POST TERRAE MOTUM FACTUM EST

Ctirad Matyska

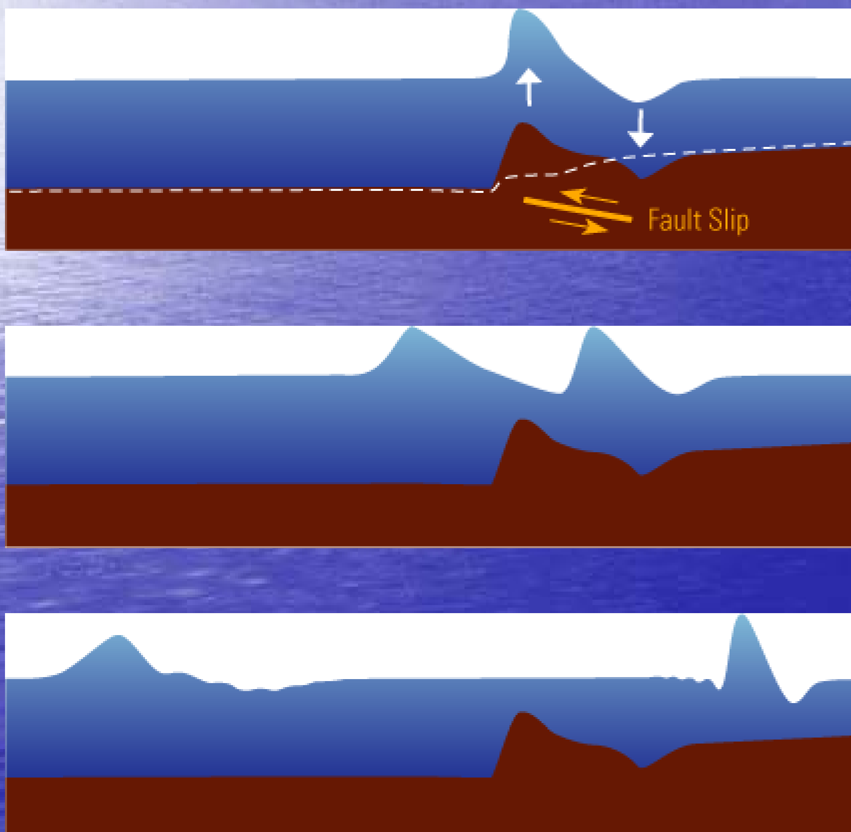
katedra geofyziky MFF UK

津波

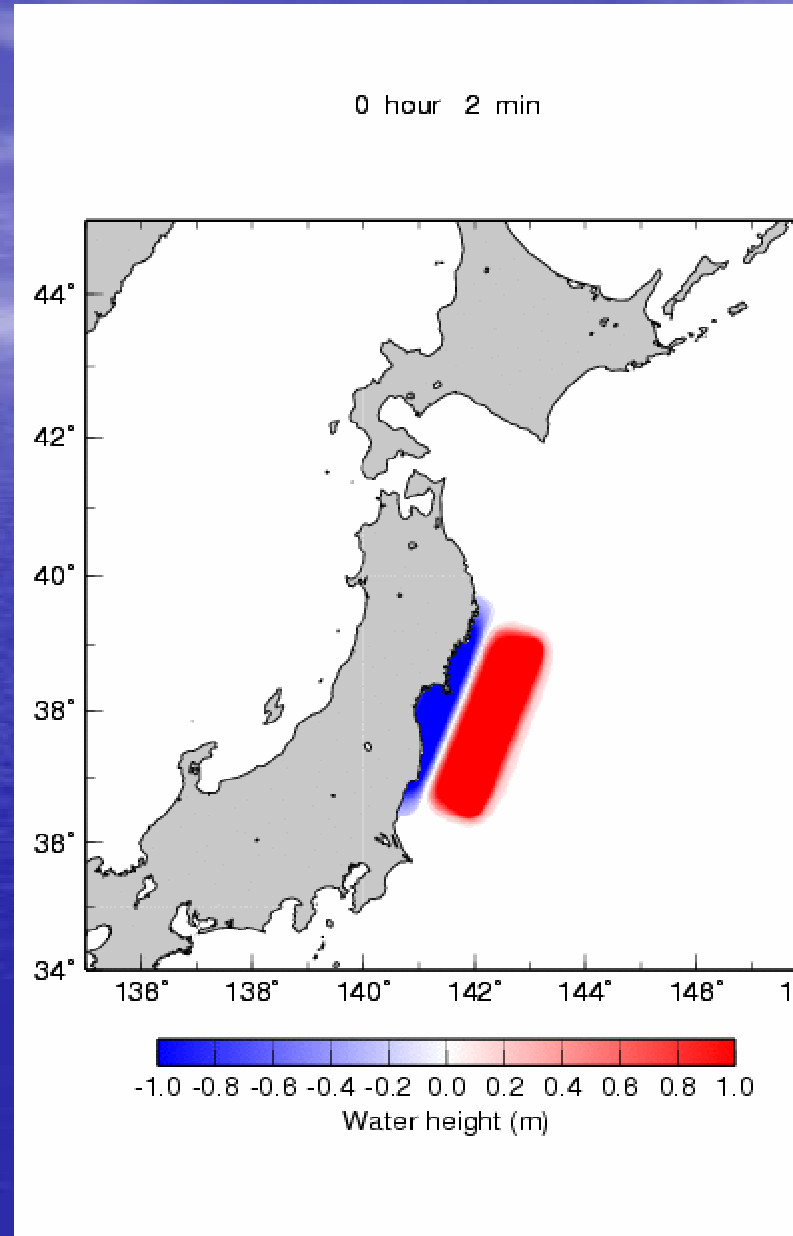
přístav **vlna**

Kacušika HOKUSAI. Velká vlna v Kanagawě, 1831; barevný dřevořez, NG v Praze

津波



USGS



Fujii a Satake

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GPS

182 C. Falck et al.: Near real-time GPS applications for tsunami early warning systems

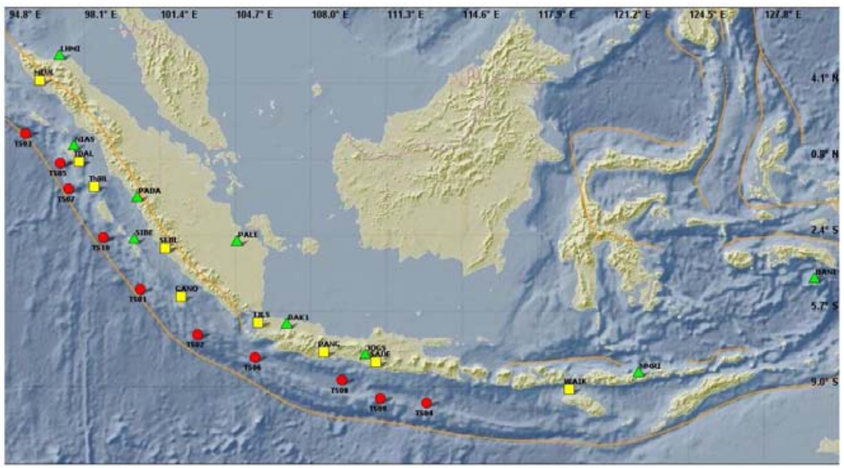
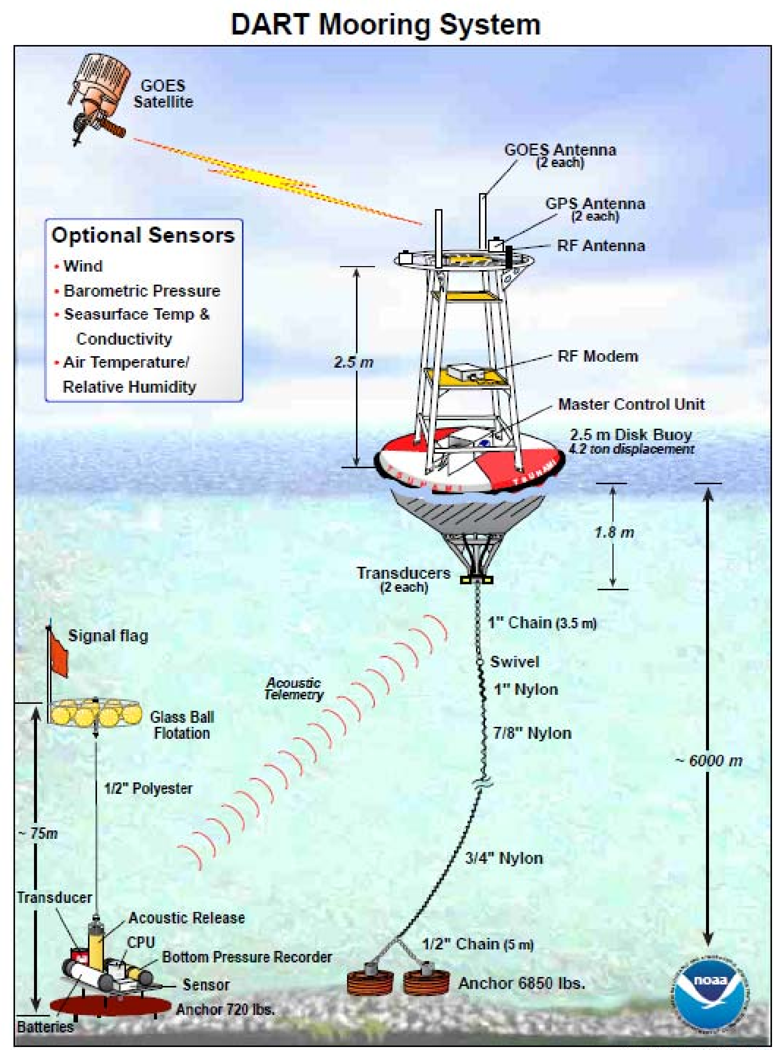
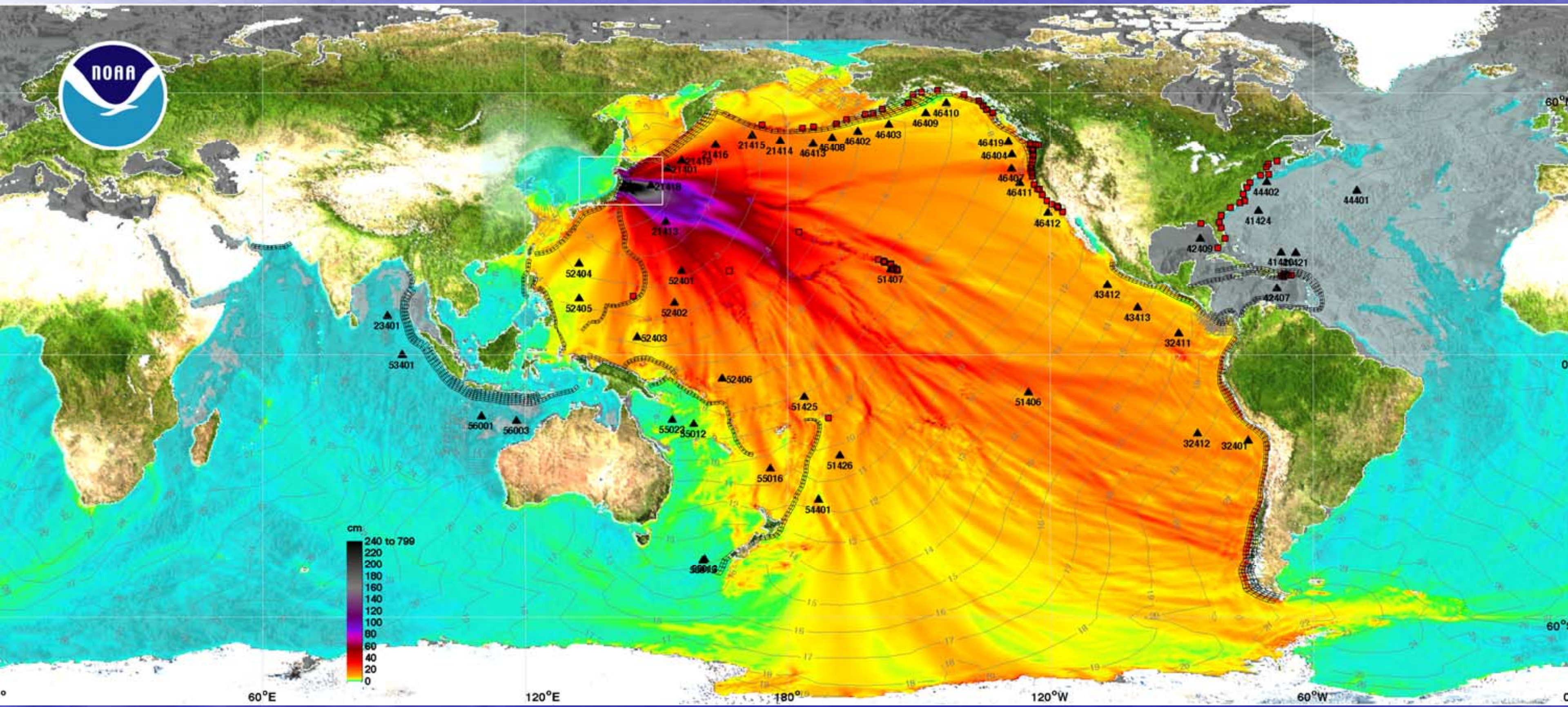


Fig. 1. GITEWS GPS locations in Indonesia [numbers in squared brackets indicate installation status of December 2009]: 9 [7] GPS real-time reference stations (green triangles), 9 [9] GPS at tide gauges (yellow squares), 10 [8] buoys with GPS (red circles).



slapové stanice na pobřeží
měřící výšku hladiny

Umístění stanic systému DART



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Předdefinované bázové zdroje

The goal is to define tsunami source functions such that a finite combination of the pre-computed tsunami model runs could closely reproduce the tsunami time series of the actual event. <u>This is feasible because of the linearity of the tsunami generation/ propagation dynamics.</u> Each pre-defined source in the Propagation Database is referred to as a *"unit source."* Each unit source is equivalent to a deformation due to an earthquake with a fault length of 100 km, fault width of 50 km, and a slip value of 1 m, equivalent to a moment magnitude of 7.5. (NOAA)

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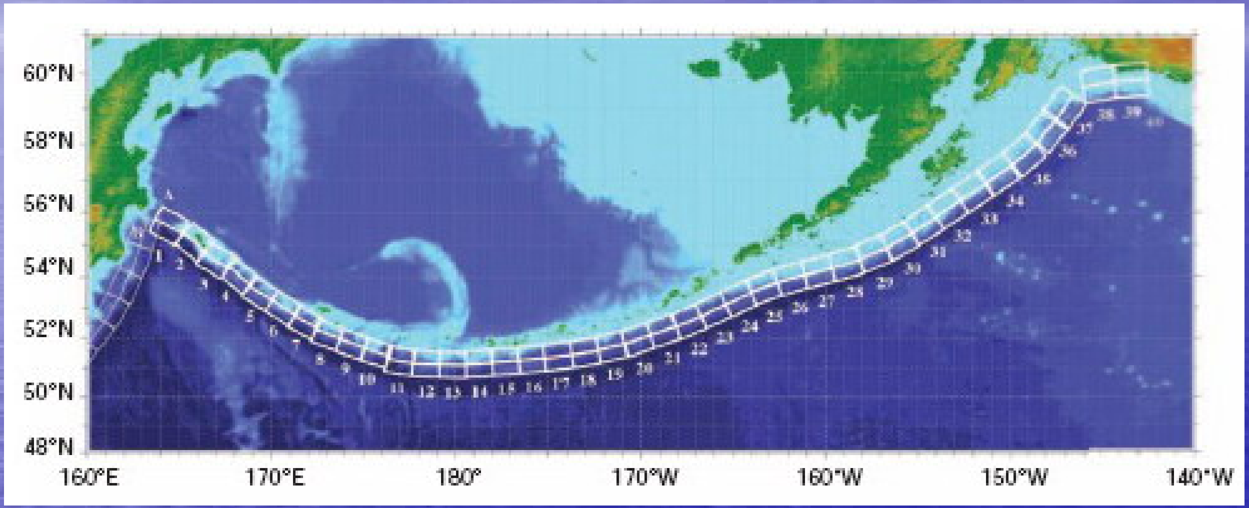

Two rows of unit sources are set up, one for the shallower region and one for the deeper region. Additional rows may be possible depending on the characteristics of the region. These unit sources are located along the known fault zones for the entire Pacific Basin, Caribbean for the Atlantic region and Indian Ocean. Figure shows how the unit sources have been set up for the Aleutian Islands. (NOAA)

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Zaplavení vybrané lokality

To reproduce the correct wave dynamics during the inundation computations high resolution bathymetric and topographic grids are used in this type of study. The high quality bathymetric and topographic data sets needed for development of inundation maps require maintenance and upgrades as better data becomes available and coastal changes occur. Inundation studies can be conducted taking a probabilistic approach in which multiple tsunami scenarios are considered, and an assessment of the vulnerability of the coast to tsunami hazard is evaluated, or they may focus on the effect of a particular ‘worst case scenario” and assess the impact of such a particularly high impact event on the areas under investigation.

The results of a tsunami inundation study should include information about the maximum wave height and maximum current speed as a function of location, maximum inundation line, as well as time series of wave height at different locations indicating wave arrival time. (NOAA)

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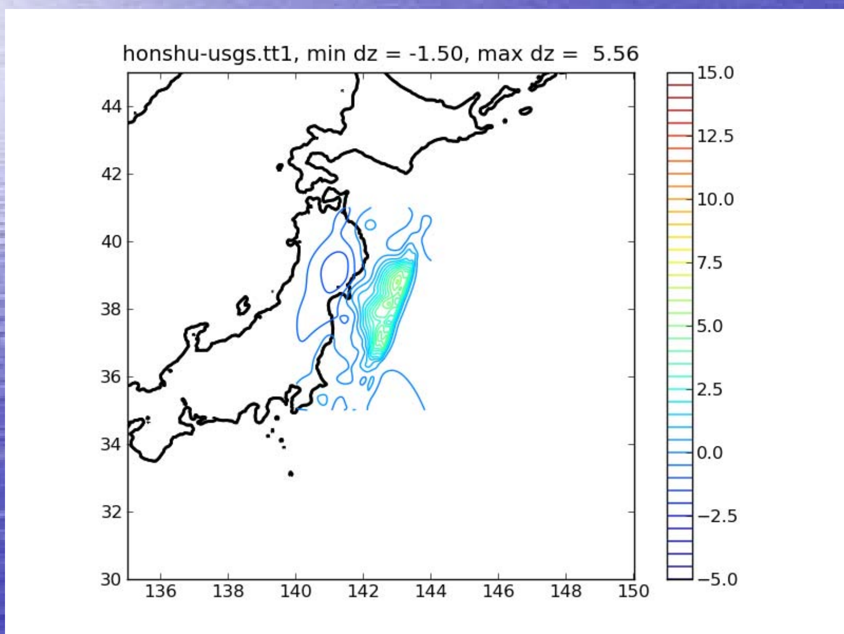
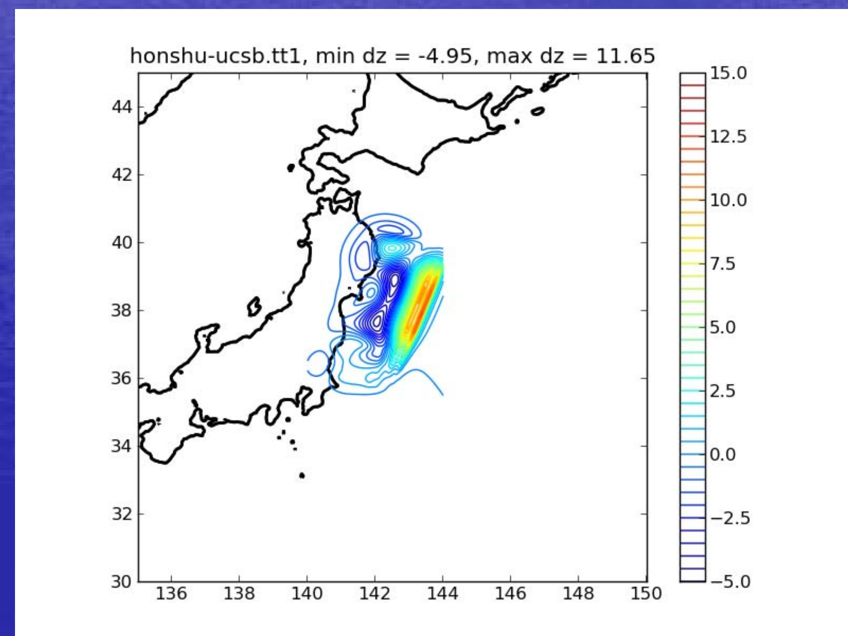
Přímé modelování v reálném čase

začíná u modelů pohybu dna získaných ze seismologie

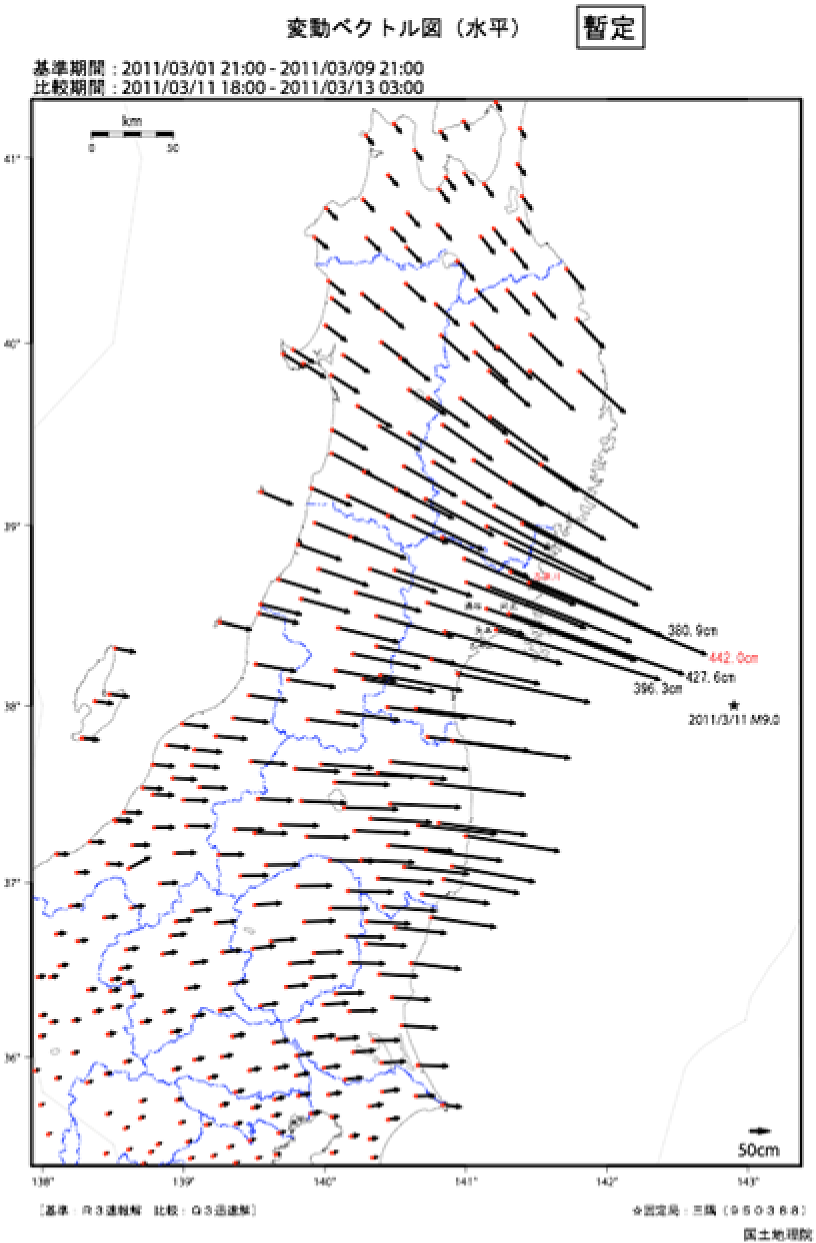


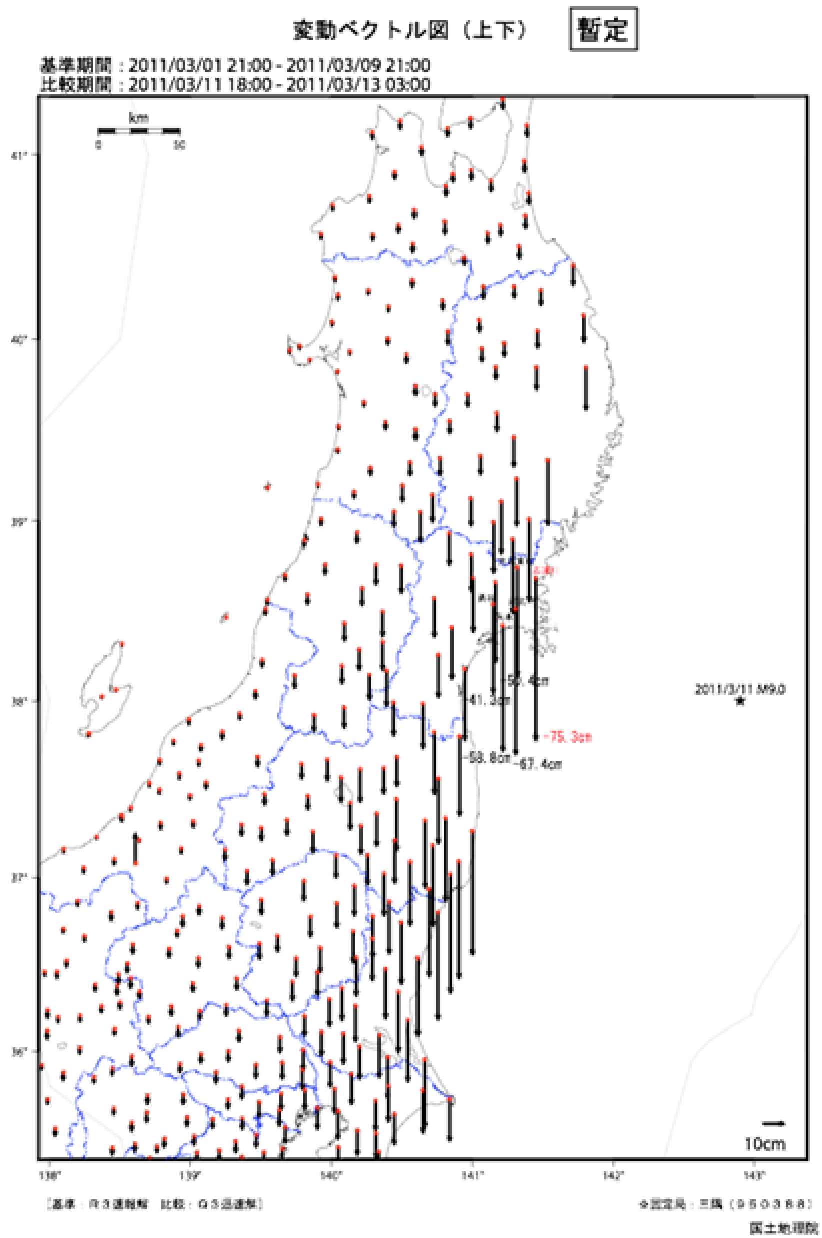
USGS



UCSB

Tohoku, Japan Earthquake: GPS Displacements
Geospatial Information Authority of Japan





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Nelineární 3-D úloha s měnící se geometrií

Navierova-Stokesova rovnice:

$$\rho\left(\frac{\partial \boldsymbol{v}}{\partial t} + (\boldsymbol{v}\cdot\nabla)\boldsymbol{v}\right) = -\nabla p + \rho\boldsymbol{g} - 2\rho\boldsymbol{\Omega}\times\boldsymbol{v} + \eta\nabla^2\boldsymbol{v}$$

Rovnice kontinuity:

$$\nabla\cdot\boldsymbol{v} = 0$$

Okrajové podmínky:

pohyb dna a volná hladina na povrchu

ρ je hustota, $\boldsymbol{v}$ je rychlost, p je tlak, $\boldsymbol{\Omega}$ je vektor úhlové rotace Země, $\boldsymbol{g}$ je gravitační zrychlení a η je viskozita

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Aproximace pro “mělkou” vodu

Nelineární rovnice pro neviskózní vodu:

$$\frac{\partial \boldsymbol{v}_H}{\partial t} + (\boldsymbol{v}_H \cdot \nabla)\, \boldsymbol{v}_H = -g\nabla_H h - 2\,\boldsymbol{\Omega} \times \boldsymbol{v}_H$$

$$\frac{\partial h}{\partial t} + \nabla_H \cdot ((h - h_B)\, \boldsymbol{v}_H) = 0$$

Linearizované rovnice:

$$\frac{\partial \boldsymbol{v}_H}{\partial t} = -g\nabla_H h - 2\,\boldsymbol{\Omega} \times \boldsymbol{v}_H$$

$$\frac{\partial h}{\partial t} = -\nabla_H \cdot ((h_0 - h_B)\, \boldsymbol{v}_H)$$

h je výška povrchu vody, h_0 je referenční výška povrchu, h_B je výška dna, $\boldsymbol{v}_H$ je horizontální rychlost a ∇_H je horizontální část operátoru ∇

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Aproximace pro “mělkou” vodu

Odhad rychlosti šíření vlny:

Položíme-li $\mathbf{\Omega} = 0$ a považujeme-li $h_0 - h_B$ za konstantu, dostáváme

$$\frac{\partial \boldsymbol{v}_H}{\partial t} = -g \nabla_H h \ ,$$

$$\frac{\partial h}{\partial t} = -(h_0 - h_B) \nabla_H \cdot \boldsymbol{v}_H \ ,$$

tedy

$$\frac{1}{g(h_0 - h_B)} \frac{\partial^2 \boldsymbol{v}_H}{\partial t^2} = \nabla_H^2 \boldsymbol{v}_H \ ,$$

$$\frac{1}{g(h_0 - h_B)} \frac{\partial^2 h}{\partial t^2} = \nabla_H^2 h \ ,$$

takže rychlost šíření je

$$c = \sqrt{g(h_0 - h_B)} \ .$$

津波

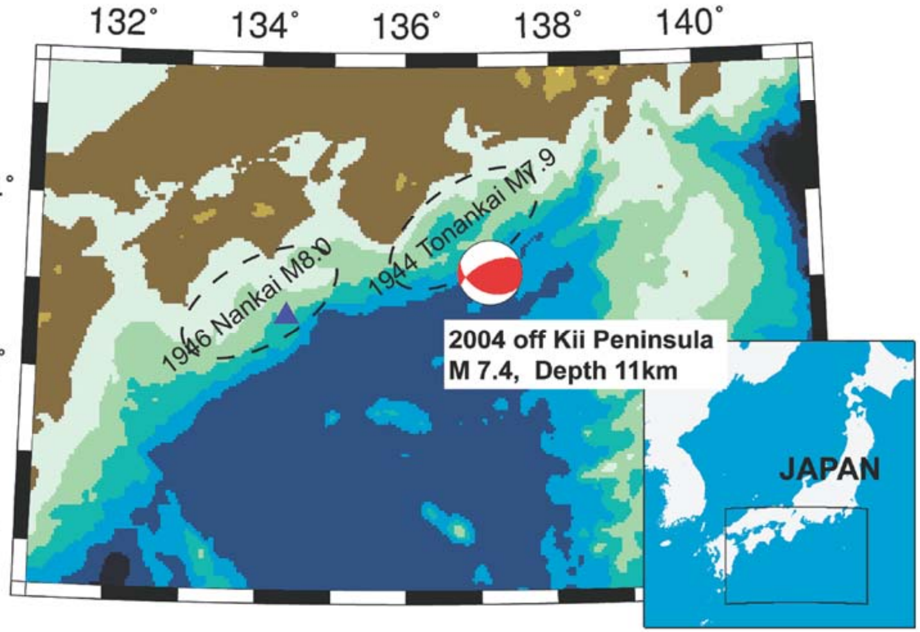
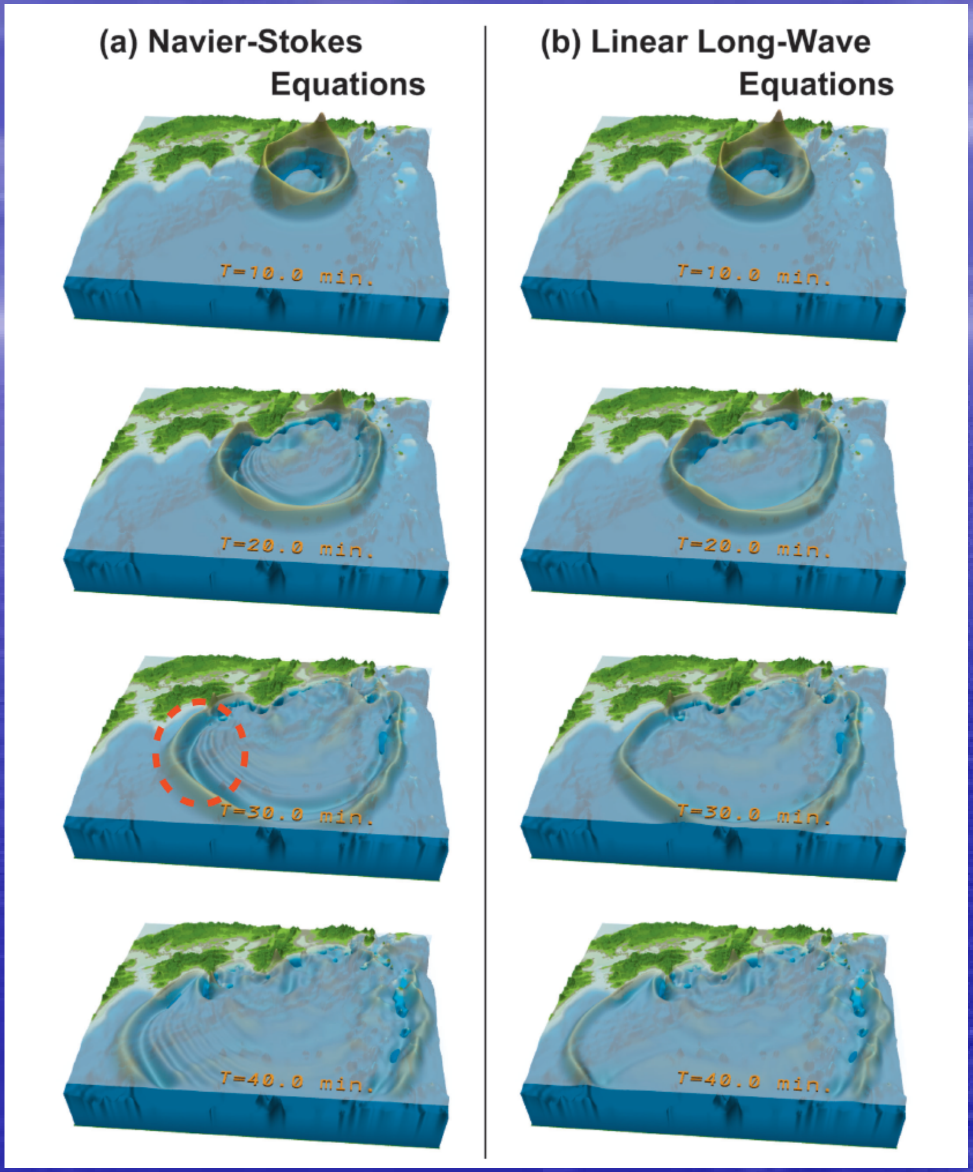


Fig. 1 The area and bathymetry for the tsunami simulation of the 2004 M 7.4 off Kii Peninsula earthquake (red). Source areas of the 1944 Tonankai (M 7.9) and the 1946 Nankai (M 8.0) earthquakes are also shown by dashed curves. The point for the tsunami records in Fig. 3 is shown by a triangle.

Saito a Furumura, 2008

津波



Saito a Furumura, 2008

Fig. 2 Snapshots of the tsunami propagation for the 2004 off Kii Peninsula earthquake, at elapsed times of 10, 20, 30 and 40 min from the earthquake origin time calculated by 3-D Navier-Stokes equations and 2-D linear long-wave equations. Tsunami dispersion is recognized in the results of the 3-D Navier-Stokes simulations [dashed circle].

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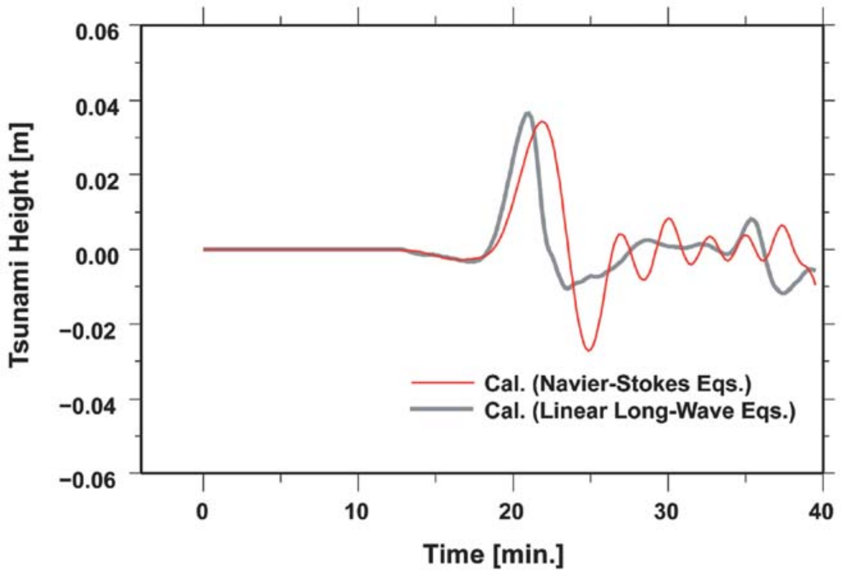

Fig. 3 The tsunami record calculated from the simulation using 3-D NS equations (red) and 2-D linear long-wave equations (black) off Muroto (a triangle in Fig. 1). The 3-D NS equations can simulate dispersive tsunami.

Saito a Furumura, 2008

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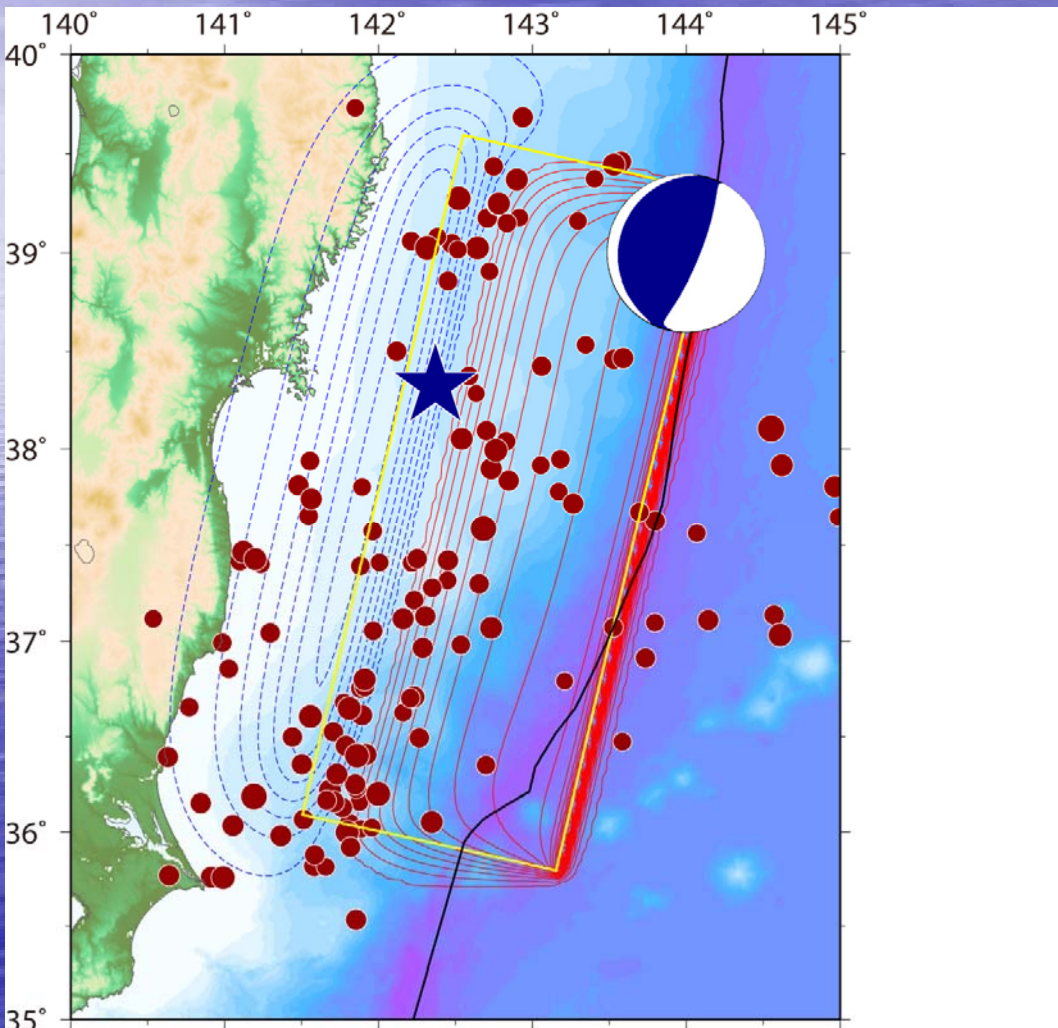
šíření a testy přesnosti

Yushiro Fujii (IISEE, BRI) a Kenji Satake (ERI, Univ. of Tokyo)



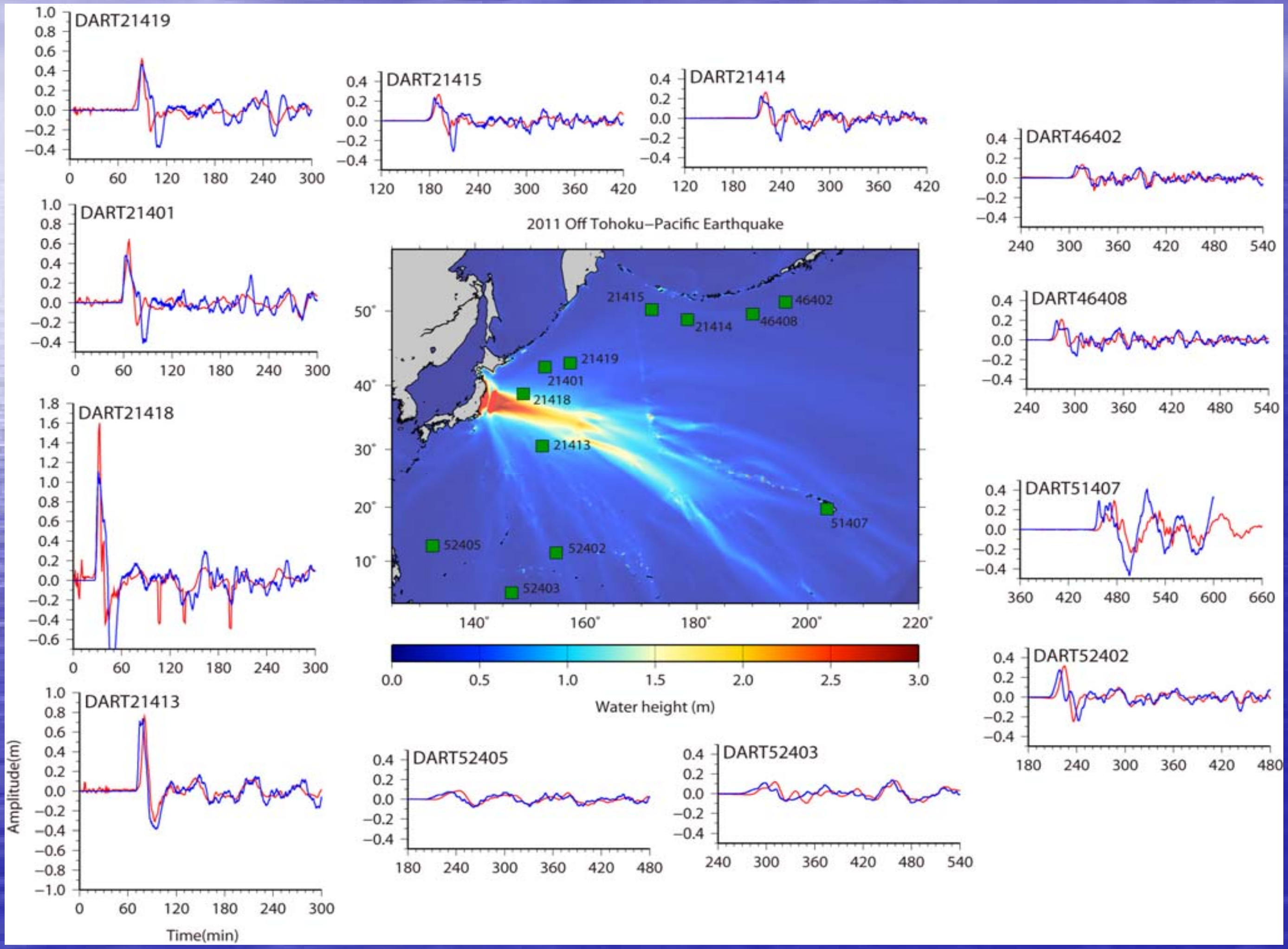
Tsunami Source Model

The red contours indicate uplift with the contour interval of 0.5 m, while the blue contours indicate subsidence with the contour interval of 0.5 m. Aftershocks (determined by USGS) during about one day after the mainshock are also shown by red circles.

津波

šíření a testy přesnosti

Yushiro Fujii (IISEE, BRI) a Kenji Satake (ERI, Univ. of Tokyo)



Maximum Height of Simulated Tsunami

Solid lines in red and blue indicate the observed tsunami waveform and synthetic ones, respectively.

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šíření a testy přesnosti

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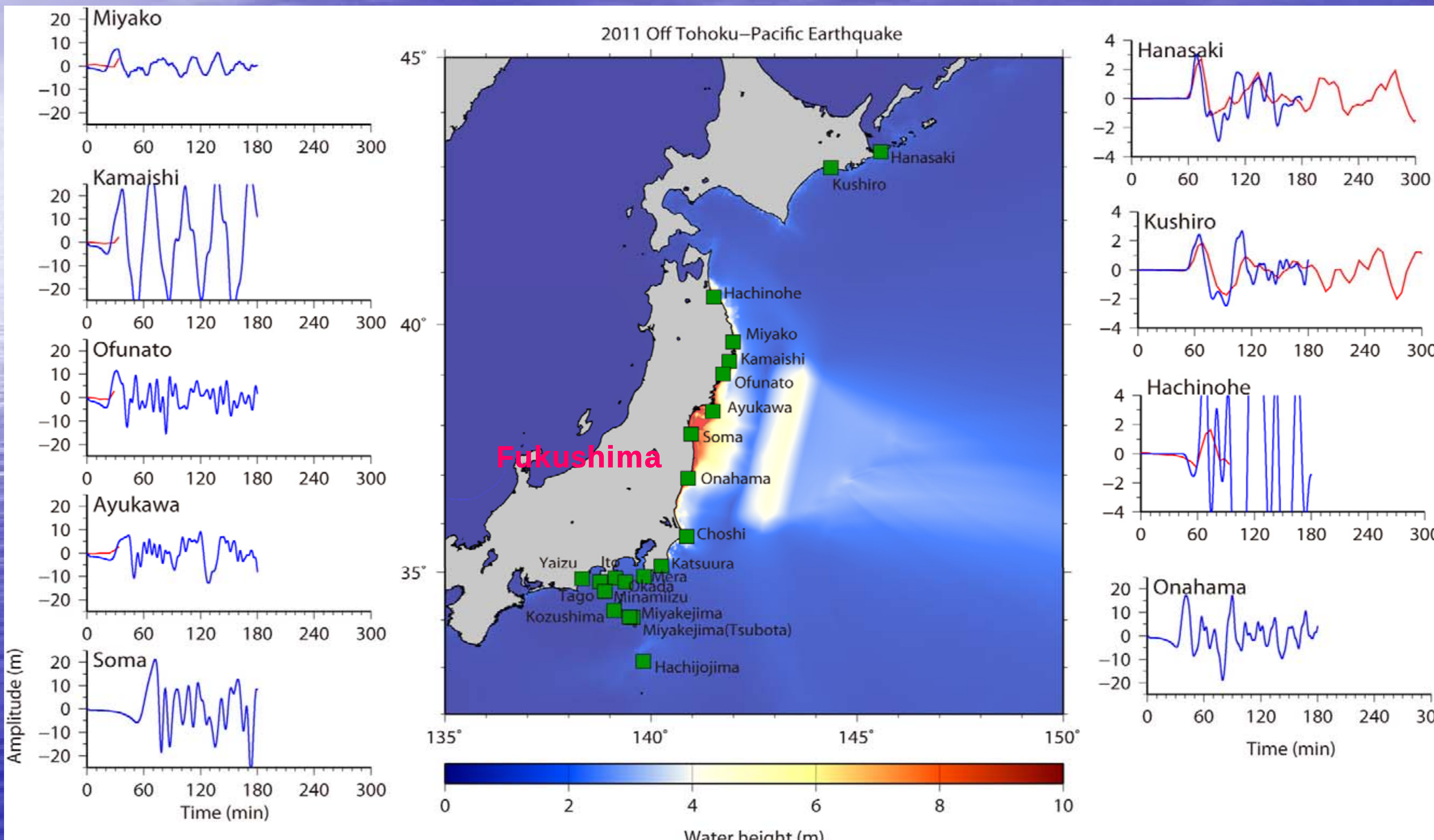

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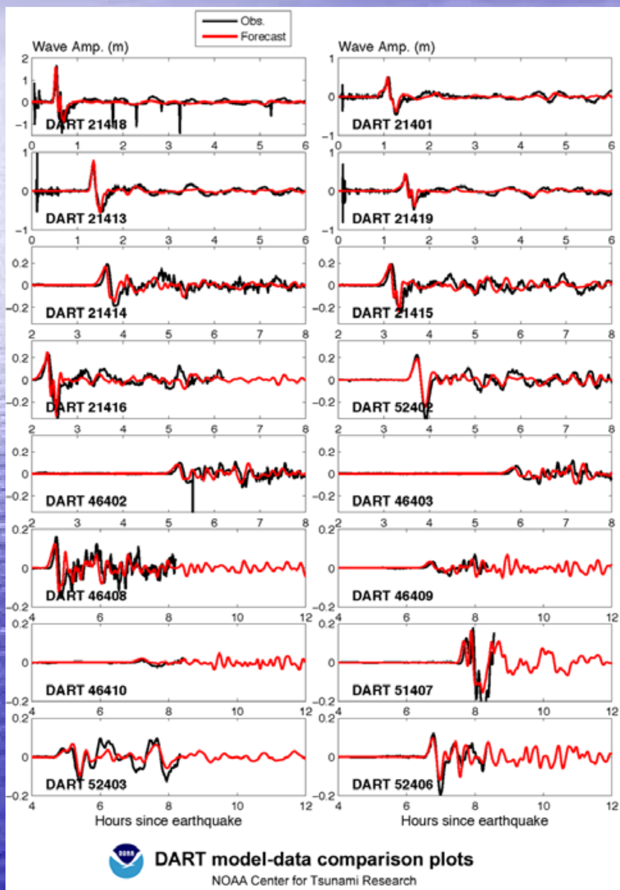
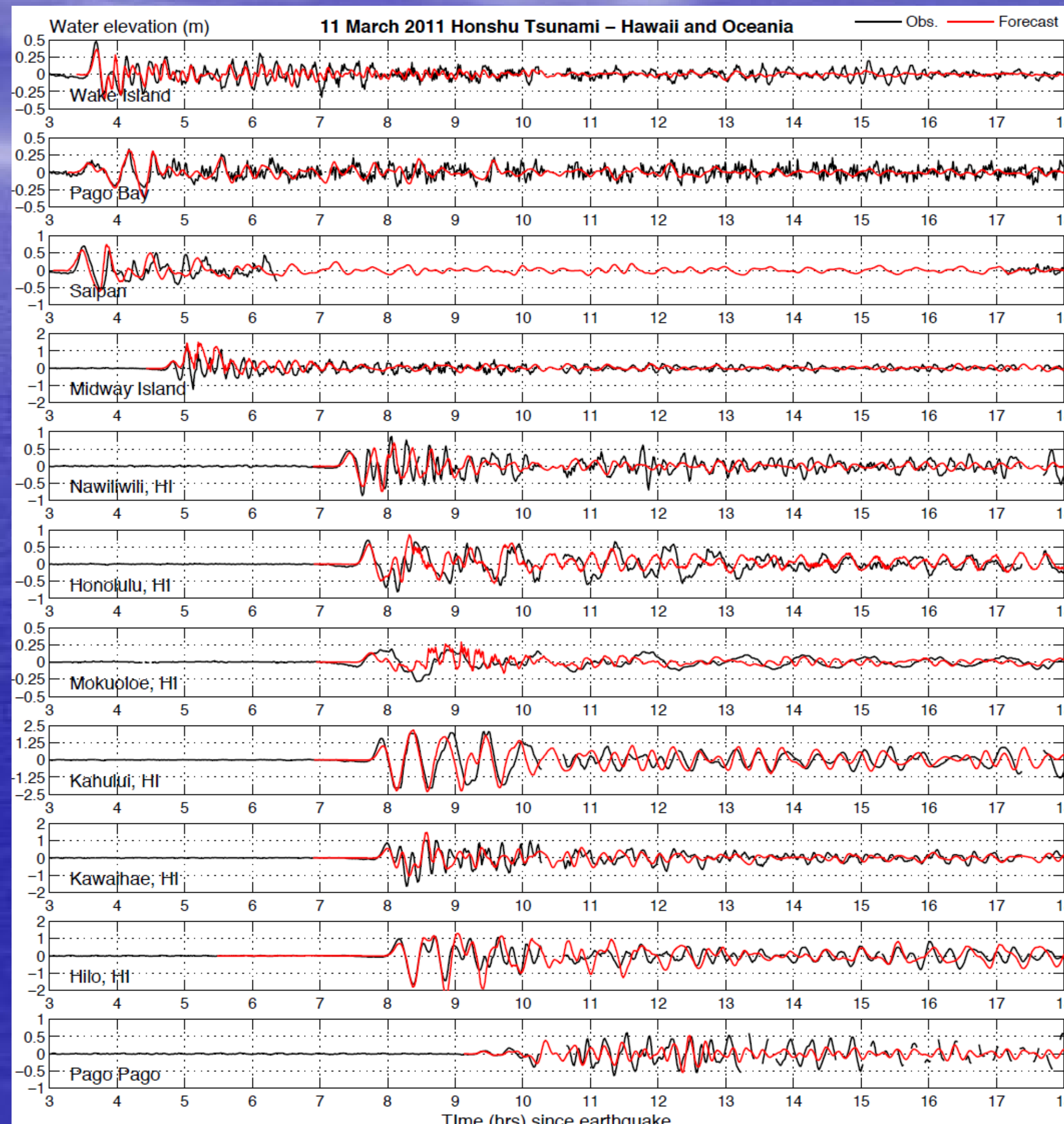
šíření a testy přesnosti





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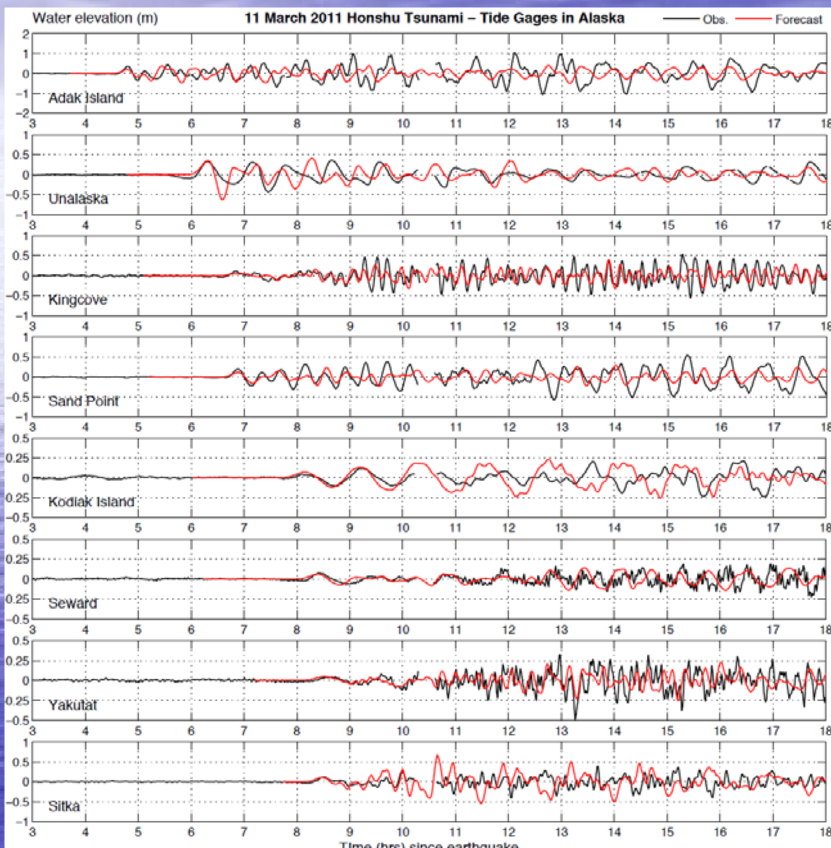
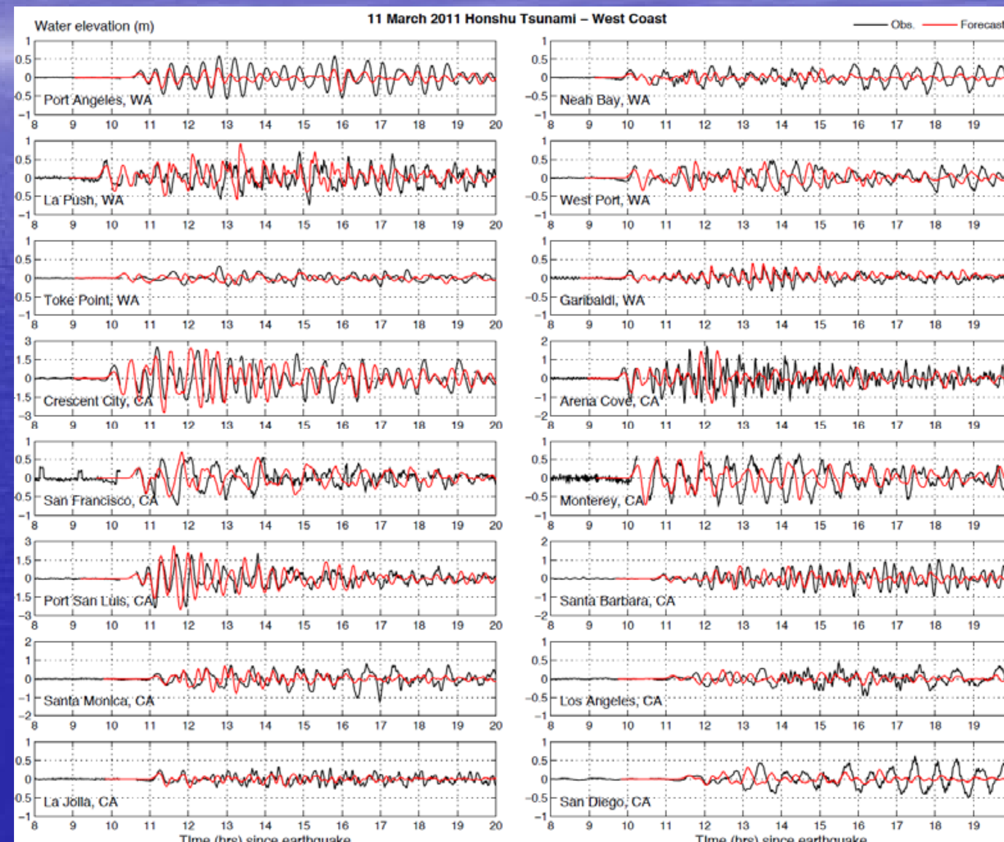
šíření a testy přesnosti





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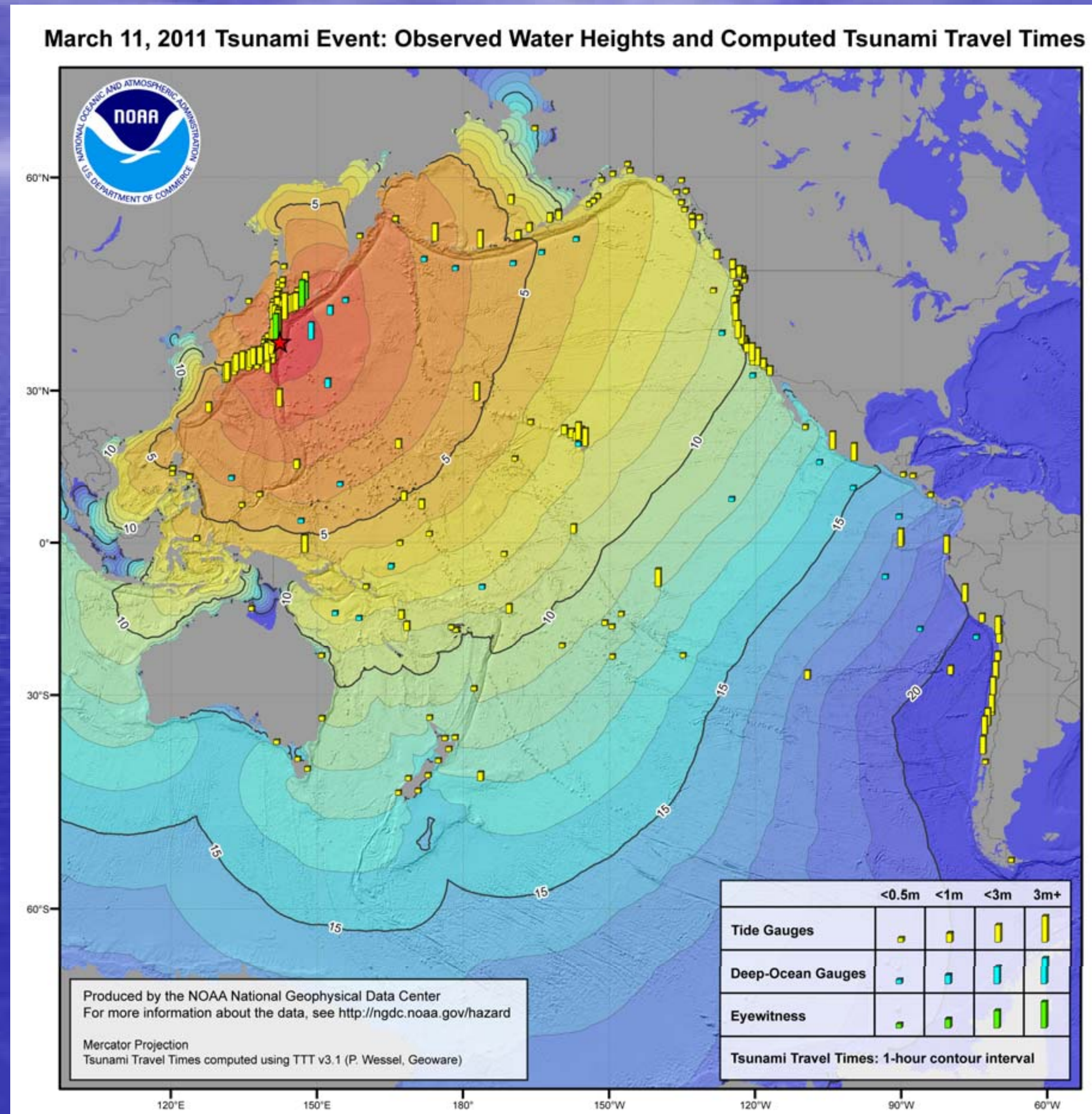
NOAA: souhrn dat a výpočtů

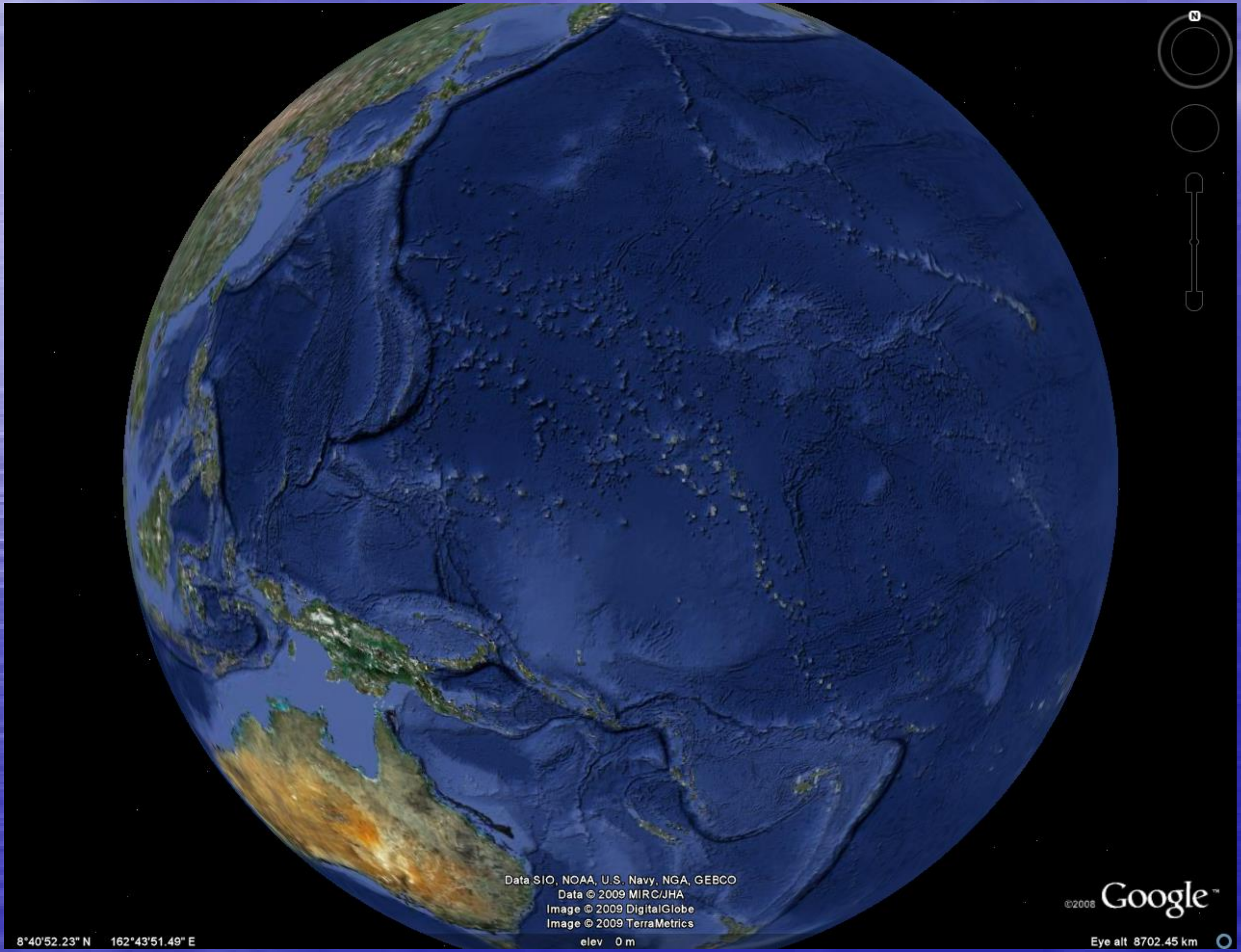


MARCH 11, 2011 JAPAN EARTHQUAKE AND TSUNAMI

The 11 March 2011 magnitude 9.0 Honshu, Japan earthquake (38.322 N, 142.369 E, depth 32 km) generated a tsunami that was observed all over the Pacific region and caused tremendous devastation locally. This is the fourth largest earthquake in the world and the largest in Japan since instrumental recordings began in 1900. The IOC/UNESCO reports that as of March 17, 2011, there are 3,617 deaths, 7,762 missing and 2,517 injuries in Japan. This is the deadliest tsunami since the 2004 magnitude 9.1 Sumatra earthquake and tsunami caused nearly 230,000 deaths and $10 billion in damage. This is the most devastating earthquake to occur in Japan since the 1995 Kobe earthquake caused over 5,500 deaths and the deadliest tsunami since the 1993 Hokkaido earthquake generated a tsunami which was responsible for over 200 deaths.

津波

šíření vln
NOAA video



+ video dr. Furumury pro oblast Japonska

津波

Konec první části


Země jako zvon

Obecná soustava parciálních diferenciálních rovnic

Hydrostatická rovnováha

- pohybová rovnice: $\nabla \cdot \boldsymbol{\tau}_0 + \boldsymbol{f}_0 = \mathbf{0}$
- Poissonova rovnice: $\Delta \varphi_0 - 4\pi G \rho_0 = 0$

$\boldsymbol{\tau}_0$ - předpětí dané Cauchyovým tenzorem napětí
$\boldsymbol{f}_0$ - referenční síla předepsaná: $\boldsymbol{f}_0 = -\rho_0 \nabla \varphi_0$
ρ_0 - referenční hustota tělesa
φ_0 - počáteční gravitační potenciál
G - Newtonova gravitační konstanta

PDR pro posunutí a přírůstkové veličiny – Lagrange-Eulerův přístup

$$\nabla \cdot \boldsymbol{\tau} - \rho_0 \nabla \varphi + \nabla \cdot (\rho_0 \boldsymbol{u}) \nabla \varphi_0 - \nabla (\rho_0 \nabla \varphi_0 \cdot \boldsymbol{u}) = \rho_0 \frac{\partial^2 \boldsymbol{u}}{\partial t^2}$$ — pohybová rovnice

$$\nabla \cdot (\nabla \varphi + 4\pi G \rho_0 \boldsymbol{u}) = 0$$ — Poissonova rovnice

$$\lambda \nabla \cdot \boldsymbol{u} \boldsymbol{I} + \mu \left[\nabla \boldsymbol{u} + (\nabla \boldsymbol{u})^{\mathrm{T}} \right] = \boldsymbol{\tau}$$ — reologický vztah

$\boldsymbol{u}$ - posunutí
φ - přírůstkový gravitační potenciál
$\boldsymbol{\tau}$ - přírůstkový tenzor napětí
λ and μ - Laméovy parametry tělesa

Sférická harmonická dekompozice

- polní veličiny rozložíme do báze sférických harmonických funkcí

$$\varphi(\boldsymbol{r}) \quad = \quad \sum_{nm} F_{nm}(r) Y_{nm}(\vartheta, \phi)$$

- F_{nm} jsou koeficienty rozvoje
- n je stupeň a m je řád

- posunutí: vektorové sférické harmonické funkce rozdělí úlohu na dvě nezávislé části

$$\boldsymbol{u}(\boldsymbol{r}) = \sum_{nm} \Big[\underbrace{U_{nm}(r) \boldsymbol{S}_{nm}^{(-1)} + V_{nm}(r) \boldsymbol{S}_{nm}^{(1)}}_{\textit{sféroidální část}} + \underbrace{W_{nm}(r) \boldsymbol{S}_{nm}^{(0)}}_{\textit{toroidální část}} \Big]$$

- toroidální kmity nevyvolávají změnu objemu: $\nabla \cdot \boldsymbol{u} = 0, \qquad \boldsymbol{u} \cdot \boldsymbol{e}_r = 0$

- sféroidální kmity: $(\nabla \times \boldsymbol{u}) \cdot \boldsymbol{e}_r = 0$

- slapový vektor posunutí dán pouze sferoidální částí: $(\nabla \times \boldsymbol{u}) \cdot \boldsymbol{e}_r = 0$

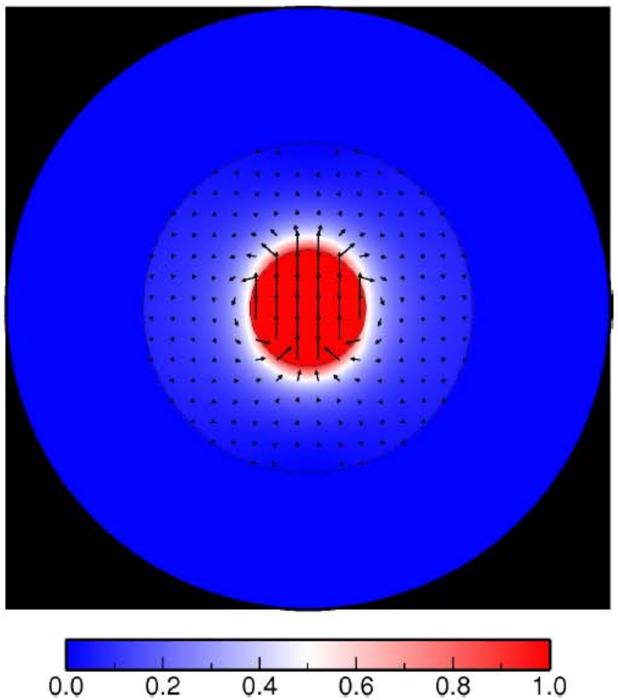
- pro sféricky symetrické modely (+ symetrický slapový potenciál) úloha (2n + 1)krát degeneruje

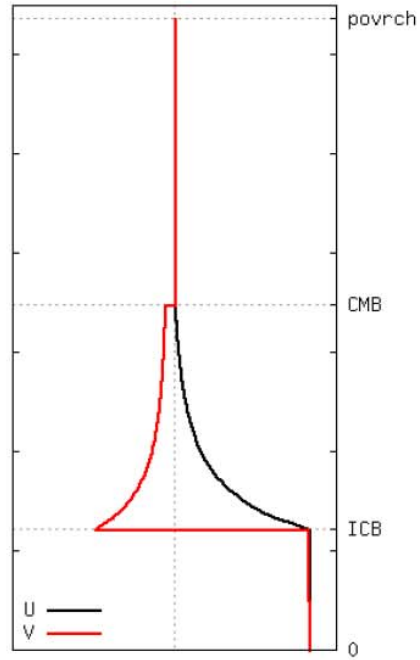
Země jako zvon

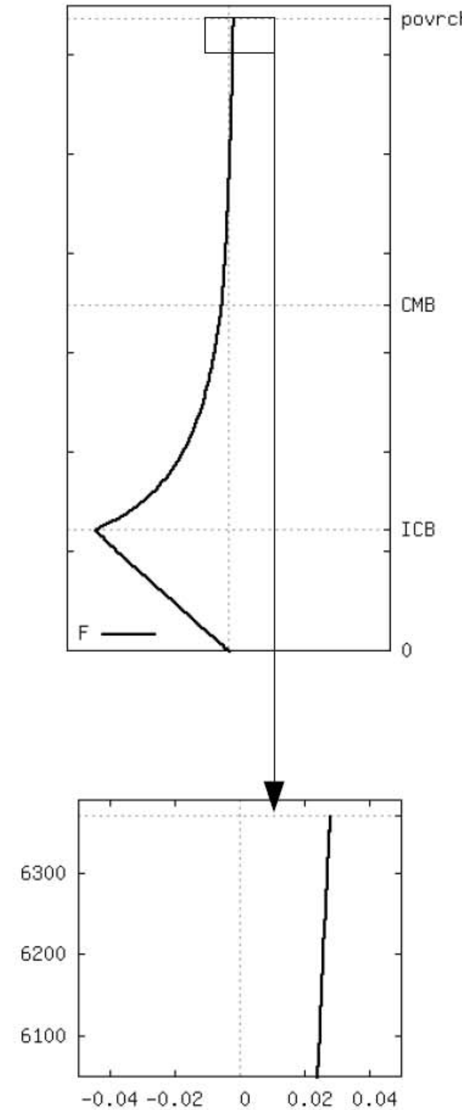
mód	perioda [s]	frekvence [mHz]	mód	perioda [s]	frekvence [mHz]	mód	perioda [s]	frekvence [mHz]
${}_1S_1$	19616	0.0510	${}_3S_1$	1060	0.9436	${}_3S_3$	706	1.4161
${}_0S_2$	3233	0.3093	${}_0S_6$	963	1.0376	${}_2S_5$	662	1.5117
${}_2S_1$	2475	0.4041	${}_3S_2$	904	1.1056	${}_1S_6$	657	1.5214
${}_0S_3$	2134	0.4686	${}_1S_4$	853	1.1722	${}_0S_9$	634	1.5761
${}_0S_4$	1546	0.6470	${}_0S_7$	813	1.2301	${}_1S_7$	604	1.6545
${}_1S_2$	1471	0.6798	${}_2S_3$	806	1.2410	${}_2S_6$	596	1.6765
${}_0S_0$	1230	0.8130	${}_1S_5$	730	1.3697	${}_5S_1$	584	1.7111
${}_0S_5$	1190	0.8401	${}_2S_4$	726	1.3772	${}_4S_2$	581	1.7209
${}_2S_2$	1066	0.9385	${}_4S_1$	709	1.4113	${}_0S_{10}$	580	1.7236
${}_1S_3$	1064	0.9395	${}_0S_8$	708	1.4119	${}_1S_8$	556	1.7980

Nejdelší sféroidální módy

${}_1S_1$: T=19628s

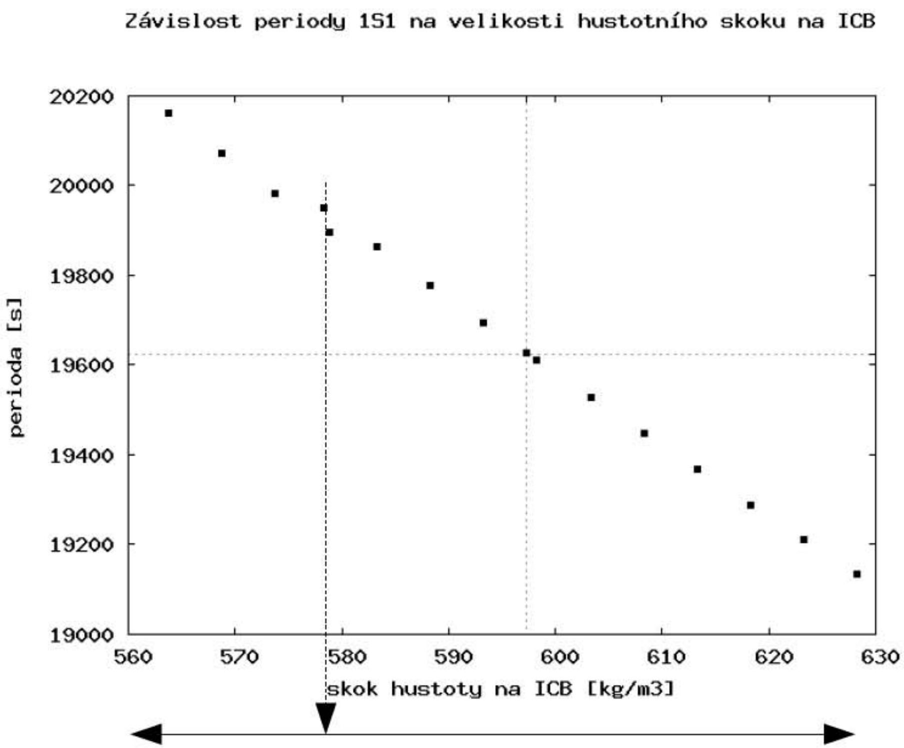






Slichterův mód: pohyb vnitřního jádra jako celku.

Perioda $_1S_1$ vs. skok hustoty na ICB

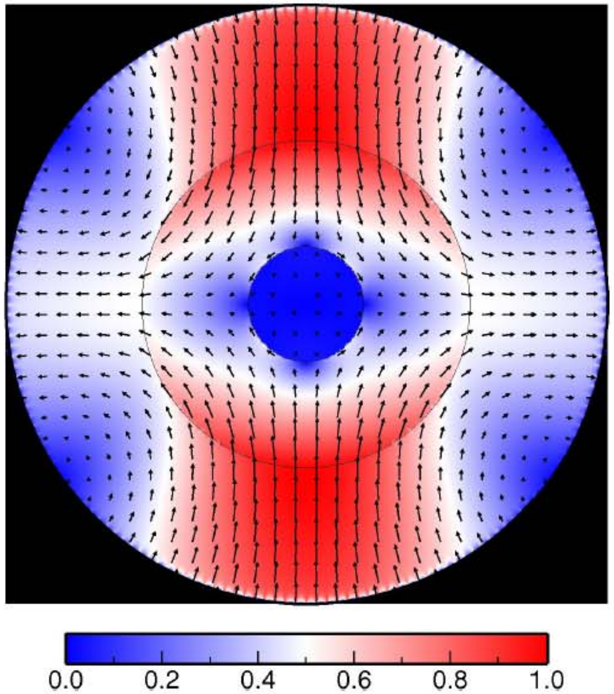


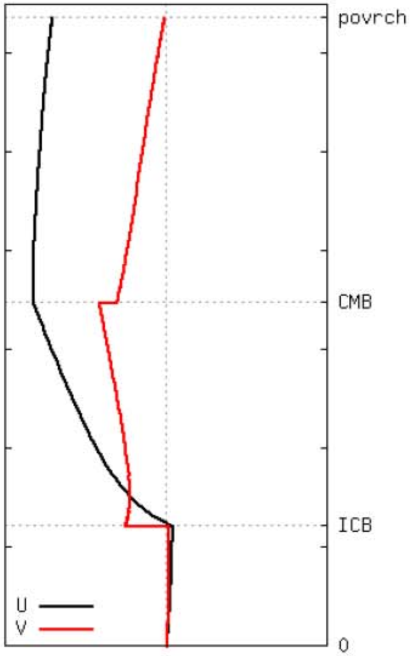
Pro vyšší módy je změna periody zcela zanedbatelná.

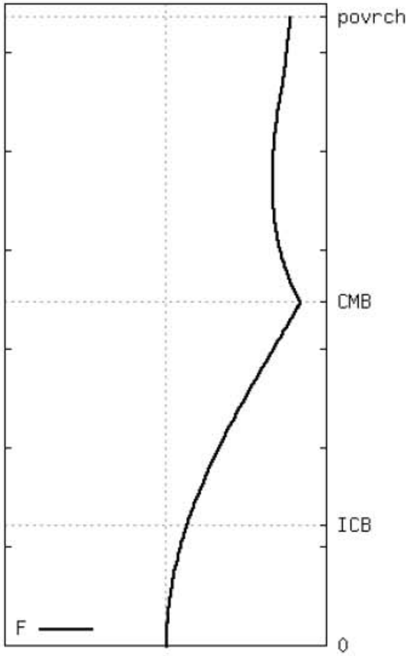
- $\Delta g < 0.1\,\%$
- $\Delta\rho \pm 0.05\,\Delta\rho \approx T \pm 0.05\,T \Rightarrow \pm 10\,min$

Nejdelší sféroidální módy

$_0S_2$: T=3218s



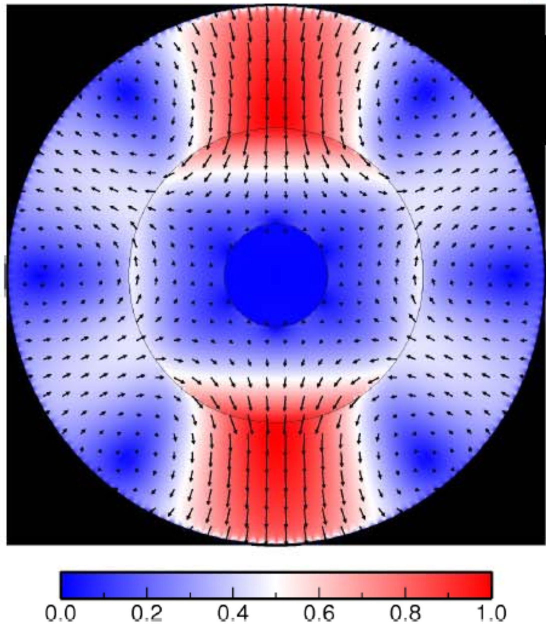


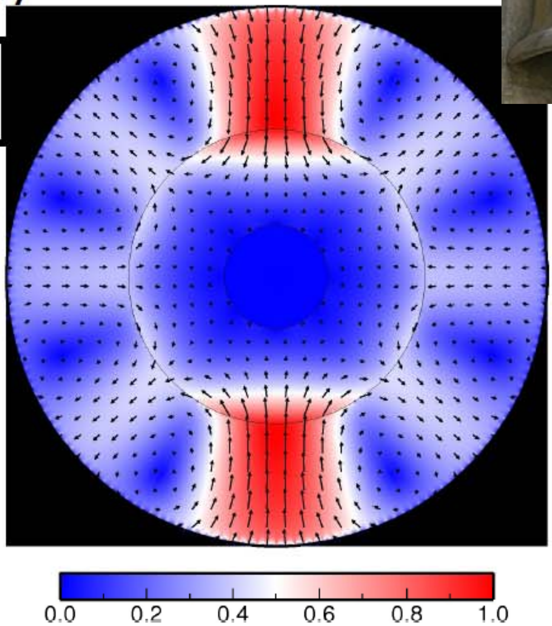


Základní sféroidální módy

${}_0S_3$: T=2122s

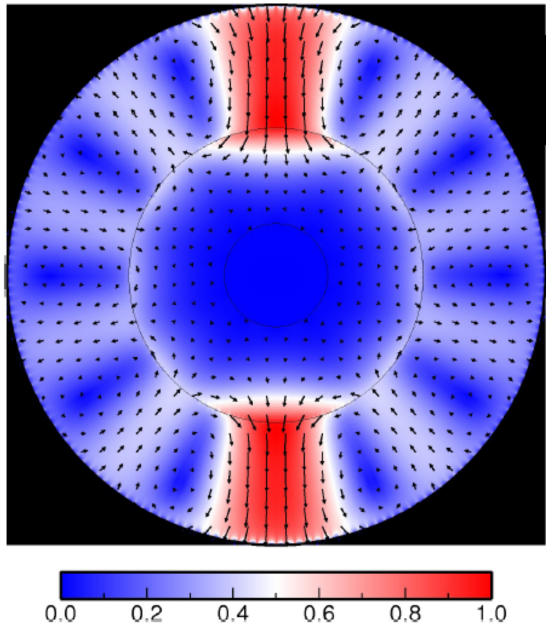
${}_0S_4$: T=1536s

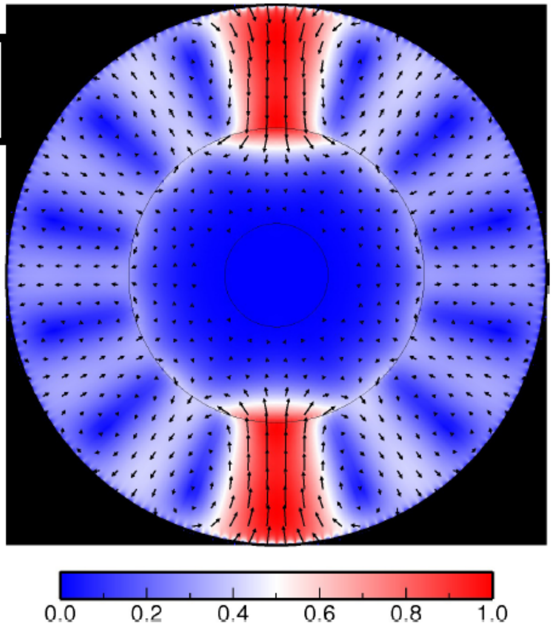




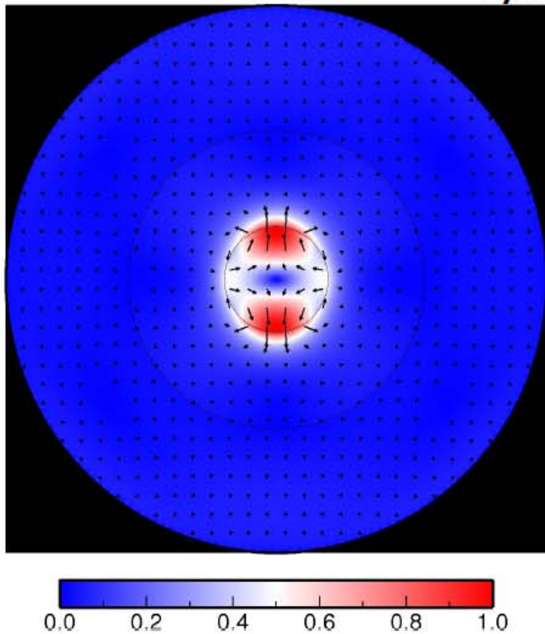
${}_0S_5$: T=1183s

${}_0S_6$: T=958s



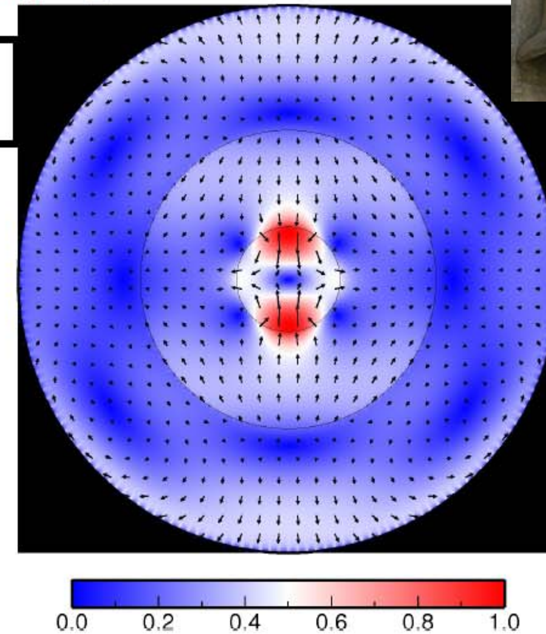


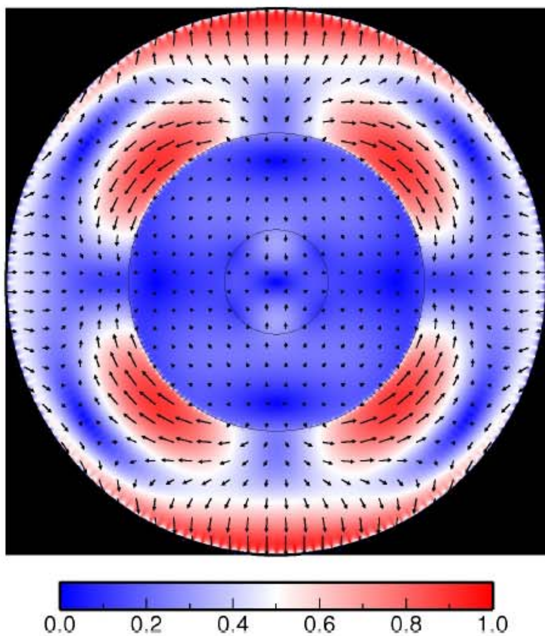
Vyšší sféroidální módy pro n=2



${}_{2}S_{2}$: T=1041s

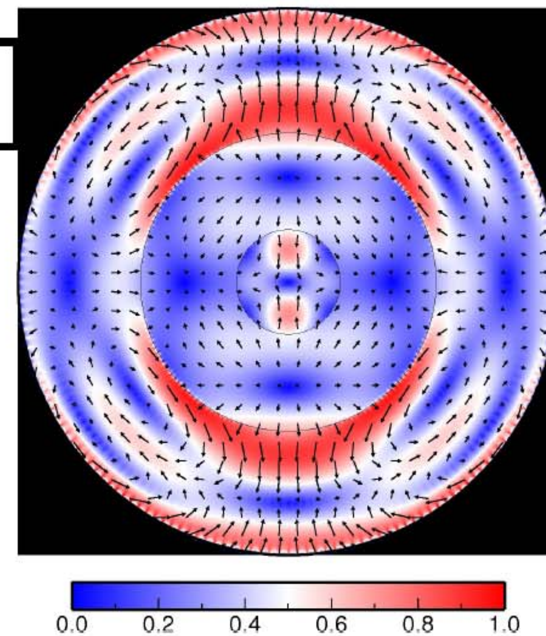
${}_{3}S_{2}$: T=899s





${}_{4}S_{2}$: T=578s

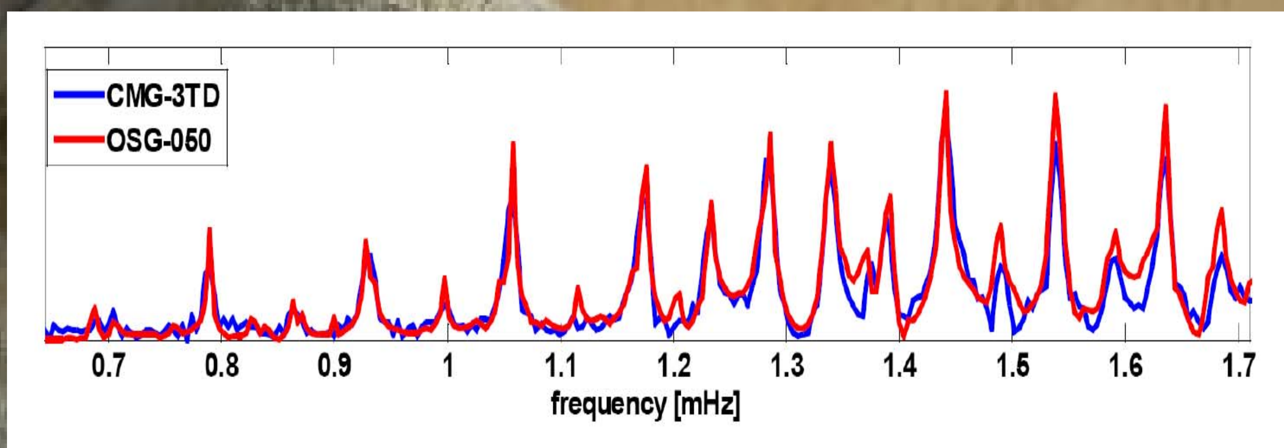
${}_{5}S_{2}$: T=476s



Zpracování záznamů supravodivého gravimetru a širokopásmového seismometru z Geodetické observatoře VÚGTK Pecný

Seismometr CMG-3TD před spuštěním do vrtu

Supravodivý gravimetr OSG-050



Děkuji Vám za pozornost

Vaše případné dotazy kvalifikovaně zodpoví:

Vlny v oceánech: Bc. David Einšpigel

Vlastní kmity Země: RNDr. Eliška Zábranová