The Design and Data Translation of the Rotaphone, with an Example of the Instrument

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

1) Institute of Rock Structure and Mechanics,
Czech Academy of Sciences, Prague
Czech Republic, malek@irsm.cas.cz

2) Dept. of Geophysics, Faculty of Mathematics and Physics,
Charles University in Prague
Czech Republic, johana.brokesova@mff.cuni.cz

3) U.S. Geological Survey, Santa Cruz,
U.S. Department of the Interior
USA CA, jrevans@usgs.gov

1. Summary

Rotaphones are special geophone systems enabling measurement of 6 axes of ground motion, 3 translational and 3 rotational (6-degrees-of-freedom; 6DOF). In 2015 a new version of this sensor was designed, built, and tested at various sites. It has 16 geophones (8 vertical and 8 horizontal) around the periphery of a rigid disk-shaped frame. The key in converting these 16 axes measurements to 6DOF axes is precise relative calibration of the geophones. The first calibration (response estimate) is by the geophone manufacturer. However, to reach the accuracy required for rotational-components, measurements derived from differential signals between geophones (~1 to 80 Hz), a procedure of relative calibrations is required. The properties of the geophones also change with temperature, pressure, and from material aging. Therefore, the calibration has to be done repeatedly during the field measurements (in-situ calibration). For this version of Rotaphone, we developed two methods of in-situ calibration. The first uses a seismic shaker that produces repeatable seismic pulses. The Rotaphone detects these pulses repeatedly while the instrument is rotated around its vertical axis by constant angle increments between pulses. By comparing individual measurements with the sum of all measurements, we can reach very precise cross-calibration anchored to the mean response of the geophones. The 2nd technique is enabled by the instrument's over-determination — we have at our disposal 16 geophones while only six components are to be determined. The calibration is made simultaneously with field measurements. Finally, we will calibrate all the Rotaphones we use at the Albuquerque Seismological Laboratory of the USGS; we expect those tests will be valid between about 0.5 and 37 Hz; they are relative to laboratory standards. Examples of Rotaphone installations are discussed.

2. Basic principle of Rotaphone

The new rotational sensor system, shortly called 'rotaphone', is designed to measure the ground motion rotation rate components

$$\begin{aligned}\Omega_1 &= \frac{1}{2}\left(\frac{\partial v_3}{\partial x_2}-\frac{\partial v_2}{\partial x_3}\right),\\ \Omega_2 &= \frac{1}{2}\left(\frac{\partial v_3}{\partial x_1}-\frac{\partial v_1}{\partial x_3}\right),\\ \Omega_3 &= \frac{1}{2}\left(\frac{\partial v_2}{\partial x_1}-\frac{\partial v_1}{\partial x_2}\right),\end{aligned}$$

where v_i denotes a ground velocity component.

The method is based on determining the spatial derivatives of ground velocity approximating them by finite differences. This requires the ground velocities to be measured at two points, the distance of which is much smaller than the wavelength, but still large enough to allow differential motion (i.e. difference in the two records due to rotation) to be detected. Very sensitive instruments, e.g., geophones with high gain, have to be used to meet this condition. The geophones are mounted in pairs on a rigid **undeformable** skeleton attached to the ground. Thus the rotation rate components simplify

$$\begin{aligned}\Omega_1 &= \frac{\partial v_3}{\partial x_2} = -\frac{\partial v_2}{\partial x_3},\\ \Omega_2 &= \frac{\partial v_3}{\partial x_1} = -\frac{\partial v_1}{\partial x_3},\\ \Omega_3 &= \frac{\partial v_2}{\partial x_1} = -\frac{\partial v_1}{\partial x_2}.\end{aligned}$$

Assume the paired geophones are identical in terms of their characteristics. The only differences in the velocities recorded by the individual geophones, making up the pair, are then due to the rotational motion of the rigid skeleton. This rotation corresponds to the rotation of the ground at the point, at which the centre of the skeleton is situated.

Depending on the specific design features, the device can measure either just one component (e.g. vertical) or two or even all three components at the same time. An important feature of our methodology is that the same rotation rate component is determined by **more geophone pairs**. These multiplex data are of two-fold use: first, they can be stacked to suppress noise and second, they can be used to **calibrate** the individual geophones.

3. Rotaphone-D

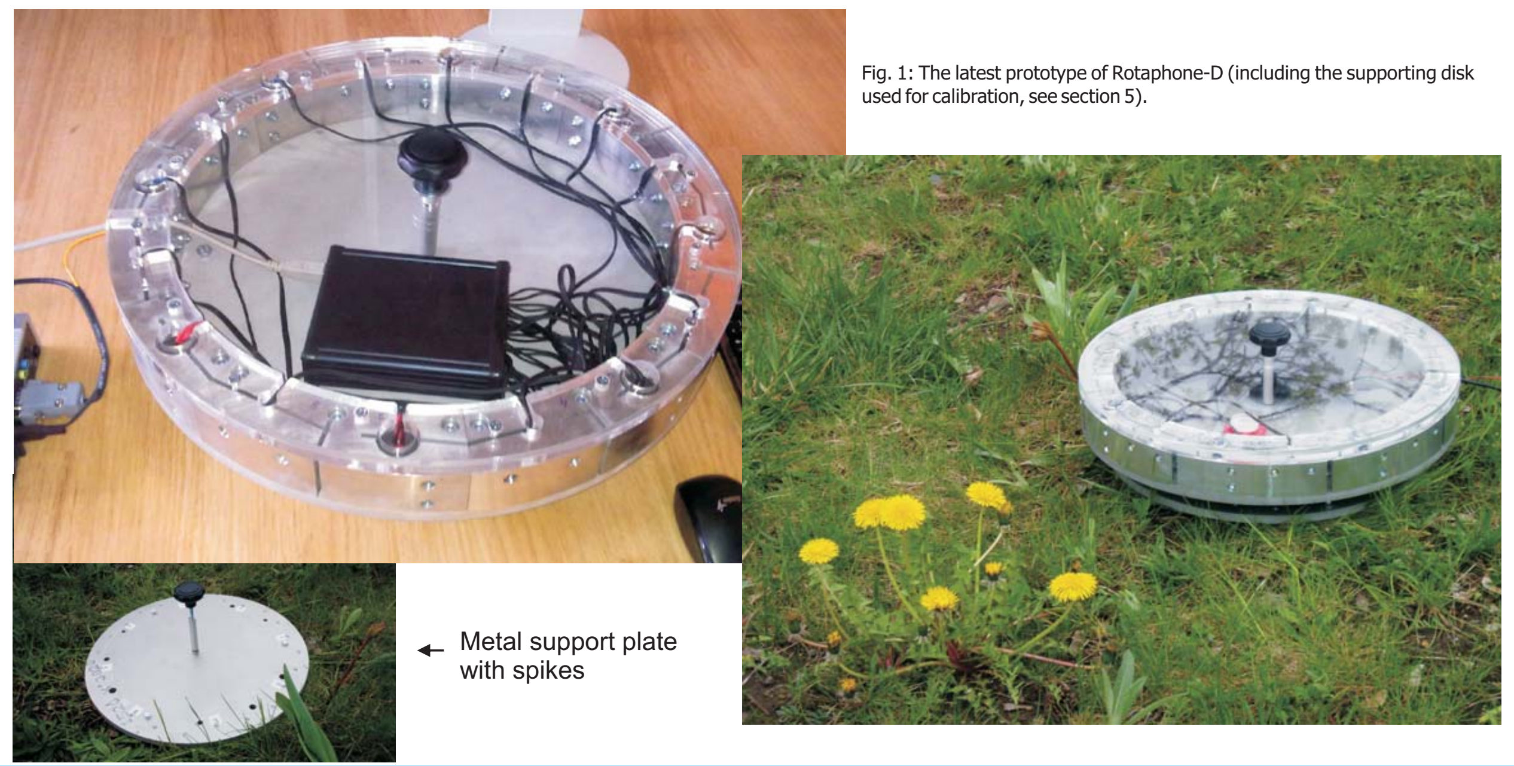


Fig. 1: The latest prototype of Rotaphone-D (including the supporting disk used for calibration, see section 5).

4. Design features of Rotaphone-D

The original Rotaphone prototype was of a cubic shape [3], see Fig.2. In 2015, a new version (Rotaphone-D, Fig.1 and 3) of this sensor was designed, built, and tested at various sites. It has 16 geophones (8 vertical and 8 horizontal) around the periphery of a rigid disk-shaped frame.

Purpose: collocated measurement of three perpendicular ground velocity components (two horizontal and one vertical) and three seismic rotation rate components (around two horizontal axes and one vertical) in a high-frequency range 2-80 Hz

Fig. 2: Older prototype of Rotaphone.

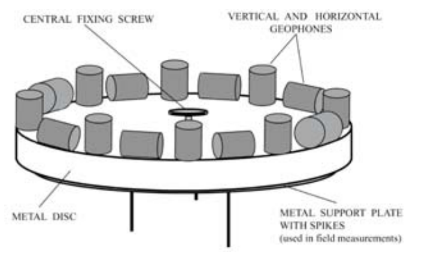


Fig. 3: A simplified basic scheme of the instrument.

Basic parameters:	
frequency range	2 - 80 Hz
sampling frequency	250 Hz
LSB - translational components	1.51 nm/s
LSB - 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

Dimensions:	
disc diameter	44.5 cm
height	11.2 cm
height without support plate	8 cm
Weight:	15.3 kg

Material of the disc and the support plate:
AlMg3 according to the Standard EN 573-3

Basic components:
8 horizontal geophones SM-6 HB 4.5 Hz
3500 ohm 1006250 (ION Sensor Nederland b.v.)
8 vertical geophones SM-6 UB 4.5 Hz
3500 ohm 1006245 (ION Sensor Nederland b.v.)
1 A/D converter 24bit
(Embedded Electronics & Solutions, Ltd.)
1 GPS receiver and antenna Garmin GPS 18
1 datalogger

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

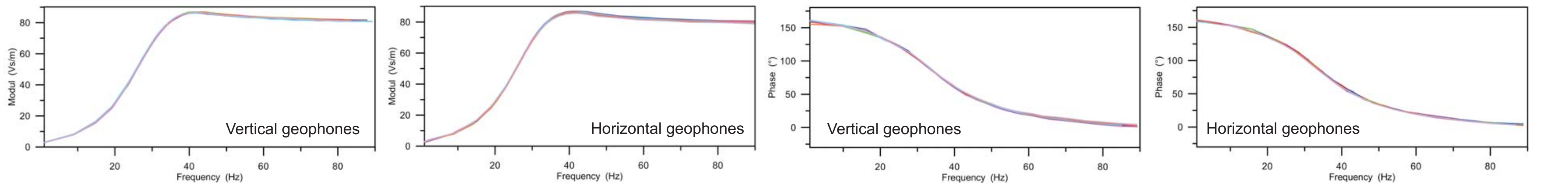
A/D converter parameters:
bits 24
channels 16

Rotaphone principal features:

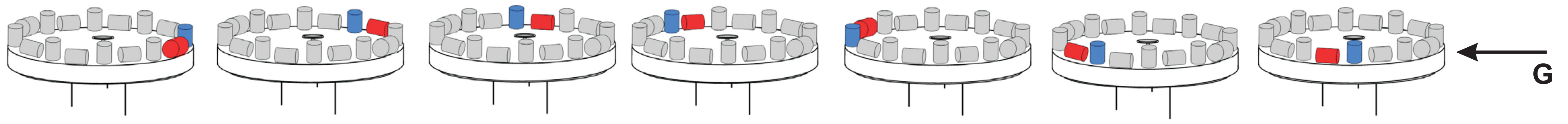
- **It consists of several pairs of highly sensitive geophones connected to a common recording device**
- **The geophones are mounted in diametrical pairs to a rigid ground-based disk-shaped frame**
- **The paired geophone separation distance (the same for all pairs) is 40 cm (much less than the wavelength)**
- **The device measures in high-frequency range from 2 Hz to 80 Hz**
- **Rotation rate is determined by more than one geophone pair, which allows to perform 'in situ' calibration**
- **Theoretical rotation rate sensitivity is 10E-9 rad/s; in practice 10E-8 rad/s is achieved due to noise**
- **Besides of rotations, the instrument provides also translations recorded by the same geophones**

5. Calibration

a) Laboratory calibration: Geophones are calibrated in a laboratory using shaking table with an adjustable frequency of generated harmonic vibrations. The results are expressed in therms of frequency-dependent modulus and phase of their transfer fuction. These characteristics of individual geophones are stored in the registration unit as the first estimation of their characteristics. The relative differences in sensitivity of individual geophones do not exceed two percents.

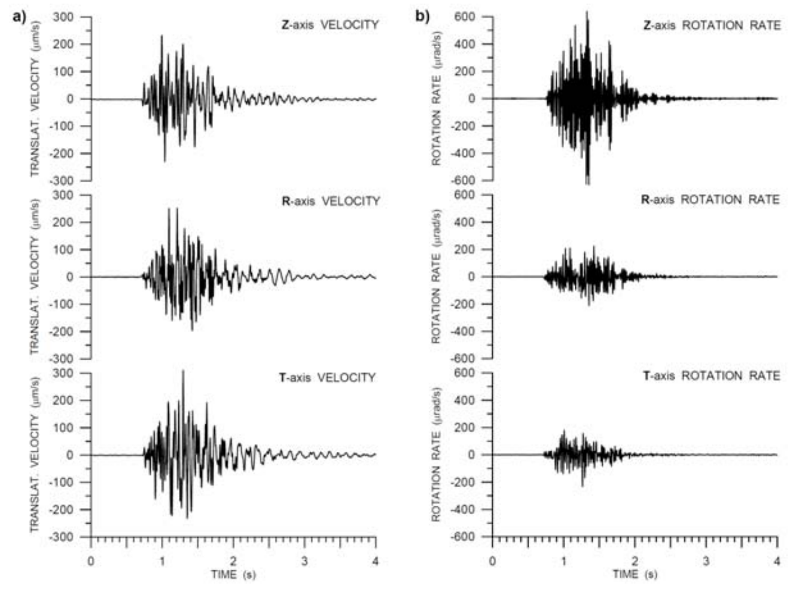


b) In-situ, using identical pulses: During instalation of Rotaphone, calibration of individual geophones are performed using identical pulses, which are generated by a special rotational generator. During the calibration, the Rotaphone is rotated 8 times by 45° with respect to the generator (G). By comparing individual measurements with the sum of all measurements, we can reach very precise cross-calibration anchored to the mean response of the geophones.

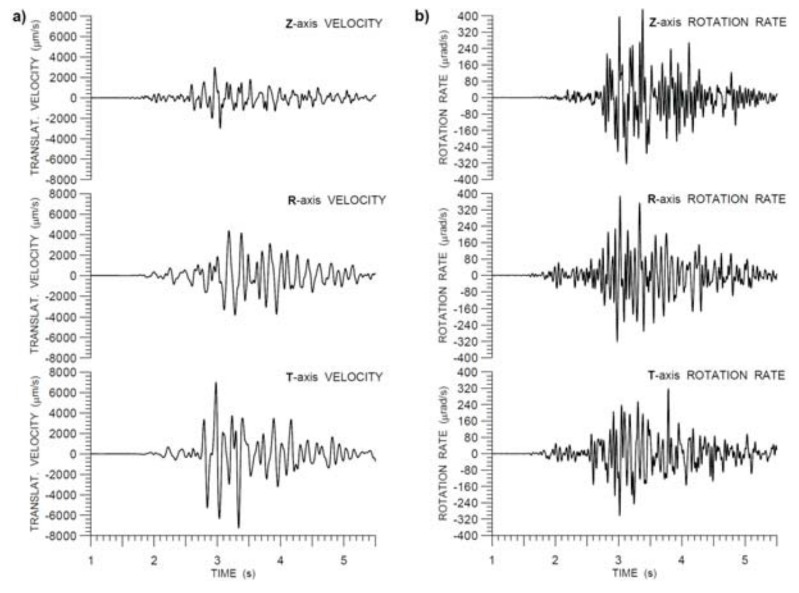


c) In-situ, numerical: The Rotaphone-D has 16 independent geophones, but only 6 independent components (three translational and three rotational) are retrieved. This represent overdetermined inverse problem, which is solved numerically (see, [2], [5]). The characteristics of individual geophones are computed during the measurements. They can compensate for temperature and press changes, which are not included into the calbration a) and b).

QUARRY BLAST HVÍŽDALKA (NEAR PRAGUE), March 30, 2016 11:30 UTC,
Distance from epicenter 1.06 km, Backazimuth 335°



LOCAL EARTHQUAKE NEAR GEOTHERMAL POWERPLANT THE GEYSERS, October 18, 13:16, 2015, ML 3.3
Distance from epicenter 7 km, Backazimuth 300°



7. Conclusions

- **A new prototype of the 6DOF Rotaphone-D has been developed**
- **It operates in the range 2-80 Hz**
- **It allows for in-situ calibration on individual geophones performed simultaneously with each measurement (precise calibration is essential for correct function of theinstrument)**
- **The Rotaphone-D was tested with a quarry blast as a source of seismic signals**
- **Three-month lasting measuring campaign in The Geysers area was conducted in order to detect rotational components of local microearthquakes in the geothermal area**
- **A small array consisting of 3 identical Rotaphones-D is being built in vaults at Long Valley long-baseline tilt meter facility**

References:

[1] Brokešová, J. and Málek, J., 2010,New portable sensor system for rotational seismic motion measurements,Rev. Sci. Instrum. 81(8), 084501;
[2] Brokešová, J., Málek, J., and Kolínský, P., 2012a, Rotaphone, a mechanical seismic sensor system for field rotation rate measurements and itsin-situ calibration, J. Seismol., doi: 10.1007/s10950-012-9274-y, in press.
[3] Brokešová, J., Málek, J., and Evans J.R., 2012b, Rotaphone, a new self-calibrated six-degree-of-freedom seismic sensor, Rev. Sci. Instrum., submitted
[4] Brokešová J. and Málek J (2015), Six-degree-of-freedom near-source seismic motions I: Rotation-to-translation relations and synthetic examples, J. Seismol., Vol.19, No. 2, 491-509, DOI: 10.1007/s10950-015-9479-y
[5] Brokešová J. and Málek J (2015), Six-degree-of-freedom near-source seismic motions II: Examples of real seismogram analysis and S-wave velocity retrieval, J. Seismol., Vol.19, No. 2, 511-539, DOI: 10.1007/s10950-015-9480-5

Acknowledgement:

This work was supported by the Czech Science Foundation, Project. No. P210/15-02363S. We thank to Stuart Wilkinson (USGS) and Craig Hartline (Calpine Corporation) for invaluable help and technical assistance.