Rotaphone-D - a new six-degree-of-freedom short-period seismic sensor: features, parameters, field records

Johana Brokešová[1], Jiří Málek[2] and John R. Evans[3]

1) Charles University, Faculty of Mathematics and Physics,
Department of Geophysics,
V Holešovičkách 2, 180 00, Prague, Czech Republic
Johana.Brokesova@mff.cuni.cz

2) Institute of Rock Structure and Mechanics, Academy of Science,
Department of Seismology,
V Holešovičkách 41, 182 09, Prague, Czech Republic
Malek@irsm.cas.cz

3) U.S. Geological Survey,
U.S. Department of the Interior
400 Natural Bridges Dr., Santa Cruz, CA 95060, U.S.A.
jrevans@usgs.gov

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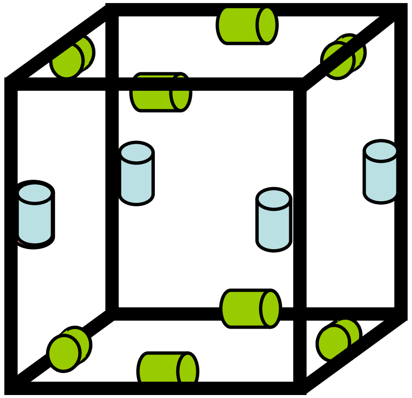
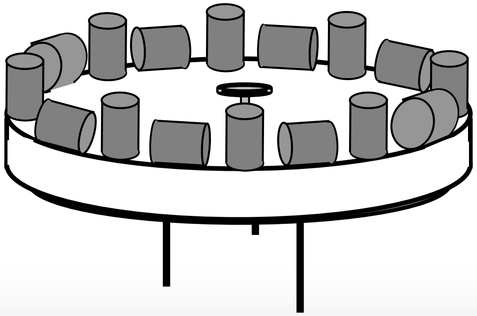
Rotaphone-D - a new six-degree-of-freedom short-period seismic sensor

Rotaphone = mechanical sensor system designed to measure spatial ground motion gradients; it consists of geophones arranged in parallel pairs

… an older version of Rotaphone (3DOF), 8 horizontal geophones, see Brokešová & Málek 2010 and Brokešová et al. 2012a

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

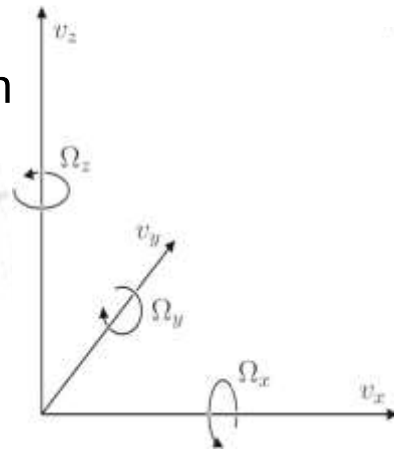




... latest prototype Rotaphone-D, 6 DOF,
8 horizontal + 8 vertical geophones

Rotaphone-D: basic features

- The instrument provides **collocated translational and rotational records** (with the **same instrumental characteristics**)
- It consists of high-sensitive low-frequency geophones mounted in **parallel pairs** to a **rigid (metal) ground-based frame**
- The distance separating the paired geophones (40 cm) is **than the wavelength of interest** (measurement at a poin
- Both vertical and horizontal geophones are used – **6DOF** Thanks to the rigidity of the frame, **rot. rate components**



$$\Omega_x = \frac{\partial v_z}{\partial y} \qquad \Omega_y = \frac{\partial v_x}{\partial z} \qquad \Omega_z = \frac{\partial v_y}{\partial x} = -\frac{\partial v_x}{\partial y}$$

- Rotation rate is determined by more than one geophone pair, which allows to perform very precise **'in situ' calibration of the geophones** (actual responses corresponding to each measurement)

Rotaphone-D: basic parameters

Basic components:

8 horizontal geophones SM-6 HB 4.5 Hz	3500 ohm
8 vertical geophones SM-6 UB 4.5 Hz	3500 ohm
1 A/D converter	
1 GPS receiver and antenna	
1 datalogger	

Parameters of the instrument:

frequency range	2 - 80 Hz
sampling frequency	250 Hz
LSB for translational components	1.51 nm/s
LSB for rotational components	3.77 nrad/s
maximum translation velocity	12.67 mm/s
maximum rotation rate	31.68 mrad/s
translational dynamic range	138 dB
rotational dynamic range	120 dB
paired sensor spacing	40 cm
disc diameter	44.5 cm
height	11.2 cm/8 cm
weight	15.3 kg

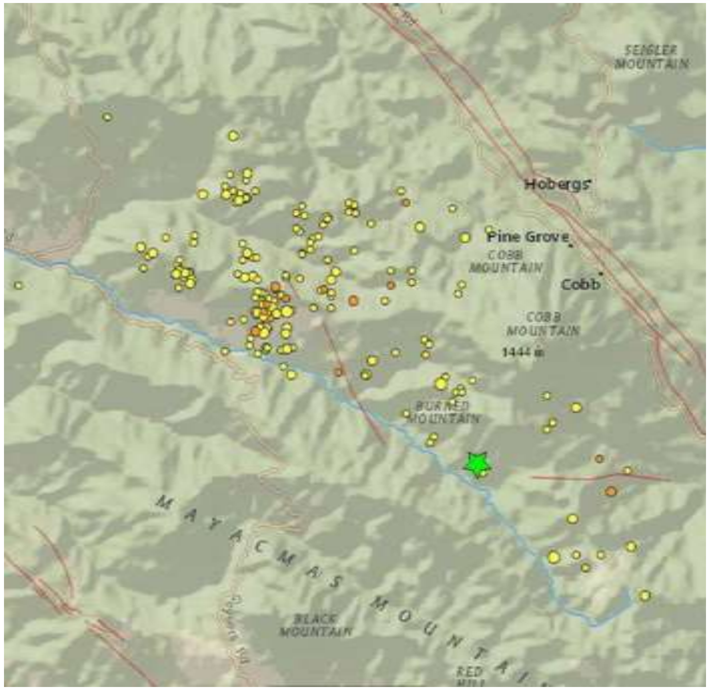
Geophone parameters:

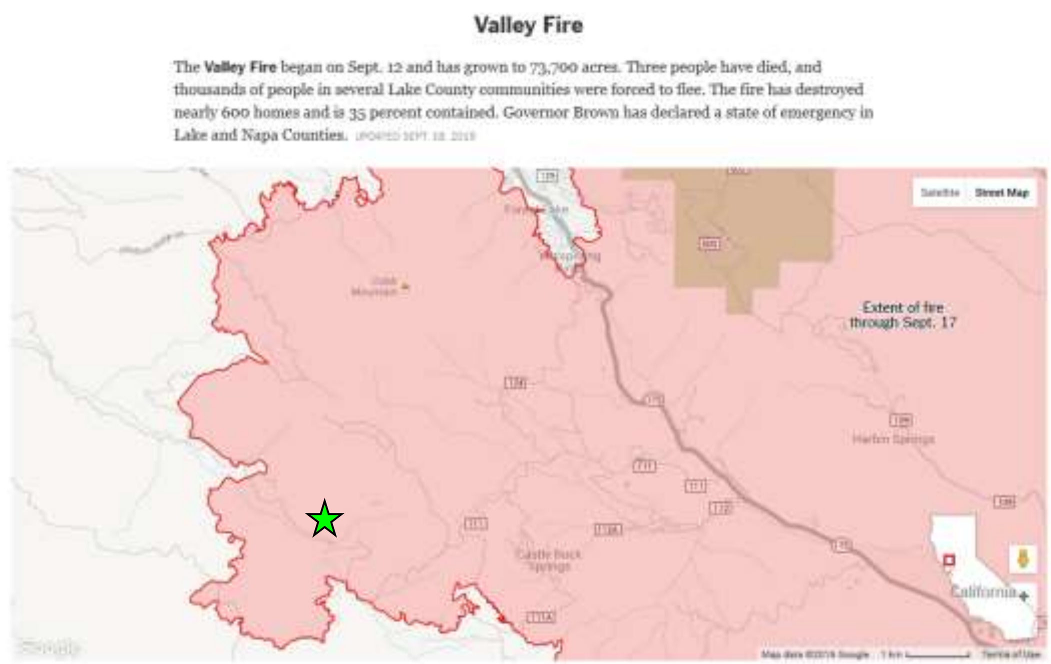
natural frequency	4.5 Hz
sensitivity	78.9 Vs/m
open circuit damping	0.58 ± 5%
maximum coil excursion p.p.	4 mm
standard coil resistance	3500 Ω ± 5%
diameter	34 mm
height	65 mm
weight	170 g
moving mass	10 g
operating temperature range	-40 – +100 °C

A/D converter parameters:

bits	24
channels	16
range	± 1 V or ± 2.5 V

Testing deployment at The Geysers geothermal field – Jun 6 – Nov 31, 2015





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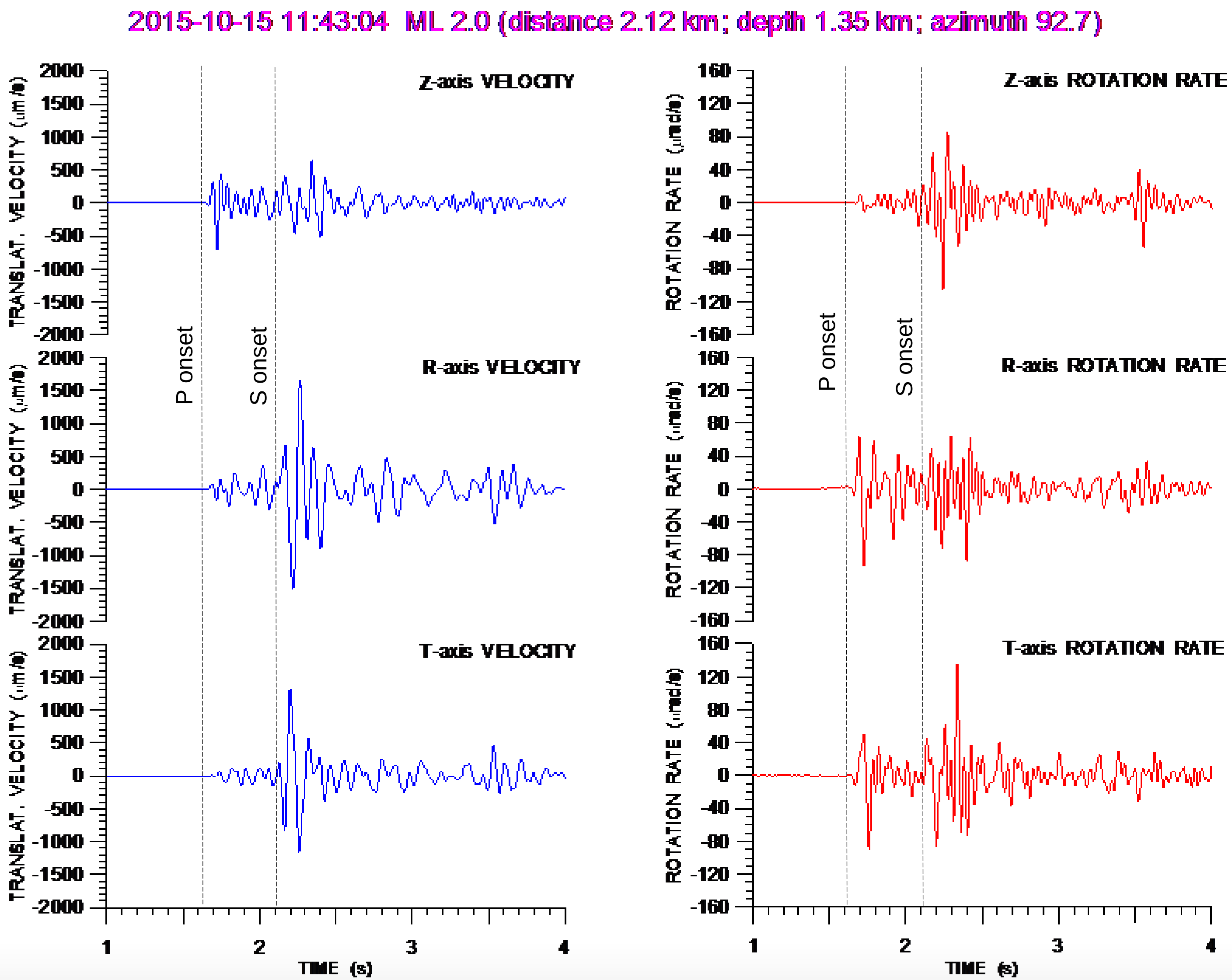
Testing deployment at The Geysers geothermal field



Testing deployment at Long Valley Cal

- an elliptic depression (approx. 15x30 km) on t

ag

up

lca

F

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Testing deployment at Long Valley Caldera (Mammoth Lakes Region)

First phase: Dec 8, 2015 – Apr 25, 2016

(a small earthquake swarm; period 3-23 Feb, 2016)

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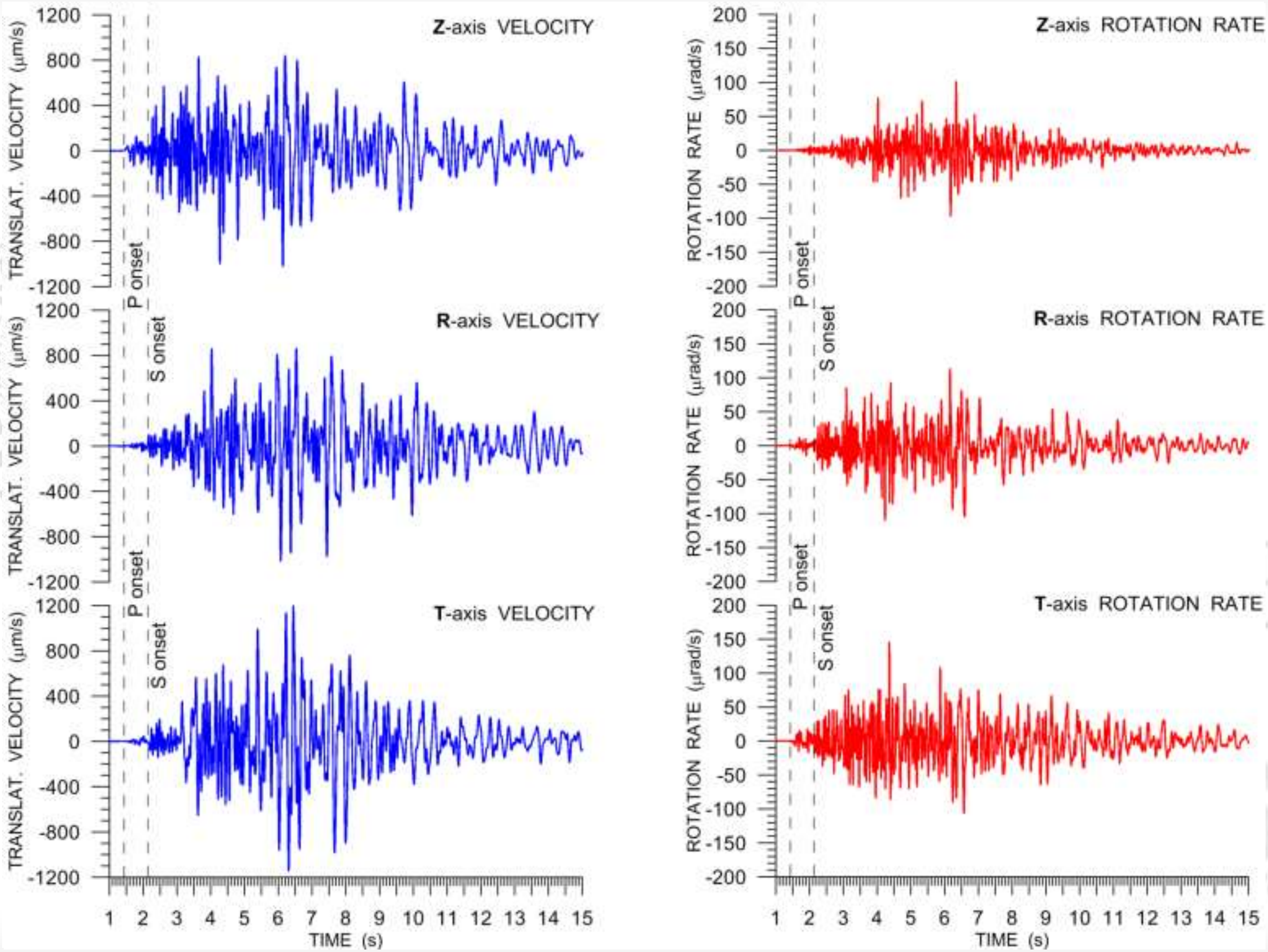
SN1 (vault A) Δ = 6.8 km BAZ = 196°



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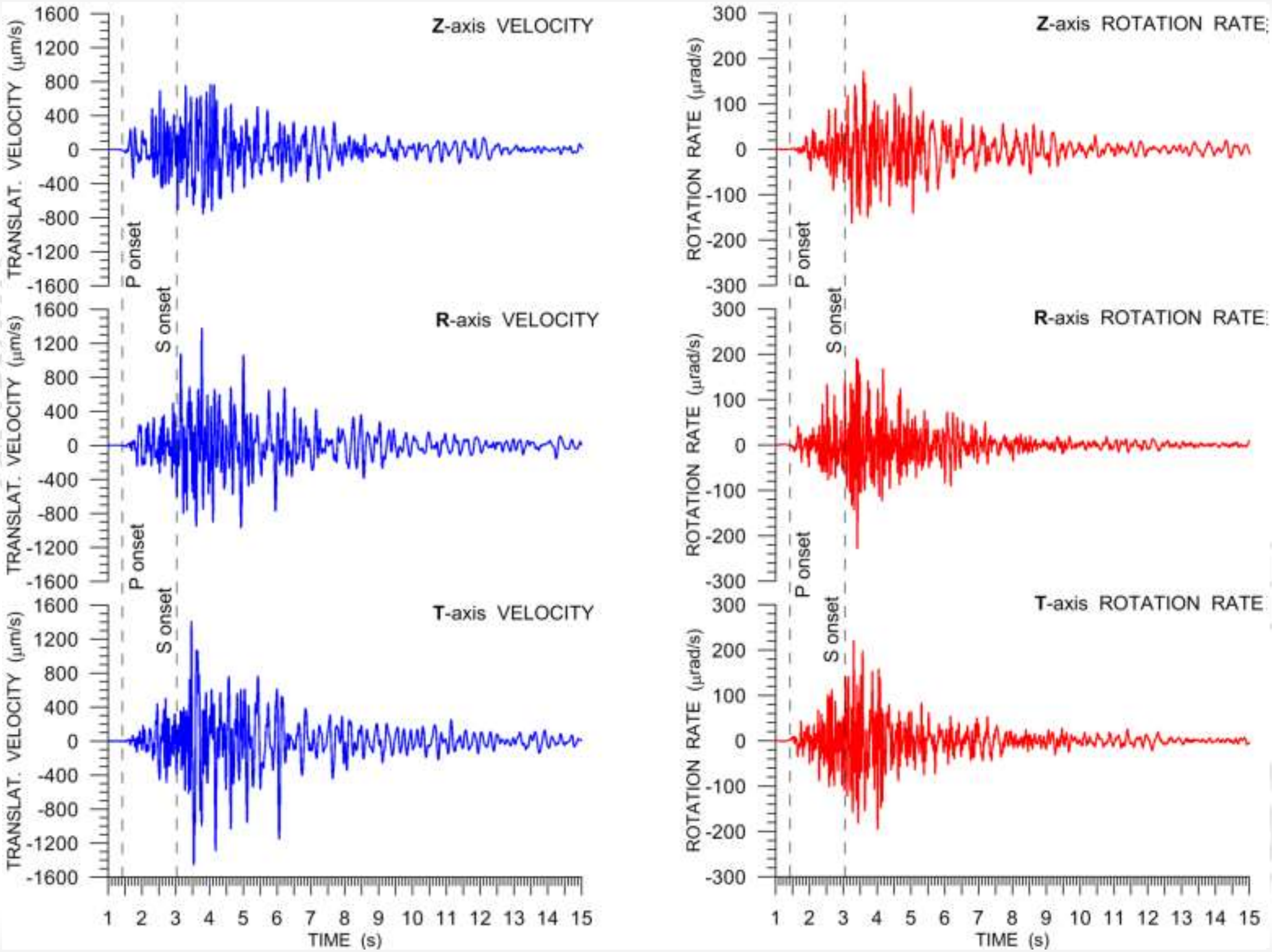
SN2 (Casa Diablo) Δ = 8.9 km BAZ = 157°



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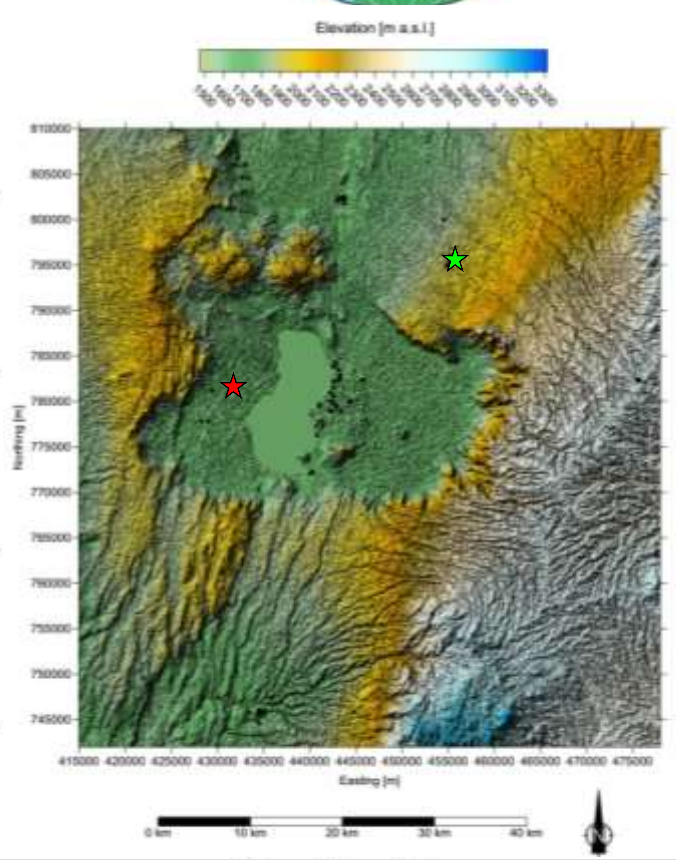
Rotaphone in Ethiopia (Shashamane): Nov 2, 2015 – until now



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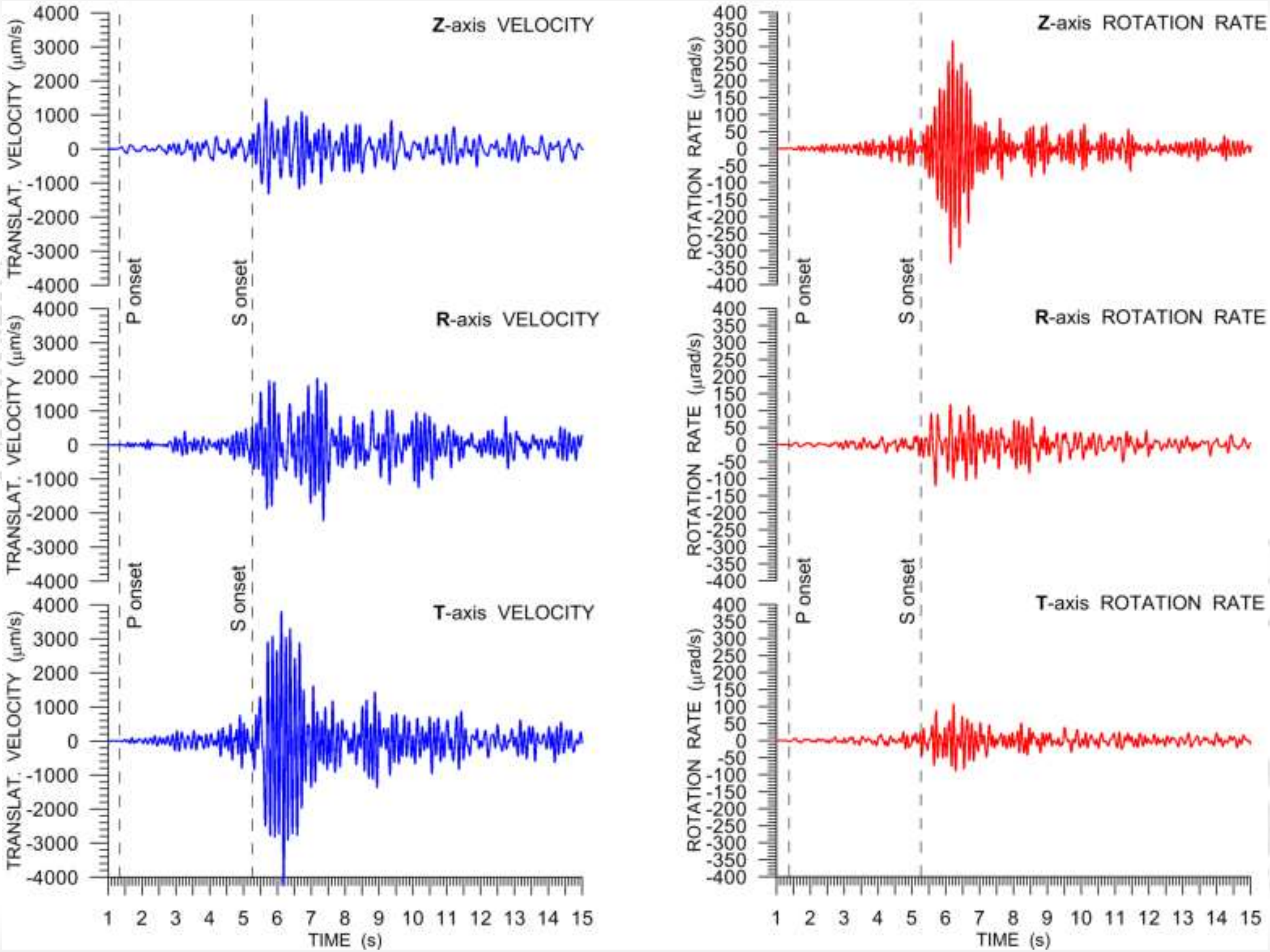
M 4.4 2016/01/24 – 18:34:32 UTC   Δ = 31 km   BAZ = 263°



Rotation to translation relations (distant earthquakes)

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

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

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

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

We assume that c obtained in this way is representative down to the depth of about one wavelength.
(Fichtner and Igel, 2009; Bernauer et al., 2012; Brokešová and Málek, 2015a)

Taking the amplitude ratio at the time of peak transverse acceleration we get the rough velocity estimate $c \sim 256$ m/s.
Prevailing frequency is 8 Hz => $\lambda \sim 30$ m => $c = v_S^{30}$ *(*soil type S_D*,* Wills et. al 2000*)*

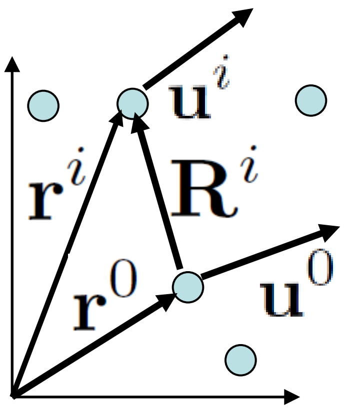
Rotaphone-D: a limitation - only a short period device

In order to measure at lower frequencies we should

1) use lower–frequency elemental sensors
2) use a larger frame (longer sensor separation distance)

An alternative is to use either a low-frequency rotational sensor (a ring laser) or the ADR method to derive spatial ground motion gradients/rotations

(Brokešová and Málek, PEPI 2016)



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

$$\mathbf{u}^i = (u_1^i, u_2^i, u_3^i)^T \quad i = 0, 1, \ldots, N$$

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

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

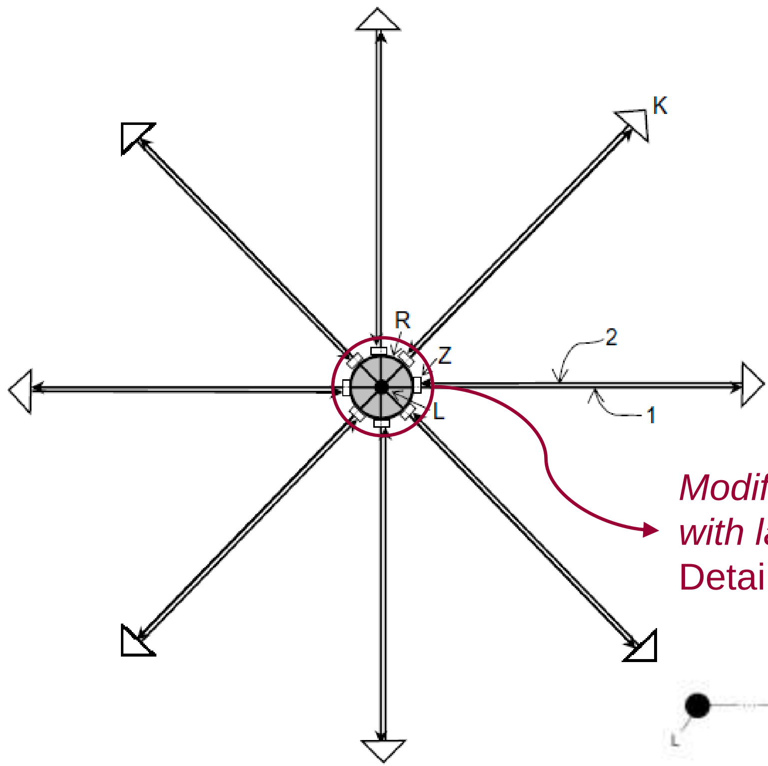
$$\begin{pmatrix} d_1^i \\ d_2^i \\ d_3^i \end{pmatrix} = \begin{pmatrix} u_{1,1} & u_{1,2} & \cdots \\ u_{2,1} & u_{2,2} & \cdots \\ u_{3,1} & u_{3,2} & \cdots \end{pmatrix} \begin{pmatrix} R_1^i \\ R_2^i \\ 0 \end{pmatrix}$$

after Spudich et al., JGR, 1995

What next? : **Opto-mechanical seismic sensor system**

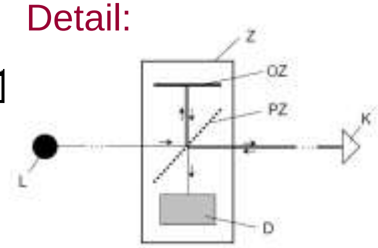
… a modified Rotaphon-D supplemented with optical elements (laser dilatometers)

Basic scheme of the instrument:



Modified Rotafon with laser elements

Detail:



- Not only mechanical, but **opto**-mechanical sensor (containing laser source and receivers, semipermeable mirrors, interferometer, and corner reflectors)
- Not only 6 but **9** seismic components (3 translational, 3 rotational + **3 strain components**)

The new instrument will allow
- to broaden the frequency range towards lower frequencies
- to process whole seismograms (including P waves)

References:

Bernauer, M., Fichtner, A., and Igel, H. (2012). Measurements of translation, rotation and strain: New approaches to seismic processing and inversion. *J. Seismol.*, 16(4):669–681.

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. (2016). Small-aperture-array translational and rotational seismograms from distant sources - An example of the Jan Mayen Mw 6.8 of 30 August 2012 earthquake. *Physics of the Earth and Planetary Interiors*, 256:1–12. DOI:10.1016/j.pepi.2016.03.013.

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.

References:

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.

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.

Cochard, A., Igel, H., Schuberth, B., Suryanto, W., Velikoseltsev, A., Schreiber, U., Wassermann, J., Scherbaum, F., and Vollmer, D. (2006). Rotational motions in seismology: theory, observations, simulation. In et al., T., editor, *Earthquake source asymmetry, structural media and rotation effects*. Springer Verlag.

Fichtner, A. and Igel, H. (2009). Sensitivity densities for rotational ground motion measurements. *Bull. Seismol. Soc. Am.*, 99:1302–1314.

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.

Willis, C. J., Petersen, M., Bryant, W. A., Reichle, M., Saucedo, G. J., Tan, S., Taylor, G., and Treiman, J. (2000). A site-conditions map for California based on geology and shear-wave velocity. *Bull. Seismol. Soc. Am.*, 90(6B):S187–S208.