

Vlastní kmity – od Q k CMT

Eliška Zábranová

Katedra geofyziky

MFF UK

Přehled

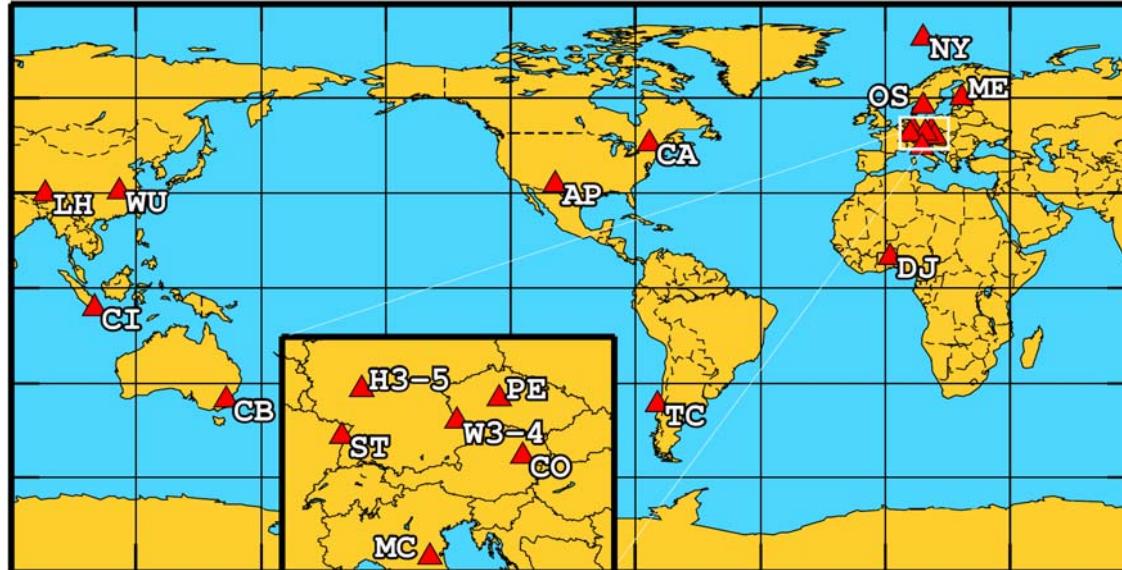
- Data
- Vlastní kmity
- Frekvence a útlum z dat
- Modelování
- Nejdelší módy
- Vysoké frekvence

• Data

- záznamy ze supravodických gravimetrů v rámci Global Geodynamics Project

<http://www.eas.slu.edu/GGP/ggphome.html>

- sběr dat po významný jevech (Sumatra 2004, Maule 2010, Tohoku 2011)
 - sekundová i minutová gravitační data, atmosférický tlak



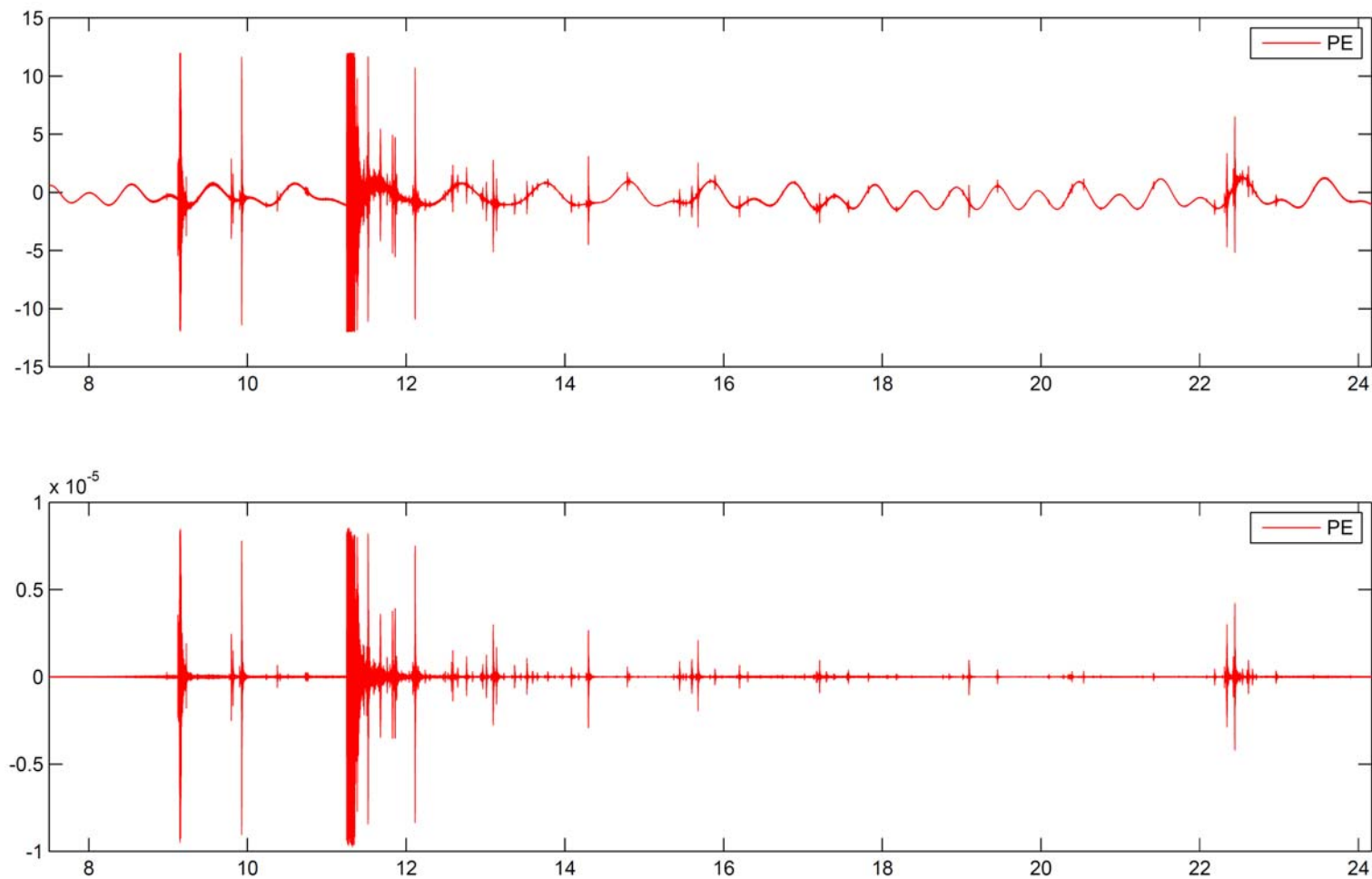
• Data

- sekundový záznam gravitačního zrychlení a atmosférického tlaku ve voltech
- potřeba odstranit vliv:
 - atmosférického tlaku
 - faktor závislý lokálně i frekvenčně : $(-0.27 - -0.43 \mu\text{Gal hPa}^{-1})$
- slapy (modelem nebo filtrací)
- trend

```
Filename      : PE110300.GGS
Station       : Pecny, Czech Republic
Instrument     : GWR OSG-050
Time Delay (sec) : 8.8600 0.0200 measured
N. Latitude (deg) : 49.9137 0.0001 measured
E. Longitude (deg) : 14.7856 0.0001 measured
Elevation MSL (m) : 534.5800 0.0500 measured
Gravity Cal (uGal/V): -73.3500 0.0200 measured
Pressure Cal (hPa/V): 1.0000 0.0060 measured
Author        : vojtech.palinkas@pecny.cz
yyyymmdd hhmmss gravity(V) pressure(V)
C*****
77777777 0.0 0.0
20110301 000000 0.313755 962.6310
20110301 000001 0.303011 962.6290
20110301 000002 0.297373 962.6270
20110301 000003 0.303552 962.6220
20110301 000004 0.319019 962.6200
20110301 000005 0.333299 962.6180
20110301 000006 0.336057 962.6180
20110301 000007 0.325090 962.6200
```

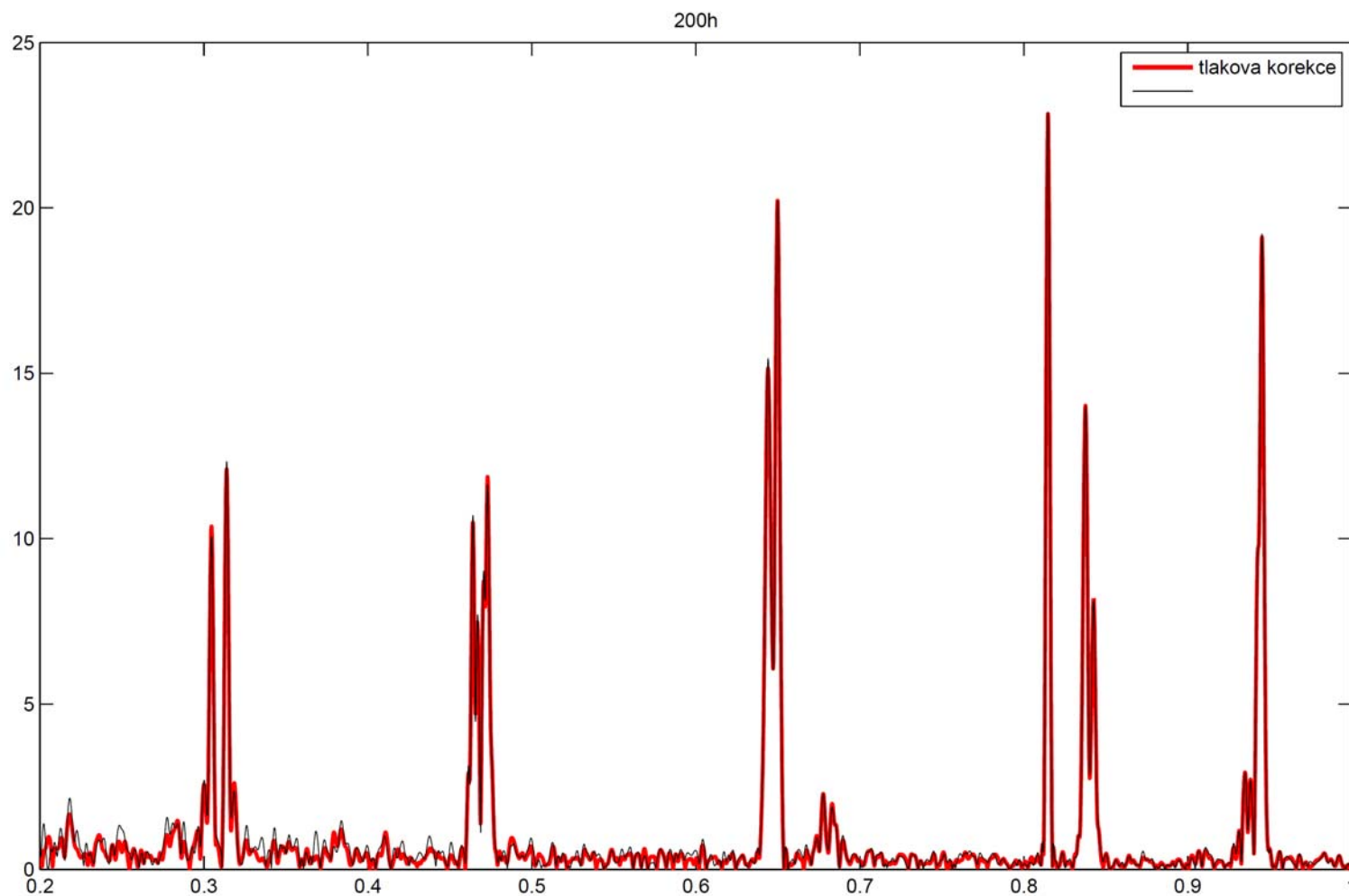
- Data – slapy, trend (Tohoku 2011)

- filtr 0.1mHz – 400mHz



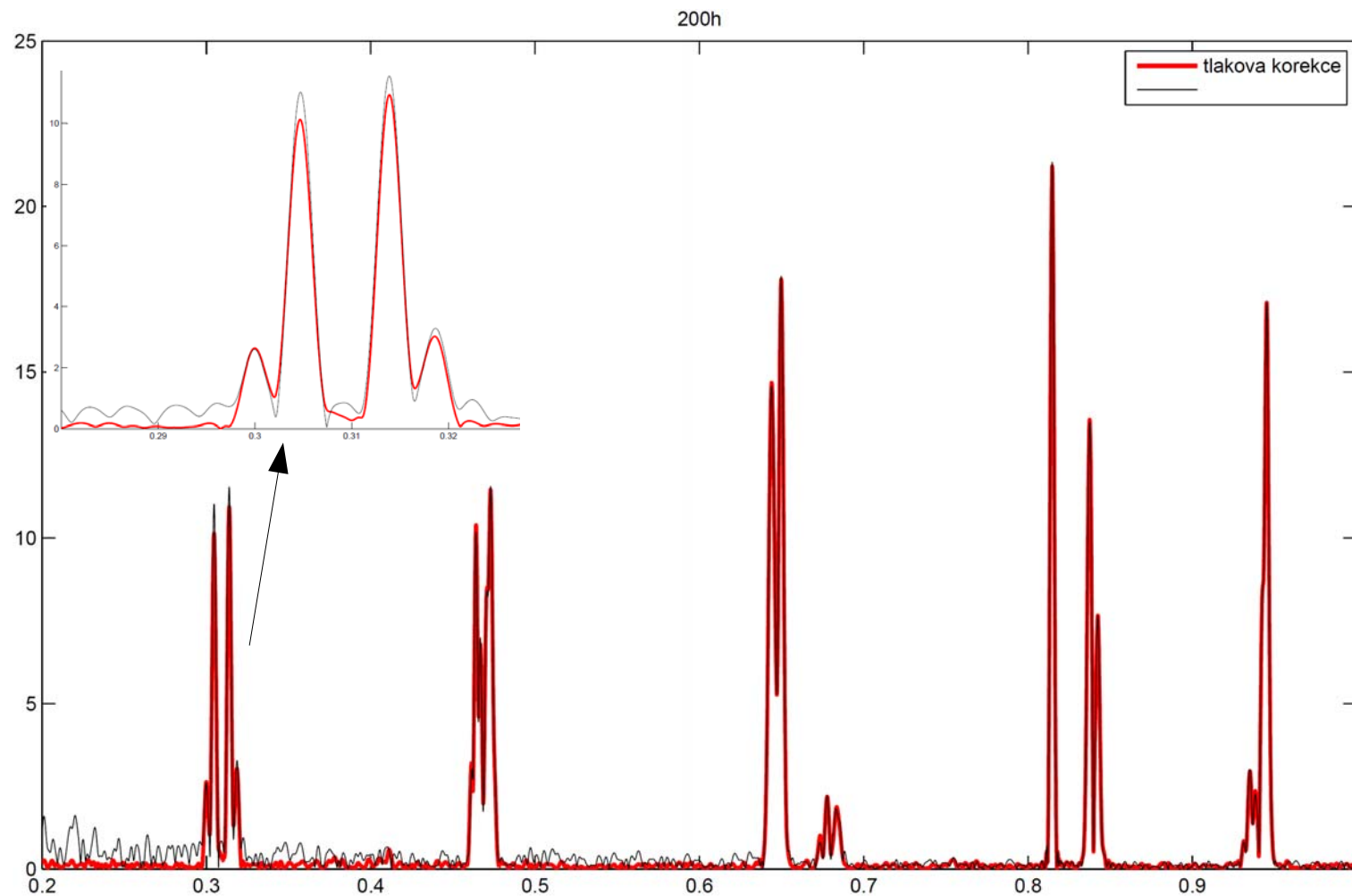
- Data – atmosférická korekce (Tohoku 2011)

- stanice PE: $-0.33 \mu\text{Gal hPa}^{-1}$



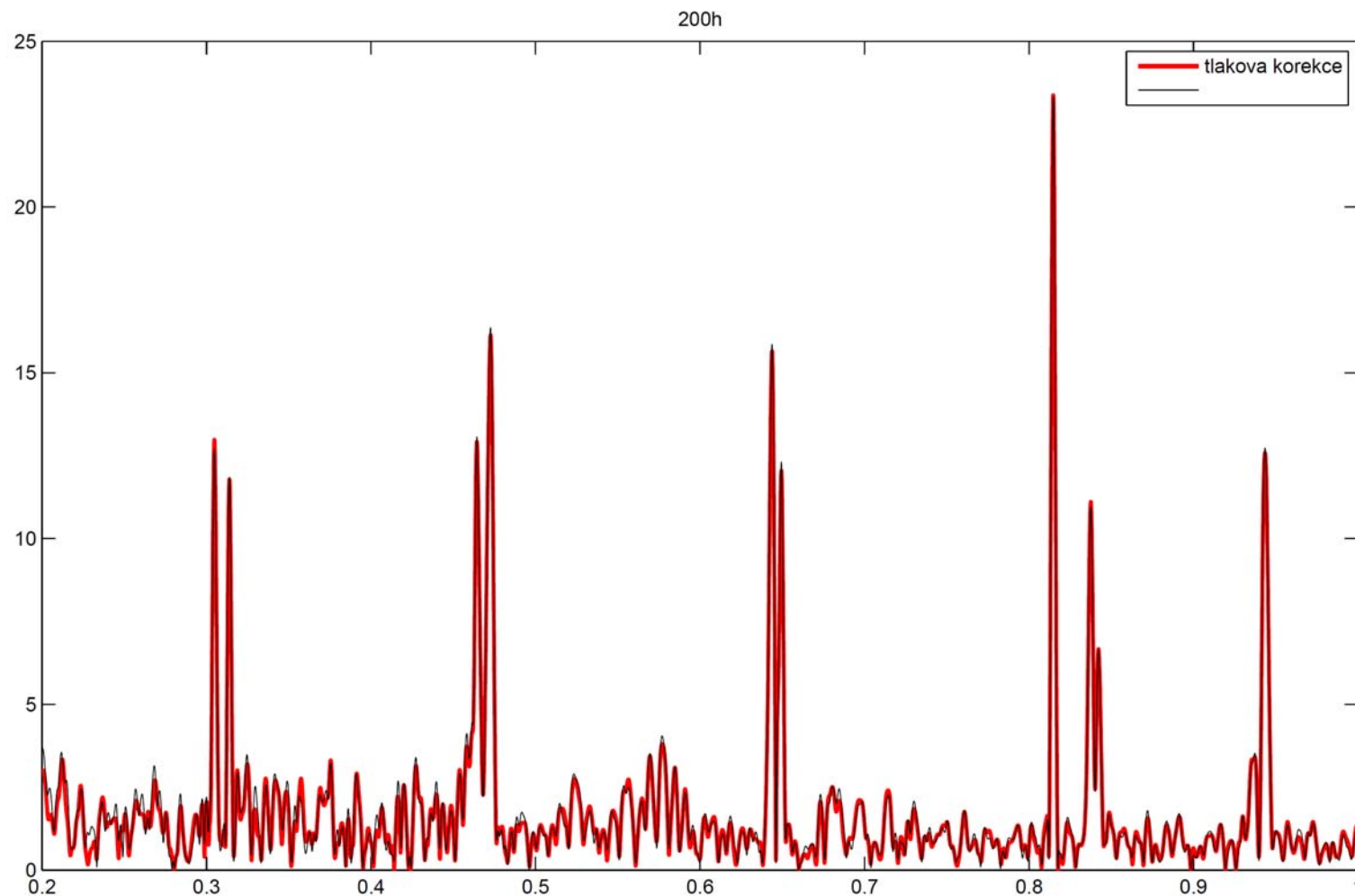
- Data – atmosférická korekce (Tohoku 2011)

- stanice ST: $-0.33 \mu\text{Gal hPa}^{-1}$

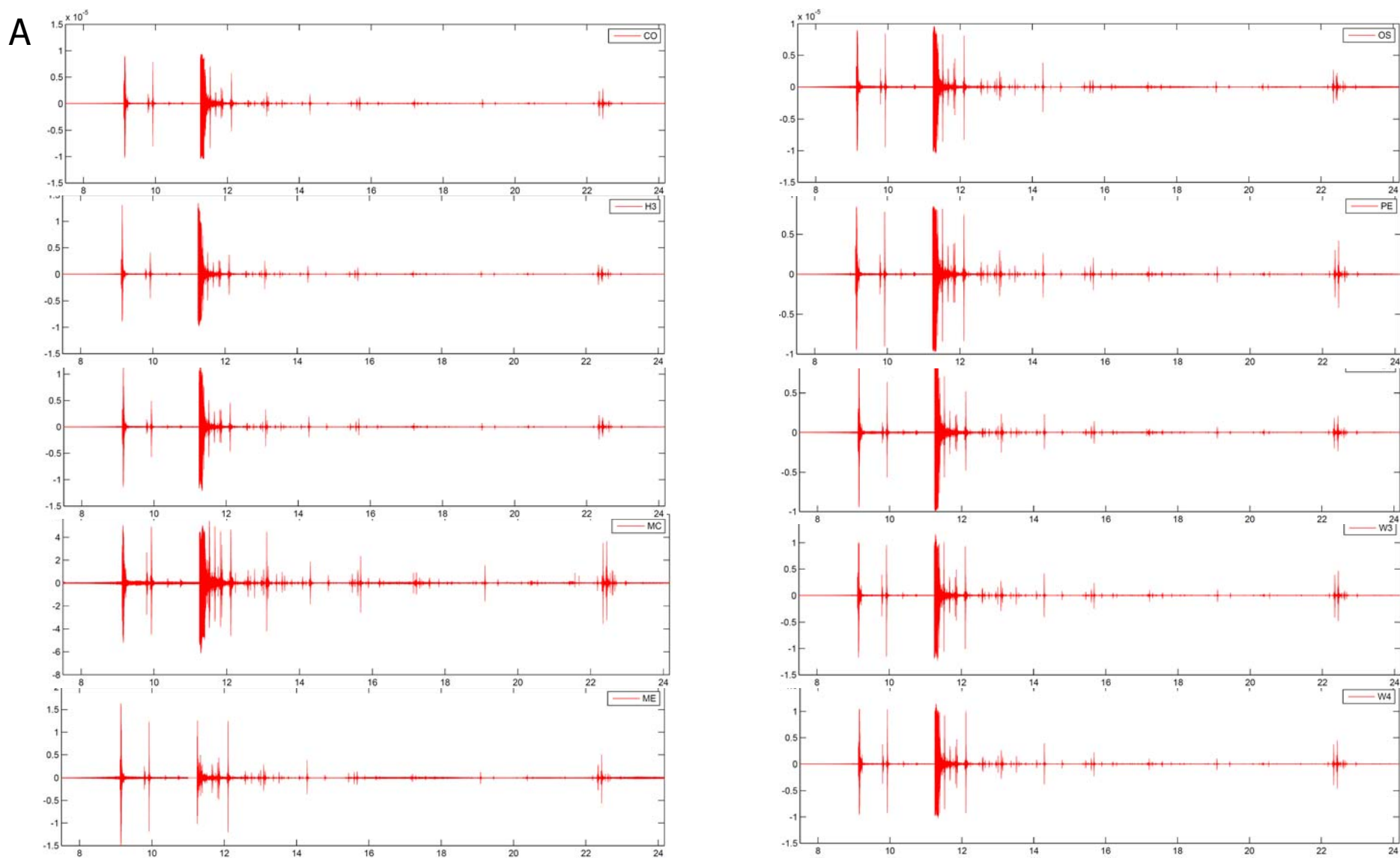


- Data – atmosférická korekce (Tohoku 2011)

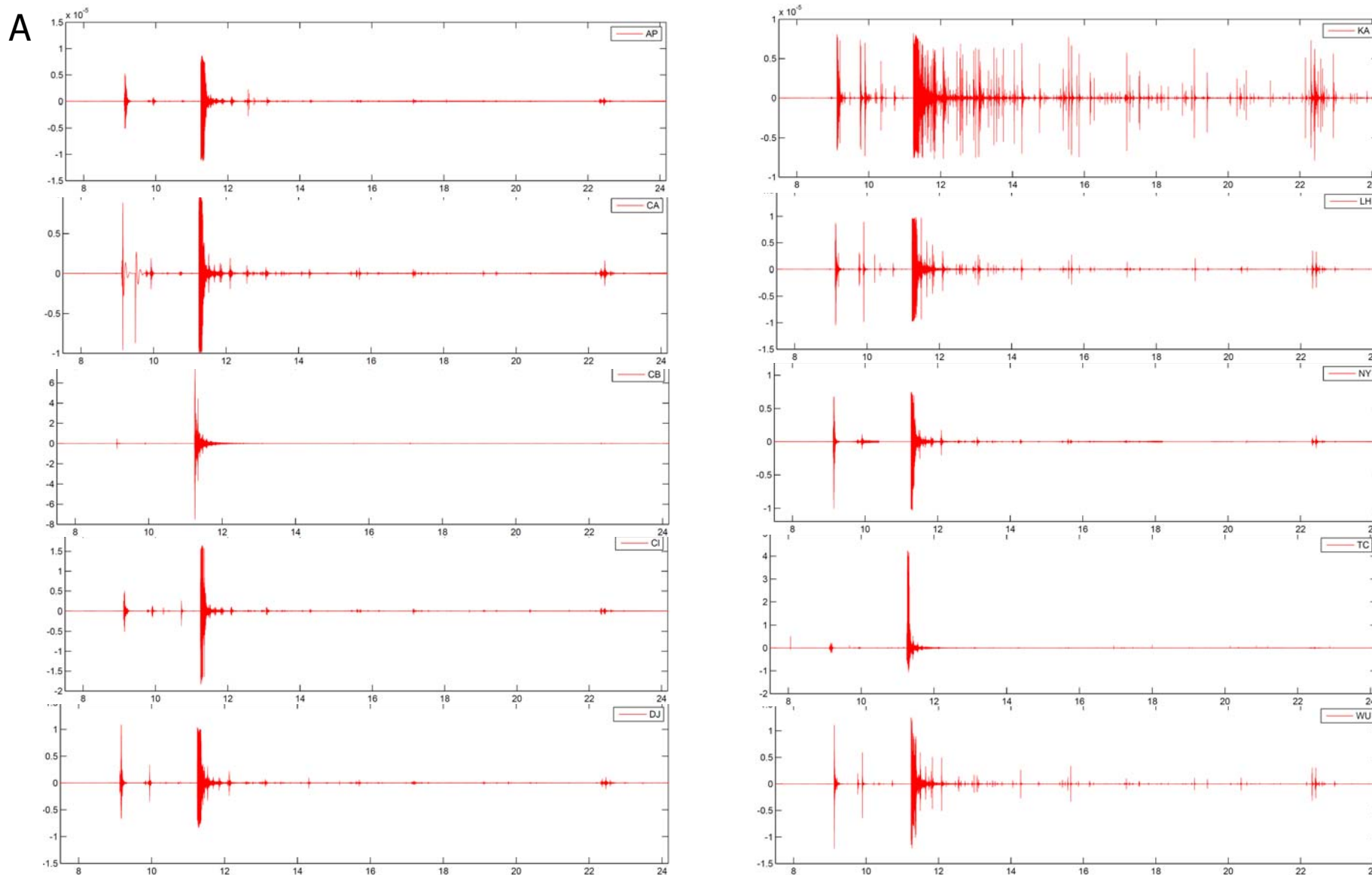
- stanice CA: $-0.33 \mu\text{Gal hPa}^{-1}$



- Data – evropské stanice (Tohoku 2011)

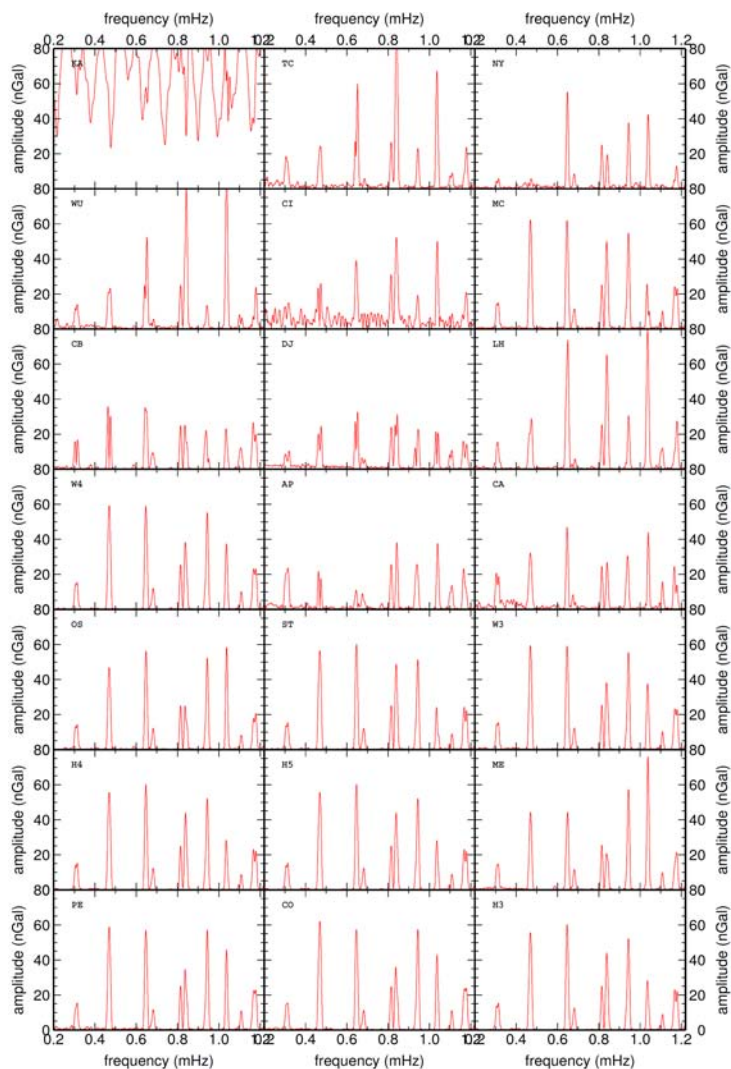


- Data – světové stanice (Tohoku 2011)

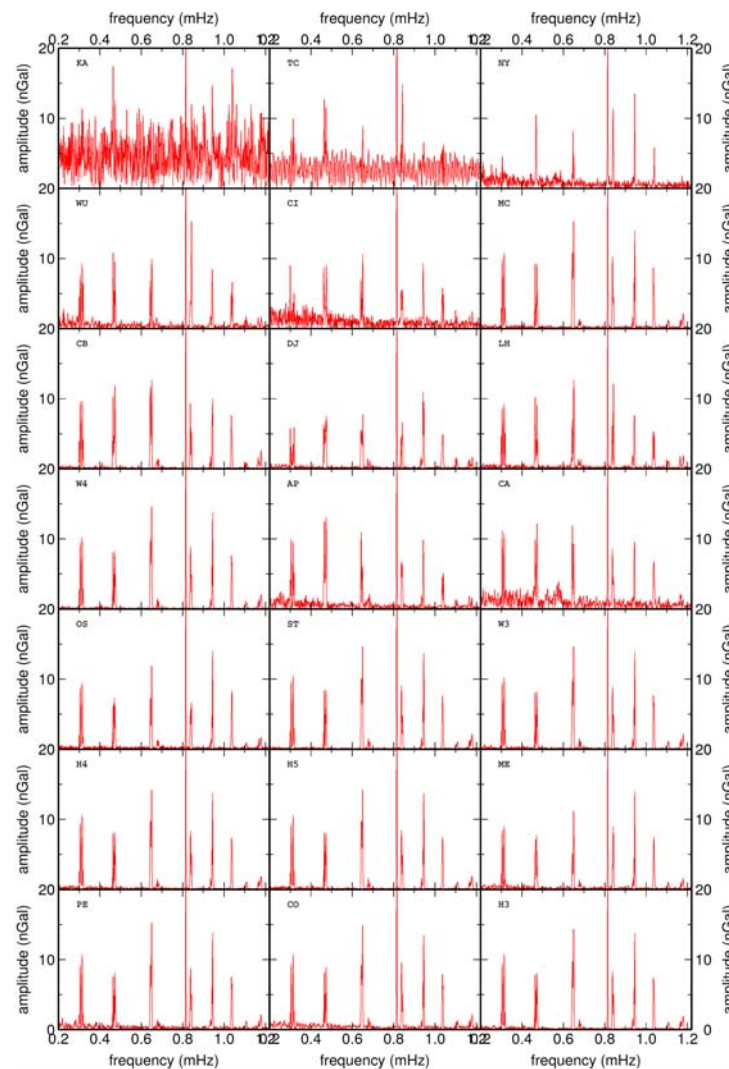


- Data – fouriérovská spektra (0.2 – 1.2mHz) (Tohoku 2011)

50+ 20h

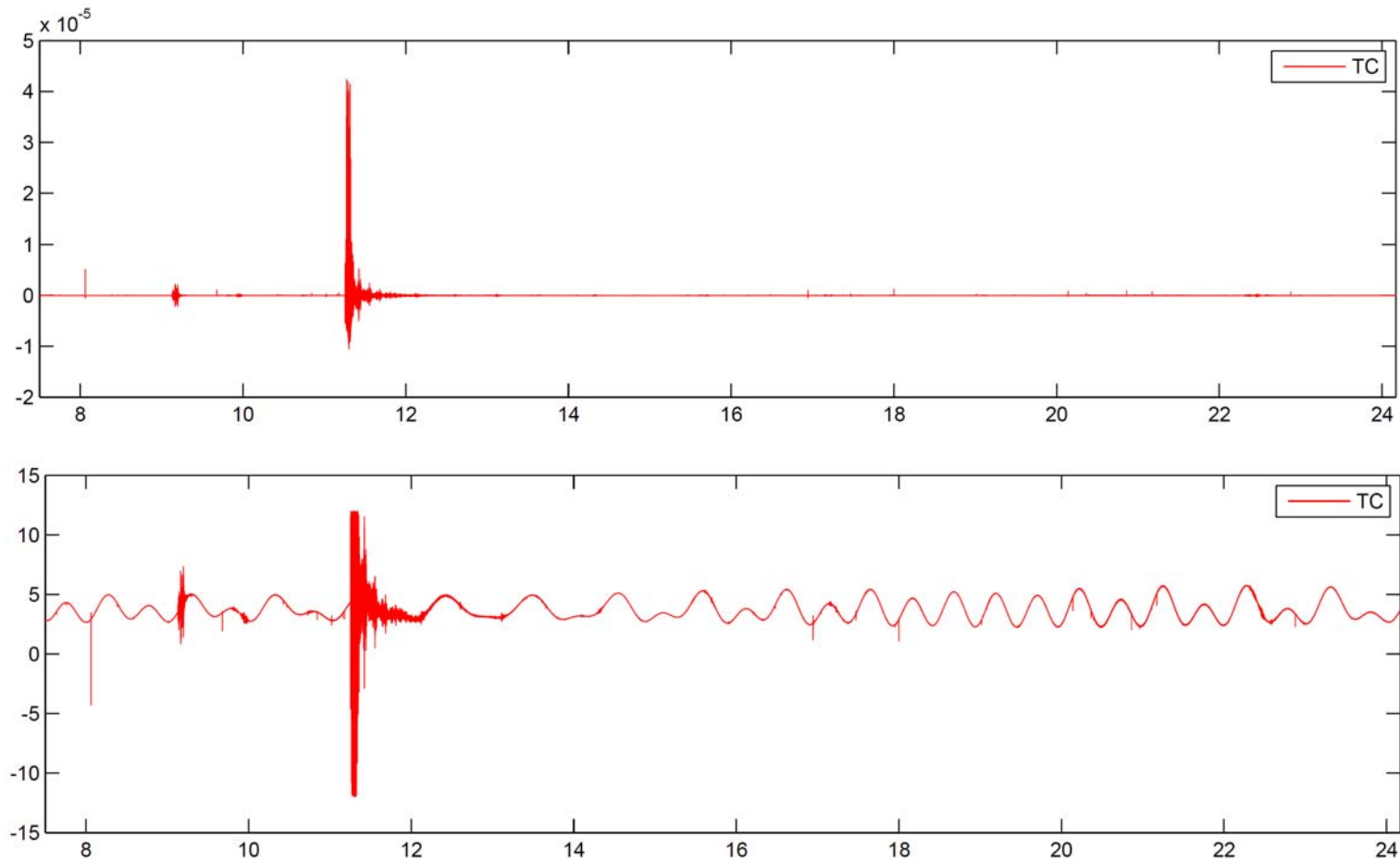


200 + 20h



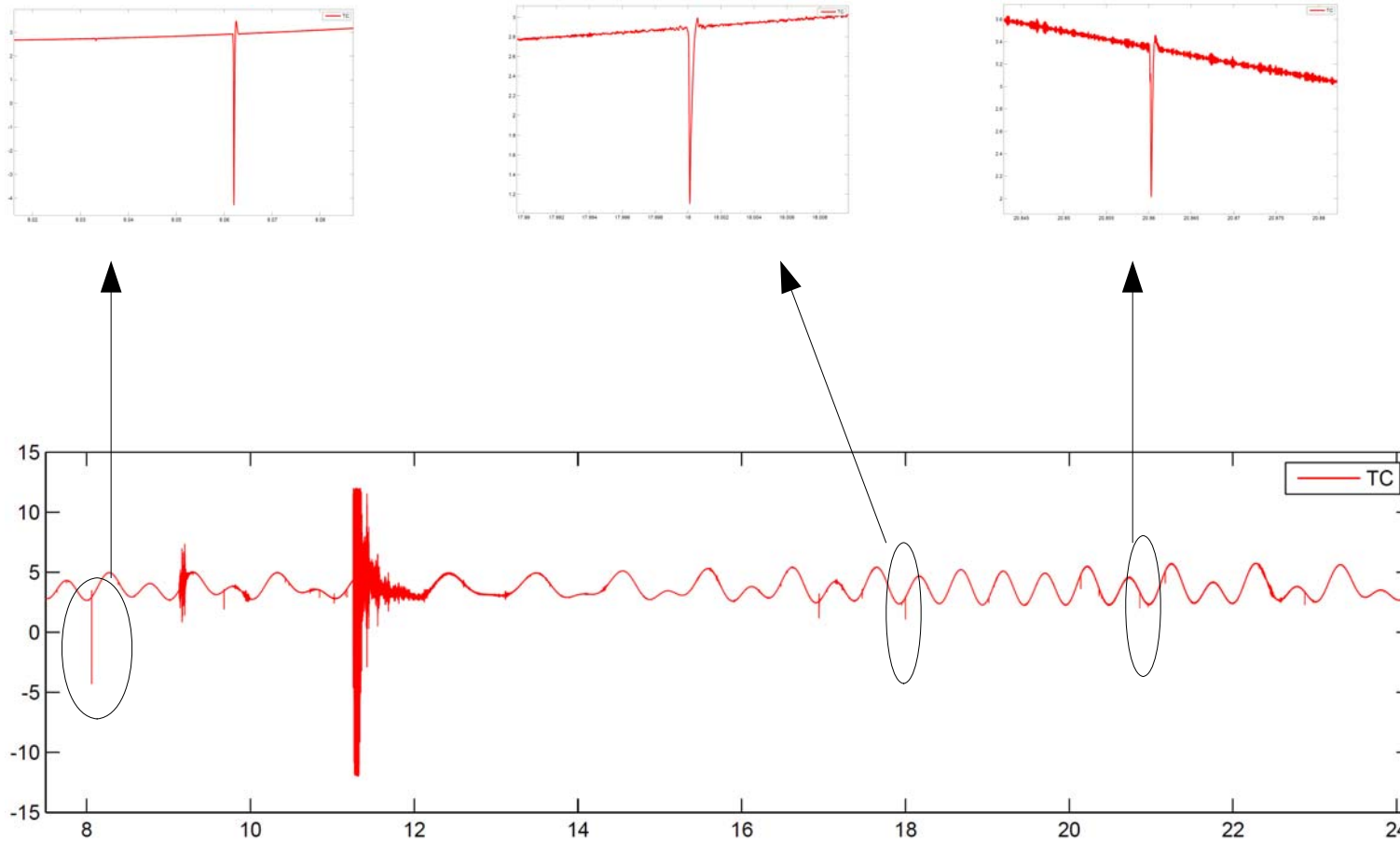
- Data – stanice TC (Tohoku 2011)

50+ 20h



• Data – stanice TC (Tohoku 2011)

50+ 20h



• Vlastní kmity

- reálná odezva aparatury (pro rotační, eliptický, anelastický model)

$$\mathbf{a}(\mathbf{x}, t) = \sum_{nlm} \mathbf{A}_{nlm}(\mathbf{x}) \cos \left[{}_n\omega_l \left(1 + a + bm + cm^2 \right) t \right] \exp \left(-{}_n\gamma_l t \right)$$

${}_n\omega_l$ - neperturovaná frekvence multipletu

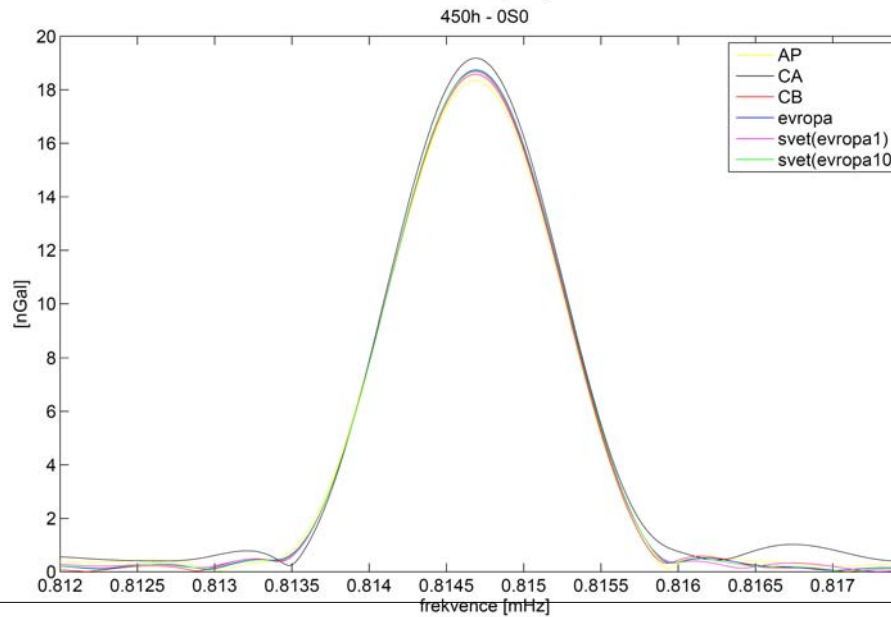
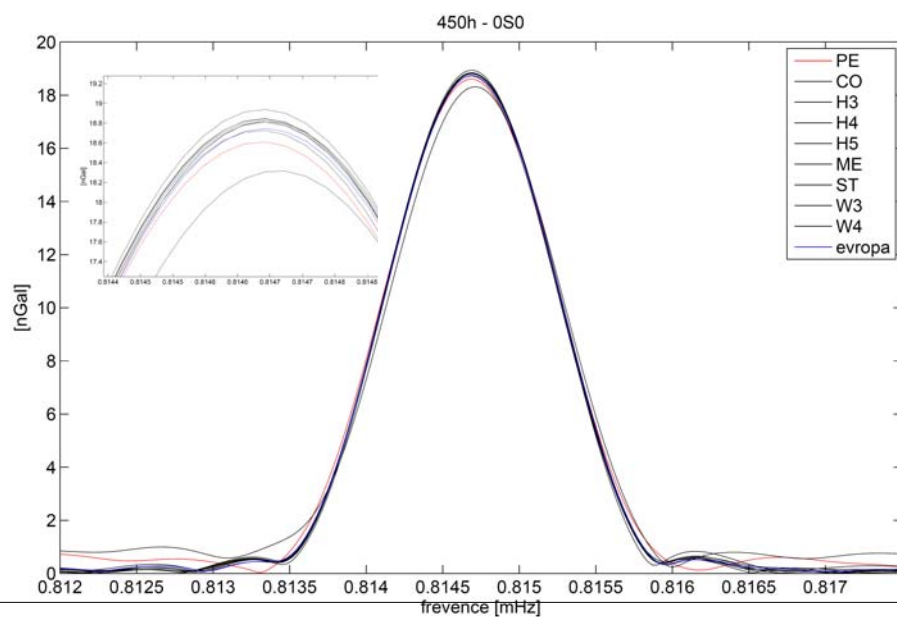
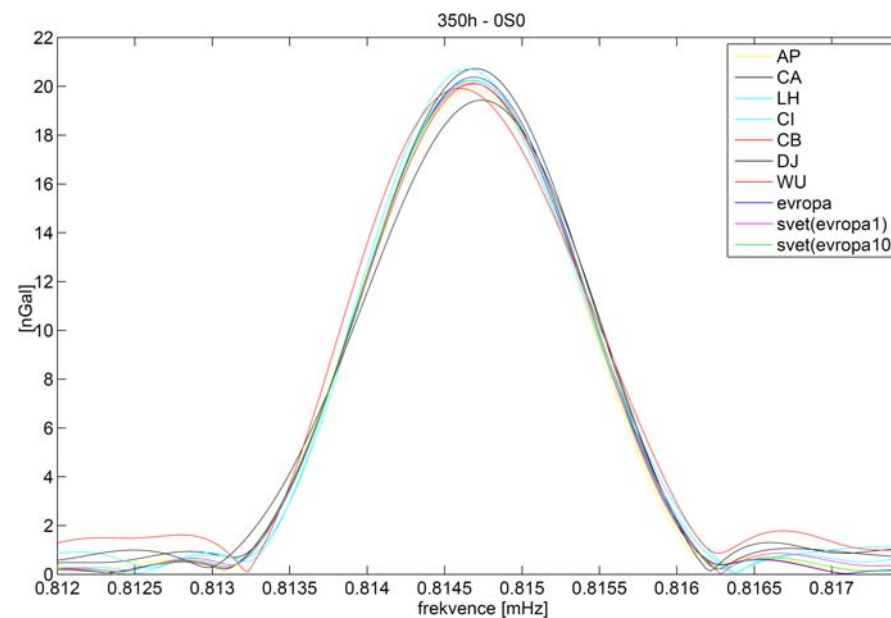
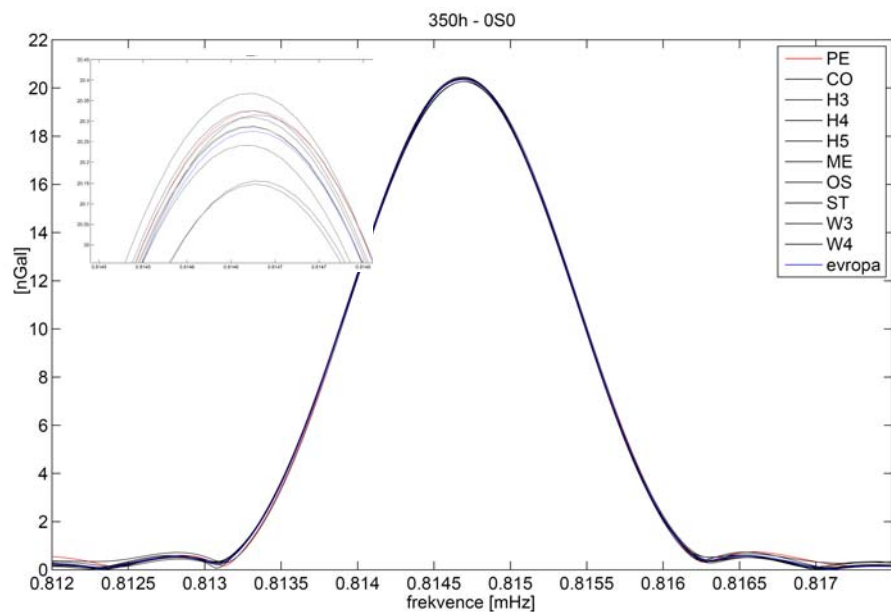
${}_n\gamma_l$ - útlum multipletu

Koeficienty $\mathbf{A}_{nlm}(\mathbf{x})$ dané:

- momentovým tenzorem (strike, dip, rake a skalární seismický moment)
- pozicí zdroje a přijímače (epicentrální vzdálenost, azimut)
- vlastními funkcemi ve zdroji a na povrchu
- korekce na volný vzduch a náklon

- štěpení v důsledku rotace, elipticity a laterálních nehomogenit

• Frekvence – radiální kmity (Tohoku 2011)

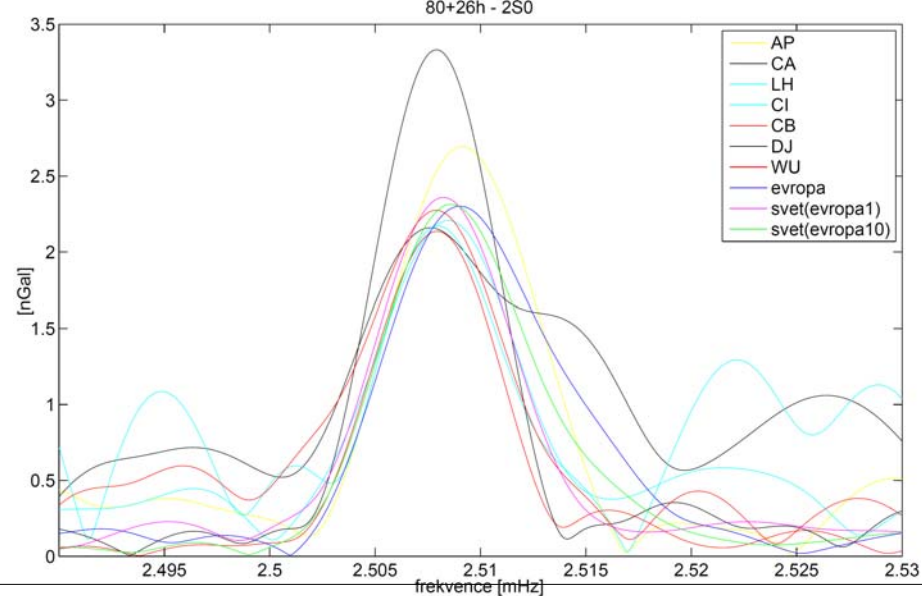
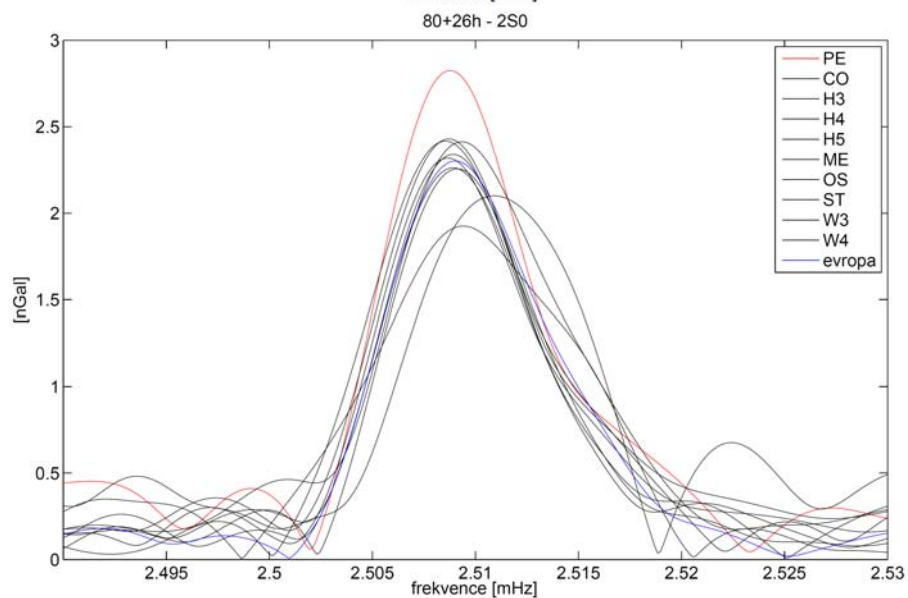
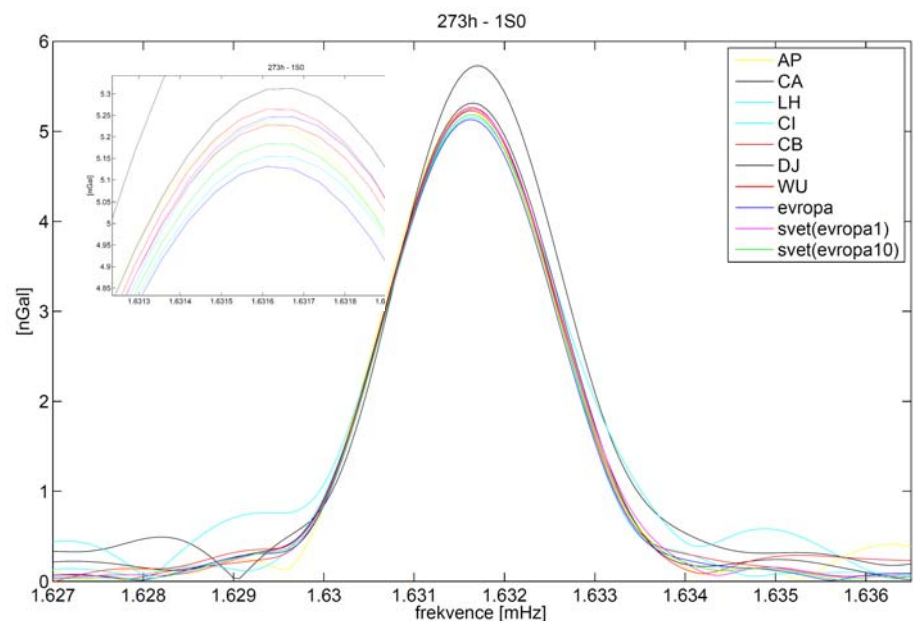
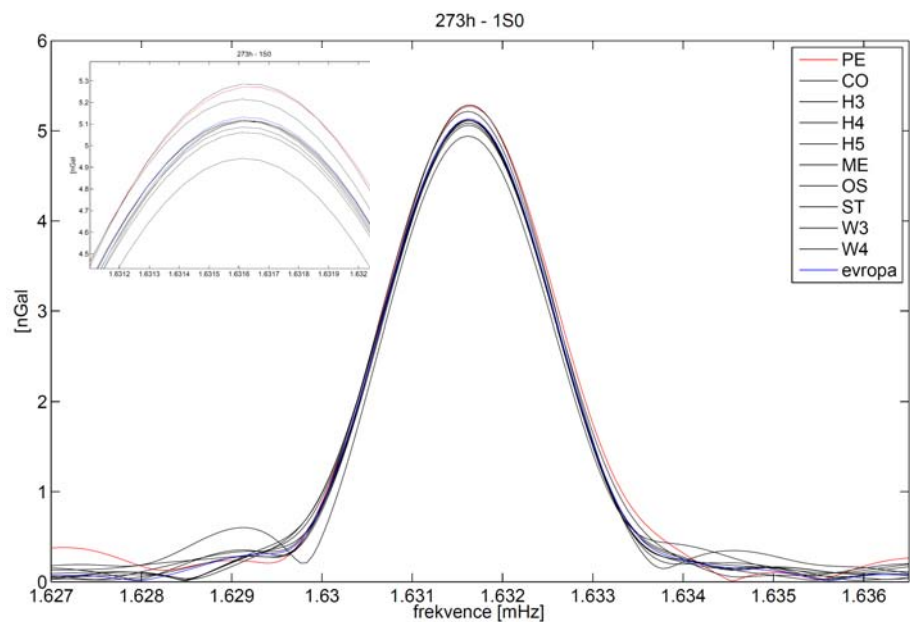


- Frekvence – radiální kmity (Tohoku 2011)

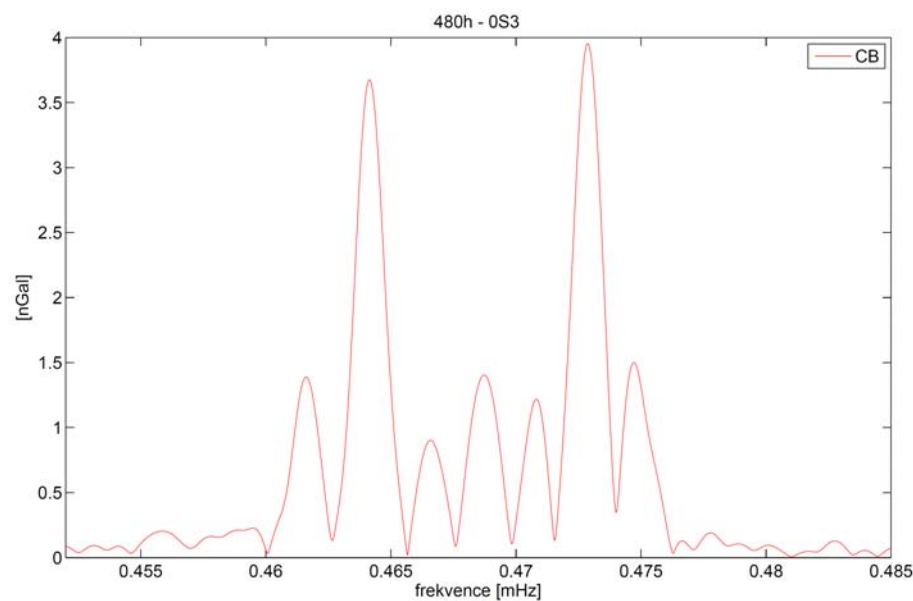
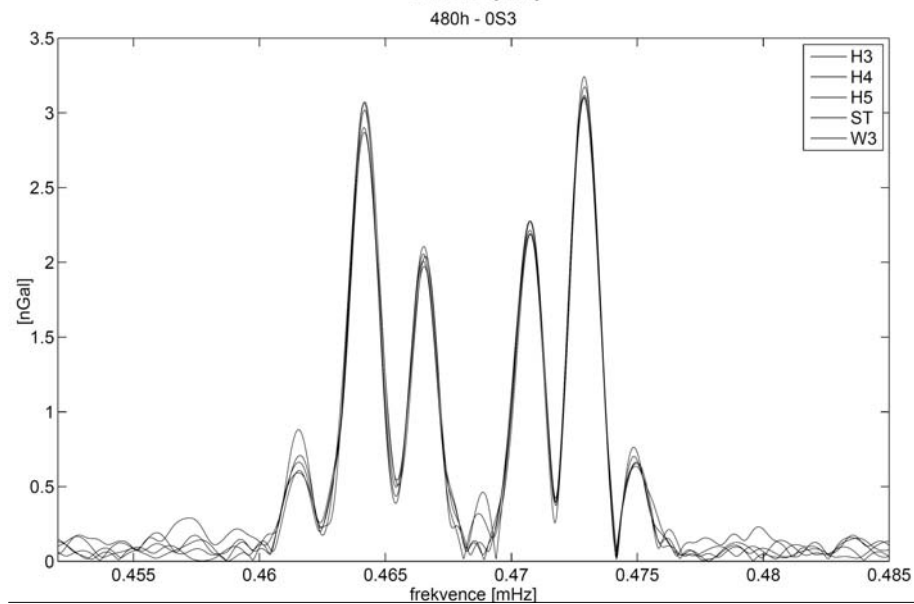
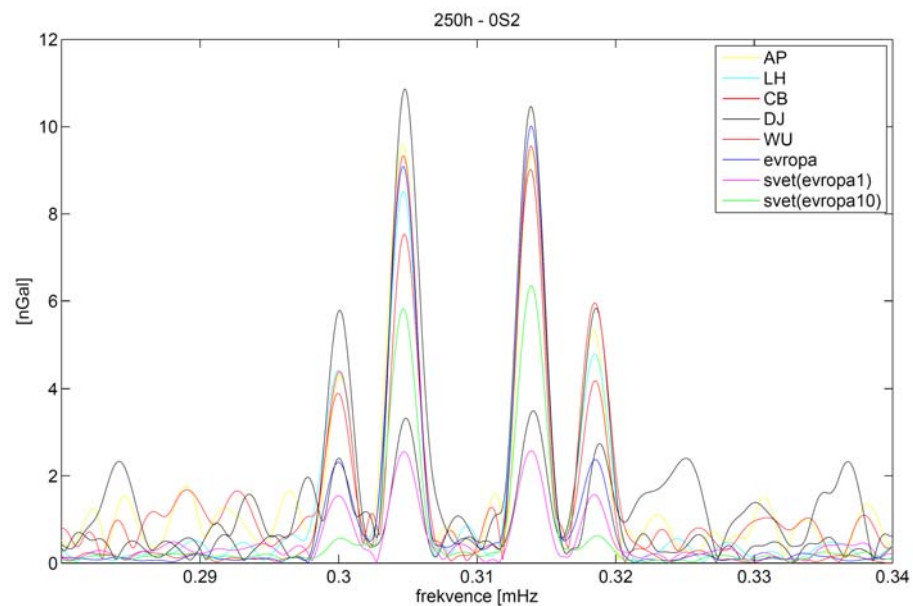
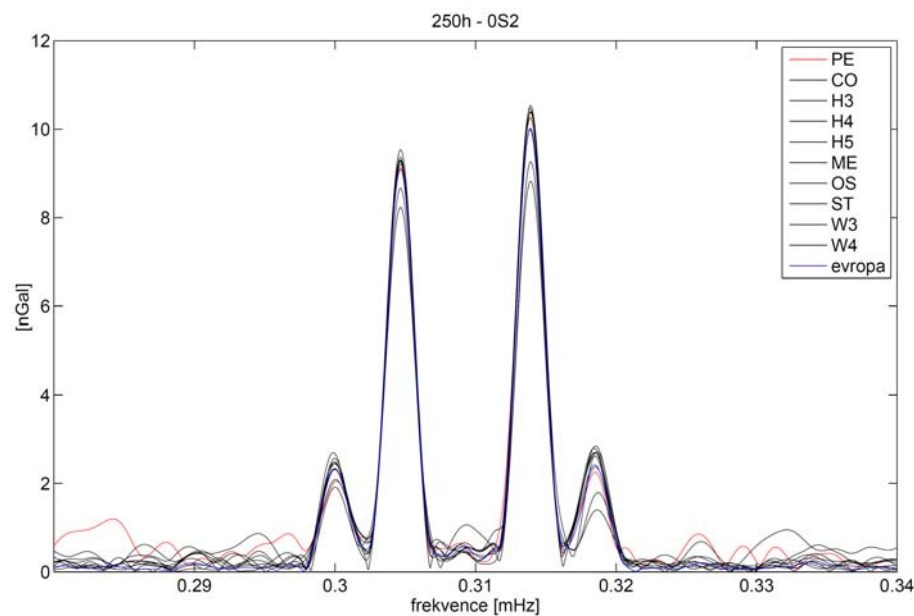
Xu et al. (2008)

TABLE 1 Comparison of ${}_0S_0$ Frequencies	
Davis <i>et al.</i> (2005)	0.814657*
Rosat <i>et al.</i> (2007) SGs	$0.8146566 \pm 1.6 \times 10^{-6}$
This paper SGs	$0.8146565 \pm 1.2 \times 10^{-6}$
*as corrected by P. Davis (personal communication)	

• Frekvence – radiální kmity 1S0 a 2S0 (Tohoku 2011)

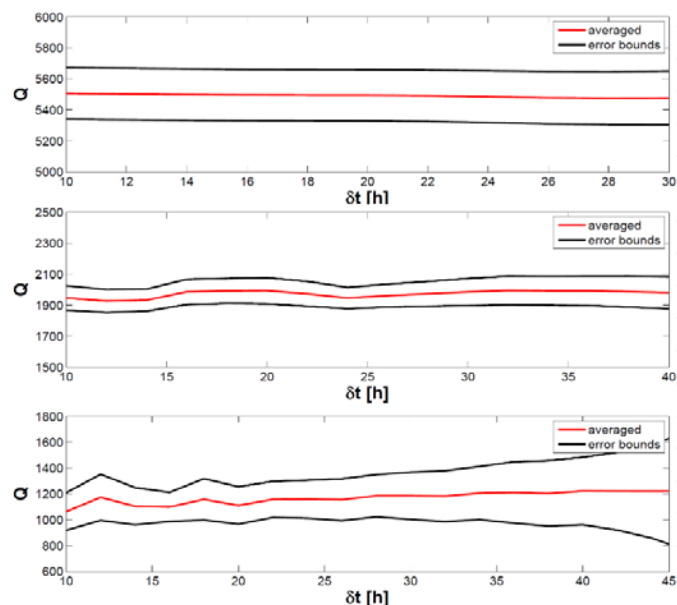


• Frekvence – sféroidální módy (Tohoku 2011)

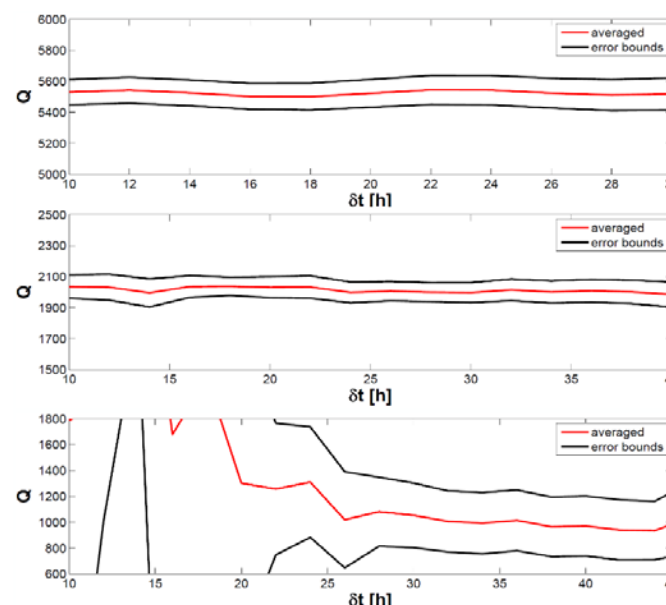


• Faktor kvality – radiální módy

• Maule 2010



• Tohoku 2011



$$Q^{-1}(\delta t) = T/(\pi \Delta t) \ln (A_{ref}(\delta t)/A(\delta t))$$

• ${}_0S_0$

Zábranová et al.(2012)– 5500 ± 140
 Okal and Stein (2009) – 5579
 Xu et al. (2008) – 5400
 Roult et al. (2006) – 5489
 Riedesel et al. (1980) – 5600-5833
 PREM – 5328 (5230)

• ${}_1S_0$

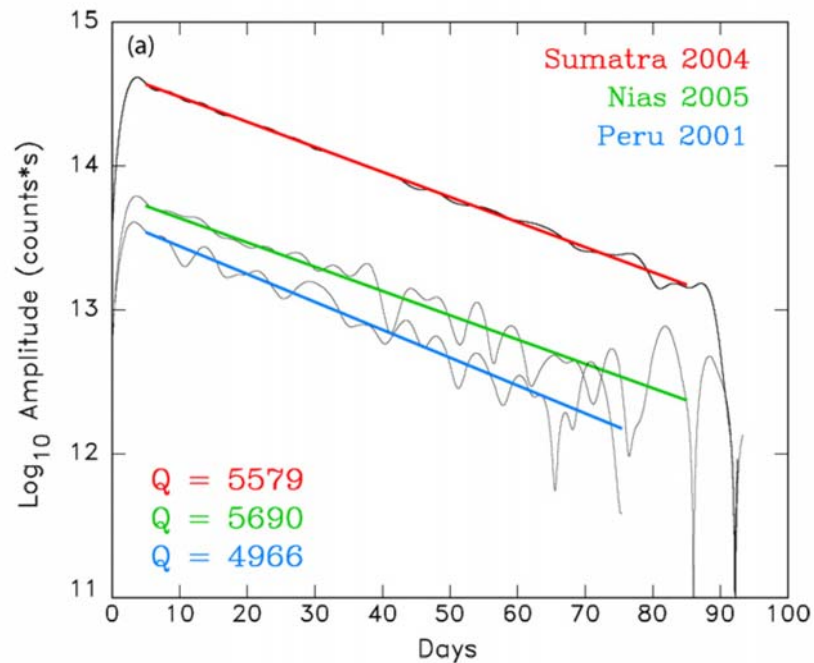
Zábranová et al.(2012)– 2000 ± 80
 Okal and Stein (2009) – 2017
 Riedesel et al. (1980) – 1850-1960
 PREM – 1499 (1970)

• ${}_2S_0$

Zábranová et al. (2012)
 – 1120 ± 270
 PREM – 1242 (1170)

- Faktor kvality – radiální módy

Okal and Stein (2009)



Rosat et al. (2007)

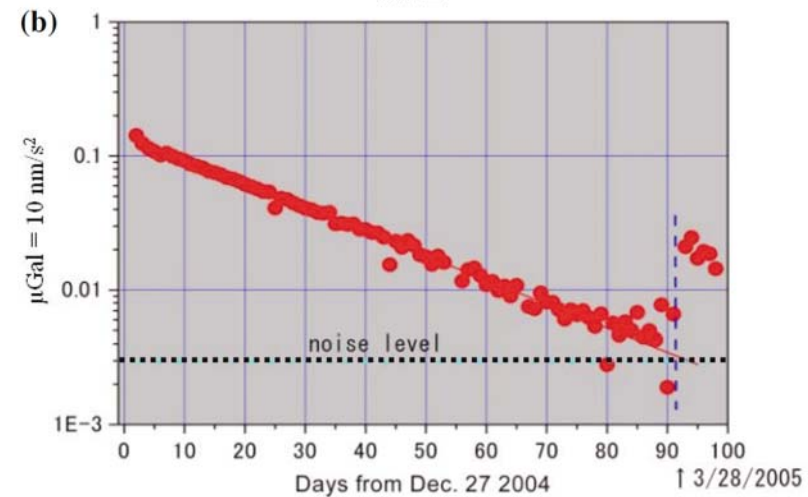
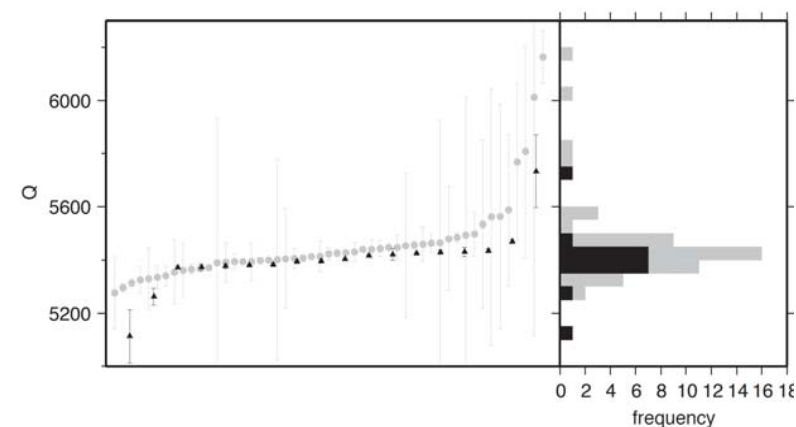
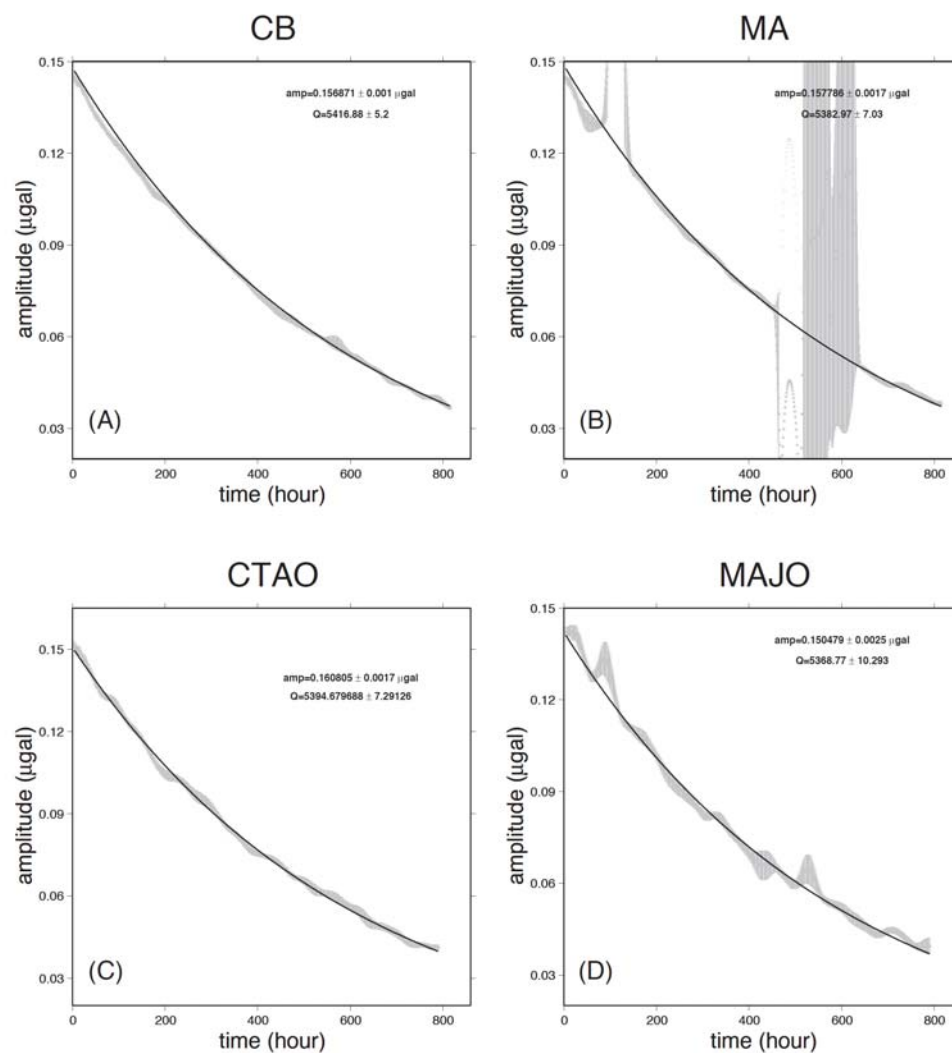


Fig. 2. (a) Amplitude spectrum on 34 days and (b) observed ${}_0S_0$ amplitude measured each day, after the 2004 Sumatra earthquake at Canberra SG site (revised from a figure by Y. Tamura).

$$Q^{-1} = 2\omega^{-1} \int_0^a [(\kappa_0 K_\kappa) Q_\kappa^{-1} + (\mu_0 K_\mu) Q_\mu^{-1}] dr$$

• Faktor kvality – radiální módy



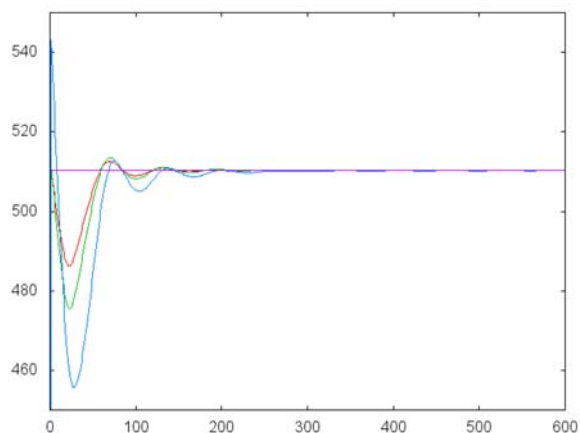
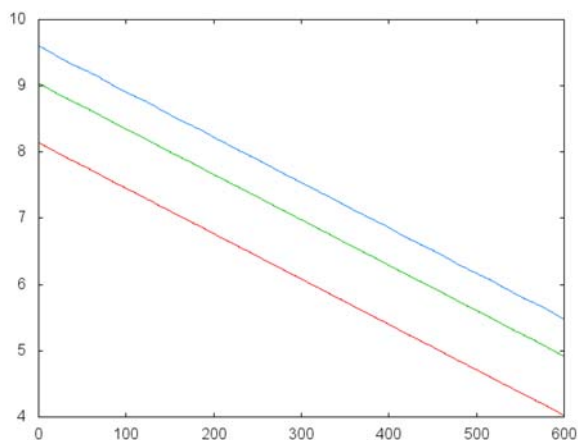
Xu et al. (2008)

▲ **Figure 4.** Examples of the decay curves for two SGs (A, B) and two seismometers (C, D). The gray lines are the observed amplitudes of ${}_0S_0$ with vertical error bars, and the black line is the fitted decay according to Equation 3. (A) CB is Canberra in eastern Australia and (B) is MA in central Japan; (C) is station CTAO, close to CB, and (D) is station MAJO, close to MA.

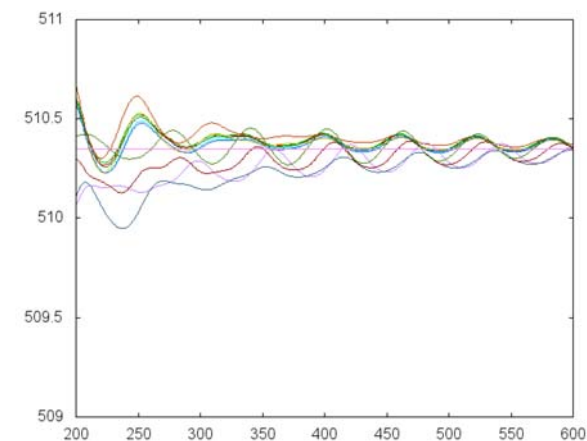
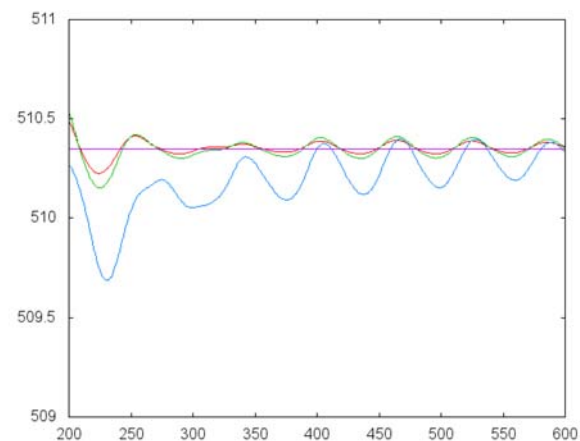
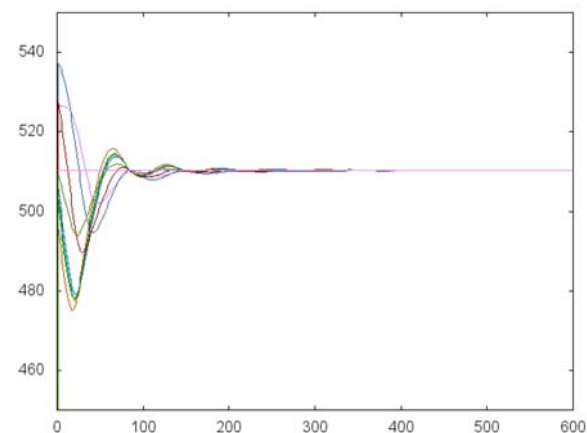
• Faktor kvality – sféroidální módy 0S2

- Syntetické testy – červená 920h, zelená 460h, modrá 230h záznamu
- $Q=510.35$

zprůměrované:



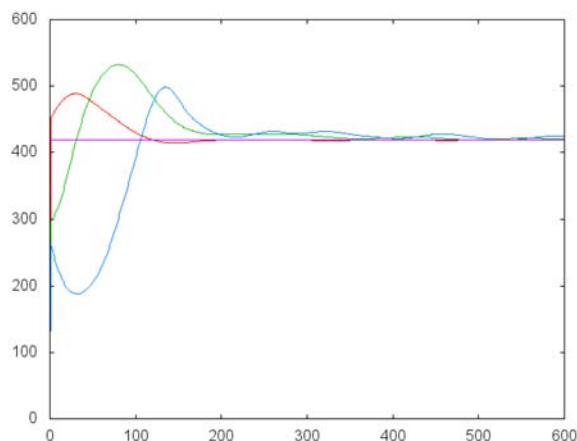
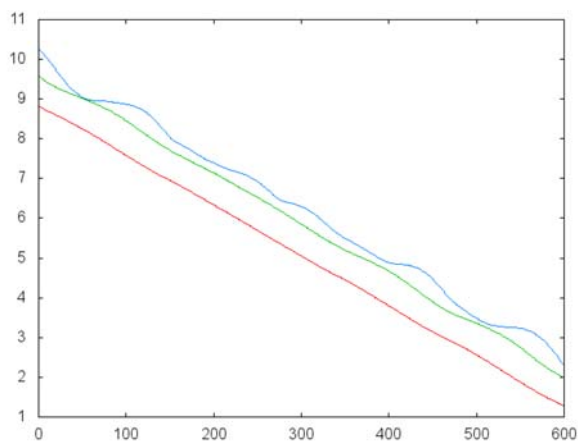
po stanicích (920h):



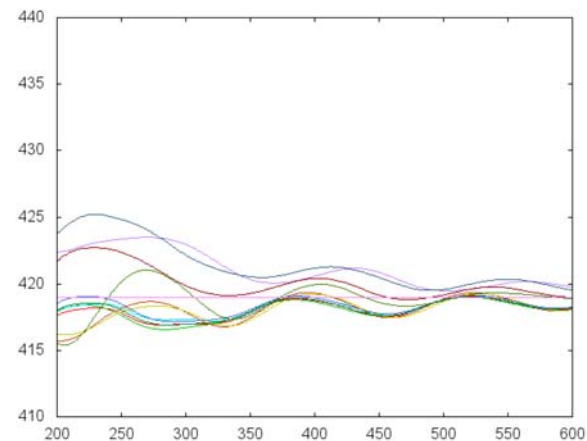
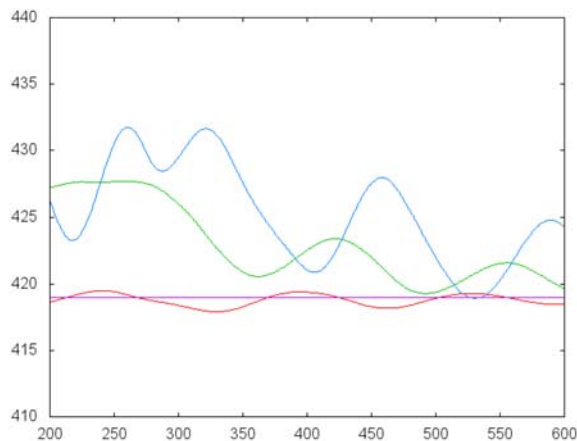
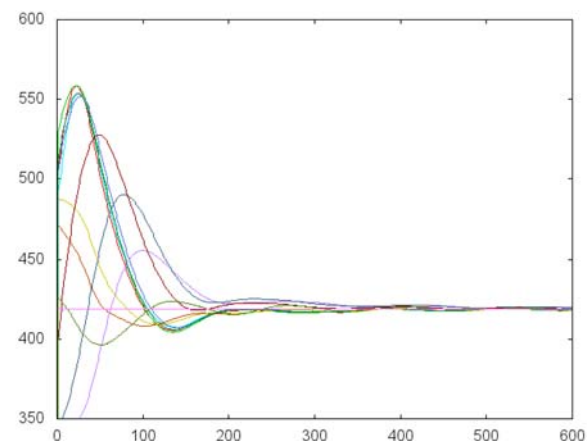
• Faktor kvality – sféroidální módy 0S3

- Syntetické testy – červená 500h, zelená 248h, modrá 124h záznamu
- Q=419

zprůměrované:



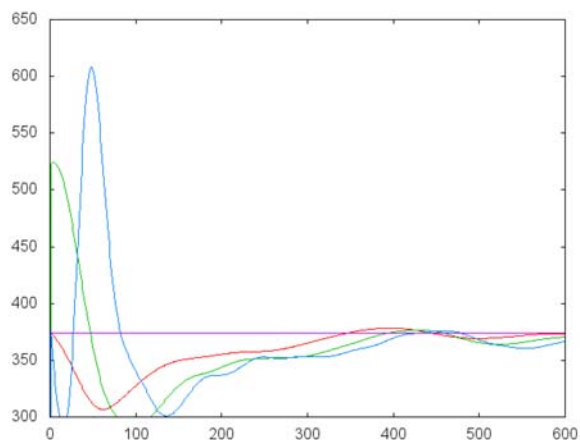
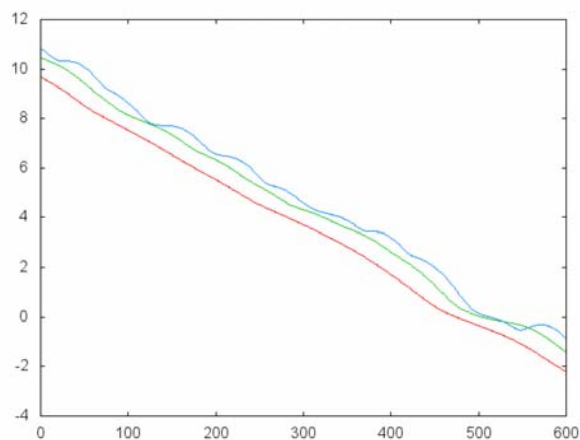
po stanicích (500h):



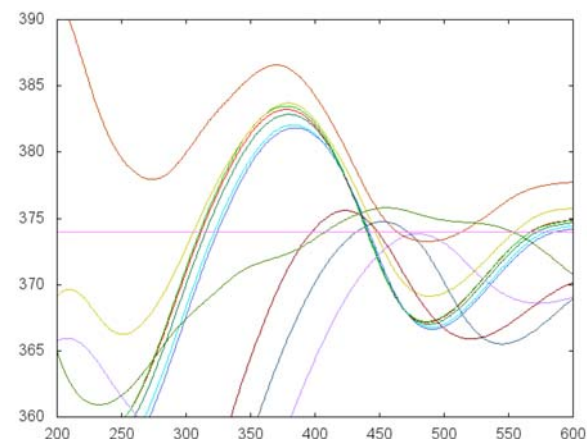
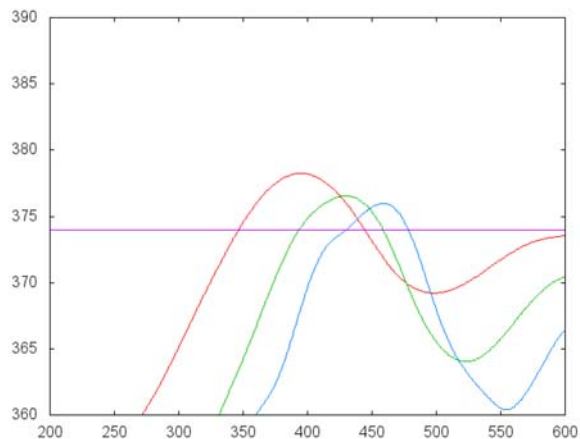
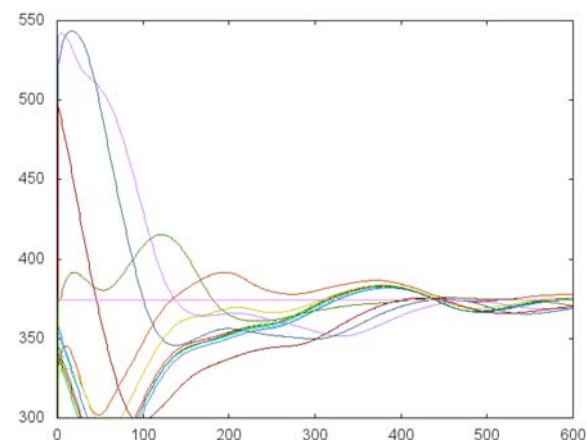
• Faktor kvality – sféroidální módy 0S4

- Syntetické testy – červená 320h, zelená 160h, modrá 80h záznamu
- Q=374

zprůměrované:



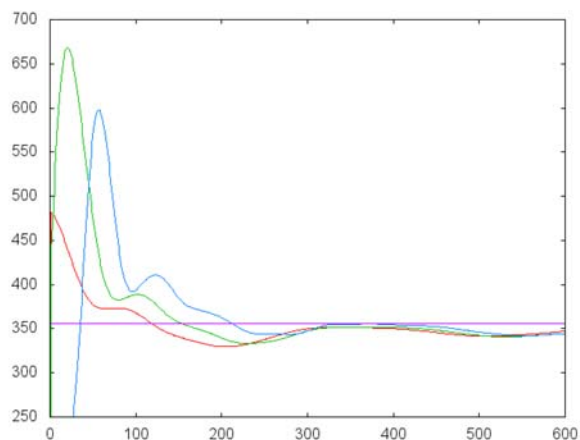
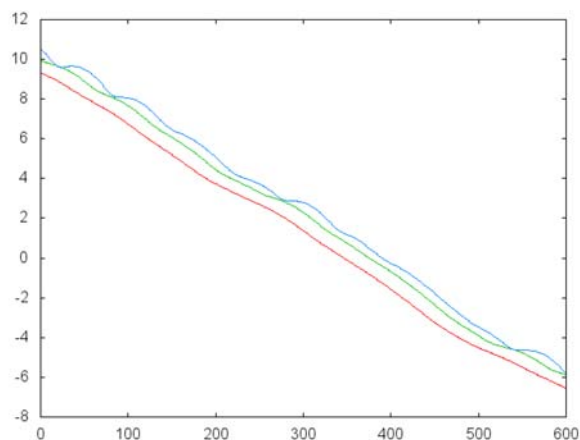
po stanicích (320h):



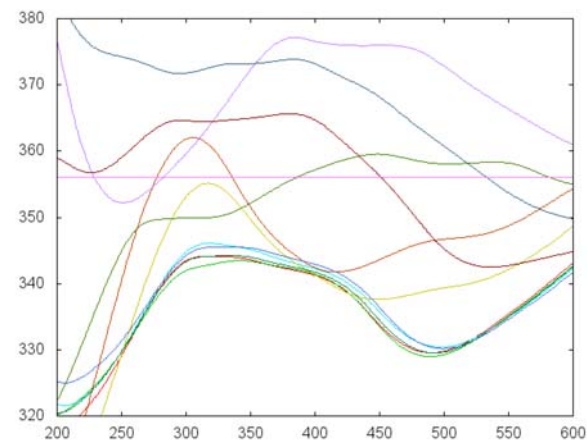
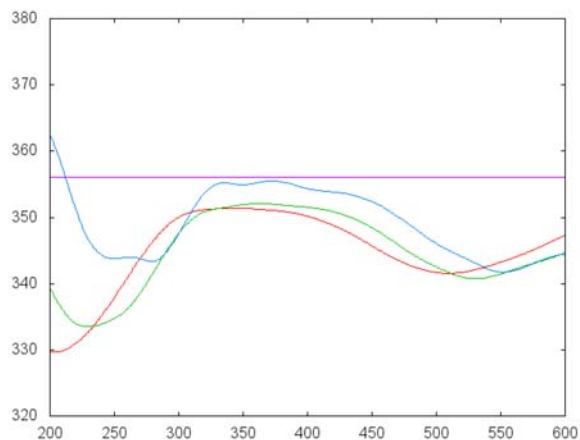
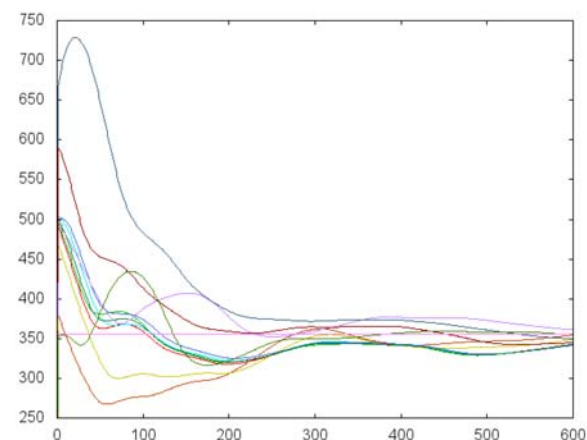
• Faktor kvality – sféroidální módy 0S5

- Syntetické testy – červená 236h, zelená 118h, modrá 59h záznamu
- Q=356

zprůměrované:



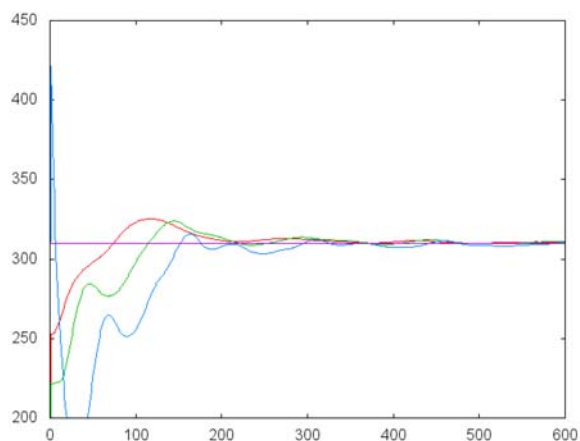
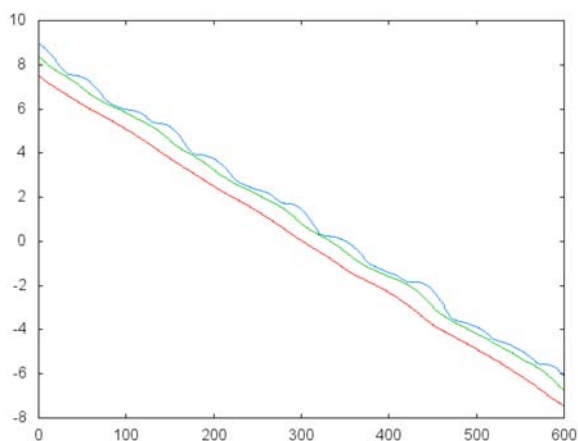
po stanicích (236h):



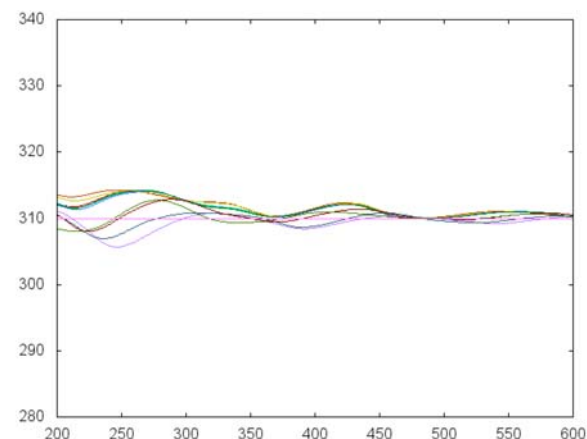
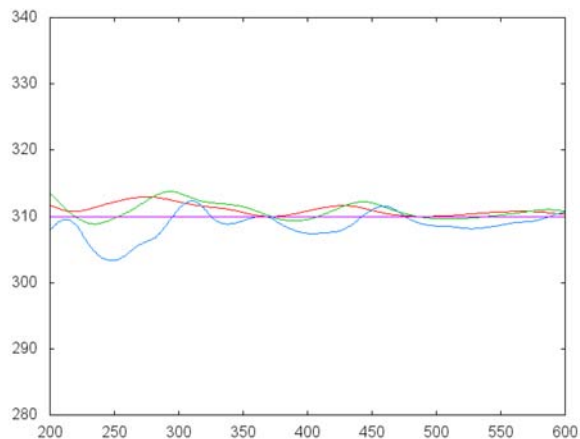
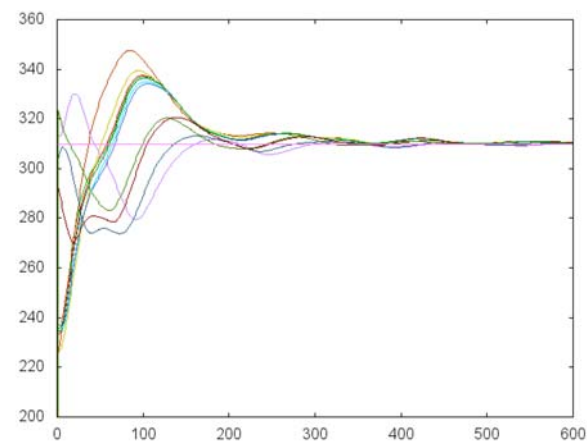
• Faktor kvality – sféroidální módy 1S2

- Syntetické testy – červená 252h, zelená 126h, modrá 63h záznamu
- $Q=310$

zprůměrované:



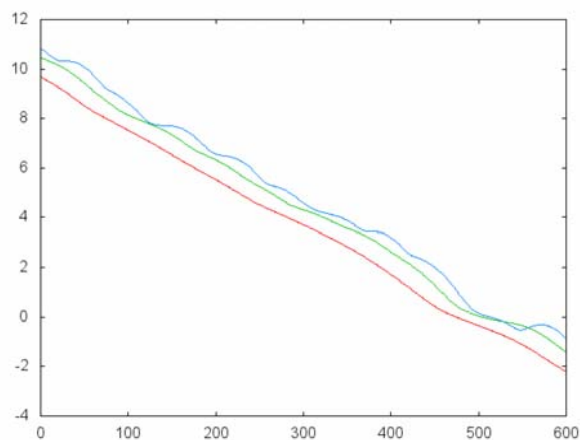
po stanicích (252h):



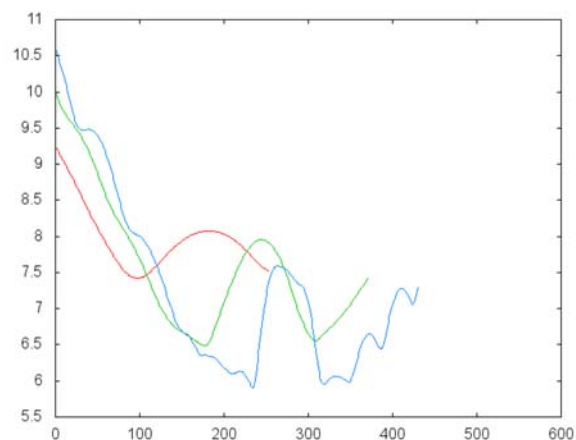
• Faktor kvality – sféroidální módy – 0S5

490h záznamu; červená 236h, zelená 118h, modrá 59h záznamu

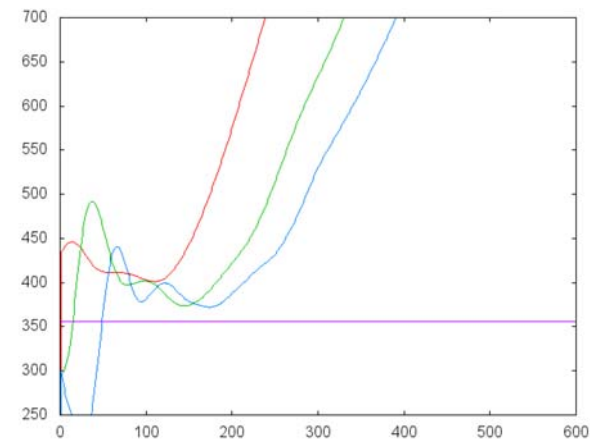
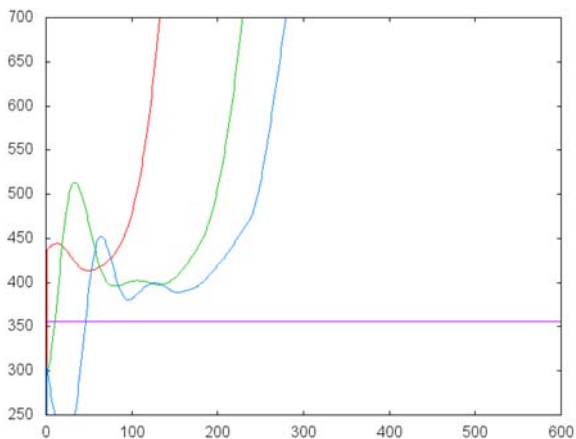
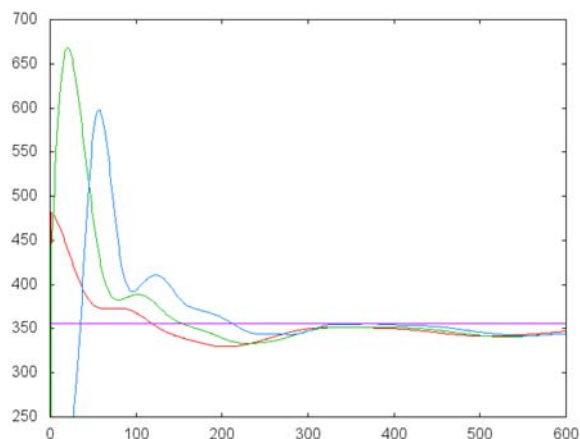
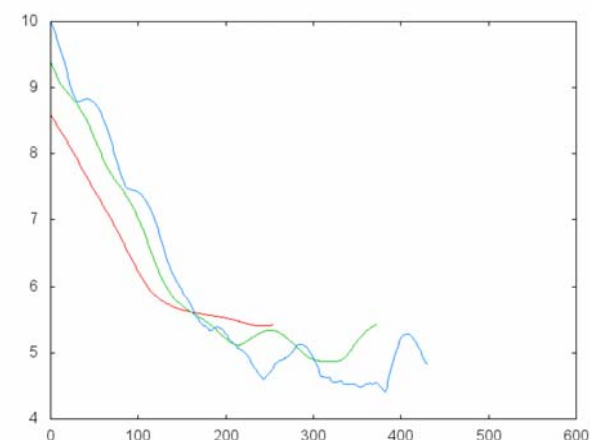
Zprůměrovaná syntetika



Průměr ze 14 stanic



Průměr ze 7 stanic



- Faktor kvality – sféroidální módy $0S_3$

Sumatra 2004

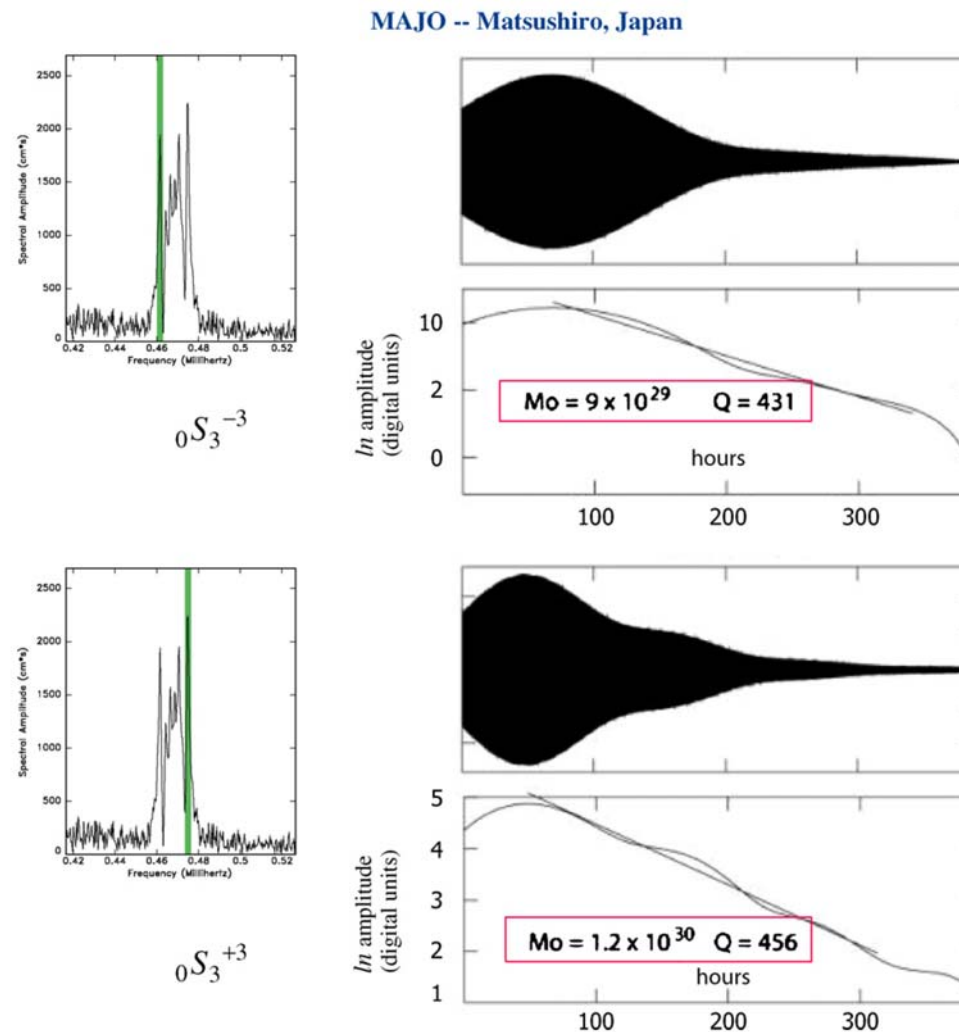


Fig. 6. Time-domain study of the outboard singlets ($m = \pm 3$) of $0S_3$ at Matsushiro (MAJO). The exceptional quality of this 17-day record allows the isolation of singlets by directly narrow band-pass filtering the record, as sketched on the frequency domain records shown at left. For both singlets, the resulting time series is shown on the top frame, and its envelope, plotted in logarithmic units on the bottom one. Least-squares fitting of the latter by a straight line yields best-fitting Q (from the slope of the regression) and moment in dyn cm (from its zero-intercept).

Okal and Stein (2009)

- Faktor kvality – sféroidální módy – singlety

Roult et al. (2006)

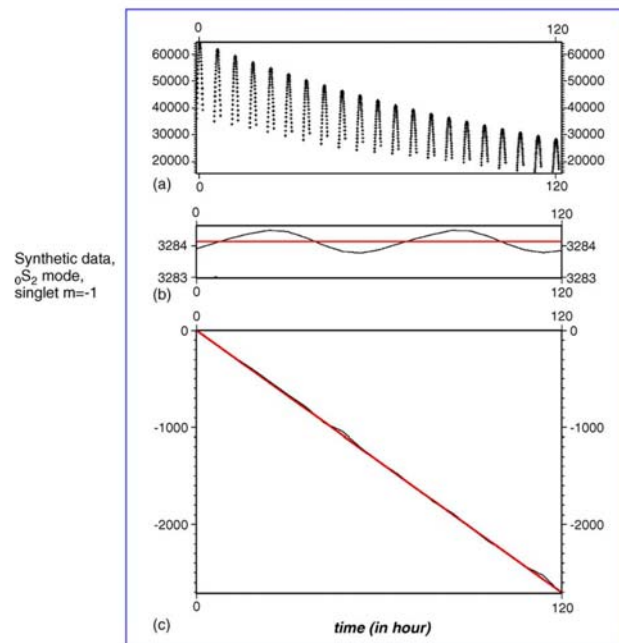


Fig. 5. Test of feasibility on synthetics. Computation of the Q quality factor for the singlet $m=-1$ of the $0S_2$ mode, from 21 time series of 240 h shifted by 3 h. The method is here applied to a synthetic seismogram corresponding to the Peruvian earthquake of 2001 June 23rd recorded at the Strasbourg station, and computed with the PREM-re model. The three plots correspond to variations with respect to time of: (a) the amplitude of the peak, (b) the free period of the singlet determined by the frequency corresponding to the maximum of amplitude of the peak plotted above (full curve), the PREM-re value (red curve), (c) the function $y(t)Q = \pi T \log(A(t)/A_{\max})$ (full curve), the slope corresponding to the observed Q value (dashed line), the slope related to the PREM-re Q value (red line). The peak is clear for all series (a), with a very small variation of the free period (b). The Q value is derived from the slope of the lower plot (c), which is quite a straight line and the error on Q is less than 1%. The observed free period for that singlet is 3284.16s instead of 3284.15s in the PREM-re model, and the observed Q value is 501.7 instead of 501.8 in the PREM-re model. The errors on Q values are very low, less than 1% for each individual singlet; it proves it is correct to determine Q values from each individual singlet.

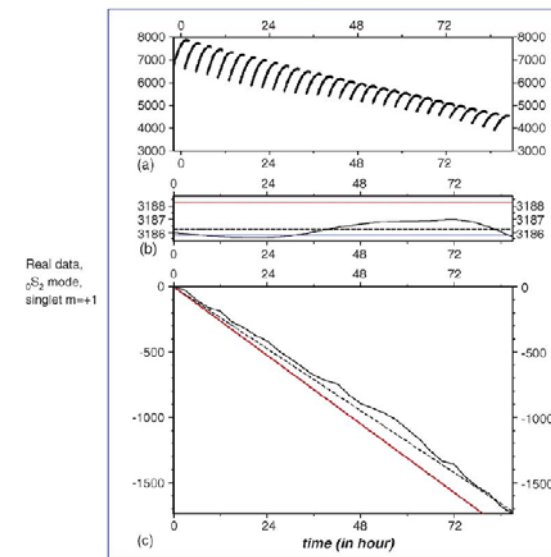


Fig. 6. Computation of the Q quality factor for the singlet $m=+1$ of the $0S_2$ mode. The method is here applied to the real record of the Peruvian earthquake at ST station (Strasbourg, France), from 30 series of 240 h shifted by 3 h. The three plots correspond to variation with respect to time of: (a) the amplitude of the peak, (b) the free period (in s) of the singlet determined by the frequency corresponding to the maximum of amplitude of the peak plotted above (full line), the PREM-re value (red curve), the mean free period (dashed line), the mean value (blue line) determined by Rosat et al. (2003b), (c) the function $y(t)Q = \pi T \log(A(t)/A_{\max})$ (full curve), the slope corresponding to the observed Q value (dashed line), the slope related to the PREM-re Q value (red line). The peak is clear for all series (a), with a small variation of the free period (b) and a mean Q value significantly different from the PREM-re Q value. The observed free period for that singlet is 3186.24 s instead of 3188.28 s in the PREM-re model, and the observed Q value is 572.2 instead of 516.8 in the PREM-re model.

• Modelování

- Rovnice

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

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

$$\lambda \nabla \cdot \mathbf{u} \mathbf{I} + \mu [\nabla \mathbf{u} + (\nabla \mathbf{u})^T] = \boldsymbol{\tau} \quad \text{—} \blacksquare \text{ reologický vztah}$$

$\mathbf{u}$ - posunutí

φ - přírůstkový gravitační potenciál

$\boldsymbol{\tau}$ - přírůstkový tenzor napětí

λ and μ - Laméovy parametry tělesa

- Sférická harmonická dekompozice

$$\mathbf{u}(\mathbf{r}) = \sum_n [U_n(r) \mathbf{S}_n^{(-1)}(\vartheta, \varphi) + V_n(r) \mathbf{S}_n^{(1)}(\vartheta, \varphi)]$$

$$\bar{\varphi}(\mathbf{r}) = \sum_n F_n(r) Y_n(\vartheta, \varphi)$$
- Diskretizace pomocí schémat s pseudospektrální přesností v kořenech Čebyševových polynomů.

- Vlastní problém

$$\begin{bmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{C} & \mathbf{D} \end{bmatrix} \begin{bmatrix} \mathbf{Y} \\ \mathbf{Z} \end{bmatrix} = \begin{bmatrix} \lambda \mathbf{Y} \\ \mathbf{0} \end{bmatrix} \xrightarrow{\text{red}} [\mathbf{A} - \mathbf{B} \mathbf{D}^{-1} \mathbf{C}] \mathbf{Y} = \lambda \mathbf{Y} \xrightarrow{\text{red}} \mathbf{Z} = -\mathbf{D}^{-1} \mathbf{C} \mathbf{Y}$$
 - vektor $\mathbf{Y}$ obsahuje posunutí na vnitřních bodech vrstvy
 - vektor $\mathbf{Z}$ obsahuje potenciál a posunutí na hranicích

- Faktor kvality

$$Q^{-1} = 2\omega^{-1} \int_0^a [(\kappa_0 K_\kappa) Q_\kappa^{-1} + (\mu_0 K_\mu) Q_\mu^{-1}] dr$$

• Radiální kmity

[4] The acceleration of a spherically symmetric, non-rotating, anelastic Earth at a receiver located at $\mathbf{x}_r(r_r, \vartheta_r, \varphi_r)$, that is excited by a moment-tensor source $\mathbf{M}$ situated at $\mathbf{x}_s(r_s, \vartheta_s, \varphi_s)$, is given by a superposition of spheroidal and toroidal modes,

$$\mathbf{a}(\mathbf{x}_r, \mathbf{x}_s, t) = \sum_k \mathbf{A}_k(\mathbf{x}_r, \mathbf{x}_s) \cos(\omega_k t) \exp\left(-\frac{\omega_k t}{2Q_k}\right). \quad (1)$$

The coefficients $\mathbf{A}_k(\mathbf{x}_r, \mathbf{x}_s)$ are linearly proportional to the moment-tensor components, and they depend on a source-receiver geometry and the mode eigenfunctions; ω_k are angular frequencies and Q_k quality factors of the modes.

[5] If we consider a part of the response caused by a radial (degree-zero) mode, we can directly determine the coefficients $\mathbf{A}_k(\mathbf{x}_r, \mathbf{x}_s)$ that are independent of the horizontal coordinates [Dahlen and Tromp, 1998, section 10.3],

$$\mathbf{A}_0(r_r, r_s) = \frac{U_r}{4\pi} \left[M_{rr} U'_s + (M_{\theta\theta} + M_{\phi\phi}) \frac{U_s}{r_s} \right] \mathbf{e}_r, \quad (2)$$

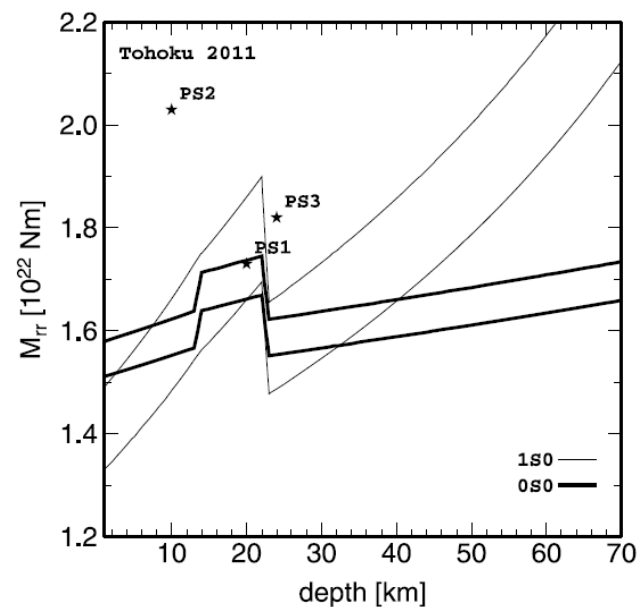
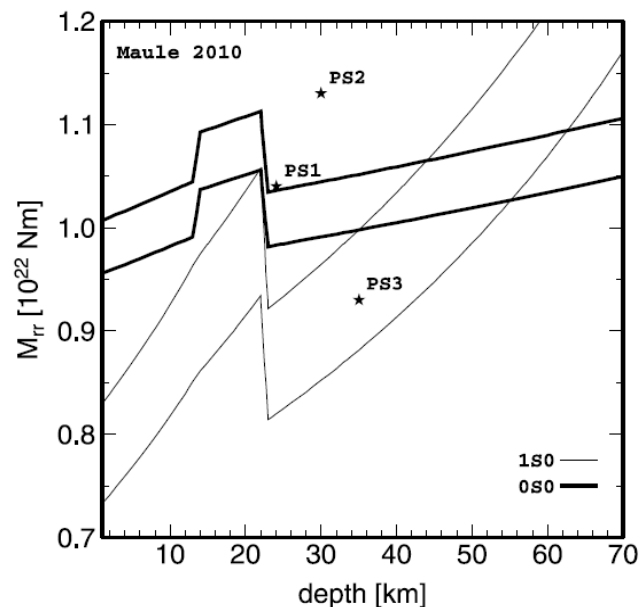
where the eigenfunction U and its derivative U' are only radially dependent, $U_r = U(r_r)$, $U_s = U(r_s)$, and M_{rr} , $M_{\theta\theta}$ and $M_{\phi\phi}$ are diagonal spherical polar components of the centroid moment tensor $\mathbf{M}$.

[6] If we take into account that the isotropic component of the source is negligible [Kikuchi and Kanamori, 1994; Okal, 1996], i.e., $M_{rr} = -(M_{\theta\theta} + M_{\phi\phi})$, the surface acceleration of a device caused by the radial modes depends on only the one component of the moment tensor M_{rr} and on the depth of the centroid,

$$\mathbf{A}_0(a, r_s) = \frac{U_a}{4\pi} \left(1 + \frac{2g}{\omega^2 a} \right) M_{rr} \left(U'_s - \frac{U_s}{r_s} \right) \mathbf{e}_r, \quad (3)$$

• Radiální kmity – Maule 2010, Tohoku 2011

0S0 – 450h záznamu, 1S0 – 170h záznamu



- PS1 – Global CMT Solution
- PS2 – USGS Centroid Moment Solution
- PS3 – USGS Wphase Moment Solution

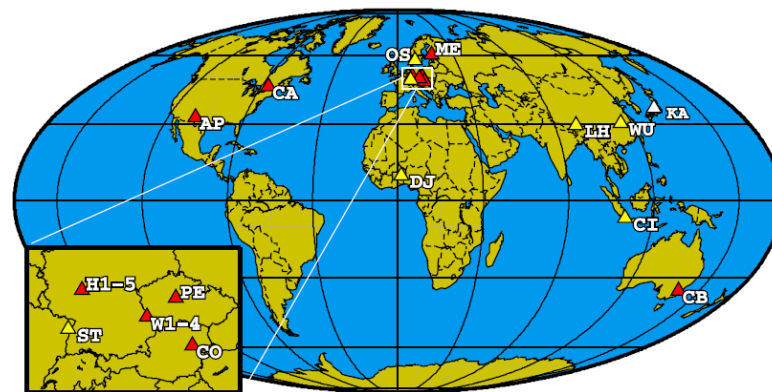


Figure 1. The triangles represent the SG sites used in this study. Red ones were employed for both events, white only for the 2010 Maule earthquake and yellow only for the 2011 Tohoku earthquake.

- Radiální kmity – Maule 2010, Tohoku 2011

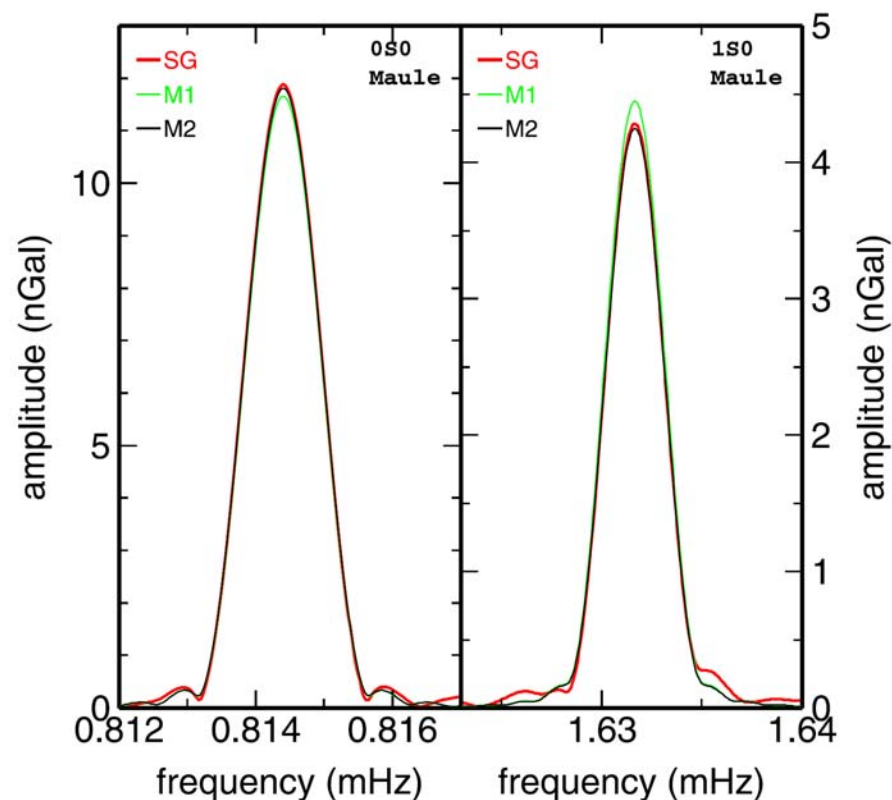


Figure 4. Vertical acceleration amplitude spectra of the modes ${}_0S_0$ and ${}_1S_0$ from the averaged SG data (red) and the two synthetics: M1 (green, depth 21 km; $M_{rr} = 1.055 \times 10^{22}$ Nm) and M2 (black, depth 44 km; $M_{rr} = 1.025 \times 10^{22}$ Nm) for the 2010 Maule earthquake. A Hann filter and Fourier transform were applied to 450- (170-)hour time series.

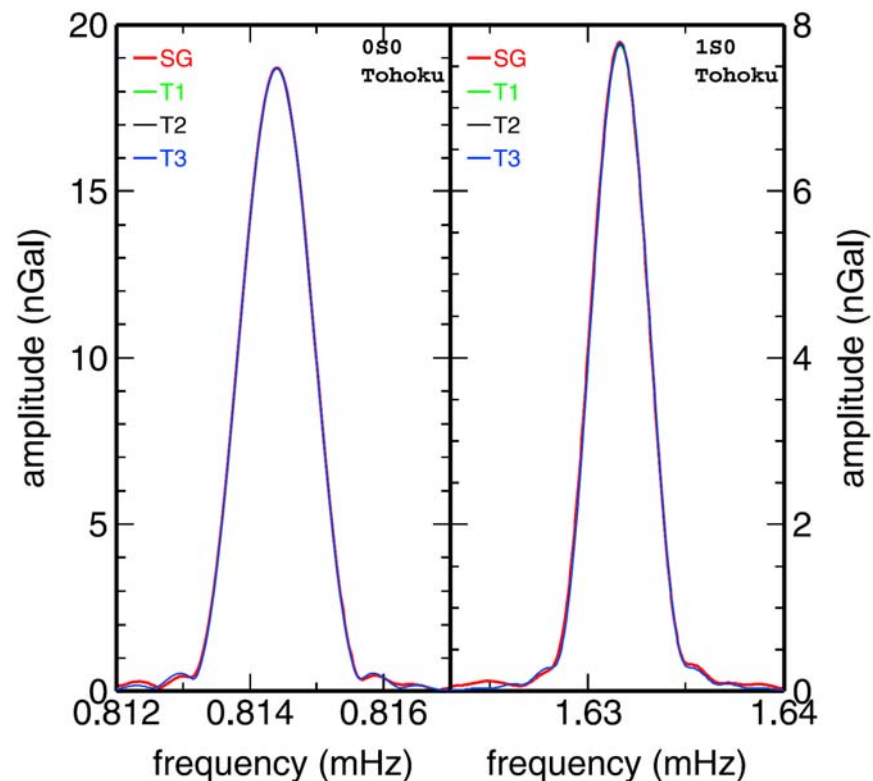
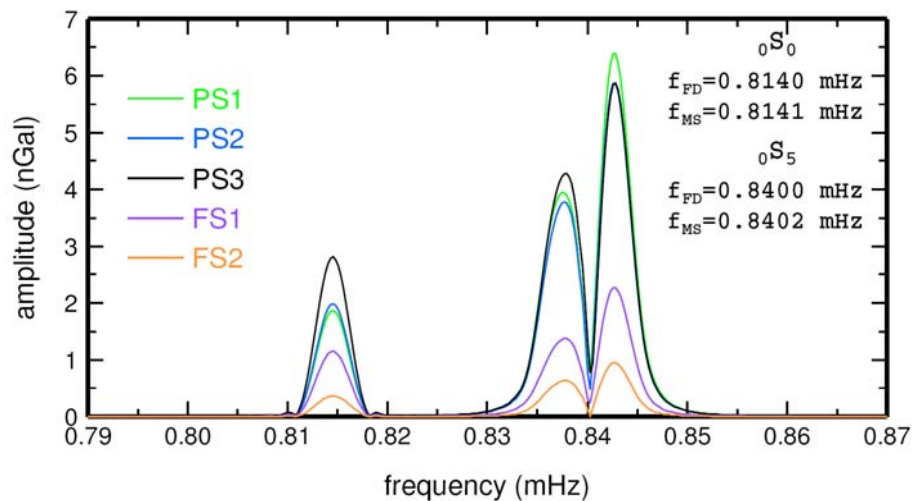
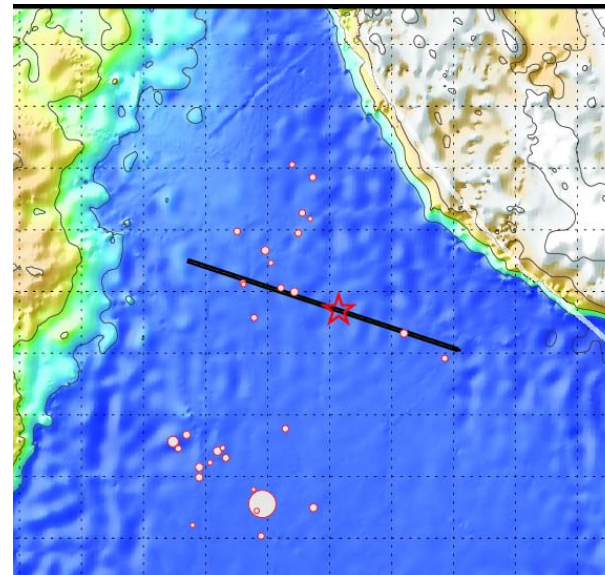
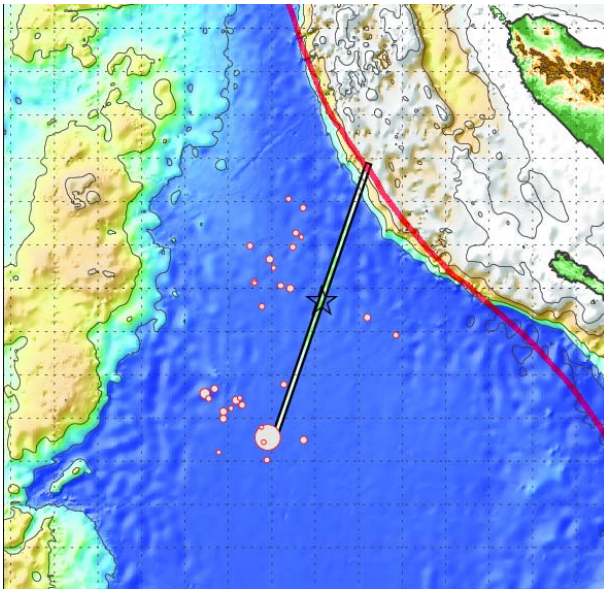


Figure 5. Vertical acceleration amplitude spectra of the modes ${}_0S_0$ and ${}_1S_0$ from the averaged SG data (red) and the three synthetics: T1 (green, depth 13 km; $M_{rr} = 1.60 \times 10^{22}$ Nm), T2 (black, depth 18 km; $M_{rr} = 1.69 \times 10^{22}$ Nm) and T3 (blue, depth 29 km; $M_{rr} = 1.60 \times 10^{22}$ Nm) for the 2011 Tohoku earthquake. A Hann filter and Fourier transform were applied to 450- (170-)hour time series.

• Radiální kmity – Sumatra 2012

http://earthquake.usgs.gov/earthquakes/eqinthenews/2012/usc000905e/finite_fault.php

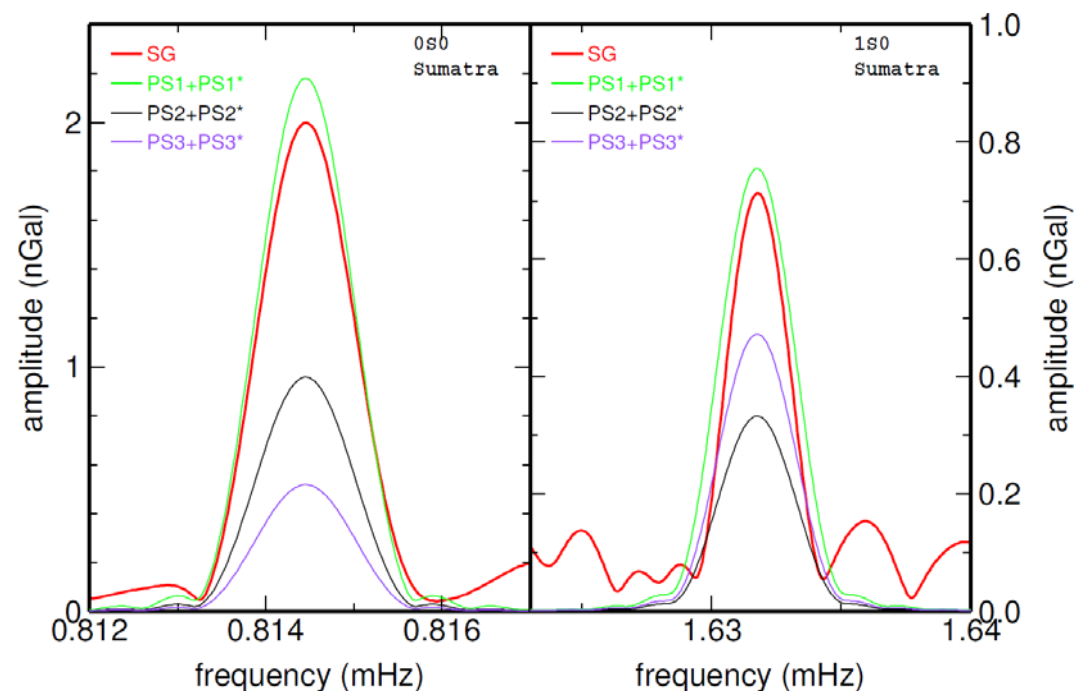


← pouze první jev Mw=8.6

- PS1 – USGS Wphase Moment Solution
- PS2 – Global CMT Solution
- PS3 – USGS Centroid Moment Solution

• Radiální kmity – Sumatra 2012

Stanice PE:



- PS1 and PS1*: Global CMT Solution

$M_{rr} = 1.36 \cdot 10^{21}$ Nm, depth = 40 km; $M^*_{rr} = 0.58 \cdot 10^{21}$ Nm, depth* = 54 km

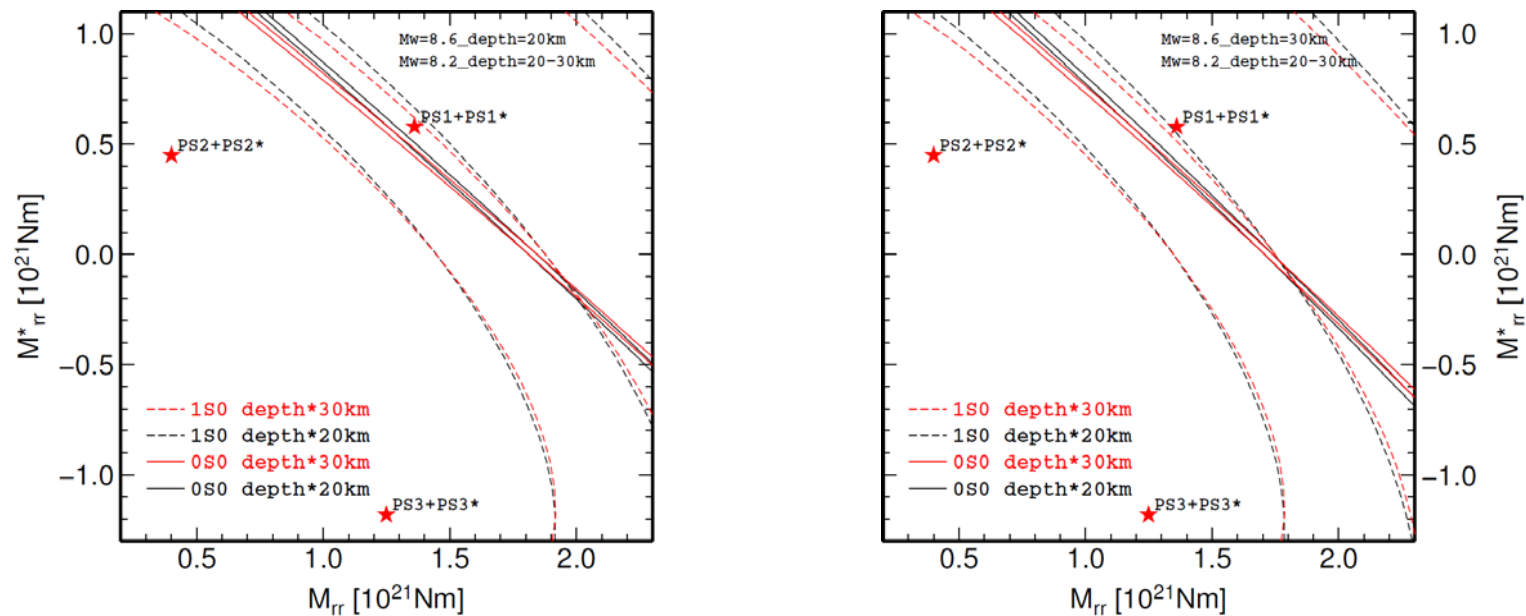
- PS2 and PS2*: USGS Centroid Moment Solution

$M_{rr} = 0.40 \cdot 10^{21}$ Nm, depth = 40 km; $M^*_{rr} = 0.45 \cdot 10^{21}$ Nm, depth* = 43 km

- PS3 and PS3*: USGS WPhase Moment Solution

$M_{rr} = 1.25 \cdot 10^{21}$ Nm, depth = 25 km; $M^*_{rr} = -1.18 \cdot 10^{21}$ Nm, depth* = 16 km

• Radiální kmity – Sumatra 2012



- PS1 and PS1*: Global CMT Solution

$M_{rr} = 1.36 \cdot 10^{21} \text{ Nm}$, depth = 40 km; $M^*_{rr} = 0.58 \cdot 10^{21} \text{ Nm}$, depth* = 54 km

- PS2 and PS2*: USGS Centroid Moment Solution

$M_{rr} = 0.40 \cdot 10^{21} \text{ Nm}$, depth = 40 km; $M^*_{rr} = 0.45 \cdot 10^{21} \text{ Nm}$, depth* = 43 km

- PS3 and PS3*: USGS WPhase Moment Solution

$M_{rr} = 1.25 \cdot 10^{21} \text{ Nm}$, depth = 25 km; $M^*_{rr} = -1.18 \cdot 10^{21} \text{ Nm}$, depth* = 16 km

• Sféroidální módy

Zrychlení přístroje

$$\mathbf{a}(\mathbf{x}_r, \mathbf{x}_s, t) = \sum_k \mathbf{A}_k(\mathbf{x}_r, \mathbf{x}_s) \cos(\omega_k t) \exp\left(-\frac{\omega_k t}{2Q_k}\right)$$

- momentový tenzor, epicentrální vzdálenost, azimut
- vlastní funkce ve zdroji a na povrchu
- korekce na volný vzduch a náklon

$$\mathbf{A}_k(\mathbf{x}_r, \mathbf{x}_s) = \mathbf{M} : \mathbf{e}_k(\mathbf{x}_s) \mathbf{s}_k(\mathbf{x}_r)$$

volba báзовých momentových tenzorů

$$\mathbf{M} = M_{rr} \mathbf{G}_1 + \frac{M_{\vartheta\vartheta} - M_{\varphi\varphi}}{2} \mathbf{G}_2 + M_{r\vartheta} \mathbf{G}_3 + M_{r\varphi} \mathbf{G}_4 + M_{\vartheta\varphi} \mathbf{G}_5$$

$$\mathbf{G}_1 = (1, -1/2, -1/2, 0, 0, 0)$$

$$\mathbf{G}_2 = (0, 1, -1, 0, 0, 0)$$

$$\mathbf{G}_3 = (0, 0, 0, 1, 0, 0)$$

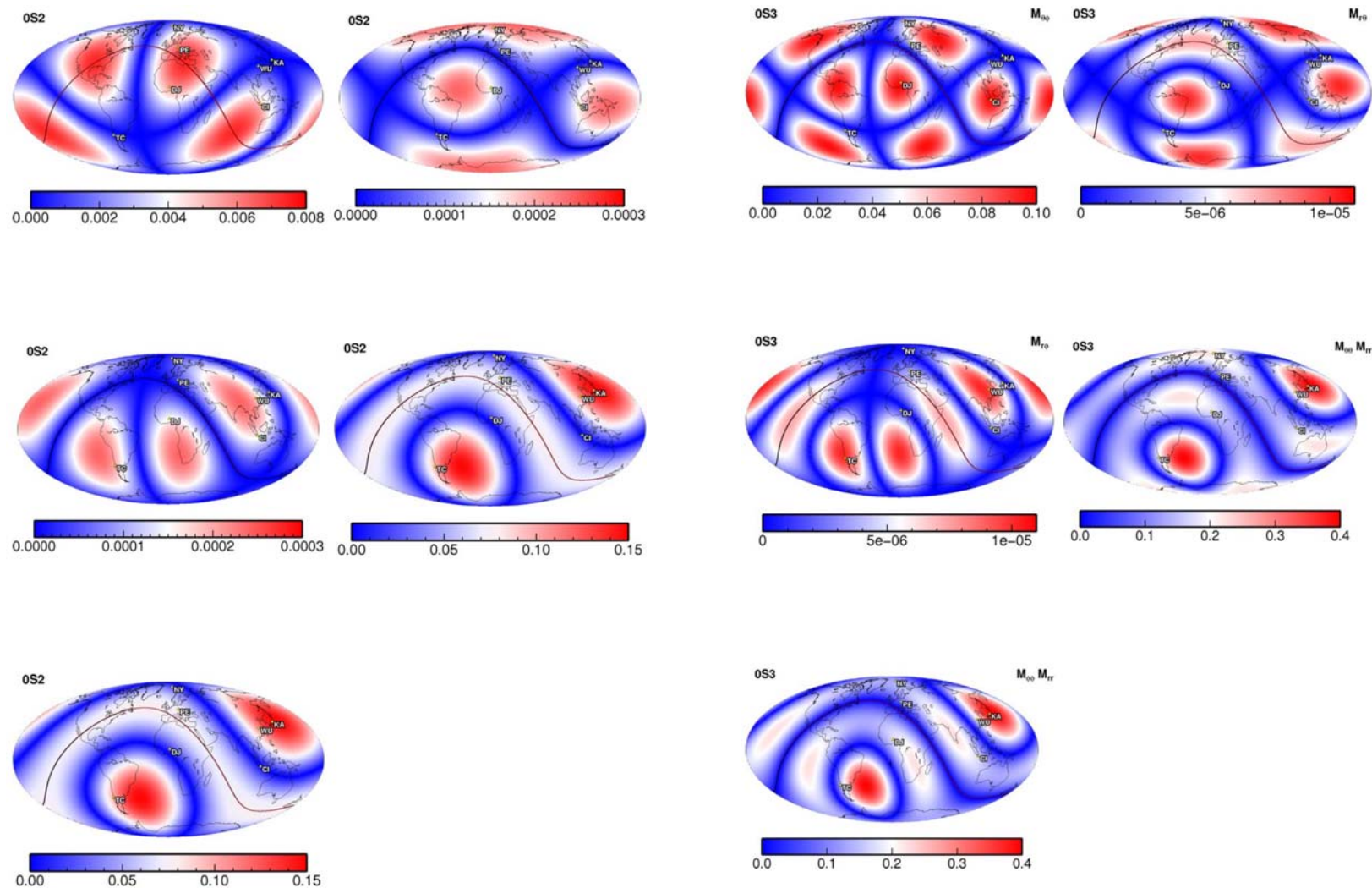
$$\mathbf{G}_4 = (0, 0, 0, 0, 1, 0)$$

$$\mathbf{G}_5 = (0, 0, 0, 0, 0, 1)$$

Módy do 1mHz izolované ve spektru

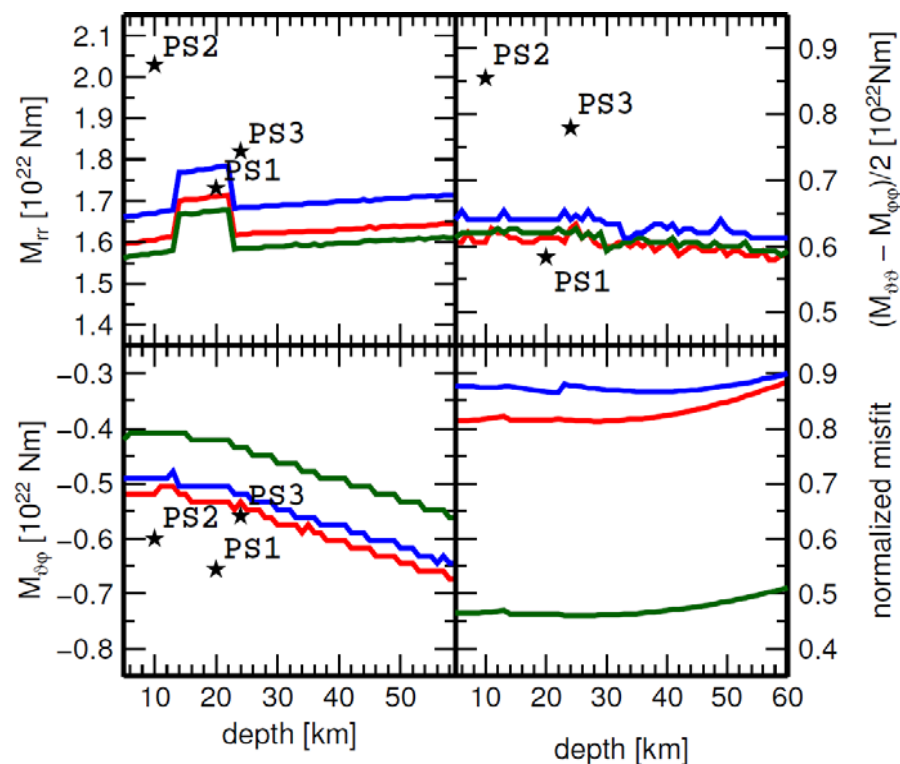
	G_1	G_2	G_3	G_4	G_5
${}_0S_2$	0.907	0.045	0.0015	0.0015	0.045
${}_0S_3$	0.671	0.165	0.0000	0.0000	0.165
${}_0S_4$	0.589	0.204	0.0010	0.0010	0.205
${}_1S_2$	0.404	0.282	0.0159	0.0159	0.282
${}_0S_0$	1.000	0.000	0.0000	0.0000	0.000
${}_0S_5$	0.553	0.221	0.0024	0.0024	0.221

- Sféroidální módy – podíl bází



• Sféroidální módy – Tohoku 2011

- společná analýza sféroidálních módů do 1mHz
- zbylé dvě složky momentového tenzoru fixované na hodnotě PS1



použité tři sady Q

	T [s]	Q_0	Q_1	Q_2	$Q_0 T/2$ [h]
${}_0S_2$	3234	510	515	525	230
${}_0S_3$	2135	417	430	380	124
${}_0S_4$	1546	373	401	365	80
${}_1S_2$	1472	310	322	310	63
${}_0S_0$	1229	5327	5500	5714	910
${}_0S_5$	1190	356	380	350	59

- červená Q0 – PREM
- zelená Q1
- modrá Q2 – Tanimoto et al. (2012)

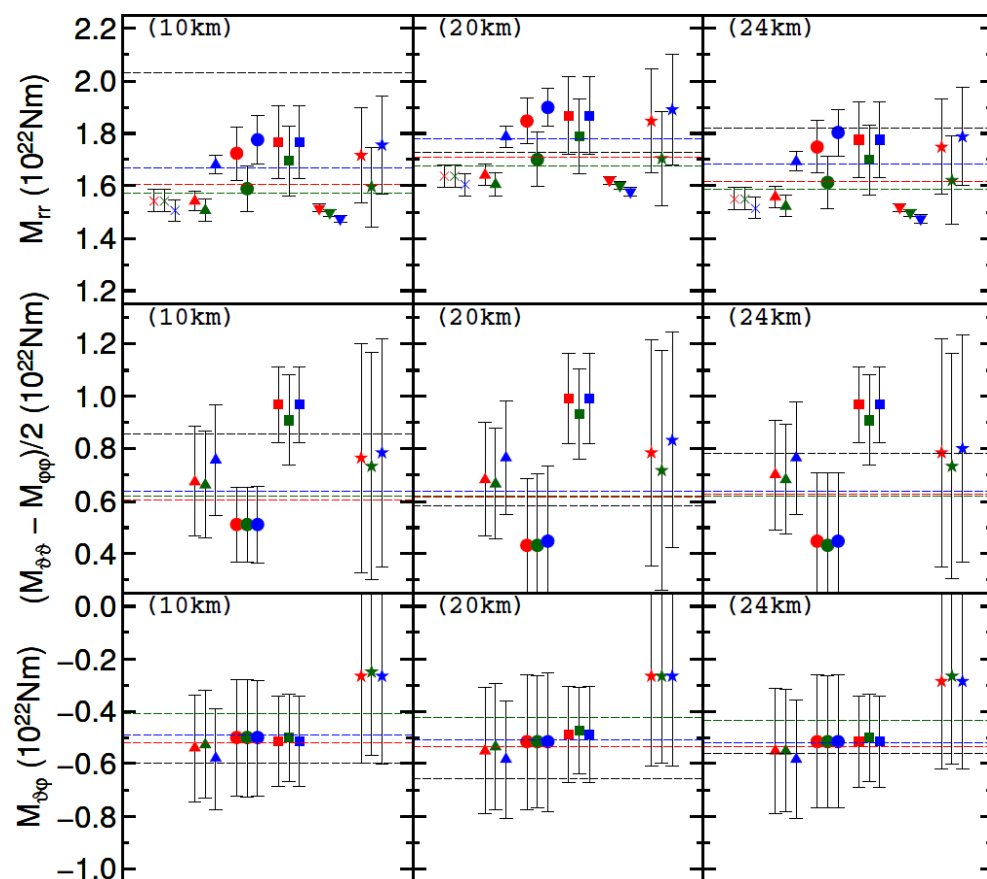
PS1 – Global CMT Solution

PS2 – USGS Centroid Moment Solution

PS3 – USGS Wphase Moment Solution

• Sféroidální módy – Tohoku 2011

Analýza jednotlivých módů přes všechny stanice
pro tři hloubky odpovídajících jednotlivým agenturám



● červená Q0 – PREM

● zelená Q1

● modrá Q2 – Tanimoto et al. (2012)

x OS2

Δ OS3

● OS4

■ 1S2

▽ OS0

☆ OS5

PS1 – Global CMT Solution

PS2 – USGS Centroid Moment Solution

PS3 – USGS Wphase Moment Solution

• Sféroidální módy – Tohoku 2011

• pokles logaritmu normované amplitudy v čase
– přes všechny stanice

• délka časových řad

– $\overline{Q_0 T/2}$ [h]

• nejlepší řešení pro Q_0 , Q_1 a Q_2

– uděláno v $\Delta t = 0$

• sklon odpovídá faktoru kvality

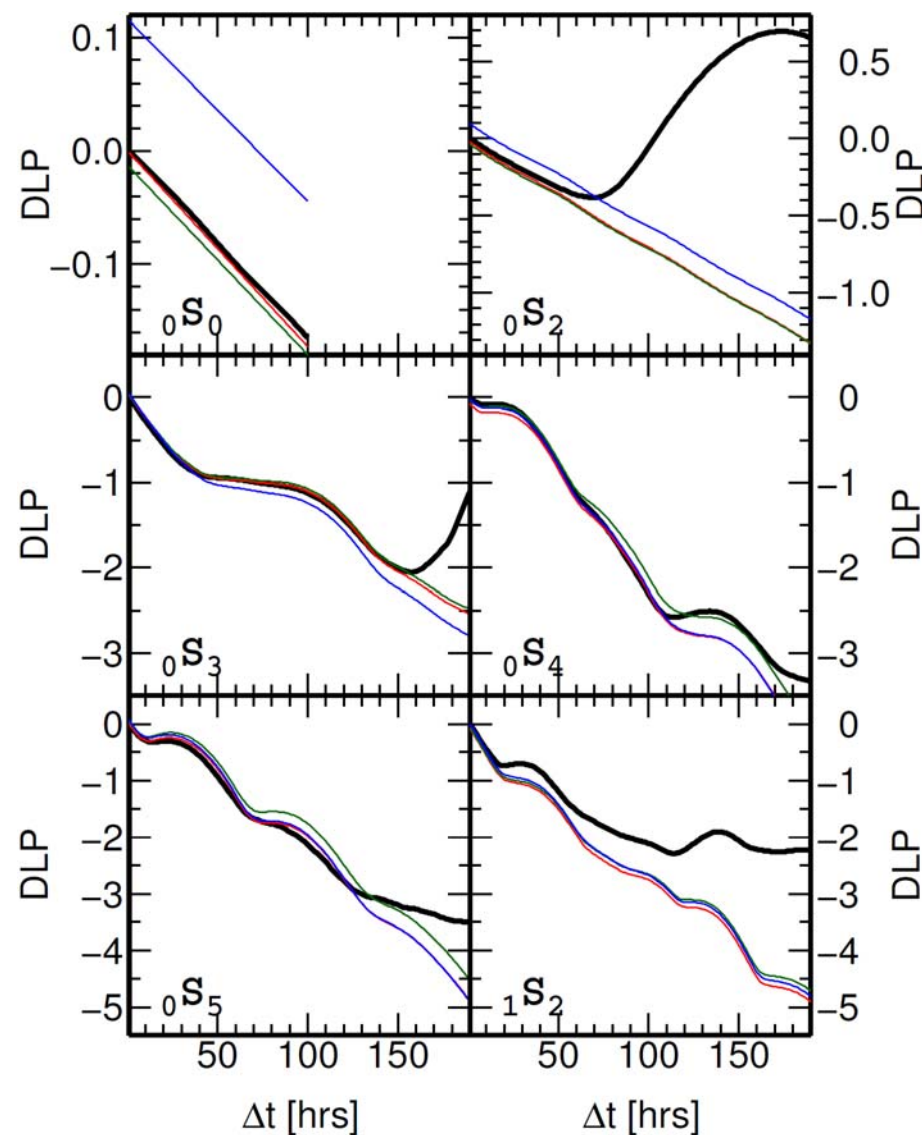
	T [s]	Q_0	Q_1	Q_2	$Q_0 T/2$ [h]
${}_0S_2$	3234	510	515	525	230
${}_0S_3$	2135	417	430	380	124
${}_0S_4$	1546	373	401	365	80
${}_1S_2$	1472	310	322	310	63
${}_0S_0$	1229	5327	5500	5714	910
${}_0S_5$	1190	356	380	350	59

• data

• červená Q_0 – PREM

• zelená Q_1

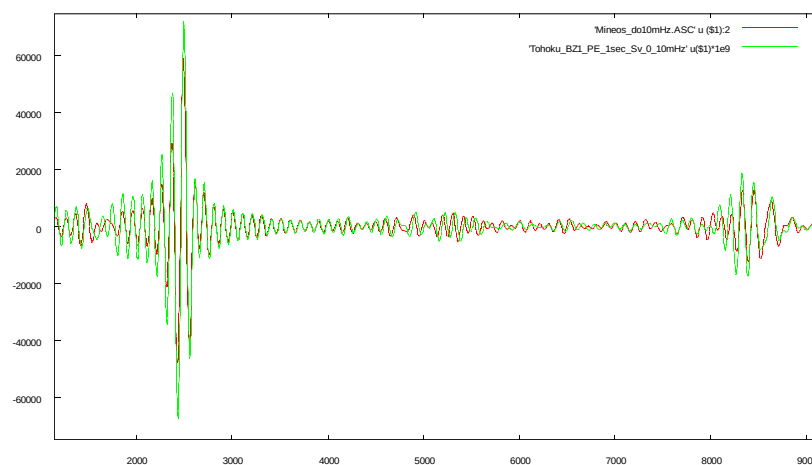
• modrá Q_2 – Tanimoto et al. (2012)



• Vysoké frekvence

• Syntetické seimogramy

$$a(\mathbf{x}_r, \mathbf{x}_s, t) = \sum_k A_k(\mathbf{x}_r, \mathbf{x}_s) \cos(\omega_k t) \exp\left(-\frac{\omega_k t}{2Q_k}\right)$$



• Statické posunutí

$$s(\mathbf{x}_r, \mathbf{x}_s) = \sum_k A_k(\mathbf{x}_r, \mathbf{x}_s) \omega_k^{-2}$$