Tsunami Modeling for Early Warning Systems

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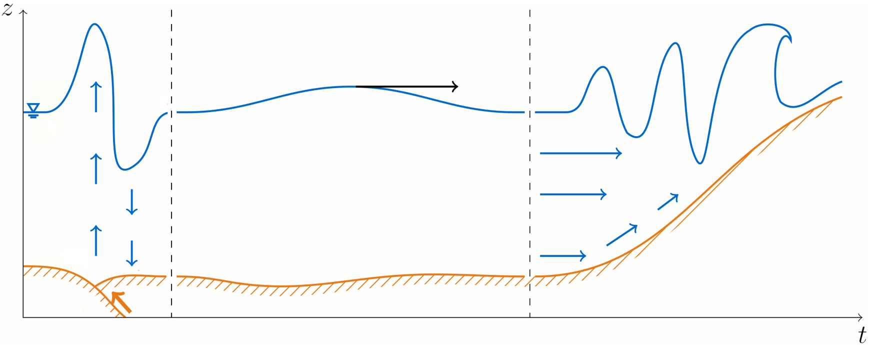
Overview

Tsunami modeling

- Model physics and discretization
- Reliability, and limitations
- From sensor data to warning products
  Example: Indonesian TEWS
- How could SMART cable help to improve the warning?

Model physics

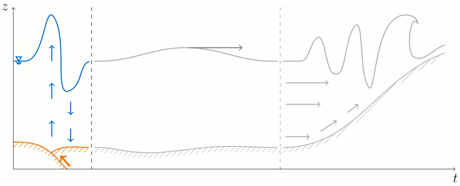
Phases of a tsunami



Origin in deep water at the coast

Model physics

Phases of a tsunami: Origin

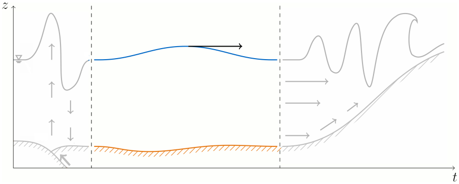


Model physics

- Complicated to simulate the full model physics
- Exact source often unknown - largest uncertainty in tsunami early warning!
- Simple approach: Add vertical bottom displacement to sea level. Works surprisingly well!

Model physics

Phases of a tsunami: Propagation in deep water



Model physics

- Shallow water equations
- Simple: Pressure gradient suffices
- Very fast models only simulate this phase

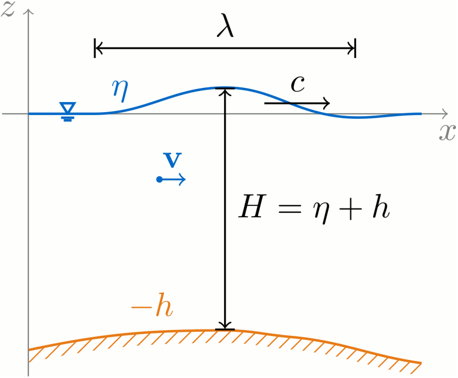
Model physics

Shallow water equations

Derived from the Navier-Stokes equations with the assumptions

- $\lambda \gg H$,
- incompressible fluid,
- constant density ρ (neglect temperatur, salinity!),
- Vertical velocity constant in the water column.

$\Longrightarrow$ **vertical average**



Model physics

Shallow water equations (SWE)

conservation of momentum

$$\frac{\partial \mathbf{v}}{\partial t} + \overbrace{g\nabla\eta}^{\text{pressure gradient}} + \overbrace{f\,\mathbf{k}\times\mathbf{v}}^{\text{Coriolis}} + \overbrace{(\mathbf{v}\cdot\nabla)\mathbf{v}}^{\text{non-lin. advection}} + \overbrace{\frac{r}{H}\mathbf{v}|\mathbf{v}|}^{\text{bottom roughness}} + \overbrace{\nabla(K_h\nabla\mathbf{v})}^{\text{viscosity}} = 0,$$

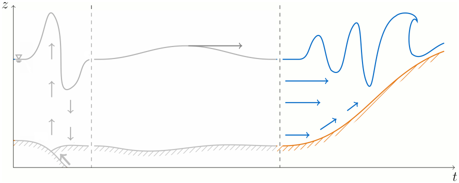
conservation of mass

$$\frac{\partial \eta}{\partial t} + \nabla\cdot(H\,\mathbf{v}) = 0$$

with Coriolis parameter f, coefficients for bottom roughness r and viscosity K_h.

Model physics

Phases of a tsunami: At the coast



Model physics

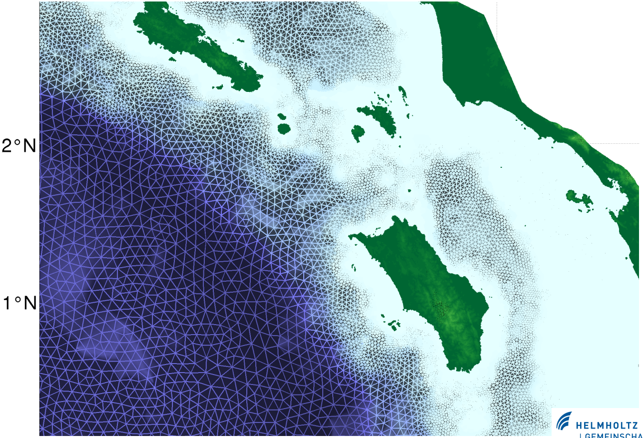
- Shallow water equations stretched to the limit
- Very sensitive to bathymetry, topography, bottom roughness
- Compute intensive (high grid resolution, short timestep)
- Important for time series: Reflection at the coast
- Fast models assume border at 50m-100m depth, extrapolate wave height by Green's law: $\eta(1\text{m}) \approx \eta(x\text{m})\sqrt[4]{x}$

Model physics

TsunAWI

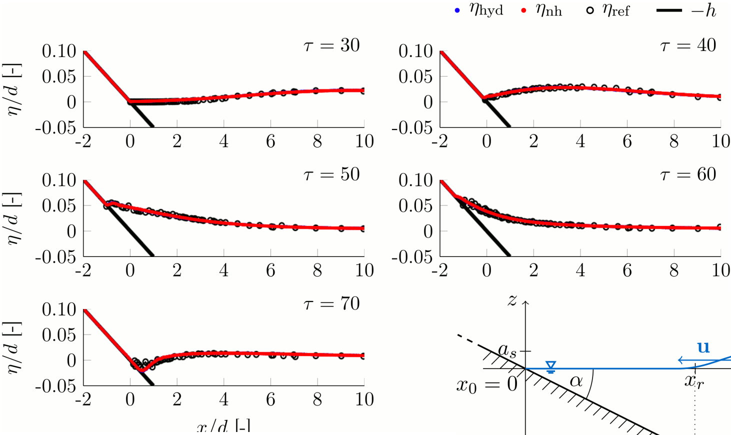
The computational domain reflects the characterics of tsunamis:
Small triangles (50m-200m) at the coast,
large triangles in the deep ocean (up to 25km).

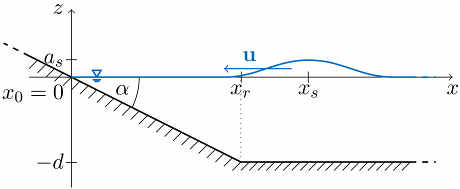
$$\Delta x \approx \min\left(\frac{c_{\mathrm{CFL}}}{\sqrt{gH}}, \frac{c_{\mathrm{bathy}}}{|\nabla H|}\right)$$



TsunAWI Verification

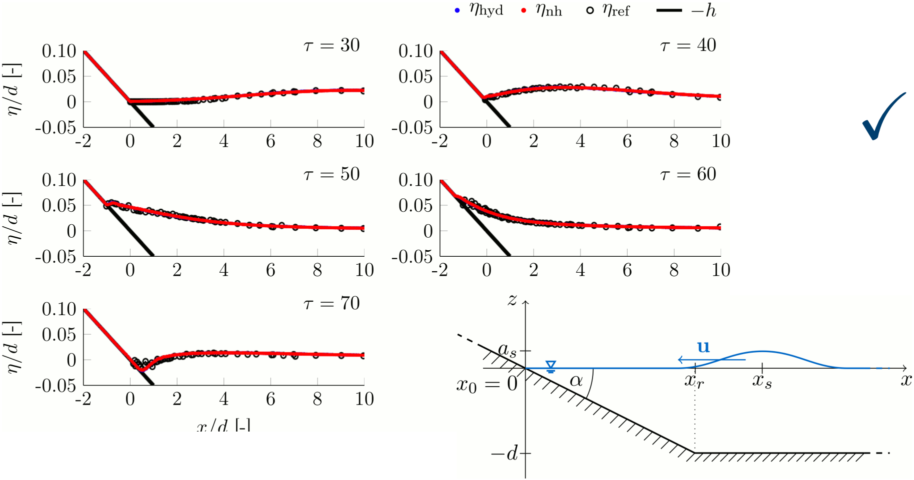
Run-up on a sloping beach





TsunAWI Verification

Run-up on a sloping beach



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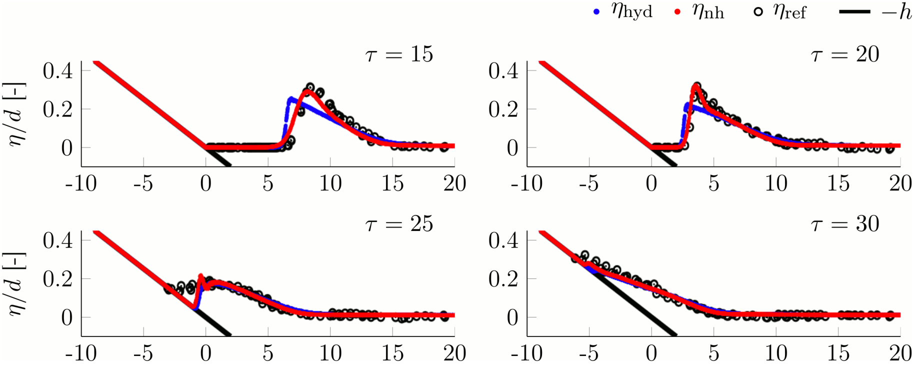
TsunAWI Verification

Run-up on a sloping beach

For higher initial waves, the hydrostatic shallow water equations are no longer valid. Furthermore, numerical errors occur.

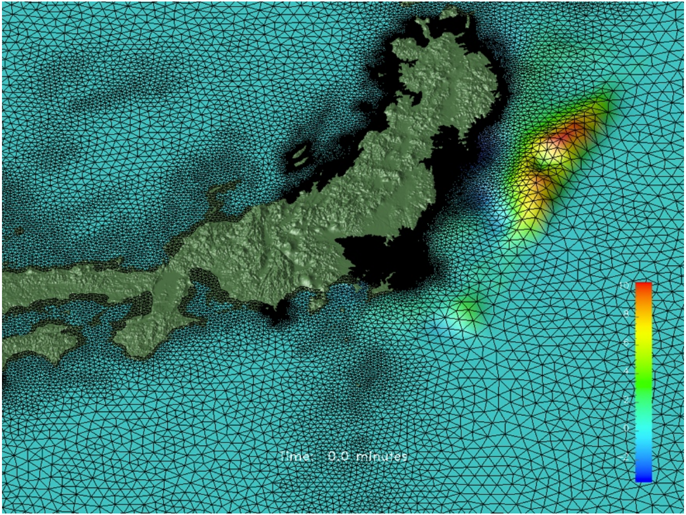


However, diagnostic variables like arrival time and maximum run up are still met well.

TsunAWI Verification

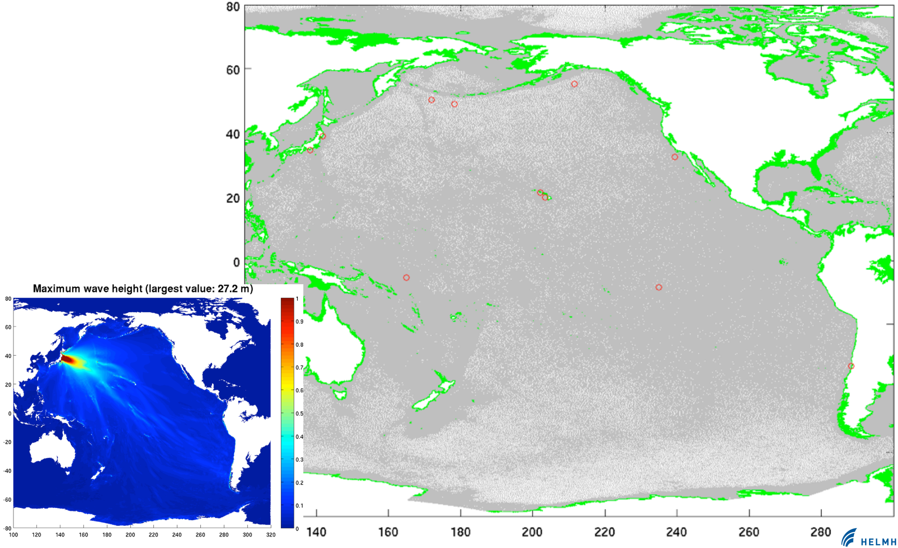
Real event, Japan 2011

Source: USGS



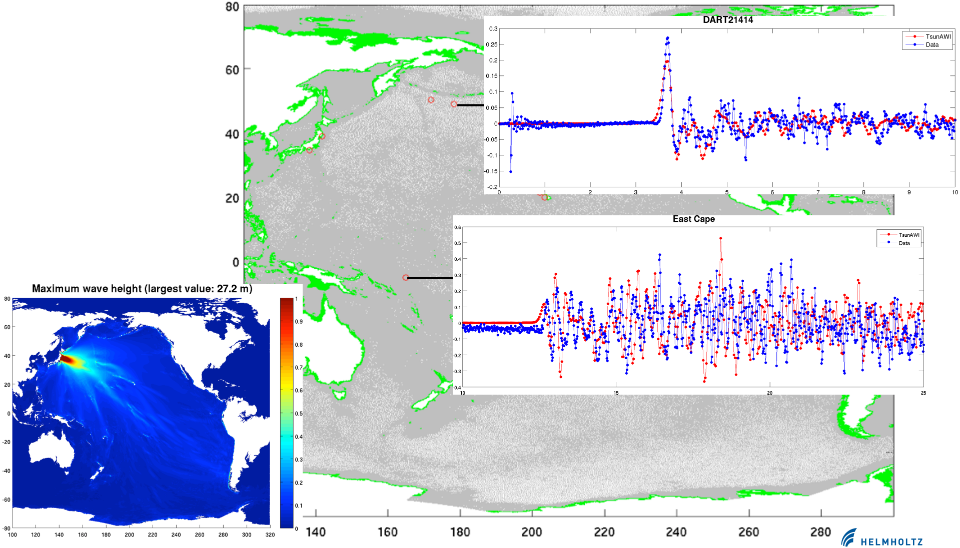
TsunAWI Verification

Real event, Japan 2011



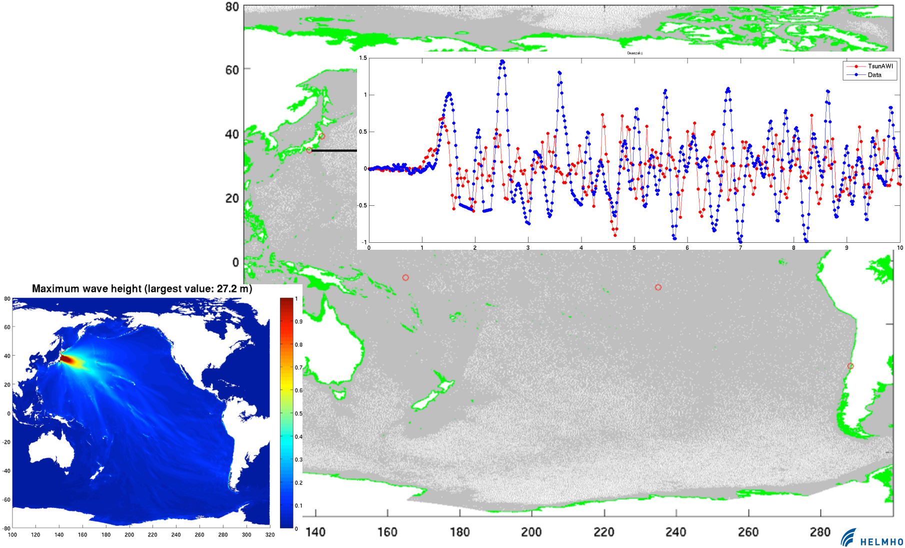
TsunAWI Verification

Real event, Japan 2011



TsunAWI Verification

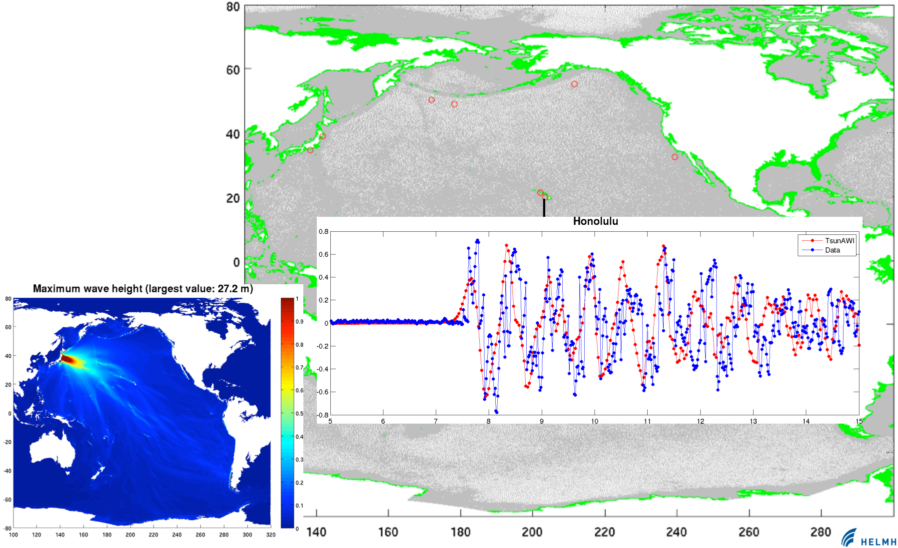
Real event, Japan 2011



Maximum wave height (largest value: 27.2 m)

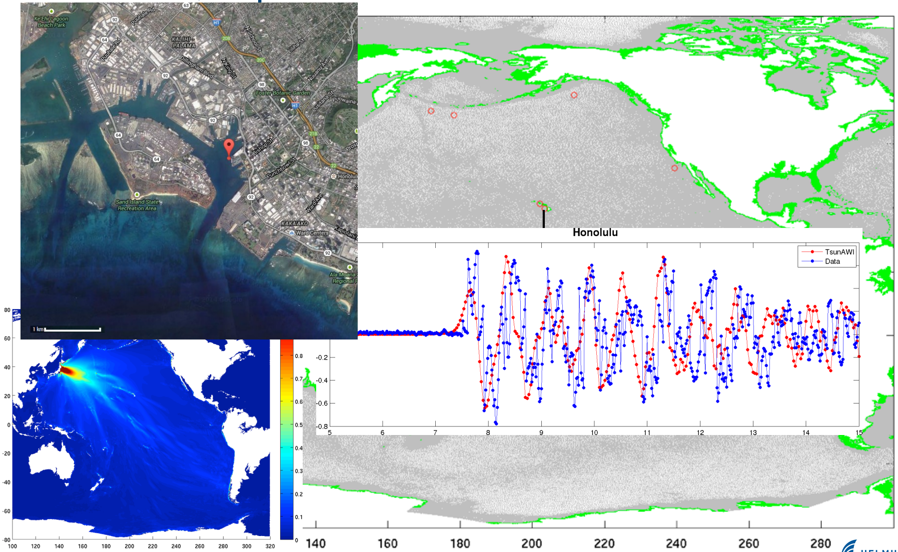
TsunAWI Verification

Real event, Japan 2011



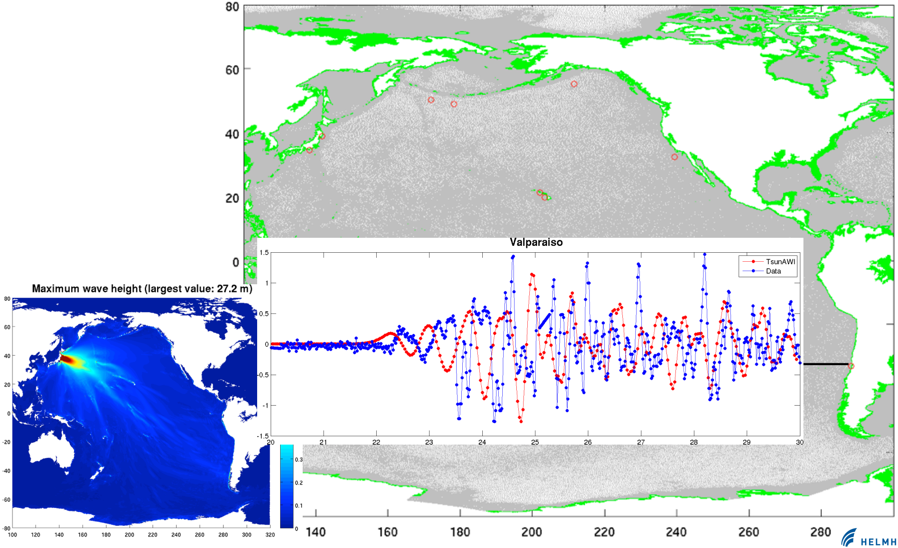
TsunAWI Verification

Real event, Japan 2011



TsunAWI Verification

Real event, Japan 2011



Maximum wave height (largest value: 27.2 m)

Valparaiso

Sensitivity study on topography data

Three groups AIFDR, ITB, AWI,

Three models ANUGA, TUNAMI-N3, TsunAWI,

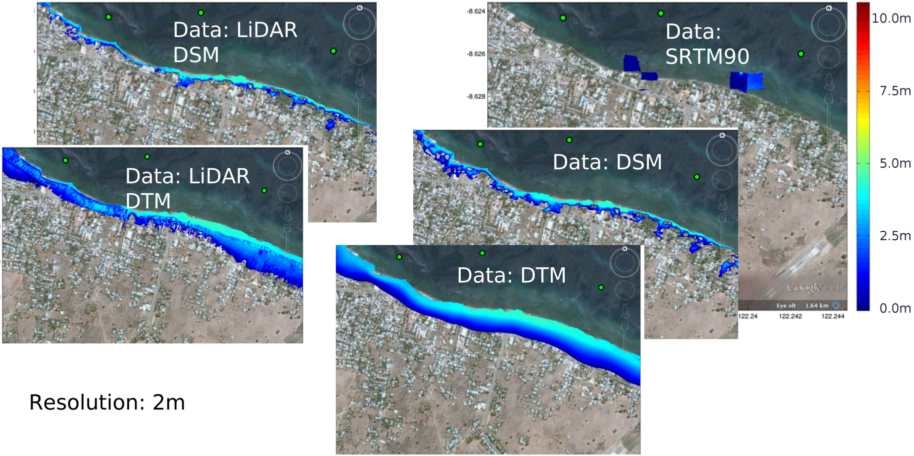
Three regions Padang (Sumatra), Maumere (Flores), Palu (Sulawesi)

One conclusion **High quality topography data is crucial!**

- Free SRTM data (90m horizontal resolution, $\leq$16m vertical accuracy) only for rough estimates,
- Intermap (5m; 0.7m) and LiDar (1m; 0.15m) comparable for shallow water models,
- Results more sensitive to varying data sets than to varying resolution.

Sensitivity study on topography data

Example: synthetic scenario for Maumere, Flores



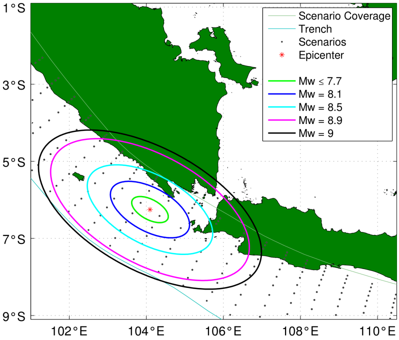
Resolution: 2m

InaTEWS

Warning based on scenario database

TsunAWI

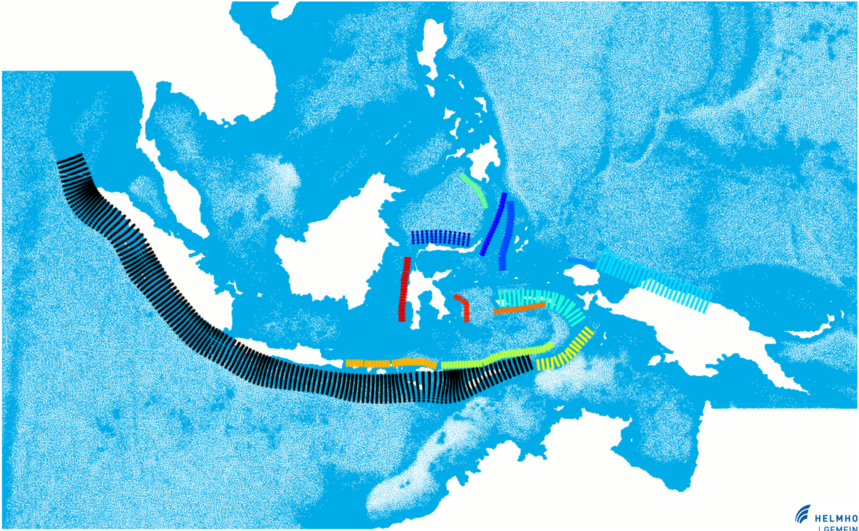
- Scenario database approach designed in 2005
- Sources provided by GFZ and Geoscience Australia
- Selection algorithm:
    - Choose possible scenarios by EQ epicenter, magnitude
    - GPS measurements can refine the selection



- Also suitable for risk assessment, e.g., inundation area (keep topography data quality in mind!), risk maps

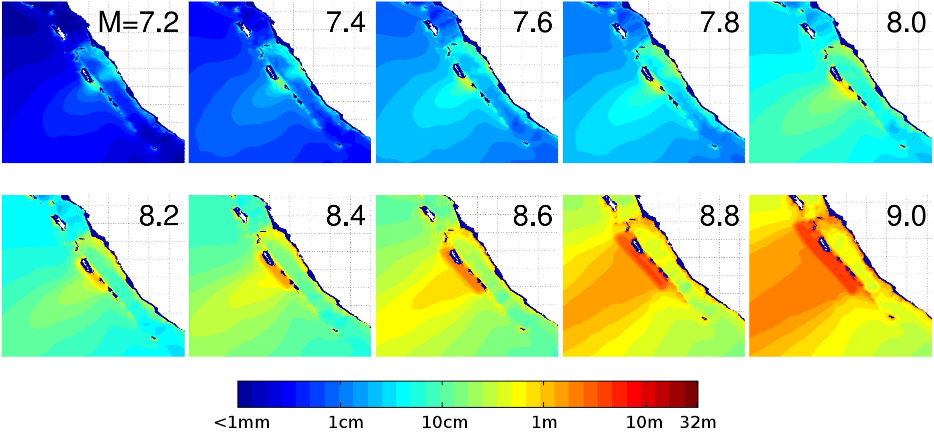
InaTEWS

Model domain for TsunAWI scenarios 2016



InaTEWS

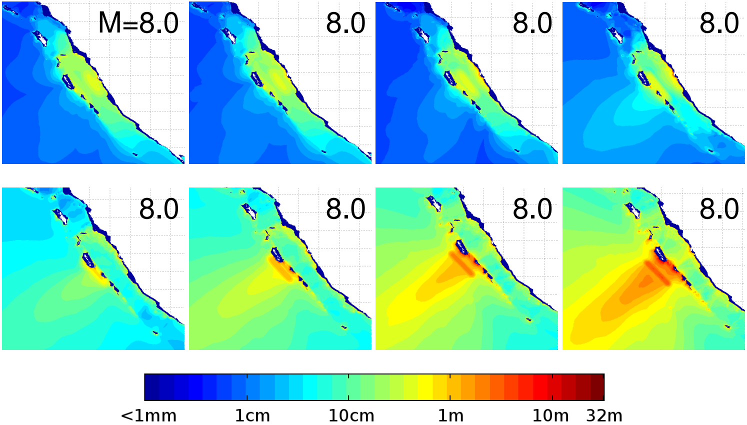
Earthquake magnitude and maximum amplitude



$M_w = \frac{2}{3}(\log_{10} M_0 - 9.1)$ with $M_0 = \mu d S$ [Nm], rigidity μ, displacement d, area of rupture S.

InaTEWS

Epicenter location and maximum amplitude

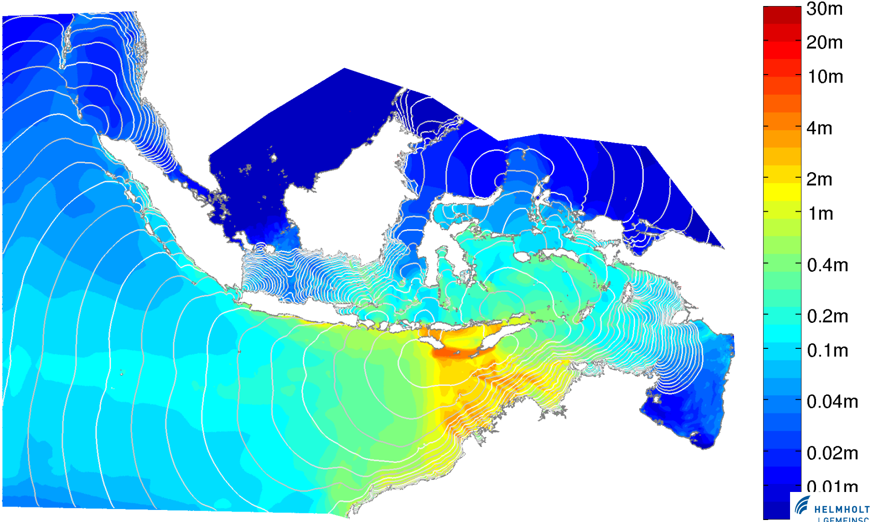


At the coast, epicenter at large depth in rigid rock (large μ),
at the trench, low epicenter in softer sediments and rock (small μ).

Scenario data products

ETA isochrones and maximum amplitude

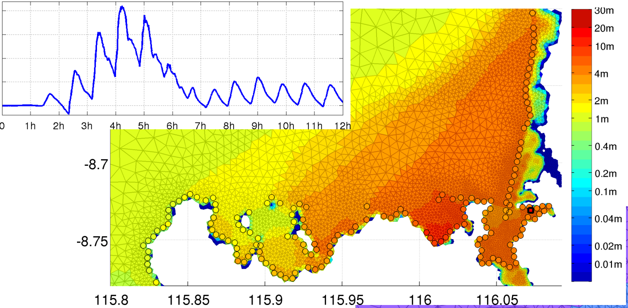
Example: Magnitude 9.0 in the Eastern Sunda Arc



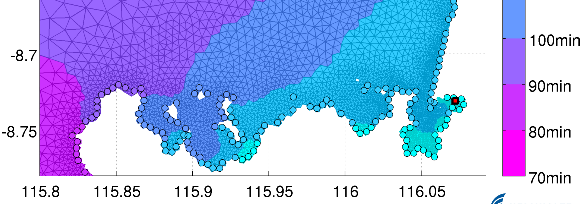
Scenario data products

Coastal forecast points

Example: Magnitude 9.0 in the Eastern Sunda Arc, zoom to Lembar, Eastern Lombok



- Maximum SSH and ETA at 134.000 coastal forecast points
- Time series at tide gauge locations

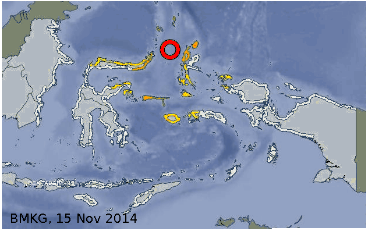


Scenario data products

Warning based on real time computation

EasyWave by A. Bebeyko, GFZ

- Very fast: $\mathcal{O}(1\mathrm{s})$
- Simplified model (but including the coasts, no Green's Law), coarse resolution
- If EQ region is not covered by scenario database or
- if more information on source becomes available, e.g. momentum tensor, source inversion
- Resulting warning levels at the coasts similar to database approach (none, yellow $\geq$10cm, orange $\geq$50cm, red $\geq$3m)


BMKG, 15 Nov 2014

SMART cable

Information on the source

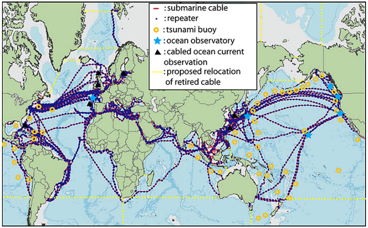
Probably the most important feature of SMART cable in tsunami early warning.

Topic of other talks today and tomorrow.

Looking forward to improve the warning!

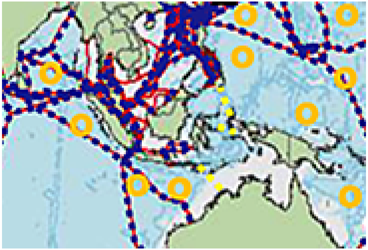
SMART cable

Wave amplitude at SMART cable locations



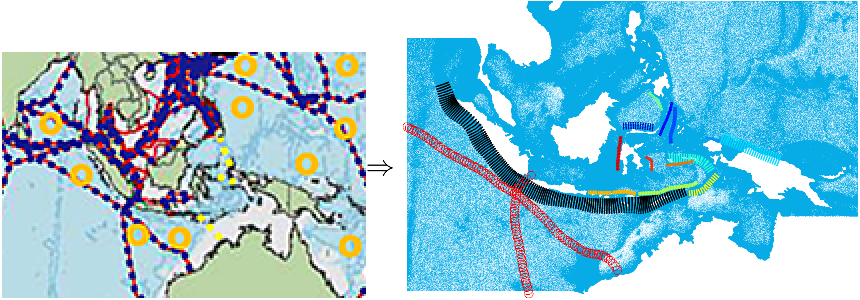
SMART cable

Wave amplitude at SMART cable locations



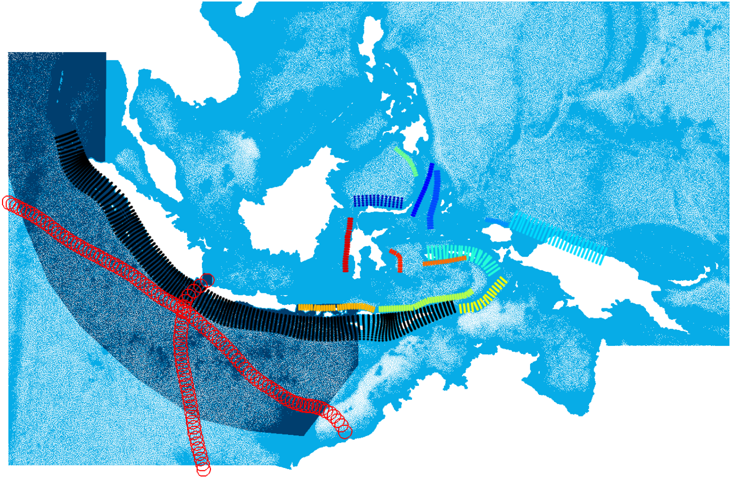
SMART cable

Wave amplitude at SMART cable locations



SMART cable

Wave amplitude at SMART cable locations

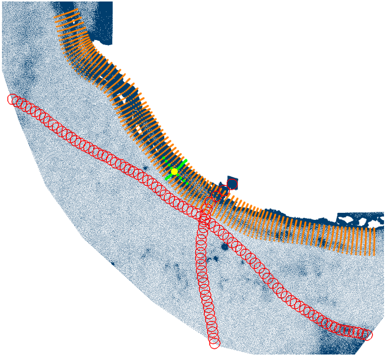


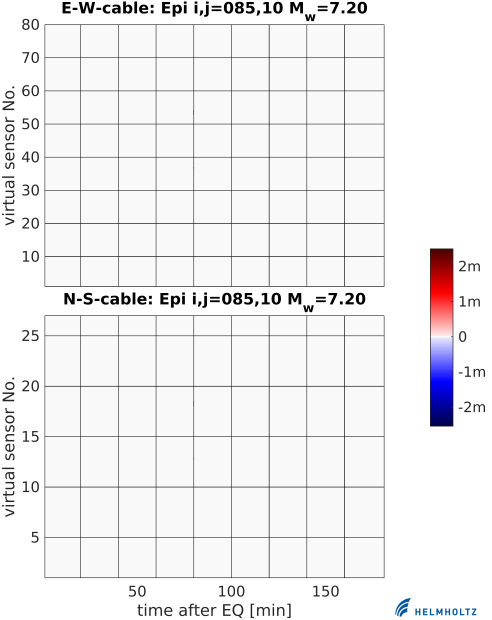
Scenarios SW of Sumatra (2011, small mesh) are suited best

SMART cable

Wave amplitude

Scenario with magnitude
$M_w = 7.2$

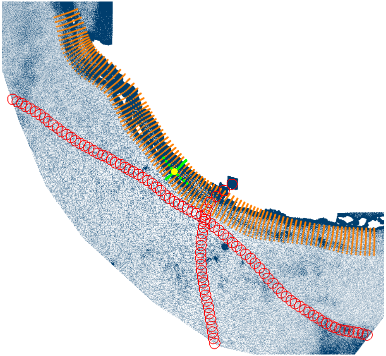


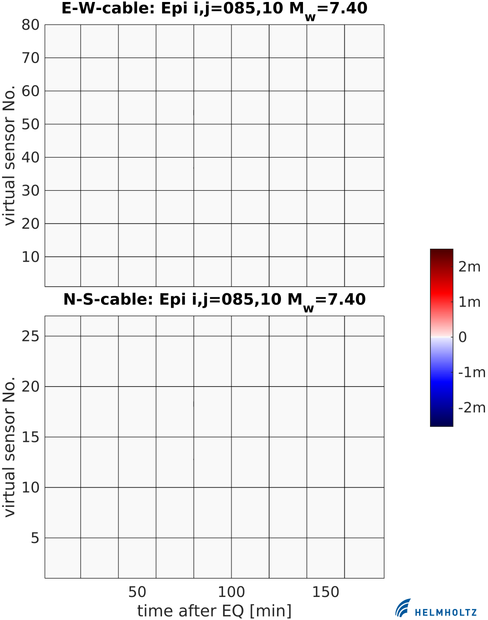


SMART cable

Wave amplitude

Scenario with magnitude
$M_w = 7.4$

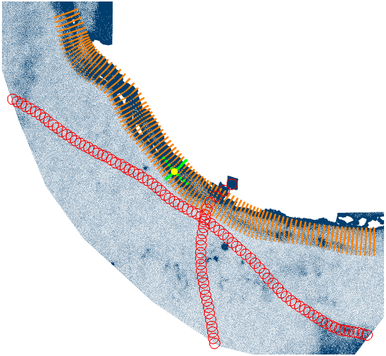


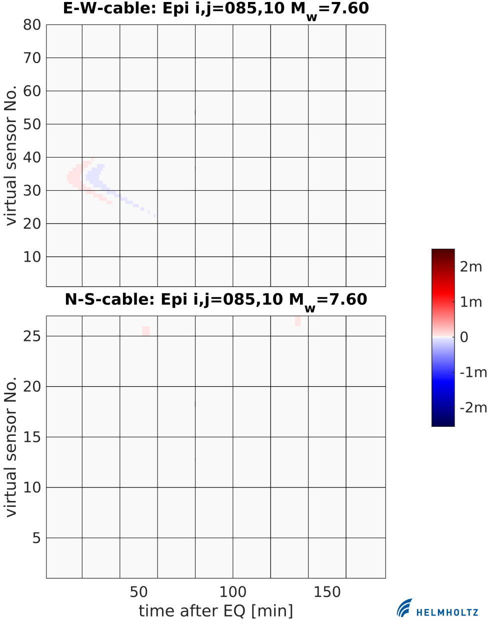


SMART cable

Wave amplitude

Scenario with magnitude $M_w = 7.6$

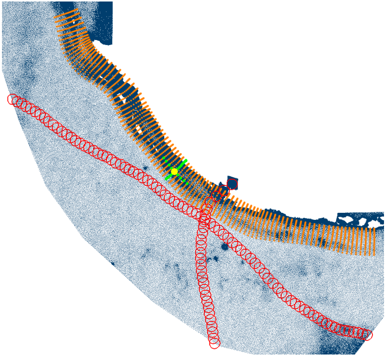


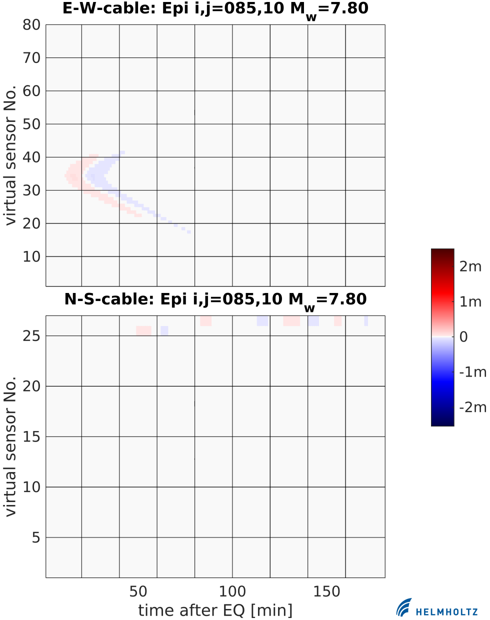


SMART cable

Wave amplitude

Scenario with magnitude $M_w = 7.8$

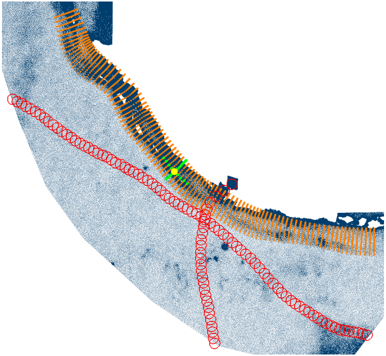


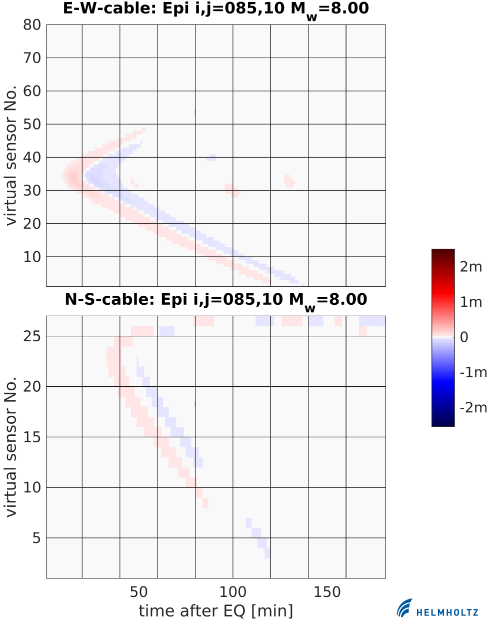


SMART cable

Wave amplitude

Scenario with magnitude $M_w = 8.0$

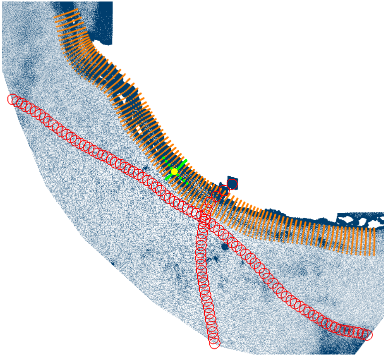


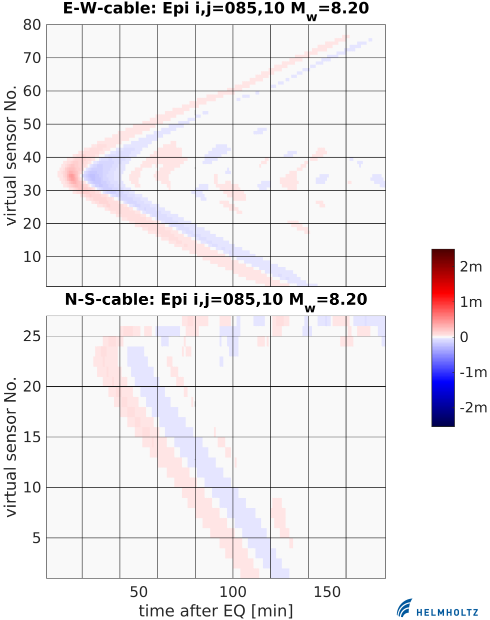


SMART cable

Wave amplitude

Scenario with magnitude
$M_w = 8.2$

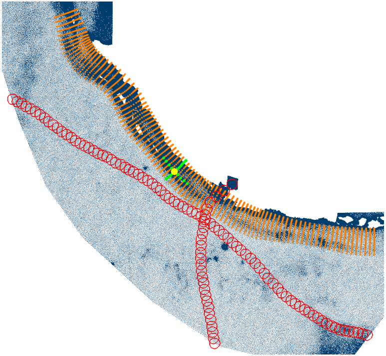


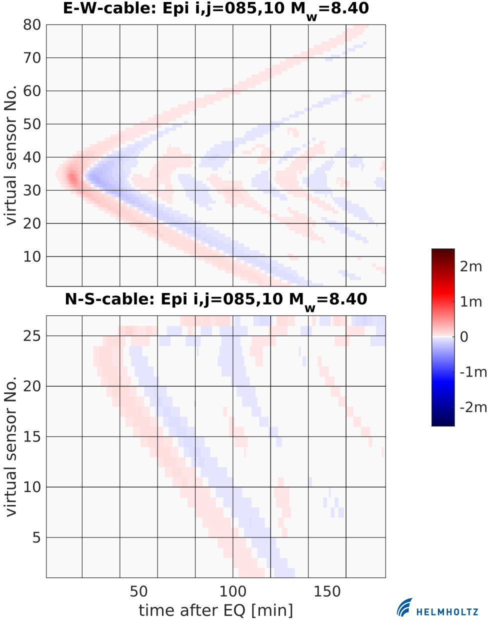


SMART cable

Wave amplitude

Scenario with magnitude
$M_w = 8.4$

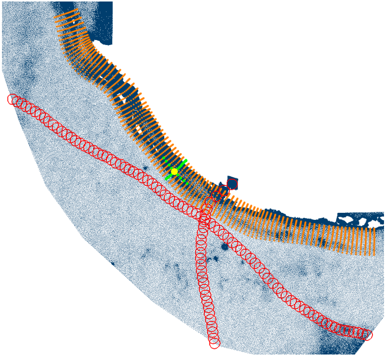


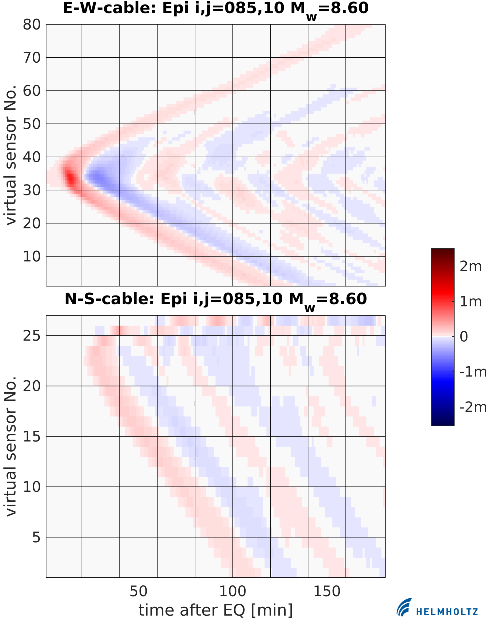


SMART cable

Wave amplitude

Scenario with magnitude
$M_w = 8.6$

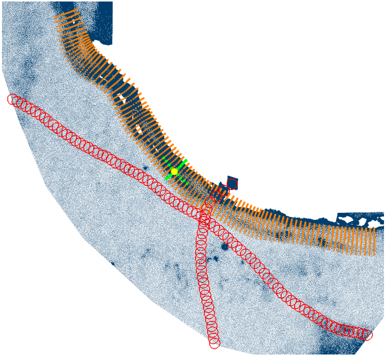


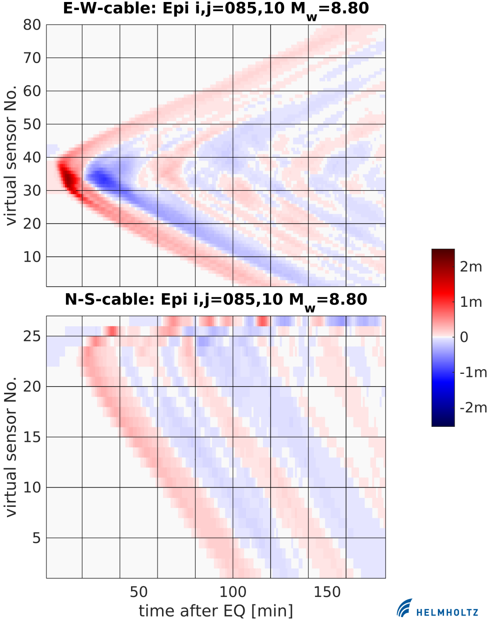


SMART cable

Wave amplitude

Scenario with magnitude $M_w = 8.8$

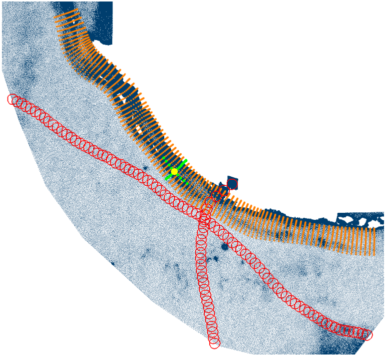


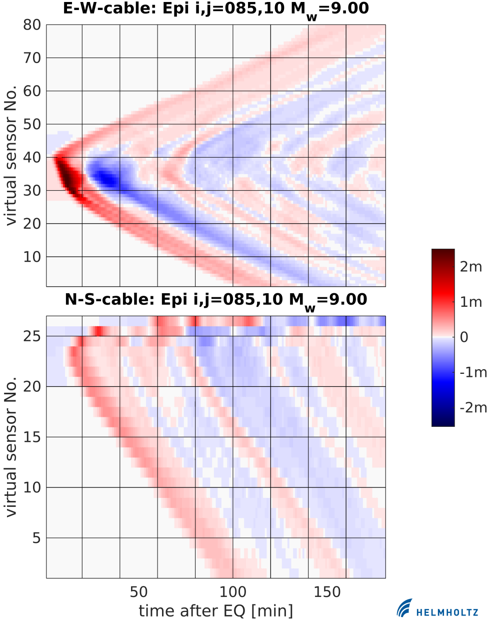


SMART cable

Wave amplitude

Scenario with magnitude
$M_w = 9.0$

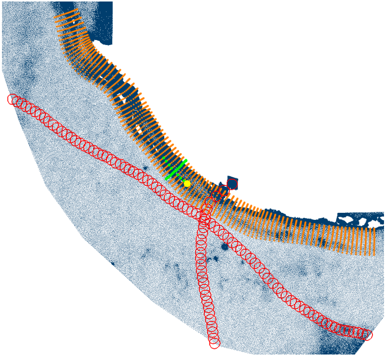


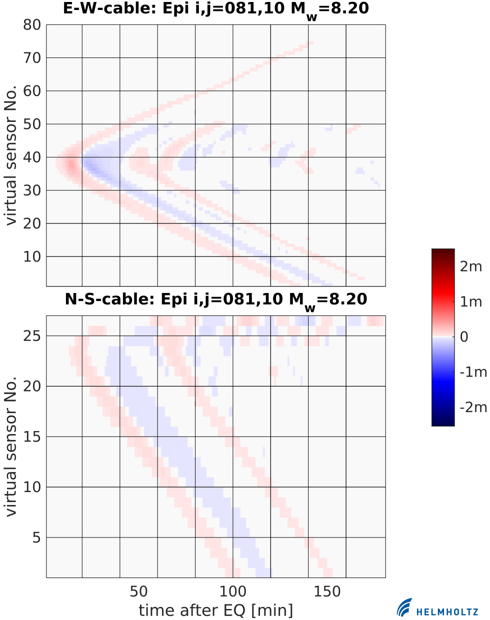


SMART cable

Wave amplitude

Scenario with M_w=8.2, epicenter i,j=81,10

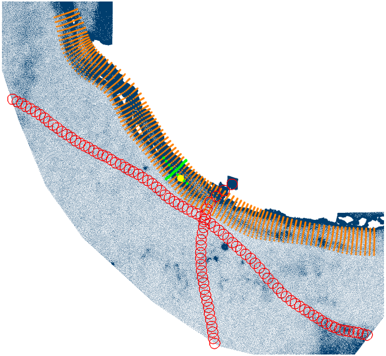


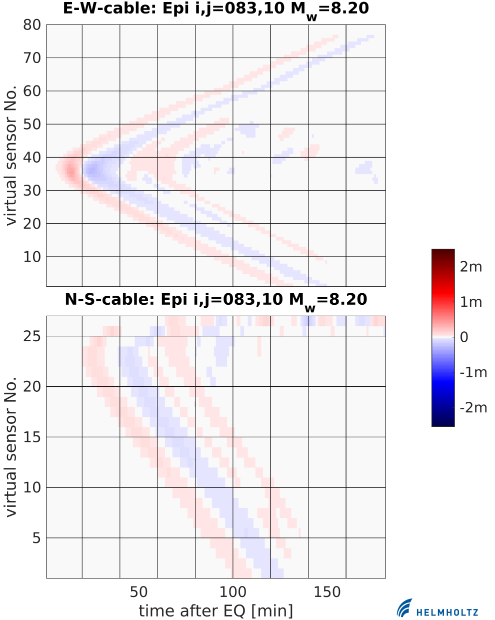


SMART cable

Wave amplitude

Scenario with M_w=8.2, epicenter i,j=83,10

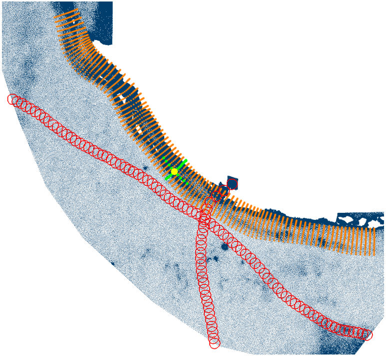


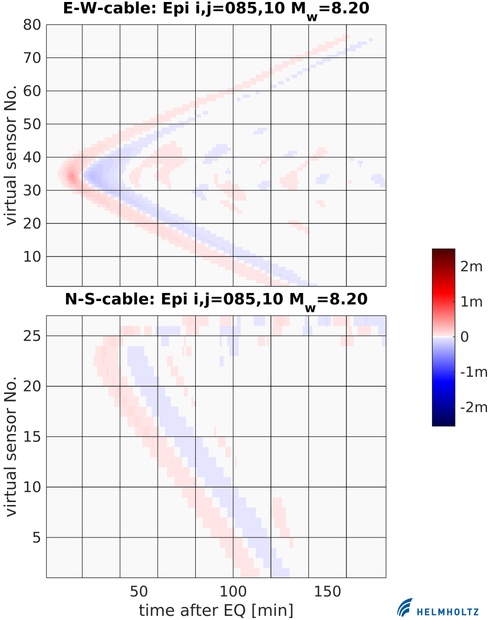


SMART cable

Wave amplitude

Scenario with M_w=8.2, epicenter i,j=85,10

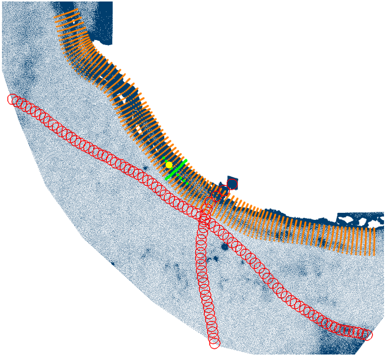


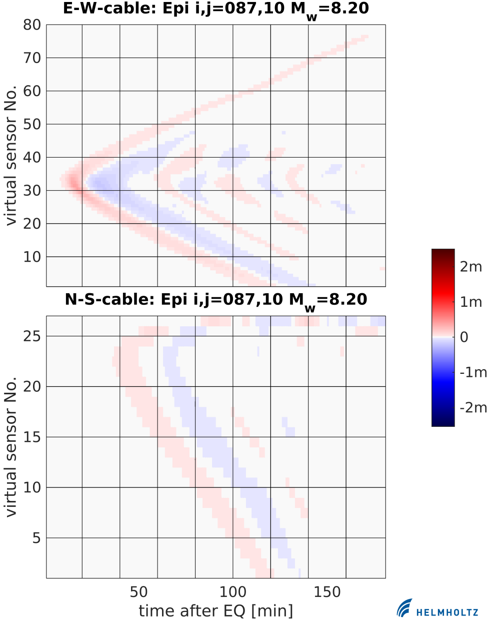


SMART cable

Wave amplitude

Scenario with M_w=8.2, epicenter i,j=87,10

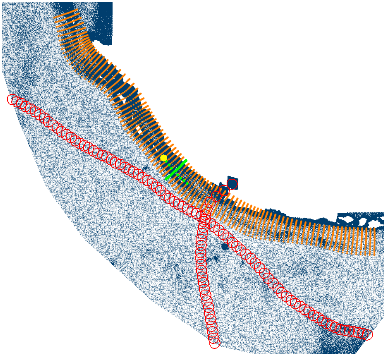


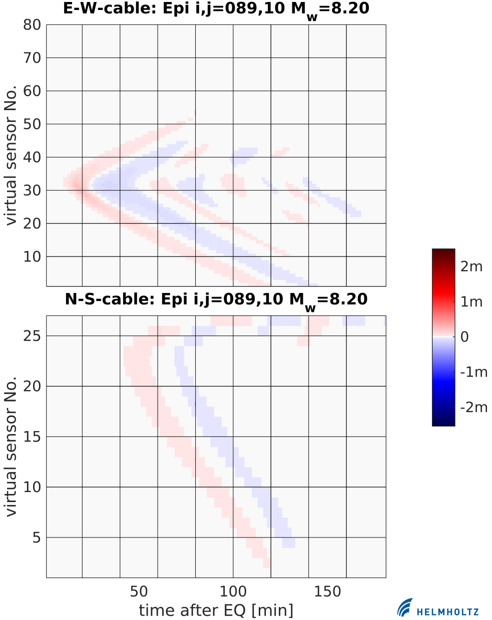


SMART cable

Wave amplitude

Scenario with M_w=8.2, epicenter i,j=89,10

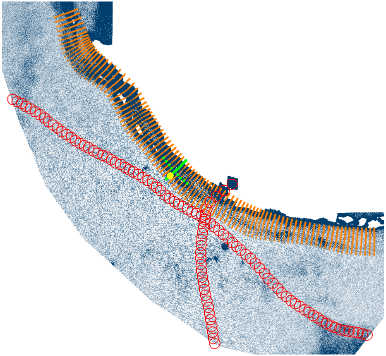


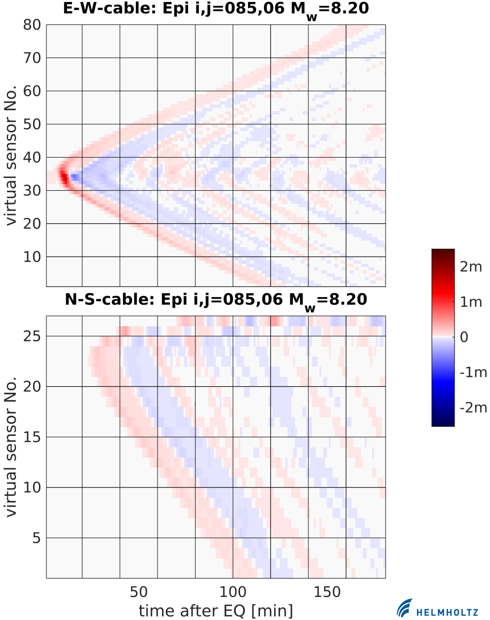


SMART cable

Wave amplitude

Scenario with M_w=8.2, epicenter i,j=85,06

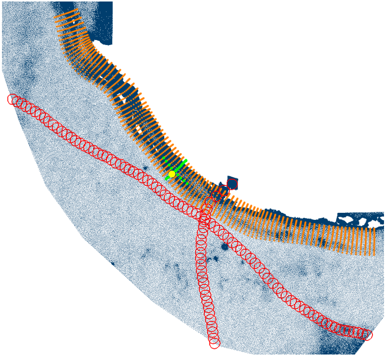


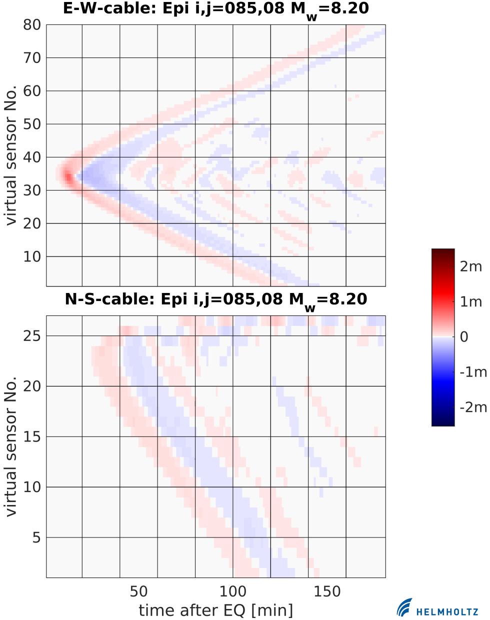


SMART cable

Wave amplitude

Scenario with M_w=8.2, epicenter i,j=85,08

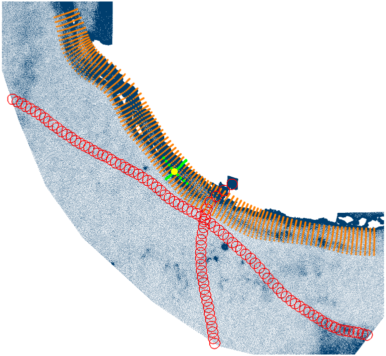


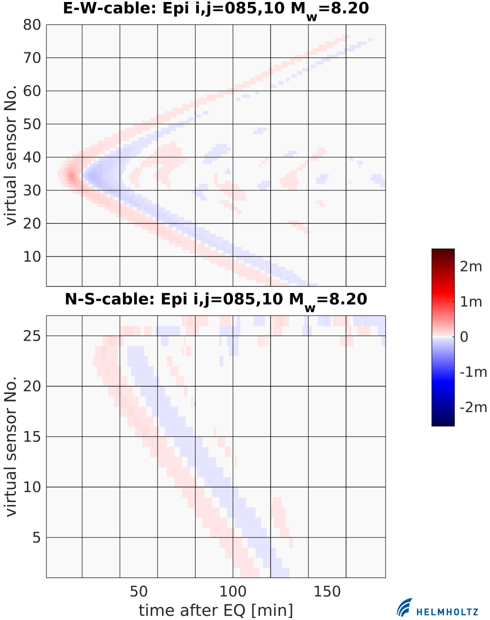


SMART cable

Wave amplitude

Scenario with M_w=8.2, epicenter i,j=85,10

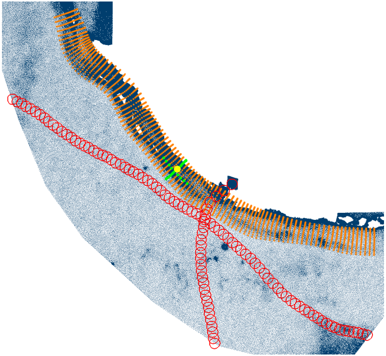


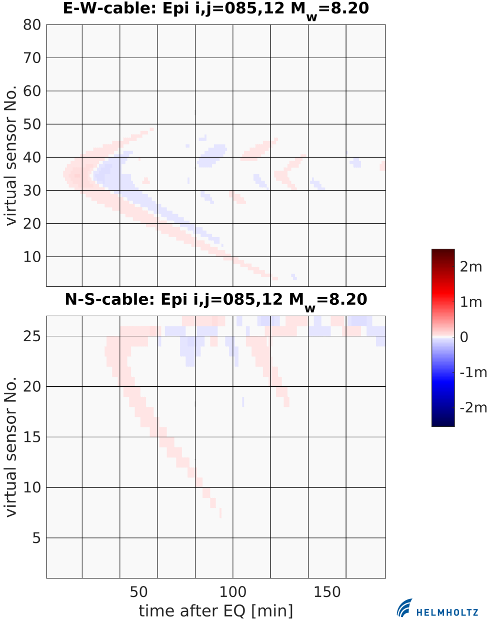


SMART cable

Wave amplitude

Scenario with M_w=8.2, epicenter i,j=85,12

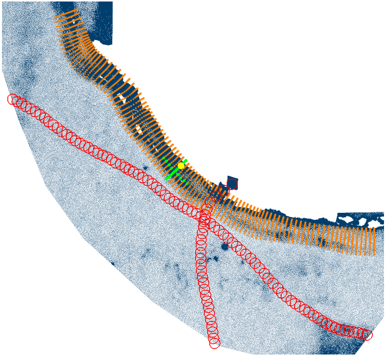


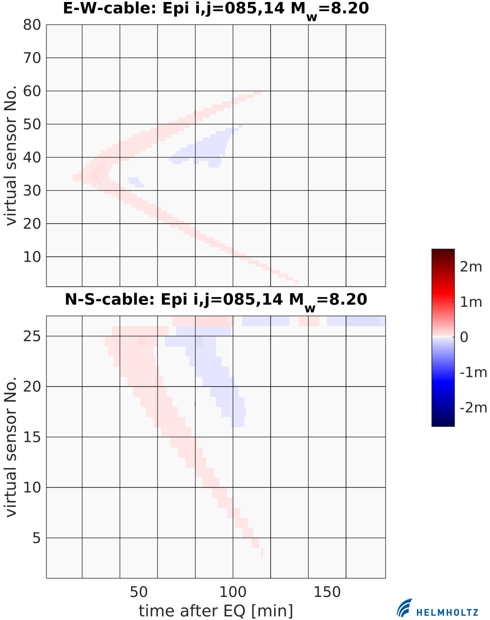


SMART cable

Wave amplitude

Scenario with M_w=8.2, epicenter i,j=85,14

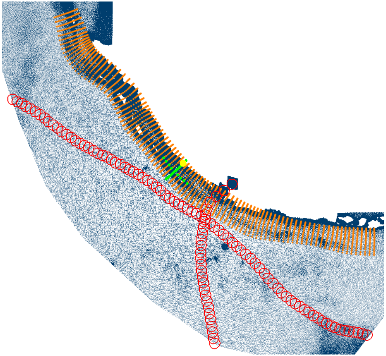


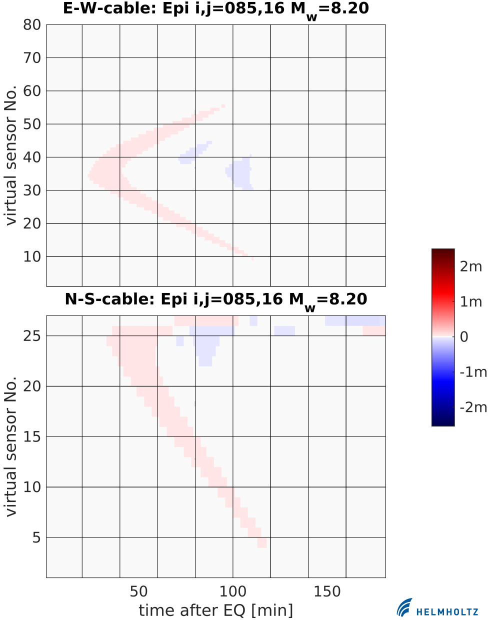


SMART cable

Wave amplitude

Scenario with M_w=8.2, epicenter i,j=85,16





SMART cable

Thoughts, comments, questions . . .

- From 0D (buoy) to 1D measurement!
- Nearfield: bottom pressure signals from EQ and tsunami overlap
- Nearfield: Wave height measurement comes too late
- Verify or refine scenario choice or simulation result
- Very helpful for tsunamis from non-EQ sources, in particular landslides!
- Measure water velocity (strong current induced by tsunami approaching the coast)?
- . . .