Synthetic models of the lunar seismic field

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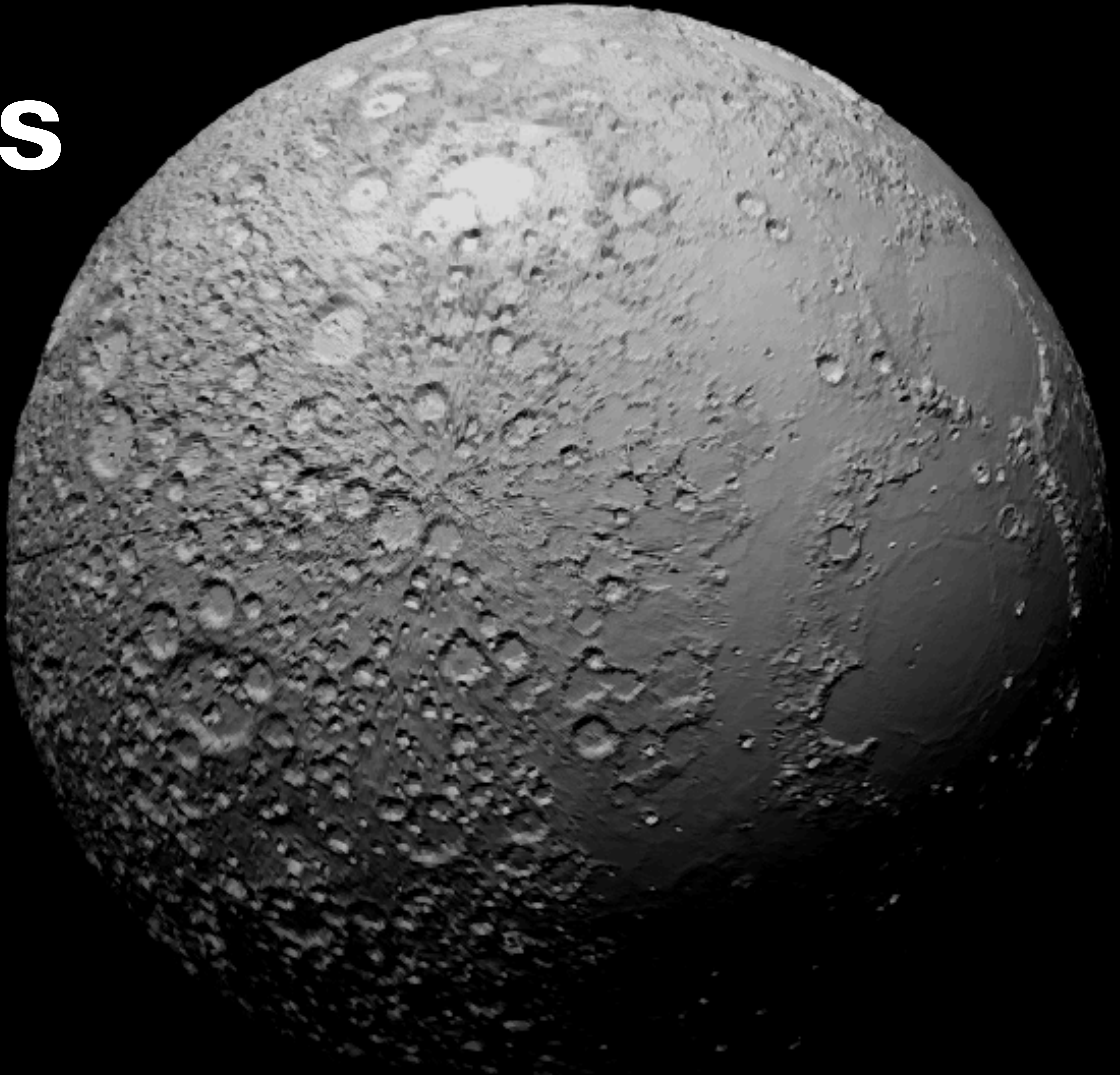


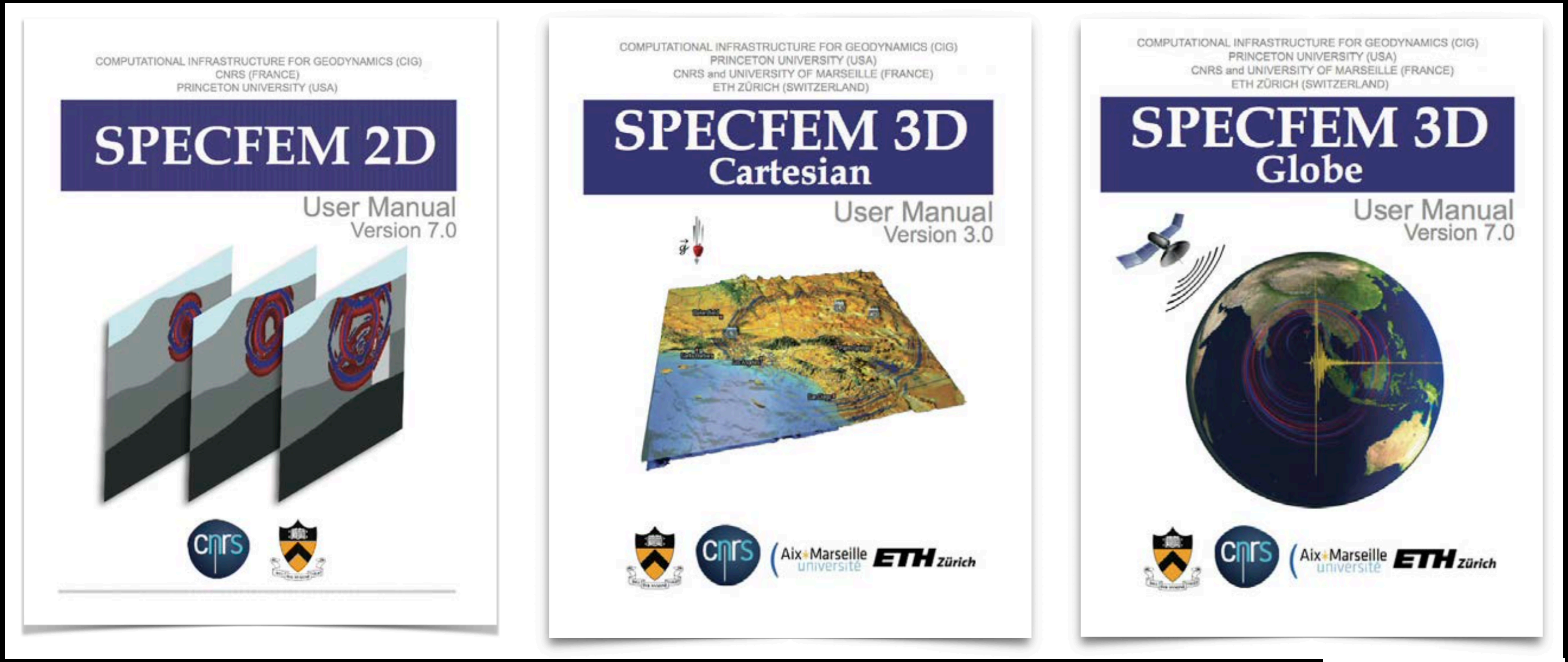
LGWA
LUNAR GRAVITATIONAL WAVE ANTENNA

07–11 ott 2024
Centro Internazionale Mariapoli - Castel Gandolfo

Outline

- SPECFEM3D suite: history, features, plans
- Simulating the moon: asteroid impact preliminary result
- Data
- Works in progress

SPECFEM3D suite https://specfem.org



We ❤ open-source.

The SPECFEM codes use the spectral-element method to simulate seismic wave propagation on different scales. They are open-source freely available on https://github.com/SPECFEM

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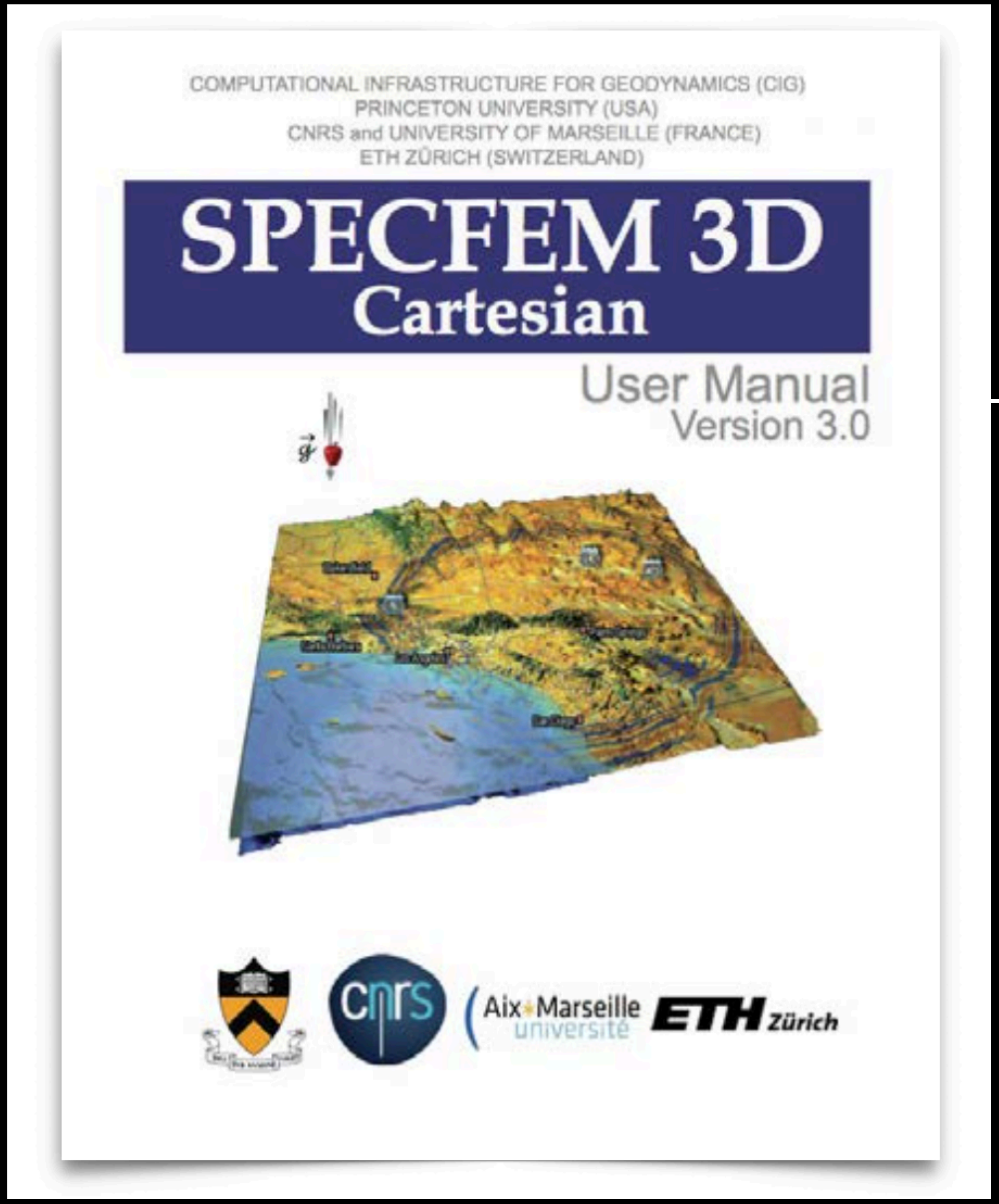
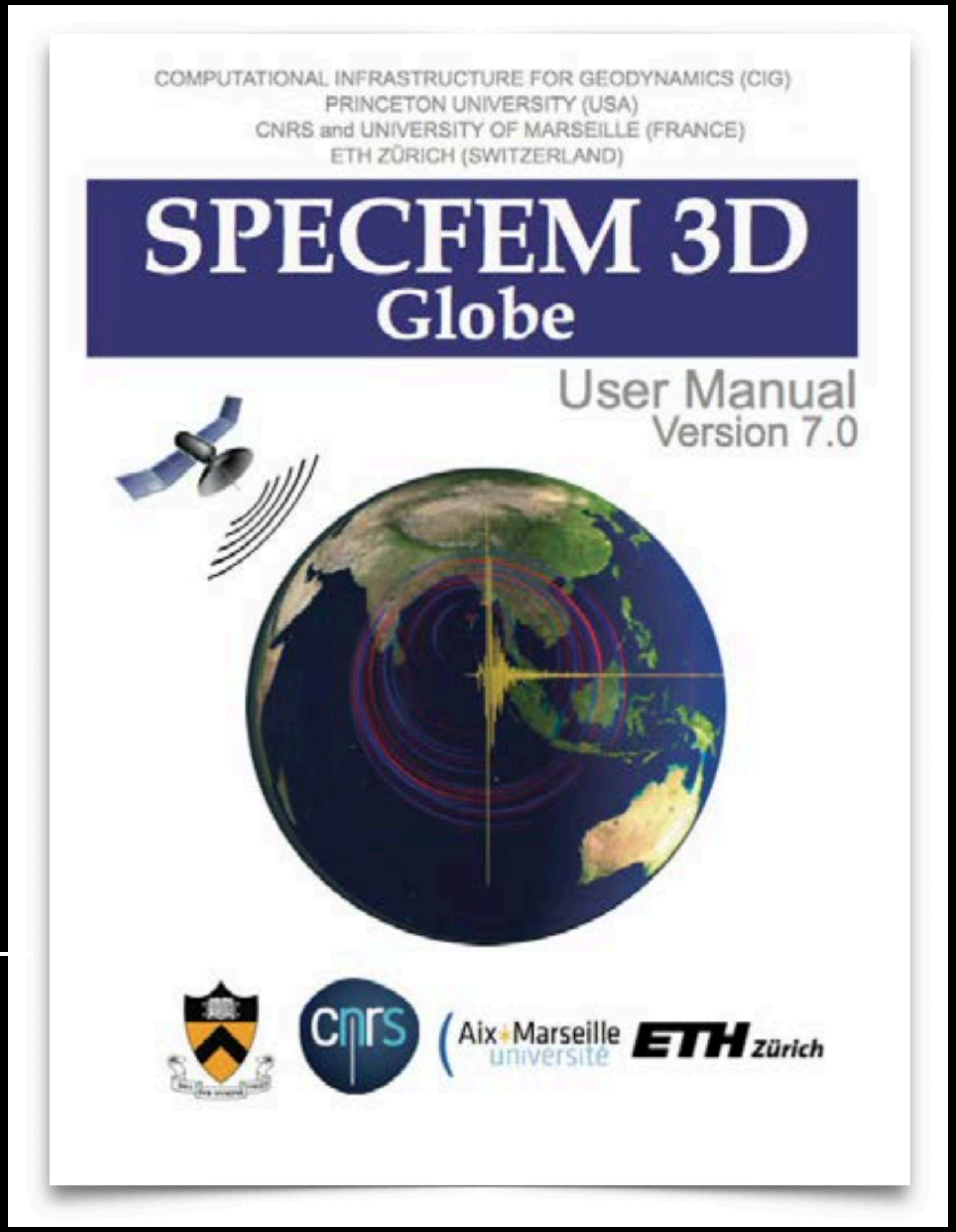
SPECFEM3D suite

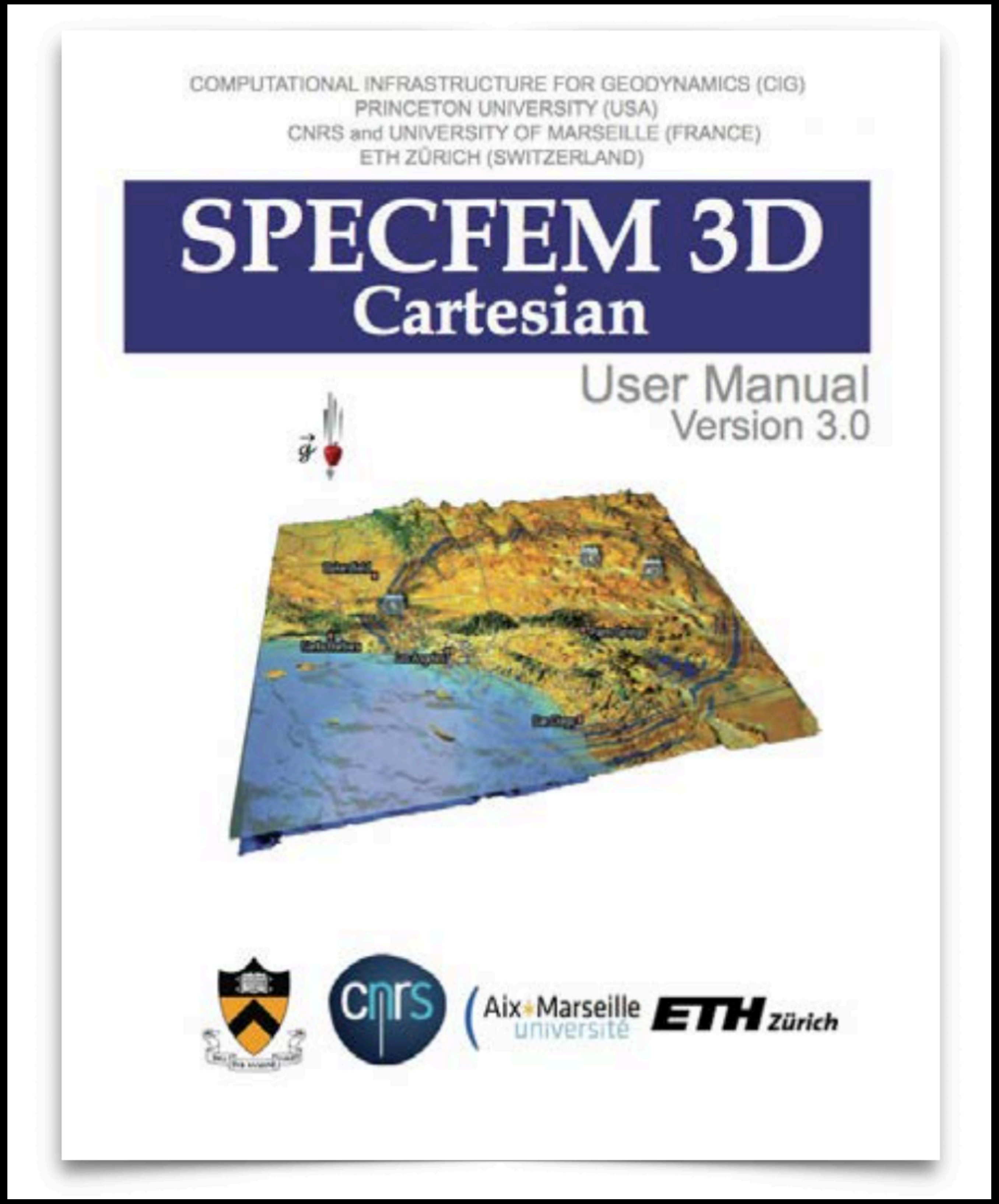


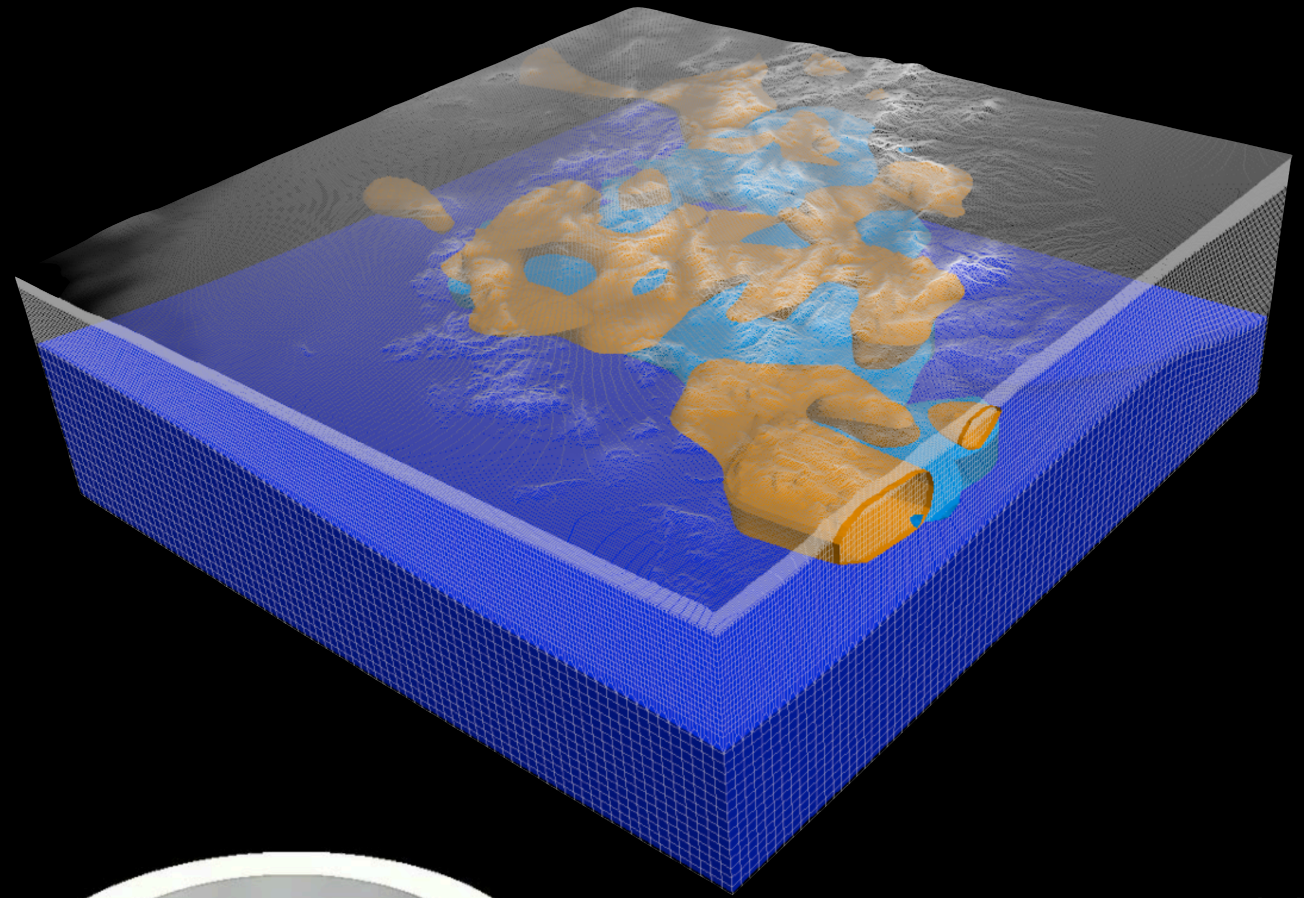
- 3D acoustic, elastic, poroelastic waves
- Unstructured meshes (CUBIT/Trelis, Gmsh)
- Load-balanced mesh partitioning
- Acoustic/elastic, Elastic/poroelastic,.. coupling
- C-PML
- fault rupture (dynamic/kinematic) simulations
- Anisotropy
- Attenuation
- Adjoint kernels
- CUDA / HIP support for GPUs

- 3D crust and mantle models
- Topography & Bathymetry
- Rotation
- Ellipticity
- Gravitation
- Anisotropy
- Attenuation
- Adjoint kernels
- CUDA / HIP / OpenCL support for GPUs



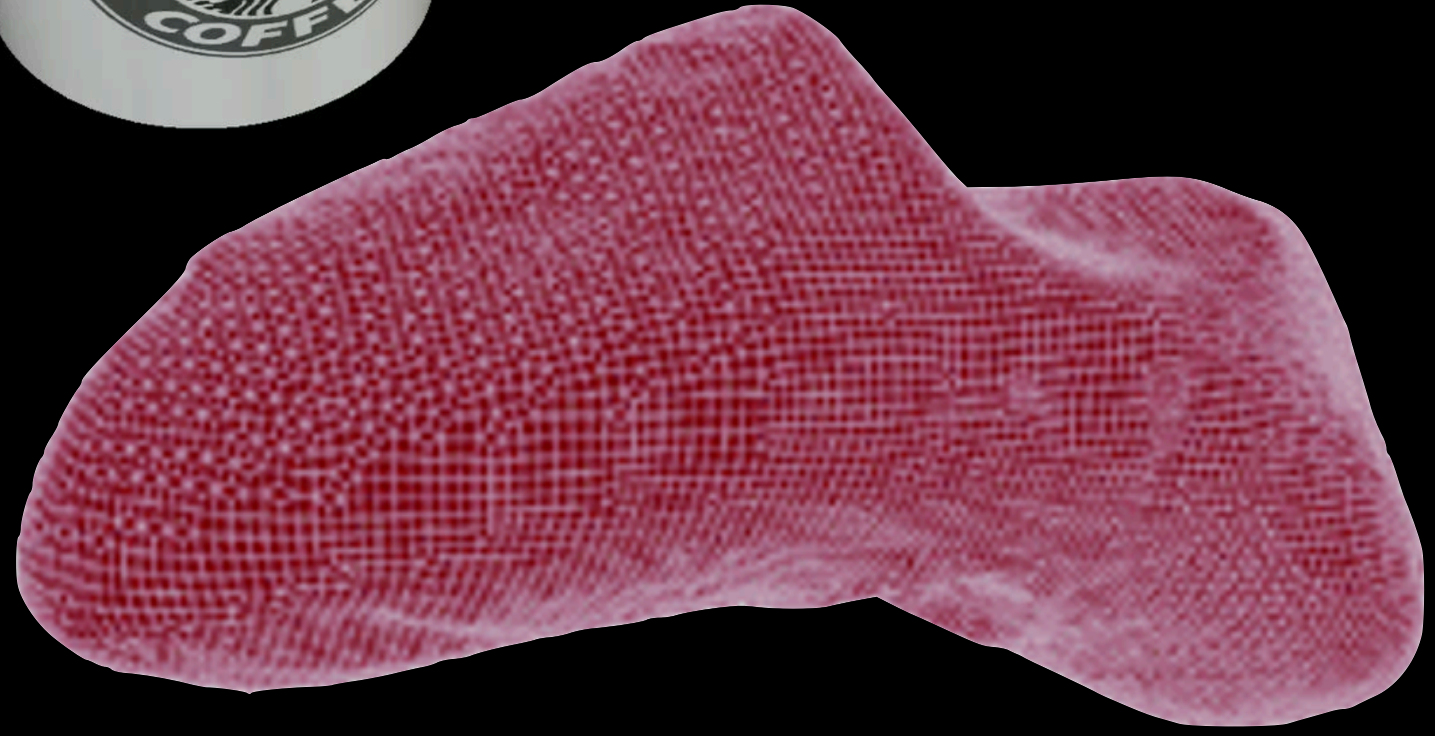
SPECFEM3D applications



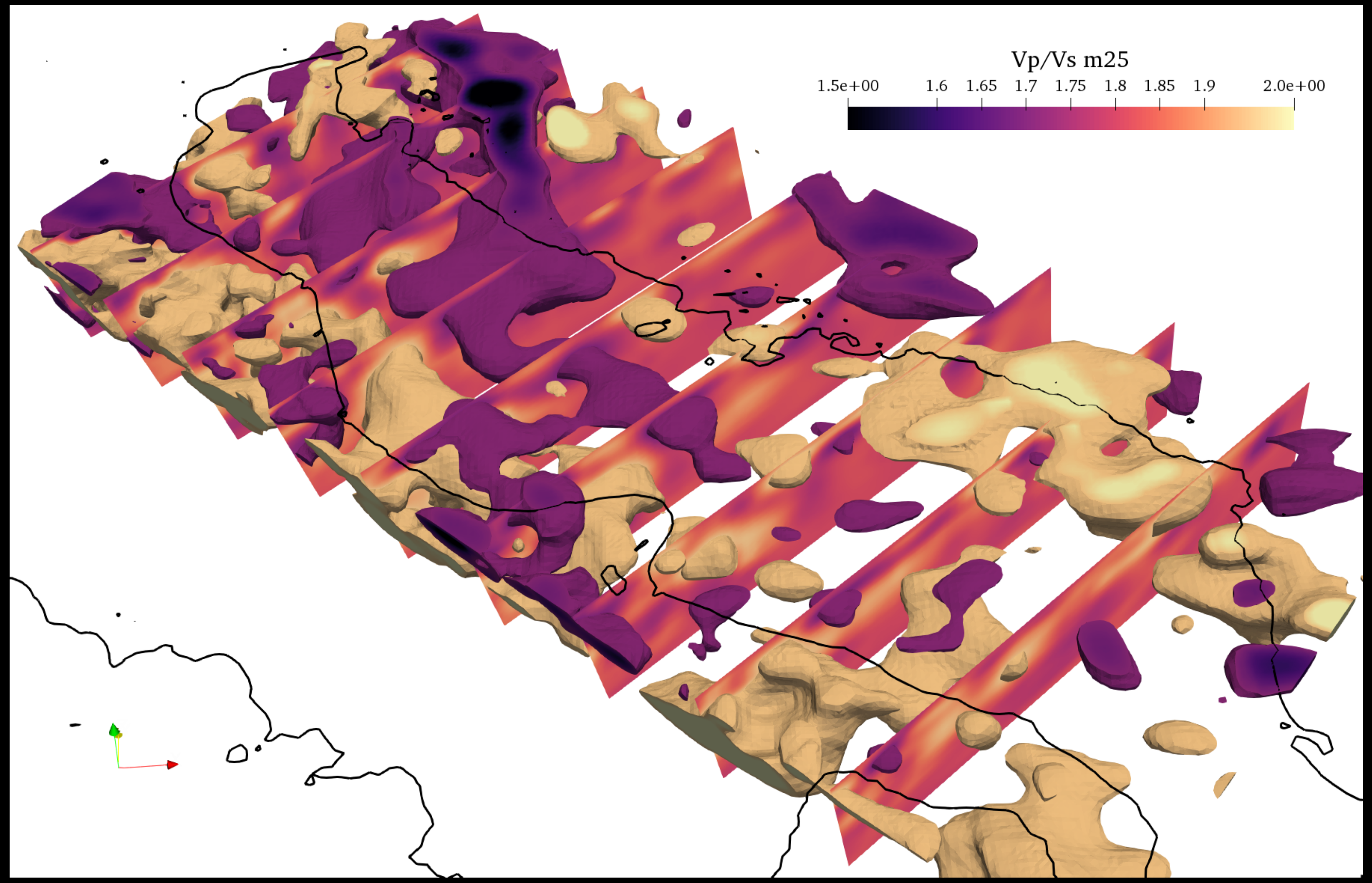


Istituto Nazionale di Geofisica e Vulcanologia

High resolution seismic wave propagation - 2009 Mw 6.3 L'Aquila



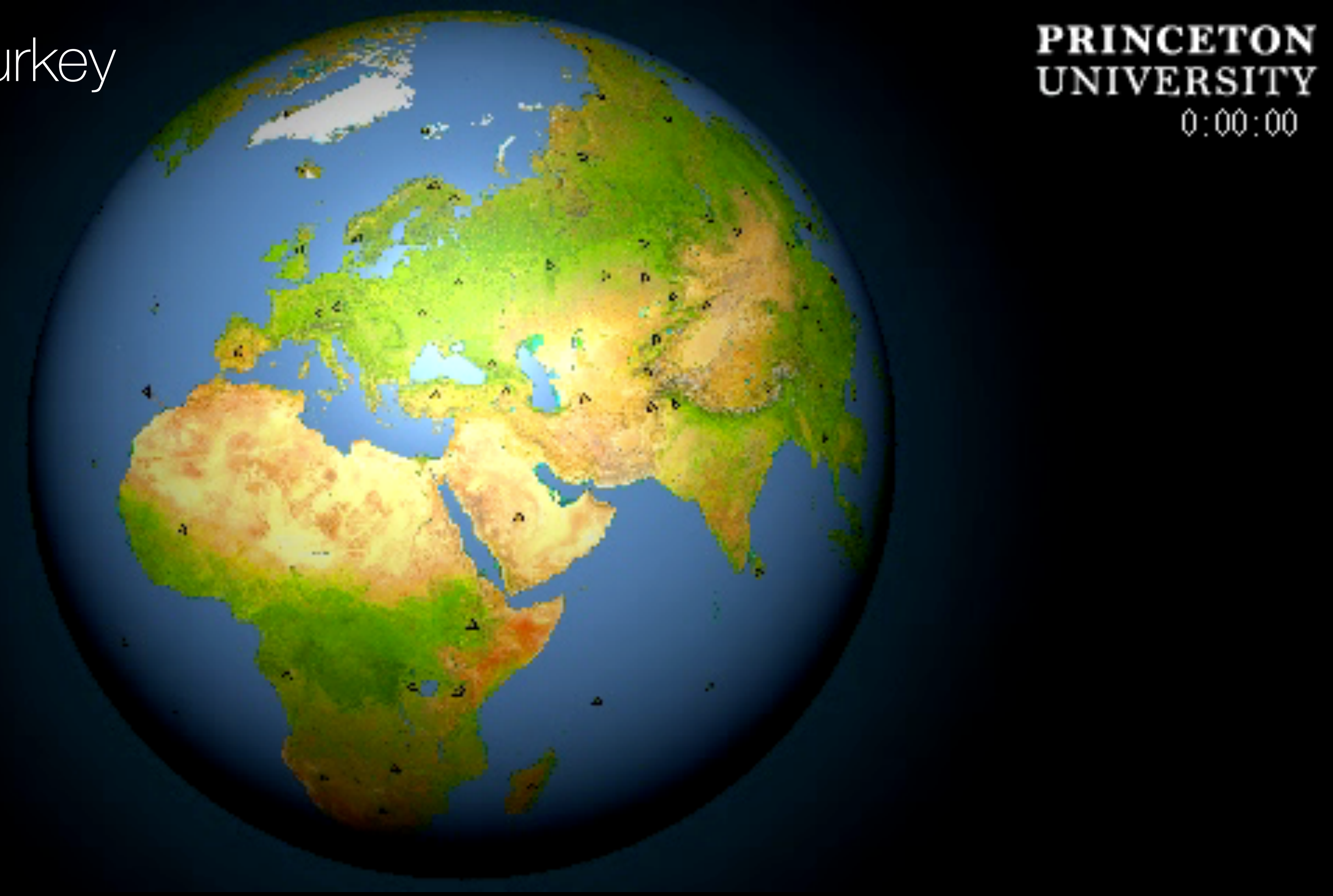
Unstructured Meshes - Asteroid Eros

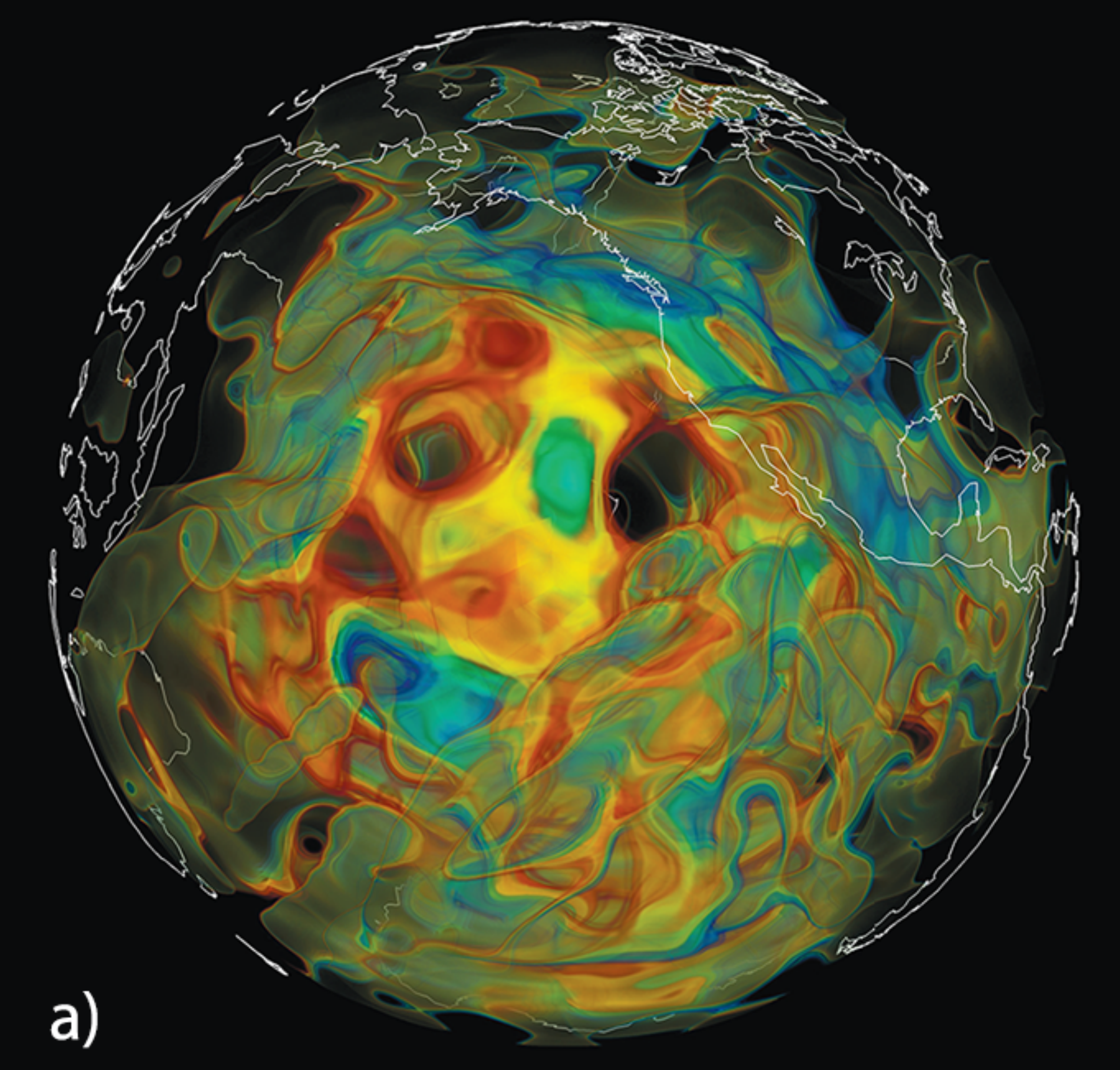


Adjoint Full Waveform Tomography - IMAGINE_IT, Italy

SPECFEM3D globe applications

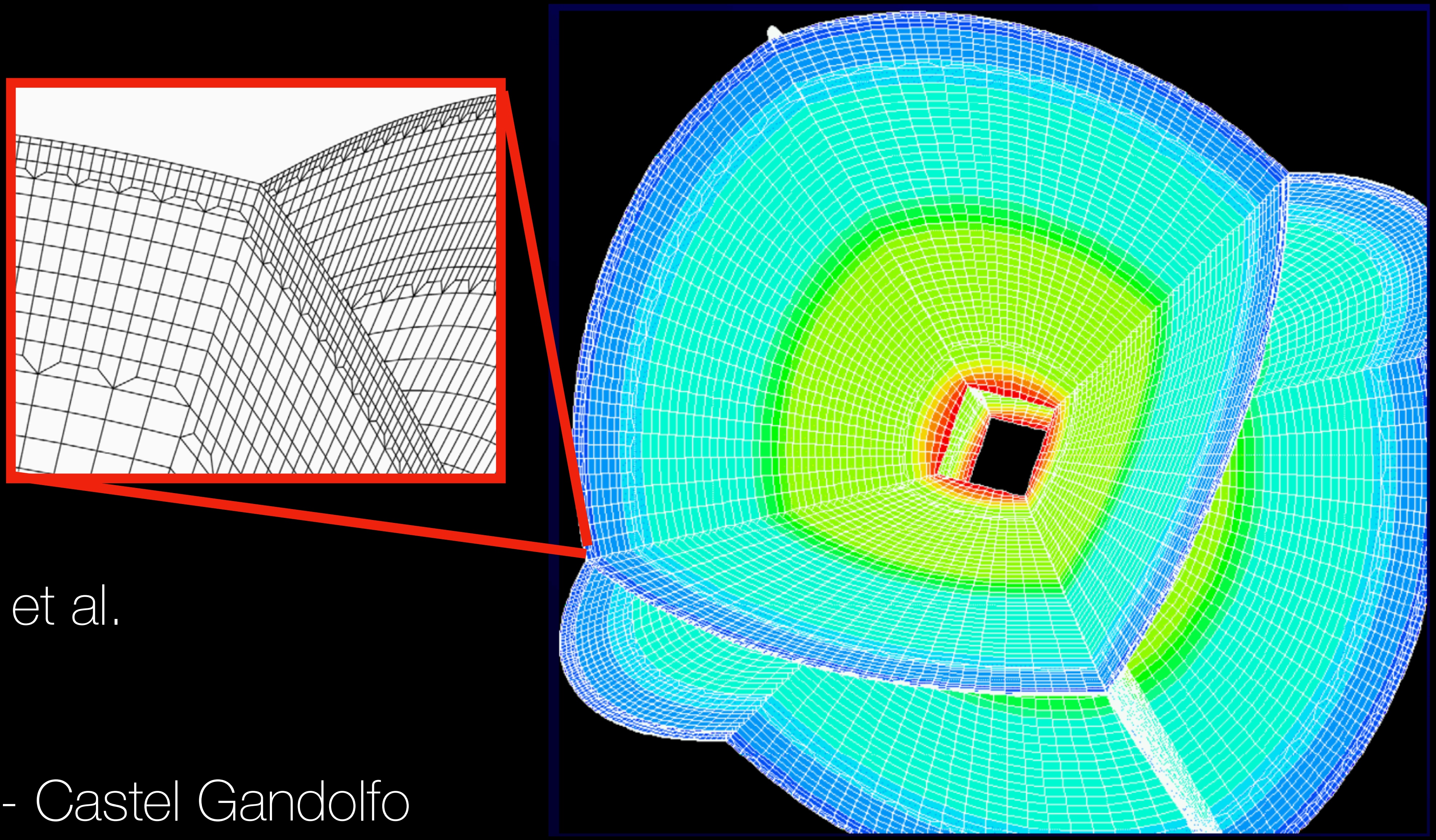
SHAKEmovie - 2023 Mw 7.9 Turkey

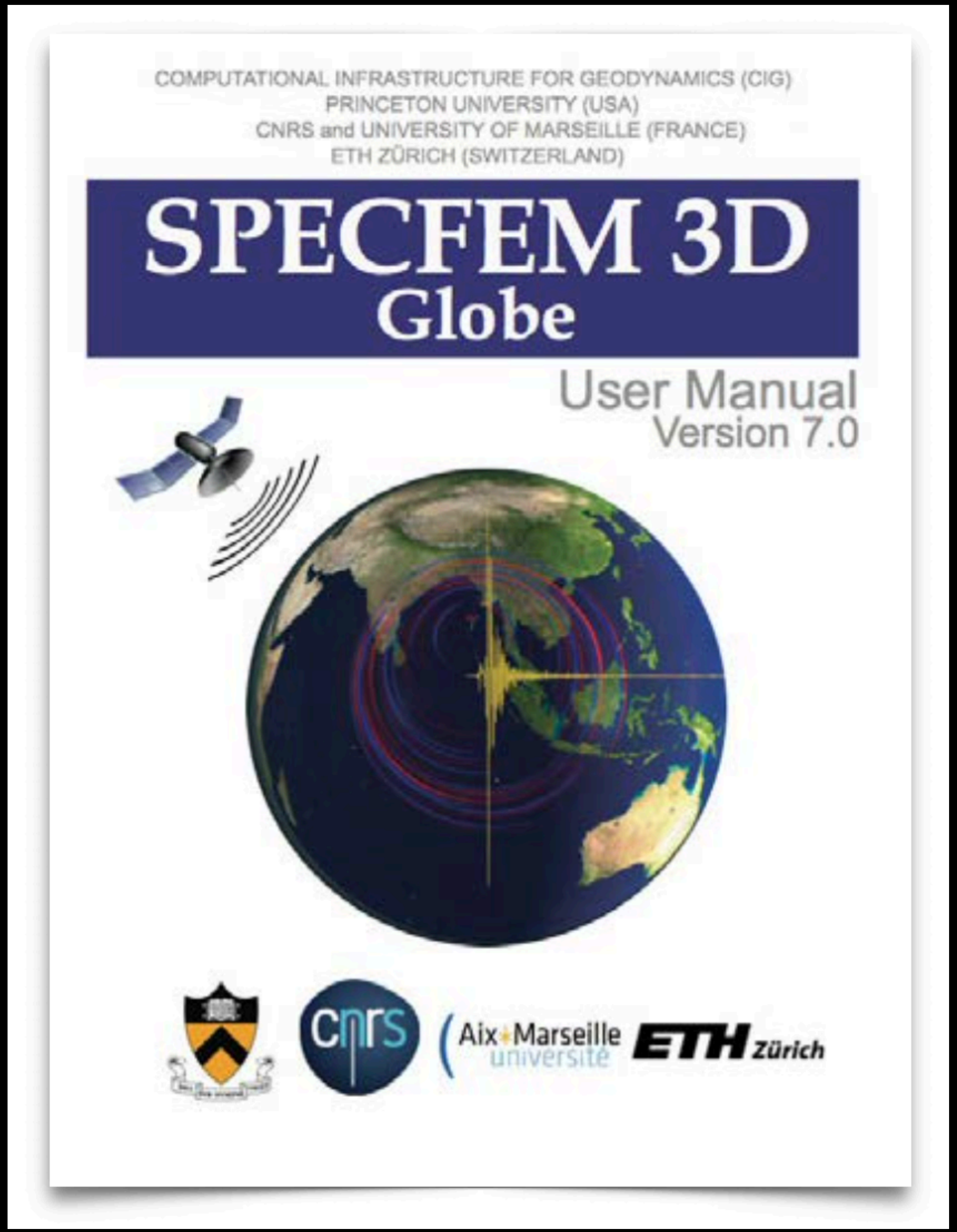




Adjoint Full Waveform Tomography - Earth - Bozdag et al.

Cubed sphere





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Spectral Element Method

Neglect mass redistribution - Cowling approximation

Wave equation solved by SPECFEM3D_GLOBE in crust, mantle and inner core:

$$\rho\left(\partial_t^2 \mathbf{s} + 2\boldsymbol{\Omega} \times \partial_t \mathbf{s}\right) = \nabla \cdot \mathbf{T} + \nabla(\rho \mathbf{s} \cdot \mathbf{g}) - \nabla \cdot (\rho \mathbf{s})\mathbf{g} + \mathbf{f}$$

Wave equation solved by SPECFEM3D_GLOBE in fluid outer core:

$$\partial_t^2 \mathbf{s} + 2\boldsymbol{\Omega} \times \partial_t \mathbf{s} = \nabla(\rho^{-1}\kappa \nabla \cdot \mathbf{s} + \mathbf{s} \cdot \mathbf{g})$$

SPECFEM3D_GLOBE uses domain decomposition between the fluid outer core and the solid inner core and mantle matching exactly:

- continuity of traction
- continuity of the normal component of displacement

- WEAK FORM
- HEX elements
- GAUSS-LOBATTO-LEGENDRE quadrature, GLL points
- Diagonal Mass Matrix (no inversion of a linear system)
- Explicit time-marching scheme

Developed in Computational Fluid Dynamics (Patera 1984)

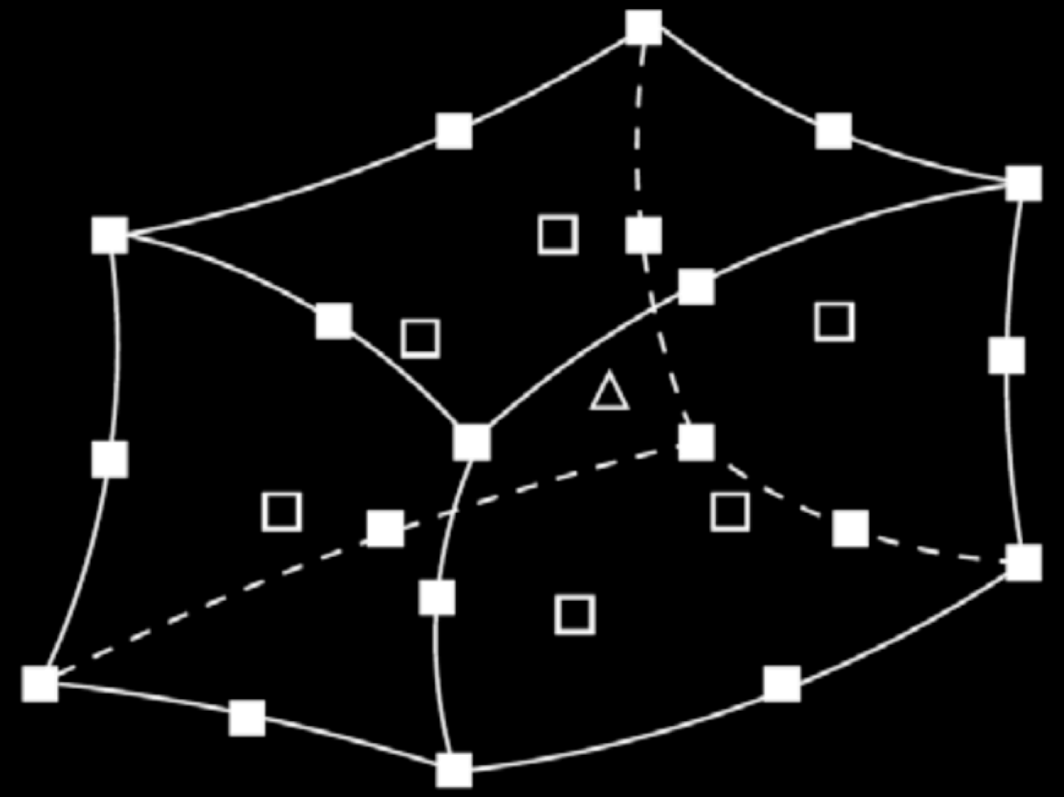
Accuracy of a pseudospectral method, flexibility of a finite-element method

Extended by Komatitsch and Tromp, Chaljub et al., Capdeville et al.

Large curved “spectral” finite-elements with high-degree polynomial interpolation

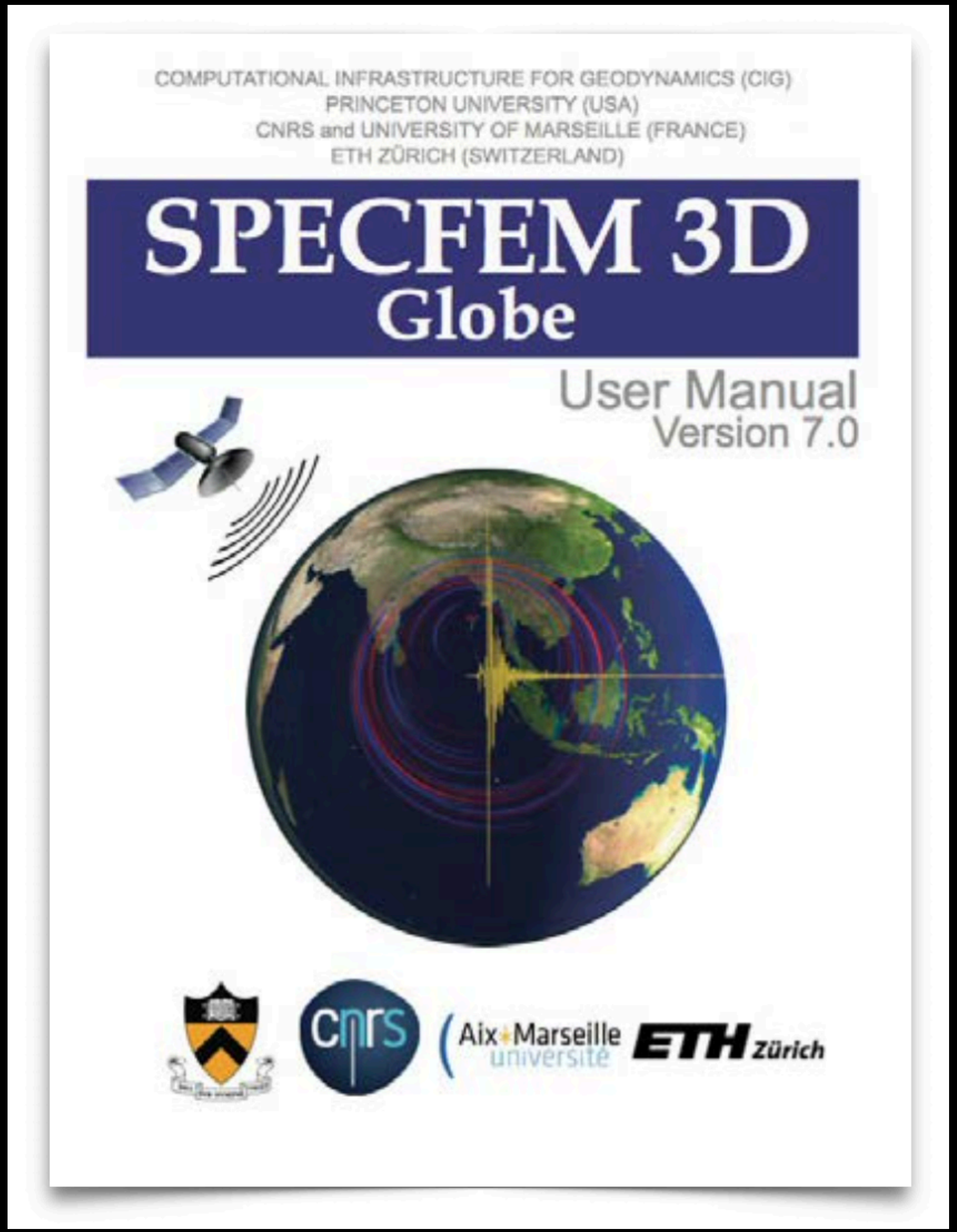
Mesh honors the main discontinuities (velocity, density) and topography

Very efficient on parallel computers, no linear system to invert (diagonal mass matrix)



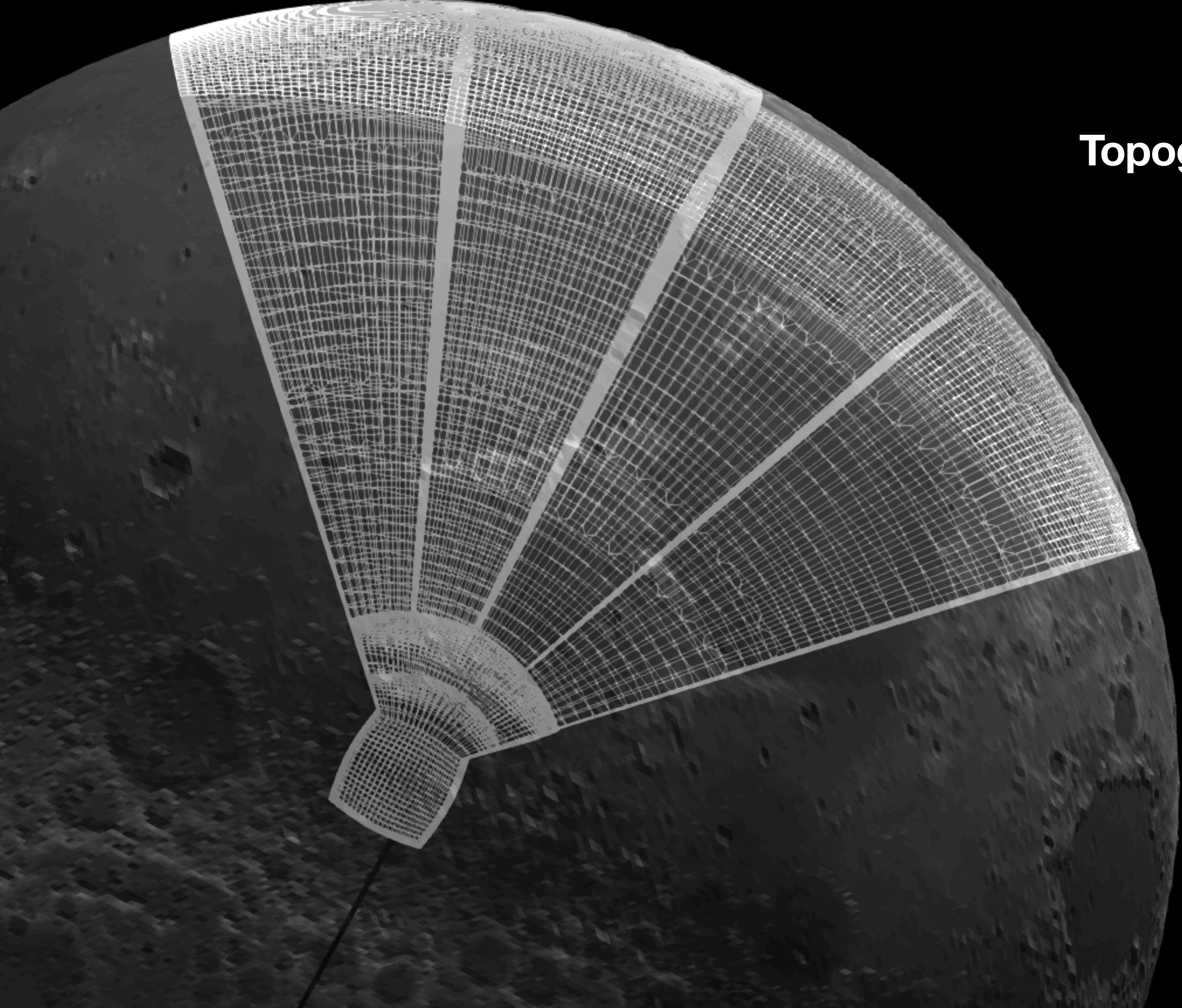
SPECFEM3D globe - planetary applications

Courtesy of D. Peter



Synthetic wavefield: meteoroid impact

SPECFEM3D_globe



Topography: Lunar Orbiter Laser Altimeter (**LOLA**)
0.9 arc-minute

Moon **radius** 1737.1 km

Elements size = 21 km (128 NEX)
~1M Hex

Moon model **VPREMOON** from reference:

Garcia et al. (2011),
Very preliminary reference Moon model,
PEPI, 188, 96 - 113.

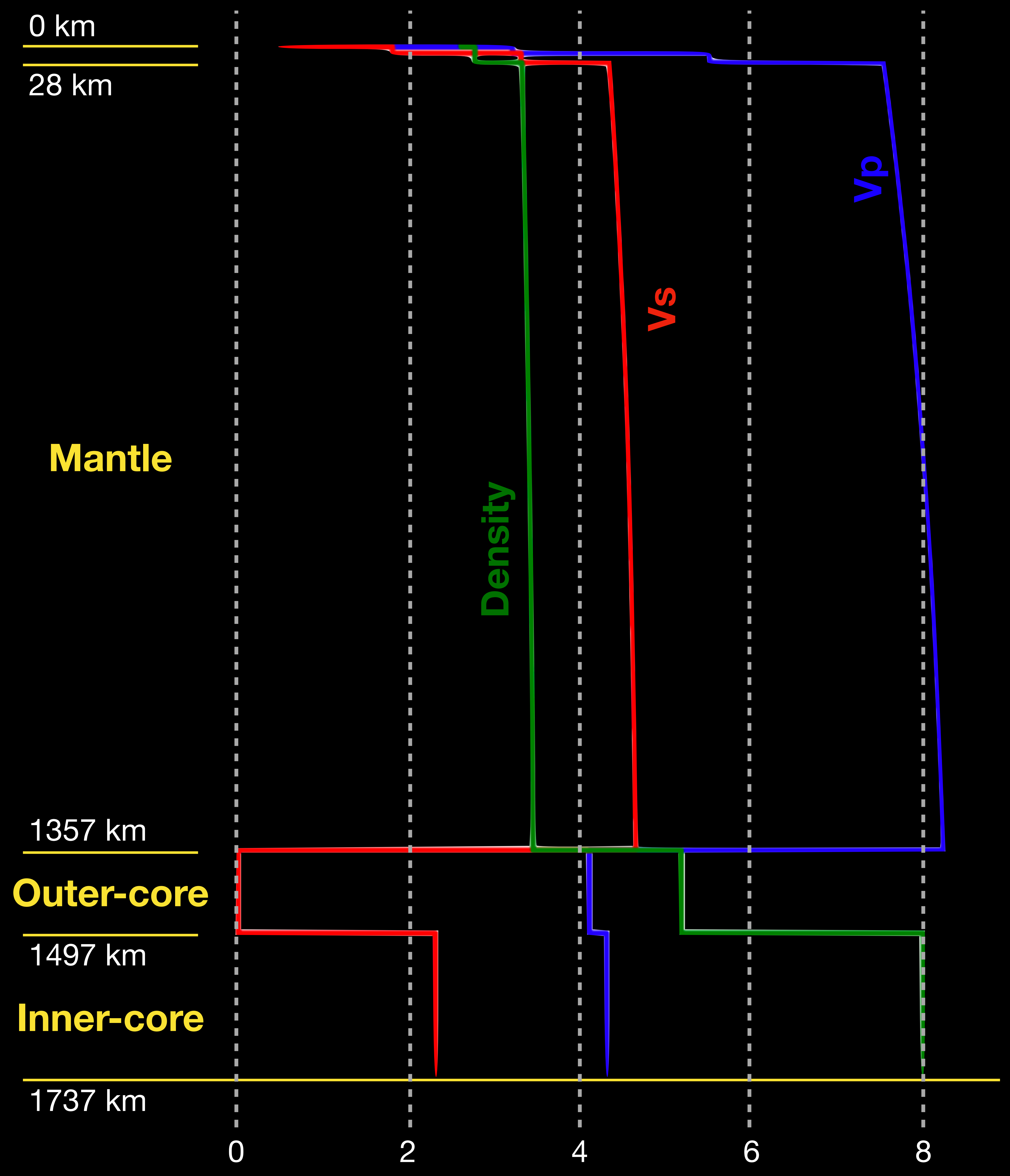
combined with core values from:

Weber et al. (2011),
Seismic Detection of the Lunar Core,
Science, 331.

Assuming a solid inner core

Synthetic wavefield: meteoroid impact

SPECFEM3D_globe



Topography: Lunar Orbiter Laser Altimeter (**LOLA**)
0.9 arc-minute

Moon **radius** 1737.1 km

Elements size = 21 km (128 NEX)
~1M Hex
The minimum period resolved is around 12 s

Moon model **VPREMOON** from reference:

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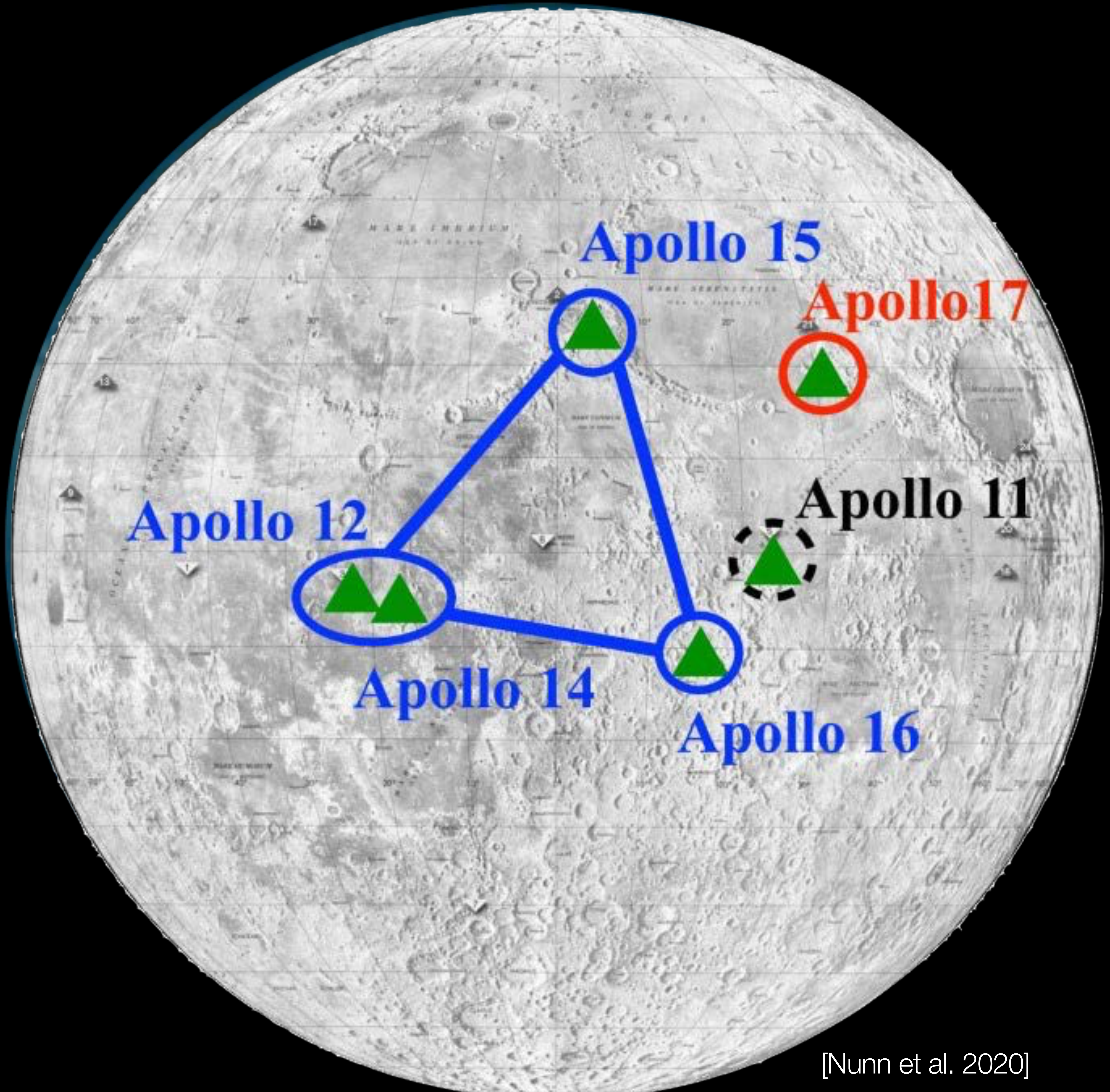


[Nunn et al. 2020]

Synthetic wavefield: meteoroid impact

SPECFEM3D_globe

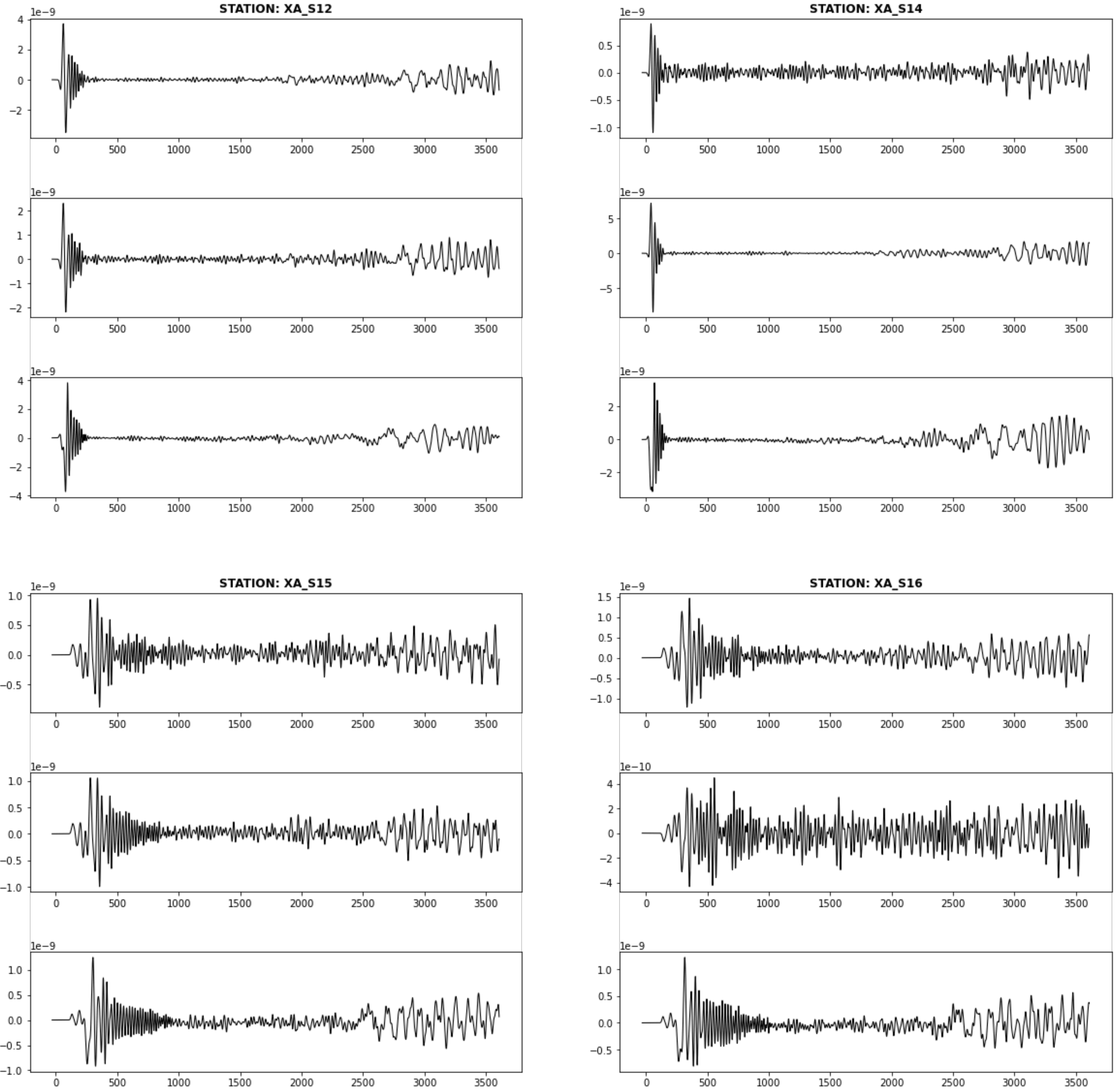
Source: perpendicular force
meteoroid impact on May 13, 1972
1.1 N, 16.9 W (+/- 0.2 degree)
factor force source: 5.e+9 N

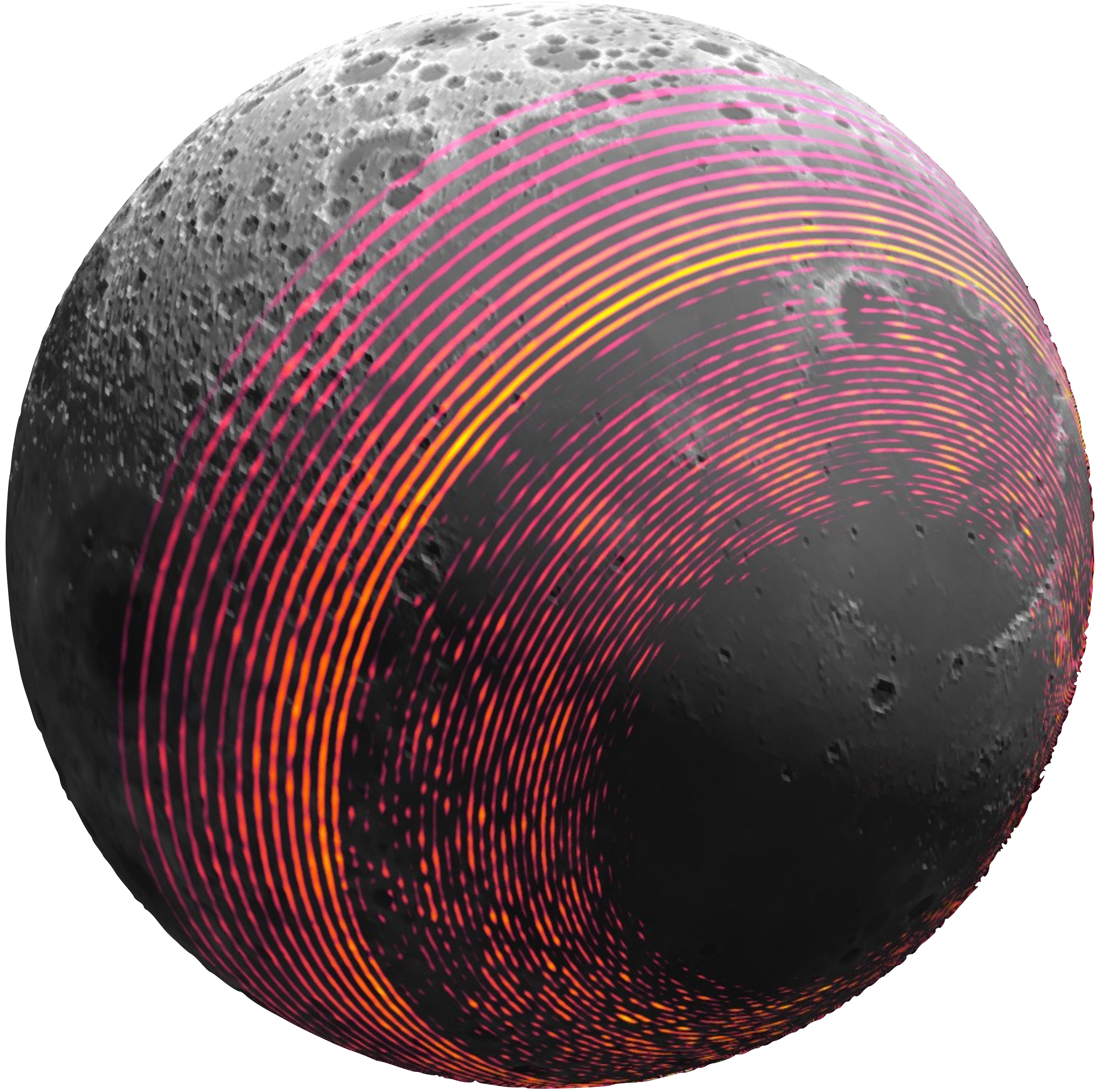
Receivers:
Apollo Passive Seismic Experiments

S12	-3.01084	-23.42456
S14	-3.6445	-17.47753
S15	26.13407	3.62981
S16	-8.97577	15.49649

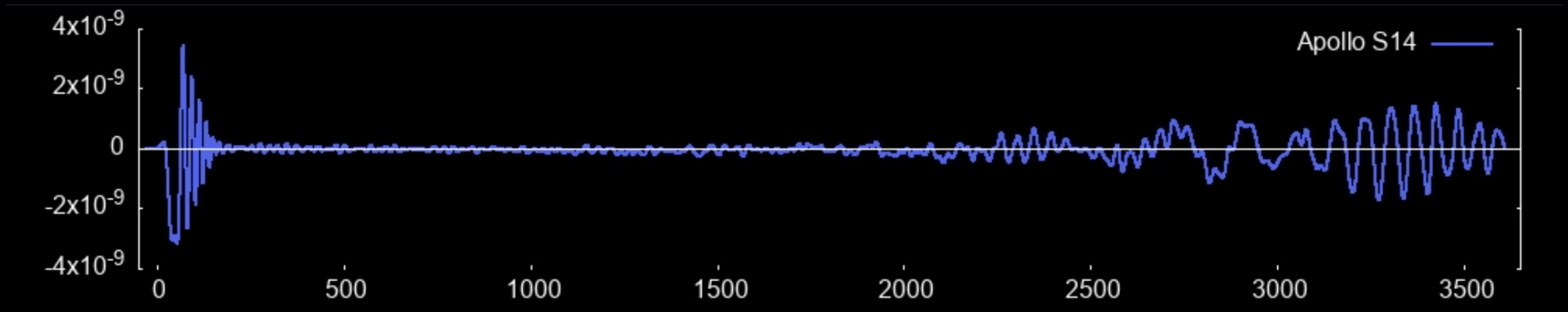
Simulations:
Seismograms 60 minutes
96 CPU processor
DT=0.95 s
1 h 41m CPU time

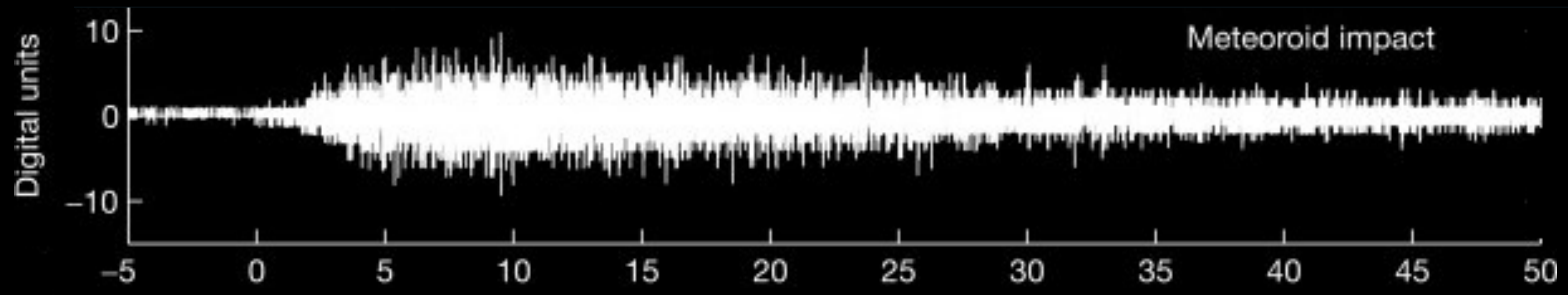
Synthetic wavefield: Meteoroid impact

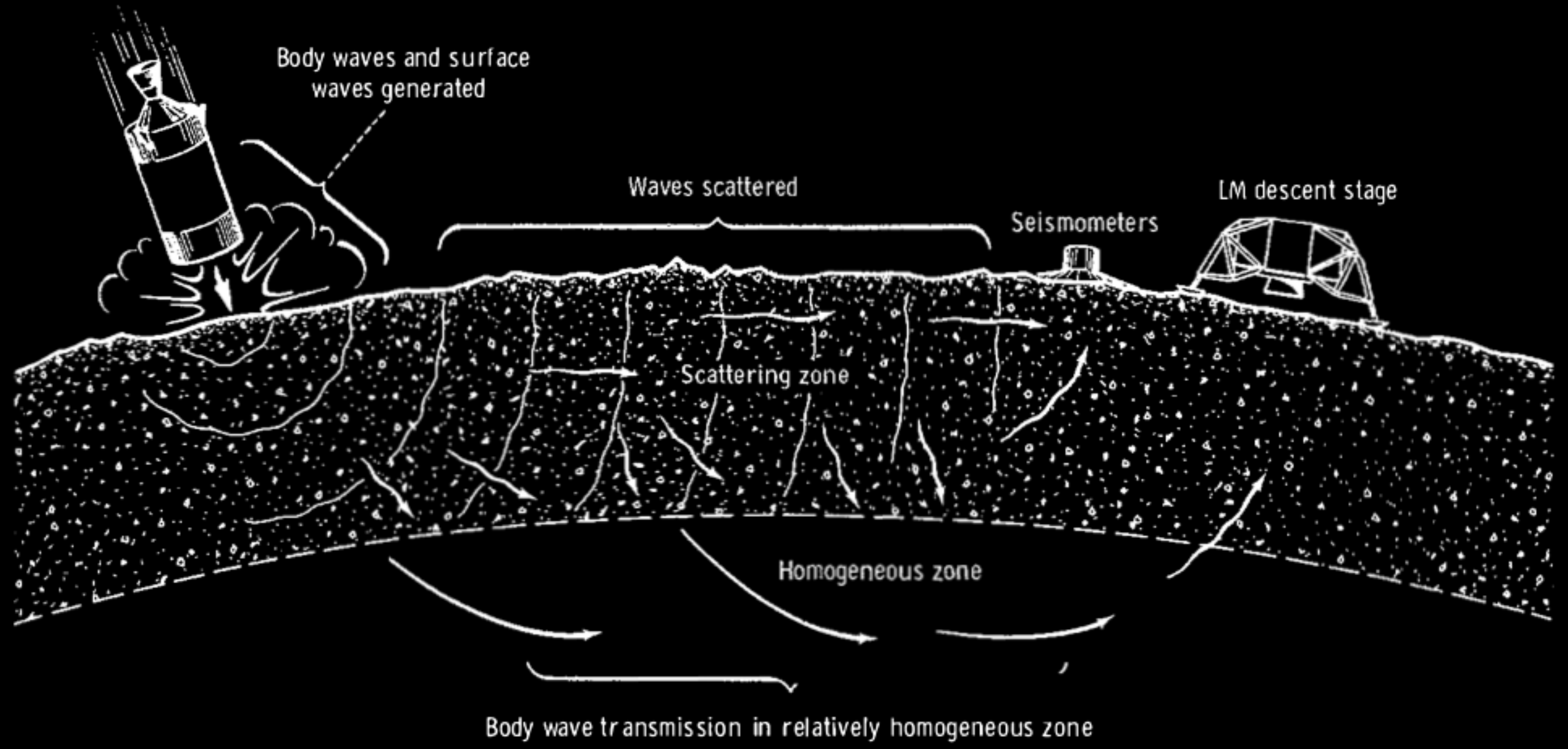


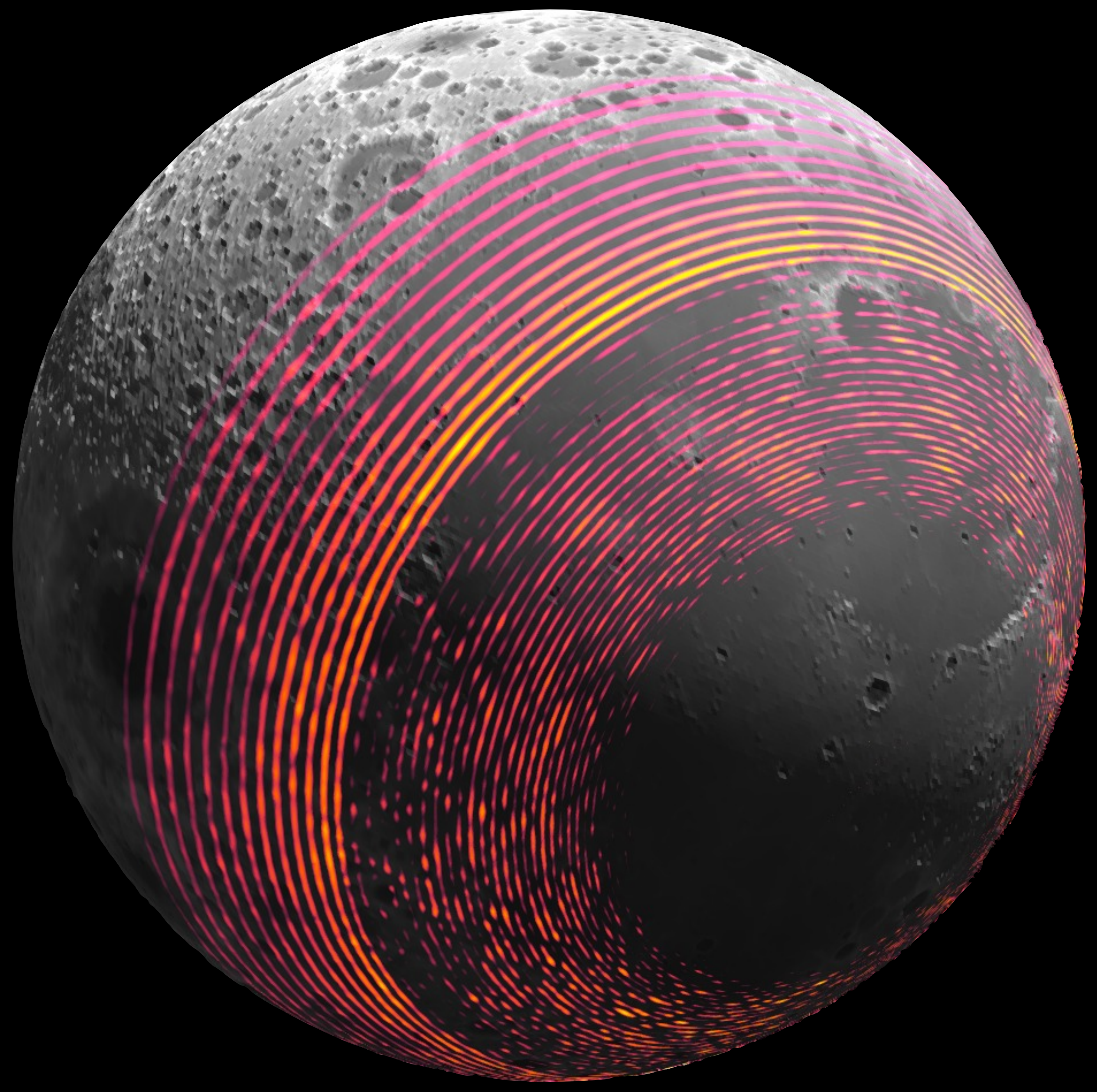


Scattering









[Apollo 14 preliminary science report, 1971]

Synthetic wavefield: Work in progress

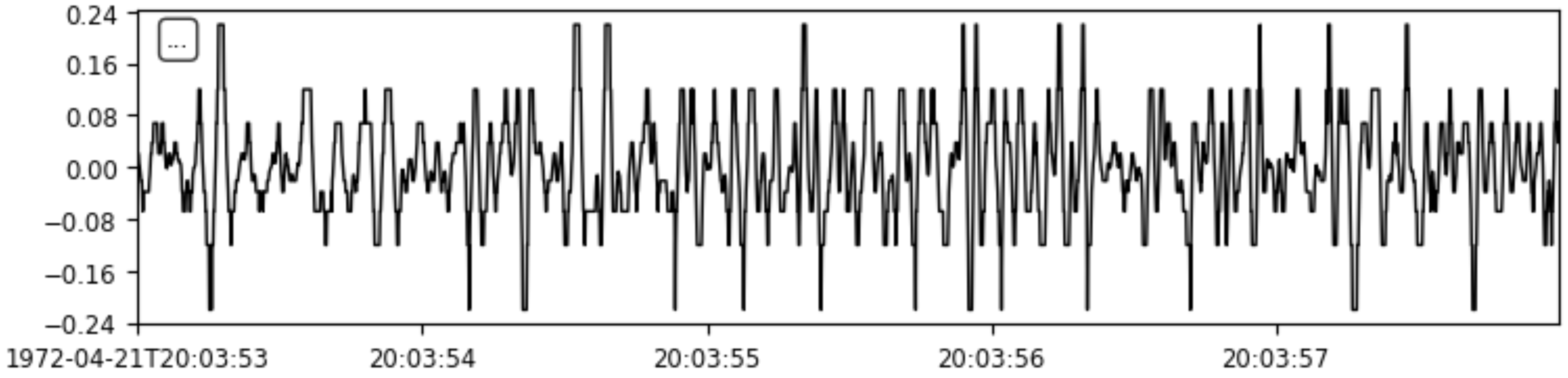
SPECFEM3D_globe

Comparison DATA and SYNTHETIC for meteoric and lander impact -> scattering

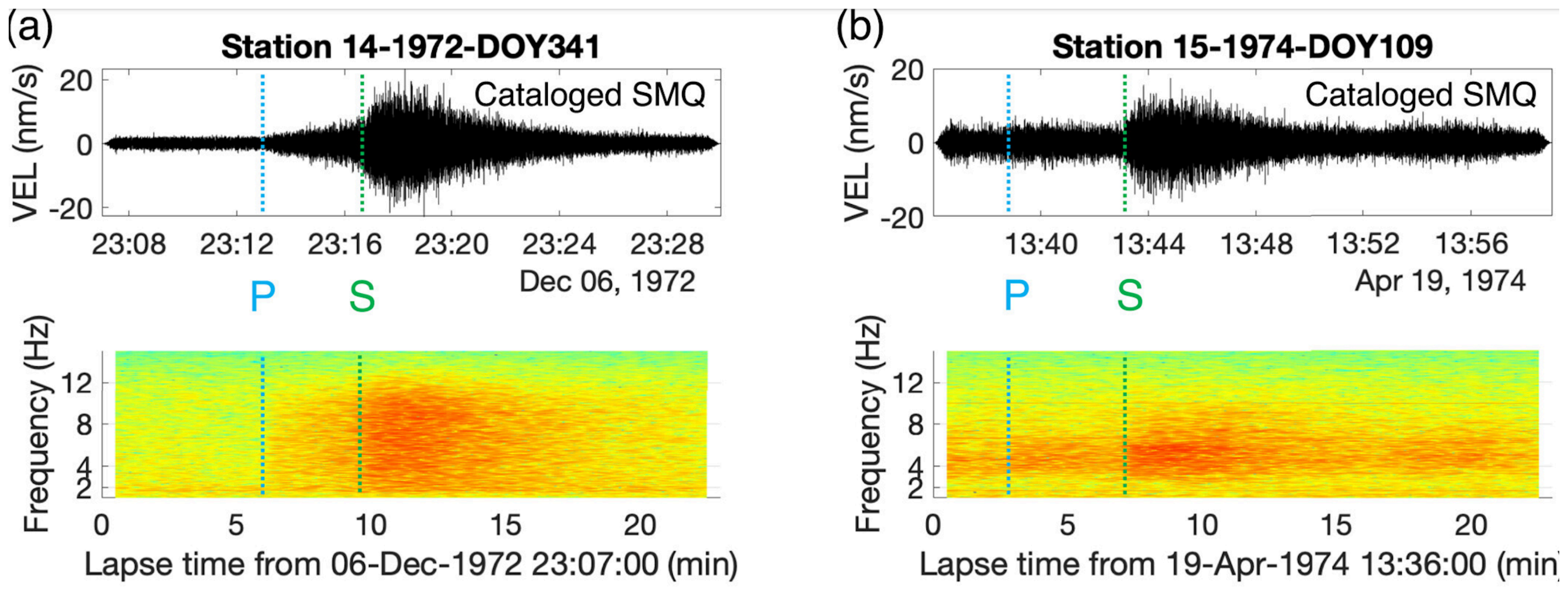
Multiple simulations for noise

SPECFEM3D

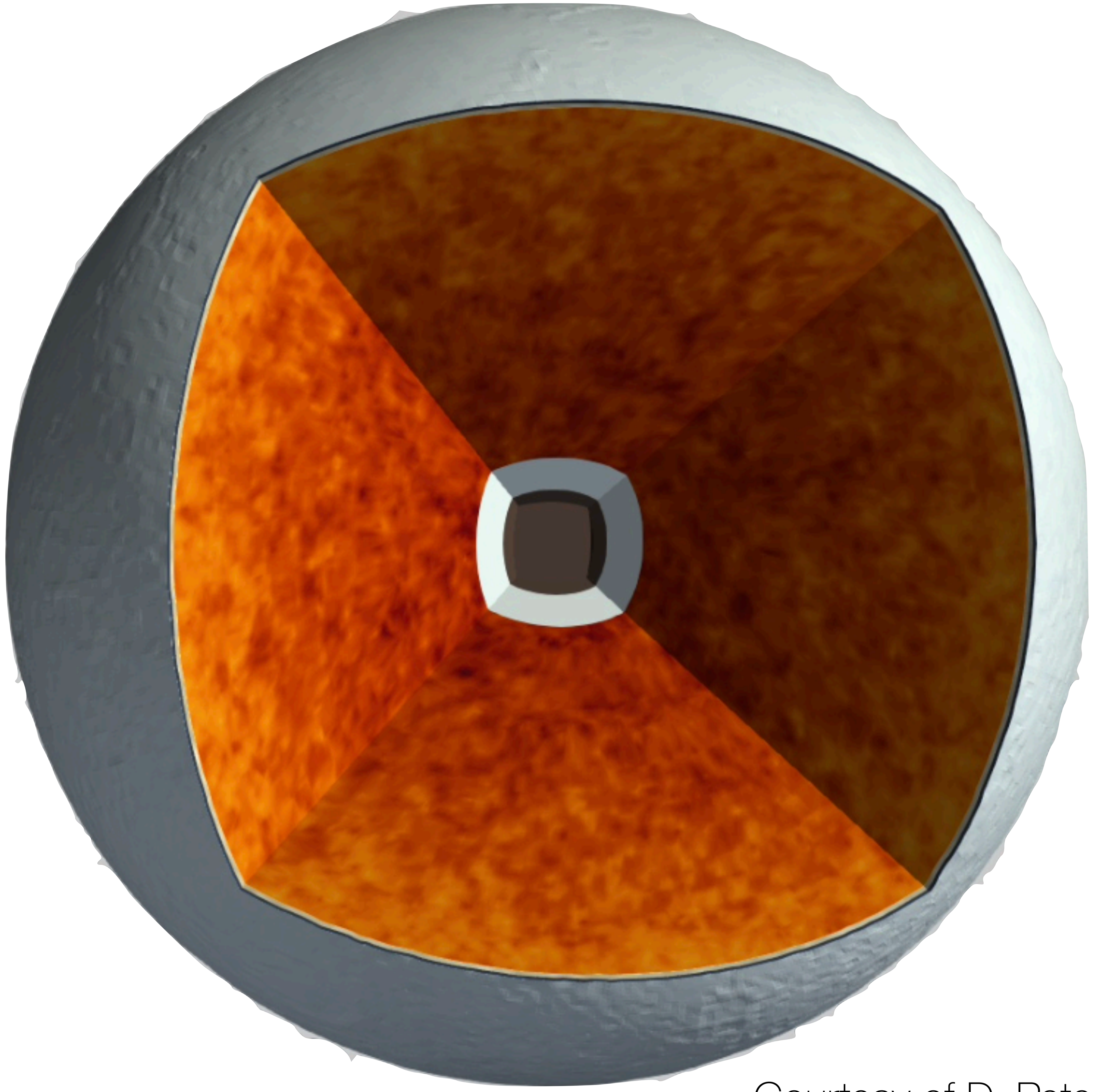
Reproducing the data from the Apollo 16 active seismic experiment



Unstructured Mesh and higher frequency



(Ondera, 2024)



Courtesy of D. Peter