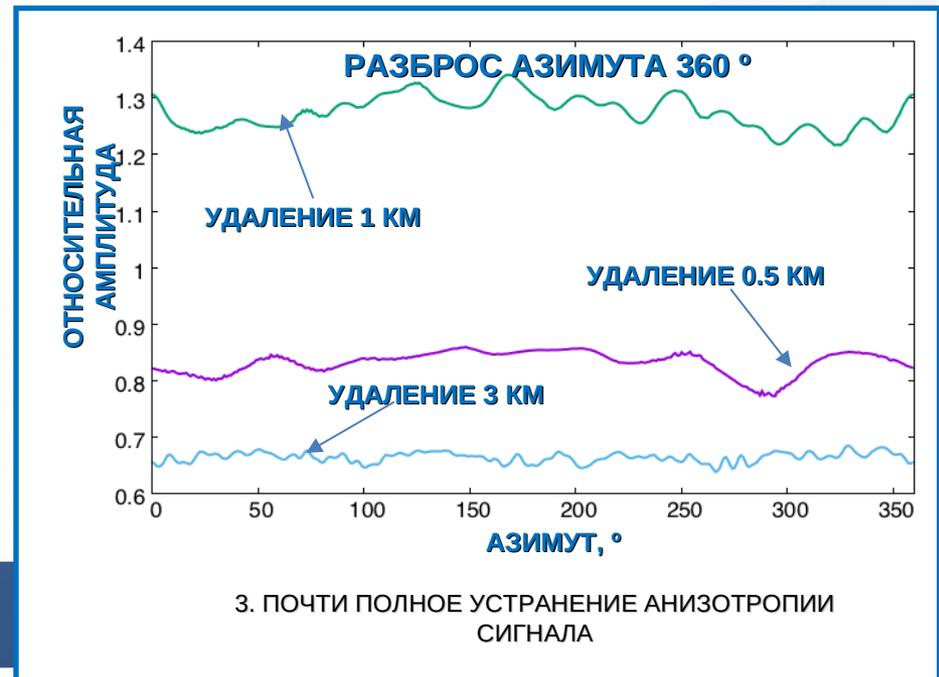
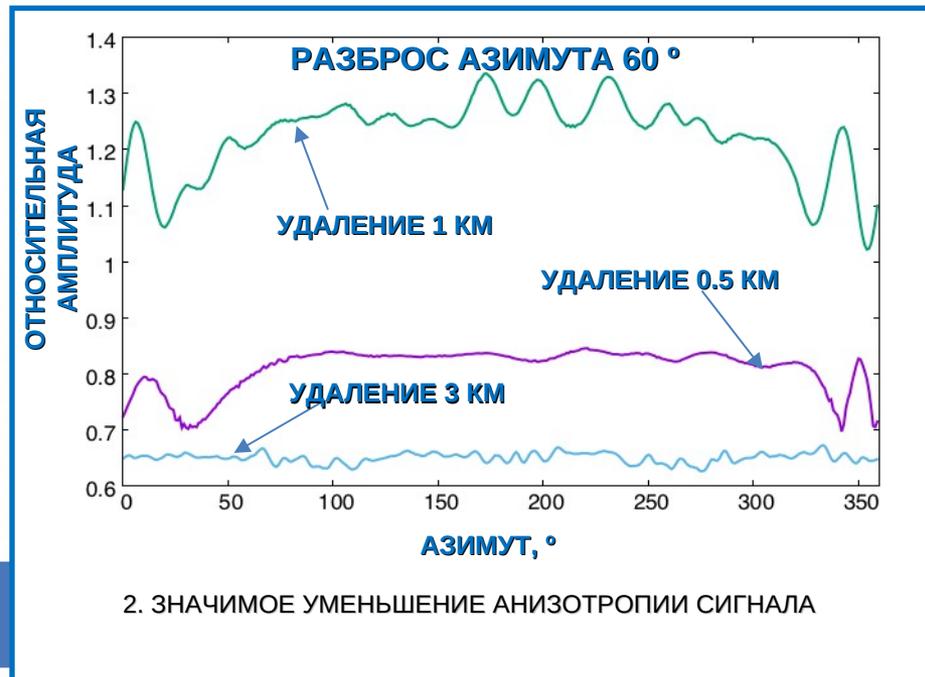
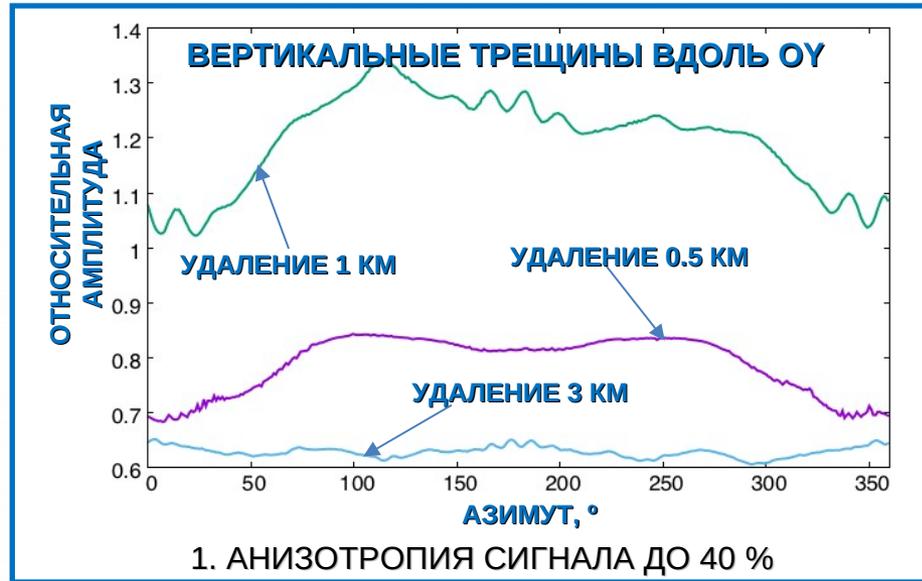
**ВЫЧТЕНА 3D
ОДНОРОДНАЯ
ГЕОЛОГИЧЕСКАЯ
МОДЕЛЬ**

Идентифицируются:

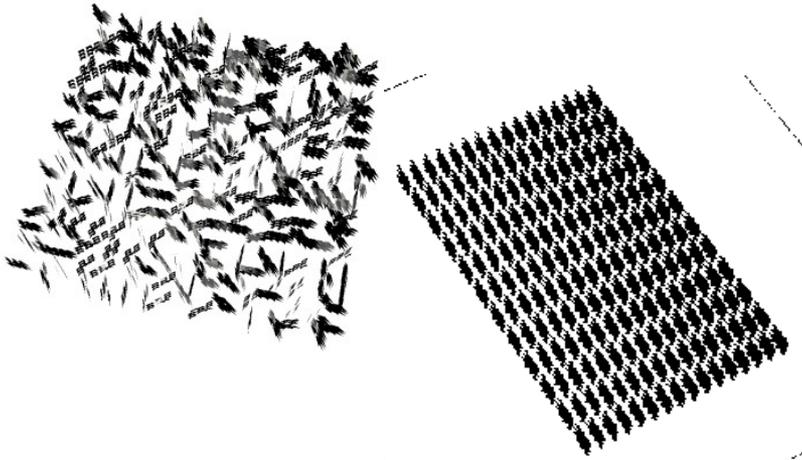
- ❖ **Поверхностные волны**
- ❖ **Отклики от границ слоёв**
- ❖ **Сейсмический сигнал от кластера трещин**



Результаты анализа

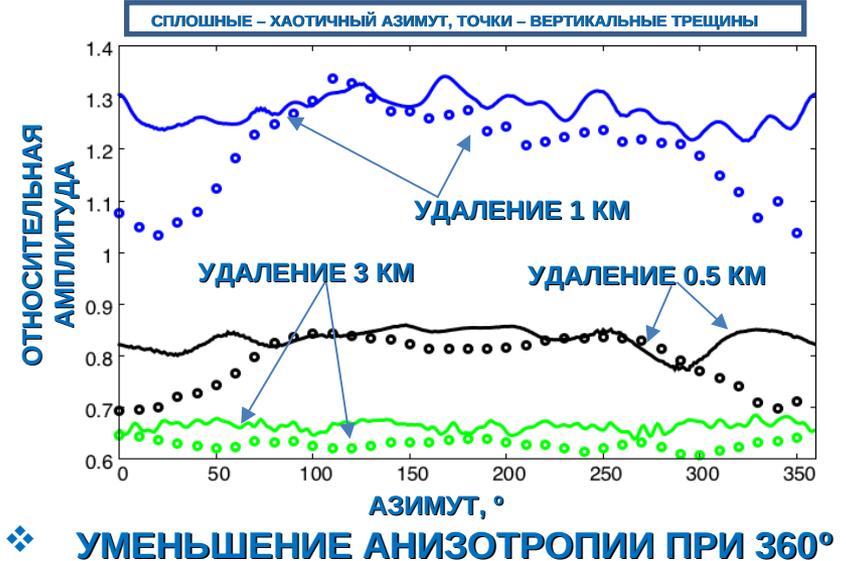
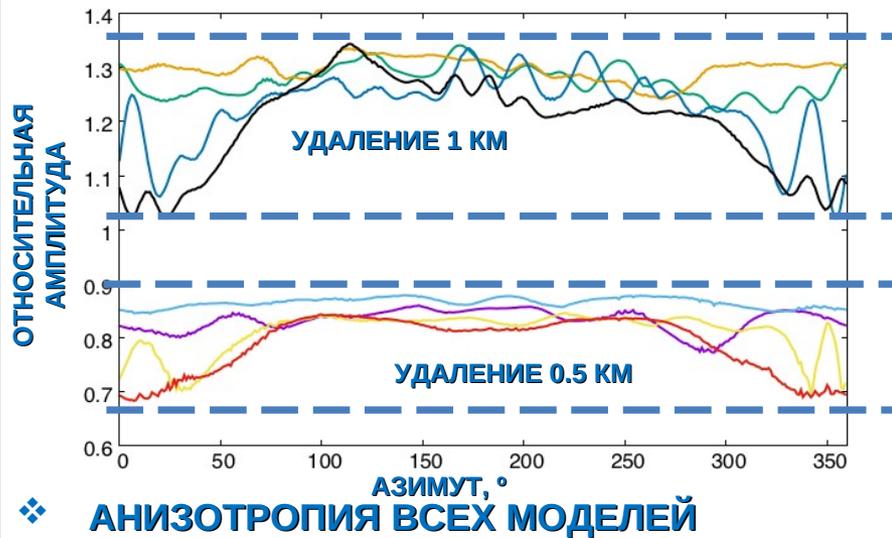


Результаты анализа



ГЕОМЕТРИЯ ТРЕЩИН:

- ❖ ВЕРТИКАЛЬНЫЕ
- ❖ 30° ОТ ВЕРТИКАЛИ
- ❖ РАЗБРОС ПО АЗИМУТУ 360°
- ❖ РАЗБРОС ПО АЗИМУТУ 60°



Earthquake modeling

Earthquake resistance

- Earthquake focus modeling
- Wave propagation through geological media
- Evaluation of earthquake resistance

Problem's Significance

1. **Consequences of earthquakes** - thousands of deaths, billions \$ of damage to property
2. Available software instruments and technologies are **insufficient**



Japan

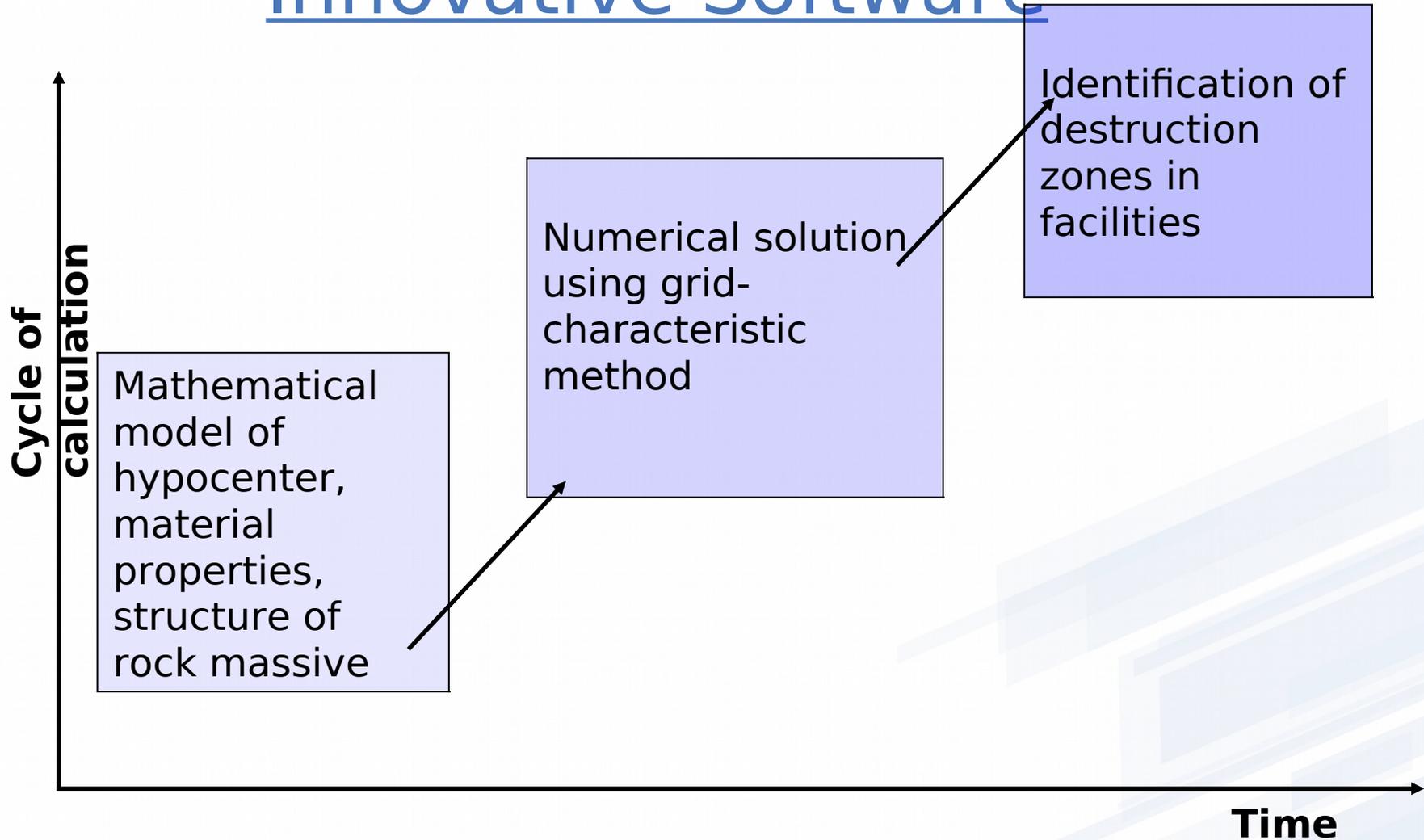


Russia



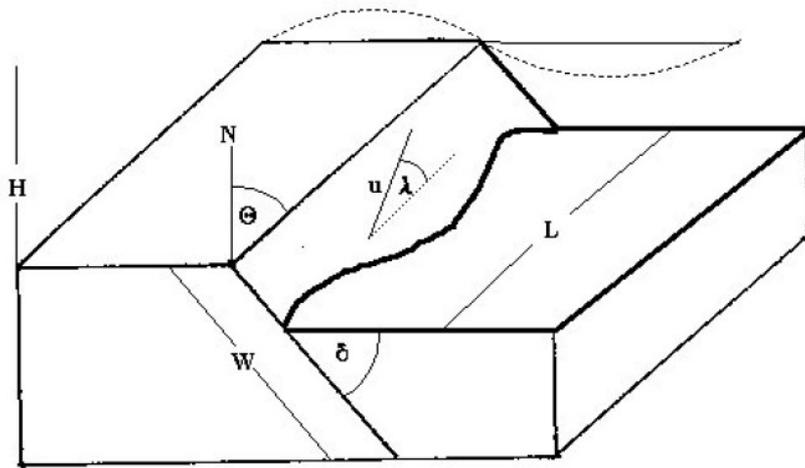
Turkey

Innovative Software



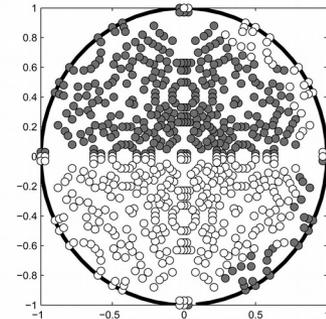
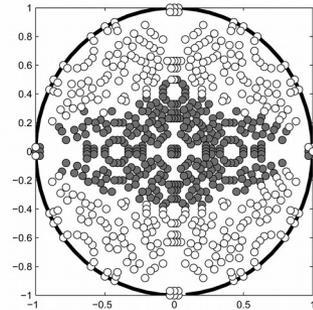
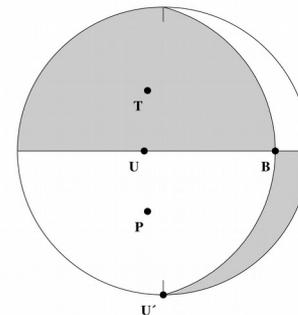
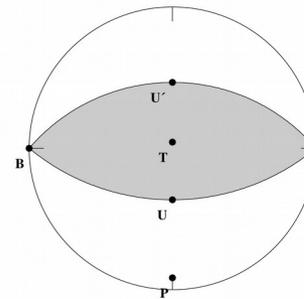
Results: Hypocenter Modeling

Mechanical model «Fault slip»



- Θ = strike angle (measured clockwise from north)
- λ = rake angle (angle between strike direction and slip direction; $-\pi < \lambda \leq \pi$)
- δ = dip angle (measured from the horizontal; $0 \leq \delta \leq \pi/2$)
- u = slip direction and magnitude

Analytical VS numerical solution



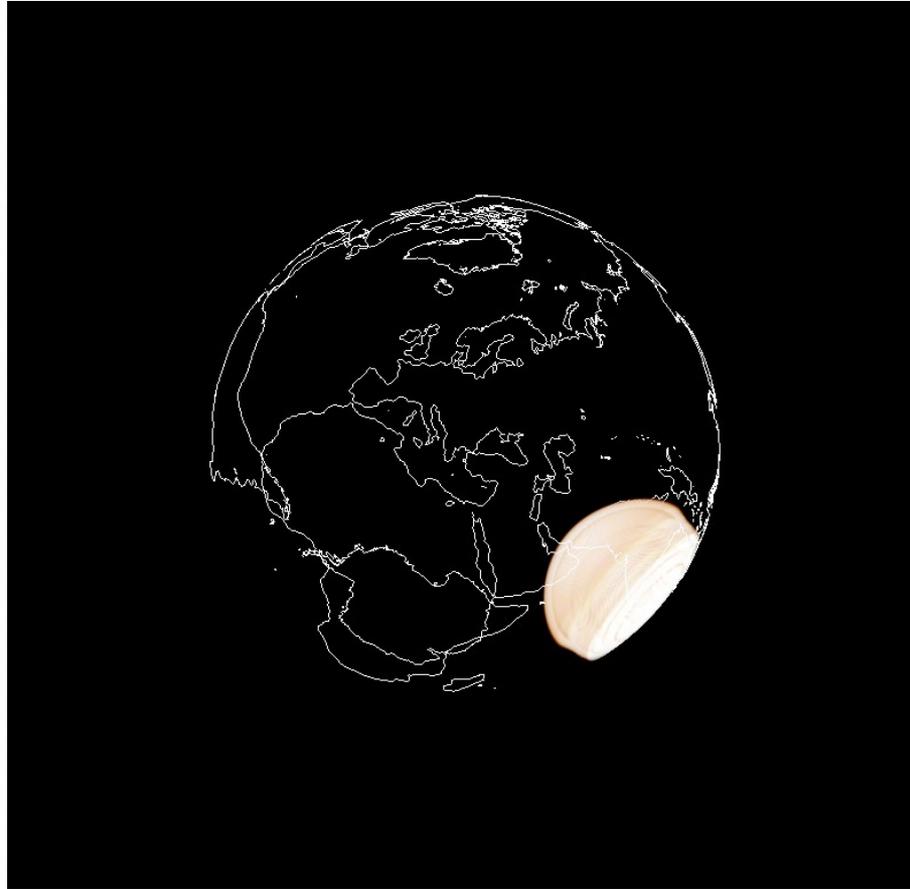
Analytical solution is available at

<http://www1.gly.bris.ac.uk/~george/focmec.html>

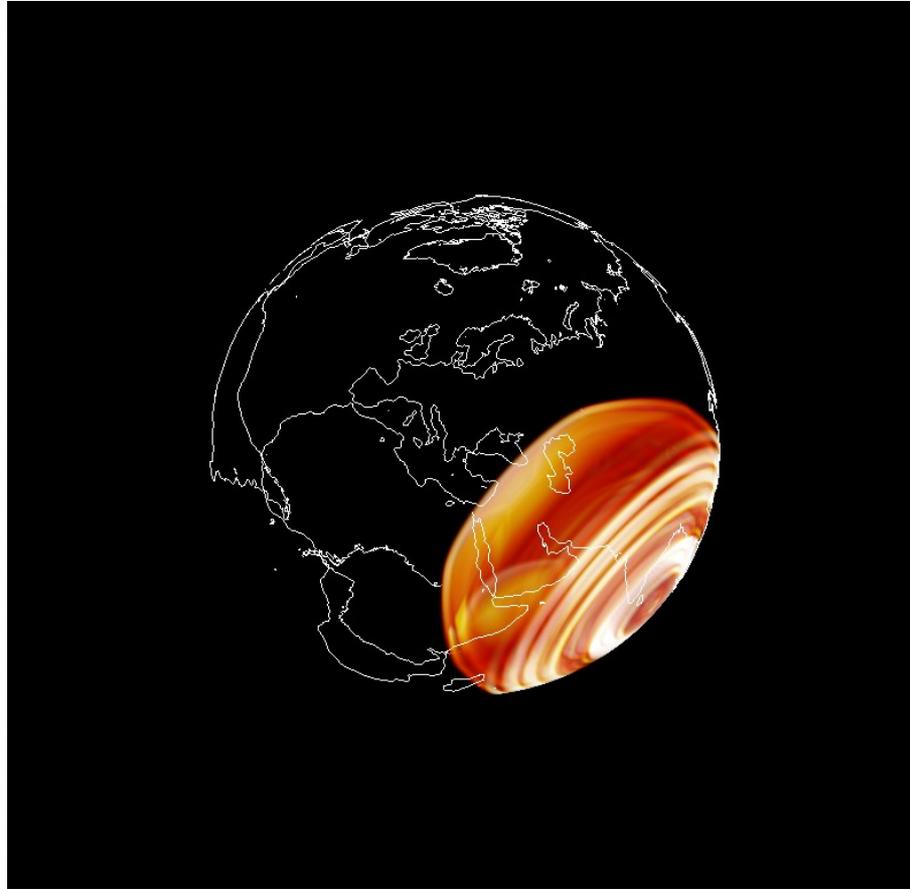
Global seismic



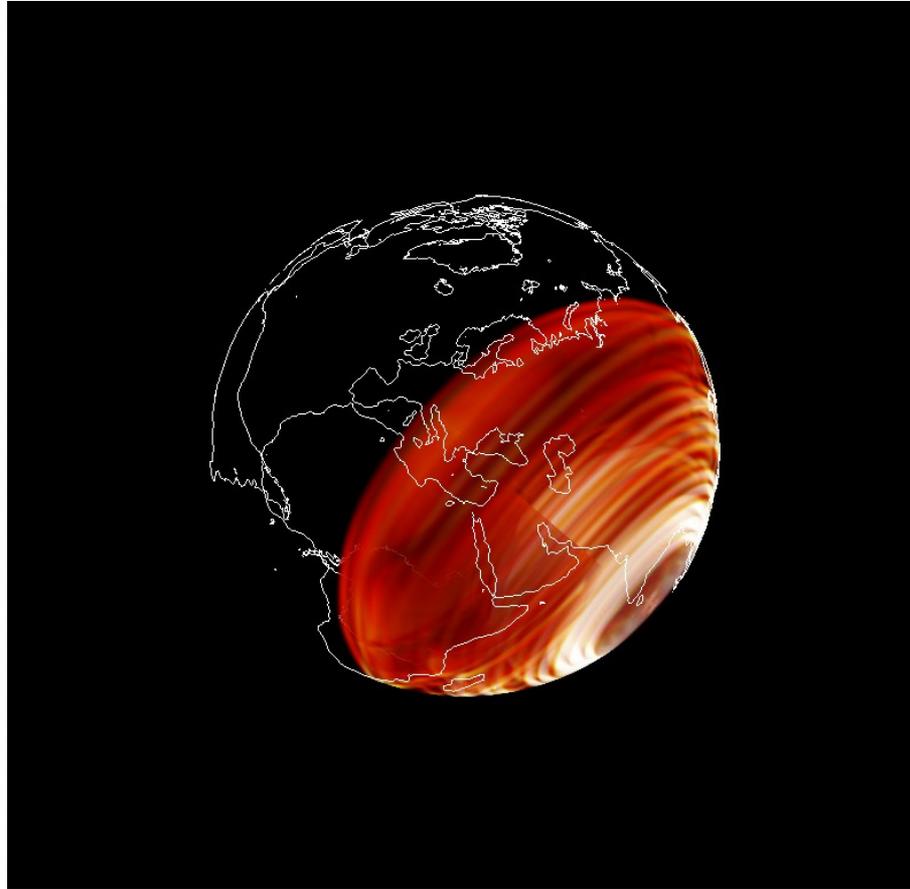
Global seismic



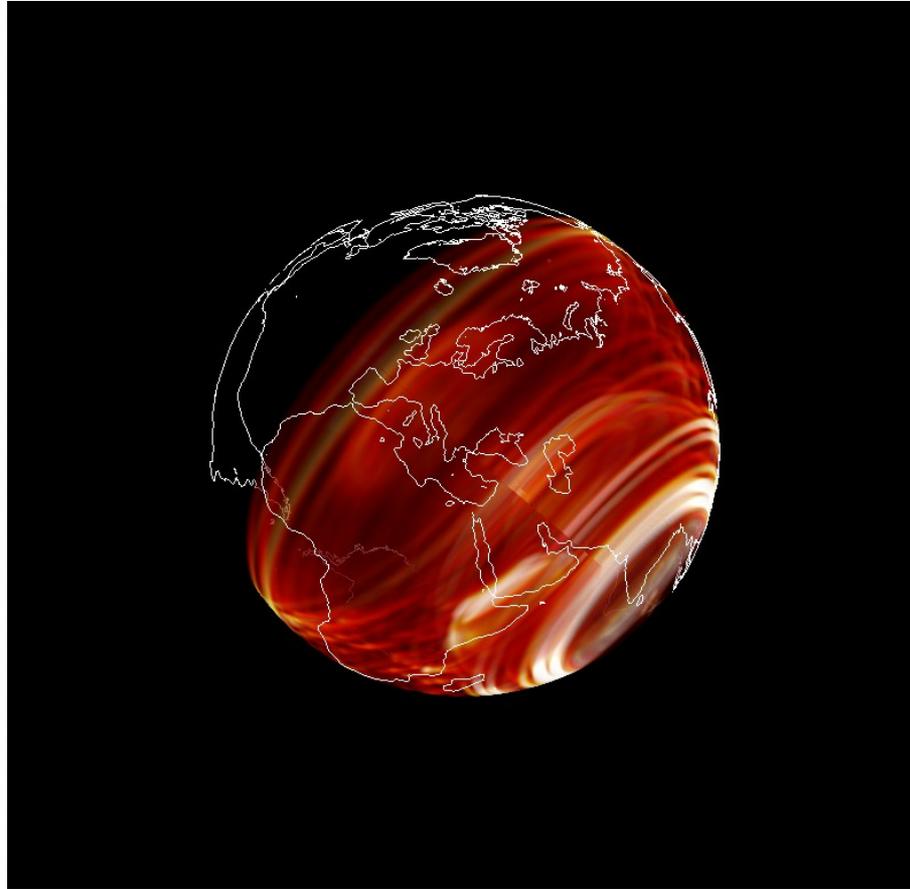
Global seismic



Global seismic



Global seismic



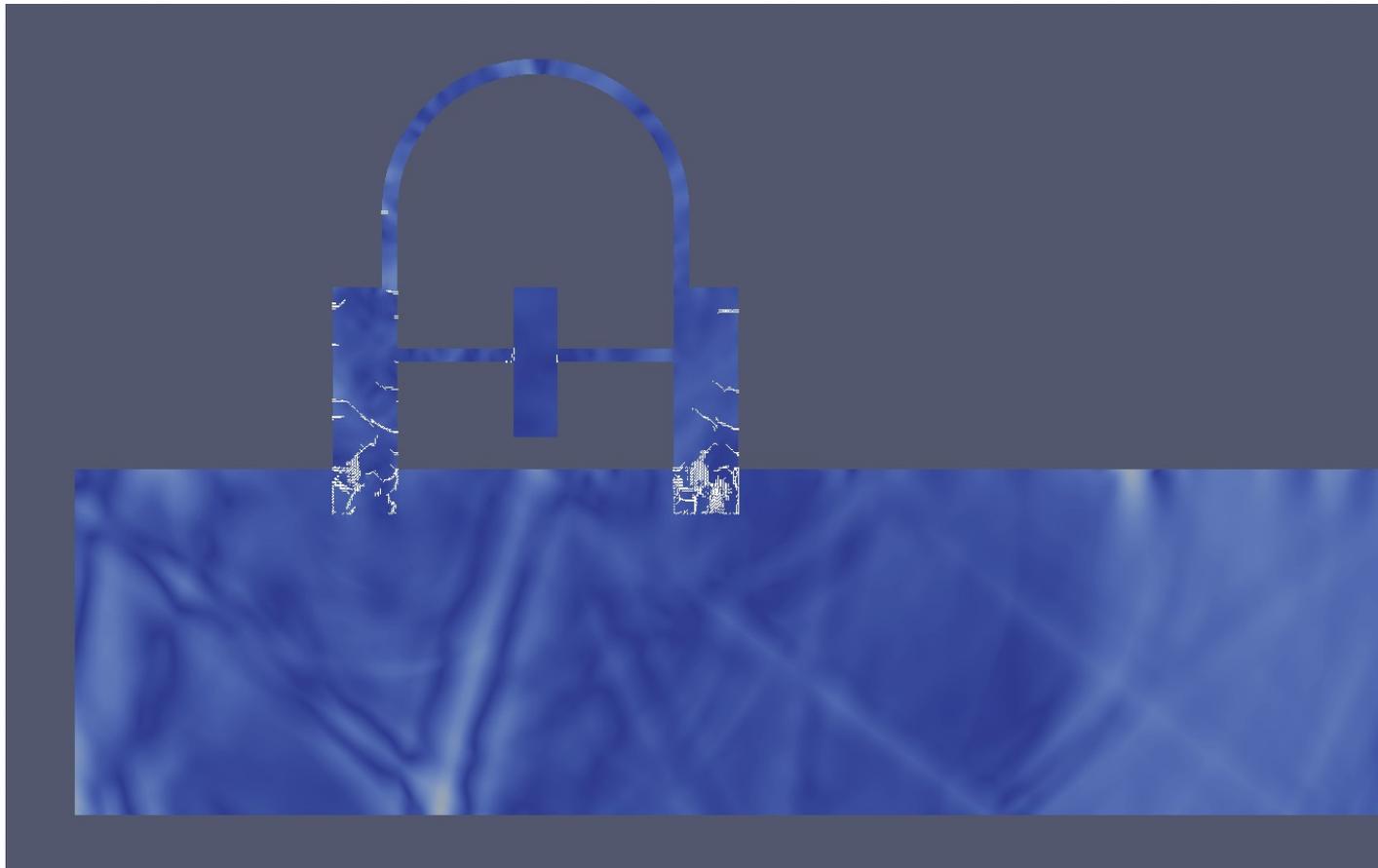
Results: dome construction



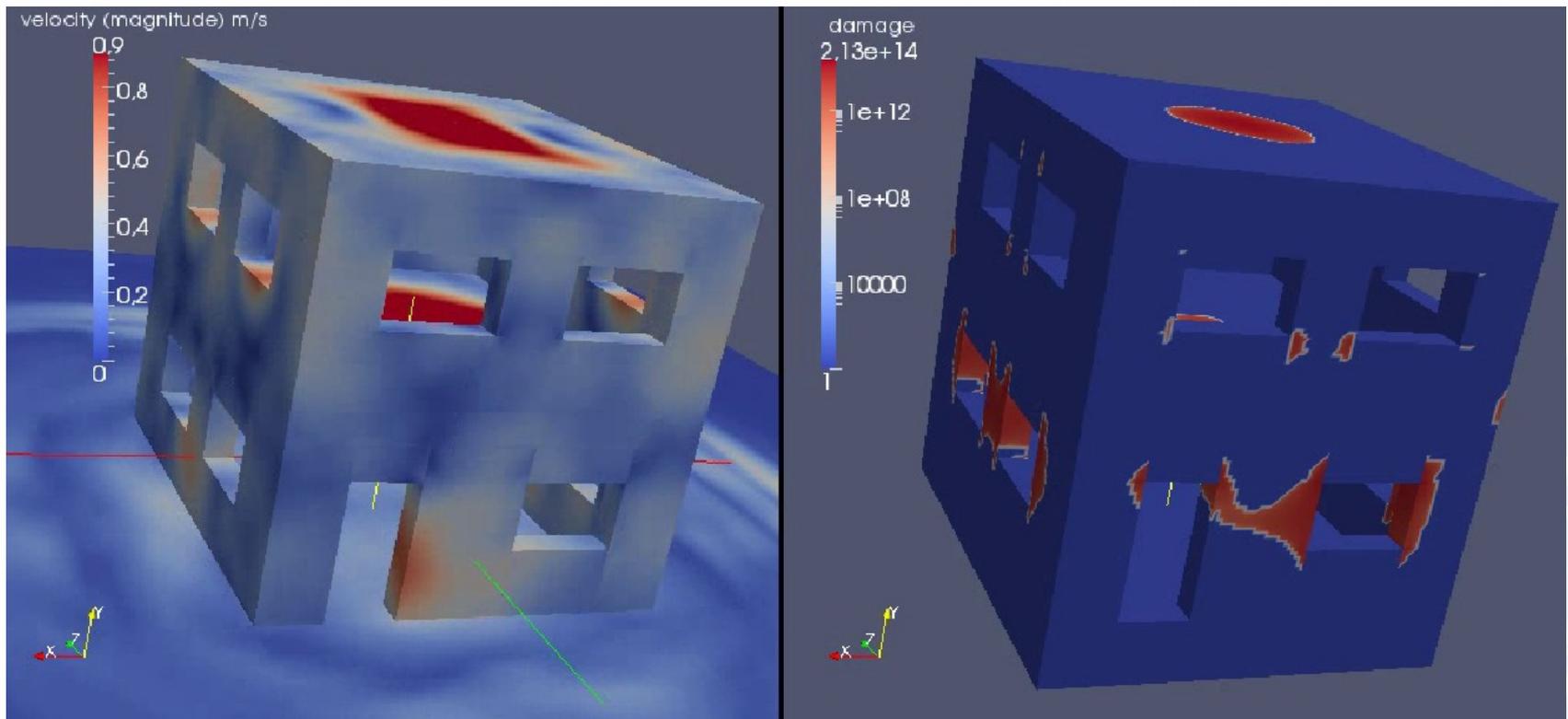
Results: dome construction



Results: dome construction

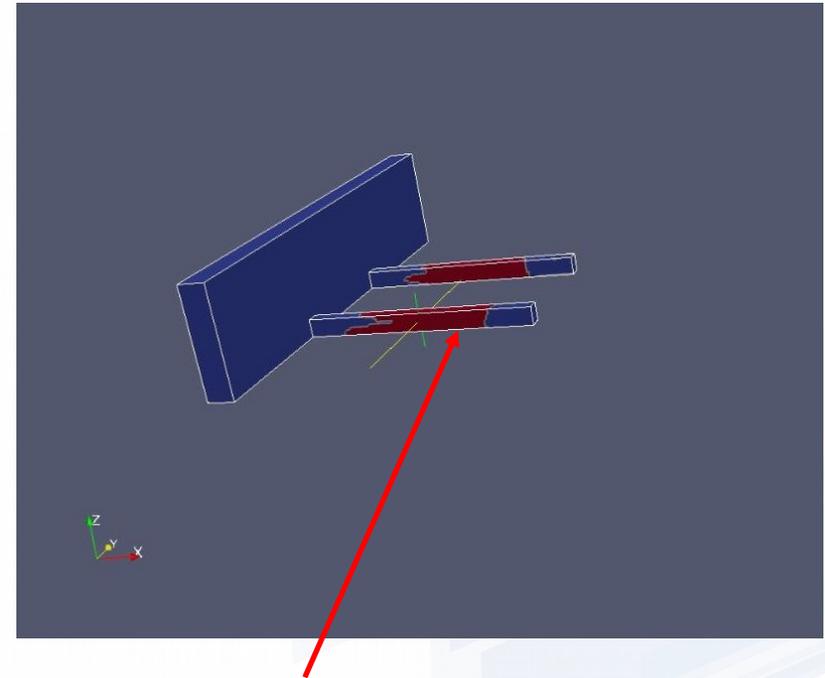
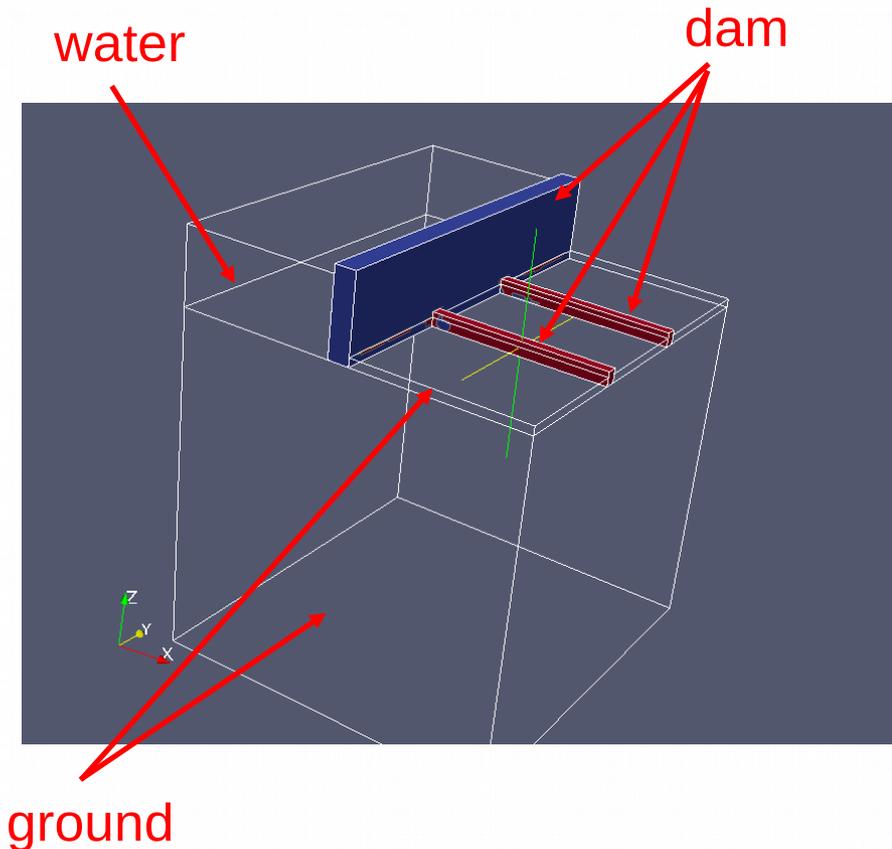


Results: Ground Facility



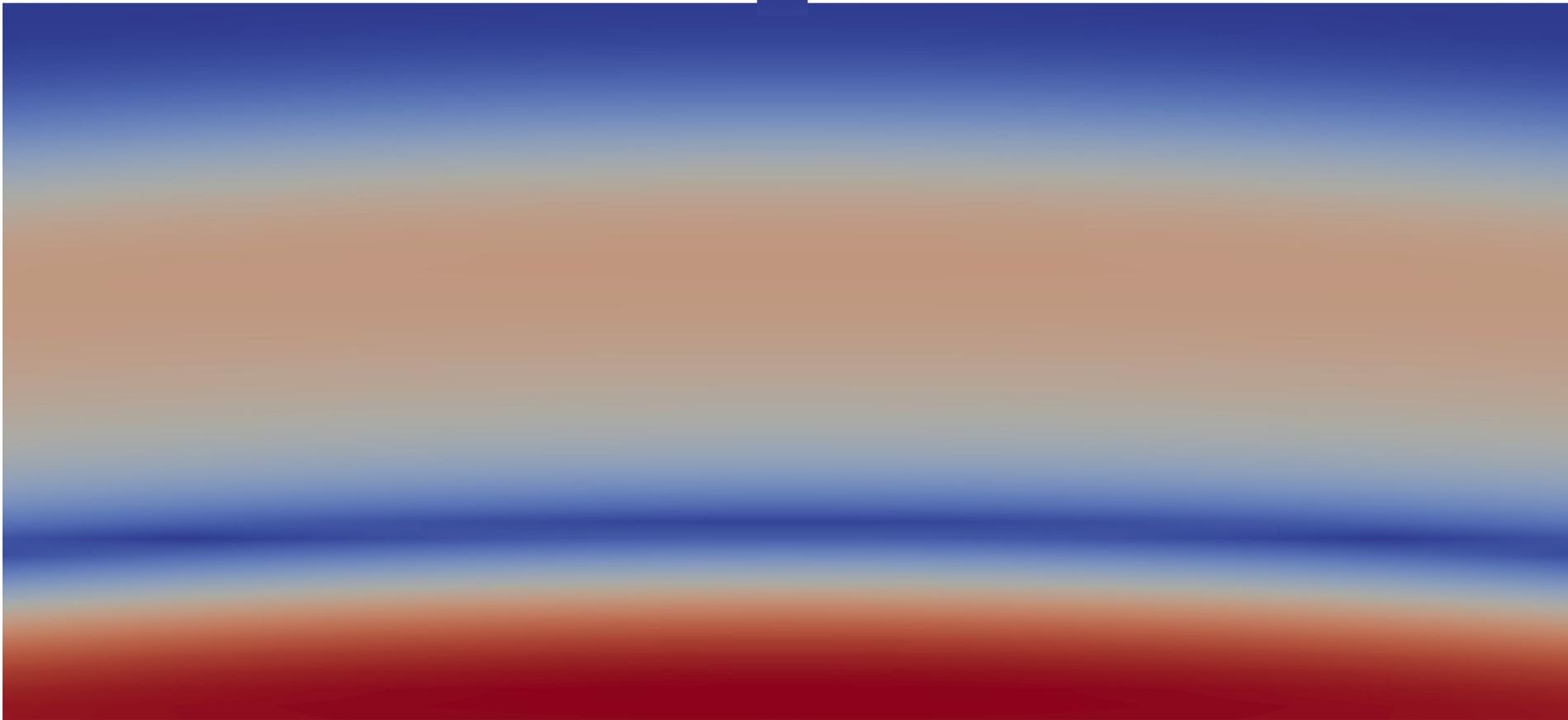
Absolute velocity (left) and destruction zones (right) in red based on «sand» model

Results: Dam

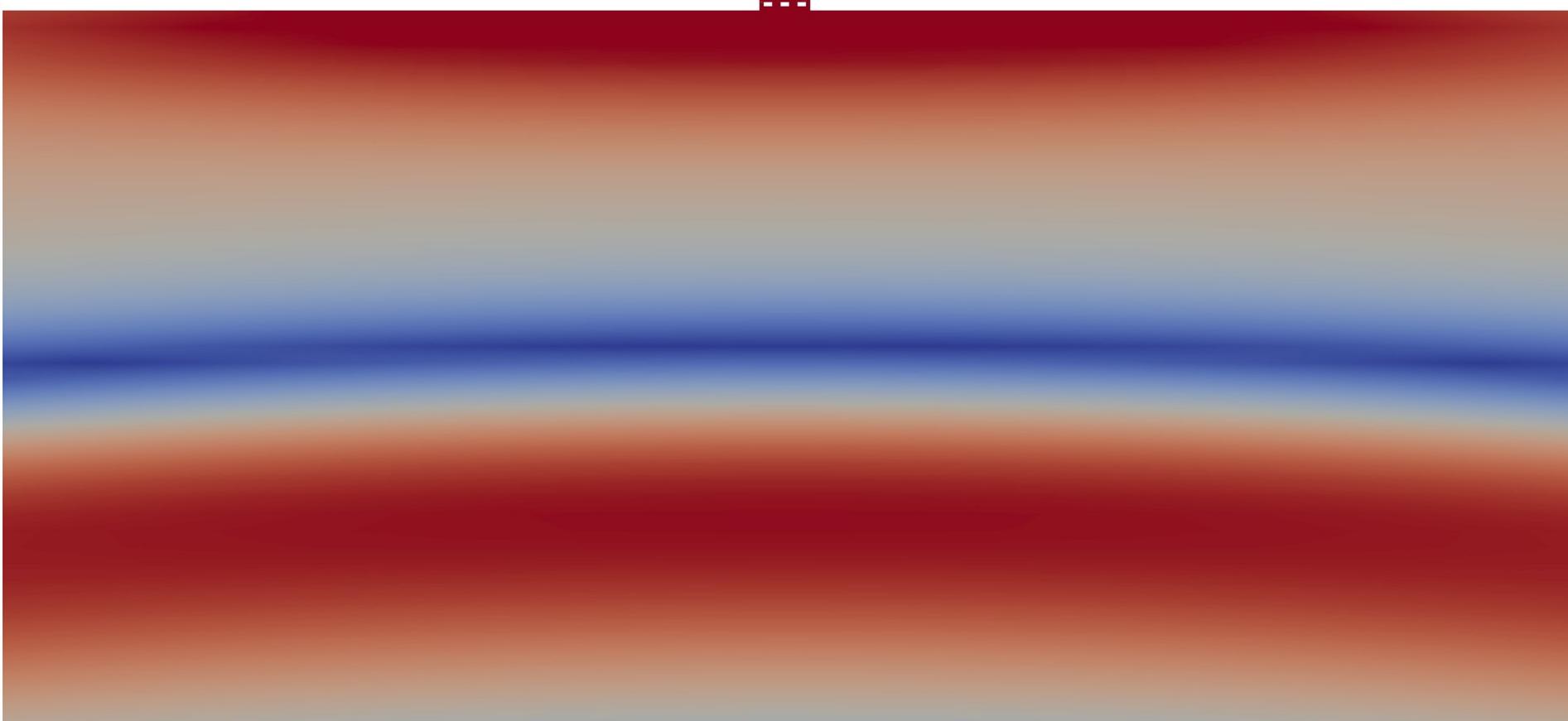


Scheme of numerical experiment and places of destruction

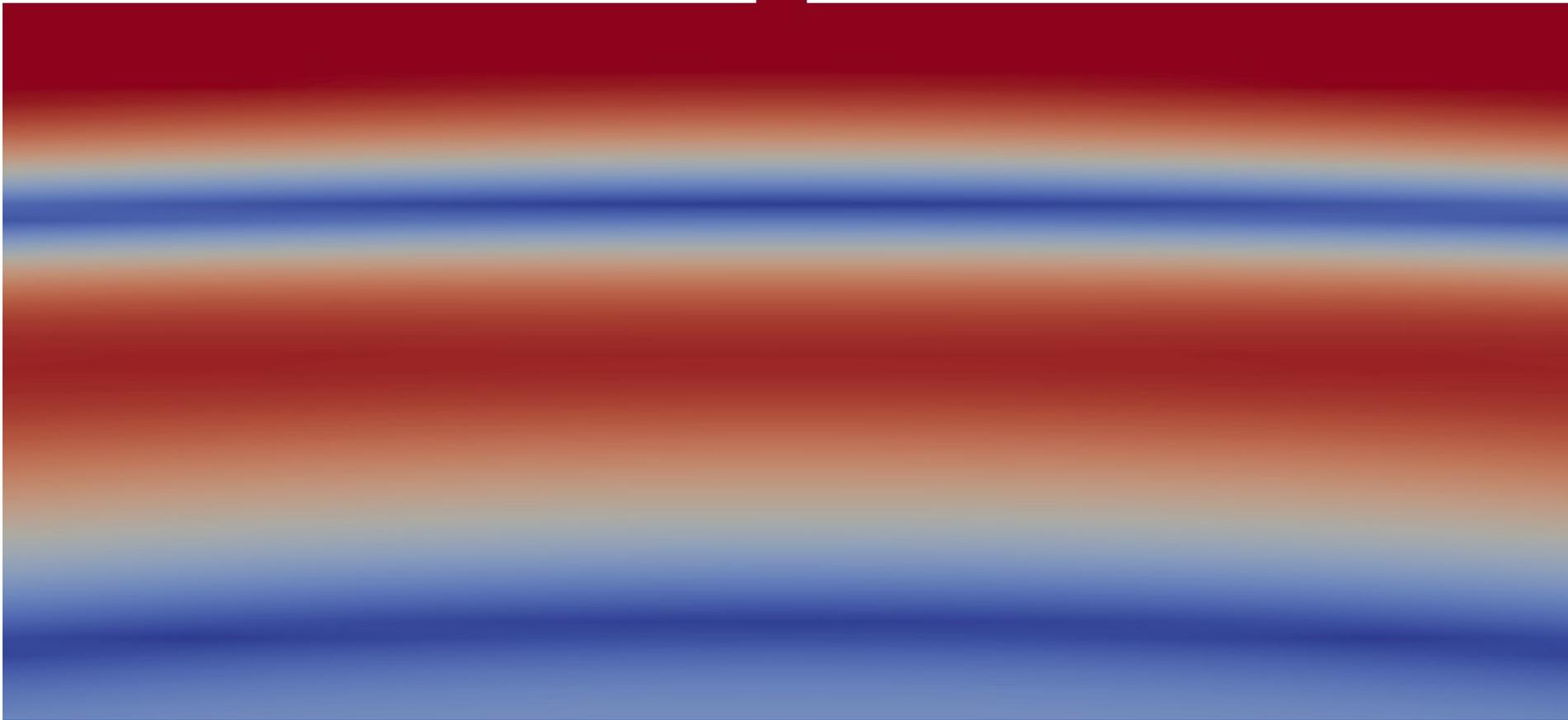
Result: earthquake modelling using hierarchical grids



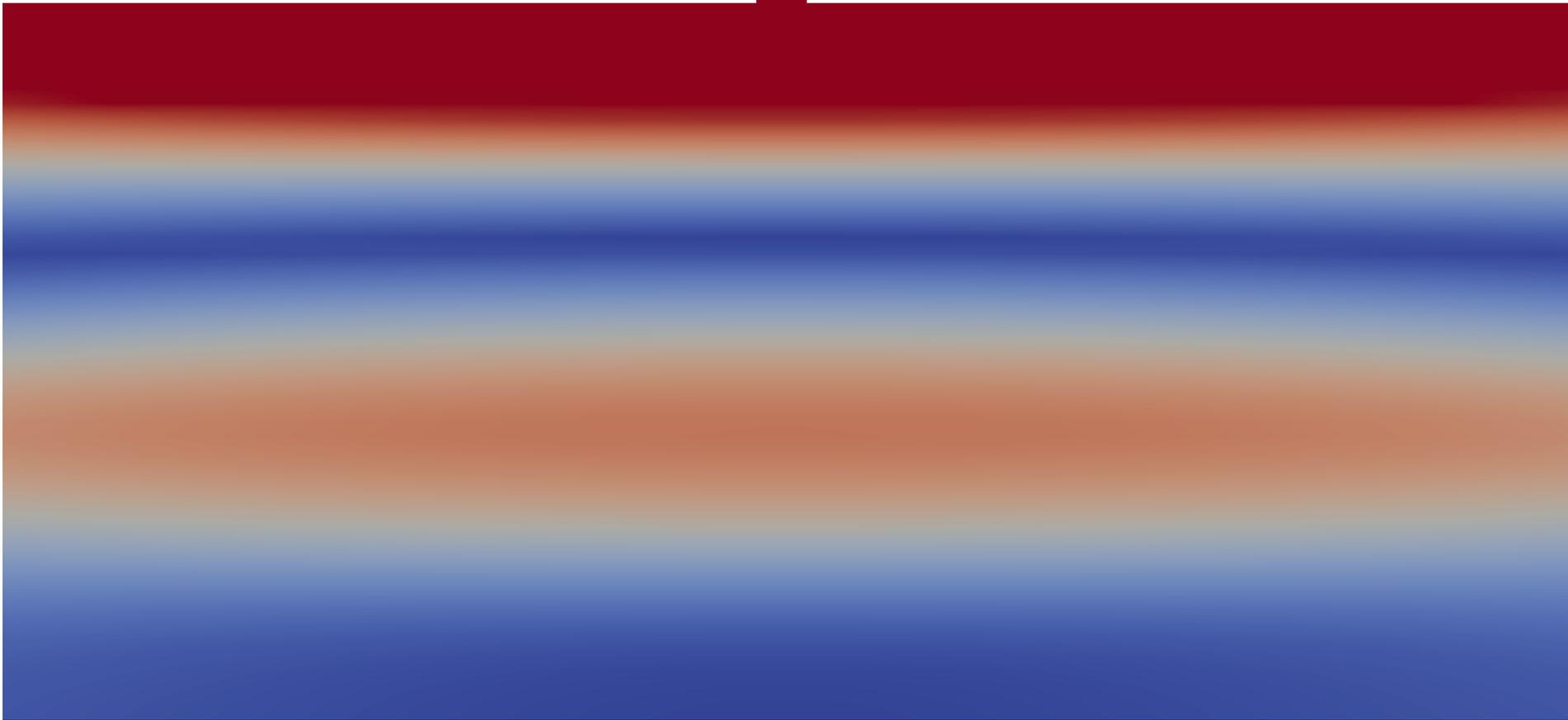
Result: earthquake modelling using hierarchical grids



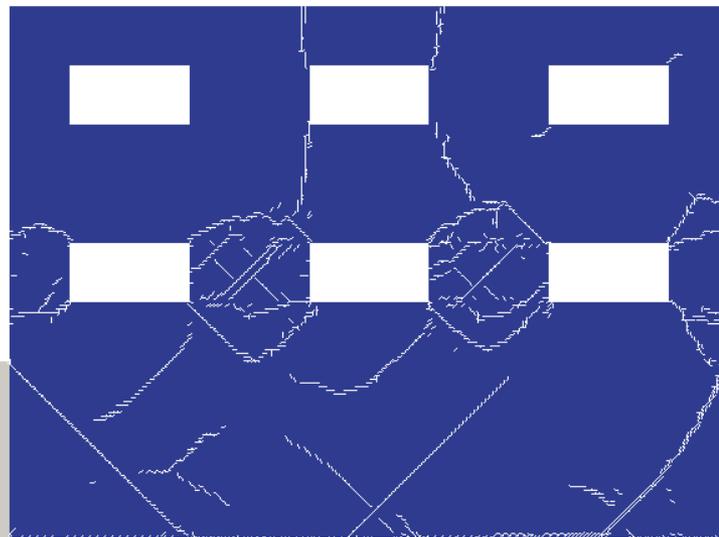
Result: earthquake modelling using hierarchical grids



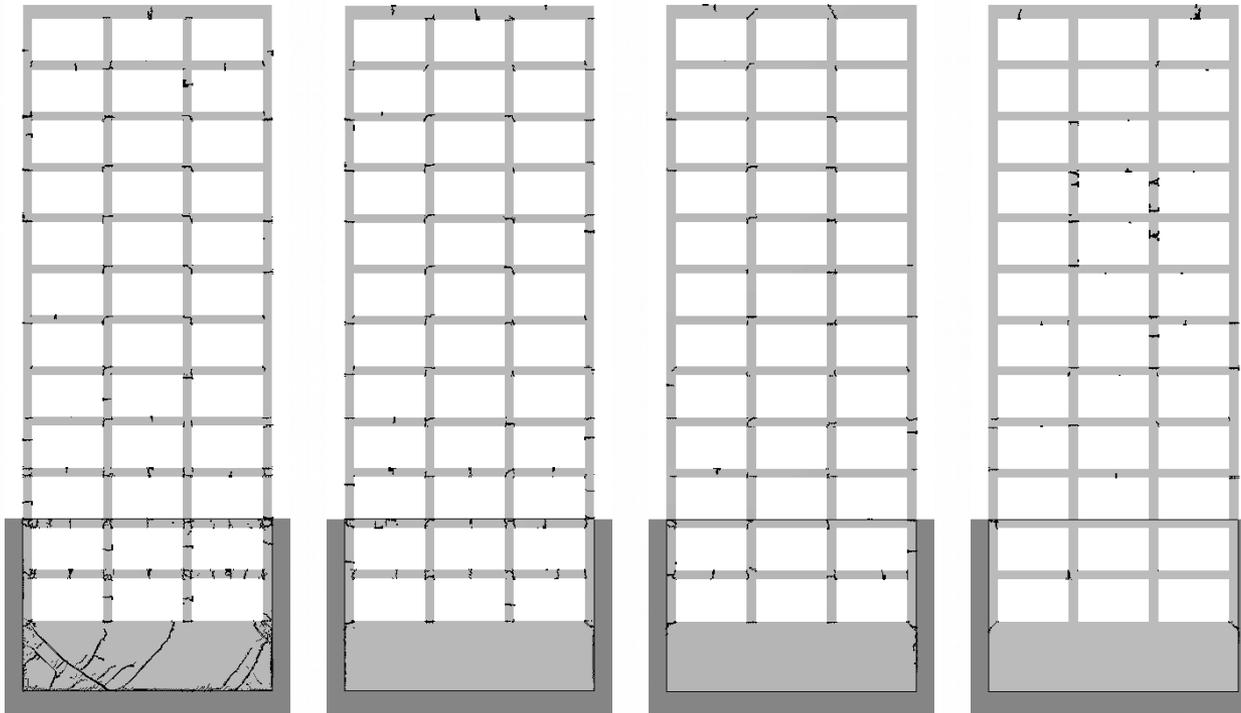
Result: earthquake modelling using hierarchical grids



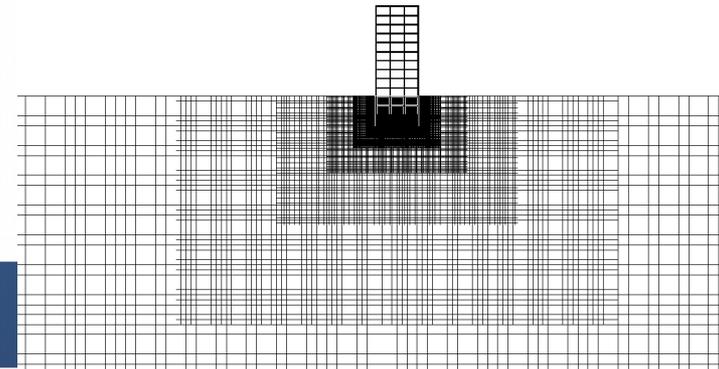
Result: earthquake modelling using hierarchical grids



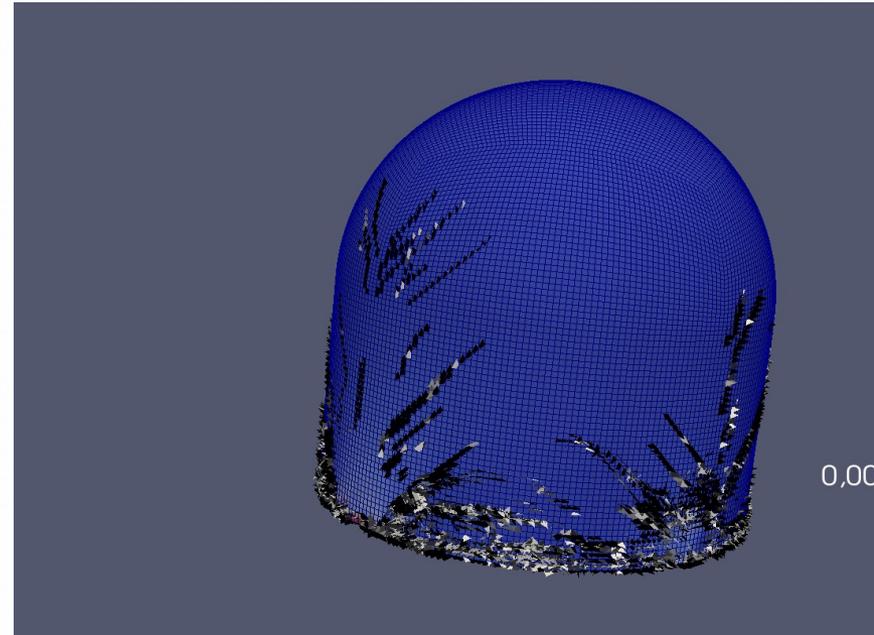
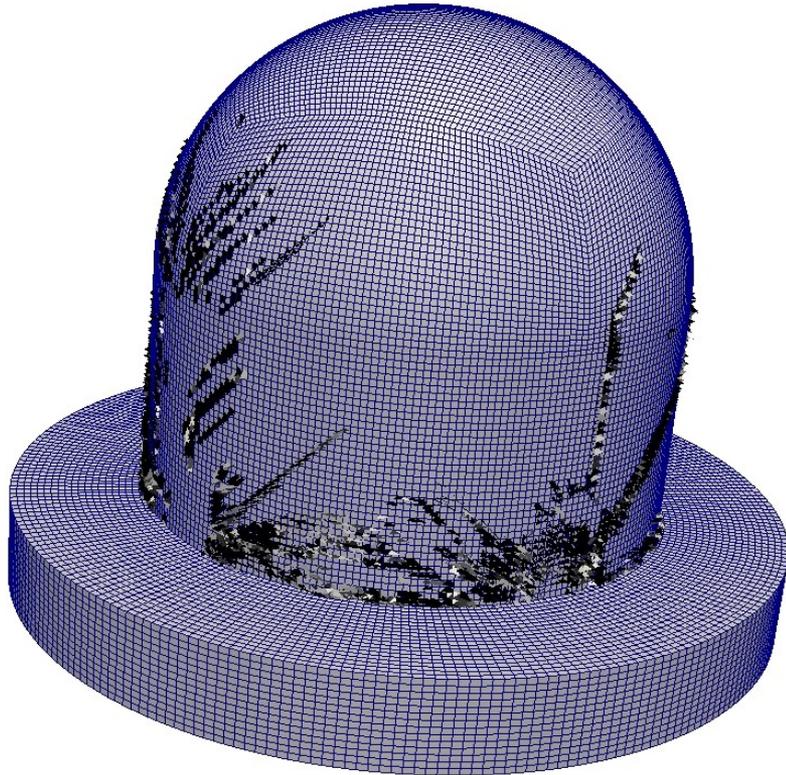
Seismic resistance of multi-storey buildings



Different depth of the hypocenter of the earthquake



Results: 3D dome constructions



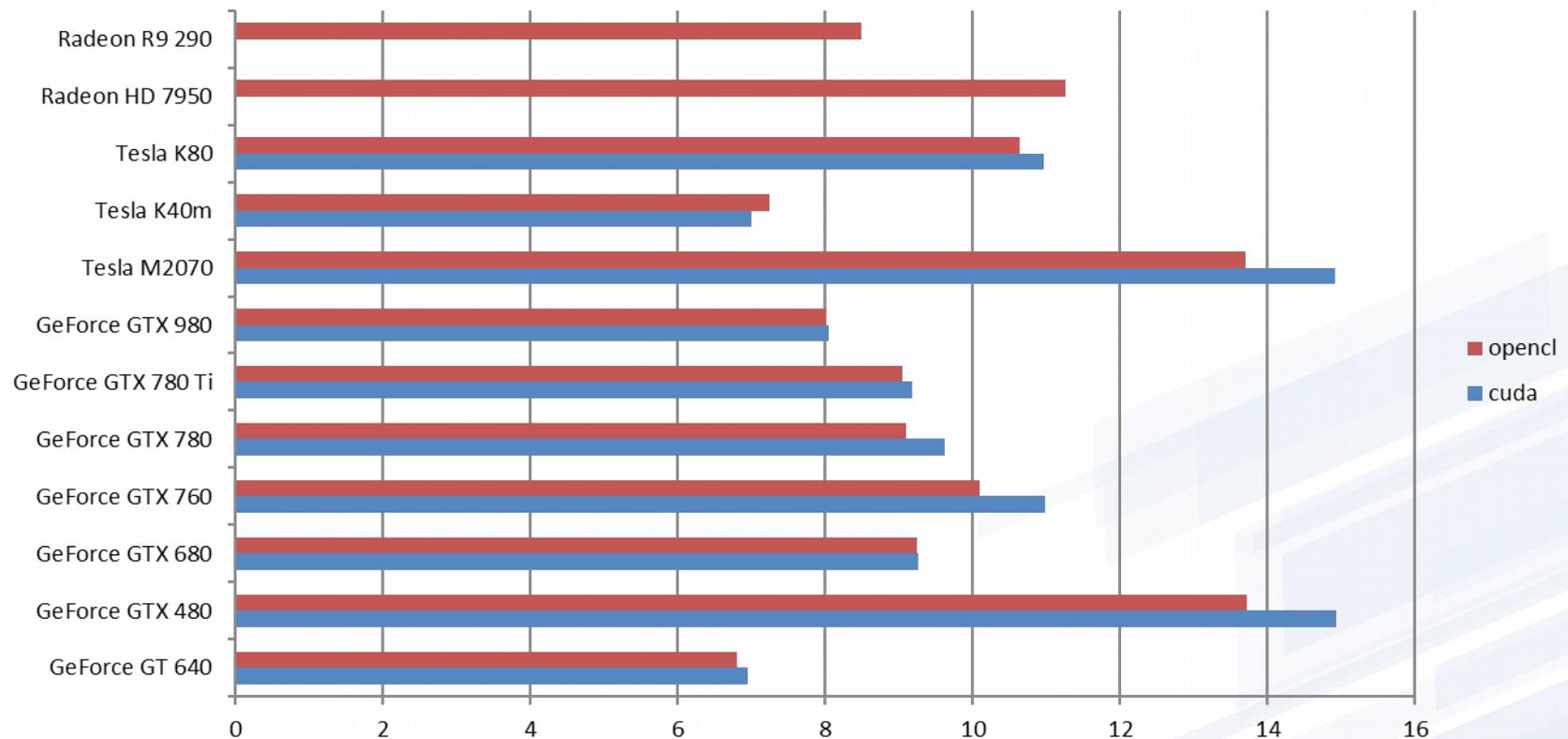
Conclusions

- possibility to calculate large spatial problems
- various models of destruction
- complex three-dimensional objects from block curvilinear grids

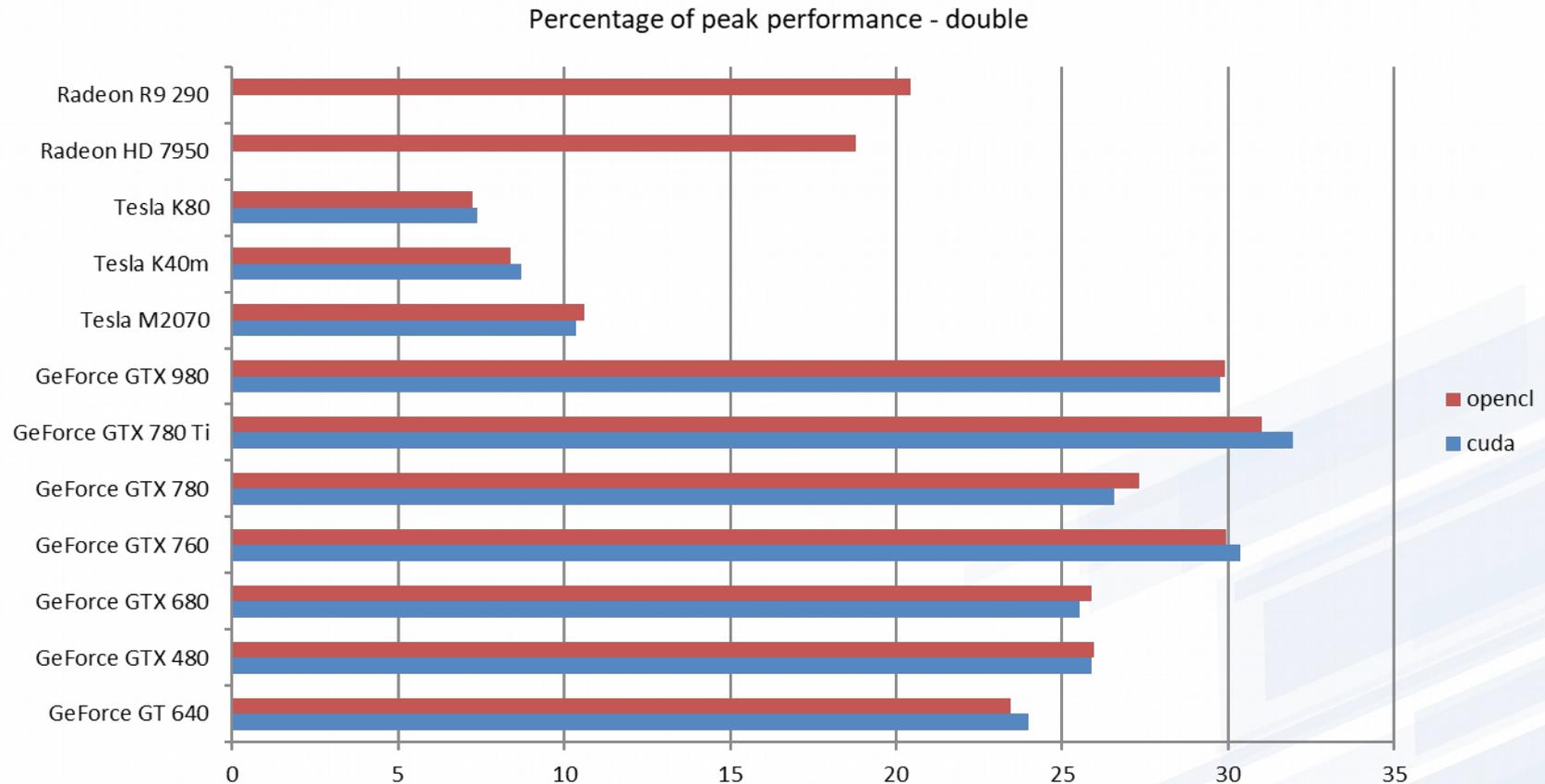
Thanks a lot!
Questions?

Percentage of peak performance

Percentage of peak performance - float + fast math

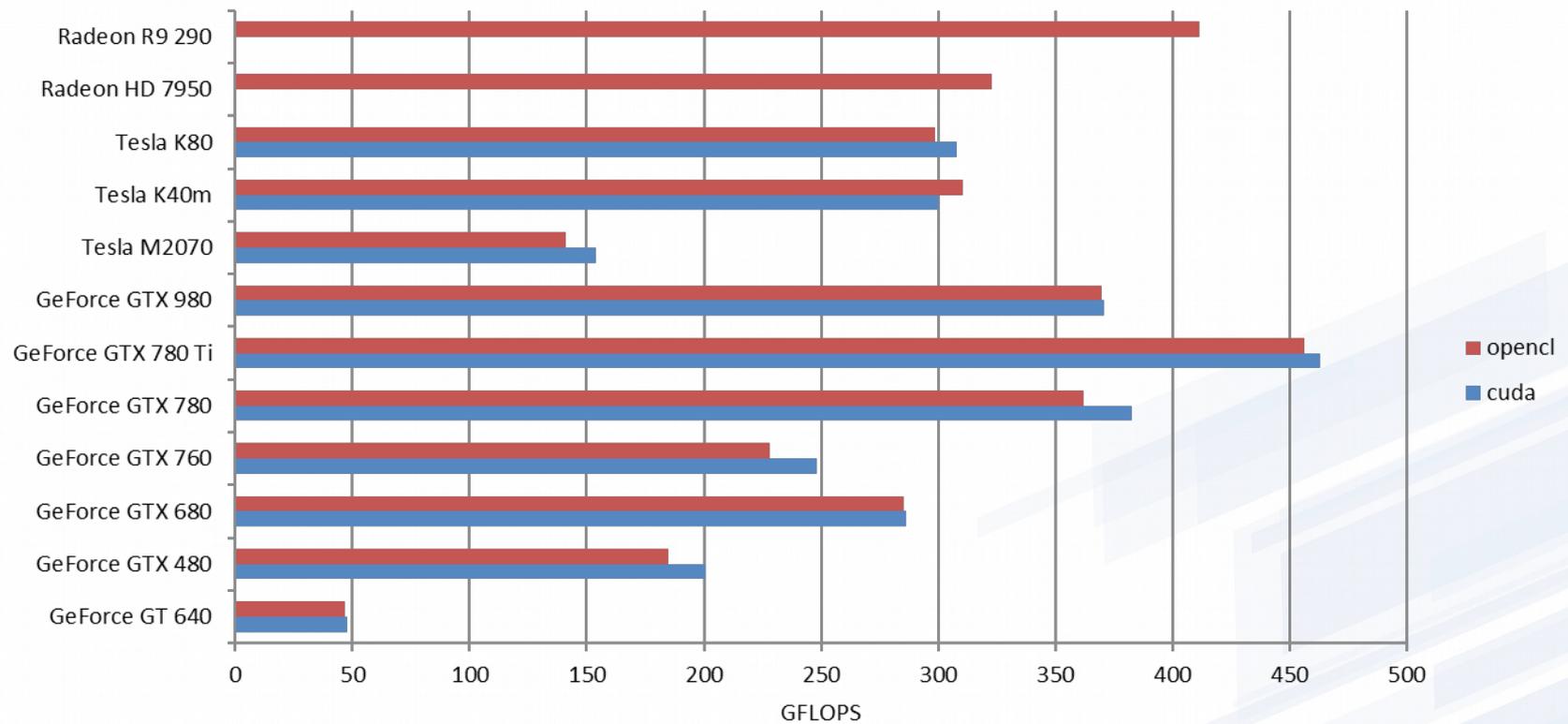


Percentage of peak performance



Performance

Performance - float + fast math



Performance

