Six-degree-of-freedom seismic records in epicentral regions of shallow microearthquakes

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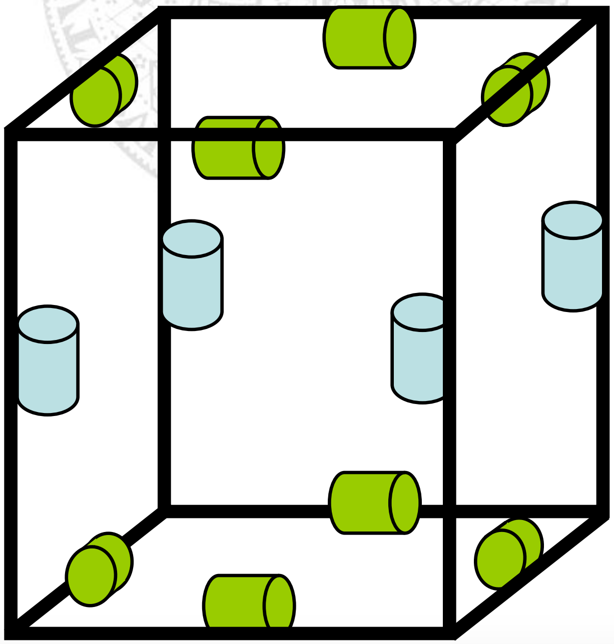
OUTLINE:

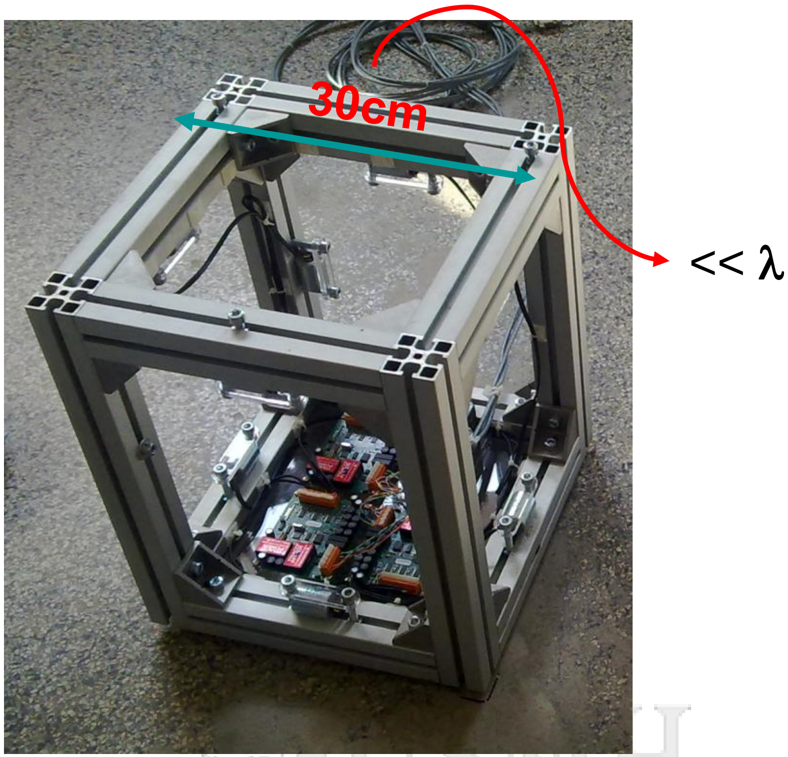
- **6DOF Rotaphone**
  - **- basic principles**
  - **- parameters**
  - **- calibration**
  - **- testing**
- **Rotation to translation relations at local distances**
  - **- RTR**
  - **- equations**
  - **- simple models**
- **Records from microearthquakes**
  - **- West Bohemia (Czech Republic), ML 2.3**
  - **- Gulf of Corinth (Greece), ML 1.9**
  - **- Provadia (Bulgaria), ML 1.6**
- **Correction of gravity-induced tilt errors in horizontal translational records**
- **Conclusions**

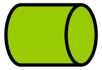
Rotaphone = mechanical sensor system designed to measure spatial ground motion gradients; it consists of sensitive low-frequency geophones, arranged in parallel pairs, connected to a common recording device

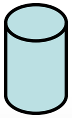
Present prototypes contain geophones **SM-6** (Sensor Nederland b.v.) with flat characteristics above **4.5 Hz**

Scheme:






horizontal geophones


vertical geophones

Basic features:

- The instrument provides collocated records of translational and rotational seismic motions (with the same instrumental characteristics)
- The geophones are mounted to a rigid (metal) ground-based frame
- Rotation rate is determined by multiple geophone pairs, which allows to perform 'in situ' calibration of the geophones simultaneously with the measurement.

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$$\Omega_1 = \frac{\partial v_3}{\partial x_2} = -\frac{\partial v_2}{\partial x_3},$$

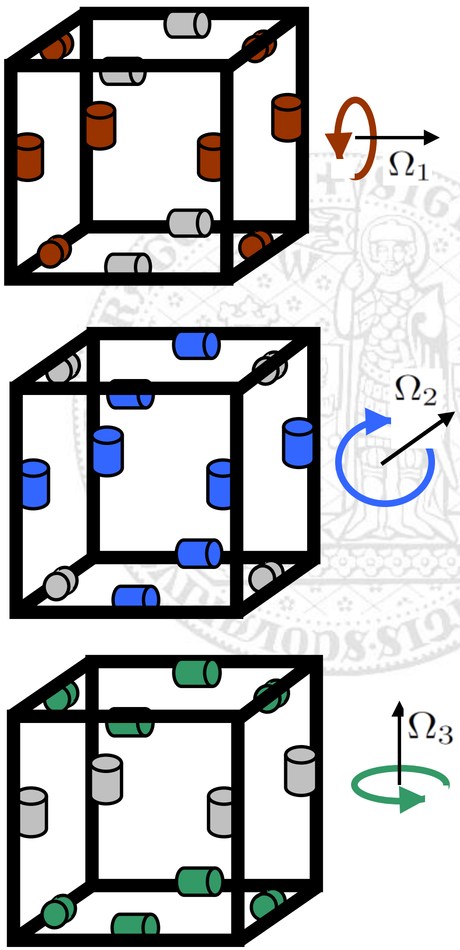
$$\Omega_2 = \frac{\partial v_1}{\partial x_3} = -\frac{\partial v_3}{\partial x_1},$$

$$\Omega_3 = \frac{\partial v_2}{\partial x_1} = -\frac{\partial v_1}{\partial x_2}.$$

Ω_i ... Rotation rate components

v_i .... Ground velocity components

Basic features:



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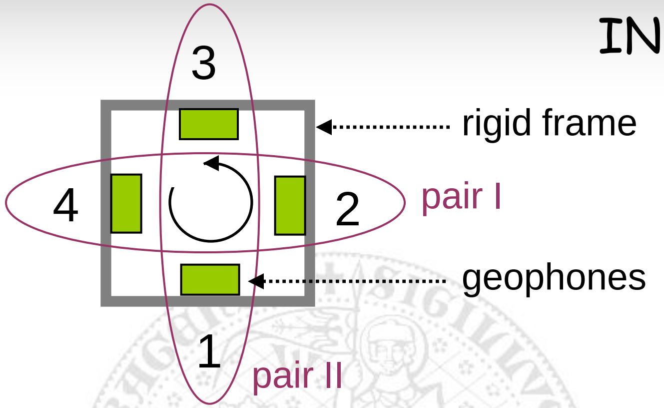
IN-SITU CALIBRATION



v_i^r ... output of the i^{th} geophone

v_i ... true velocity (i^{th} geophone)

Δ_{ij} ... separation distance between paired geophones

$$\frac{v_1 - v_3}{\Delta_{13}} = \frac{v_2 - v_4}{\Delta_{24}}$$

Assume that $\Delta_{13} = \Delta_{24}$. In the frequency domain ($V_i = \mathcal{F}(v_i)$) then

$$V_1 - V_3 = V_2 - V_4; \quad V_i = V_i^r / T_i; \quad T_i \ \ldots \ \text{transfer function of the } i^{\text{th}} \text{ geophone}$$

$$\Downarrow$$

$$\frac{V_1^r}{T_1} - \frac{V_3^r}{T_3} = \frac{V_2^r}{T_2} - \frac{V_4^r}{T_4}$$

$$\Downarrow \quad \text{(after simple algebra)}$$

$$V_1^r - V_3^r \frac{T_1}{T_3} = \frac{T_1}{T_2} \left(V_2^r - V_4^r \frac{T_2}{T_4} \right)$$

← for each frequency, i.e., m equations (m typically **thousands**)

unknowns (suitably parametrized)

$$T_i(f)/T_j(f) = \phi(p_1, p_2, p_3, \ldots, p_{N(i,j)}; f); \quad n = N(1,2)+N(1,3)+N(2,4)$$

poles and zeros or values at discrete f_k

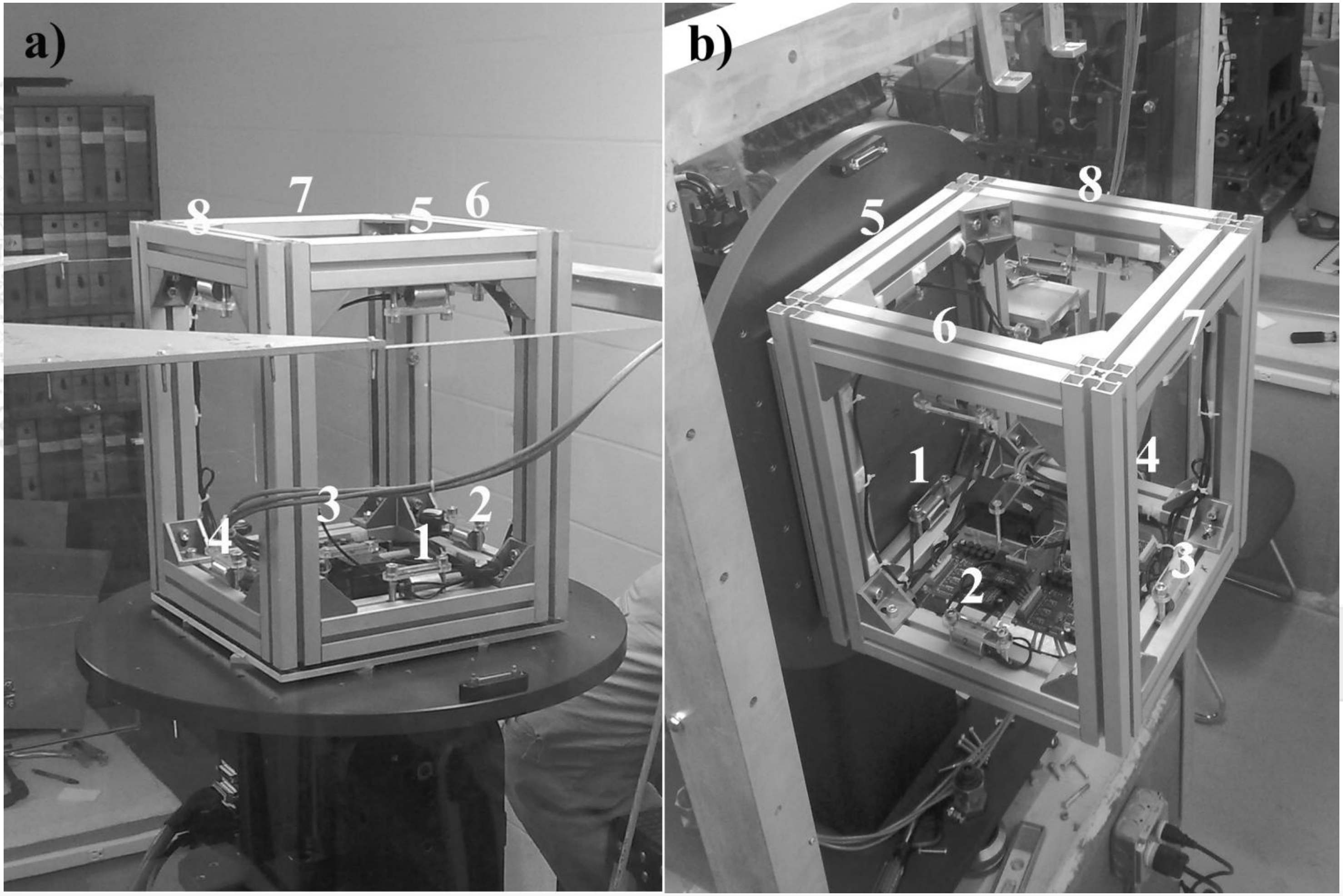
typically **tens**

The inversion is performed by the so-called isometric method (Malek et al., 2007), but any other method suitable for weakly nonlinear problems can be used as well.

Specific features and parameters: (component-dependent)

- Dimensions 35 x 35 x 43 cm
- Weight 9.5 kg
- Frequency range 2 Hz – 60 Hz; upper limit due to the first resonance frequency of the cubic frame (~70 Hz)
- Dynamic range 120 dB
- Largest detectable motion 10^{-1} m/s (clipping level of the geophones) and 10^{-1} rad/s
- Least detectable motion 10^{-9} m/s, 10^{-9} rad/s (theoretical, noise-free); in practice 10^{-7} m/s and 10^{-7} rad/s (conditioned by the in-situ calibration)

Rotaphone was tested at Albuguerque Seismological Laboratory (ASL), U.S. Geological Survey, New Mexico



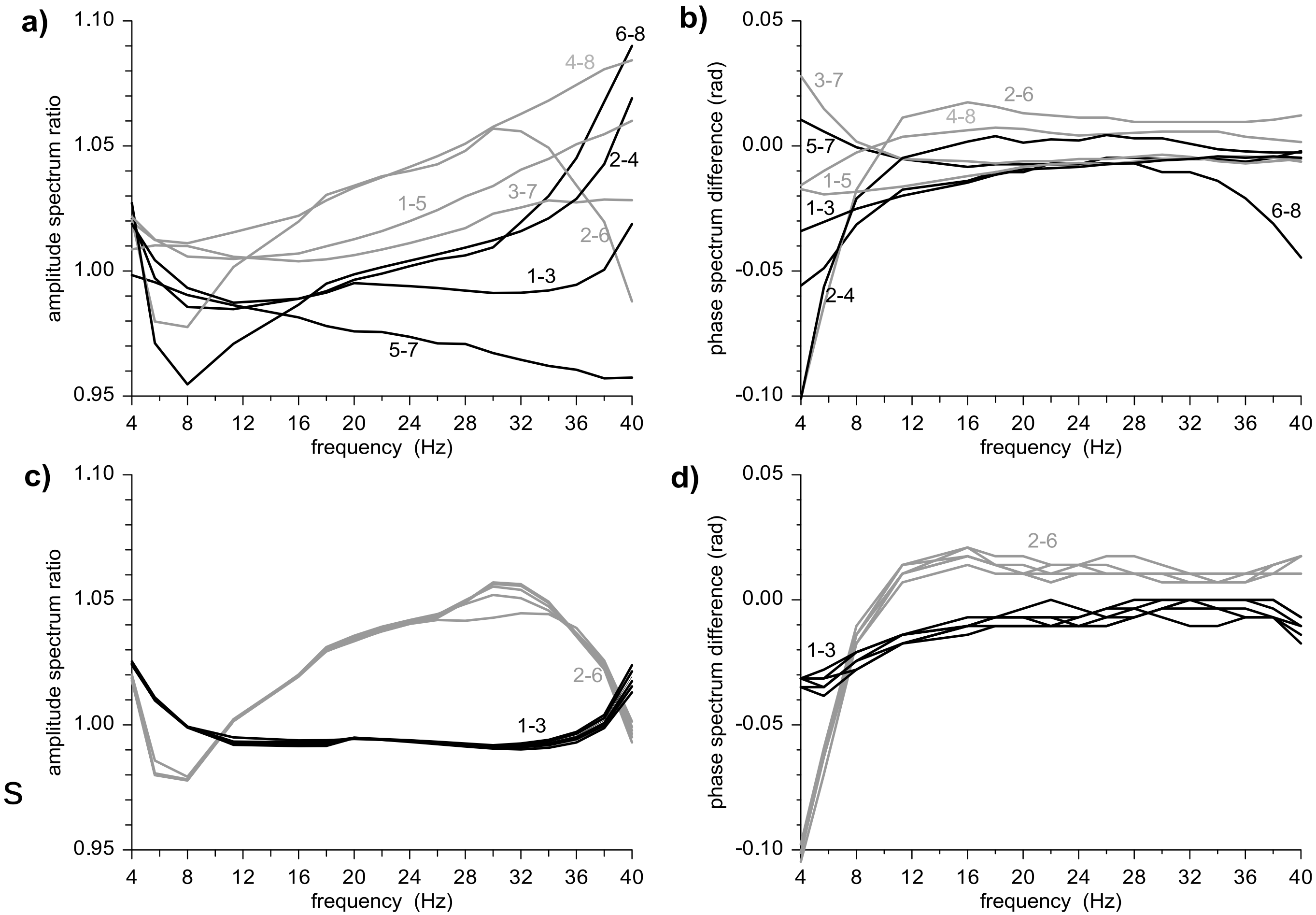
ASL testing

Spectral ratios
for paralell pairs

pairs for torsion (black line)

pairs for tilts (grey line)

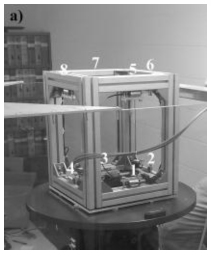
Linearity test:
spectral ratios
for pairs 1-3 and 2-6
for six amplitude levels
from 0.15 to 1.15º/s

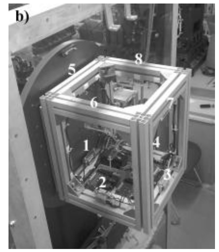


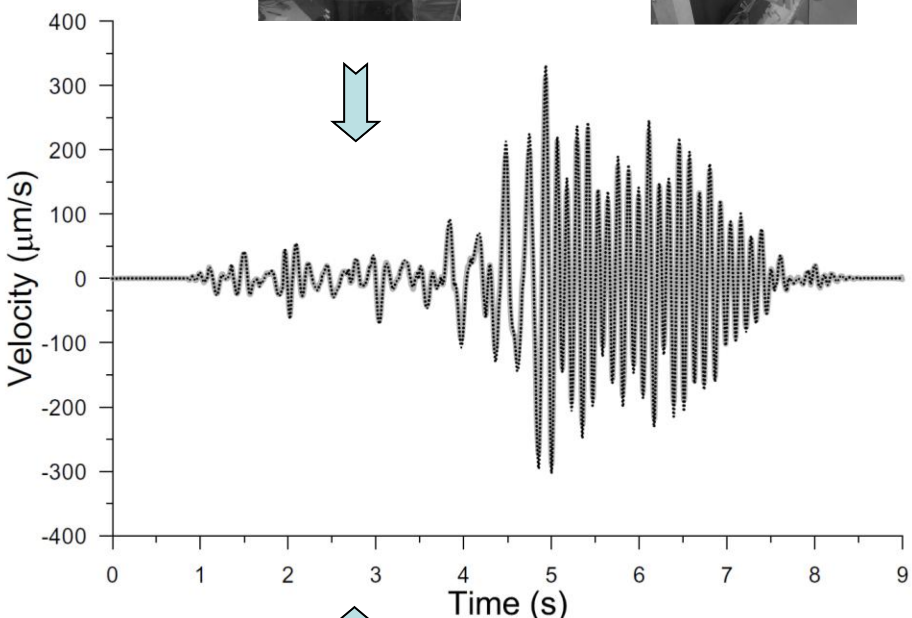
(Brokesova et al., 2012b)

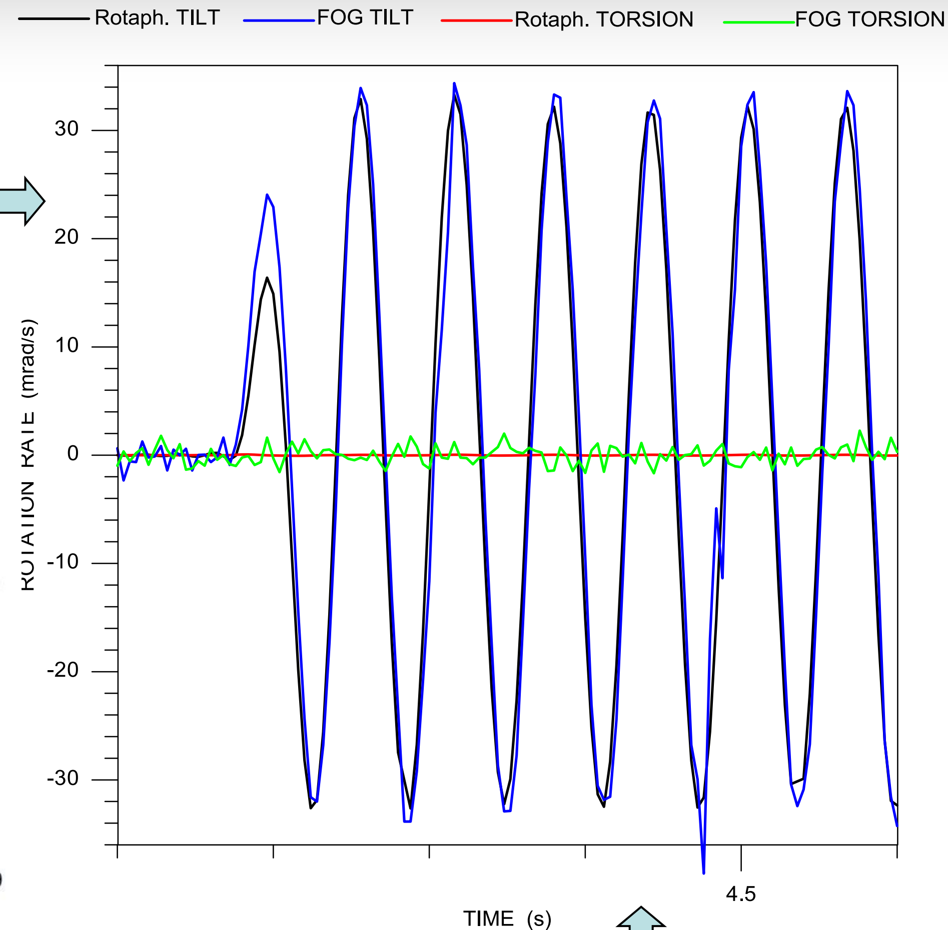
6DOF Seismic Records in epicentral regions of shallow micro-earthquakes

ASL testing









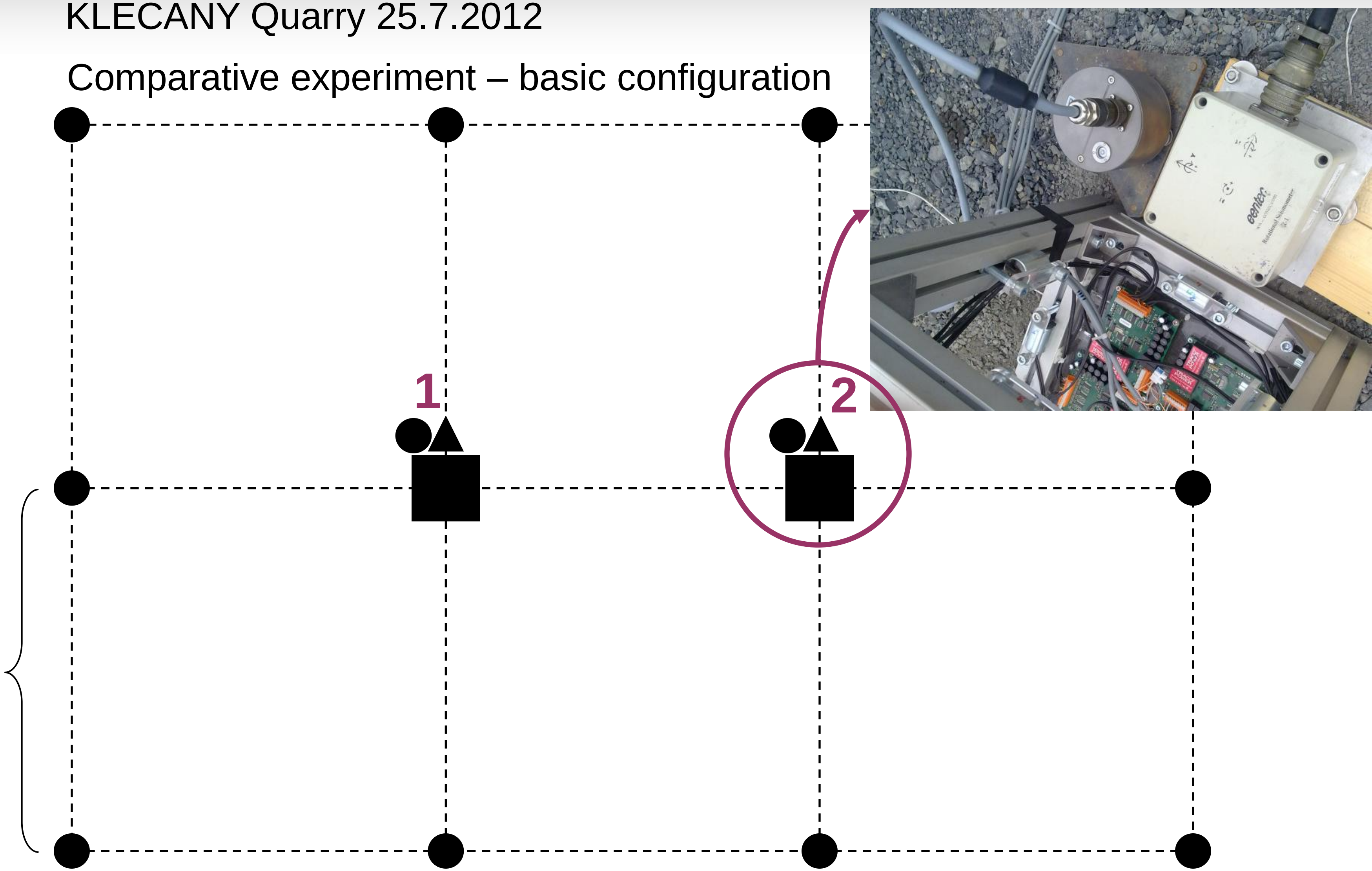
Instantaneous, tangential, translational velocity of the Rotaphone (centered 7.62 cm from rotation axis) inferred by direct Rotaphone measurement (black dotted) compared to that obtained from rotation rate and radius (gray)

Horizontal-axis shaking, comparing a 16 Hz sinusoidal rotation signal measured by the Rotaphone and FOG

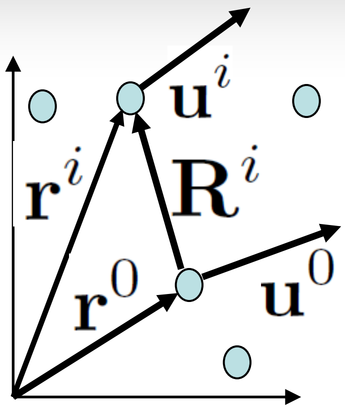
CROSS-AXIS TEST

KLECANY Quarry 25.7.2012

Comparative experiment – basic configuration



Symbols: □ Rotaphone △ R1 ○ LE-3D



Array derived rotations (ADR)

(after Spudich et al., JGR, 1995)

$$\mathbf{r}^i = (x_1^i, x_2^i, 0)^T \quad i = 0, 1, \ldots, N$$

$$\mathbf{u}^i = (u_1^i, u_2^i, u_3^i)^T$$

$$\mathbf{R}^i = \mathbf{r}^i - \mathbf{r}^0 \qquad \mathbf{d}^i = \mathbf{u}^i - \mathbf{u}^0$$

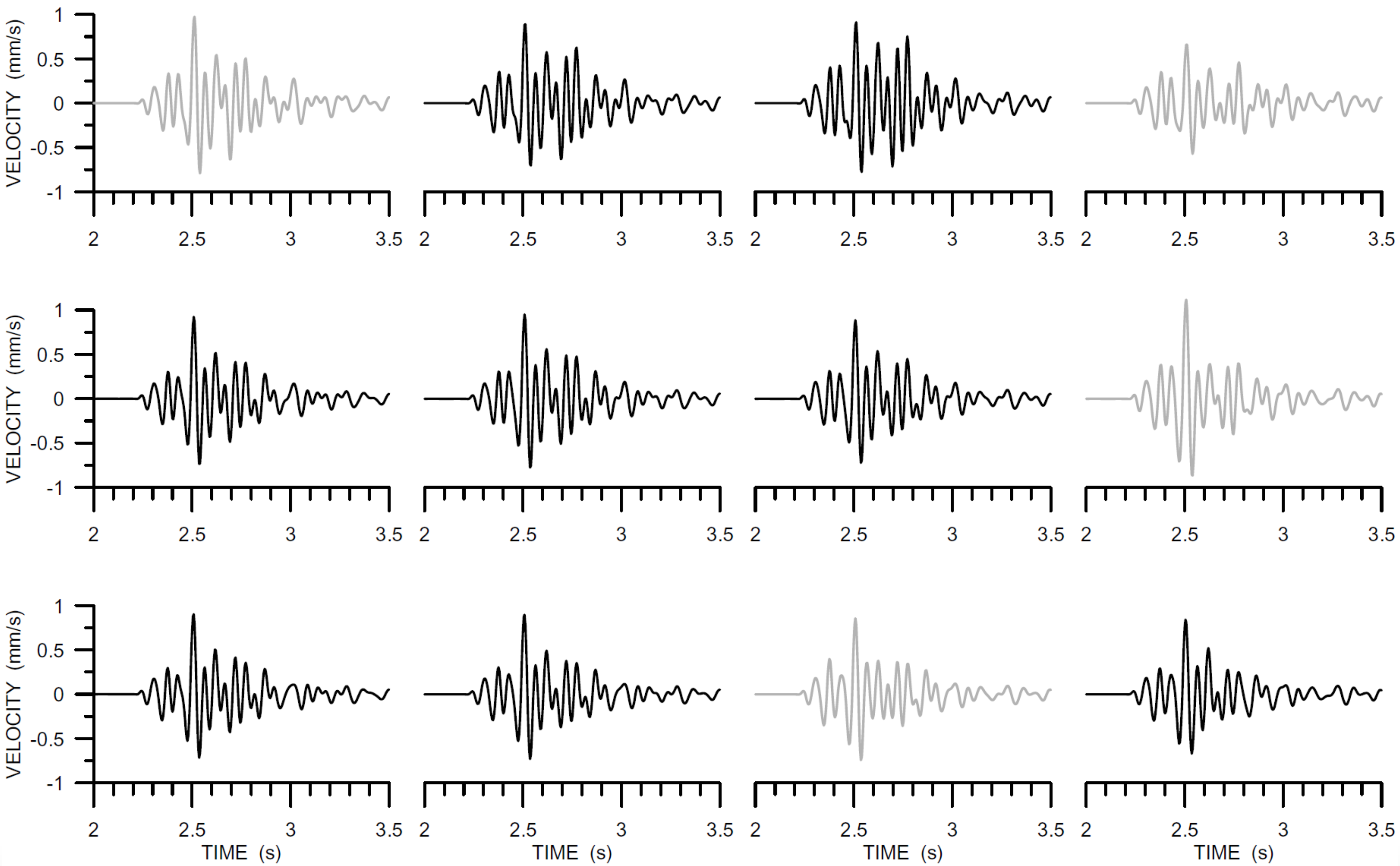
$$\mathbf{d}^i = \mathbf{G}\mathbf{R}^i; \quad G_{ij} = u_{i,j}$$

Spatially uniform displacement gradients !!!

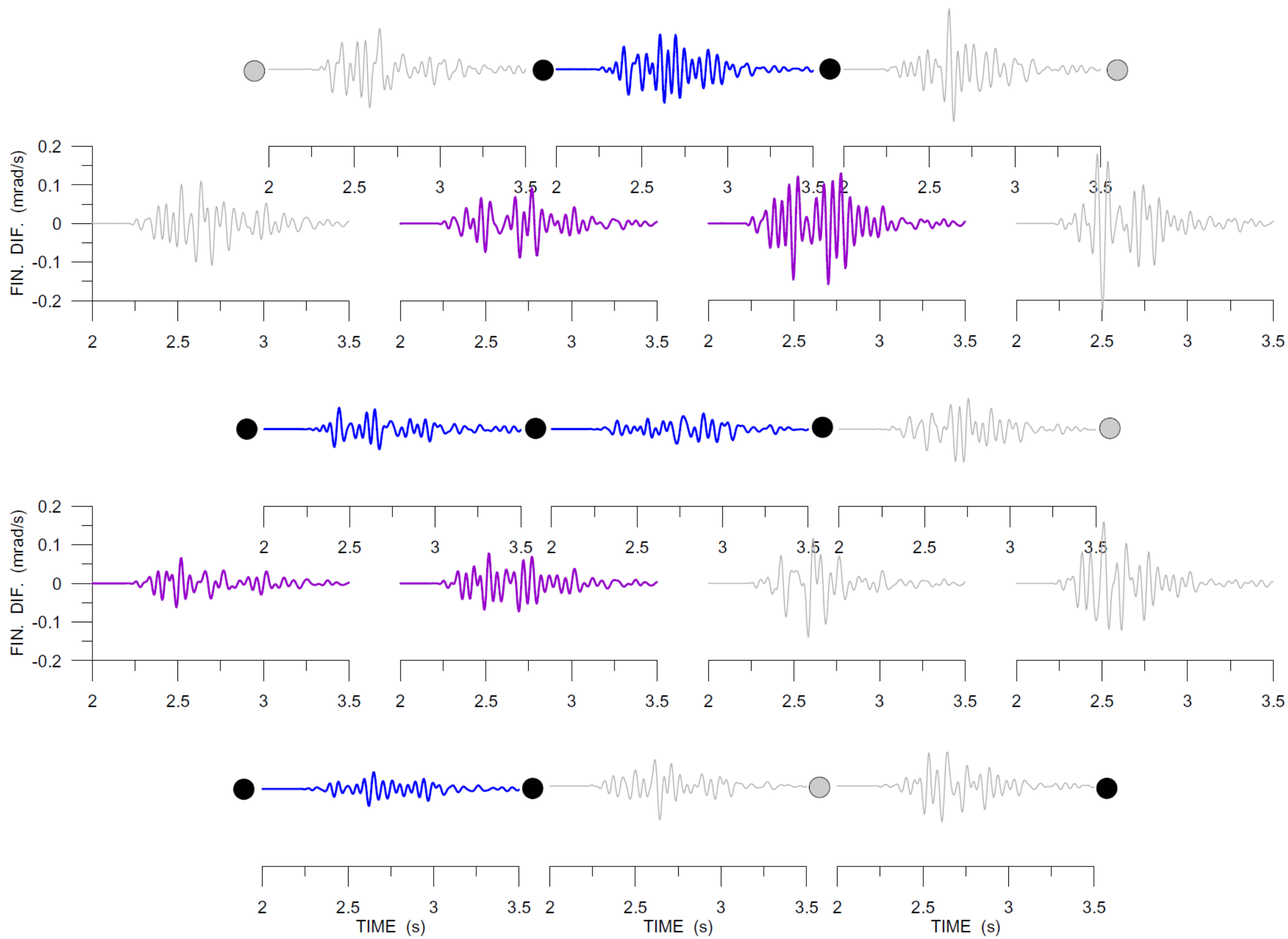
$$\begin{pmatrix} d_1^i \\ d_2^i \\ d_3^i \end{pmatrix} = \begin{pmatrix} u_{1,1} & u_{1,2} & \cdots \\ u_{2,1} & u_{2,2} & \cdots \\ u_{3,1} & u_{3,2} & \cdots \end{pmatrix} \begin{pmatrix} R_1^i \\ R_2^i \\ 0 \end{pmatrix}$$

Minimum number of stations: 3

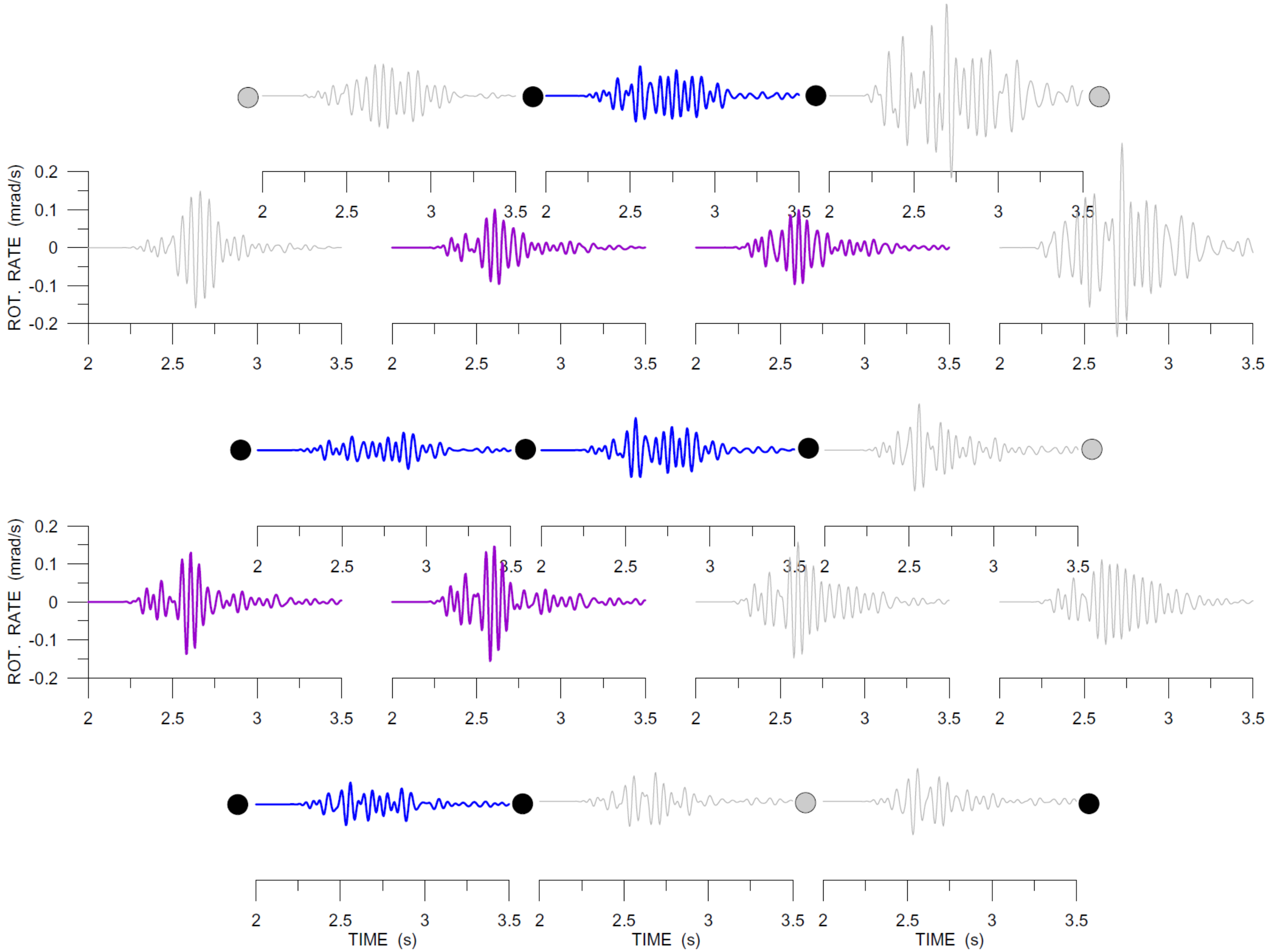
KLECANY Quarry, BLAST 2, E-component, 6-20 Hz



KLECANY Quarry 25.7.2012, finite differences dv_y/dx and dv_x/dy

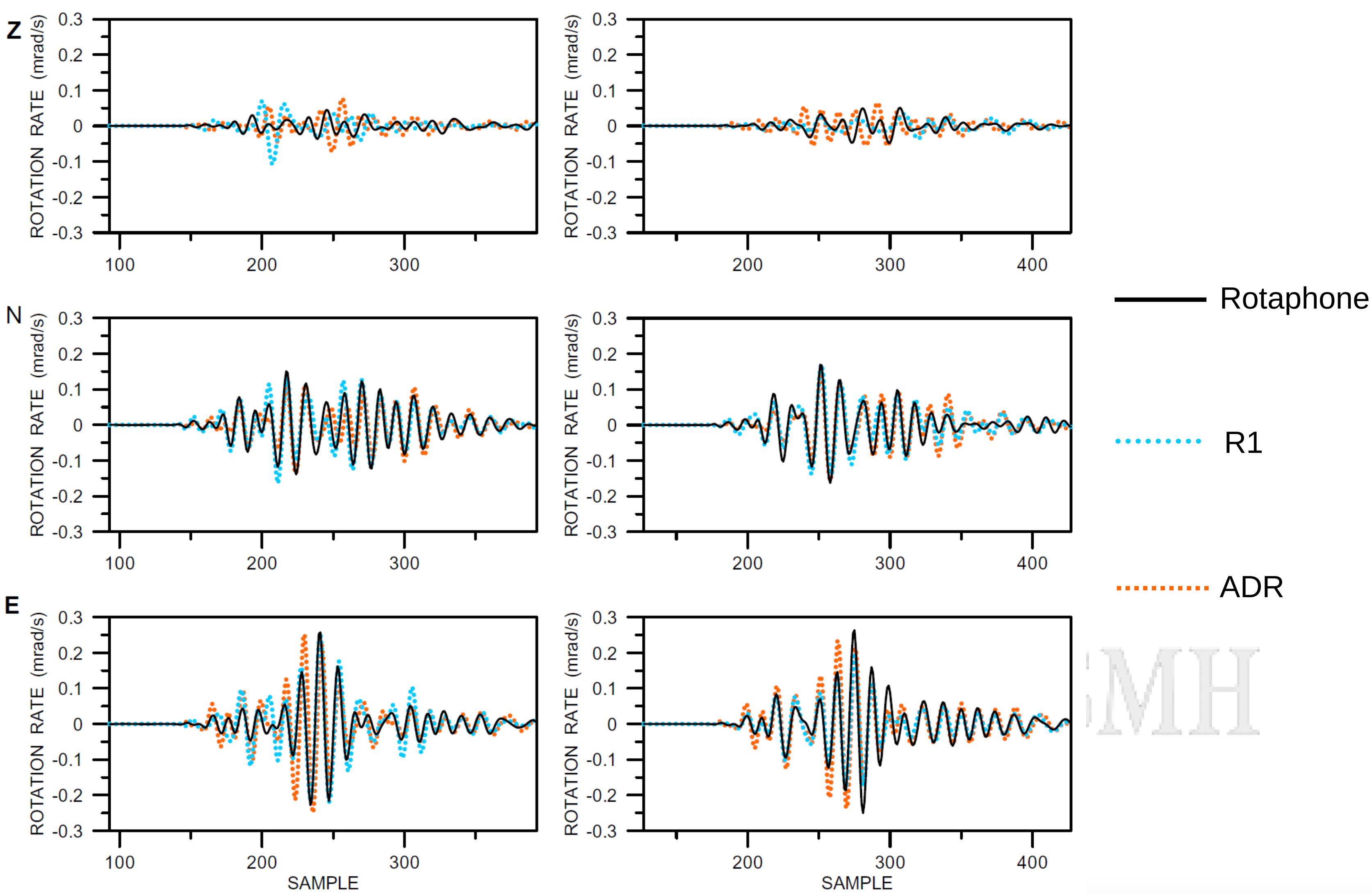


KLECANY Quarry 25.7.2012, finite differences dv_z/dx and dv_z/dy



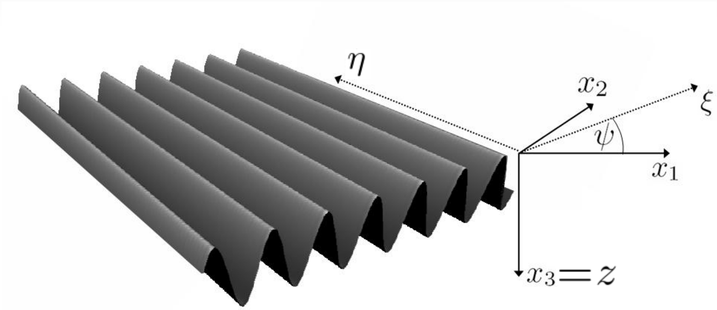
6DOF Seismic Records in epicentral regions of shallow micro-earthquakes

KLECANY Quarry 25.7.2012, Rotaphone vs. ADR vs. R1



1 2

Rotation to translation relations



At greater distances we can assume a **plane wave** with apparent velocity *c* along surface:

$$\mathbf{v} = \mathbf{V} F\left(t - \frac{\xi}{c}\right)$$

For the z-axis rotation we have

$$\Omega_z = \frac{1}{2}\left(\frac{\partial v_\eta}{\partial \xi} - \frac{\partial v_\xi}{\partial \eta}\right) = \frac{1}{2}\frac{\partial v_\eta}{\partial \xi} = -\frac{1}{2c} V_\eta F'\left(t - \frac{\xi}{c}\right)$$

=

$$\dot{v}_\eta = V_\eta F'\left(t - \frac{\xi}{c}\right)$$

$$\Rightarrow \quad \Omega_z = -\frac{1}{2c}\dot{v}_\eta$$

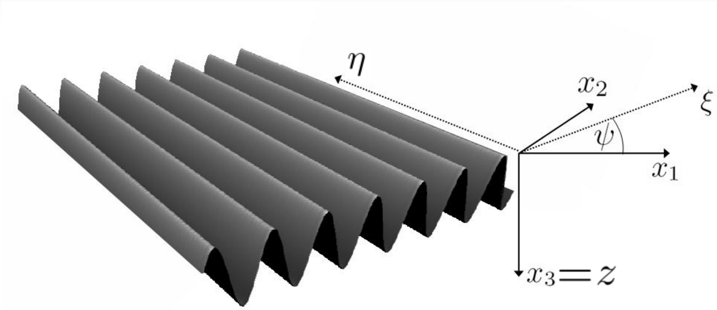
The **z-axis rotation rate** and the **transverse acceleration** waveforms coincide.

In analogy:

The **transverse-axis rotation rate** waveform corresponds to the **vertical acceleration** waveform

$$\Omega_\eta = \frac{1}{c}\dot{v}_z$$

Rotation to translation relations



At local distances the plane wave assumption is, in general, no more applicable

$$\mathbf{v} = \mathbf{V}F\left(t - \frac{\xi}{c}\right)$$

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Rotation to translation relations

Let us assume a point source generating a spherical wave

$$\mathbf{v} = \frac{\mathbf{V}}{r} F\left(t - \frac{r}{\beta}\right)$$

$$r = \sqrt{x^2 + y^2 + z^2}$$

For example, the **z-axis rotation rate** component reads:

$$\Omega_z = \frac{1}{2}\left[\frac{\partial v_y}{\partial x} - \frac{\partial v_x}{\partial y}\right] = \frac{1}{2}\left[\frac{y}{r^2}v_x + \frac{y}{\beta r}\dot{v}_x - v_x V_x^{-1}\frac{\partial V_x}{\partial y} - \frac{x}{r^2}v_y - \frac{x}{\beta r}\dot{v}_y + v_y V_y^{-1}\frac{\partial V_y}{\partial x}\right]$$

Rotating to the radial and transverse directions (x$\rightarrow \xi$ and $y \rightarrow \eta$), receiver at $(\xi, 0, z)$:

$$\Omega_z = \frac{1}{2}\left[\frac{\partial v_\eta}{\partial \xi} - \frac{\partial v_\xi}{\partial \eta}\right] = \frac{1}{2}\left[\frac{z}{r^2}v_\eta V_\eta^{-1}\frac{\partial V_\eta}{\partial \xi} - \frac{\xi}{r^2}v_\eta - \frac{\xi}{\beta r}\dot{v}_\eta - \frac{1}{\xi}v_\xi V_\xi^{-1}\frac{\partial V_\xi}{\partial \eta}\right]$$

for a large r and a shallow depth $(\xi \approx r)$

$$\Omega_z = \frac{1}{2}\left[\frac{\partial v_\eta}{\partial \xi} - \frac{\partial v_\xi}{\partial \eta}\right] = \frac{1}{2}\left[\frac{z}{r^2}v_\eta V_\eta^{-1}\frac{\partial V_\eta}{\partial \xi} - \frac{\xi}{r^2}v_\eta - \frac{\xi}{\beta r}\dot{v}_\eta - \frac{1}{\xi}v_\xi V_\xi^{-1}\frac{\partial V_\xi}{\partial \eta}\right]$$

$$\Omega_z \approx -\frac{1}{2\beta}\dot{v}_\eta$$

Analogously, the **ξ-axis** and **η-axis rotation rate** components can be derived.

Rotation to translation relations

Unknowns

Data

$$\Omega_\xi = \frac{\partial v_z}{\partial \eta} = v_z \bar{V}_z^{-1} \frac{\partial \bar{V}_z}{\partial \eta},$$

$$\Omega_\eta = -\frac{\partial v_z}{\partial \xi} = \frac{\xi}{r^2} v_z + \frac{\xi}{\beta r} \dot{v}_z - v_z \bar{V}_z^{-1} \frac{\partial \bar{V}_z}{\partial \xi},$$

$$\Omega_z = \frac{1}{2}\left[\frac{\partial v_\eta}{\partial \xi} - \frac{\partial v_\xi}{\partial \eta}\right] = \frac{1}{2}\left[v_\eta V_\eta^{-1} \frac{\partial V_\eta}{\partial \xi} - \frac{\xi}{r^2} v_\eta - \frac{\xi}{\beta r} \dot{v}_\eta - v_\xi \bar{V}_\xi^{-1} \frac{\partial \bar{V}_\xi}{\partial \eta}\right].$$

$$\bar{\mathbf{V}} = (q_\xi V_\xi, 2V_\eta, q_z V_z)$$

The three constraints hold at any time
(as long as the S-wave is separated from other waves in the seimograms).

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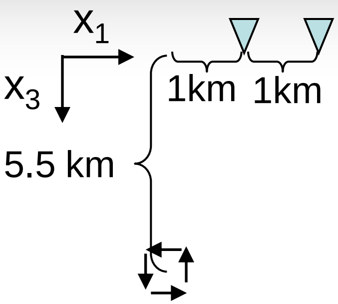
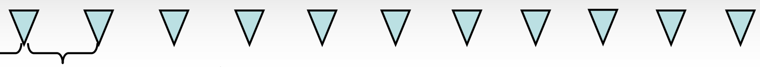
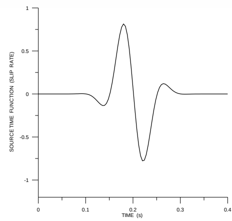


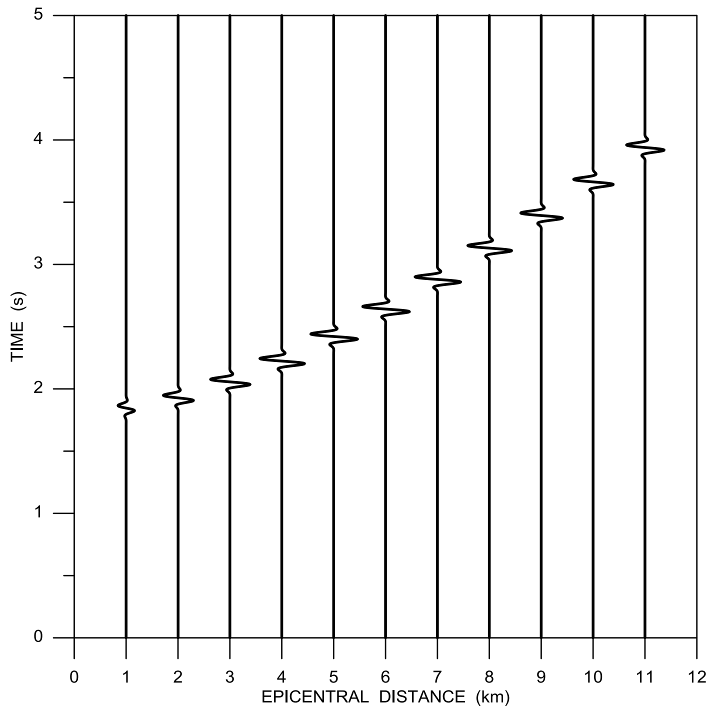


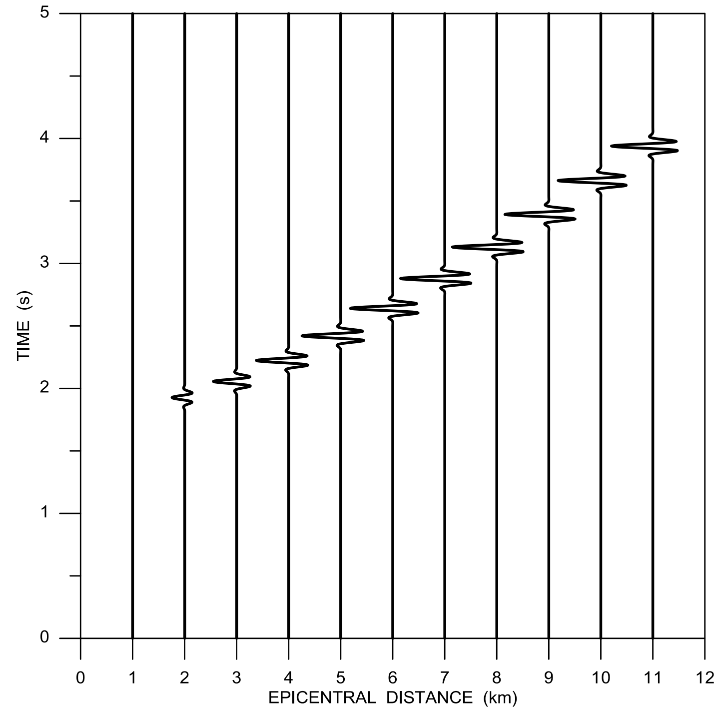


Gabor signal, prevailing frequency 10 Hz

Homogeneous, isotropic, unbounded medium with β=3.204 km/s; center of rotation in x_1-x_3 plane

ANALYTICAL SOLUTION





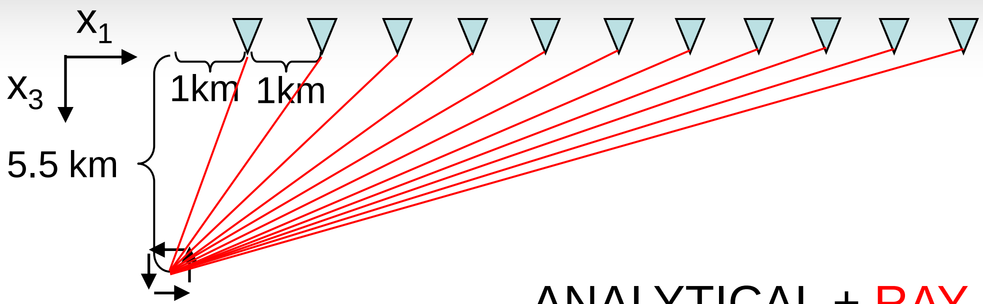
v_z

~10^{-3} m/s

Ω_η

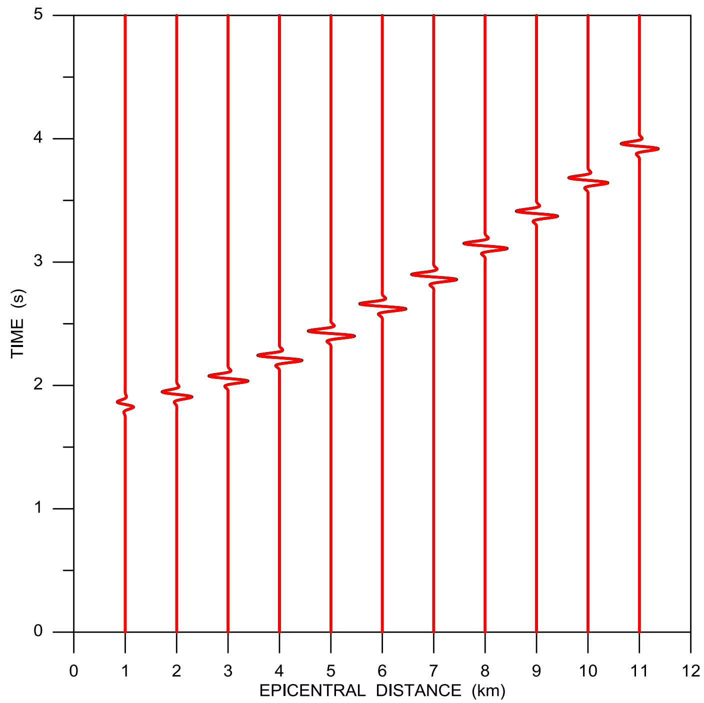
~10^{-5} rad/s

6DOF Seismic Records in epicentral regions of shallow micro-earthquakes



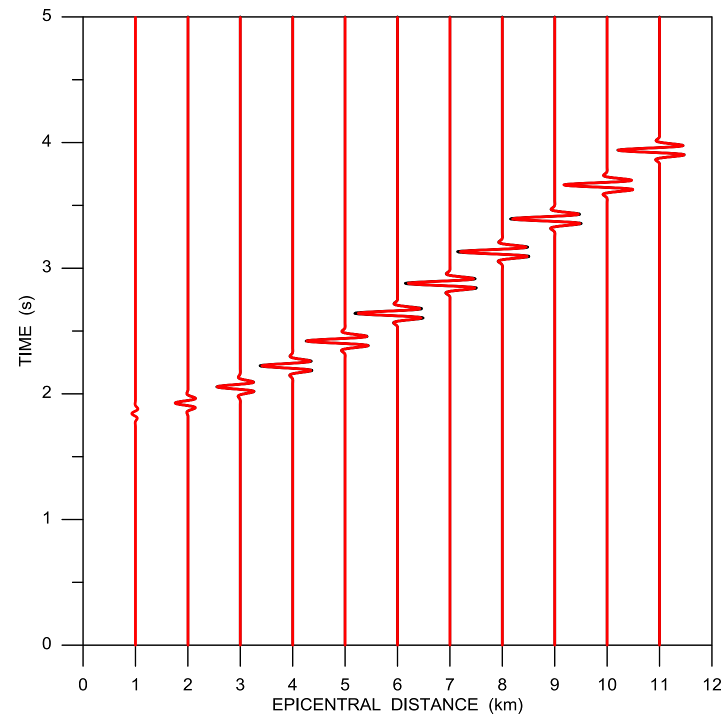
Homogeneous, isotropic, unbounded medium with β=3.204 km/s; center of rotation in x_1-x_3 plane

ANALYTICAL + RAY SOLUTION



v_z

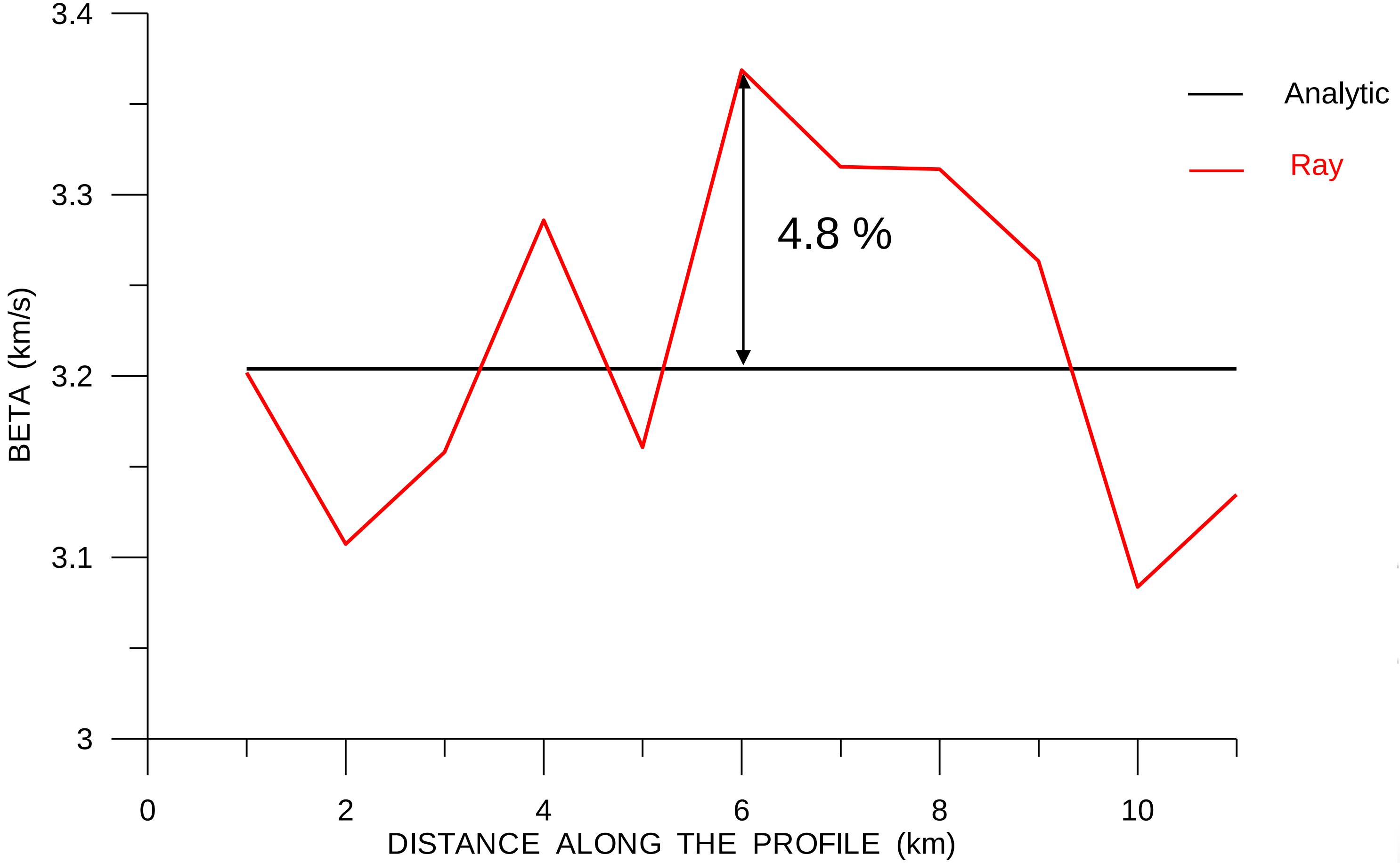
~10^{-3} m/s



Ω_η

~10^{-5} rad/s

$$\Omega_\eta = -\frac{\partial v_z}{\partial \xi} = \frac{\xi}{r^2} v_z + \frac{\xi}{\beta r}\dot{v}_z - v_z \bar{V}_z^{-1}\frac{\partial \bar{V}_z}{\partial \xi}$$



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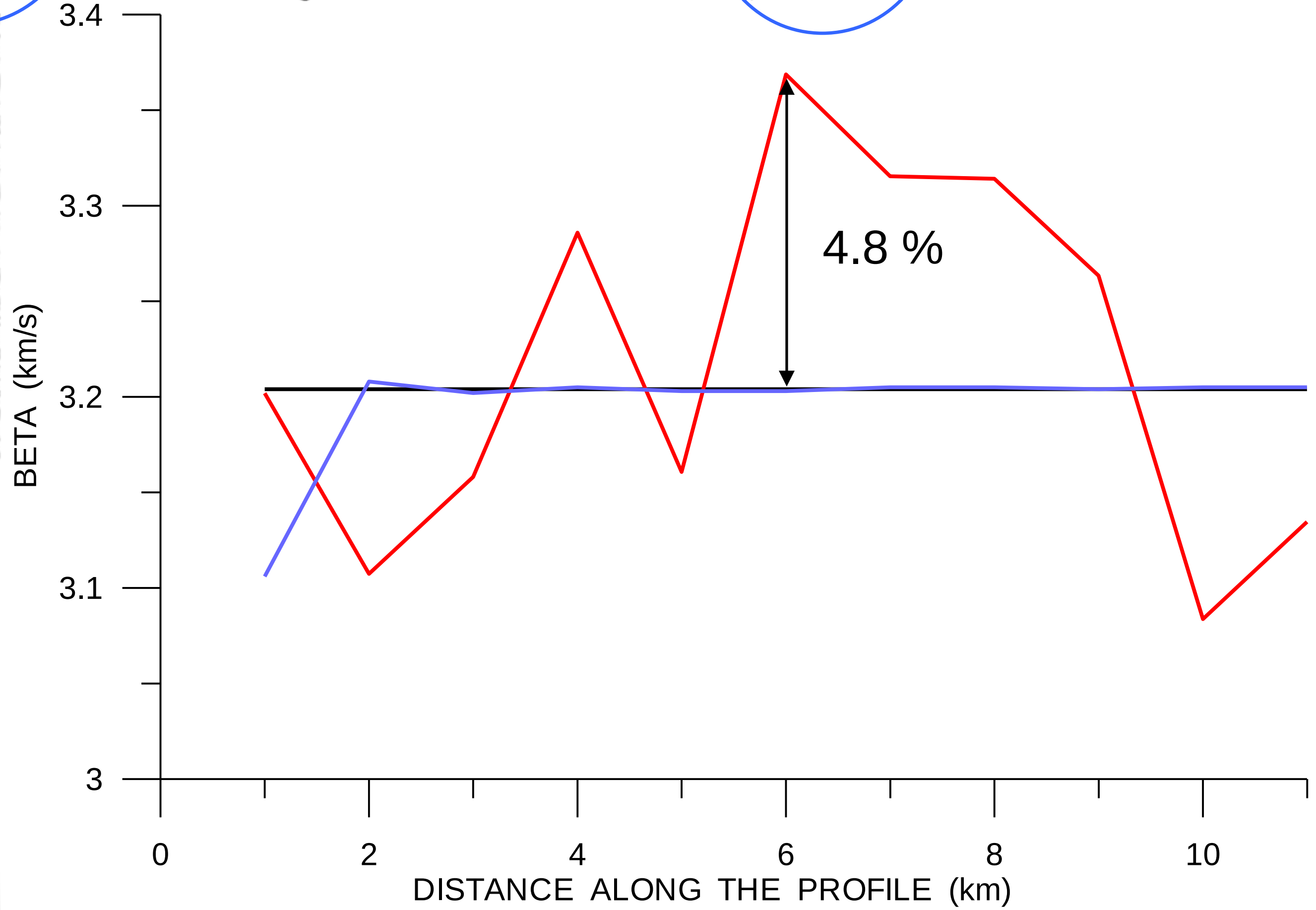

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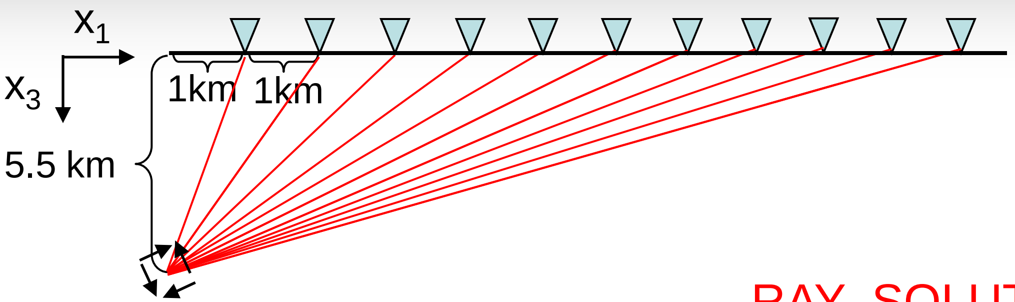
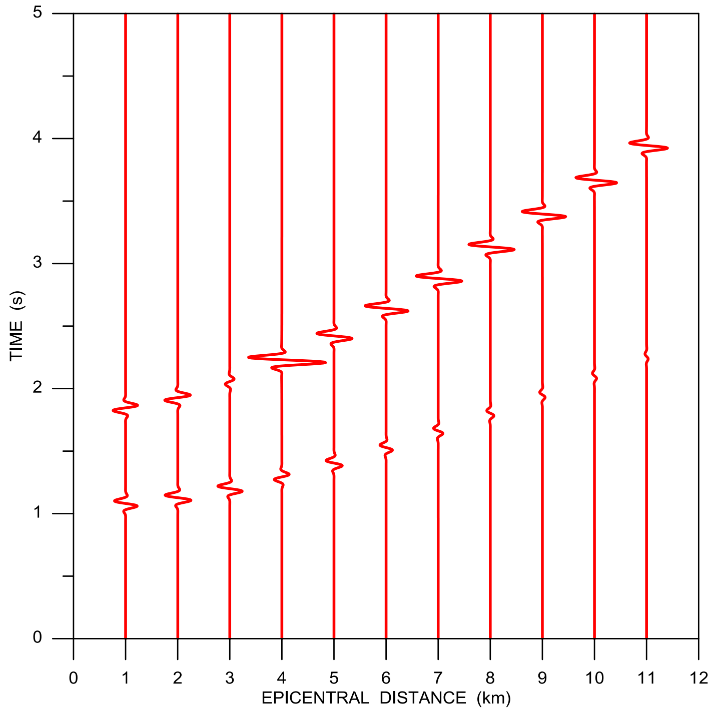
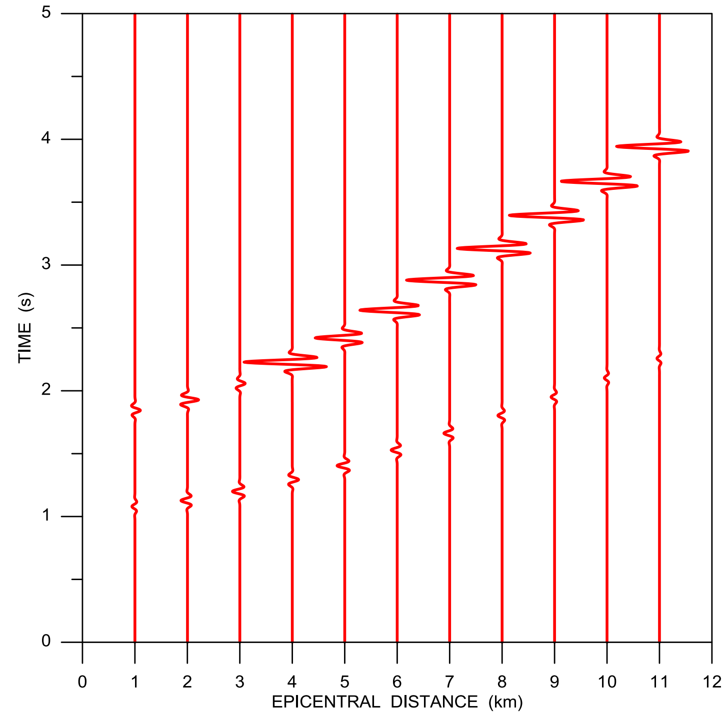


Homogeneous, isotropic, halfspace with β=3.204 km/s; double couple -90, 77, 90 (nodal plane at 3km on the profile)

RAY SOLUTION





v_z

~10^{-3} m/s

Ω_η

~10^{-5} rad/s

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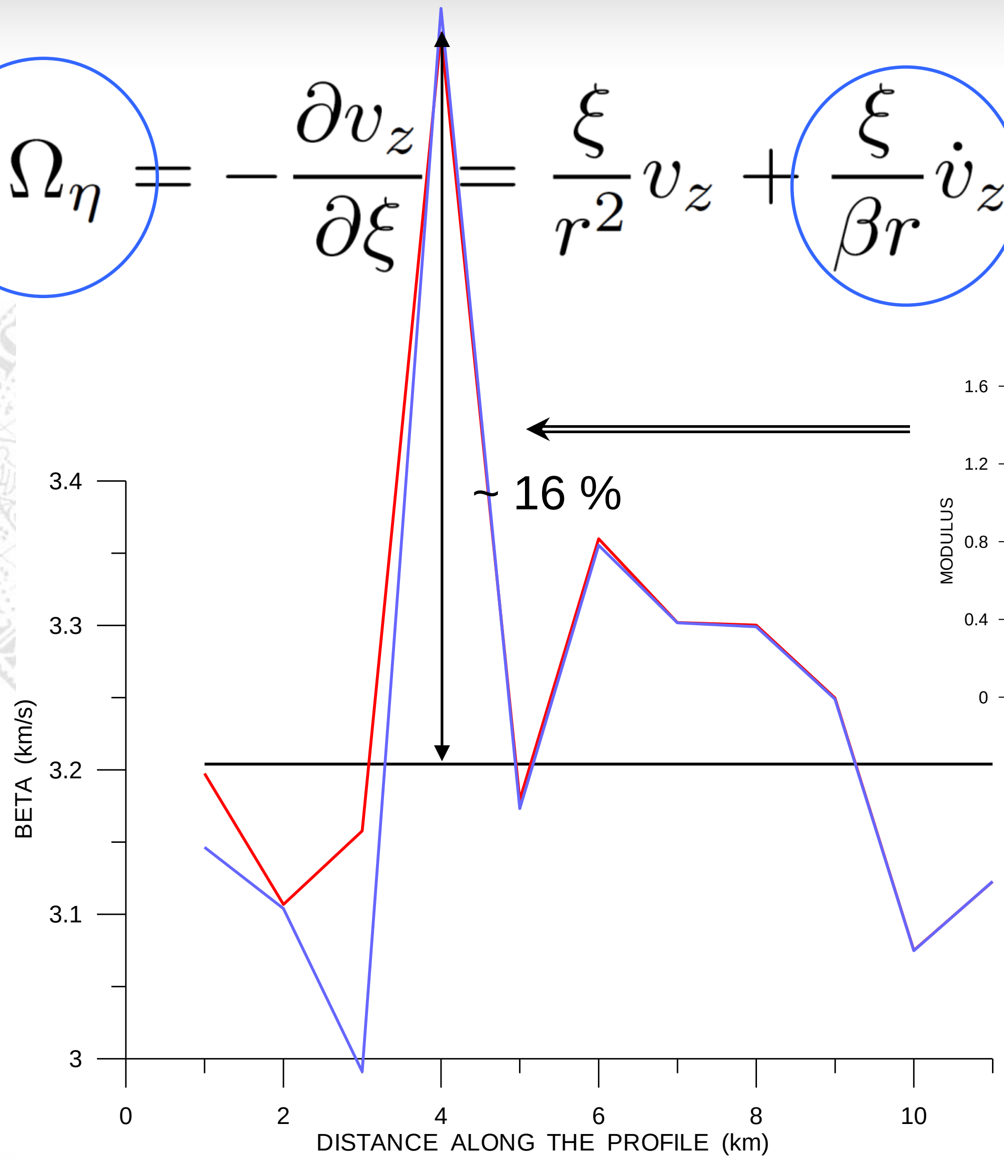
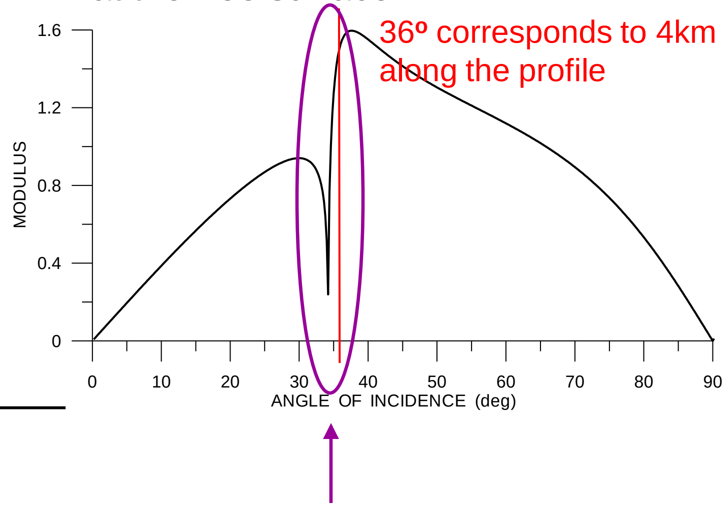
$$\Omega_\eta = -\frac{\partial v_z}{\partial \xi} = \frac{\xi}{r^2} v_z + \frac{\xi}{\beta r}\dot{v}_z - v_z \bar{V}_z^{-1} \frac{\partial \bar{V}_z}{\partial \xi}$$



Sz-coefficient of conversion at the free surface

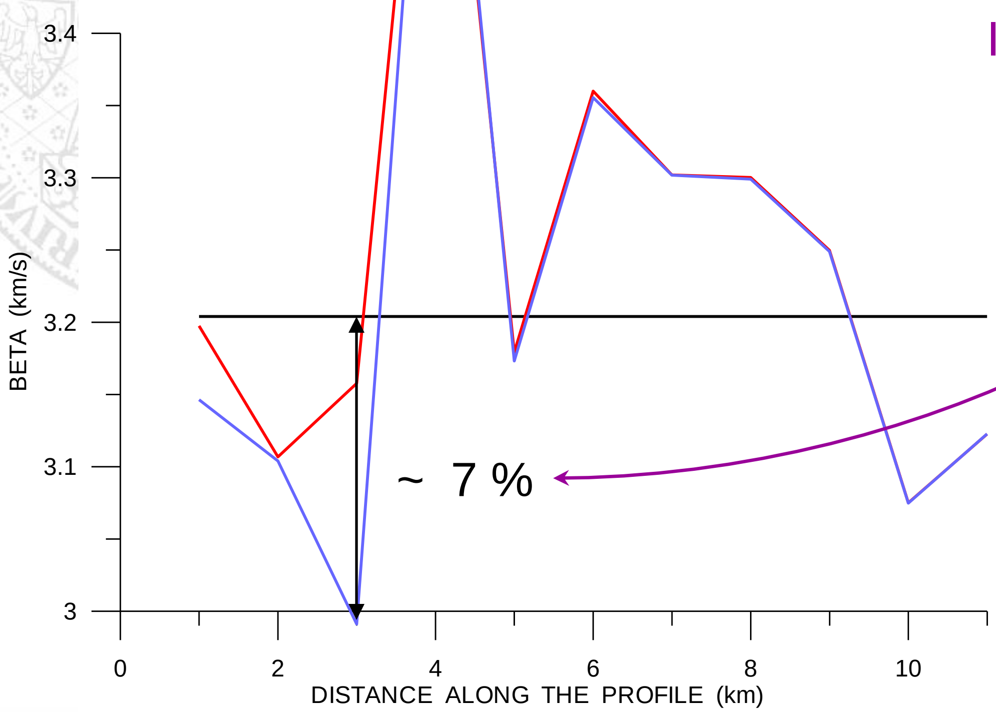


Ray theory singular region

6DOF Seismic Records in epicentral regions of shallow micro-earthquakes

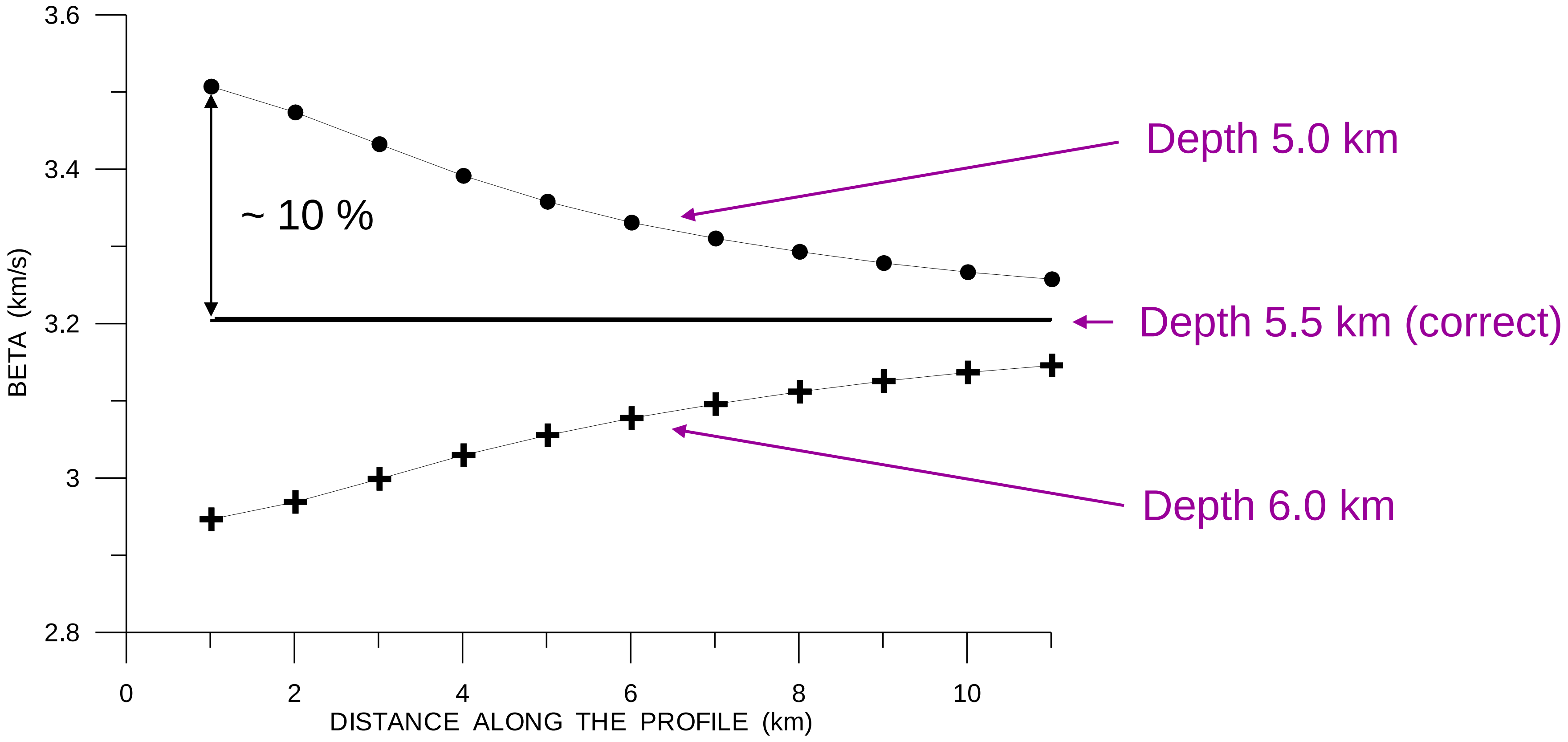
$$\Omega_\eta = -\frac{\partial v_z}{\partial \xi} = \frac{\xi}{r^2} v_z + \frac{\xi}{\beta r}\dot{v}_z - v_z \bar{V}_z^{-1} \frac{\partial \bar{V}_z}{\partial \xi}$$

This term cannot be neglected
In the vicinity of a nodal plane



ANALYTICAL SOLUTION - Uncertainty in depth

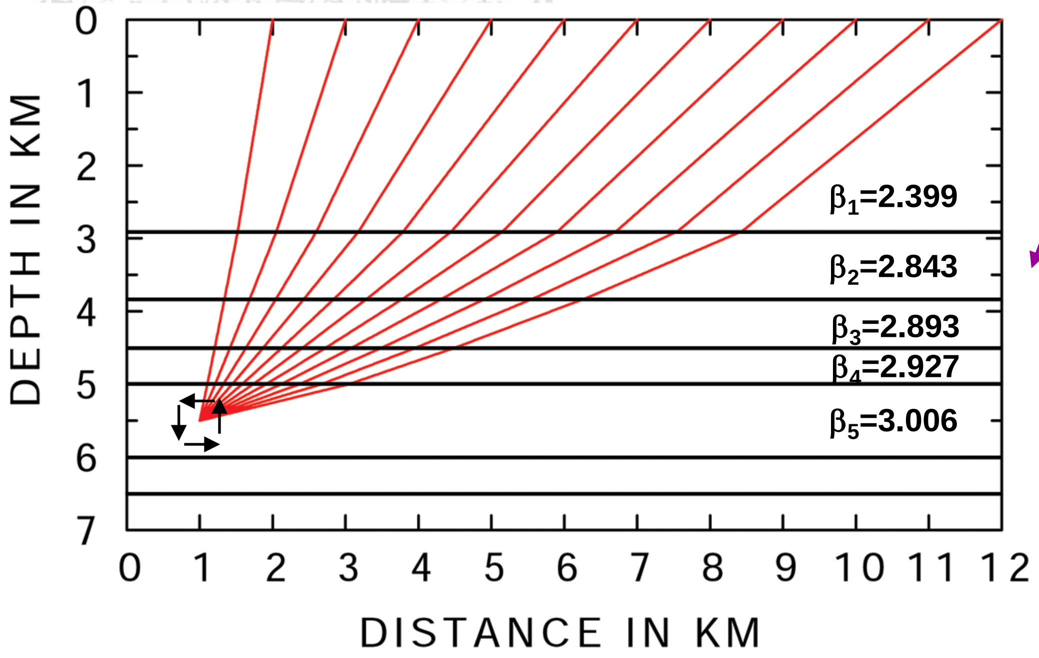
$$\Omega_\eta = -\frac{\partial v_z}{\partial \xi} = \frac{\xi}{r^2} v_z + \frac{\xi}{\beta r}\dot{v}_z - v_z \bar{V}_z^{-1} \frac{\partial \bar{V}_z}{\partial \xi}$$



RAY SOLUTION – Vertically inhomogeneous model

$$\Omega_\eta = -\frac{\partial v_z}{\partial \xi} = \frac{\xi}{r^2} v_z + \frac{\xi}{\beta r}\dot{v}_z - v_z \bar{V}_z^{-1} \frac{\partial \bar{V}_z}{\partial \xi}$$

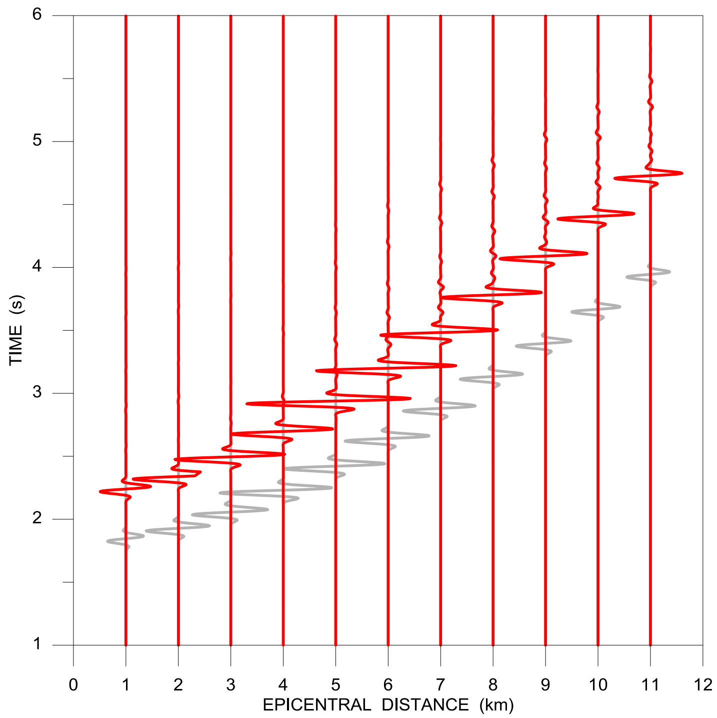
Equation corresponds to a homogeneous model while synthetic seismograms are calculated for
a layered, isotropic, halfspace;
center of rotation in x1-x3 plane



RAY SOLUTION – Vertically inhomogeneous model

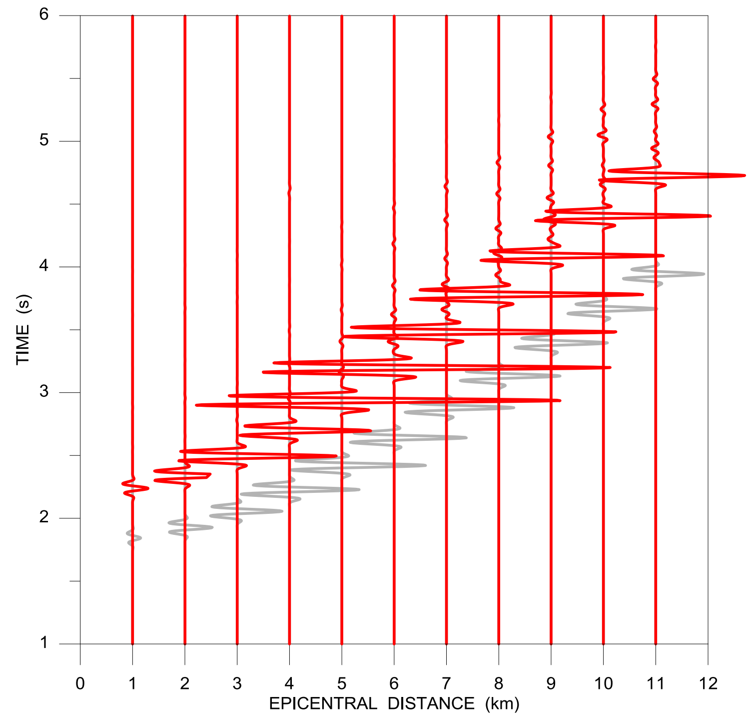
$$\Omega_\eta = -\frac{\partial v_z}{\partial \xi} = \frac{\xi}{r^2} v_z + \frac{\xi}{\beta r} \dot{v}_z - v_z \bar{V}_z^{-1} \frac{\partial \bar{V}_z}{\partial \xi}$$

In grey: ray solution for homogeneous halfspace; the same source (center of rotation) at the depth of 5.5 km



v_z

~10^{-3} m/s

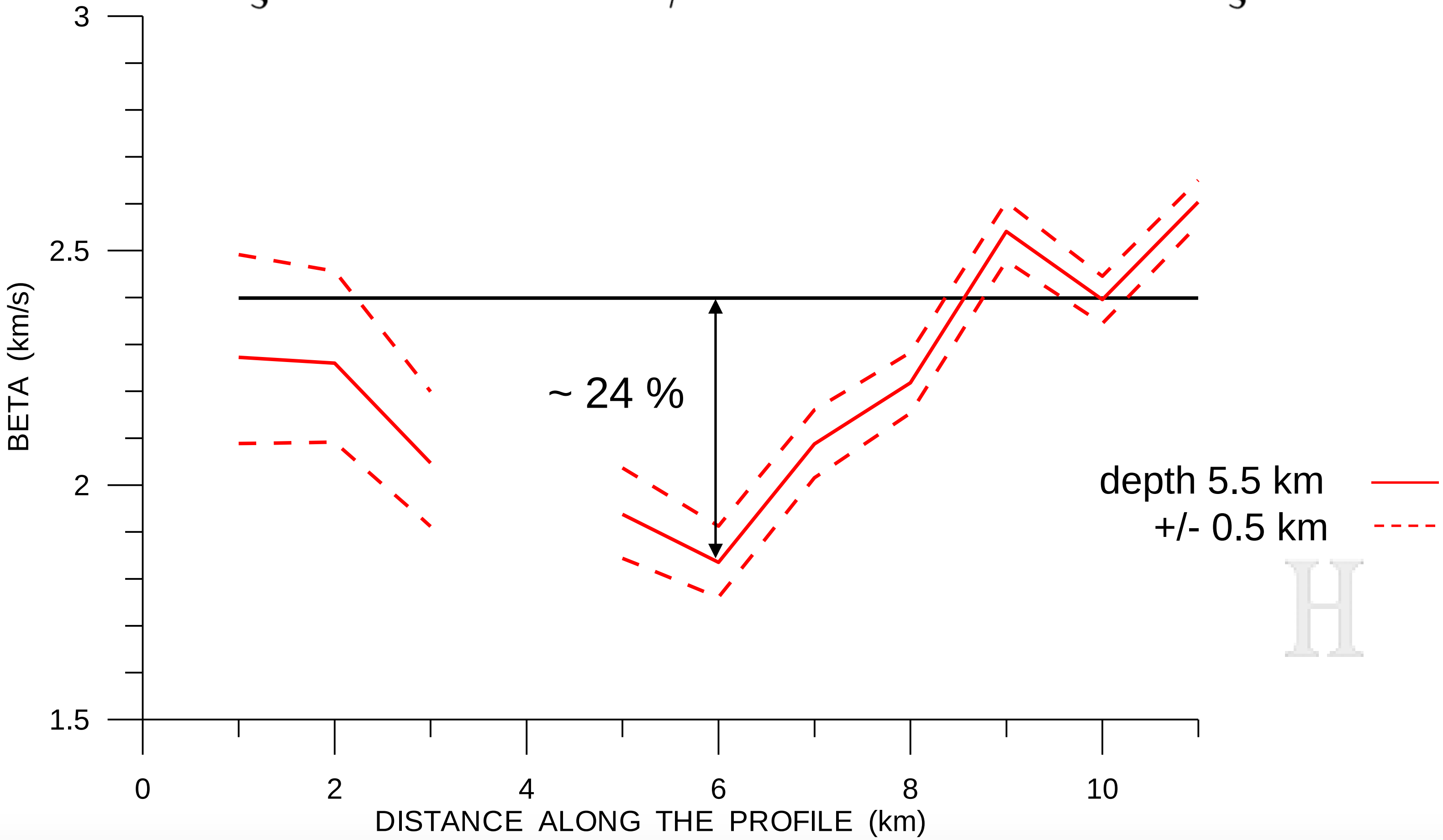


Ω_η

~10^{-5} rad/s

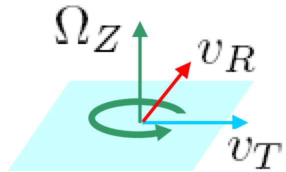
RAY SOLUTION – Vertically inhomogeneous model

$$\Omega_\eta = -\frac{\partial v_z}{\partial \xi} = \frac{\xi}{r^2} v_z + \frac{\xi}{\beta r} \dot{v}_z - v_z \bar{V}_z^{-1} \frac{\partial \bar{V}_z}{\partial \xi}$$



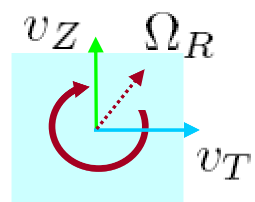
How to quantify the importance of rotation versus translation:
- we use '**rotation to translation ratio**' (RTR) expressed in rad/m.
In our case it relates maximum rotation rate amplitude to maximum translational velocity amplitude **in a given coordinate plane**.

Z-axis RTR
(motion in R-T plane)



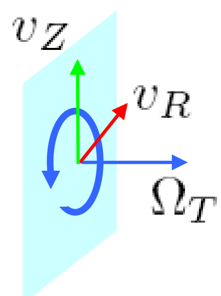
$$|\Omega_Z|/\sqrt{v_R^2 + v_T^2}$$

R-axis RTR
(motion in Z-T plane)



$$|\Omega_R|/\sqrt{v_T^2 + v_Z^2}$$

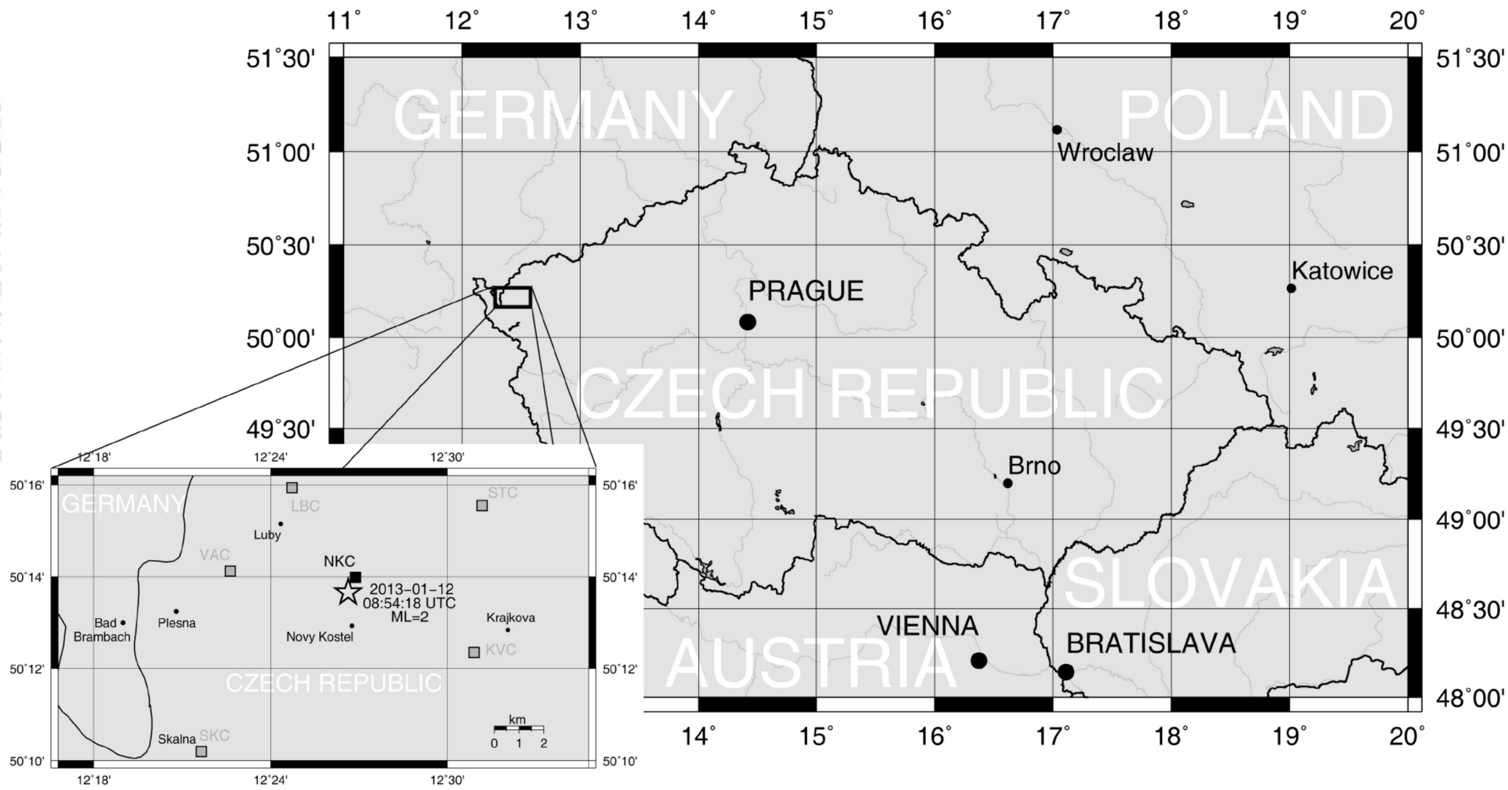
T-axis RTR
(motion in Z-R plane)



$$|\Omega_T|/\sqrt{v_R^2 + v_Z^2}$$

RTR depends on **frequency**, hypocentral distance, source type, radiation pattern, structure along the wavepath, local structure …
(systematic investigation of many records is necessarry)

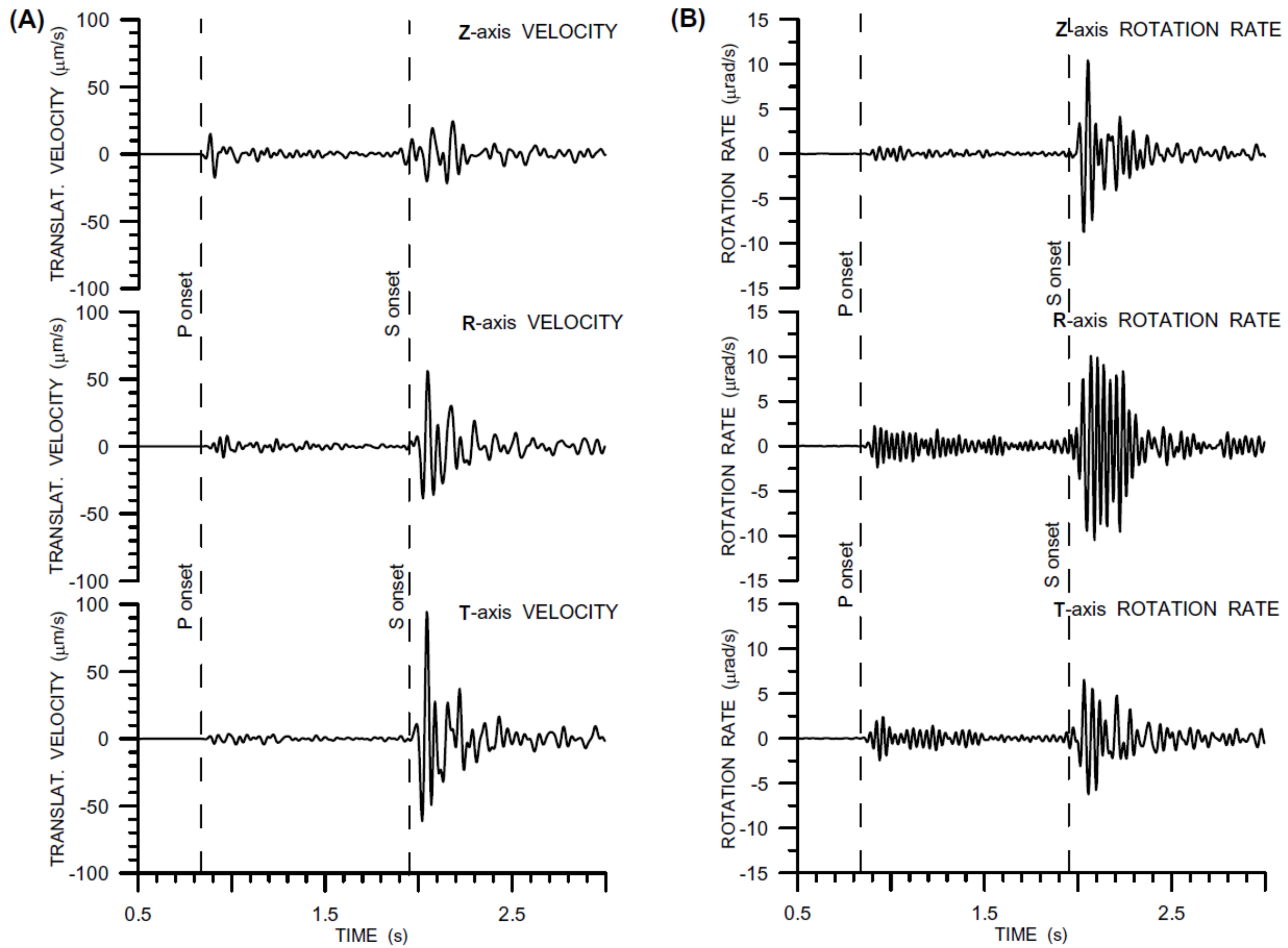
Rotaphone at Nový Kostel station (West Bohemia seismic network WEBNET)
2013-01-12 08:54:18 UTC; ML 2.0
Distance from the station **675 m**, depth **9.2 km**, BAZ 205º from North



Intraplate geodynamically active region known
for recurrent earthquake swarm activity, CO_2 emissions,
mineral springs and other post-volcanic events.

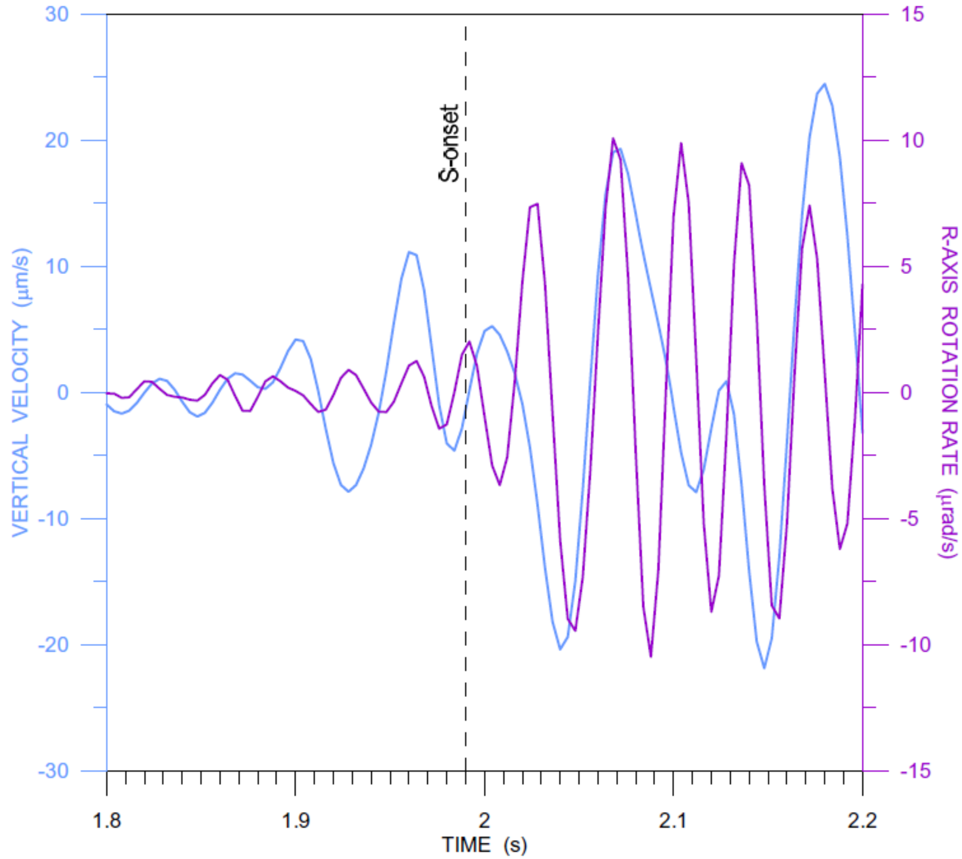
6DOF Seismic Records in epicentral regions of shallow micro-earthquakes

Rotaphone at NKC station (West Bohemia seismic network WEBNET)
2013-01-12 08:54:18 UTC; ML 2.0; dist. **0.7 km**, depth **9.2 km**, BAZ 205º



Rotation to translation relations

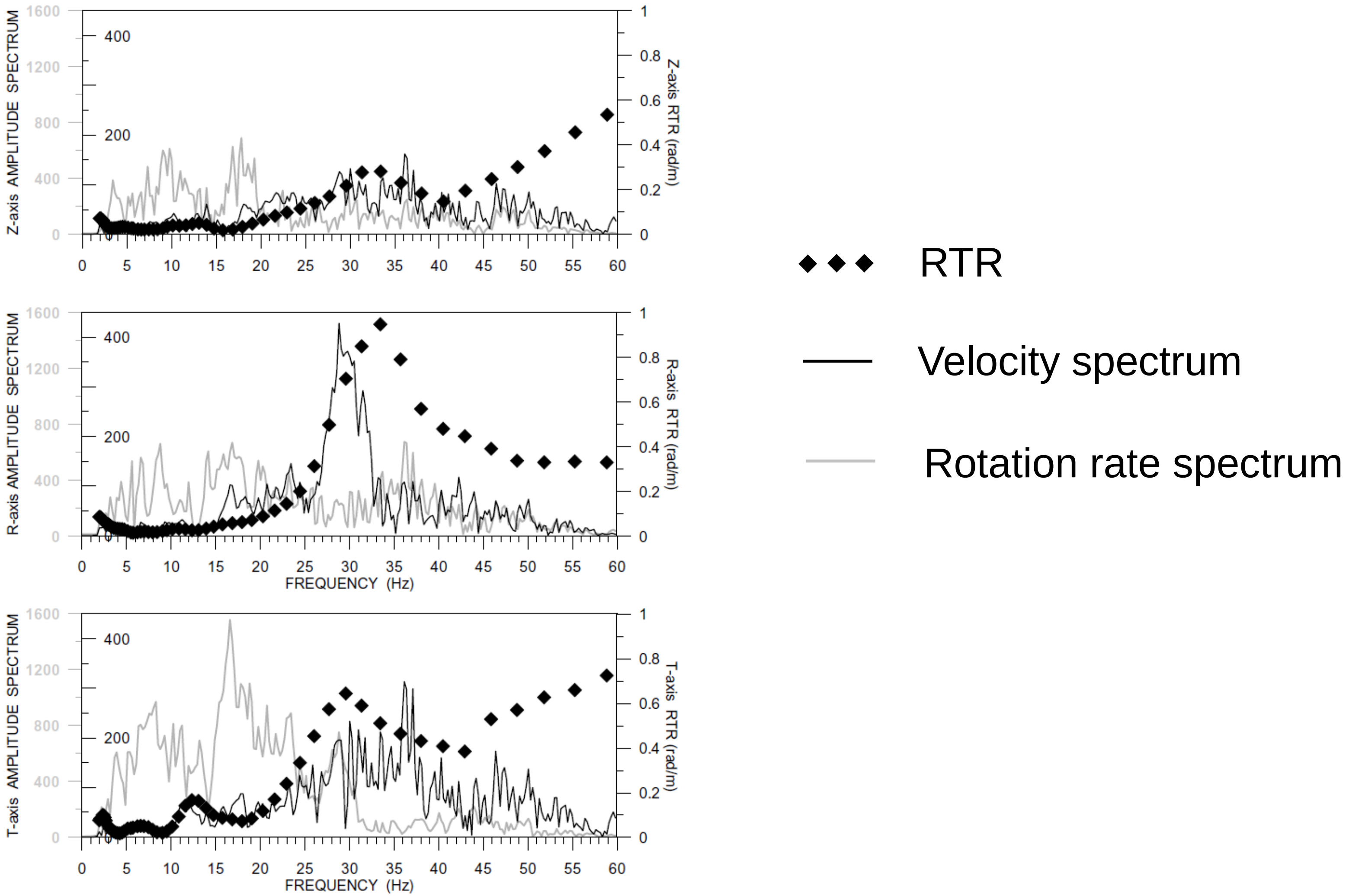
$$\Omega_\xi = \frac{\partial v_z}{\partial \eta} = v_z \bar{V}_z^{-1} \frac{\partial \bar{V}_z}{\partial \eta},$$



UNCORRELATED ! The method of retrieving β is inapplicable

6DOF Seismic Records in epicentral regions of shallow micro-earthquakes

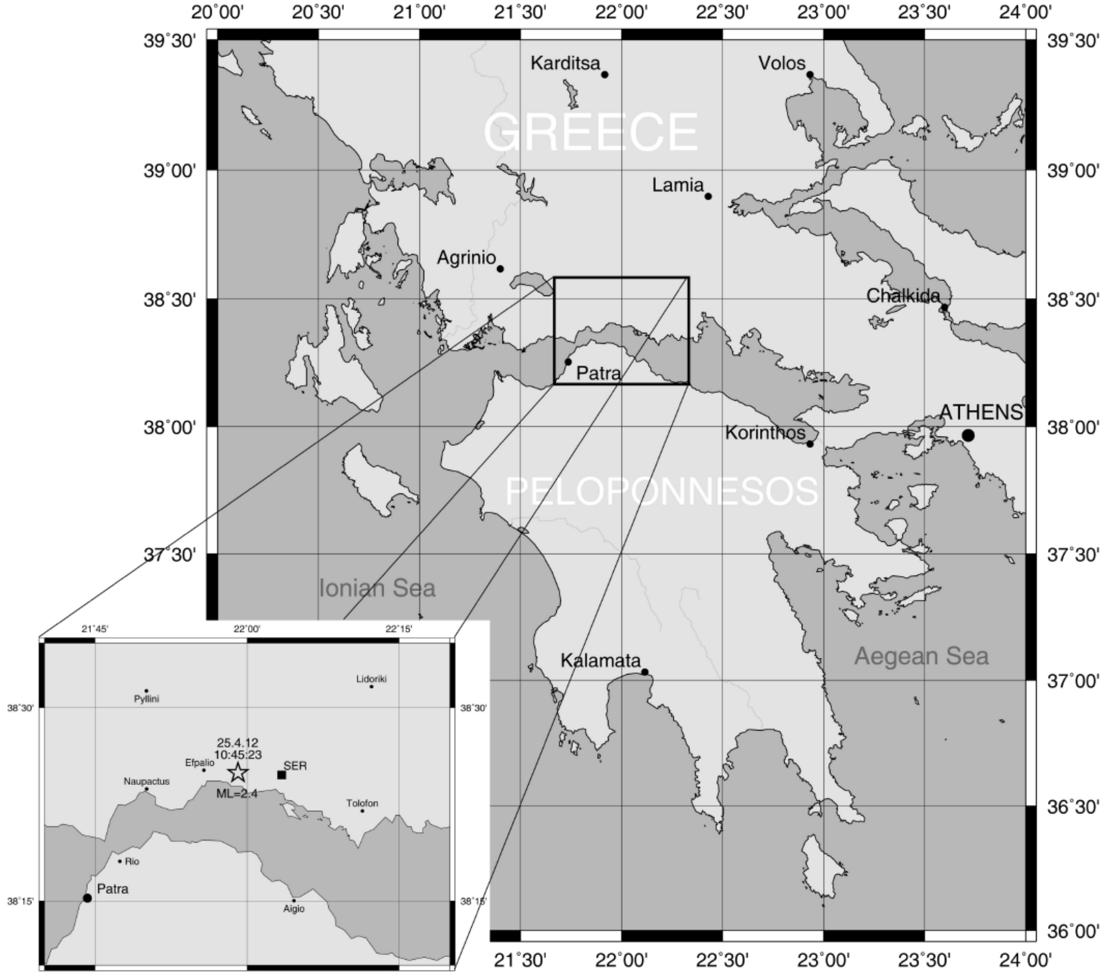
Rotaphone at NKC station (West Bohemia seismic network WEBNET)
2013-01-12 08:54:18 UTC; ML 2.0; dist. **0.7 km**, depth **9.2 km**, BAZ 205º



Rotaphone at Sergoula station (Western Greece seismic network PSLNET)

2012-04-25 10:45:22 UTC; ML 2.4

Distance from the station **6.3 km**, depth **10.4 km**, BAZ 273º from North

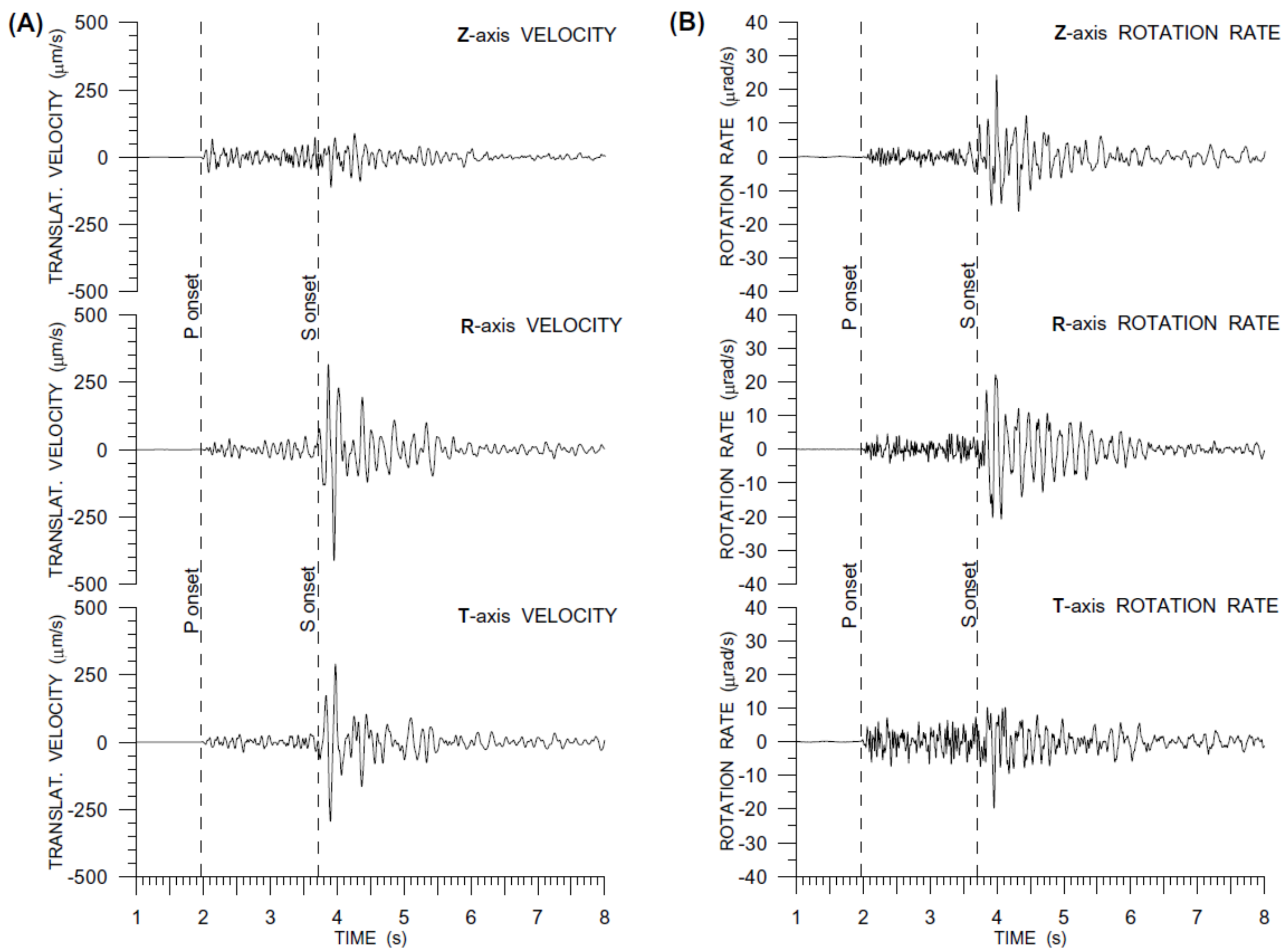


A well-known active rift
opening at a rate of 1.5 cm/year
with a complex seismogenic fault system.

6DOF Seismic Records in epicentral regions of shallow micro-earthquakes

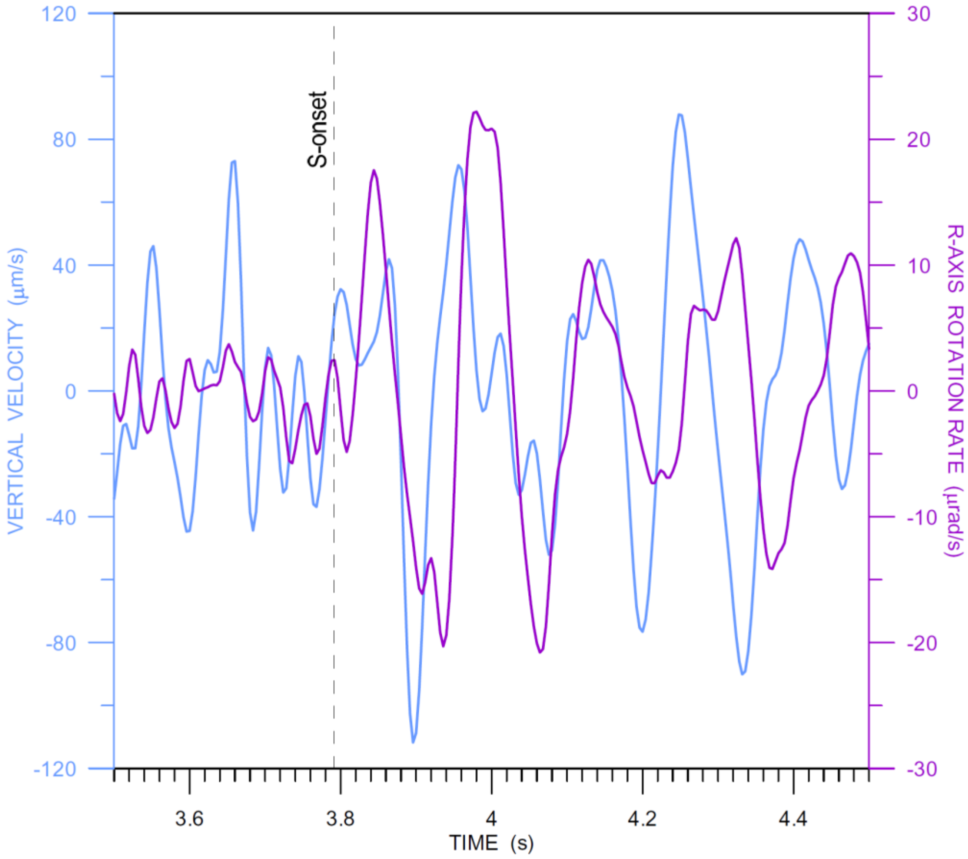
Rotaphone at Sergoula station (Western Greece seismic network PSLNET)

2012-04-25 10:45:22 UTC; ML 2.4; dist **6.3 km**, depth **10.4 km**, BAZ 273º



Rotation to translation relations

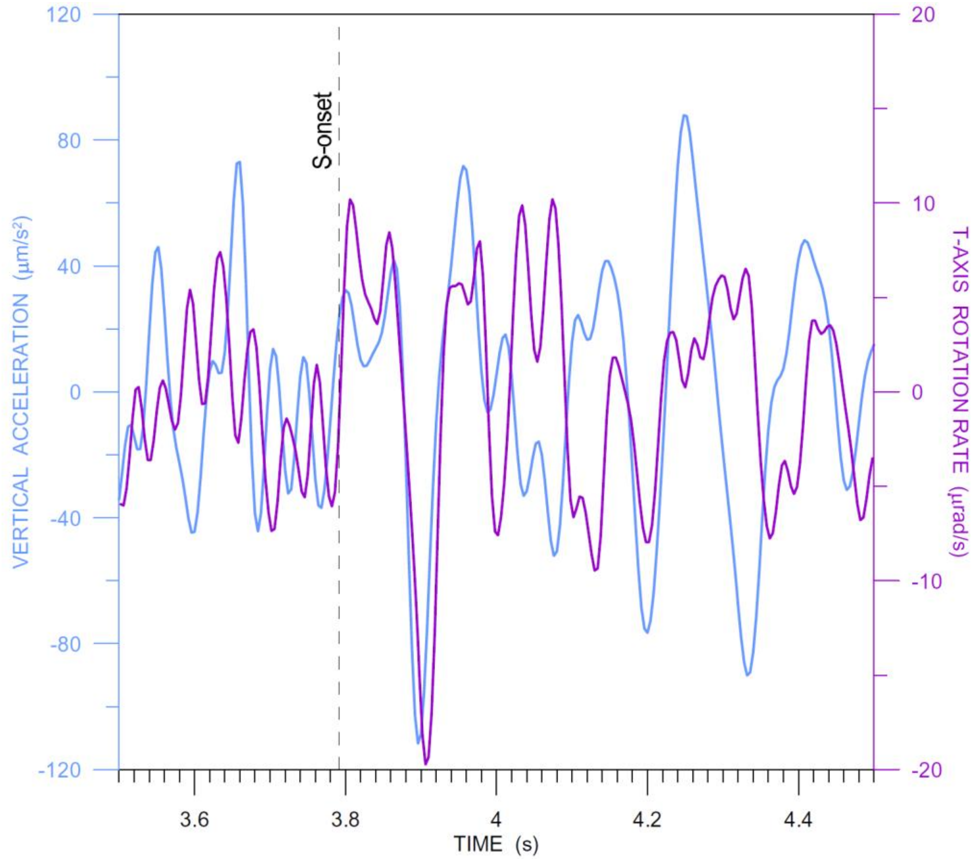
$$\Omega_\xi = \frac{\partial v_z}{\partial \eta} = v_z \bar{V}_z^{-1} \frac{\partial \bar{V}_z}{\partial \eta},$$



CORRELATION NOT GOOD! The applicability of retrieving β is questionable

Rotation to translation relations

$$\Omega_\eta = -\frac{\partial v_z}{\partial \xi} = \frac{\xi}{r^2} v_z + \frac{\xi}{\beta r} \dot{v}_z - v_z \bar{V}_z^{-1} \frac{\partial \bar{V}_z}{\partial \xi}$$



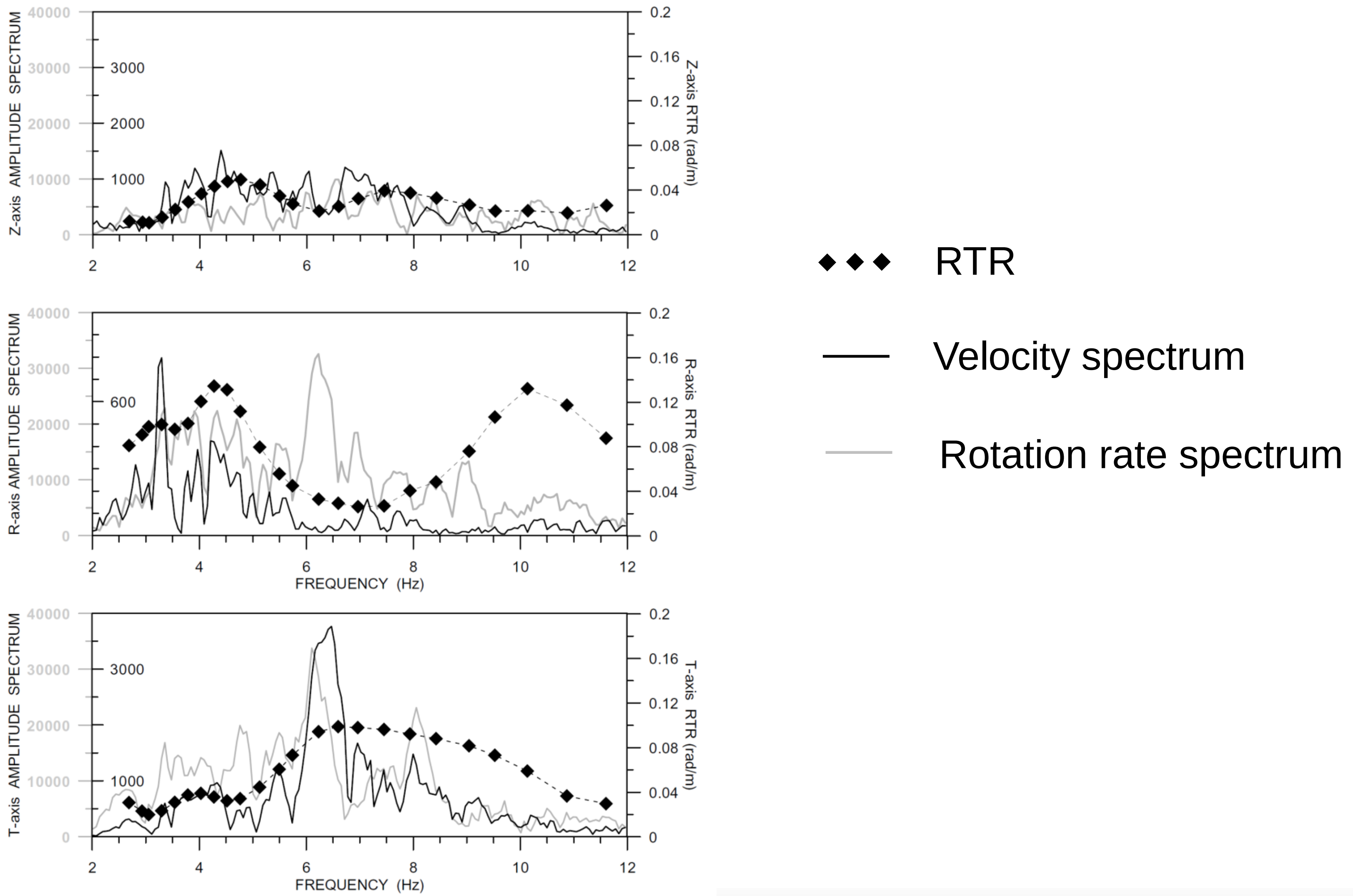
β ~ 700 m/s

CORRELATION NOT GOOD! The applicability of retrieving β is questionable

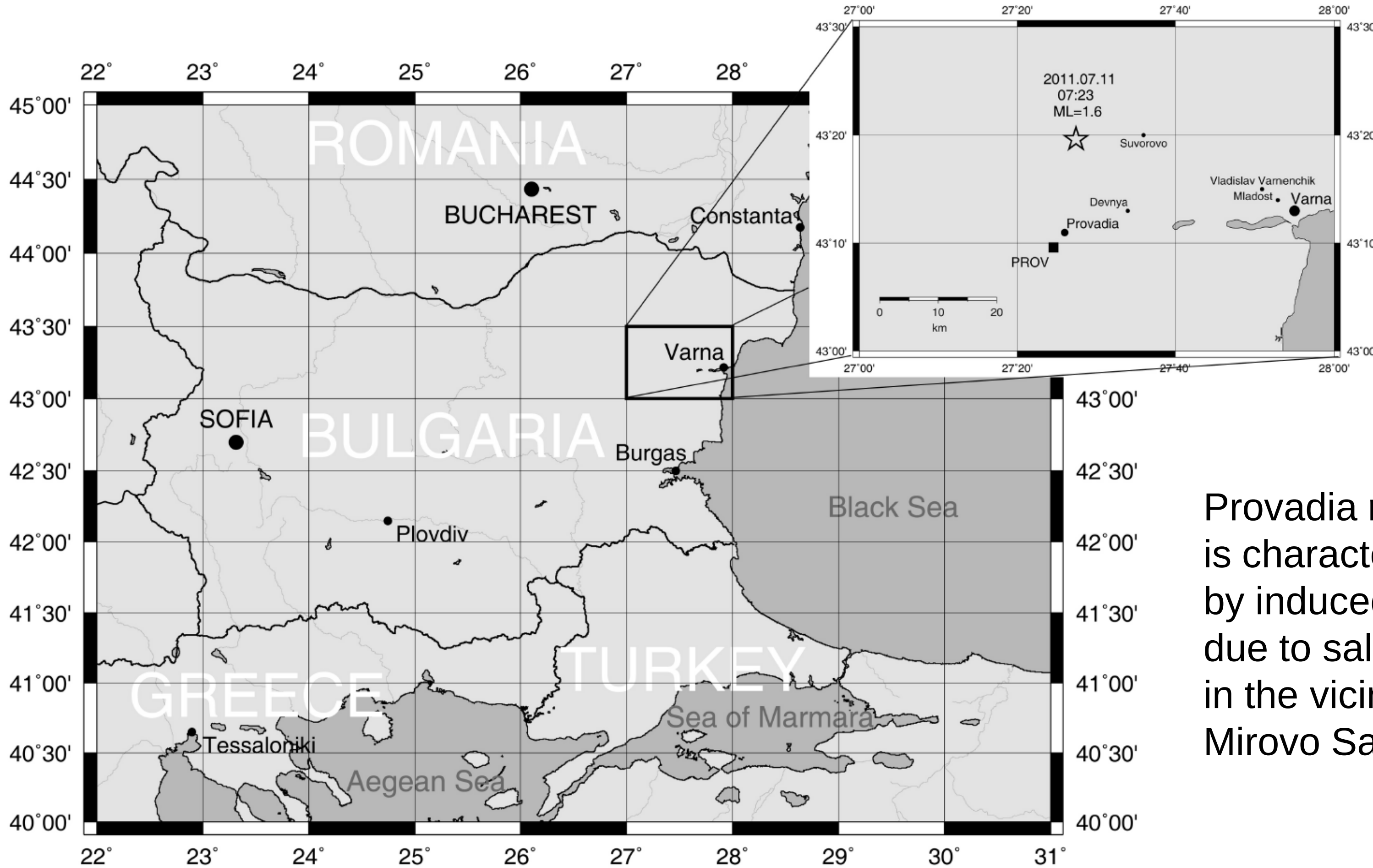
6DOF Seismic Records in epicentral regions of shallow micro-earthquakes

Rotaphone at Sergoula station (Western Greece seismic network PSLNET)

2012-04-25 10:45:22 UTC; ML 2.4; dist **6.3 km**, depth **10.4 km**, BAZ 273º



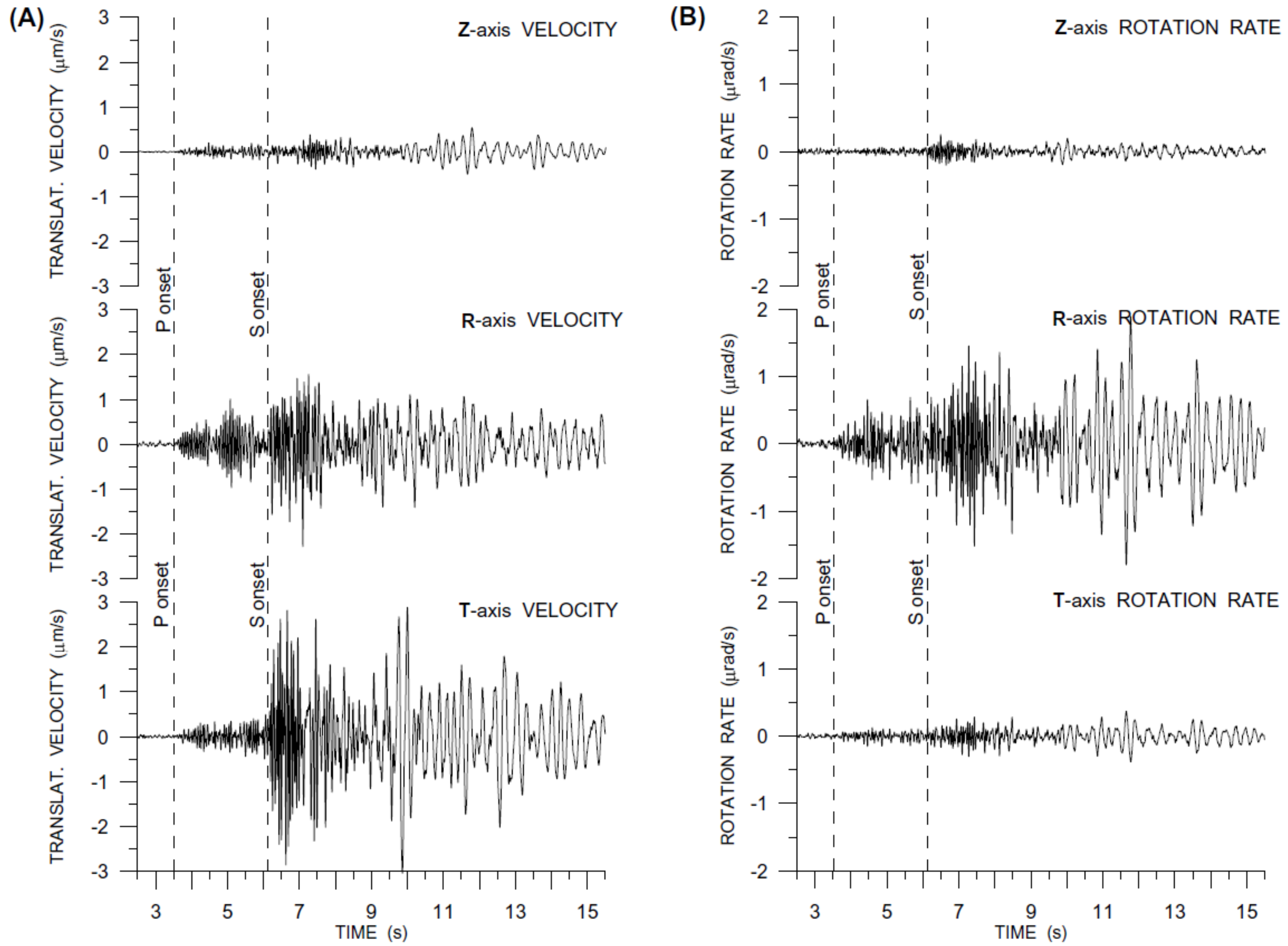
Rotaphone at Provadia station (Eastern Bulgaria, Provadia local seismic network)
2011-07-11 07:22:47 UTC; ML 1.6
Distance from the station **18.9 km**, depth **2 km**, BAZ 11º from North



Provadia region
is characterized
by induced seismicity
due to salt-works
in the vicinity of the
Mirovo Salt Dome

6DOF Seismic Records in epicentral regions of shallow micro-earthquakes

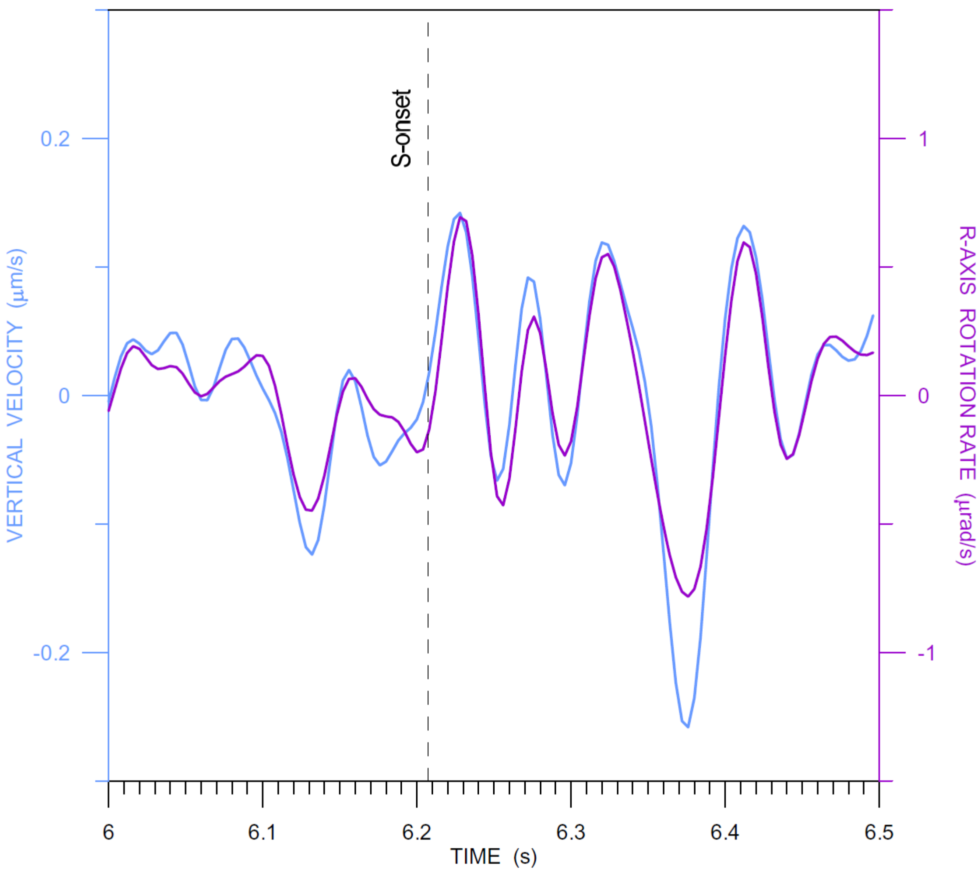
Rotaphone at Provadia station (Eastern Bulgaria, Provadia local seismic network)
2011-07-11 07:22:47 UTC; ML 1.6; dist.**18.9 km**, depth **2 km**, BAZ 11º



Rotation to translation relations

$$\Omega_\xi = \frac{\partial v_z}{\partial \eta} = v_z \bar{V}_z^{-1} \frac{\partial \bar{V}_z}{\partial \eta},$$

β ~ 1000 m/s



6DOF Seismic Records in epicentral regions of shallow micro-earthquakes

Rotaphone at Provadia station (Eastern Bulgaria, Provadia local seismic network)
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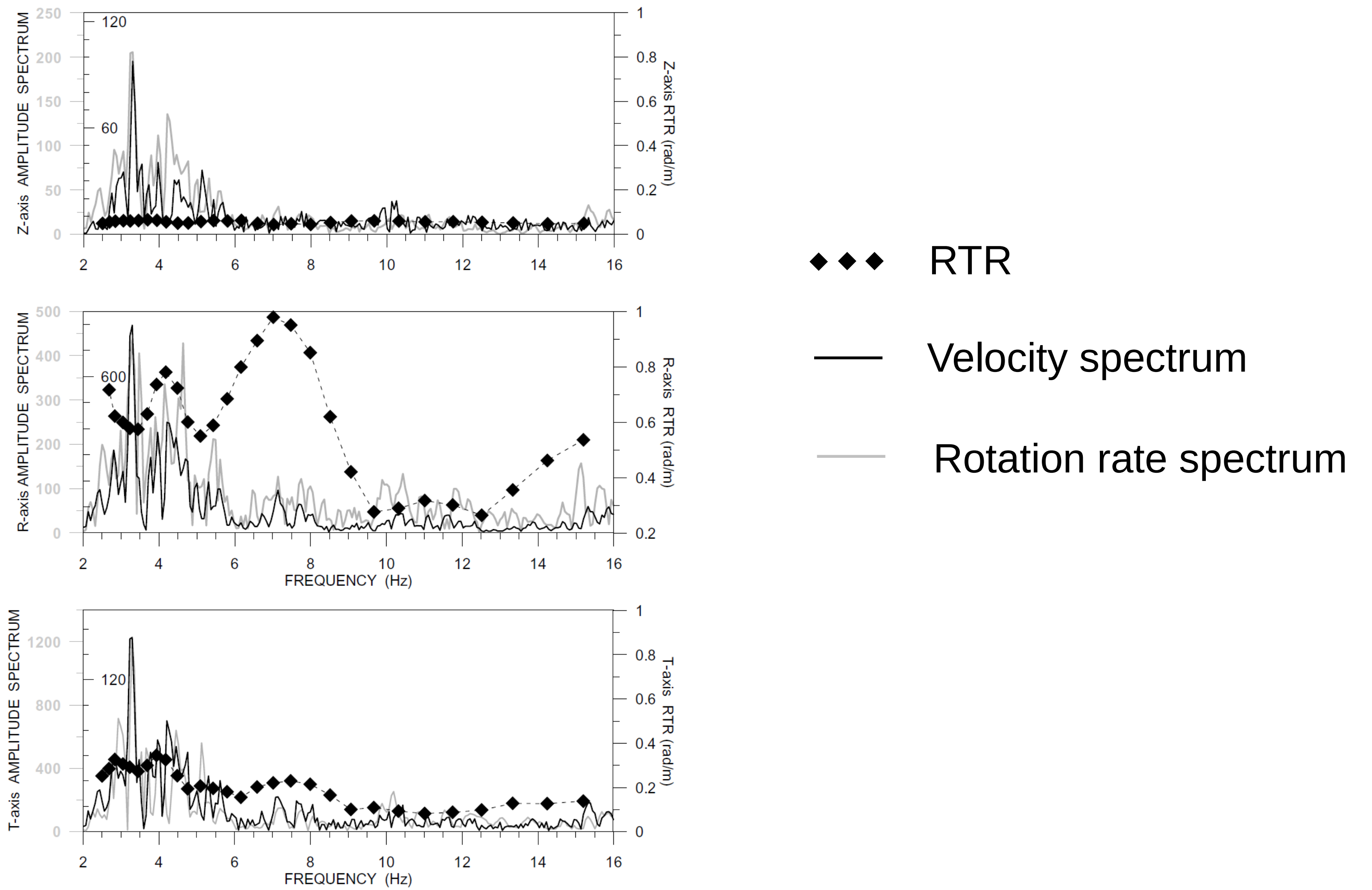
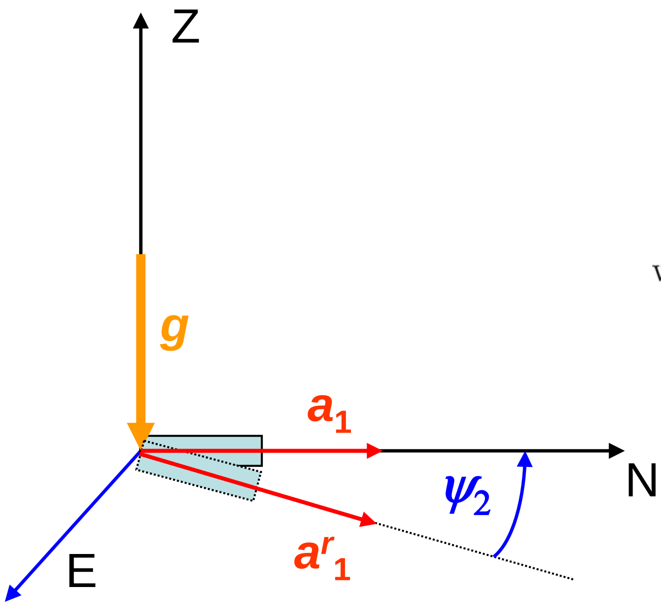


Do tilts contaminate significantly horizontal translational components ?

(the problem discussed, e.g., by Graizer 2005)



Ψ_2 … E-axis tilt

g … gravitational acc.
a₁ … true horizontal acc.
a^{r}₁ … recorded 'horizontal' acc.

Correction for N-component:

acceleration $a_1^r = a_1 - g \sin\phi_2 \approx a_1 - g\phi_2$ for small ϕ_2 $(\ll 1)$

velocity $v_1^r \approx v_1 - g\int \phi_2 \mathrm{d}t; \quad v_1 = \int a_1 \mathrm{d}t$

we measure $\Omega_2 = \dot{\phi}_2$, so

$$v_1 \approx v_1^r + g \iint \Omega_2 \mathrm{d}t^2$$

(in frequency domain) …$\sim 9.81/(i\omega)^2$ x RTR

This correction is **NEGLIGIBLE** in our frequency range (above 2 Hz) and for the RTRs recorded up to now (mostly <1)

CONCLUSIONS

- We have developed a 6DOF seismic sensor suitable for field measurements (small size, portability, easy installation and operation)
- Presented prototype is designed to record both weak and strong motions (10^{-7} – 10^{-1} rad/s) in the high frequency range 2 Hz – 60 Hz
- High accuracy is achieved by the use of our in-situ calibration technique (based on multivaluedness of rotation rate data)
- Rotation rate records from local events are extremely variable in overall appearance, namely depending on the source type (anthropogenic/tectonic) and distance.
- Three examples of 6DOF records from shallow micro-earthquakes in different seismically active areas were presented (ML 1.6 - 2.4, dist 0.7 -19 km, velocities 10^{-4} – 10^{-6} m/s, rot. rates 10^{-5} – 10^{-6} rad/s)
- We have investigated the rotation to translation relations for small epicentral distances both on synthetic and measured data; application to real seismograms of local shallow earthquakes will be systematically studied in future
- We define the RTR as the frequency dependent ratio between max. amplitude of the corresponding rotation and translation components; above 2 Hz we have mostly found RTR ~ 10^{-1} (rad/m)
- Under such conditions it is not necessary to correct horizontal translational velocity components for the influence of tilts

THANK YOU FOR YOUR ATTENTION

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