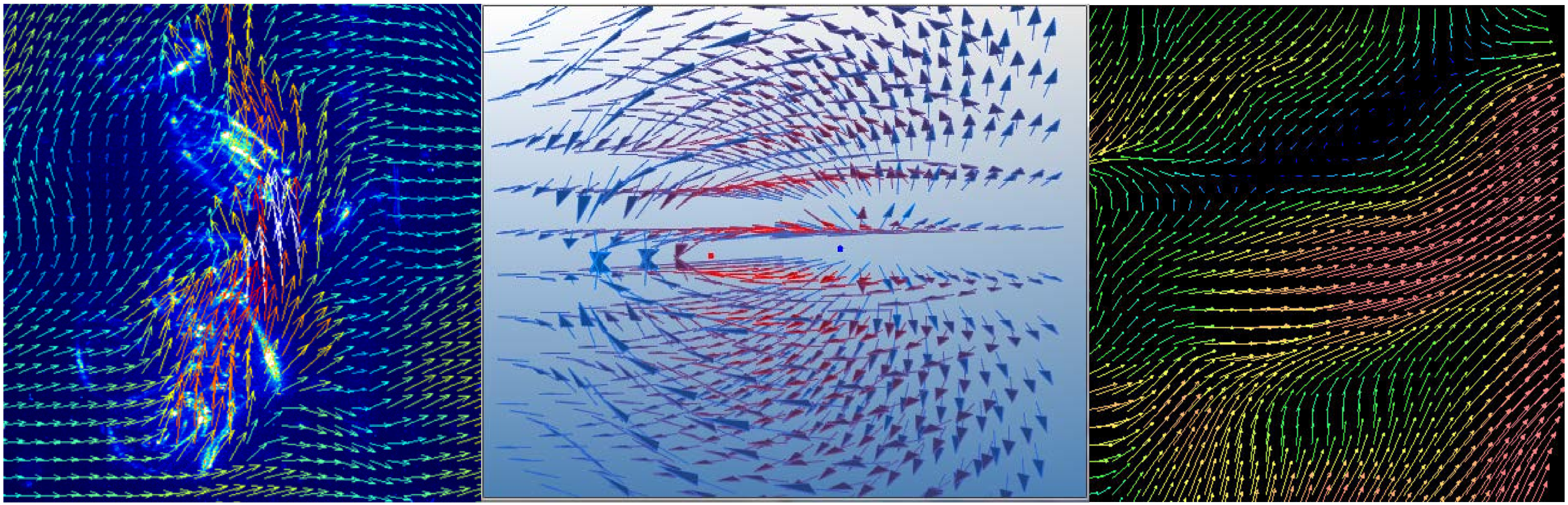
Introduction to rotational seismology



Examples of wave fields with curl – images from internet sources

Johana Brokešová
Charles University in Prague

Advanced Course of Seismology,
University of Arba Minch, Nov 2015

CZECH REPUBLIC
DEVELOPMENT COOPERATION
aquatest

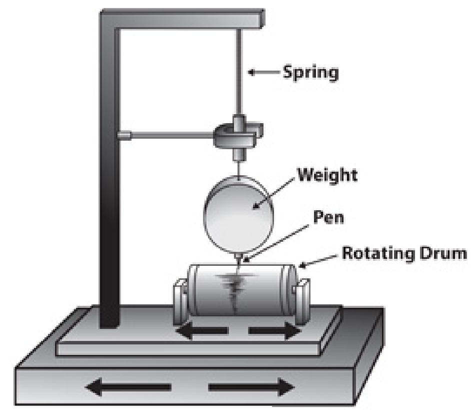
What is rotational seismology?

It is an emerging seismological discipline studying all aspects of rotational ground motions induced by earthquakes, explosions, and ambient vibrations.

International Working Group on Rotational Seismology (IWGORS) has been established to promote investigations of rotational motions in seismology and their implications for related fields such as, earthquake engineering, geodesy, strong-motion seismology, tectonics, etc.

Anyone can become a member, join to share ideas, data and software in an open web-based environment
http://www.rotational-seismology.org/

Classical seismograph



Definition of basic terms:

TRANSLATIONAL COMPONENTS

$$\mathbf{u}(\mathbf{x})$$

$$u_1, u_2, u_3$$

ROTATIONAL COMPONENTS

$$w_1 = \frac{1}{2}(u_{3,2} - u_{2,3}) = \frac{1}{2}(\nabla \times \mathbf{u})_1$$

$$w_2 = \frac{1}{2}(u_{1,3} - u_{3,1}) = \frac{1}{2}(\nabla \times \mathbf{u})_2$$

$$w_3 = \frac{1}{2}(u_{2,1} - u_{1,2}) = \frac{1}{2}(\nabla \times \mathbf{u})_3$$

Seismic medium is considered as elastic continuum characterized by the Hook's law

$$\tau_{ij} = \lambda\delta_{ij}u_{k,k} + \mu(u_{i,j} + u_{j,i})$$

At the Earth's surface (free of stress)

$$\left.\begin{array}{l}\tau_{31} = \mu(u_{3,1} + u_{1,3}) = 0 \\ \tau_{32} = \mu(u_{3,2} + u_{2,3}) = 0\end{array}\right\} \Rightarrow \left\{\begin{array}{lllll} w_1 & = & -\dfrac{\partial u_2}{\partial x_3} & = & \dfrac{\partial u_3}{\partial x_2} \\ w_2 & = & \dfrac{\partial u_1}{\partial x_3} & = & -\dfrac{\partial u_3}{\partial x_1}\end{array}\right.$$

$$\tau_{33} = \lambda(u_{1,1} + u_{2,2}) + (\lambda + 2\mu)u_{3,3} = 0$$

$$w_3 = \frac{1}{2}\left(\frac{\partial u_2}{\partial x_2} - \frac{\partial u_1}{\partial x_2}\right)$$

Ground Particle Motions have 6 Degrees of Freedom

A thorough understanding of the seismic wave field at a point requires the measurement of 3 components of vector displacement **u** or velocity **v** and 3 components of rotation ***w*** or rotation rate **Ω**.

$$\mathbf{v}(\mathbf{x}) = \dot{\mathbf{u}}(\mathbf{x})$$

TRANSLATIONAL COMPONE

v_1, v_2, v_3

ROTATIONAL COMPONENTS

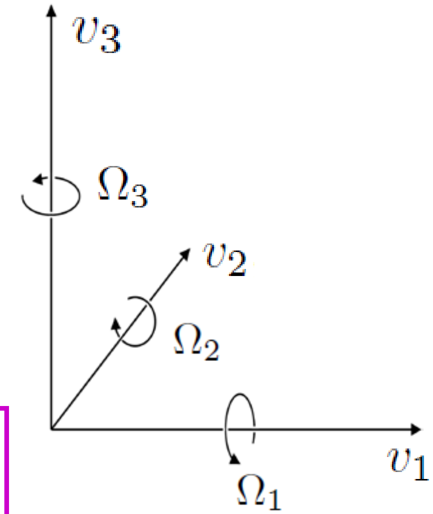
tilts

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

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

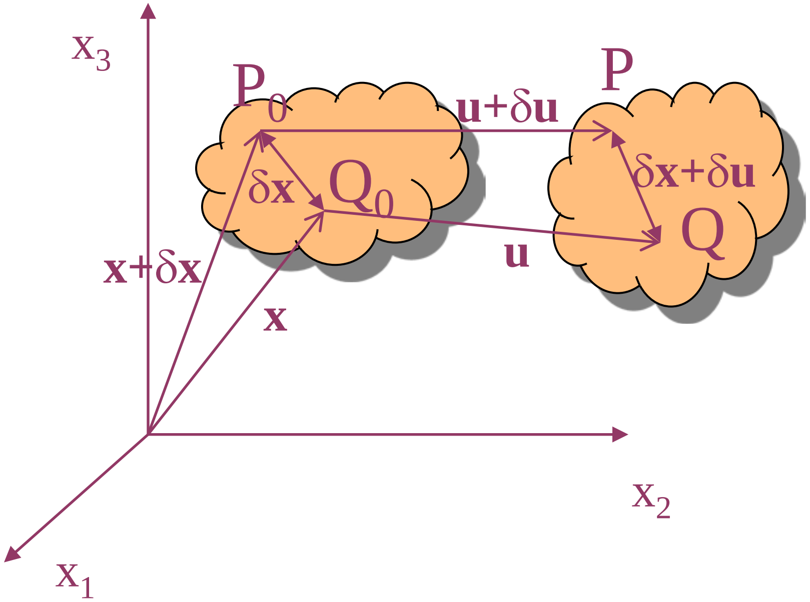
torsion

$$\Omega_3 = \frac{1}{2}\left(\frac{\partial v_1}{\partial x_2} - \frac{\partial v_2}{\partial x_1}\right)$$



Where do the rotational components come from?

Deformation of a continuum

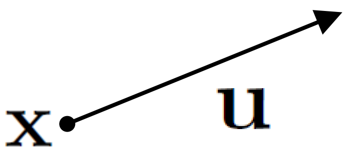


P_0, Q_0 … undeformed medium

P, Q ….. deformed medium

$$u_i(\mathbf{x}+\delta\mathbf{x}) = u_i(\mathbf{x}) + \frac{\partial u_i(\mathbf{x})}{\partial x_j}\delta x_j + O\left(\frac{\partial \mathbf{u}}{\partial \mathbf{x}}\right)^2$$

Where do the rotational components come from?



$$\mathbf{u}(\mathbf{x}), \quad u_i(\mathbf{x} + \delta\mathbf{x}) \approx u_i(\mathbf{x}) + \frac{\partial u_i(\mathbf{x})}{\partial x_j}\delta x_j$$

Displacement derivatives represent a second-rank tensor resolvable into **symmetric** and **anti-symmetric** parts:

$$u_{i,j} = \frac{1}{2}(u_{i,j} + u_{j,i}) + \frac{1}{2}(u_{i,j} - u_{j,i})$$

(small) **strain** tensor → ϵ_{ij}

(small) **rotation** tensor → ω_{ij}

anti-symmetric rotation tensor has three independent components w_1, w_2, w_3

$$\omega_{ij} = \begin{pmatrix} 0 & -w_3 & w_2 \\ w_3 & 0 & -w_1 \\ -w_2 & w_1 & 0 \end{pmatrix}$$

$$w_1 = \omega_{23} = \frac{1}{2}(u_{2,3} - u_{3,2}) = -\frac{1}{2}(\nabla \times \mathbf{u})_1$$

$$w_2 = \omega_{13} = \frac{1}{2}(u_{3,1} - u_{1,3}) = -\frac{1}{2}(\nabla \times \mathbf{u})_2$$

$$w_3 = \omega_{21} = \frac{1}{2}(u_{1,2} - u_{2,1}) = -\frac{1}{2}(\nabla \times \mathbf{u})_3$$

In the classical elasticity theory, rotation appears as the curl of the displacement field

$$\mathbf{w} = \begin{pmatrix} w_1 \\ w_2 \\ w_3 \end{pmatrix} = -\frac{1}{2}\nabla \times \mathbf{u} \quad \ldots \text{ infinitisemal rotation vector}$$

$$|\mathbf{w}| = \frac{1}{2}|\nabla \times \mathbf{u}| \ldots \quad \text{small rotation angle about axis } \parallel \text{ to } \mathbf{w}$$

Until a few past decades …

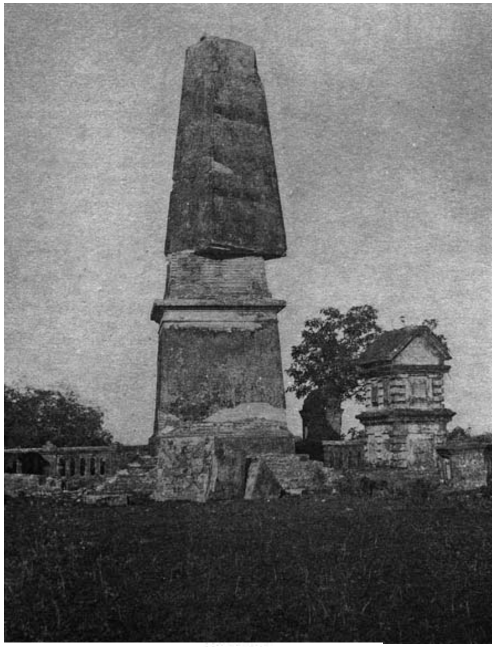
Seismic rotational motions were not measured because of lack of sufficiently sensitive instruments for their detection.

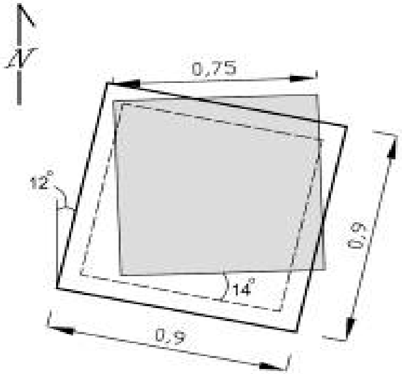
At present, seismic rotations are currently measured at teleseismic, regional and local distances (various methods are discussed in this course). Rotational database is being created (http://www.rotational-seismology.org/).

It was also believed that these motions have only a little importance both in theory and in seismological practice.

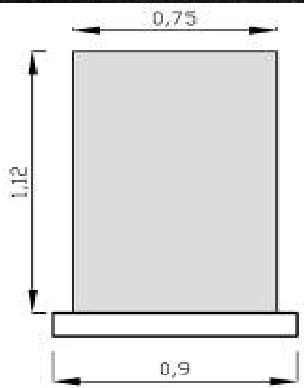
The rotational data are analyzed and interpreted with regard to the relationship between the rotational and the translational components. They contain information on the geological structure as well as the seismic source. Engineering applications are intensively studied.

Can these examples be evidence od strong torsional ground motions capable of serious damages?





Plan view



Cross section

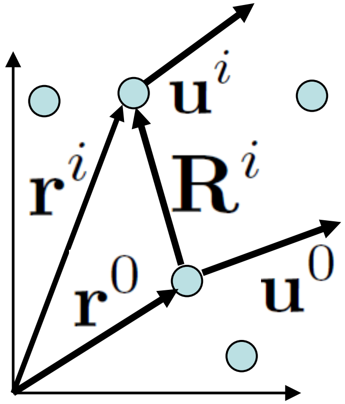
No, all of them can be explained without seismic torsion, but these finding played an important “historical” role and evoked an interest in measuring of seismic rotations.

BASIC METHODOLOGIES OF SEISMIC ROTATIONAL MEASUREMENTS

1. **Small-aperture arrays** measuring differential motions (finite spatial derivatives) – indirect measurement, array derived rotations (ADR method)

2. **Ring laser gyrospopes** utilizing the Sagnac effect – direct measurement

3. **Small portable rotational sensors** – both direct and indirect measurements



ARRAY-DERIVED ROTATIONS

(ADR method)

$$\mathbf{r}^i = (x_1^i, x_2^i, 0)^T \qquad i = 0, 1, \ldots, N$$
$$\mathbf{u}^i = (u_1^i, u_2^i, u_3^i)^T$$
$$\mathbf{R}^i = \mathbf{r}^i - \mathbf{r}^0 \qquad \mathbf{d}^i = \mathbf{u}^i - \mathbf{u}^0$$

(podle Spudich et al., JGR, 1995)

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

BASIC ASSUMPTION: uniform spatial gradients over the array !!!

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

Minimum number of stations: 3

ADR – example (Brokesova & Malek, 2015)

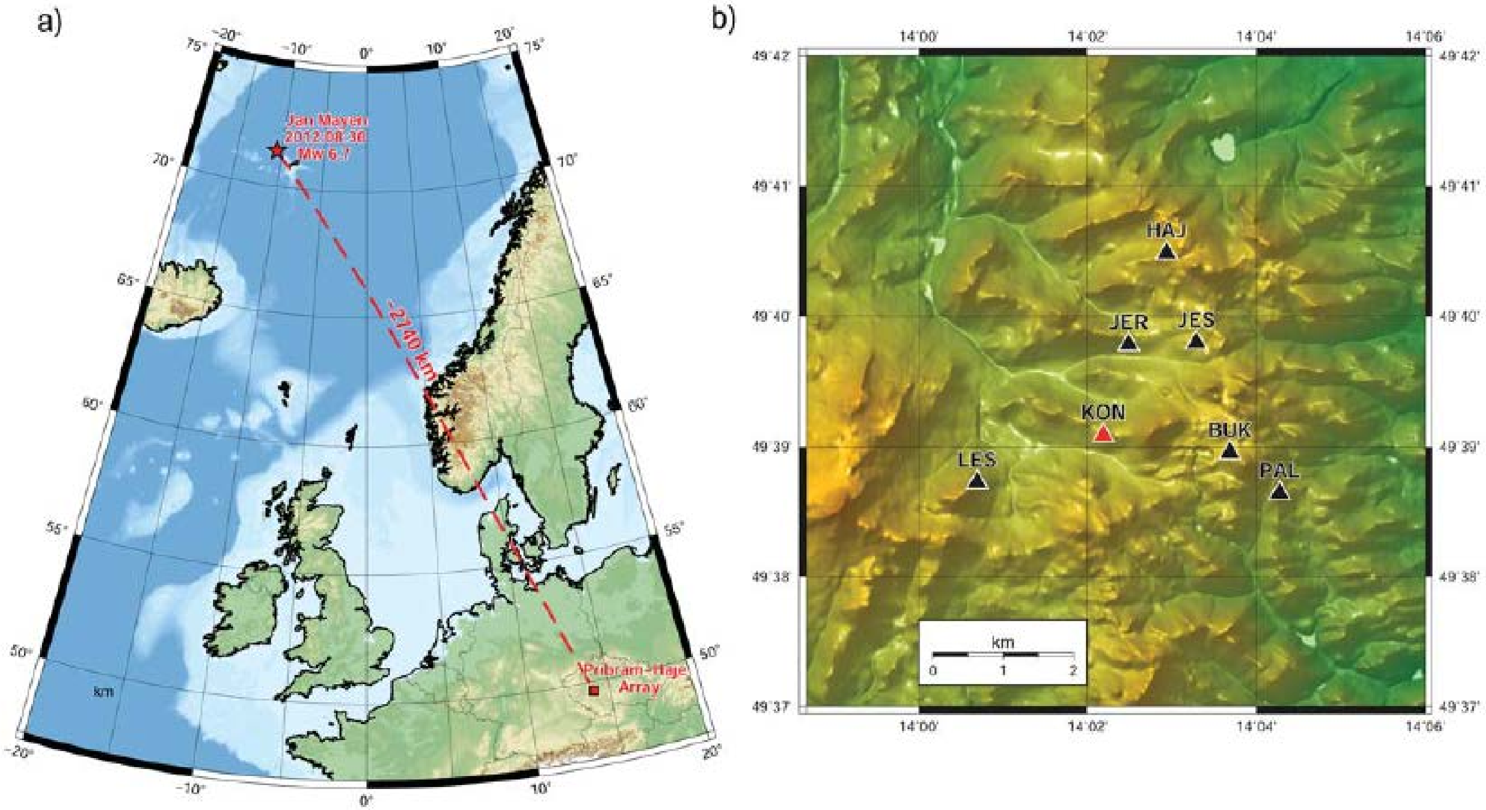
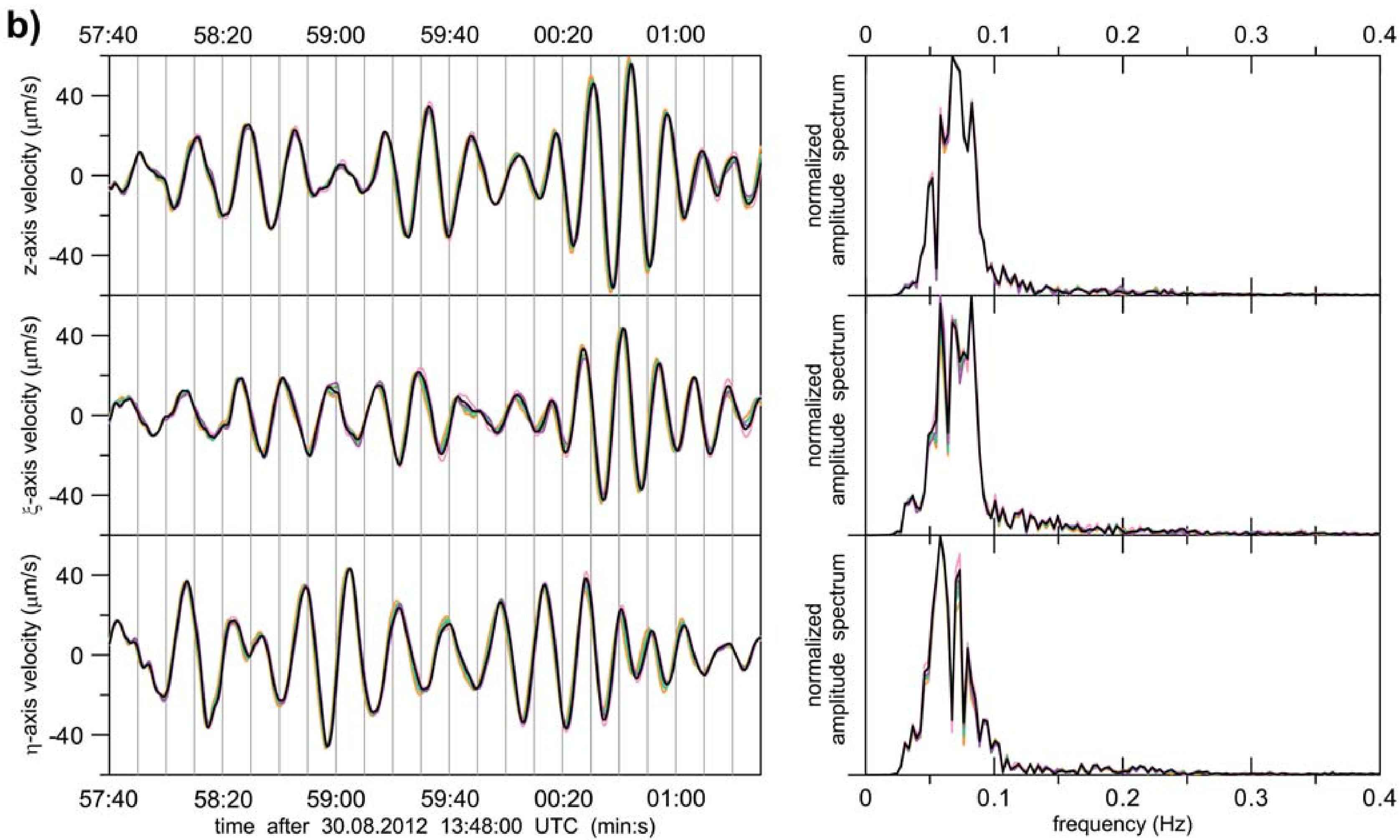


Figure 1. (a) Epicenter of the Jan Mayen earthquake, Mw 6.7, 30 August 2012 (red star) and the location of the Příbram-Háje array (red square). (b) a map of the Příbram-Háje array area in geographic coordinates. Station positions shown as triangles. The red filled triangle denotes the KON station which serves as a reference in this study.

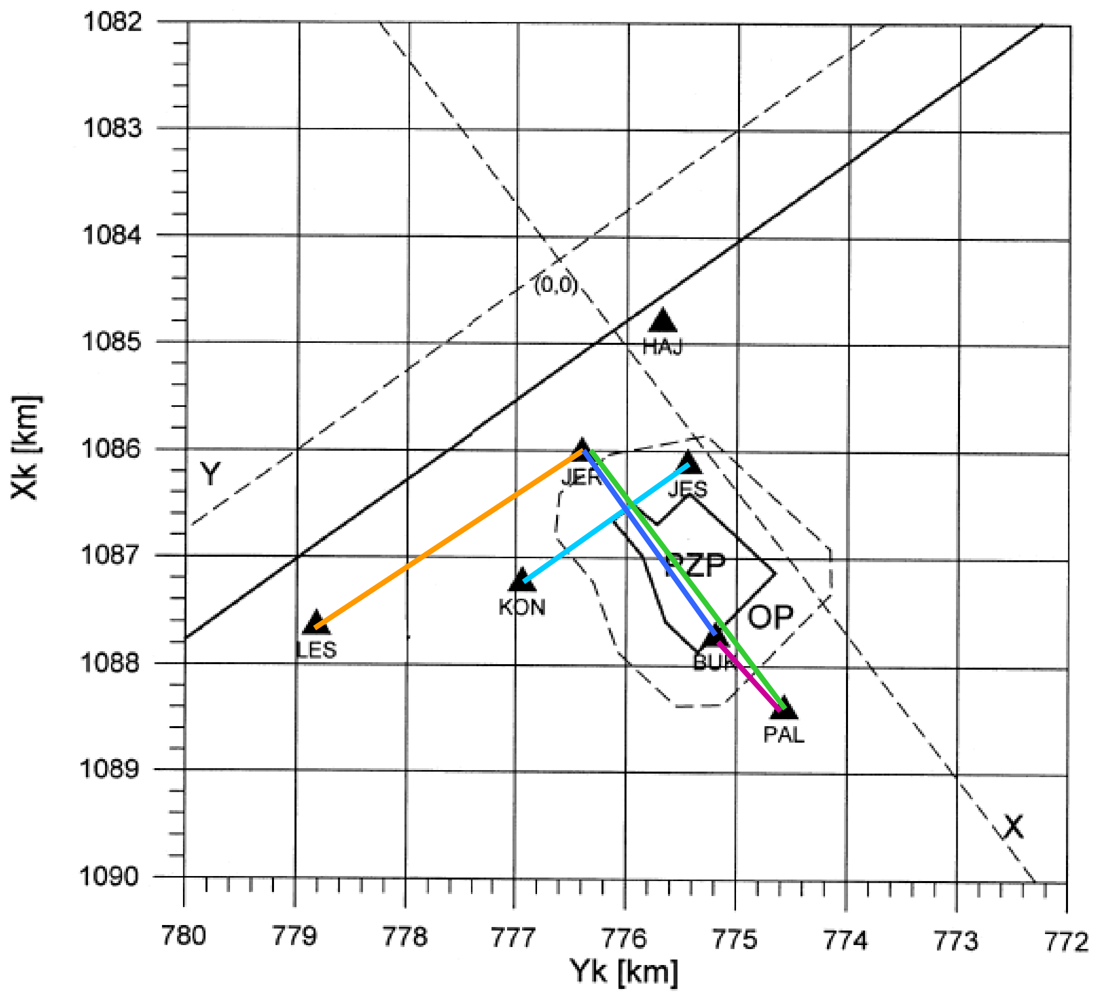
ADR – example (Brokesova & Malek, 2015)

Surface waves



ADR – example (Brokesova & Malek, 2015) …. Basic assumption test

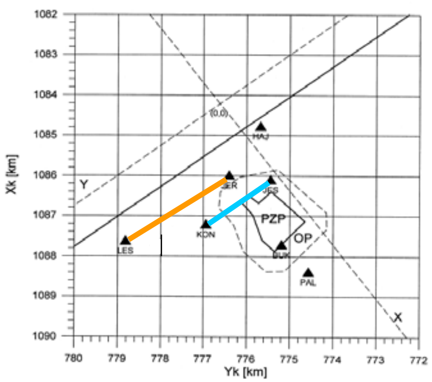
1st-order spatial gradients roughly approximated by finite differences

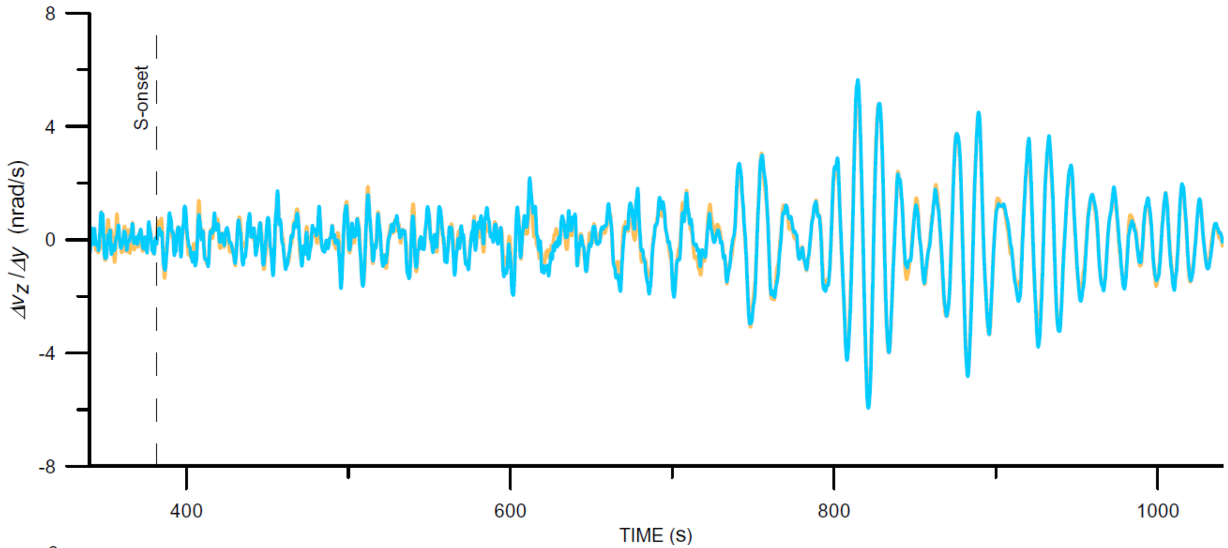


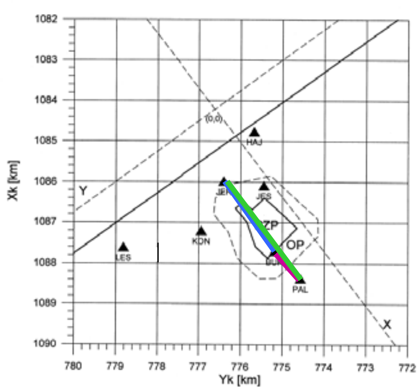
ADR – example (Brokesova & Malek, 2015) … Basic assumption test

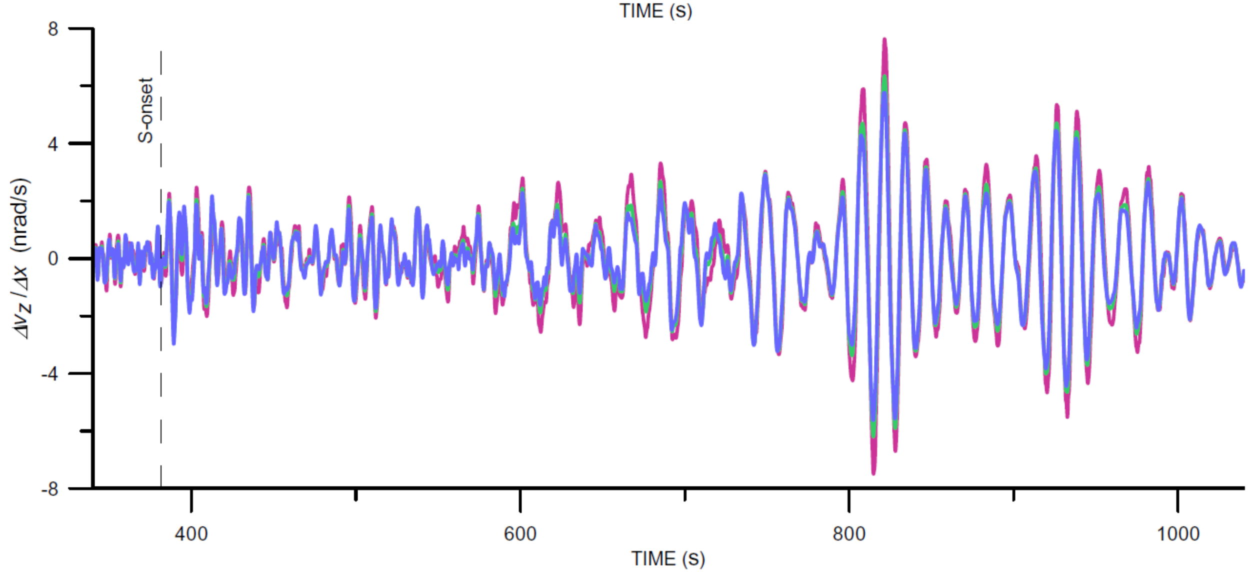
1st-order spatial gradients roughly approximated by finite differences

(Z-component)

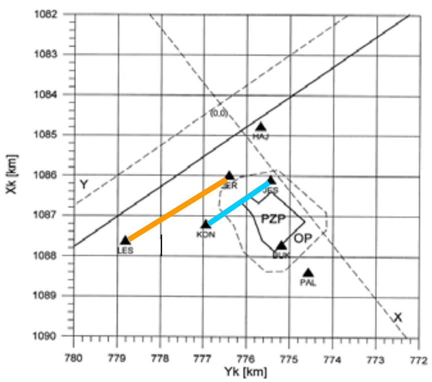


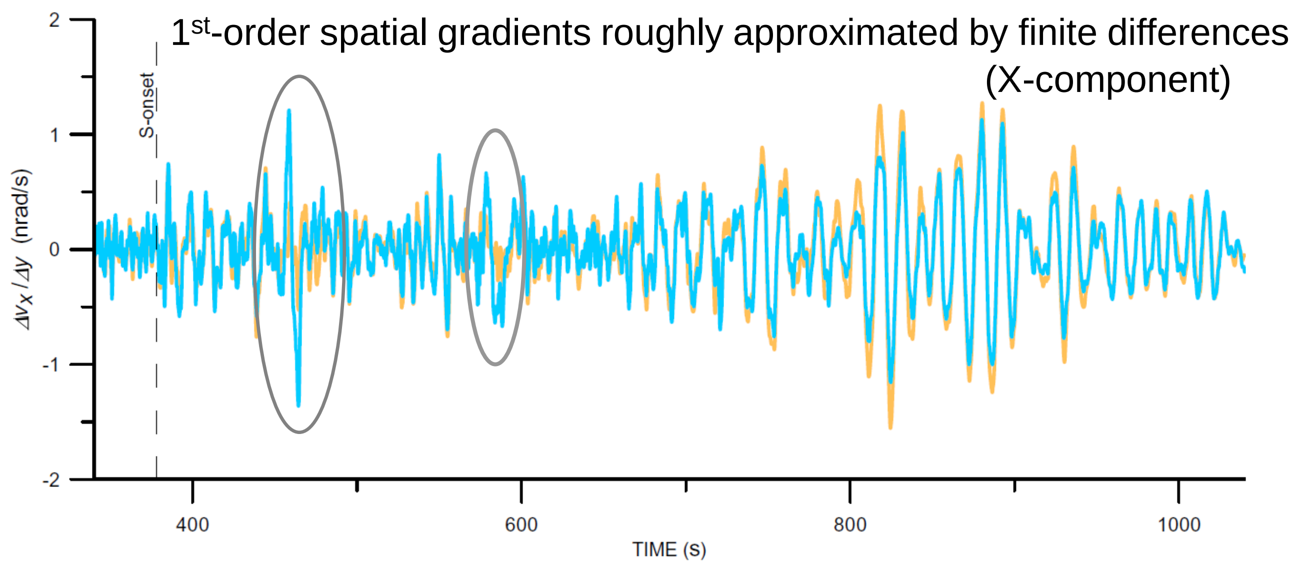


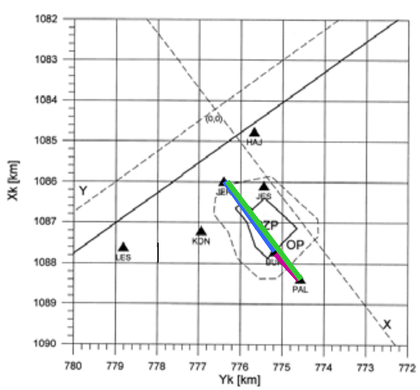


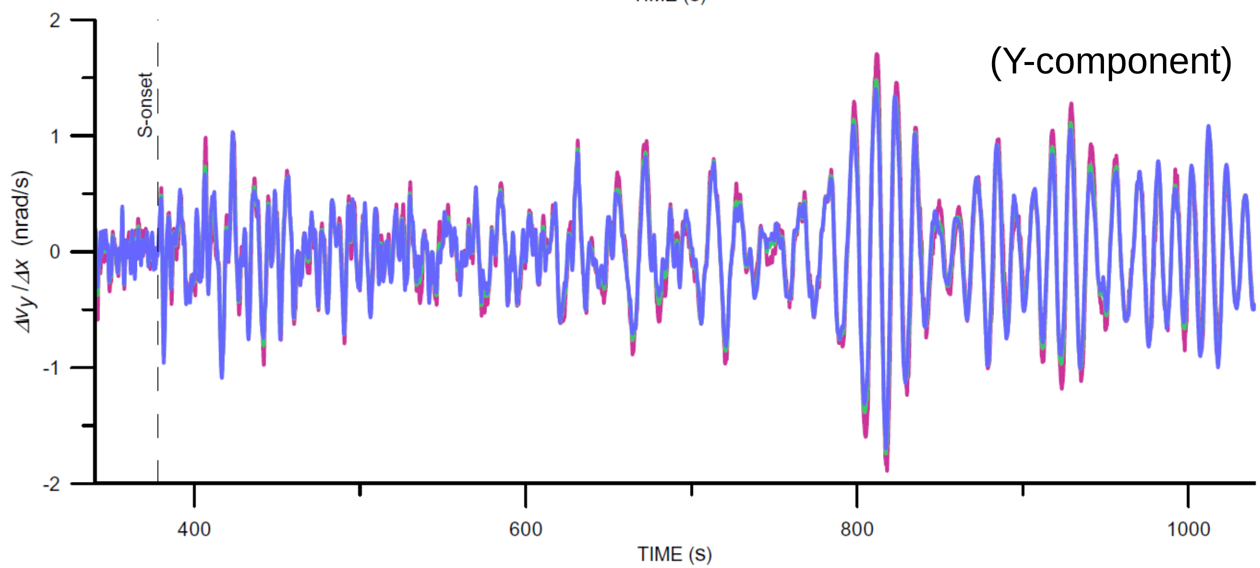


ADR – example (Brokesova & Malek, 2015) … Basic assumption test



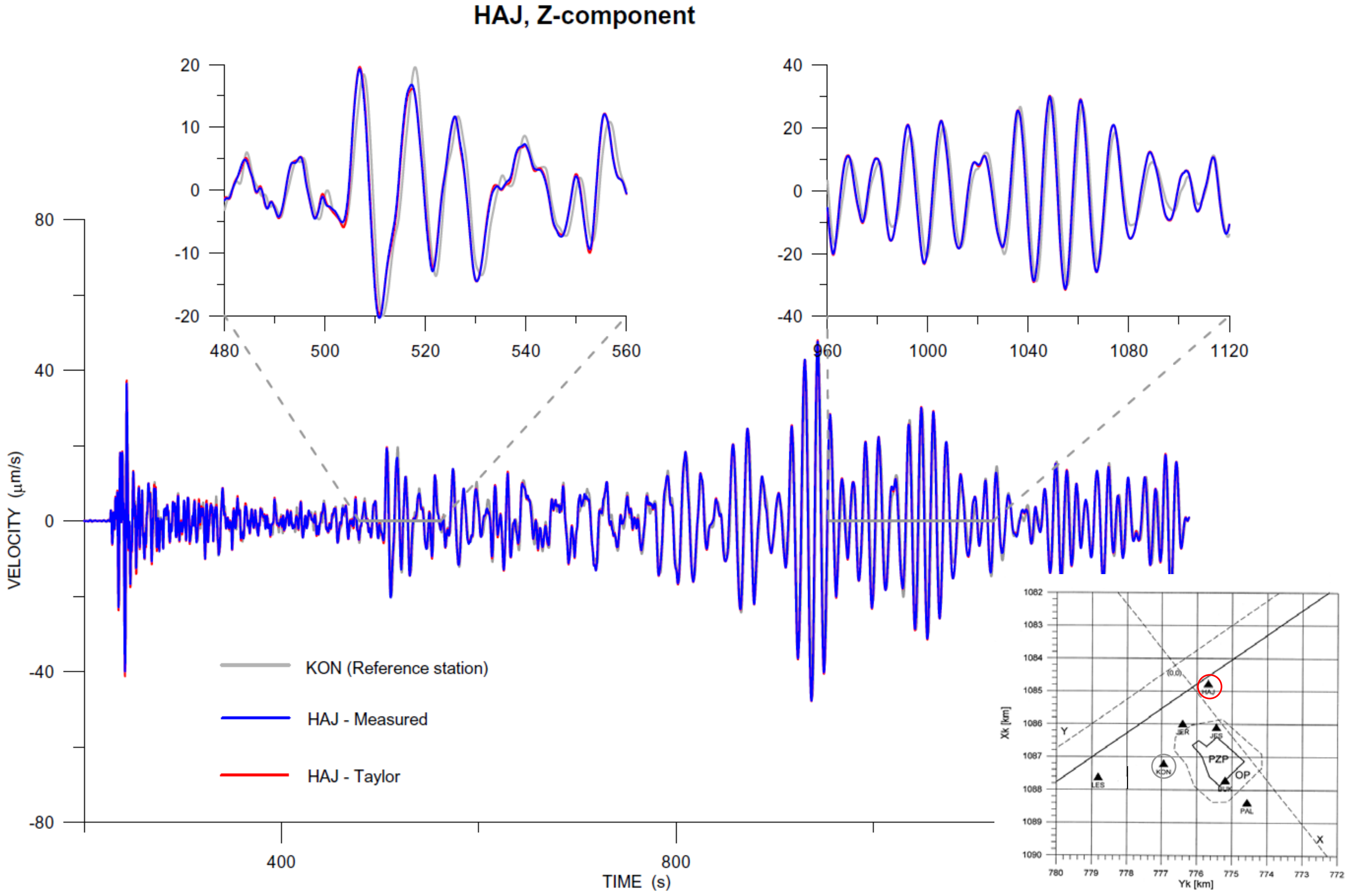






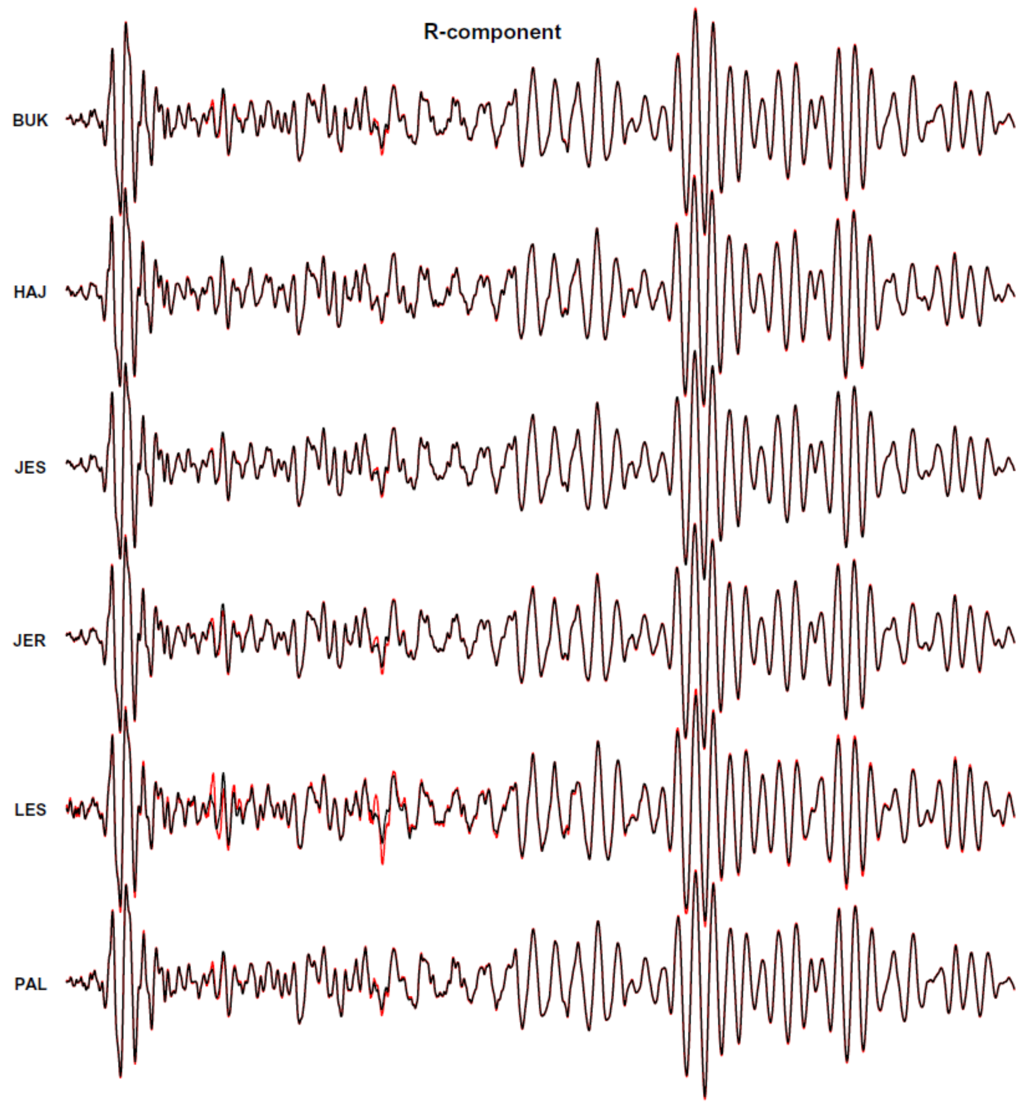
ADR – example (Brokesova & Malek, 2015)

How good is the 1st order Taylor expansion?

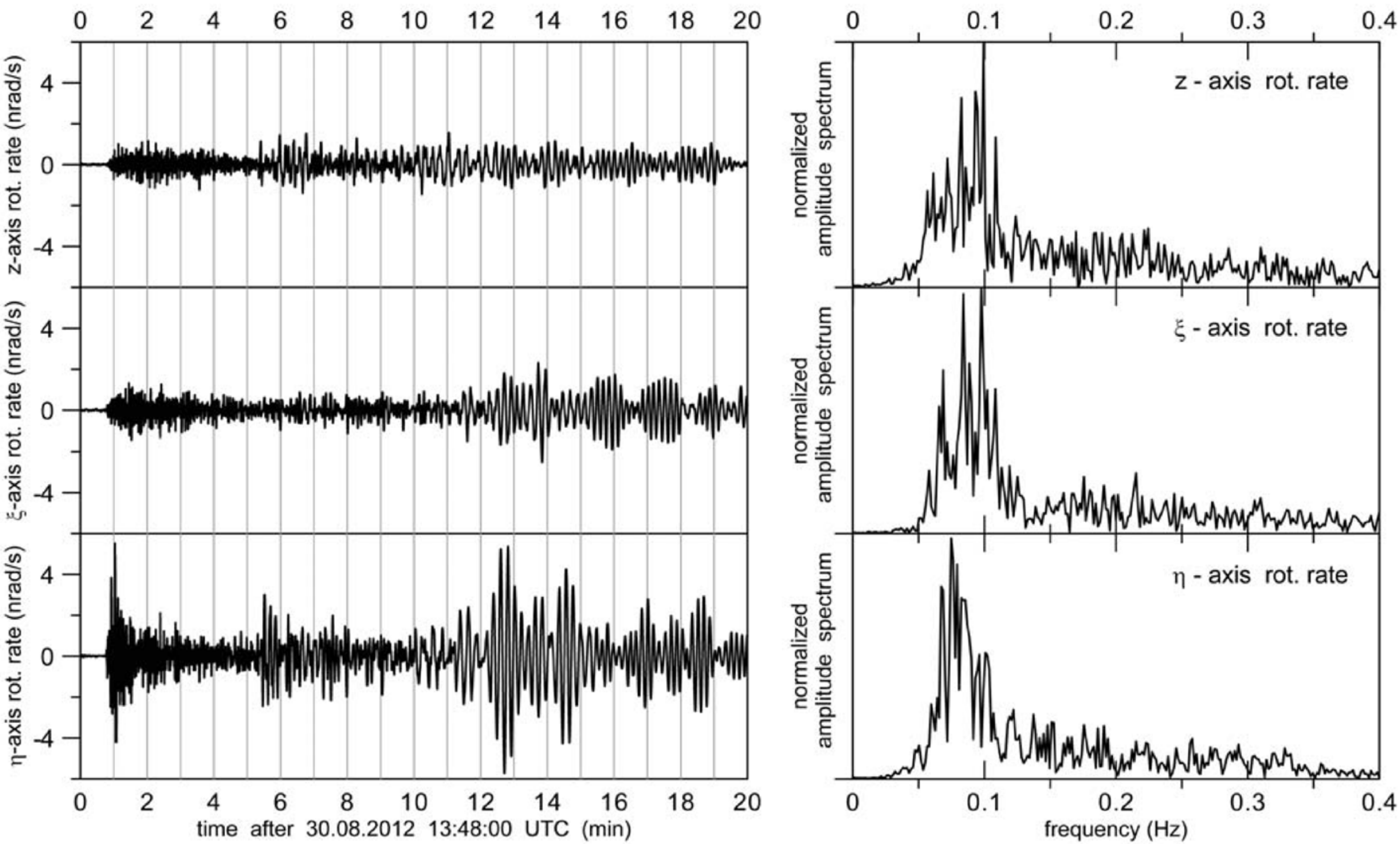


ADR – example (Brokesova & Malek, 2015)

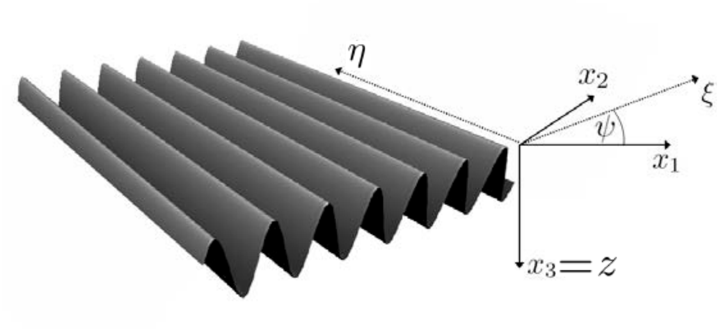
Taylor expansion up to the 1st order (red) vs. measured data (black)



ADR – example (Brokesova & Malek, 2015)



Rotation-to-translation relations (DISTANT EARTHQUAKES)



Under the assumption of a plane wave with apparent velocity *c* along the surface:

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

we get

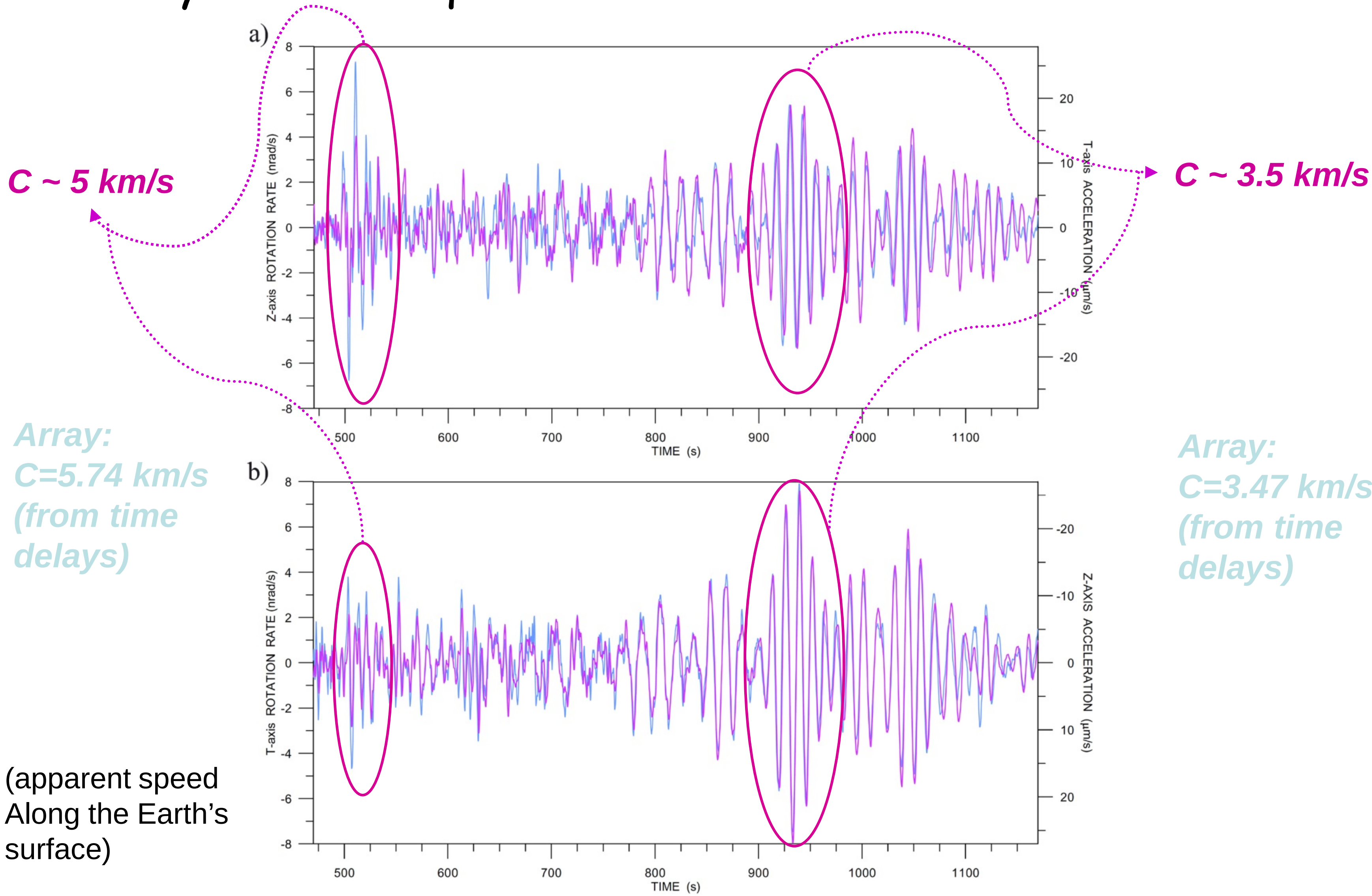
$$\Omega_\xi = 0$$

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

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

← (e.g.,Cochard et al., 2006, Igel et al., 2005)

Jana Mayena Earthquake – 2012-08-30 13:43:23.0 UTC



(apparent speed
Along the Earth's
surface)

Brokesova & Malek 2015c

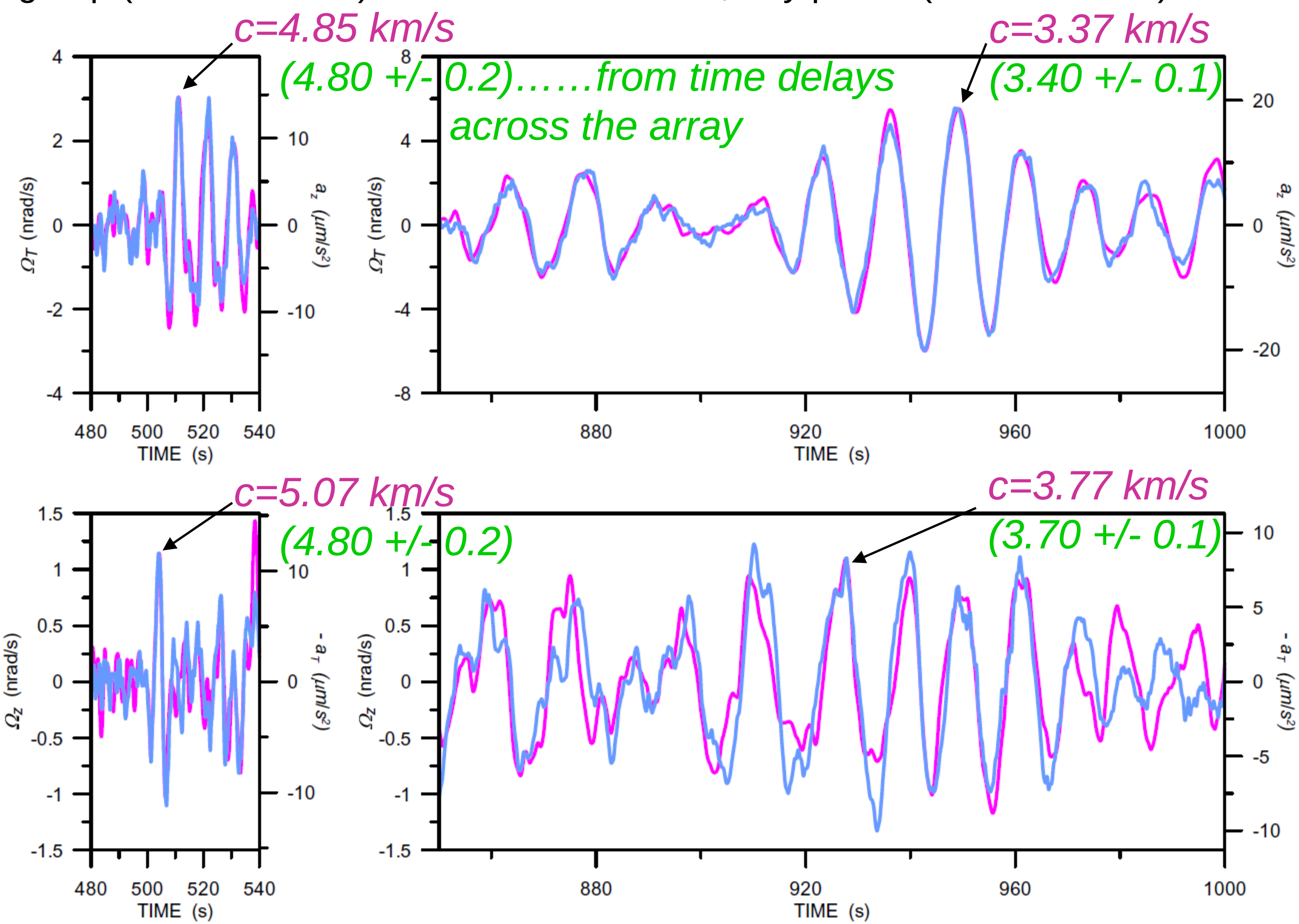
... in detail :

Matching the relevant rotation rate and acceleration components

S-wave group (real BAZ 338°) Surface waves, Airy phase (real BAZ 357°)

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

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



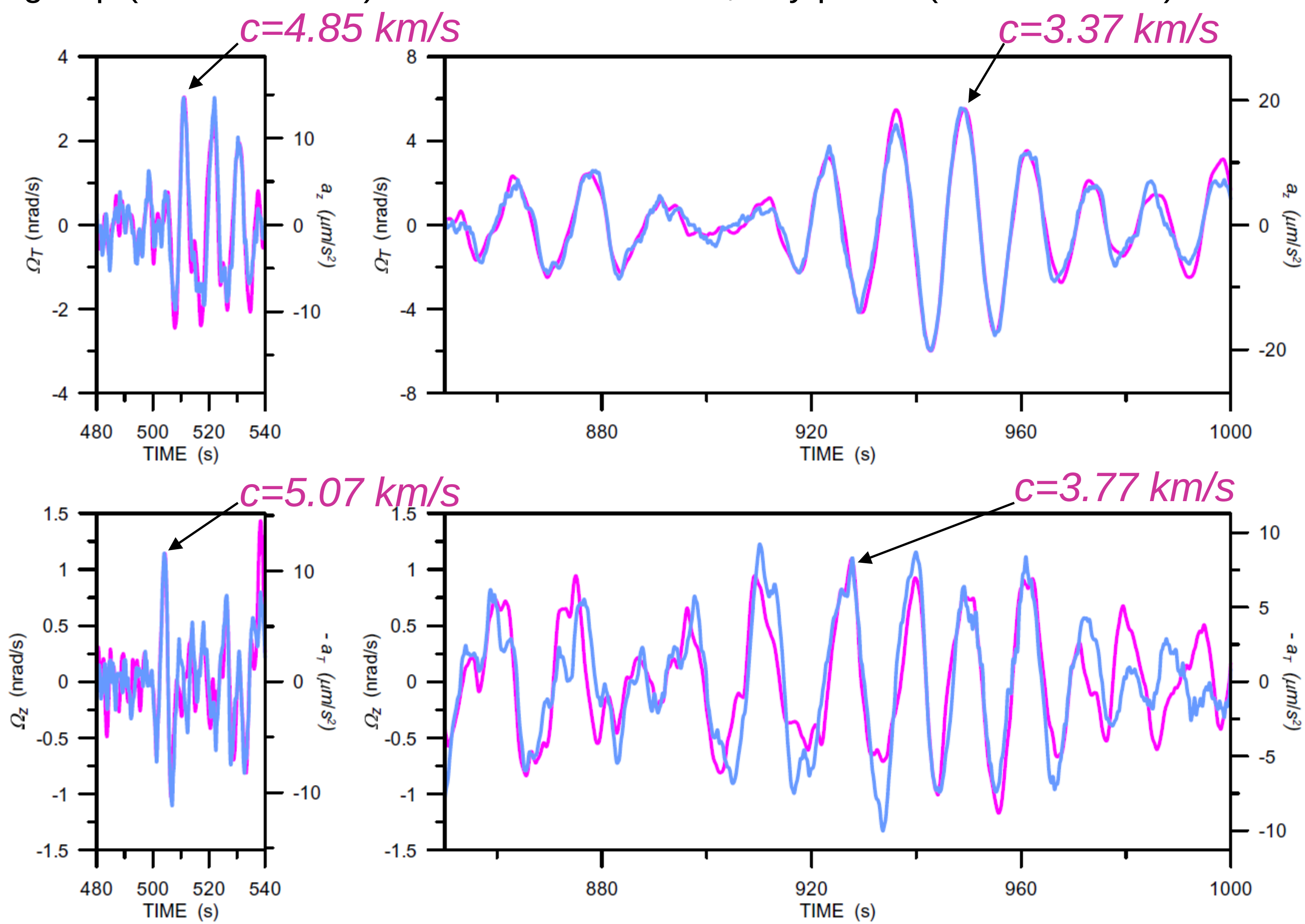
... in detail :

Matching the relevant rotation rate and acceleration components

S-wave group (real BAZ 338º) Surface waves, Airy phase (real BAZ 357º)

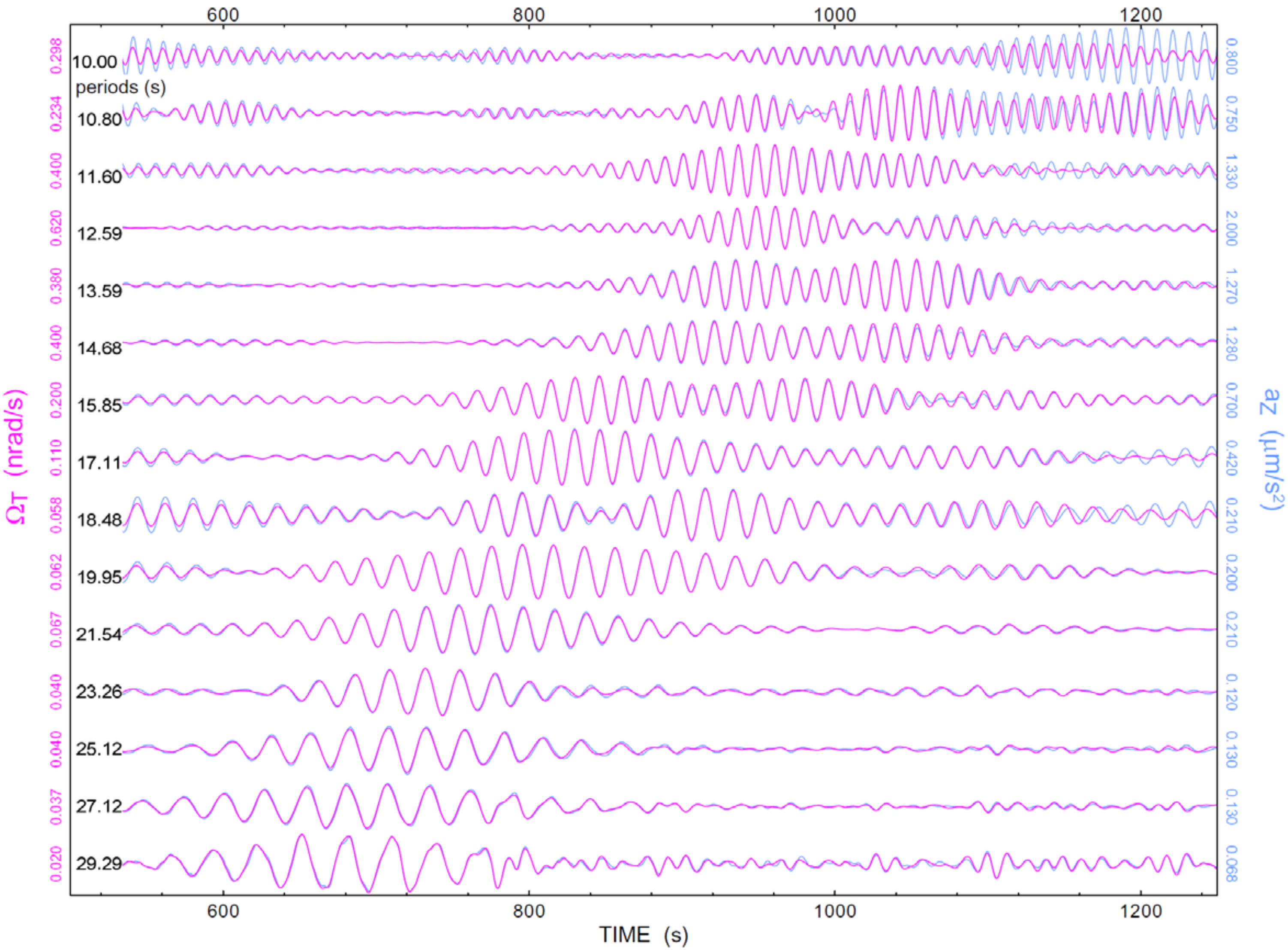
$$\Omega_\eta = \frac{1}{c}\dot{v}_z \rightarrow$$

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



Brokesova & Malek 2015c

Multiple filtering: matching Ω_T and a_Z



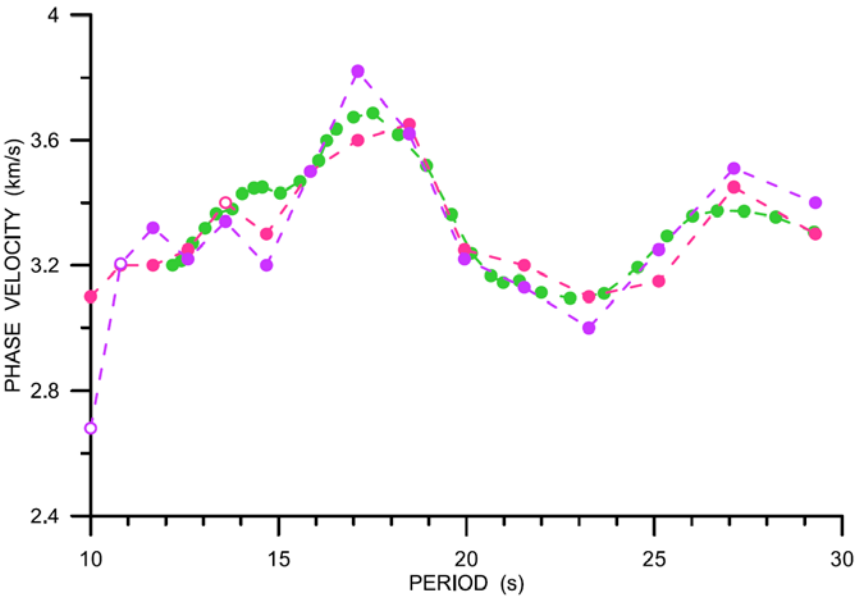
true backazimuth
(minimizing Ω_R)

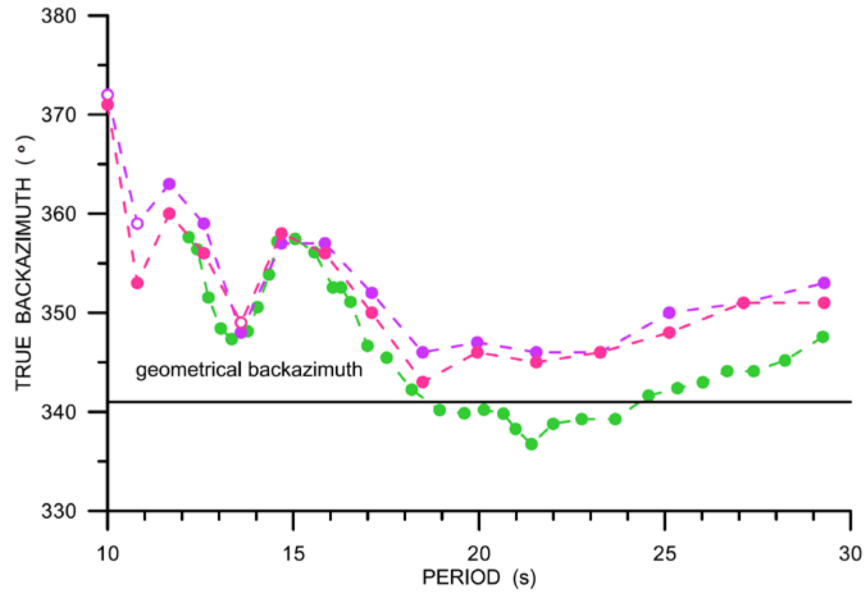
372^{o}
359^{o}
363^{o}
359^{o}
348^{o}
357^{o}
357^{o}
352^{o}
346^{o}
347^{o}
346^{o}
346^{o}
350^{o}
351^{o}
353^{o}

Brokesova & Malek 2015c

Surface wave phase velocity dispersion and true backazimuth

Comparison of three different methods





- Ω_T and a_Z matching
- Time delays across the array, zero amplitude beamforming
- Time delays across the array (4 stations), waveform correlation (standard procedure, SVAL package, Kolínský 2004, Kolínský & Brokešová 2007)

Brokesova & Malek 2015c

ADR method – pros and cons

Advantages:

- **standard seismographs are used, no specialized equipment is necessarry**

- **relatively inexpensive**

- **relatively easy instalation**

Disadvantages:

- **limited applicability in focal regions**

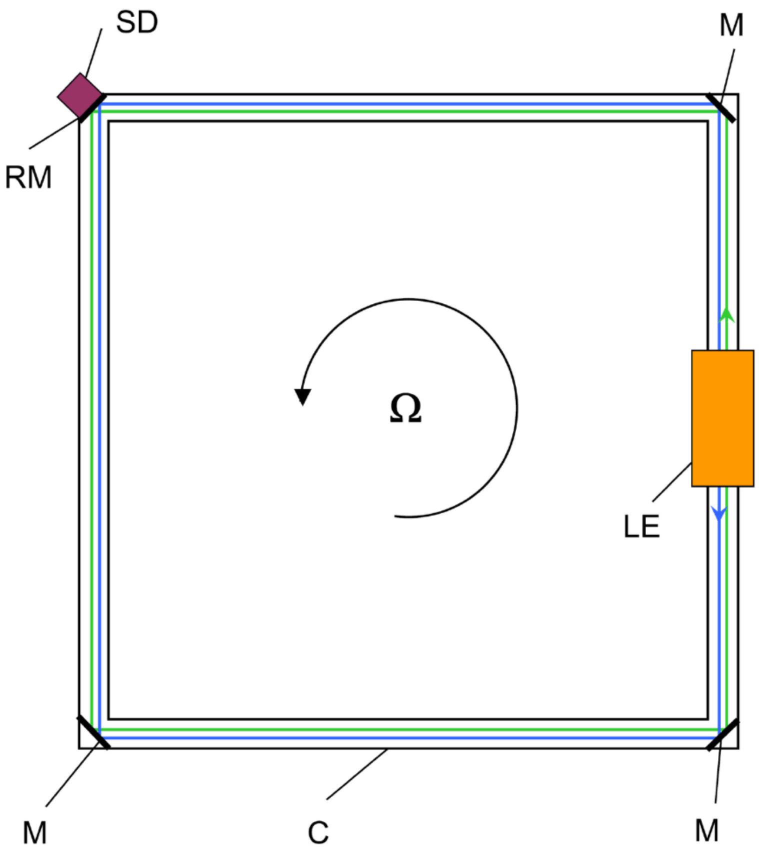
- **applicable only for relatively low frequencies**

- **various site conditions under individual stations**

- **differences in instrumental characteristics of individual seismographs**

- **translational components contaminated by rotational ones**

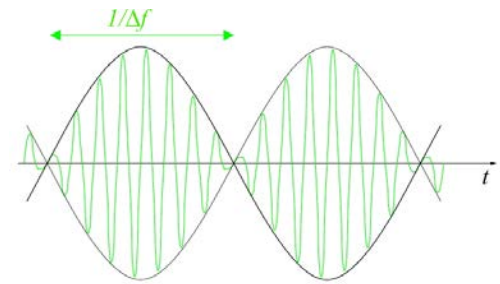
Ring Laser Gyroscopes (RLG)



Laser beam traveling clockwise

Laser beam traveling counter-clockwise

LE …Laser excitation
C …Cavity
M …Mirror (R=1)
RM …Readout mirror (R<1)
SD …Beam splitter and detector



$$\delta f = \frac{4A}{\lambda P}\mathbf{n}\cdot\mathbf{\Omega}_{total} = \frac{4A}{\lambda P}\Omega'_{total}$$

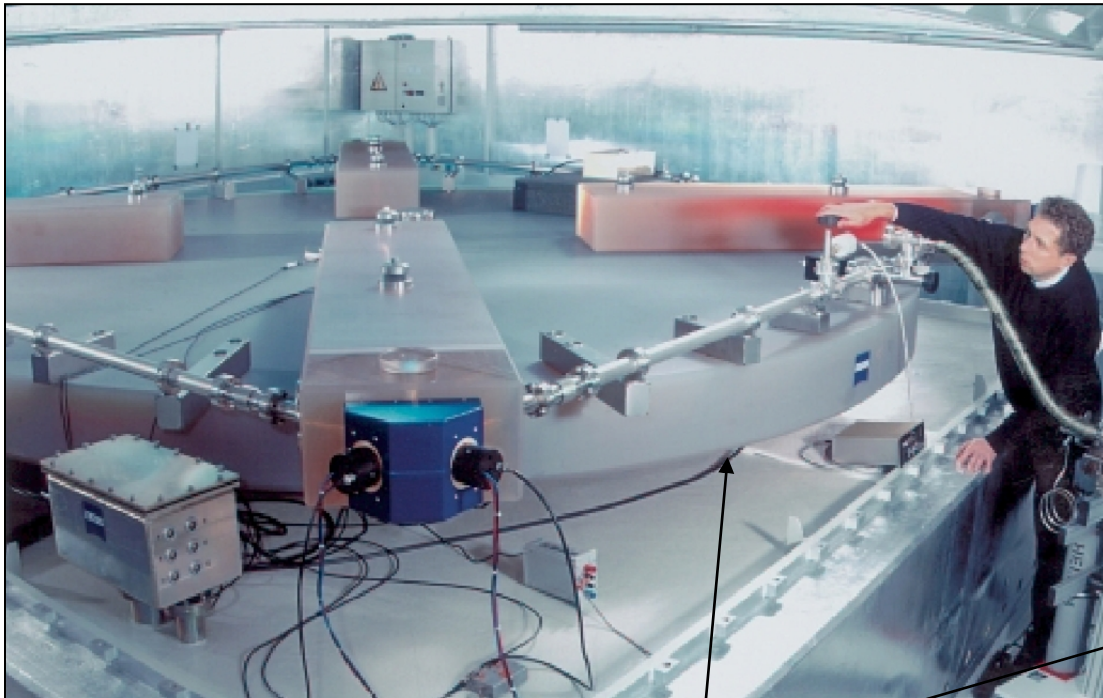
$$\Omega'_{total} = \Omega'_{Earth} + \Omega'_{seism}$$

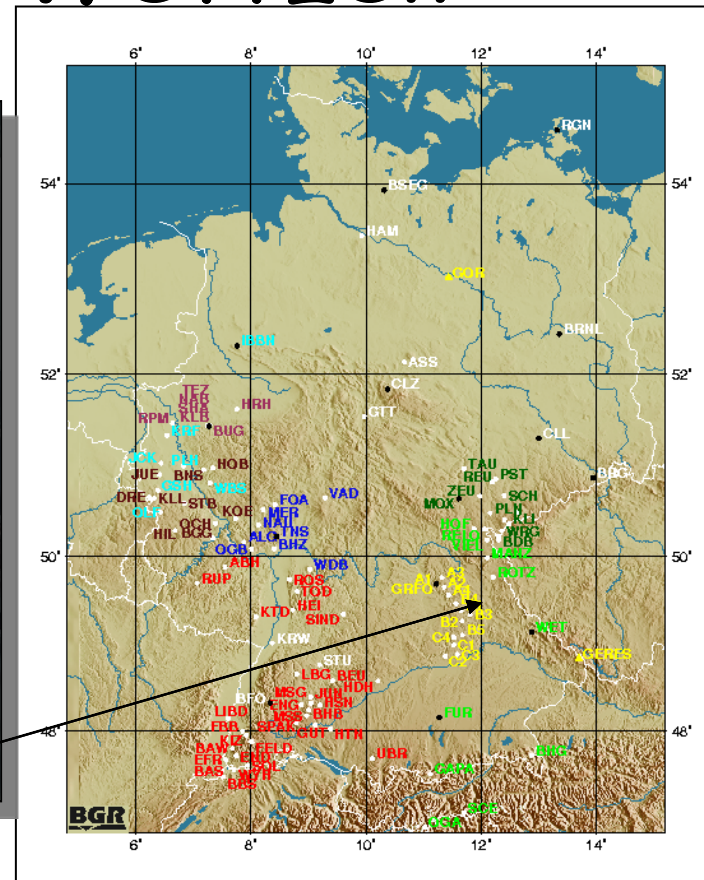
(e.g., Stedman, 1997)

Figure 1: A scheme of a square-shaped ring laser gyroscope.

Ring Laser Gyroscopes (RLG)

The ring laser at Wettzell





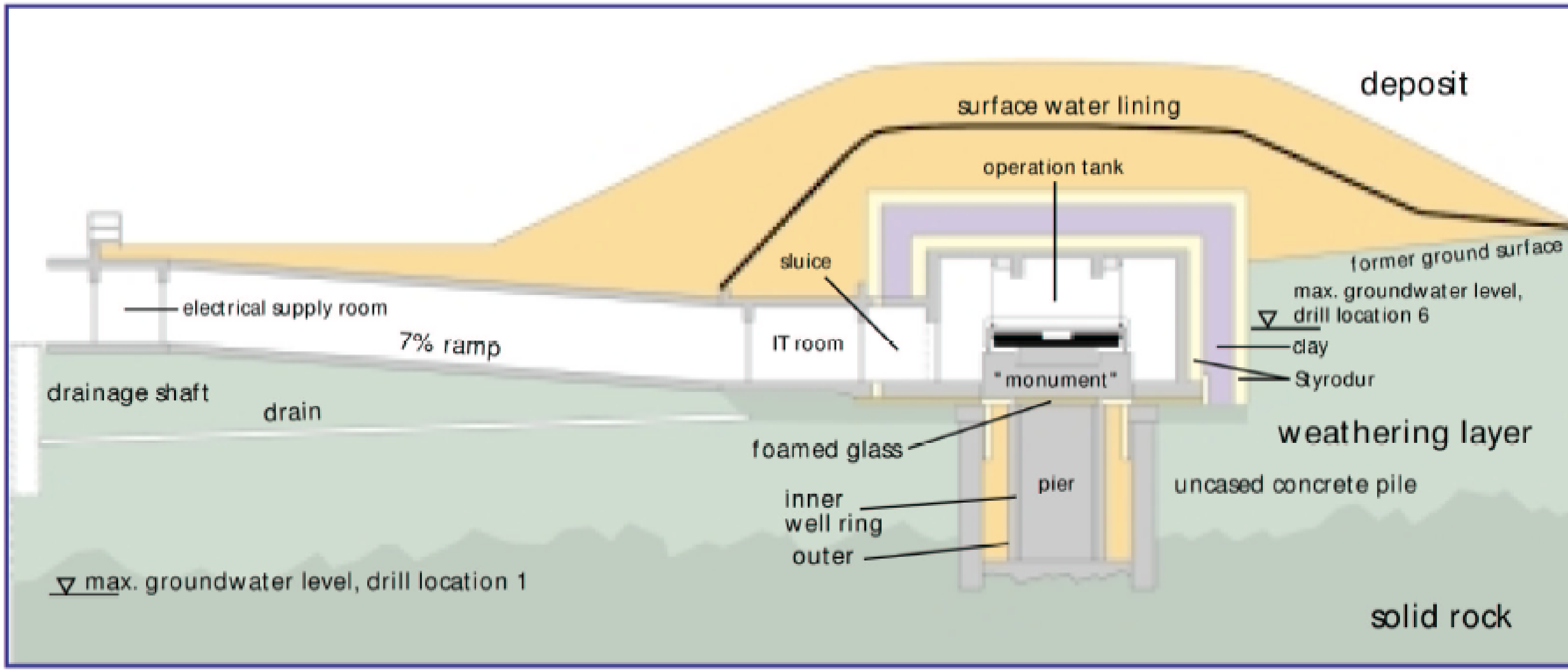
4 x 4 m ring laser

(resolution 10^{-11} rad/s)

(Igel et al., GJI, 2007)

Ring Laser Gyroscopes (RLG)

Ring laser installation at Wettzell



The cavern is located in southern Germany (49.1 N, 12.9 E)

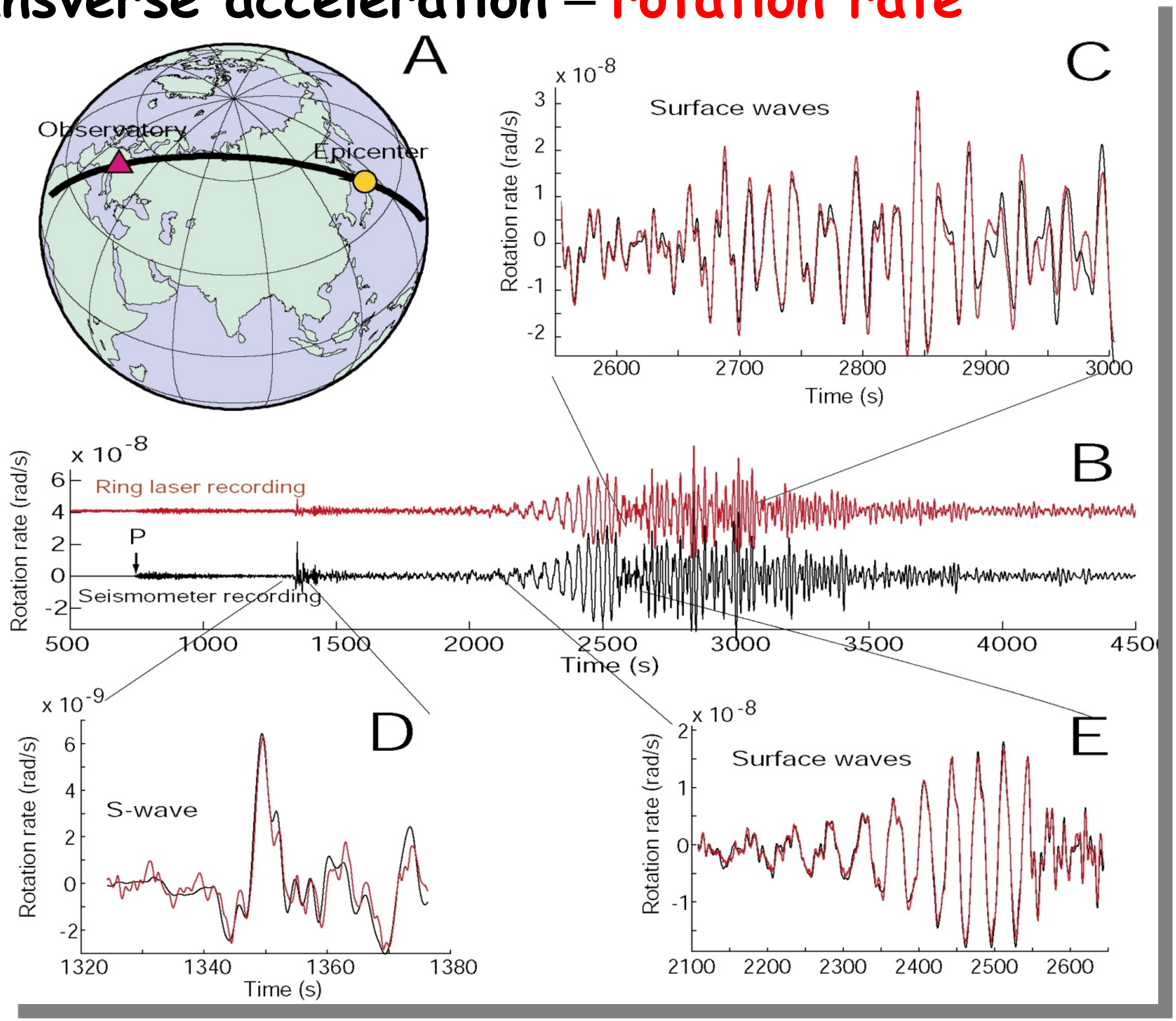
(Lee et al., SRL, 2009)

RLG example

(Igel et al., GRL, 2005; Lee et al., SRL. 2009)

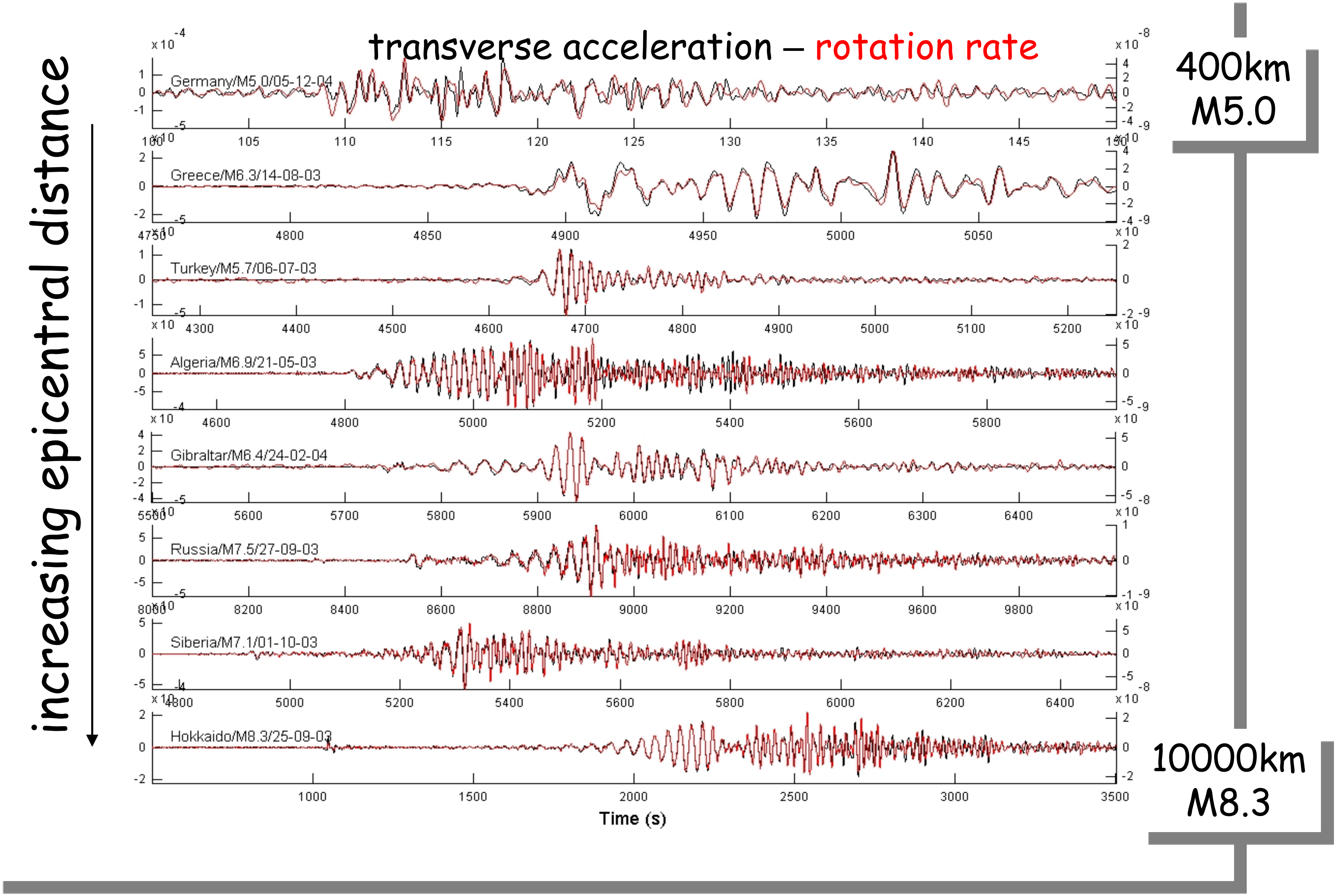
Mw = 8.3 Tokachi-oki 25.09.2003

transverse acceleration – **rotation rate**



(Igel et al., GJI, 2007)

Rotational data base - events with varying distance



RLG method – pros and cons

Advantages:

- **<u>most sensitive of all the methods, up to ~10^{-12} rad/s</u> (Schreiber et al., 2009)**

- **rotation independent on translation**

Disadvantages:

- **<u>measures only one rotational component (mostly around the vertical)</u>**

- **<u>long-period records only</u> (up to ~ 1 Hz)**

- **expensive device**

- **require special installation (e.g., special building,etc.), RLG maintenance is relatively demanding**

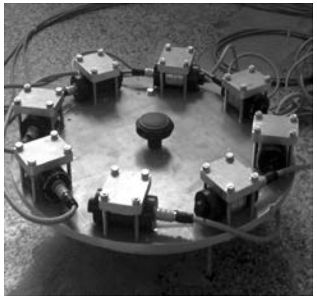
There is a need to develop a reliable, portable rotation sensor for broadband seismology.

Various kinds of small portable rotational sensors suitable for seismic measurements:

- Fiber optic gyros
- Liquid based sensors (e.g., R1)
- Atom interferometry (Kasevich and others)
- Tuning fork (MEMS)
- Induction principle sensors (Strunc)
- Seismometer couples (e.g., Rotaphone)

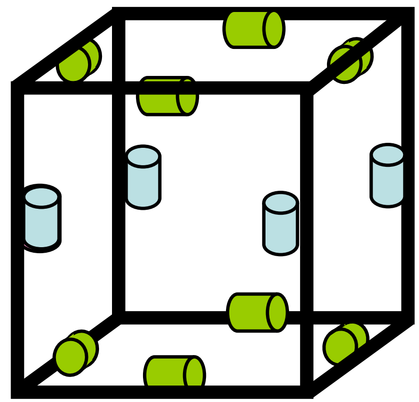
Rotafon = mechanical sensor system for measuring of spatial gradients; it consists of parallel pairs of geophones mounted to a rigid frame

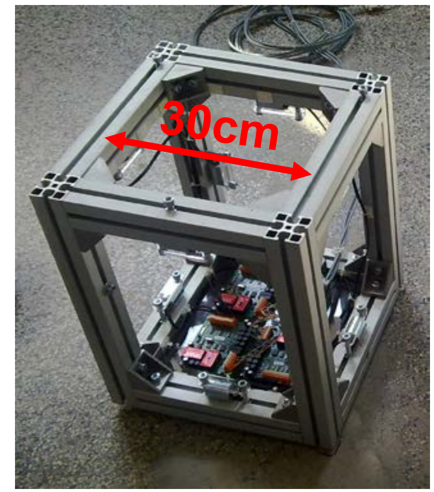
(Brokešová et al., 2009, patent CZ 301217 B6)

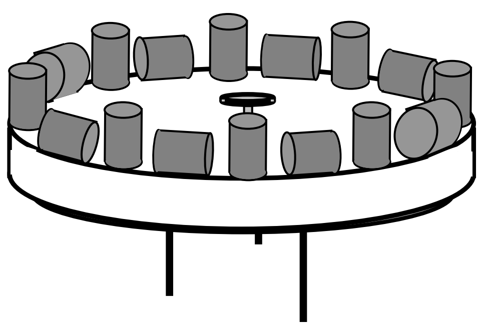


… An older prototype of Rotafonu - 3 DOF only,
8 horizontal geophones
(Brokešová & Málek 2010, Brokešová et al. 2012a)

A newer prototype - 6 DOF,
8 horizontal + 4 vertical geophones
(Brokešová et al. 2012b,
Brokešová & Málek 2013, **…**
Brokešová & Málek 2015a,b)







The latest prototype, 6 DOF,
8 horizontal + 8 vertical geophones

… installed recently at Shashamane

ROTAPHONE

Basic features:

- It consists of highly sensitive geophones connected to a common recording device
- The geophones are mounted in parallel pairs to a rigid (metal) ground-based frame
- The distance separating the paired geophones is much smaller than λ
- The instrument provides collocated records of translational and rotational seismic motions (with the same instrumental characteristics)
- Rotation rate is determined by more than one geophone pair, which allows to perform 'in situ' calibration of the geophones simultaneously with the measurement.

ROTAPHONE

Basic features:

- It consists of highly sensitive geophones connected to a common recording device
- The geophones are mounted in parallel pairs to a rigid (metal) ground-based frame
- The distance separating the paired geophones is much smaller than λ
- The instrument provides collocated records of translational and rotational seismic motions (with the same instrumental characteristics)
- Rotation rate is determined by more than one geophone pair, which allows to perform 'in situ' calibration of the geophones simultaneously with the measurement.

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

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

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

Ω_i ... Rotation rate components

v_i .... Ground velocity components

ROTAPHONE

Basic features:

- It consists of highly sensitive geophones connected to a common recording device
- The geophones are mounted in parallel pairs to a rigid (metal) ground-based frame
- The distance separating the paired geophones is much smaller than λ
- The instrument provides collocated records of translational and rotational seismic motions (with the same instrumental characteristics)
- Rotation rate is determined by more than one geophone pair, which allows to perform 'in situ' calibration of the geophones simultaneously with the measurement.

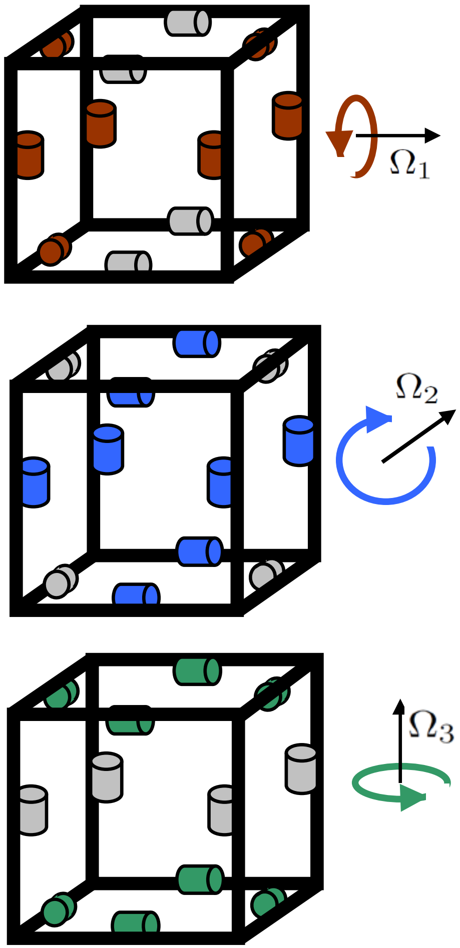
ROTAPHONE

Basic features:

- It consists of highly sensitive geophones connected to a common recording device
- The geophones are mounted in parallel pairs to a rigid (metal) ground-based frame
- The distance separating the paired geophones is much smaller than λ
- The instrument provides collocated records of translational and rotational seismic motions (with the same instrumental characteristics)
- Rotation rate is determined by more than one geophone pair, which allows to perform 'in situ' calibration of the geophones simultaneously with the measurement.

ROTAPHONE

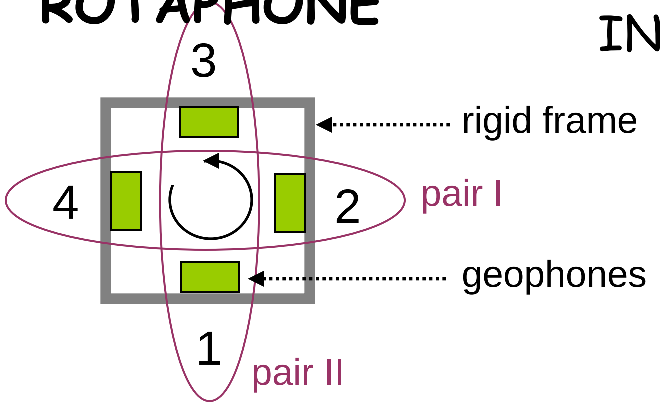
Basic features:



- It consists of highly sensitive geophones connected to a common recording device
- The geophones are mounted in parallel pairs to a rigid (metal) ground-based frame
- The distance separating the paired geophones is much smaller than λ
- The instrument provides collocated records of translational and rotational seismic motions (with the same instrumental characteristics)
- Rotation rate is determined by more than one geophone pair, which allows to perform 'in situ' calibration of the geophones simultaneously with the measurement.

Essential feature of our method

ROTAPHONE



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

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

$$\Downarrow$$

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

$\Downarrow$ (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)

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

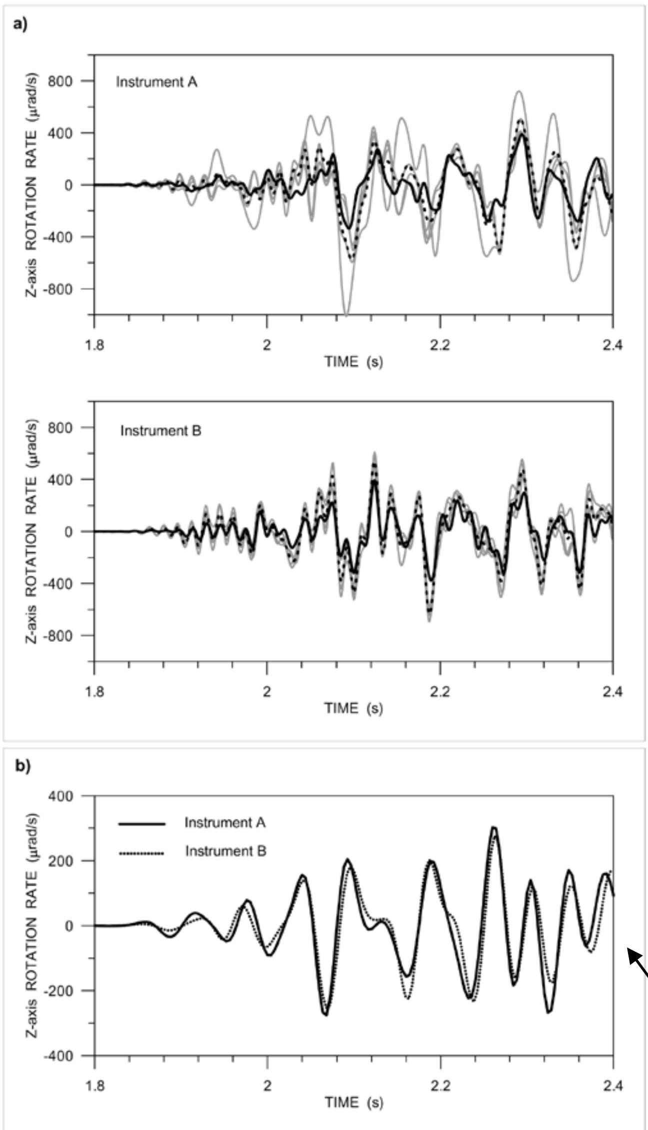
poles and zeros or values at discrete f_k

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.

IN-SITU CALIBRATION - EXAMPLE

QUARRY BLAST 23.1.2012, 3044 kg
Distance 368 m



2 - 30 Hz

(Brokešová & Málek., 2015b)

ROTAPHONE

Basic features:

- It consists of highly sensitive geophones connected to a common recording device
- The geophones are mounted in parallel pairs to a rigid (metal) ground-based frame
- The distance separating the paired geophones is much smaller than λ
- The instrument provides collocated records of translational and rotational seismic motions (with the same instrumental characteristics)
- Rotation rate is determined by more than one geophone pair, which allows to perform 'in situ' calibration of the geophones simultaneously with the measurement.

Specific features:
(component-dependent)

Frequency range 2 Hz – 40 (or 60) Hz
Dynamic range 120 dB
Least detectable motion in practice 10^{-8} rad/s
Largest detectable motion 10^{-1} m/s, 10^{-1} rad/s

ROTAPHONE pros. and cons.

Advantages:

- it is optimized for measurements in focal regions
- low price (full-value short-period 6-component seismograph)
- collocated rotational and translational data
- rotation free of translation, translation can easily be corrected for rotation
- applicability at high frequencies (seismic prospection)
- easy instalation (in a fast response to the current seismic situation)
- temperature range from -20 to +60˚C

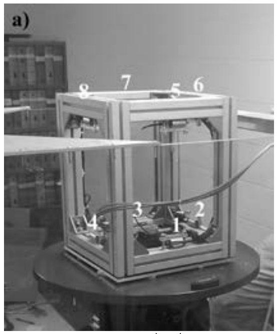
Disadvantages:

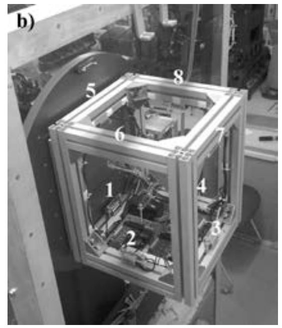
- short-period measurement only (above 2 Hz)

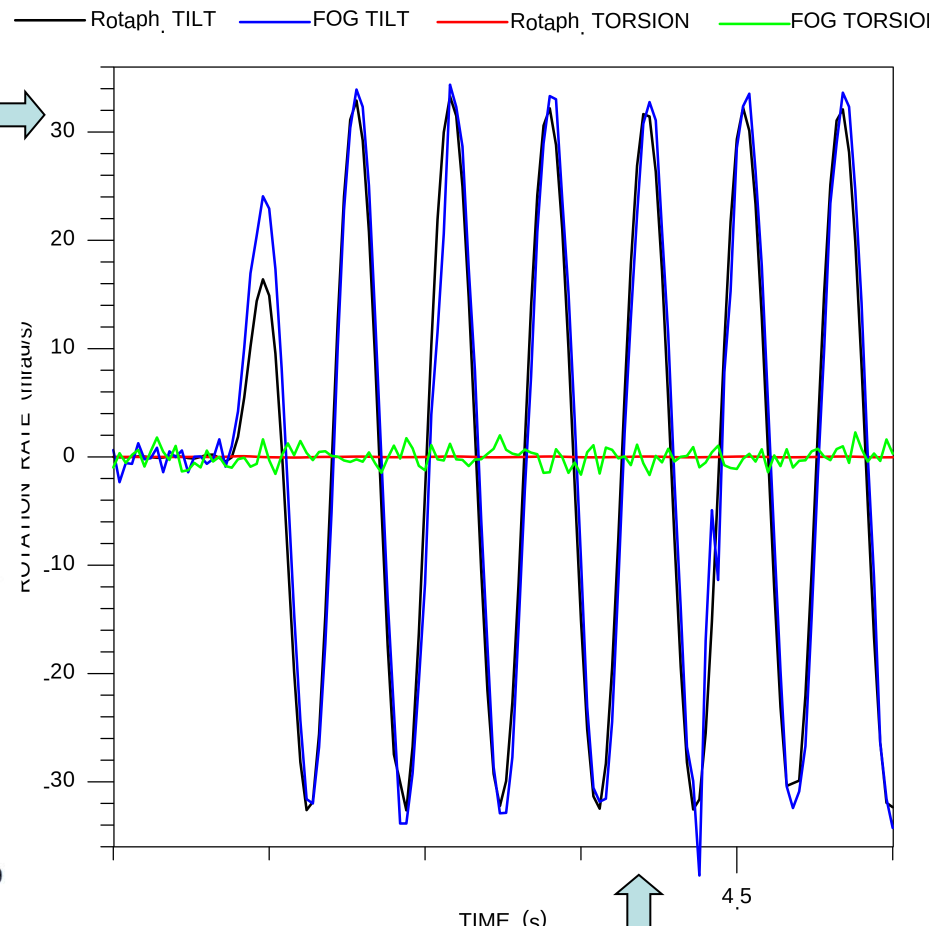
ROTAPHONE – testing in the laboratory

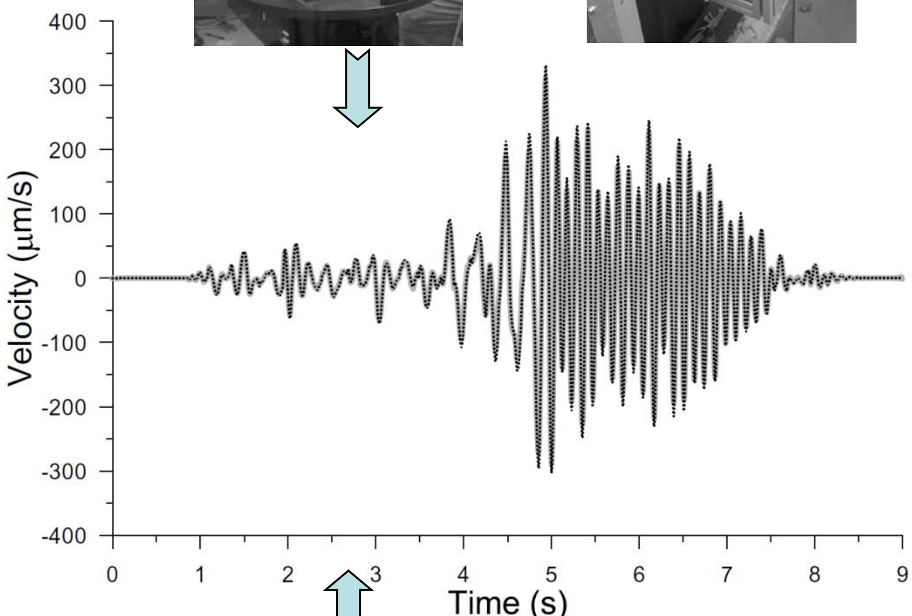
Albuquerque Seismological Laboratory (USGS, New Mexico, USA)

(Brokešová et al., 2012a)









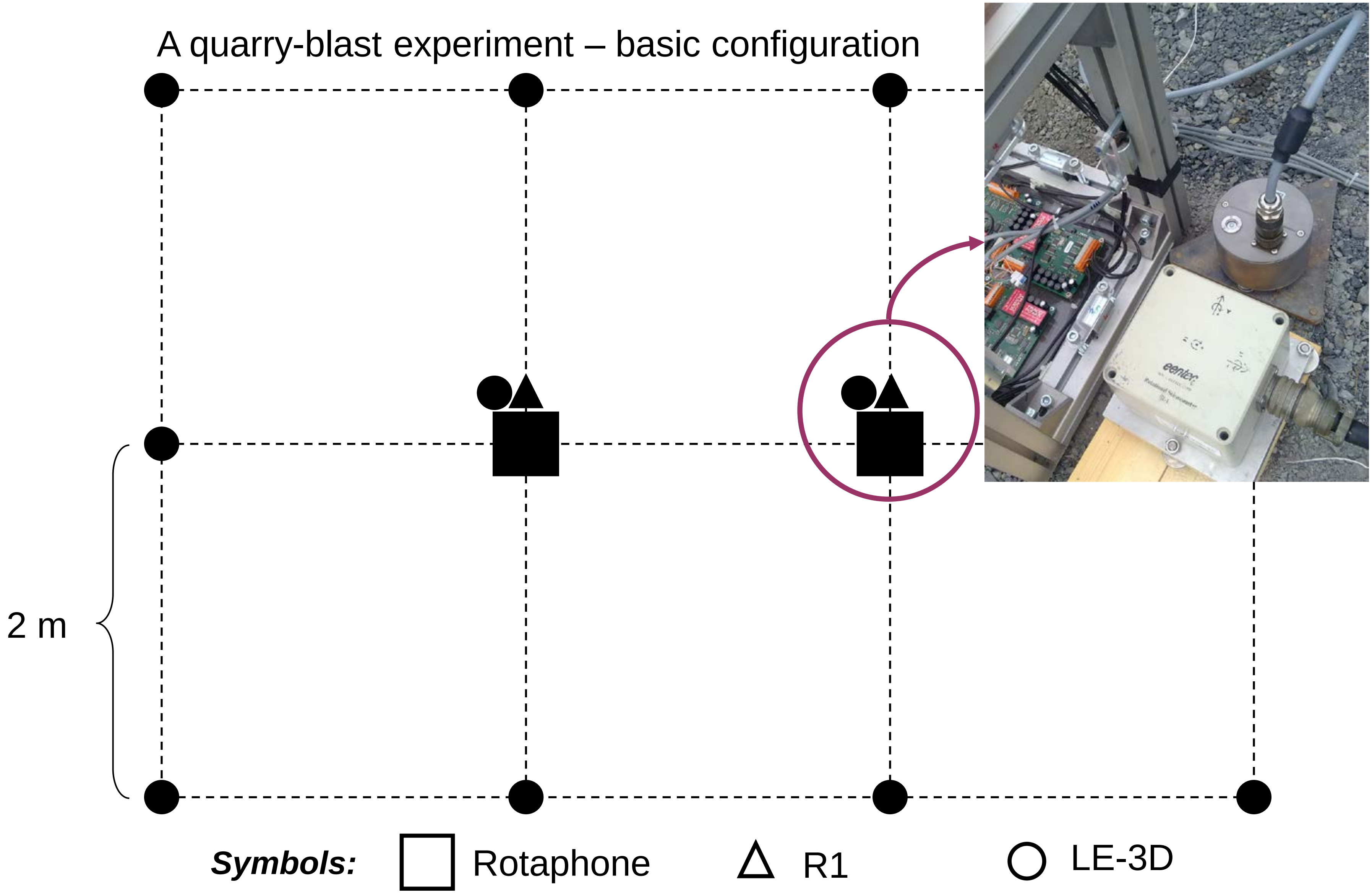
Instant ttangential translational velocity of the Rotaphone at off-center position (7.62 cm from the axis of rotation) measured directly (dotted) and indirectly – derived from rotation rate and radius (grey)

Tilt around the horizontal axis, Comparison of the 16Hz harmonic rotational signal measured by the Rotaohon and the FOG sensor

CROSS-AXIS TEST

ROTAPHONE – testing in the field

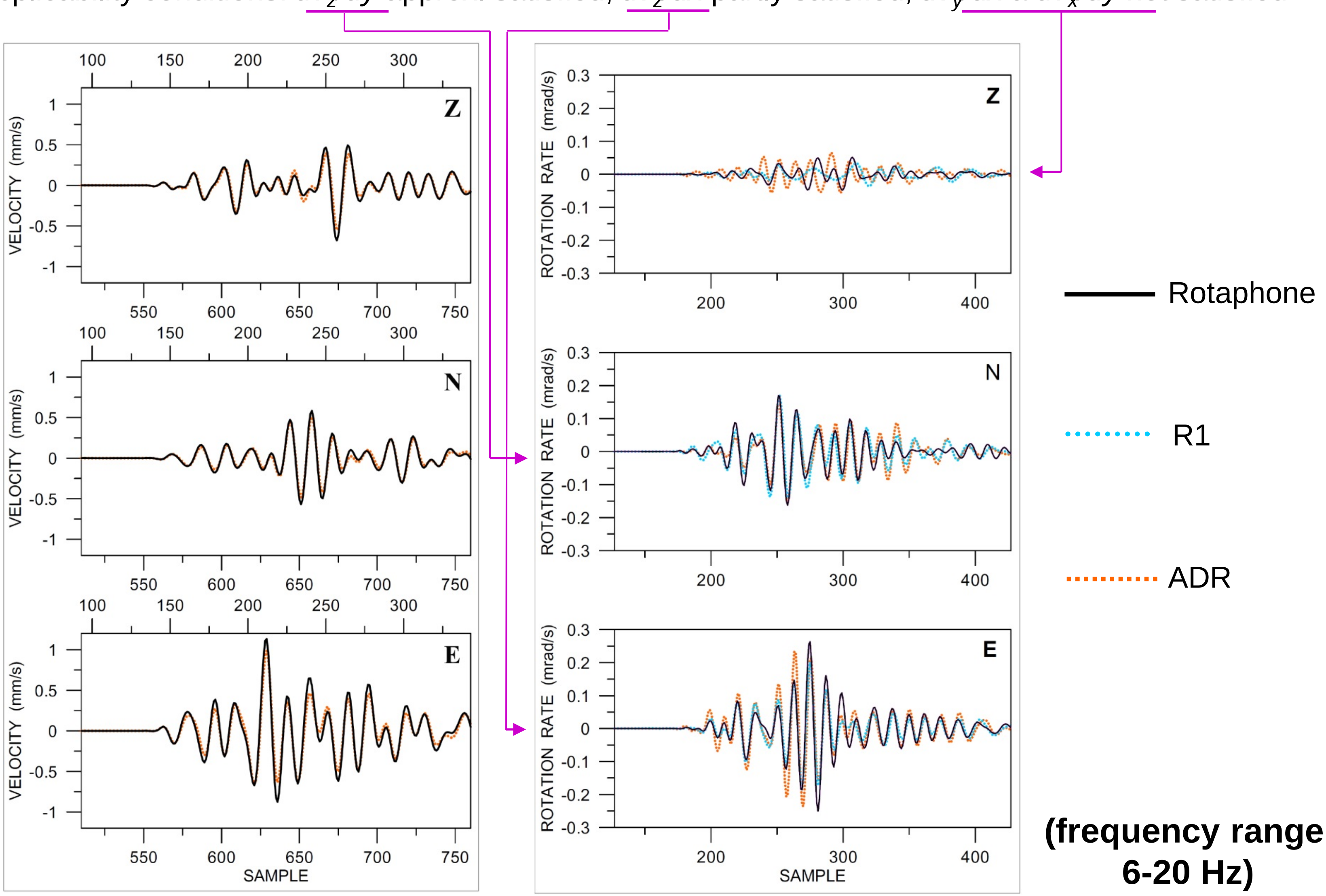
A quarry-blast experiment – basic configuration



ROTAPHONE – testing in the field

A quarry-blast experiment – Klecany quarry, 25.7.2012, m = 1.4 t, Δ = 238 m

ADR applicability conditions: dv_z/dy approx. satisfied, dv_z/dx partly satisfied, dv_y/dx a dv_x/dy not satisfied



TRANSLATIONAL COMPs.

ROTATIONAL COMPs.

(frequency range 6-20 Hz)

Examples of micro-earthquake records measured by Rotaphone (2010 - 2013)

Date and time (UTC)	Station	$\dot{\Omega}_z$ [μrad/s]	$\dot{\Omega}_{hor}$ [μrad/s]	Δ [km]	Depth [km]	f_M [Hz]	M_L	Prot.
12.01.2012 08:54:18	NKC	9.2	23	0.67	9.2	37	2.0	6DOF I
09.05.2010 13:44:37	NKC	1.9	–	1.4	7.6	30	0.3	3DOF
21.02.2012 16:20:26	SERG	3.5	9.0	1.8	11.8	21(7)	1.6	6DOF II
15.12.2011 13:57:18	LBC	12	54	2.6	8.0	33	2.3	6DOF I
15.10.2008 16:00:04	KVC	150	–	4.4	8.6	20	2.2	3DOF
25.04.2012 10:34:12	SERG	400	700	5.0	11.0	11(20)	4.3	6DOF II
25.04.2012 10:45:22	SERG	23	22	5.8	11.1	5(7)	2.4	6DOF II
22.02.2012 20:10:03	SERG	4.0	8.1	9.2	8.5	13	1.9	6DOF II
21.02.2012 20:15:45	SERG	7.1	8.0	9.5	8.0	19(5)	1.9	6DOF II
17.05.2010 18:42:57	NKC	1.6	–	11.1	10.5	24	0.9	3DOF
11.05.2010 15:11:18	NKC	0.5	–	11.1	10.5	24	0.5	3DOF
11.05.2010 13:41:54	NKC	0.3	–	11.1	10.5	24	0.3	3DOF
17.10.2013 15:44:53	ESK	0.06	0.1	14.8	0.1	5	1.8	6DOF II
22.03.2014 17:05:02	ESK	3.6	1.9	14.9	4.8	7.5	2.3	6DOF II
11.07.2011 07:22:47	PROV	0.2	0.6	18.9	2.0	3	1.6	6DOF I
21.03.2012 05:50:47	SERG	15	50	37.2	18.0	4	3.8	6DOF II
22.02.2012 02:23:13	SERG	19	39	112.0	15.0	3.5	3.8	6DOF II
13.10.2013 07:32:16	ESK	2.7	2.4	163.2	4.9	2	4.7	6DOF II
30.08.2010 16:33:53	NKC	0.4	–	290.0	0.0*	4.5	3.7	3DOF

*) A rockburst in the Lubin copper mine, Poland; depth is set to zero.

West Bohemia (Czech Rep.)

Geodynamically active region known for recurent earthquake swarms, CO_2 emissions, mineral springs, and other post-volcanic phenomena.

Korinthian Gulf (Greece)

Active-rift region (rift openning at a speed cca 1.5 cm/y). Charakteric complex fault system and distinguished seismic activity.

Provadia (northern Bulgaria)

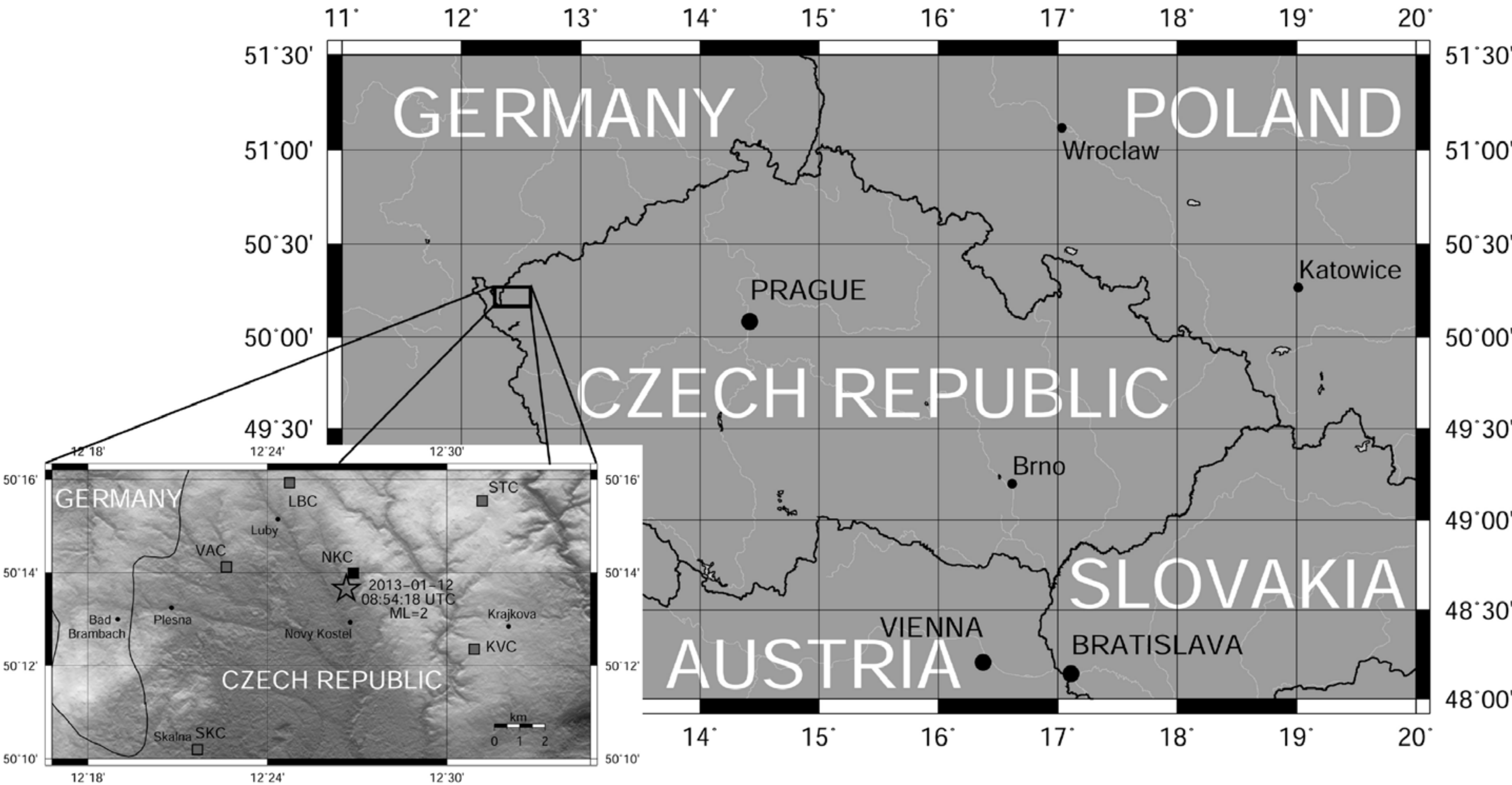
Region characterized by induced seismicity Connected with salt production (Mirovo Salt Dome).

Katla (southern Iceland)

Volcanic complex Eyafjalla-Katla. Current volcanic activity and seismicity Connected with magma movements.

ROTAPHONE – examples of records EXAMPLE 1

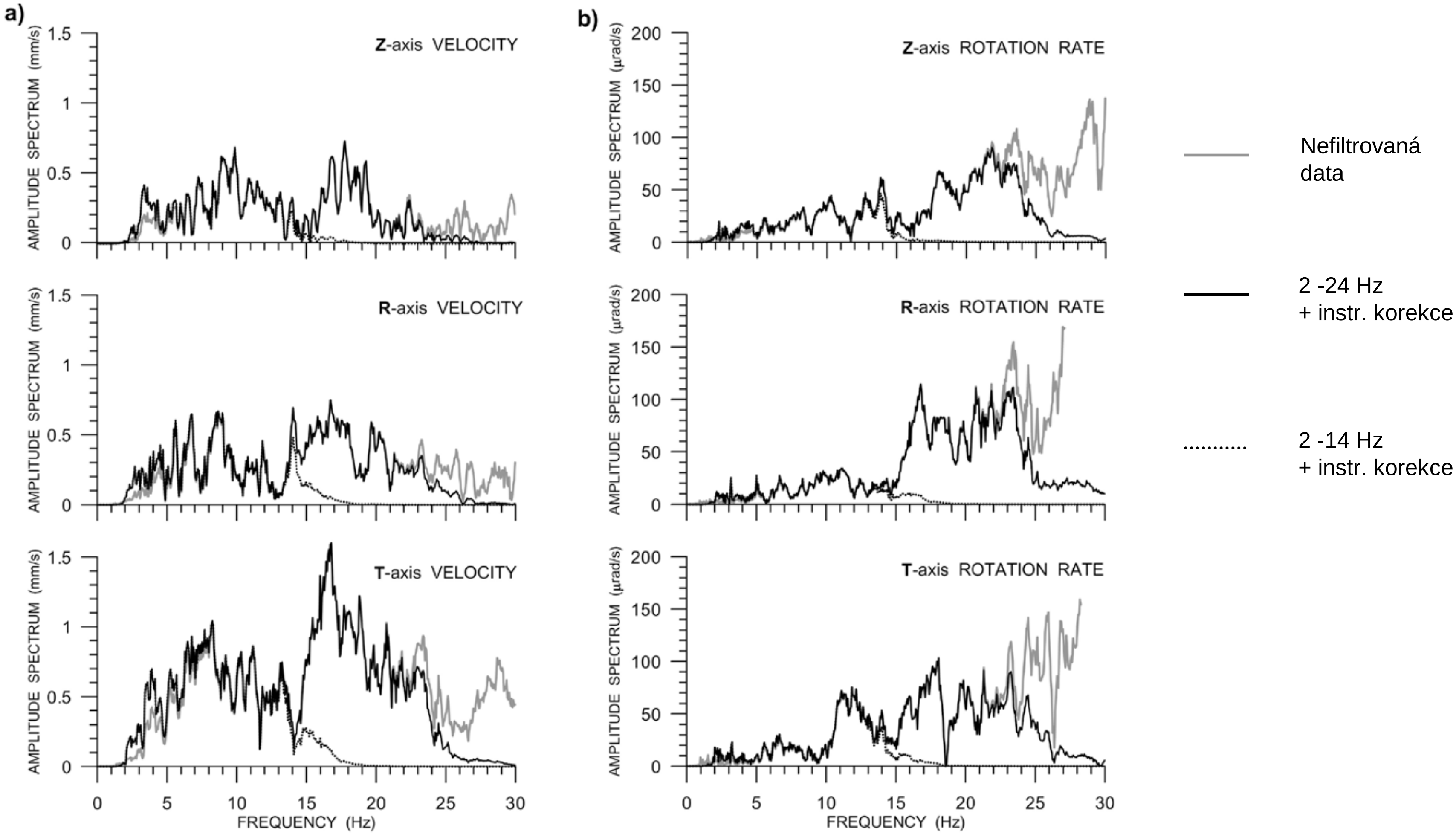
Rotaphone at the NKC station (WEBNET seismic network)
2012-01-12 08:54:18 UTC; ML 2
distance **0.7 km**, depth **9.2 km**, geometrical backazimuth 205º from N



Rotaphone at the NKC station (WEBNET seismic network) **EXAMPLE 1**

2012-01-12 08:54:18 UTC; *ML 2*

distance **0.7 km**, depth **9.2 km**, geometrical backazimuth 205º od N

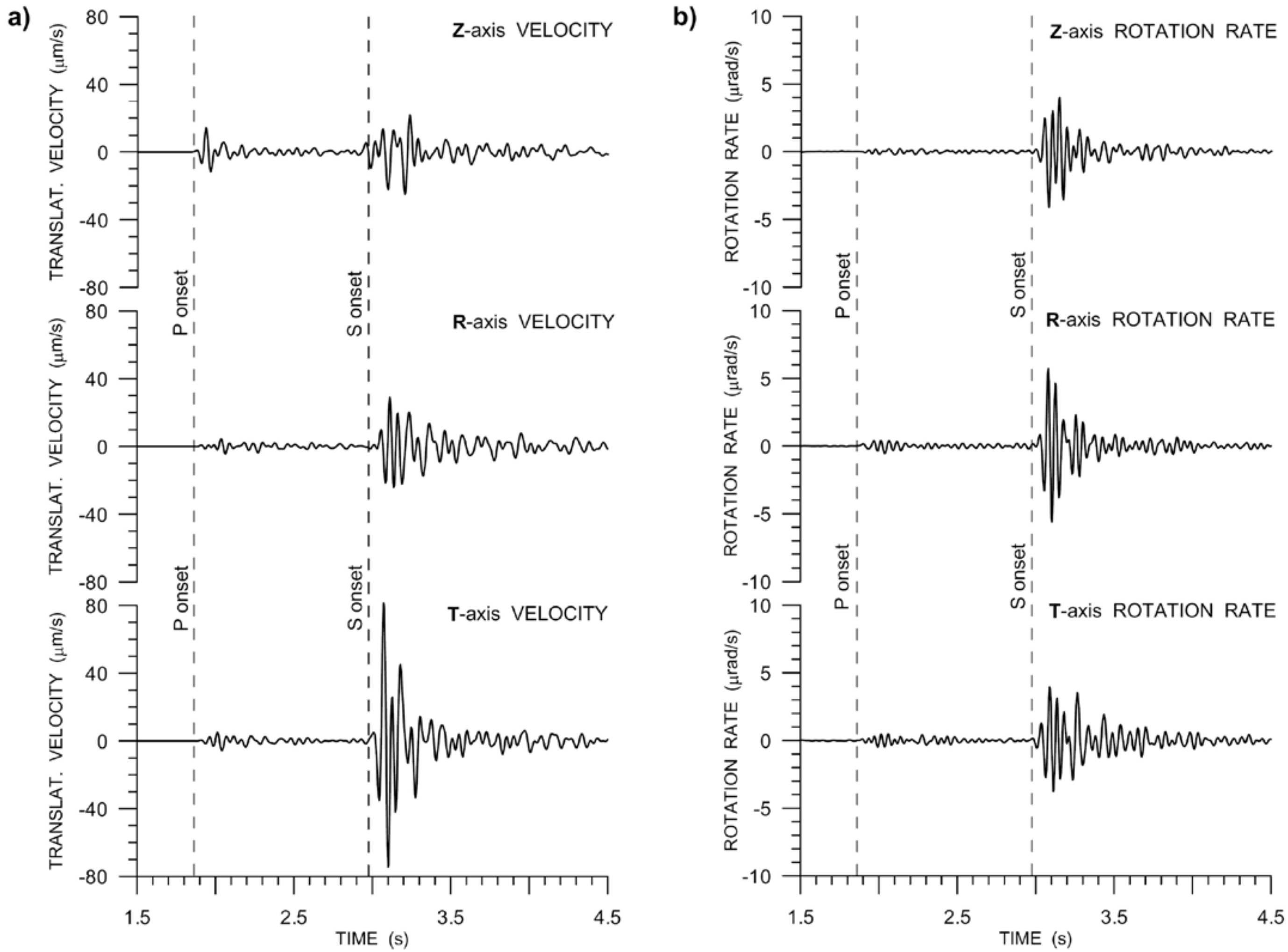


(Brokešová, 2014)

Rotaphone at the NKC station (WEBNET seismic network) **EXAMPLE 1**

2012-01-12 08:54:18 UTC; ML 2

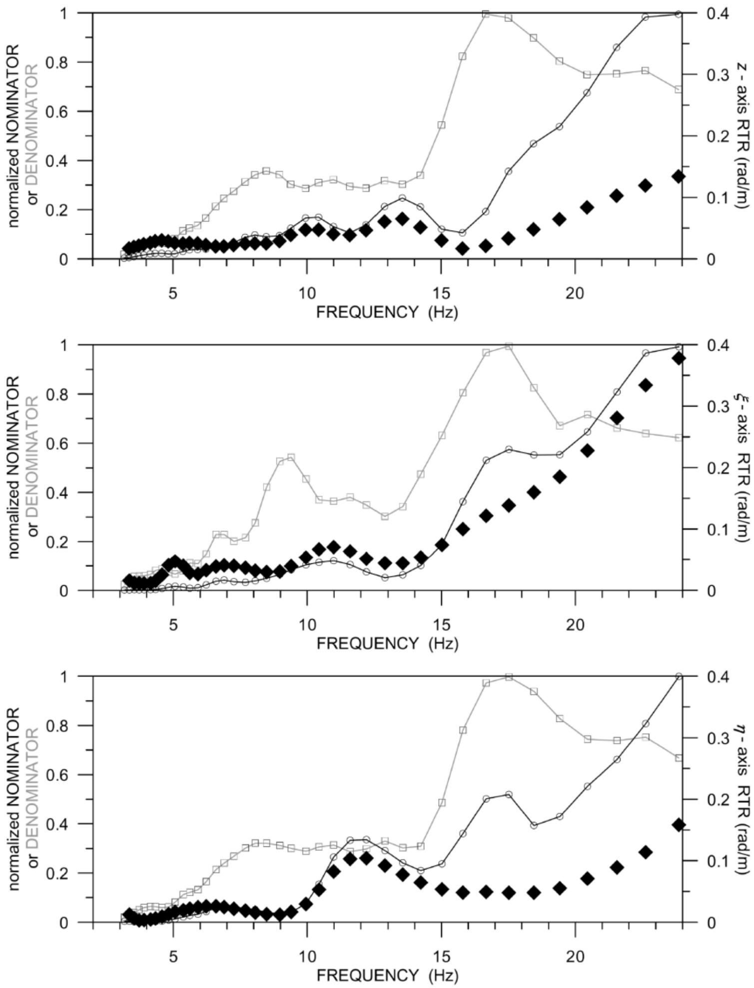
distance **0.7 km**, depth **9.2 km**, geometrical backazimuth 205º od N



2 - 24 Hz

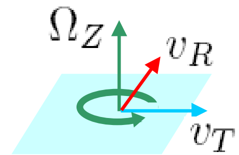
(Brokešová, 2014)

Rotaphone at the NKC station (WEBNET seismic network) **EXAMPLE 1**
2012-01-12 08:54:18 UTC; ML 2
distance **0.7 km**, depth **9.2 km**, geometrical backazimuth 205º od N

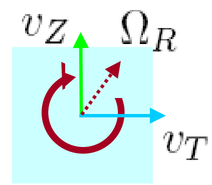


(Brokešová, 2014)

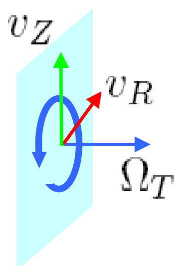
Rotation-to-translation ratios (RTR):



$$\mathrm{RTR}^z = \max(|\Omega_z|)/\max\left(\sqrt{v_x^2 + v_y^2}\right)$$



$$\mathrm{RTR}^x = \max(|\Omega_x|)/\max\left(\sqrt{v_y^2 + v_z^2}\right)$$

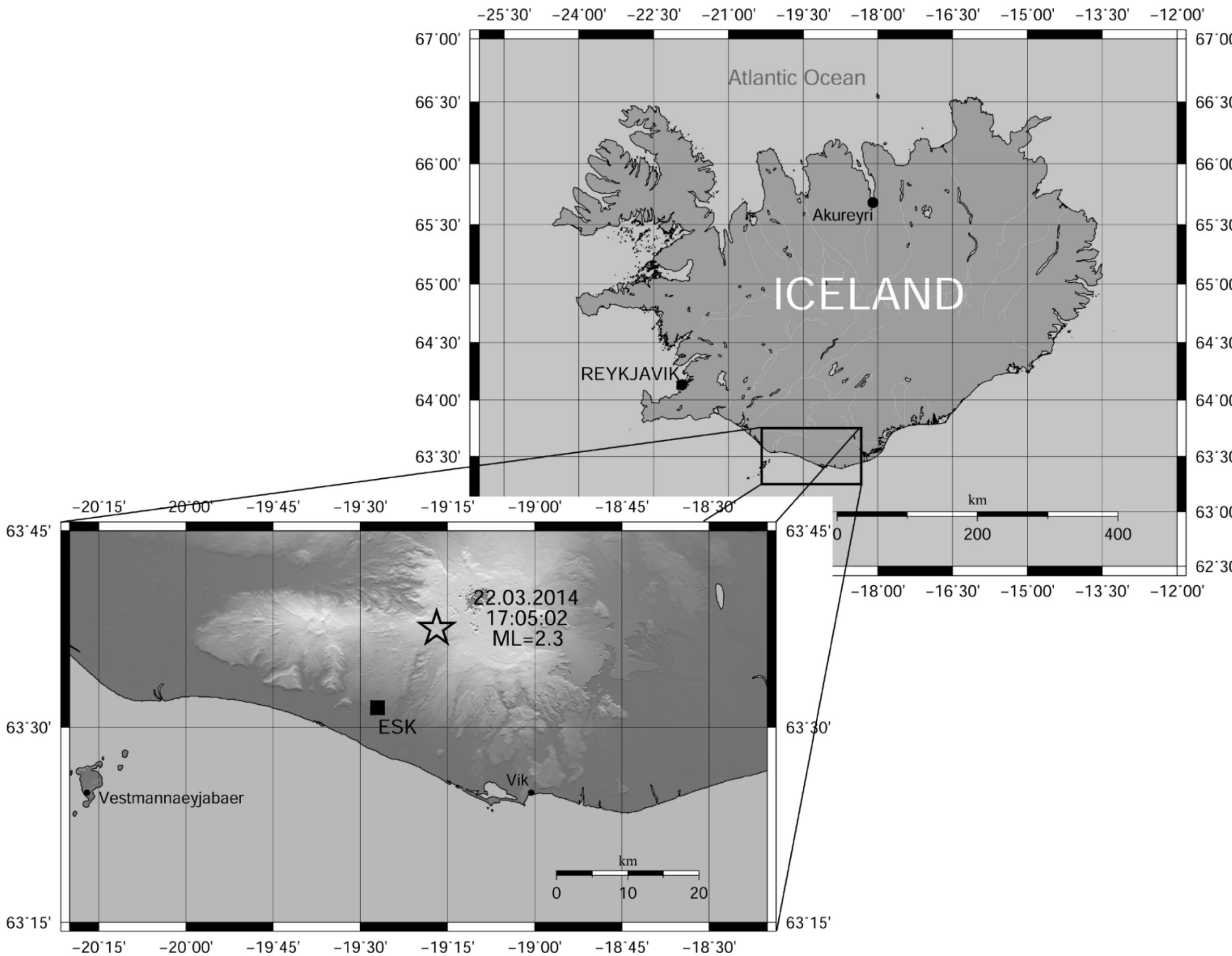


$$\mathrm{RTR}^y = \max(|\Omega_y|)/\max\left(\sqrt{v_x^2 + v_z^2}\right)$$

RTR závisí na frekvenci, hypocentrální vzdálenosti, typu zdroje, vyzaŸovací charakteristice, struktuŸe podél trajektorie, lokální struktuŸe & ..
…… systematický výzkum dobudoucna nutný

ROTAPHONE – examples of records EXAMPLE 2

Rotaphone at the ESK station (SIL network)
2014-03-22 17:05:02 UTC; ML 2.3
distance **14.9 km**, depth **4.8 km,** geometrical backazimuth 36º from N

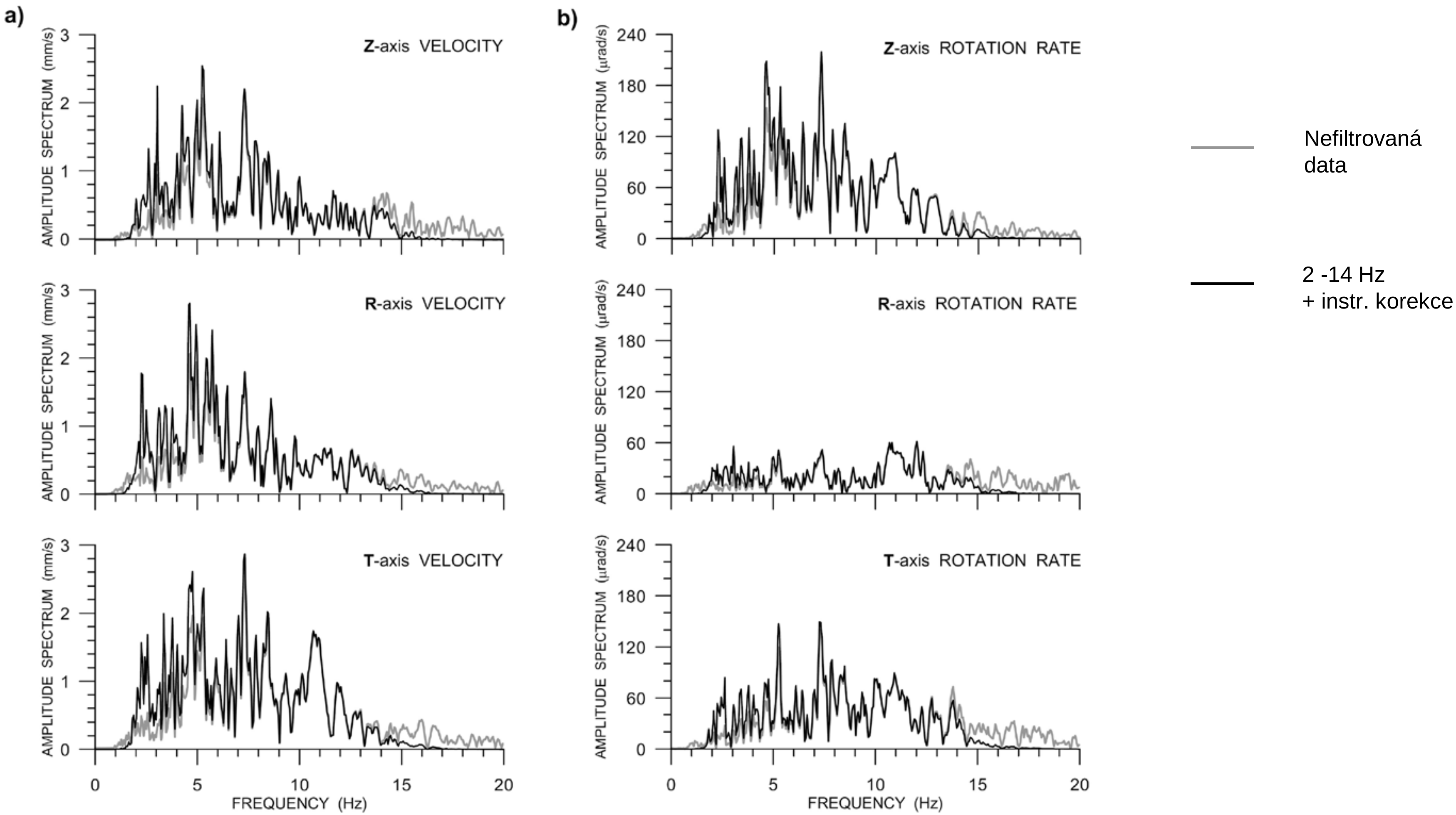


Rotaphone at the ESK station (SIL network)

2014-03-22 17:05:02 UTC; ML 2.3

distance **14.9 km**, depth **4.8 km,** geometrical backazimuth 36º from N

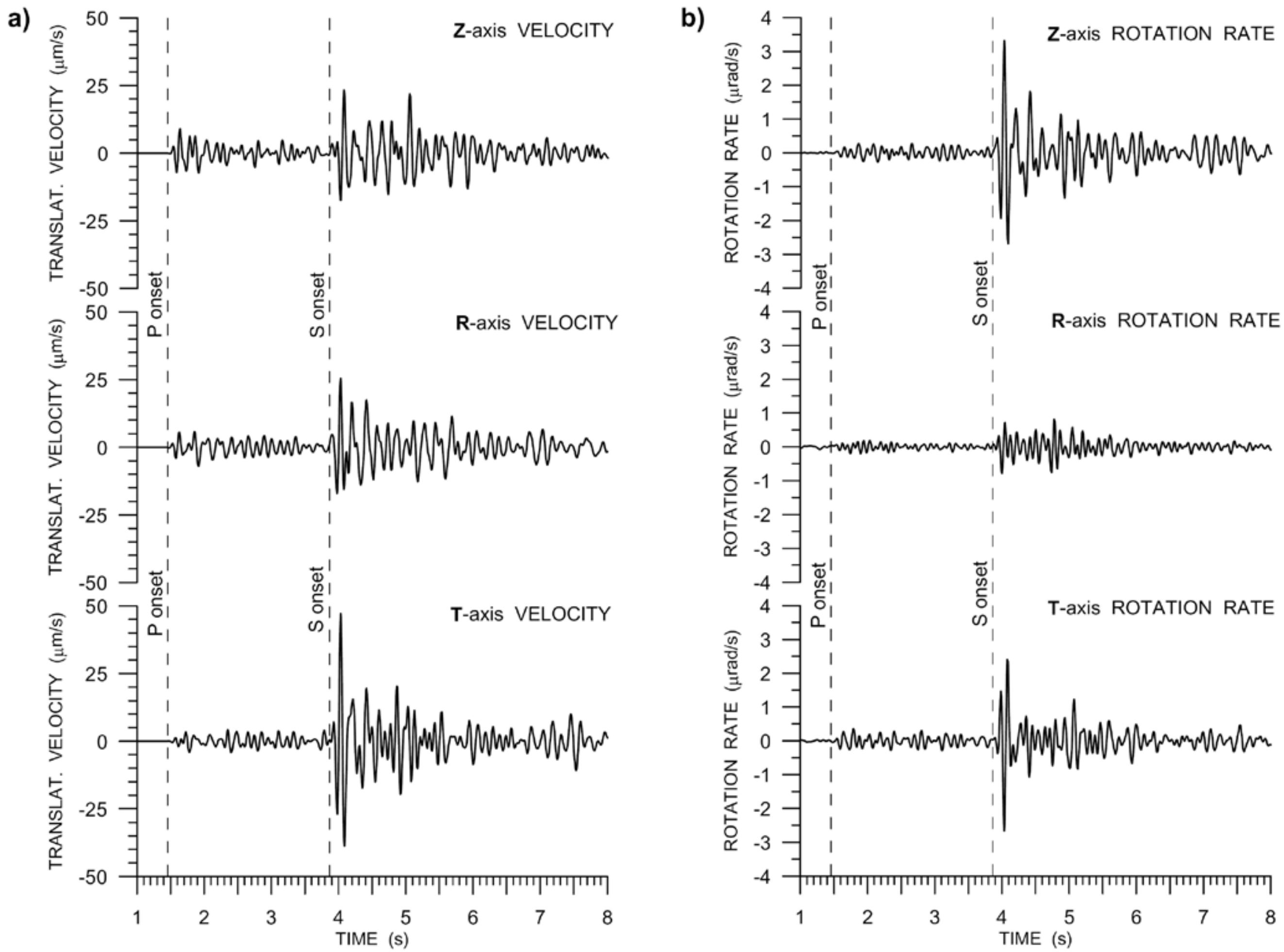
EXAMPLE 2



(Brokešová & Málek., 2015b)

Rotaphone at the ESK station (SIL network)
2014-03-22 17:05:02 UTC; ML 2.3
distance **14.9 km**, depth **4.8 km,** geometrical backazimuth 36º from N

EXAMPLE 2



(Brokešová & Málek., 2015b)

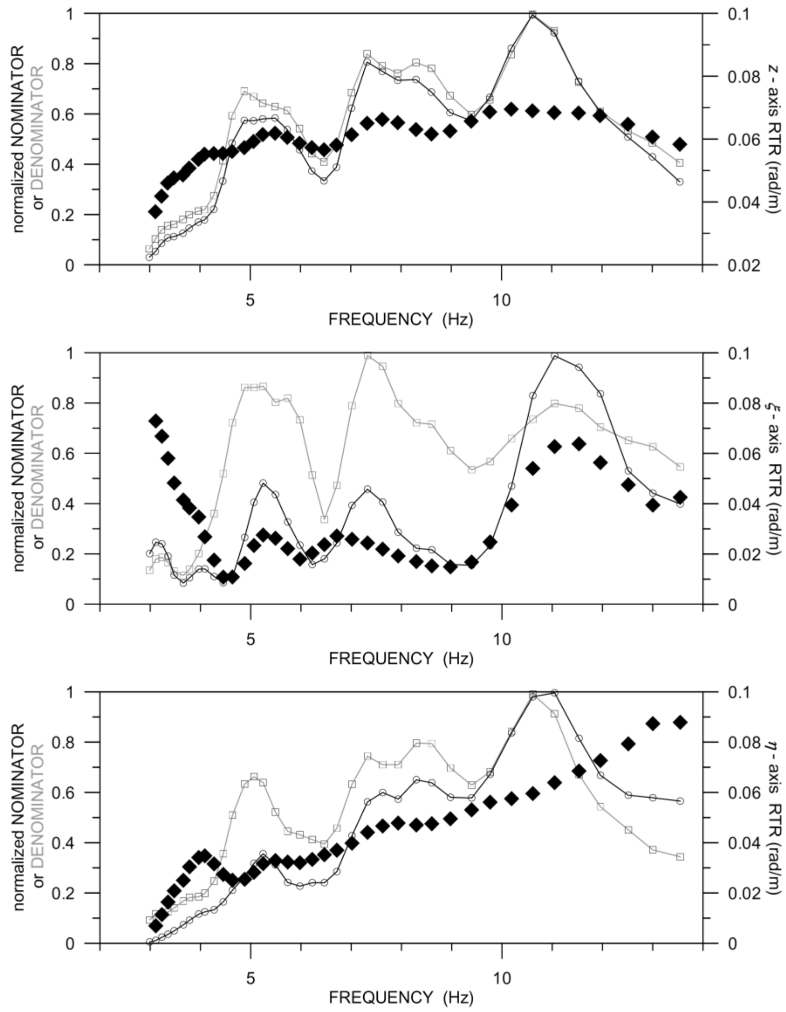
2 - 14 Hz

Rotafon at the ESK station (SIL network)

EXAMPLE 2

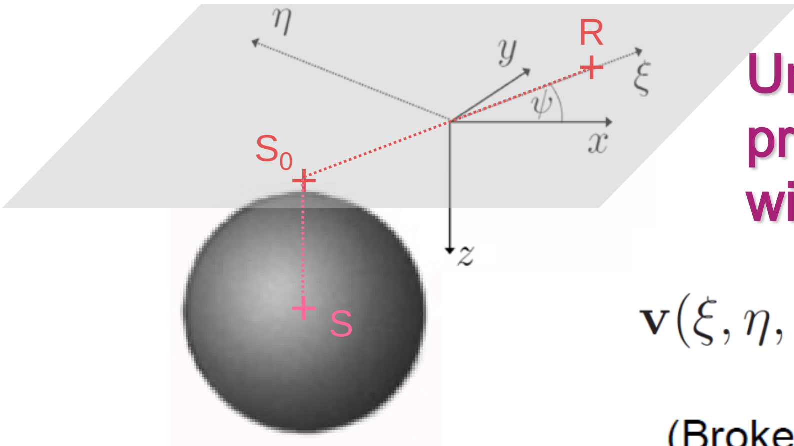
2014-03-22 17:05:02 UTC; ML 2.3

distance **14.9 km**, depth **4.8 km,** geometrical backazimuth 36º from N



(Brokešová & Málek., 2015b)

Rotation-to-translation relations (LOCAL EARTHQUAKES)



Under the assumption of a spherical wave propagating from a point source S with phase velocity β :

$$\mathbf{v}(\xi,\eta,z,t) = \frac{\mathbf{V}}{r} F\left(t - \frac{r}{\beta}\right) \qquad r = \sqrt{\xi^2 + \eta^2 + z^2}$$

(Brokešová & Málek, 2015a,b)

$$\Omega_\xi = \frac{1}{\bar{V}_z}\frac{\partial V_z}{\partial \eta} v_z = C_{11} v_z, \qquad (2.1)$$

$$\Omega_\eta = \left(-\frac{1}{\bar{V}_z}\frac{\partial \bar{V}_z}{\partial \xi} + \frac{\Delta}{r^2}\right) v_z + \frac{\Delta}{r\beta} a_z = C_{21} v_z + C_{22} a_z, \qquad (2.2)$$

$$\Omega_z = \frac{1}{2}\left(\frac{1}{\bar{V}_\eta}\frac{\partial \bar{V}_\eta}{\partial \xi} - \frac{\Delta}{r^2}\right) v_\eta - \frac{1}{2}\frac{1}{\bar{V}_\xi}\frac{\partial \bar{V}_\xi}{\partial \eta} v_\xi - \frac{\Delta}{2r\beta} a_\eta = C_{31} v_\eta + C_{32} a_\eta, \qquad (2.3)$$

$$C_{11} = \frac{1}{\bar{V}_z}\frac{\partial \bar{V}_z}{\partial \eta}, \quad C_{21} = \left(\frac{\Delta}{r^2} - \frac{1}{\bar{V}_z}\frac{\partial \bar{V}_z}{\partial \xi}\right), \quad C_{22} = \frac{\Delta}{r\beta}, \quad C_{31} = \frac{1}{2}\left[\left(\frac{1}{\bar{V}_\eta}\frac{\partial \bar{V}_\eta}{\partial \xi} - \frac{\Delta}{r^2}\right) - C_\xi \frac{1}{\bar{V}_\xi}\frac{\partial \bar{V}_\xi}{\partial \eta}\right], \quad C_{32} = -\frac{1}{2}\frac{\Delta}{r\beta}$$

$$C_\xi = v_\xi / v_\eta$$

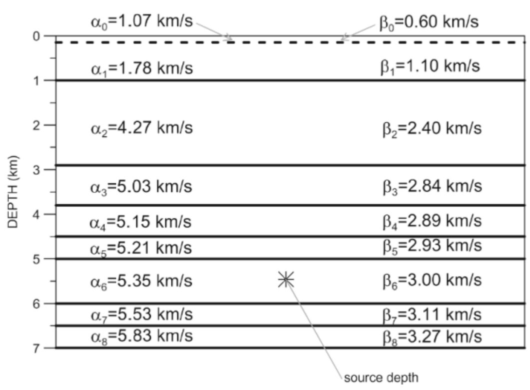
Rotation-to-translation relations
– LOCAL EARTHQUAKES

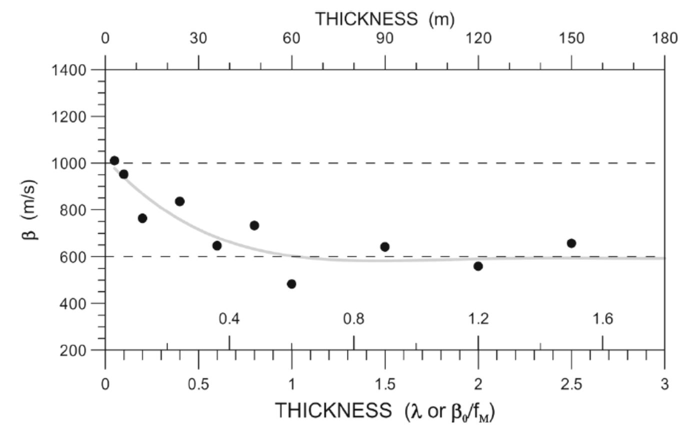
Velocity terms cannot be neglected in focal regions
They may be important in an immediate vicinity of the epicenter, in the vicinity of nodal planes, in the vicinity of the critical angle, or in a region with high subsurface S-wave velocity

An inverse problem – we seek for the coeficients C_{ij}
C_{22}, C_{23} … information about the structure $(\sim 1/\beta)$, C_{11},C_{21} ,C_{31} source mechanism

The relations hold in each time (until the wave under study is masked with other phases) =>
it is possible to take sufficient number of tsamples to make the inverse problem overdetermined

Synthetic studies prove that **the equations can be applied also in a vertically inhomogeneous layered medium** (thanks to high localization of the method's sensitivity to a small vicinity of a receiver, ~ 1 λ**)**



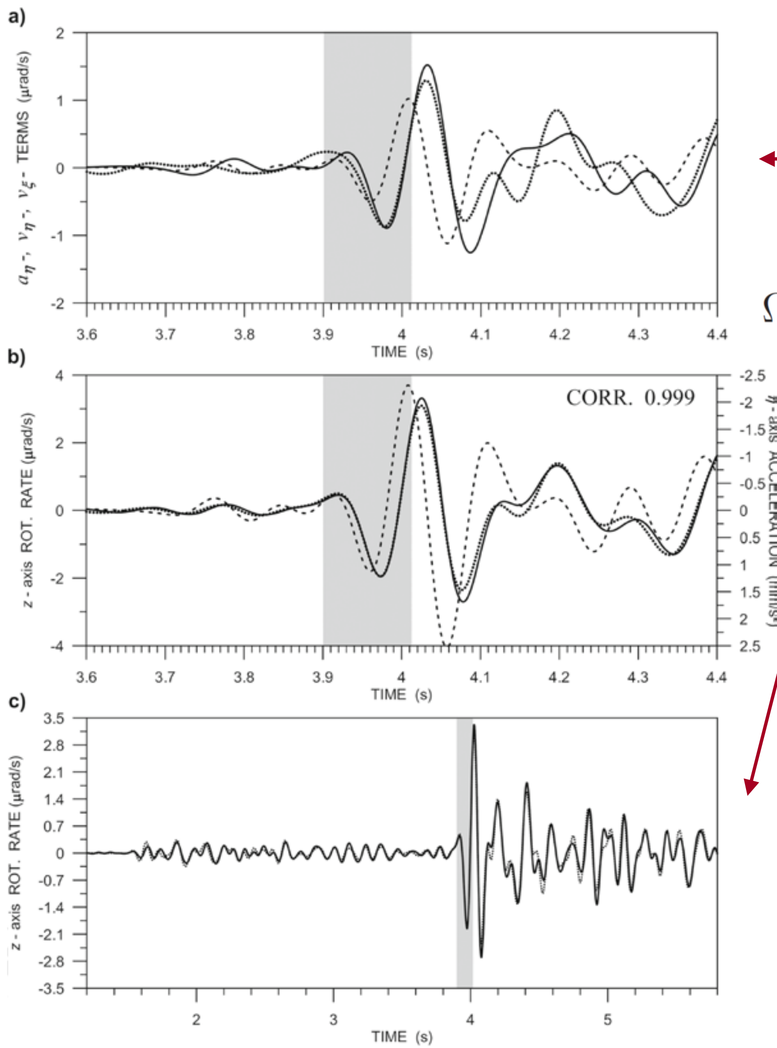


(Brokešová & Málek., 2015a)

Rotafon at the ESK station (SIL network) **(EXAMPLE 2)**

2014-03-22 17:05:02 UTC; ML 2.3

distance **14.9 km**, depth **4.8 km,** geometrical backazimuth 36º from N



2 - 14 Hz

Individual terms on the r.h.s of the 3rd equation (relation between Ω_z and a_η, v_η, v_ξ)

$$\Omega_z = \frac{1}{2}\left(\frac{1}{\bar{V}_\eta}\frac{\partial \bar{V}_\eta}{\partial \xi} - \frac{\Delta}{r^2}\right) v_\eta - \frac{1}{2}\frac{1}{\bar{V}_\xi}\frac{\partial \bar{V}_\xi}{\partial \eta} v_\xi - \frac{\Delta}{2r\beta} a_\eta$$

Bilance of the 3rd equation (relation between Ω_z and a_η, v_η, v_ξ)

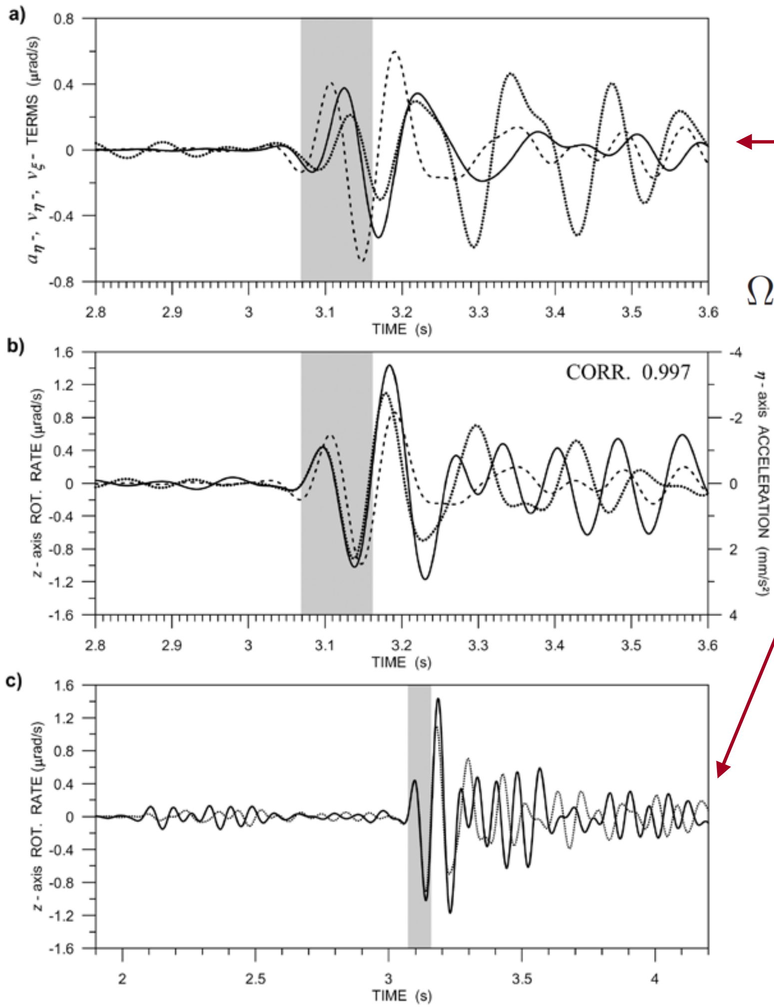
(Brokešová & Málek., 2015b)

Rotaphone at the NKC station (WEBNET seismic network) **(EXAMPLE 1)**

2012-01-12 08:54:18 UTC; ML 2

distance **0.7 km**, depth **9.2 km**, geometrical backazimuth 205° od N

2 - 14 Hz



Individual terms on the r.h.s of the 3rd equation (relation between Ω_z and a_η, v_η, v_ξ)

$$\Omega_z = \frac{1}{2}\left(\frac{1}{\bar{V}_\eta}\frac{\partial \bar{V}_\eta}{\partial \xi} - \frac{\Delta}{r^2}\right) v_\eta - \frac{1}{2}\frac{1}{\bar{V}_\xi}\frac{\partial \bar{V}_\xi}{\partial \eta} v_\xi - \frac{\Delta}{2r\beta} a_\eta$$

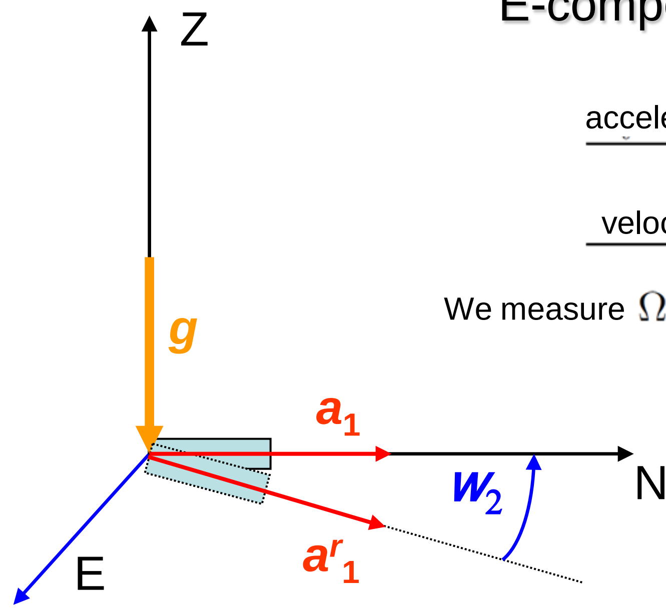
Bilance of the 3rd equation (relation between Ω_z and a_η, v_η, v_ξ)

(Brokešová & Málek., 2015b)

Are horizontal translational components contaminated with tilts ?

(a problem widely discussed in the literature, e.g., Graizer 2005)

E-component example



acceleration $a_1^r = a_1 - g \sin w_2 \approx a_1 - g w_2$ for small w_2 $(\ll 1)$

velocity $v_1^r \approx v_1 - g \int w_2 \mathrm{d}t; \quad v_1 = \int a_1 \mathrm{d}t$

We measure $\Omega_2 = \dot{w}_2,$ so

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

(in the frequency domain) …~9.81/(iω)^2 x RTR

w_2 **…** tilt around the E-axis

g **…** gravitational acceleration

a_1 **…** true horizontal acceleration

a^r_1 **…** recorded horizontal acceleration

This correction is **NEGLIGIBLE** in the Rotaphone frequency range (>2 Hz) and for RTR obtained up to now from micro-earthquakes in focal regions (<1)

This correction is **usually IMPORTANT** for the ADR and RLG methods

Instead of conclusions:

Rotational seismology is a beautiful and attractive science which explores a new observable quantity, the curl of the seismic wave-field.

It is not too exaggerated if I say that, at present, the science is going through a very exciting and adventurous phase similar to that which the traditional seismology, based on translational motions measured by traditional seismographs, underwent in the late 19th century and early 20th century. I mean a transition phase from the era of fascination by the new possibility to measure something as imperceptible as seismic rotation, when a rotational record as such was a "discovery" by itself for being so new, into the era of systematic research based on in-depth analysis, interpretation and inversion of the data obtained. I believe that rotational seismology has the potential to give seismologists and engineering seismologists alternative methods and supplementary procedures using the new observable (mostly in connection with traditional translation) as well as new discoveries of substantial importance.

References

Brokešová, J. (2014). Short-period seismic rotations and translations. Habilitation thesis, Charles University in Prague, Faculty of Mathematics and Physics.

Brokešová, J. and Málek, J. (2010). New portable sensor system for rotational seismic motion measurements. *Rev. Sci. Instrum.*, 81(8):084501.

Brokešová, J. and Málek, J. (2013). Rotaphone, a self-calibrated six-degree-of-freedom seismic sensor and its strong-motion records. *Seismol. Res. Let.*, 84(5):737–744.

Brokešová, J. and Málek, J. (2015a). Six-degree-of-freedom near-source seismic motions I: Rotation-to-translation relations and synthetic examples. *J. Seismol.* DOI: 10.1007/s10950-015-9479-y.

Brokešová, J. and Málek, J. (2015b). Six-degree-of-freedom near-source seismic motions II: Examples of real seismogram analysis and s-wave velocity retrieval. *J. Seismol.* DOI: 10.1007/s10950-015-9480-5.

Brokešová, J. and Málek, J. (2015c). Small-apperture seismic array data processing using the representations of seismograms at zero-amplitude points. *J. Geophys. Res.*, page submitted.

Brokešová, J., Málek, J., and Evans, J. R. (2012a). Rotaphone, a new self-calibrated six-degree-of-freedom seismic sensor. *Rev. Sci. Instrum.*, 83(8):086108.

Brokešová, J., Málek, J., and Kolínský, P. (2012b). Rotaphone, a mechanical seismic sensor system for field rotation rate measurements and its in-situ calibration. *J. Seismol.*, 16(4):603–621.

References (continuation)

Brokešová, J., Málek, J., and Štrunc, J. (2009). Rotational seismic sensor system, seismic measuring set containing that system, and seismic survey method. Věstník Úřadu průmyslového vlastnictví, No. 49/2009, B6, p. 5, G 01V 1/143. Patent CZ 301217.

Graizer, V. M. (2005). Effect of tilt on strong motion data processing. *Soil Dynamics and Earthquake Engineering*, 25:197–204.

Igel, H., Cochard, A., Wassermann, J., Flaws, A., Schreiber, U., Velikoseltsev, A., and Pham, D. N. (2007). Broad-band observations of earthquake-induced rotational ground motions. *Geophys. J. Int.*, 168(1):182–196.

Igel, H., Schreiber, U., Flaws, A., Schuberth, B., Velikoseltsev, A., and Cochard, A. (2005). Rotational motions induced by the M8.1 Tokachi-oki earthquake, September 25, 2003. *Geophys. Res. Lett.*, 32:L08309.

Lee, W. H. K., Igel, H., and Trifunac, M. D. (2009b). Recent advances in rotational seismology. *Seismol Res. Let.*, 80(3):479–490.

Schreiber, U., Hautmann, J., Velikoseltsev, A., Wassermann, J., Igel, H., Otero, F., Vernon, F., and Wells, P. (2009). Ring Laser Measurements of Ground Rotations for Seismology.

Stedman, G. E. (1997). Ring-laser tests of fundamental physics and geophysics. *Rep. Prog. Phys.*, 60:615–688.