

Rotaphone-D, a New Model of Six-Degree-of-Freedom Seismic Sensor: Description and Performance

Johana Brokešová¹ and Jiří Málek²

¹*Charles University, Faculty of Mathematics and Physics, Department of Geophysics, V Holešovičkách 2, 180 00 Prague, Czech Republic*

²*Institute of Rock Structure and Mechanics, Department of Seismotectonics, Czech Academy of Sciences, V Holešovičkách 41, 182 09 Prague, Czech Republic*

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ABSTRACT

A new model of the Rotaphone-D short-period seismic sensor with six degrees of freedom is introduced. The basis of the instrument are horizontal and vertical geophones in a special paired arrangement. The instrument is designed for simultaneous and collocated measurements of rotational and translational components of ground motion. The basic principle of measurement is briefly described. Careful calibration is necessary for this type of measurement, which has two parts: a preliminary calibration based on laboratory measurements of the characteristics the individual geophones, and a subsequent in-situ calibration which takes into account the actual physical conditions during field measurements and is performed during the processing of the measured data. The effect of the calibration is clearly demonstrated by specific laboratory tests. The laboratory tests have confirmed the correct functioning of the instrument. The frequency range of Rotaphone-D is from 2 to 80 Hz and is therefore optimal for monitoring local seismicity. The instrument was subsequently used in field measurements during two several-month measurement campaigns in California, U.S.A. Examples of six-component records from two sites, The Geysers and Long Valley Caldera, are presented and briefly interpreted from a seismological perspective. Basic instrument parameters are given. The instrument is lightweight, portable, easy to install, and offers a number of interesting applications, which are briefly discussed. Six-component measurements (translational and rotational) have become a powerful tool especially in volcanic seismology and in monitoring induced seismicity.

INTRODUCTION

In the last decade, we have observed rapid developments in the field of rotational seismometry. Much attention has been paid to small rotational sensors, that are light, operable and easy to install (possibly in large numbers) in areas of interest according

to current seismic situation at a given location. There are studies focusing on mutual comparisons of different types of these sensors with the aim of testing their performance and parameters in real field conditions (Bernauer et al., 2022, Brokešová and Málek, 2020). Nowadays, a growing number of these sensors are already being installed in various areas of interest around the world and are starting to produce large amount of data suitable for processing both in theoretical studies and for immediate practical use.

It turns out that currently most applications use simultaneous and collocated measurements of both rotational and translational ground-motion components. Rotational sensors are therefore often complemented by conventional seismographs standing nearby. However, such a solution has its drawbacks — higher cost and potential measurement problems at higher frequencies, where the rotational wave field can change rapidly in space (Brokešová et al., 2021). Therefore, there is a growing need for six-degree-of-freedom (6DOF) devices, which include, for example, rotaphones (6DOF inclusive of rotations, thus rotaphones). They are short-period mechanical sensor systems for measurement of seismic rotation, based on measuring spatial gradients that constitute the rotational components, as well as very precise measurement of seismic translation. They have been developed continuously since 2009 and currently exist in the form of several different prototypes (Brokešová and Málek, 2010, Brokešová et al., 2012a, Brokešová et al., 2021).

An older version of the rotaphone 6DOF sensor system, Rotaphone-C (Fig. 1, top), was described in detail by Brokešová and Málek (2012a). It was cubic shaped and suffered from resonances in its frame. This paper describes a new version of the instrument, the Rotaphone-D, which is much stiffer in all axes and does not suffer from such resonances. This new model is comprised of eight horizontal and eight vertical 4.5-Hz geophones arranged in a ring on a thick disc-shape base plate (Fig. 1, bottom). The instrument is about 15 kg with assembly and costs about 6000 USD in the prototype form. At present, it is sampled at 4-ms intervals, so is appropriate for high-frequency studies from about 2 to 80 Hz.

The same analysis applied to earlier models applies to model D as well. The method called in-situ calibration (Brokešová et al., 2012b) cross-calibrates each type of geophone, vertical or horizontal, to the mean response of the set so that precise differences between geophones on opposite sides of the ring can be used to measure rotations about three orthogonal axes, while their means equal translational motions along three orthogonal axes.

We describe the instrument, its performance (transfer functions, instrument noise ceilings, and cross-calibration) as measured at the Albuquerque Seismological Laboratory (ASL) of the U.S. Geological Survey. We briefly review the analysis method and the instrument's potential applications. Rotaphones have been used in the Czech Republic, Iceland, Greece, the U.S., and Ethiopia in pursuit of many types of targets. Targets include tectonically active areas, volcanic and geothermal systems, and rock bursts in mines (Brokešová and Málek, 2013, Brokešová and Málek, 2015a). We show a few examples of Rotaphone-D records from two locations.

DESCRIPTION OF THE INSTRUMENT

Basic principle

Rotaphone-D is based on the same principle as all the rotaphone model designs. They are mechanical sensor systems utilizing low-frequency velocity geophones and measuring thus ground motion velocity. The geophones, both horizontal and vertical, are attached to a rigid frame in parallel (co-axial) pairs with a separation distance of few tens of cm. The records from co-axial geophones are averaged to obtain ground-motion velocities (more precise than from individual geophones). Rotation rates are obtained by differencing records from the paired geophones which yield spatial velocity gradients at a point.

Knowing the spatial gradients of velocity $\mathbf{v}$ it is possible to determine seismic rotation rate $\mathbf{\Omega} = \text{curl } \mathbf{v}$. The frame moves (up to the frame's resonance frequency) as a rigid body so that the rotation rate components simplify to individual spatial derivatives instead of their linear combinations. Assume a right-handed Cartesian coordinate system with horizontal axes x, y and vertical z . Then, in the case of Rotaphone-D installed horizontally, only the following derivatives are relevant

$$\begin{aligned}\Omega_x &= \frac{\partial v_z}{\partial y}, \\ \Omega_y &= -\frac{\partial v_z}{\partial x}, \\ \Omega_z &= \frac{\partial v_y}{\partial x} = -\frac{\partial v_x}{\partial y}.\end{aligned}\tag{1}$$

Regarding the polarity of the $\mathbf{\Omega}$ vector components with respect to the axes of the given Cartesian system, the convention proposed by Evans (2009) is followed in Rotaphone-D (as in all other Rotaphone model designs). In the following, the Ω_x and Ω_y components (possibly also after rotating the axes into the transverse and radial directions with respect to the epicenter, see below) are called tilts and the Ω_z component is called torsion.

Derivatives in (1) are approximated by finite differences between the co-axial geophones in a pair suitably oriented with respect to the horizontal axes. The appropriate projection is used for generally oriented pairs. Both derivatives in Ω_z are of the same applicability, which results in desirable data redundancy. Moreover, the geophone pairs are arranged so that each rotation rate component is obtained from multiple pairs. These multiplex data are essential for our approach. They enable us to perform in-situ cross-calibration of individual geophones in the system (see below) and also to increase sensitivity and accuracy by suppressing noise via stacking records from co-axial geophones.

Design features and basic specifications

In the case of Rotaphone-D, the frame is represented by a thick metal disc and the separation distance between paired geophones is 40 cm. Fig. 1 shows Rotaphone-D in comparison with the earlier cubic-shaped Rotaphone-C prototype. Regarding the rotational

components, in contrast to Rotaphone-C the roles of the different types of geophones are separated here — vertical geophones are only used to determine tilts while horizontal ones are only used to determine vertical-axis rotation.

The elemental sensors in the system are 8 horizontal geophones SM-6 HB and 8 vertical SM-6 UB geophones by ION (formerly Sensor Nederland B.V.). Geophones of each type are mounted around the perimeter of the disk at the vertices of a regular octagon. The geophone characteristics are shown in Fig. 2.

The most important Rotaphone-D parameters are summarized in Tab. 1. The parameters, except for the dimensions, weight and parameters of the A/D converter, are based on the manufacturer's specification. According to our experience, we can confirm a temperature range of $-20^{\circ}\text{C} - +40^{\circ}\text{C}$, based on our laboratory tests and our field measurement campaigns. The least reliable rotation rate depends strongly on the background noise. During our measurements, we detected the smallest values in the order of 10^{-8} rad/s. We never reached the clips during field measurements.

The frequency range is limited from above by the first resonant mode of the metal disc at about 80 Hz. Records from typical seismic sources rarely reach this limit. The low frequency limit of 2 Hz is based on laboratory tests. Below this frequency, the shape of the geophone response is somewhat distorted compared to the input signal. Note that even replacing the used geophones with other elementary sensors would not lead to a significant reduction in the lower frequency limit of the 6DOF instrument. Since the rotational components are derived from differential motions in the geophone pairs, reducing the frequency (i.e., increasing the wavelength) would require increasing the size of the instrument and would come at the expense of its portability.

Rotaphone-D is compact, portable, easy to install and operate. It has a wide dynamic range enabling the detection both weak (even very weak) and stronger seismic events.

Calibration

When determining spatial gradients (and rotations) using records from paired geophones, a major problem is that the geophones are never exactly the same in their properties. If not perfectly calibrated, the mutual inconsistency of paired geophones separated by a relatively very small distance (relative to the wavelength of the recorded motions) can cause serious errors, especially in their differential records.

Laboratory measurements confirm that there are differences in the characteristics of individual geophones involved in the system that may reach 0.5 % in sensitivity and few degrees in phase lag (Fig. 2). These differences can be considerably amplified when the geophones are mounted to the frame due to additional sources of mutual inconsistencies (uneven attachment, disc material inhomogeneities, etc.). Fig. 3 shows relative corrections in characteristics of individual geophones fixed to the frame of one Rotaphone-D piece as measured at ASL. The scatter of sensitivity values can even exceed 10 % at lower frequencies. While the maximum scatter of phase lag corrections for horizontal geophones is less than 3 degrees (at about 4 Hz), the scatter for vertical geophones is much larger -

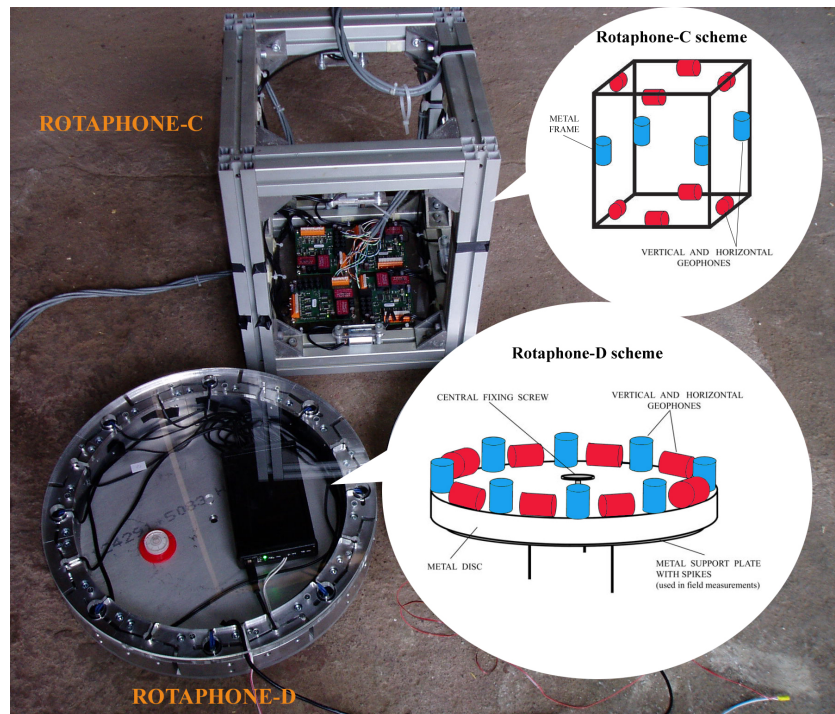


Figure 1: Rotaphone-D in comparison to the earlier model design Rotaphone-C.

approximately 25 degrees (at about 2 Hz). This shows that a thorough cross-calibration of individual frame-fixed geophones is unavoidable. The figure also suggests that in the case of this particular device it is worth considering lower frequency limit of 3 Hz (instead of 2 Hz) for those ground motion components that require the use of vertical geophones.

Laboratory pre-calibration of individual geophones is a necessary but not a sufficient condition. It does not take into account the current physical conditions at the time of field measurements or the ageing of geophones. Rotaphone-D offers an alternative to laboratory pre-calibration – the so called in-situ pre-calibration which better matches the actual measurement conditions, e.g., eliminates the ageing problem. The device is equipped with a metal base pad with pre-drilled regular holes allowing the protrusions on the bottom of the disk to fit into place so that the rotaphone can be rotated by a precisely defined angle, in this case 45 degrees. Thus, after seven turns in the same direction, the eighth would bring Rotaphone into its original position (Fig. 4). This can be used with advantage for pre-calibration provided an artificial seismic source is available that generates exactly the same pulse each time (e.g., vibroseis or the special S-wave generator according to patent CZ 301217, etc.).

The procedure is usually performed during field installation of the instrument. The source generates a sequence of pulses for each Rotaphone orientation between two consec-

Table 1: The most important specifications of the Rotaphone-D model design

paired sensor spacing	40 cm
disc diameter	44.5 cm
height	8 cm/11.2cm*
total weight (without accessories)	15.3 kg
operating temperature range	-40 – +100
frequency range	2 – 80 Hz
sampling frequency	250 Hz
translational LSB	1.51 nm/s
rotational LSB	3.77 nrad/s
clipping translation velocity	12.67 mm/s
clipping rotation rate	31.68 mrad/s
translation dynamic range	138 dB
rotation dynamic range	120 dB
geophone natural frequency	4.5 Hz
geophone sensitivity	78.9 Vs/m
A/D converter bits	24
A/D converter channels	16

* without/with the supporting metal pad

utive turnings. The records in each sequence are stacked for noise suppression and then used to derive rotation components according to Eq. 1. Due to the identity of the source pulses and the stiffness of the Rotaphone frame, the rotational records from the relevant geophone pairs should be the same for all sequences, but they are not because of differences between the individual geophones' transfer functions. When summing (averaging) rotation data for all of Rotaphone orientations, we obtain reliable mean rotation rate components, since the differences in the transfer functions cancel out in the sum. By comparing individual measurements with the sum of all measurements, we can achieve relatively accurate geophone cross-calibration (after a similar inversion as described below).

However, transfer function corrections obtained from laboratory and/or in-situ pre-calibration do not include changes due to actual physical conditions (temperature, pressure, humidity, etc.) during field measurements. The solution is the so-called in-situ post-calibration, and integral part of data processing, which provides corrections accurate enough to obtain the correct differential motions from each pair of geophones. The method is again conditioned by the rigidity of the Rotaphone frame and related redundancy in determining both the translational and rotational components. Multiple geophone pairs should give the same ground velocity or rotation rate when averaging or subtract-

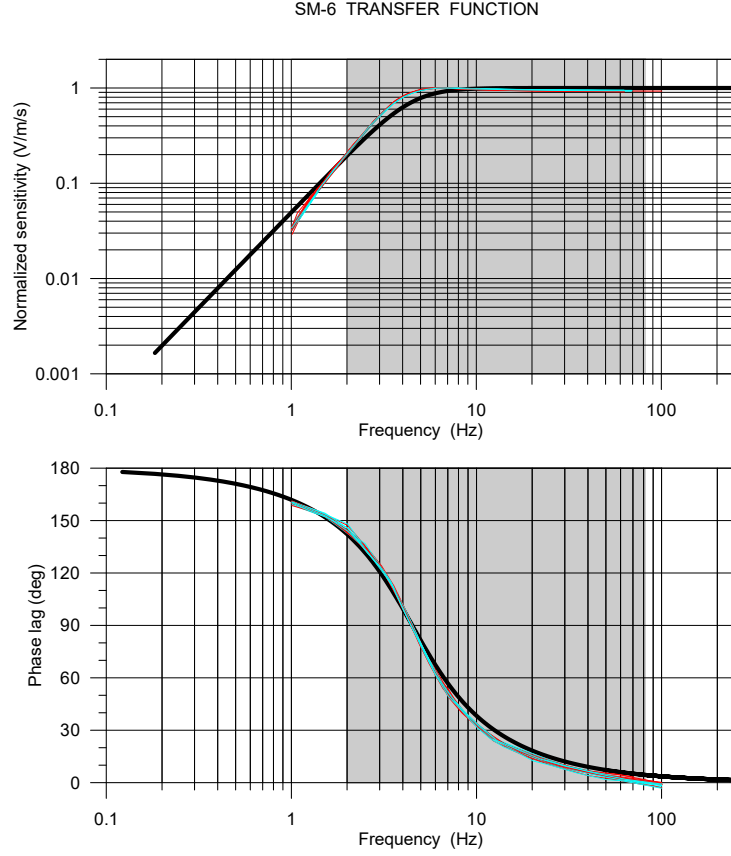


Figure 2: SM-6 transfer function calculated from poles and zeros (black). Rotaphone-D frequency range is shown in gray. Thin curves are manufacturer provided characteristics of individual horizontal (red) and vertical (cyan) geophones.

ing the geophone records, respectively, which provides constraints on accurate corrections of individual geophone transfer functions. The principle of the method was described by Brokešová et. al. (2012b) for Rotaphone-C. An analogous approach is applied here, only the number of constraints is different. For each of the three perpendicular velocity components, any geophone of a given type (vertical/horizontal) and of suitable orientation (in the case of horizontal geophones) is chosen as reference. The transfer functions of the remaining 7 vertical and 6 horizontal geophones should be corrected with respect to those of the reference ones. The transfer functions are suitably parametrized with the number of parameters on the order of tens. Thus, we are looking for $(7 + 6) \times$ tens of parameters, while the number of equations is in the order of thousands (the number of constraints $\times$

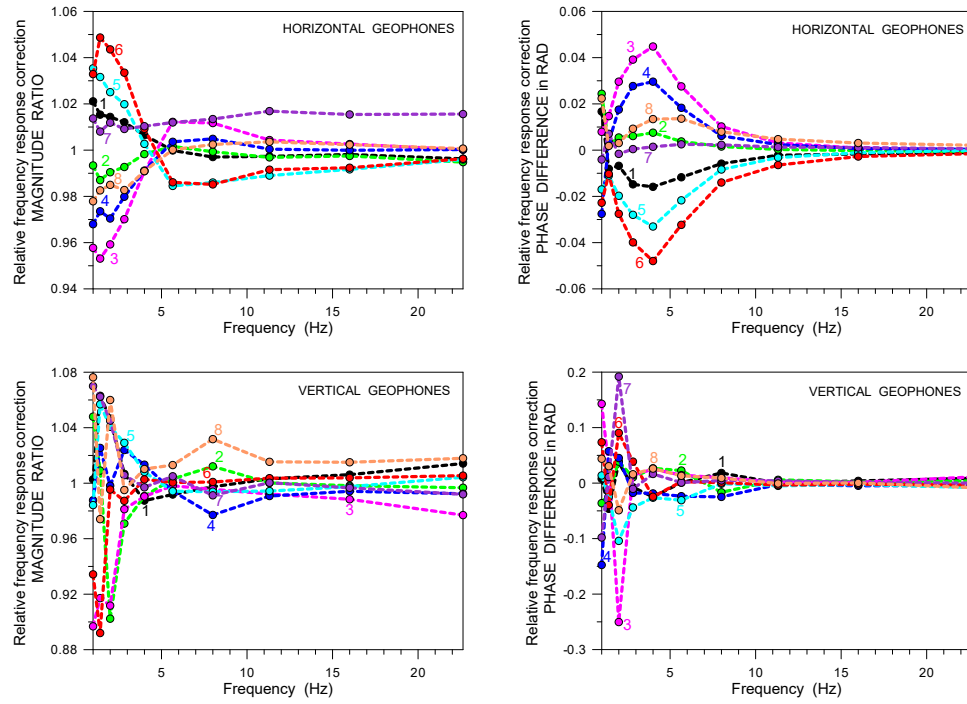


Figure 3: Relative sensitivity (left) and phase lag (right) corrections for individual horizontal (top) and vertical (bottom) geophones mounted to the frame of one particular Rotaphone-D. The individual geophones in each group are distinguished by labeled color curves.

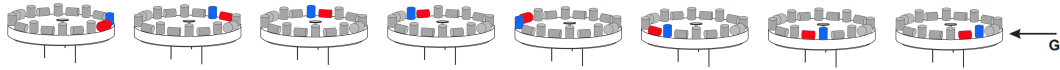


Figure 4: Scheme of eight successive 45° turns of the 6DOF Rotaphone-D prototype during in-situ pre-calibration with an artificial source (generator denoted by G).

the number of samples in the record spectra). The method can be modified easily when working in the time domain instead of the spectral domain. The problem of finding the transfer function parameters can be solved using any suitable standard inverse method (for an overview see, e.g., the book by Tarantola, 2005). We prefer using the so-called isometric method by Málek et al. (2007), recently updated by Málek et al. (2023), which is fast and suitable even for slightly non-linear inversions.

PERFORMANCE SELF-TEST

Since the Rotaphone-D measures both translational velocity and rotation rate, it offers a convenient laboratory performance test by comparing the directly measured rotation rate with the rotation rate derived from circumferential translational velocity at a known rotational radius. Such a performance self-test is best performed with the instrument off-center on the rotational shaking table. The example in Fig. 5 correspond to the off-center displacement of 5.38 cm along a line connecting the paired co-axial horizontal geophones with axes perpendicular to this line. Averaging their translational records gives the translational velocity at the center of Rotaphone-D. This is tangent to the circle along which the center point of Rotaphone-D moves, and thus gives the corresponding circumferential speed at that point. Dividing this by the radius of rotation (the distance between the center of the shaking table and the center of the Rotaphone-D) gives the angular velocity, i.e., rotation rate about the vertical axis. In this performance self-test, we consider the rotation rate thus obtained to be correct because it is based on direct measurements by geophones, standard short-period ground-motion velocity sensors that have been in common use by seismologists for decades. The vertical-axis rotation rate measured directly by Rotaphone-D instrument should be verified against this quantity. Fig. 5 shows a comparison with the directly measured rotation rate both with and without in-situ post-calibration. The effect of post-calibration is clearly visible, significantly refining the rotation rate for both large amplitudes (e.g., at 3.7 s) and for amplitudes an order of magnitude smaller (at the end of the recording, after 4.7 s), which is similar to recordings of seismic strong motions.

Perhaps it can be argued that the rotational and translational components in this experiment are not independent because they both originate from the same geophones implemented in the same instrument. However, due to the completely different way in which they were derived (averaging and radius division vs. finite difference within pairs of geophones), they can be considered as independent quantities and can therefore be used to verify the rotation rate data within the range of amplitudes given by the possibilities of the rotational shaking table used.

EXAMPLES OF FIELD RECORDS

Six-component seismograms, including three translational-velocity and three rotational-rate components, as recorded by Rotaphone-D at two different locations (both in California, U.S.A.), are shown in this section. The examples are chosen to demonstrate the ability of the instrument to record relatively weak motions due to local microearthquakes.

The records are transformed into R-T-Z Cartesian coordinate system, with Z-axis being vertical, positive up, R-axis (radial) pointing toward the epicenter of the event, and T-axis (transverse) making the coordinate system right-handed. The corresponding components are either velocities along or rotation rates about the axis. The radial and transverse

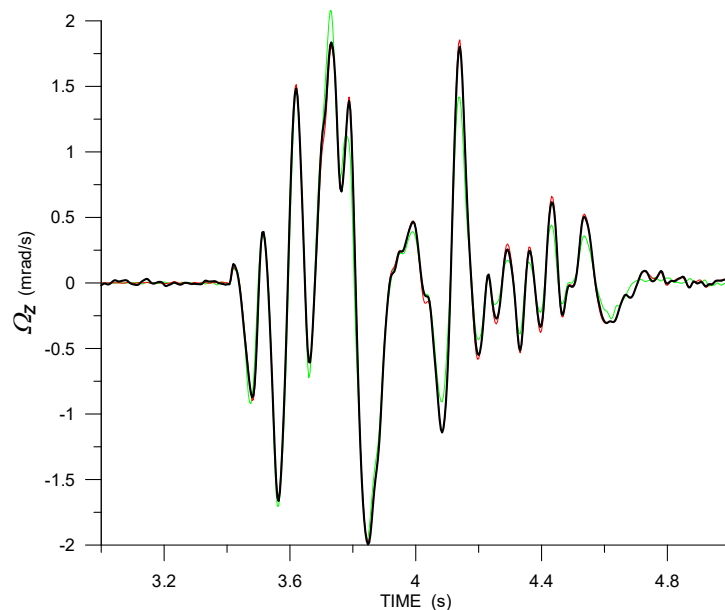


Figure 5: Vertical-axis rotation rate with an input signal produced randomly by hand. The center of the Rotaphone-D is located in the off-center position relative to the axis of the rotational shaking table. Rotation rate derived from circumferential speed and known radius (black) is compared with the rotation rate directly measured by the Rotaphone-D, including in situ post-calibration (red) and without the post-calibration (in green).

directions are set with respect to the catalogue locations of the earthquakes. For clarity, the translational components are drawn in blue while the rotational ones in red.

The Geysers geothermal field, California, USA

The first field measurement example is from a major geothermal region of California, about 116 km north of San Francisco — a large dry-steam electricity generating area known as The Geysers. This area is volcanic within the Franciscan formation, with the pluton overlain by a mixed dry and liquid water zone and that overlain by a dry-steam zone (Stanley and Blakely, 1995; Stimac et al., 2001). Recent tomographic studies performed in the area indicate the existence of a large magma chamber at depths of 5–13 km with shallow-depth (> 7 km) intrusions of silicic magma (Qi and Tong, 2022). The near-surface intrusions might be the source of heat for the geothermal activity in the region. The Geysers is a seismically active area. Small shallow (above 6 km) earthquakes are regularly recorded there. Some of them are triggered by larger earthquakes occurring along regional faults that are located miles away from the geothermal field. Many events are induced

along numerous small fractures in the rock by injecting water to extract steam for the production of electricity. Much of the seismic activity at The Geysers occurs in the form of earthquake swarms (Johnson and Majer, 2017).

During field testing of Rotaphone-D, the device (SN1) was deployed on the ground-floor of the Calpine Corporation administrative center ($38^{\circ}46'36.84''\text{N}$, $122^{\circ}44'39.84''\text{W}$, elevation 833 m), located in the southwest part of the steam production zone, for three months. Hundreds of shallow proximal microearthquakes with magnitudes up to 3.8 ML and epicentral distances from 260 m to 14.2 km and depths up to 6 km below sea level were recorded. Thanks to relatively low noise, these 6DOF records are suitable for analysis discussed in the last section.

The example shown (Fig. 6) was chosen with the aim to demonstrate the ability of the device to record relatively weak ground motions. An earthquake of Md 1.5 occurred at epicentral distance of 1.3 km and depth of 0.65 km b.s.l. (USGS catalogue location), i.e., at hypocentral distance of 2 km, at a back azimuth of 79 deg. A detailed seismological discussion of the record is out of scope of this paper, however, let us just add some notes. While the highest translational velocity amplitude, seen on transverse component, is of 2.08×10^{-4} m/s, the maximum rotational rate, seen on radial component, is of 2.75×10^{-5} rad/s. Such rotation-to-translation (RT) ratio is typical for records of proximal earthquakes, in contrast to distant ones, for which the ratio may be by several orders of magnitude lower. Delay between S- and P- onsets is several hundredths of a second longer than that predicted by broadly accepted velocity model of the area (Gritto, 2013), which may indicate a somewhat slower near-surface S-wave velocity. Horizontal-axes rotation rates associated with P-wave are relatively high, in principle comparable to S waves, which contradicts the generally accepted notion that P-wave rotation should be weak. While, in theory, P waves will not induce any rotation in a homogeneous isotropic unbounded medium, there is no reason for this to be the case in the strongly heterogeneous and anisotropic free-surface environment of The Geysers (Evans et al., 1995). Another interesting feature is the apparently lower frequency content of rotational P waves compared to the translational components. This suggests much more complex RT relationships than those used for distant earthquakes, where the plane wave approximation leads to a proportionality of rotational rate and translational acceleration, hence a higher frequency content of rotational signals. A striking feature in the 6DOF record is an S-to-P converted wave arriving between the P- and S- onsets. The P-wave nature of the wave is deduced from its frequency character in rotational components resembling that of direct P wave as well as from its relatively high amplitude on the vertical translation component. Note that the R- and T- axis rotation rate records allow one to set its onset much more precisely than standard translational records. Despite the low peak amplitude, the quality of the 6DOF record is relatively good considering the noise. Rotational noise as analyzed in the interval of several minutes prior the first onset is the smallest in the Z-axis component where it does not exceed 5×10^{-7} rad/s, yielding the signal-to-noise ratio (SNR) of 54. In the remaining two rotational components the noise is roughly twice as high.

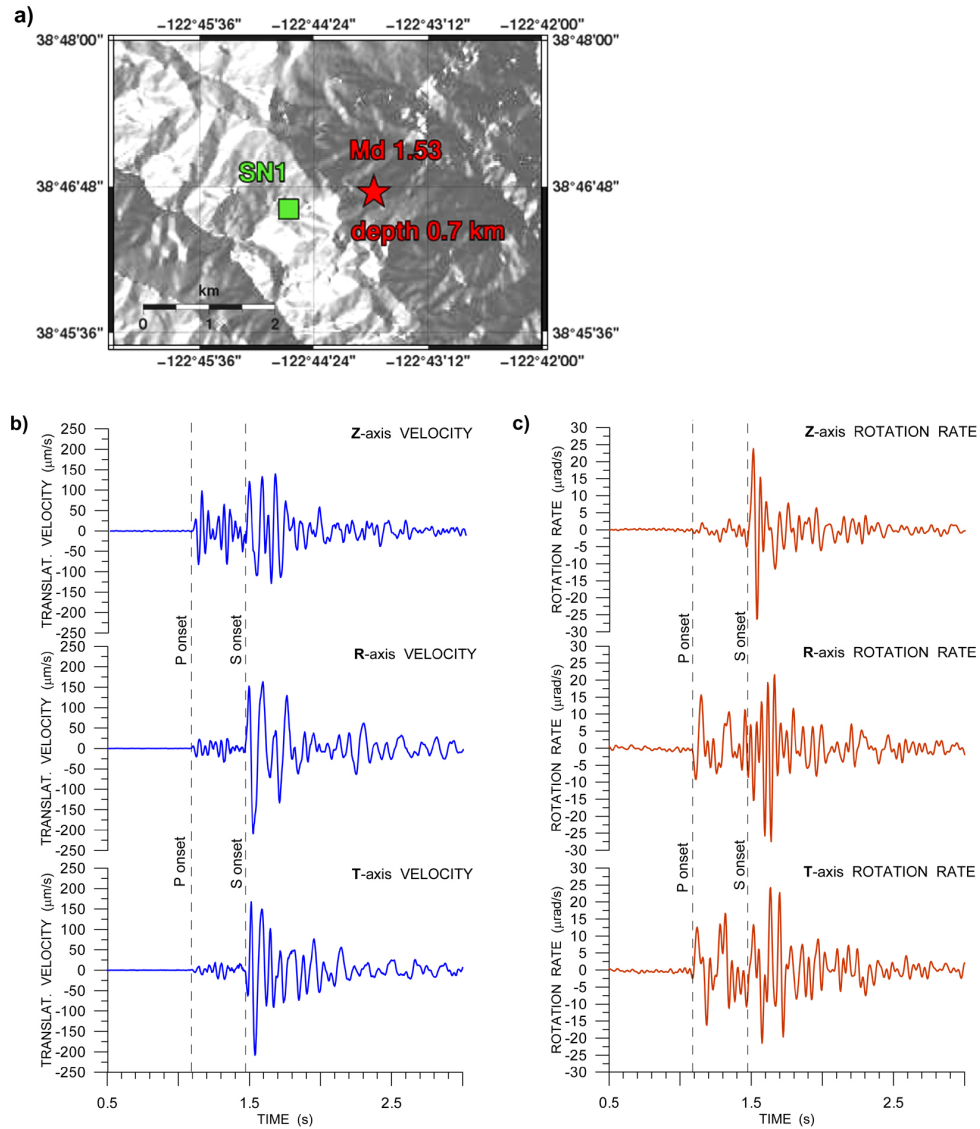


Figure 6: The Geysers — 1.5 Md shallow earthquake at hypocentral distance of 2 km: (a) topographic map, (b) translational components, (c) rotational components.

Long Valley Caldera, California, USA

As the second example, a 6DOF record (Fig. 7) of a microearthquake located at the southwest rim of Long Valley Caldera (California, U.S.A), east of the central Sierra Nevada Range, is shown. The caldera is an ellipsoidal depression, 32 km long and 18 km wide, that formed 760,000 years ago as a result of very large volcanic eruption. Near its center, there is a resurgent dome formed by magmatic uplift. In addition to geothermal activity in the area, characterized by hot springs and steam vents, the caldera has shown pronounced

unrest in the last five decades, including recurring earthquake swarms, inflation of the resurgent dome, carbon-dioxide emissions near the southwest rim, etc. (Hill, 2006; Hill et al., 2014).

Rotaphone-D (SN2) was briefly deployed at the USGS-NCSN station MCB. The station is located at Casa Benchmark peak ($37^{\circ}38'40.56''\text{N}$, $118^{\circ}53'48.12''\text{W}$, elevation 2391 m), a locality rich of obsidian material, situated at southwestern margin of the resurgent dome. On the slope of Casa Benchmark, the Casa Diablo hot spring area with the geothermal power plant of the same name is situated.

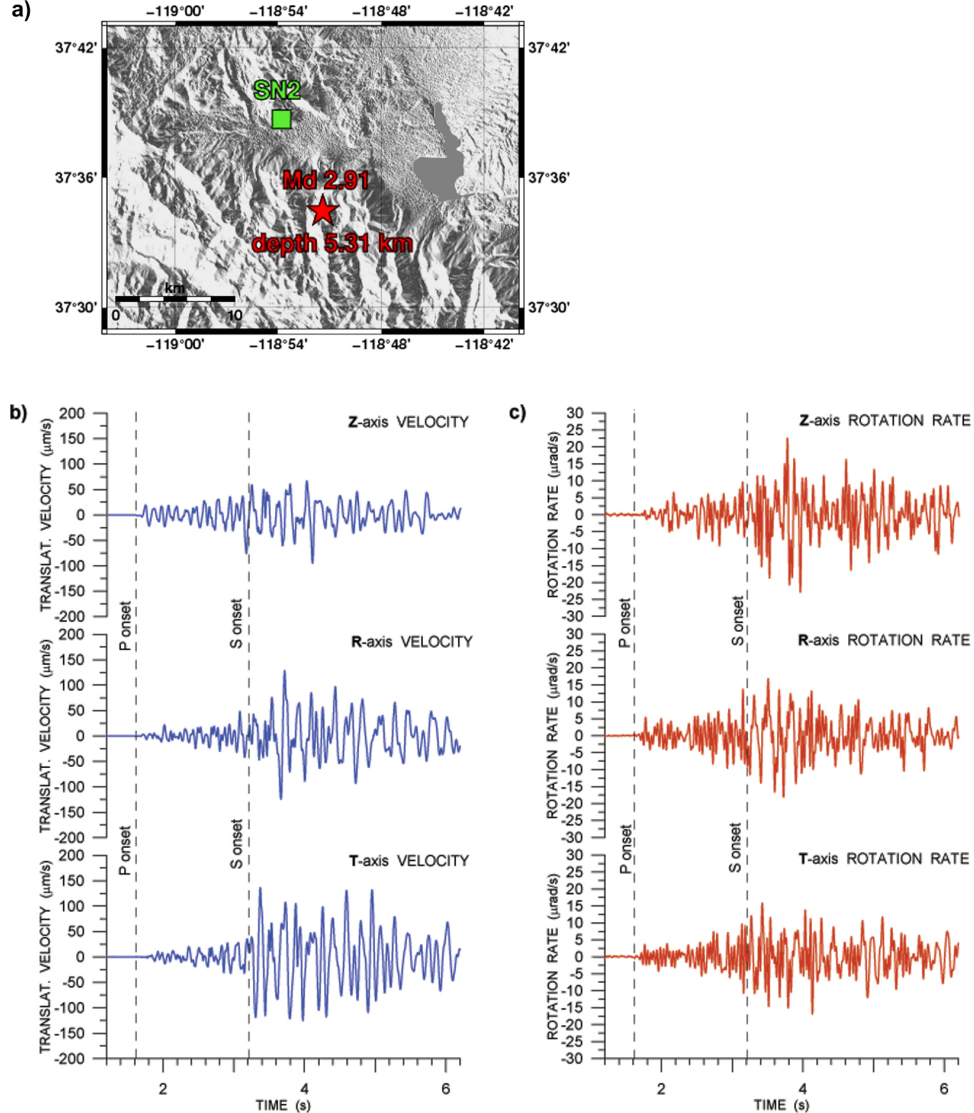


Figure 7: Long Valley Caldera — 2.9 Md earthquake at hypocentral distance of 10 km: (a) topographic map, (b) translational components, (c) rotational components.

The microearthquake of Md 2.91 occurred at epicentral distance of 8.57 km and depth of 5.31 km b.s.l. (USGS catalogue location), i.e., at hypocentral distance of 10.08 km, at a back azimuth of 156 deg. Despite five times greater distance than the previous example, due to the larger magnitude, the peak values in both 6DOF records are roughly similar — the largest velocity is 1.36×10^{-4} m/s in transverse component and maximum rotation rate of 2.28×10^{-5} rad/s is in vertical component. Also RT ratio is of the same order of magnitude as in the previous example. The peak values are associated with S waves, P waves are here much weaker compared to Fig. 6, especially in rotational components. The seismograms are much more complex, suggesting more complex rock structure and/or a mixture of volcanic and tectonic character of the event indicative of tectonic-magmatic interactions typical for the area (Hill, 2006). In both types of records, translational and rotational, there are many phases of similar amplitude both in the P- and S-wave groups. We interpret these phases as waves reflected (and, possibly, converted) in a near-receiver structure. We assume that some of those reflections are side reflections from relatively steep slopes of the Casa Benchmark peak (see the topographic map in Fig. 7). Due to the complexity of seismograms, it is quite difficult to accurately determine the onset of a direct S wave from translational records alone. Rotational records can help, see the clear onset of a low frequency wave at 2.21 s. Its low-frequency character may have similar causes to the P waves in the previous example. Time interval between S- and P- onsets roughly corresponds to the velocity model presented by Panning et al. (2001). With the exception of this wave, the significantly higher frequency content of the rotational seismograms relative to the translational ones is evident. The largest rotational noise prior to the onset of the P wave ($1.7 \mu\text{rad/s}$) was detected on the T-axis component, and is significantly lower on the other two. This allows us to speculate that the relatively large noise on the horizontal components in the previous example is more likely to be of natural origin and is not intrinsic (instrumental) noise. However, a detailed analysis of instrumental noise has yet to be performed. Among rotational components, the largest SNR, of 52, was in Z-axis rotation rate.

DISCUSSION

A new model of short-period 6DOF seismic sensor, Rotaphone-D, has been developed. Its development started in 2015 and required several years of laboratory and field testing. Rotational records are not obtained directly during measurement but they are results of post-processing that involves precise calibration of individual geophones in the system. The calibration has two phases, laboratory pre-calibration and 'in situ' post-calibration. Although called pre-calibration, even this part can be performed after acquiring the measured geophone data. The authors took advantage of this opportunity when, due to anti-covid measures, the calibration phase was delayed by several years. This allowed additional processing of the records taken at the initial stage of the field measurements. Two such examples are presented in this study. In 2022, the device was significantly improved by

using advanced 32-bit A/D converters from Tedia Ltd with range ± 2.5 V. This allowed the dynamic range to be further extended. The instrument is now equipped with a new recording unit with lower power consumption. This allows year-round operation with solar panel power. Data is transmitted over mobile networks using the Seedlink protocol as standard.

The instrument is rather inexpensive, lightweight, relatively small, easy to install in a wide variety of environments and can withstand a relatively wide range of temperatures. Among other portable seismic rotational sensors, Rotaphone main advantage is that it provides exactly collocated (at one point) rotational and translational recordings. The same transfer function shape for both types of records allows to avoid instrumental correction in many applications working simultaneously with rotations and translations. Focus on high frequencies allows potentially greater resolution in inversion tasks. Low intrinsic noise typical for rotaphones (Bernauer et al, 2021), makes it possible to obtain 6DOF records from very weak events (in low-noise environments), but this issue has yet to be investigated in detail for a given prototype.

The instrument is now ready for a wide range of novel applications — most based on simultaneous use of both rotational and translational data, but some using rotational and translational data separately. What follows is a far from complete list of applications, most of which have yet to be refined and tested in practice.

Collocated and simultaneous measurement of tilts and horizontal translations allow one to correct the latter for contamination by tilts in the Earth's gravity field. This well known phenomenon (Graizer, 2005) is most pronounced at low frequencies, below the Rotaphone-D frequency range. However, in our experience, contamination can still be around one percent of the horizontal ground velocity near the instrument's low-frequency limit and is therefore worth correcting for.

Rotaphones are a kind of miniarrays that are characterized by data redundancy for individual components. In the case of translations, this allows the application of sophisticated noise suppression methods, in particular, for example, the generalized seismogram averaging technique (Málek et al., 2007; Málek and Brokešová, 2024) based on non-linear record stacking. The method improves signal-to-noise ratio of coherent seismograms considerably and can thus be used to detect very weak events, not visible in individual geophone records.

Many applications employ RT relations. They relate individual rotational components to individual translational components or their linear combination. The simplest relations are derived under the condition that the wavefield can be approximated by a plane wave propagating along the Earth's surface in radial direction at a constant apparent speed. This condition may be satisfied by more distant earthquakes and lower frequencies. Given that assumption, transverse or vertical rotation rate time course is proportional to that of vertical or transverse translational acceleration (Igel et al., 2007 and others). The apparent wave speed can be derived from the constant of proportionality. Rotaphones are optimized for recording of proximal smaller earthquakes at higher frequencies for which the plane-wave assumption is usually not acceptable. In that case generalized RT relations may be

useful, derived for a spherical wave generated by a directional point source (Brokešová and Málek, 2015b). In addition to the above mentioned acceleration terms, the equations contain also velocity-proportional terms. However, the equations can be applied at exactly determined velocity zero-crossing times (Brokešová and Málek, 2018), in which case only the acceleration terms remain (moreover at acceleration maxima) and can be used in the same way as above to retrieve the apparent wave speed in radial direction. Synthetic tests (Fichtner and Igel, 2009; Bernauer et al., 2012 or Brokešová and Málek, 2015b) indicate that the apparent speed determined in this way corresponds to the depth range of approximately one wavelength. Using proper filtering, this kind of analysis can be performed in various frequency windows with the aim to retrieve depth-dependent seismic velocities. The higher the prevailing frequency, the shallower the depths to which the 6DOF data are sensitive.

Rotaphone data can also be very useful for determining the locations of earthquake epicenters. Rotation rate components can be used to estimate the true back azimuth, again from a single station. For distant earthquakes and plane wave approximation, there is an option to minimize one of the horizontal rotation rates by rotating the coordinate axes to find radial direction. For proximal earthquakes, the above mentioned RT relations based on the spherical wave assumption should be used. The equations yield the back azimuth as arctangent of the ratio of the two horizontal components at zero-crossing points of vertical ground velocity. The epicenter is then located at the intersection of two back azimuth directions determined from two suitably spaced rotaphones. It is important to note that in this way the epicenter is located without knowledge of the velocity structure. Given it is realistic to assume the ratio v_P/v_S constant throughout the velocity model, then the epicentral distance can even be obtained from a single-point measurement without knowledge of the detailed structure: from the time difference between the onsets of P and S waves when the apparent velocities of these waves have been determined from the RT relations. Knowledge of the velocity model is necessary to determine the depth, but even this task is greatly simplified and stabilized if we have independently determined the location of the epicenter.

In complex heterogeneous near-surface structures, seismograms can be very complex (as seen in the second example) because they contain many reflected/scattered waves overlapping in time. While it is usually easier to identify direct P wave and its onset, the S wave onset can be masked within the P-wave group (containing also converted S waves). As shown in the second example, sometimes just a simple look at the 6DOF data may help identify the direct S wave provided it is relatively strong in amplitude. In other cases, a deeper analysis of the 6DOF data is needed, and wave types in other parts of the seismograms should be similarly identified. For a plane wave assumption, there are particular patterns in the 6DOF data that are typical for particular wave types. They are characterized by certain components vanishing (e.g., for general orientation of horizontal axes; Sollenberger et al., 2019). These patterns simplify considerably in the R-T-Z coordinates, for example, vertical and radial rotation rates as well as transverse ground velocity vanish

for P- SV (mixed at free surface because of conversion) and Rayleigh waves while for SH and Love waves the only non-vanishing components are torsion rate and transverse ground velocity. Such approach requires one to find the true back azimuth in each time interval in question as the reflected/scattered waves can come from different directions than direct waves. Surface waves can usually be distinguished from body waves according to prevailing frequency or phase velocity. P waves also differ from SV waves in phase velocity and polarization (namely particle motion diagrams in Z-R plane). Thus, detecting typical patterns in 6DOF data may help to detect wave types dominant in a given time interval.

Performance examples presented come from the first phases of the field test carried out in the U.S.A (2015–2017). The additional calibration allows for the detailed analysis of rotational data at greater precision. As far as the authors know, the rotational seismograms presented represent first seismic rotations ever recorded in the two localities considered, which are extremely interesting from seismological, volcanological and geodynamical point of view. The examples have been selected from hundreds (The Geysers) and even thousands (Long Valley Caldera) of 6DOF records which are now to be analyzed in detail with the focus on the above mentioned applications.

DATA AND RESOURCES

Seismograms used in this study were collected during the testing phase of the Rotaphone-D instrument developed by the authors. The data are included in Supplemental Material for this article. Hypocenters of the two microearthquakes discussed in this study were obtained from the USGS catalogue (<https://earthquake.usgs.gov/earthquakes/>).

The geophone characteristics in Fig. 2 as well as some of the geophone parameters in Tab. 1 were provided by the manufacturer, ION (formerly Sensor Nederland B.V.). It has gone out of business, but the sensor data sheets are available from the successor company HGS Products B.V., http://hgsproducts.nl/Pdf/250HG-6HS_20v1.2.pdf.

Parts of Figs. 6 and 7 were created using Generic Mapping Tools version 6.4.0 (www.soest.hawaii.edu/gmt). Topographic data were obtained from the on-line database <https://data.usgs.gov/datacatalog/data/USGS:35f9c4d4-b113-4c8d-8691-47c428c29a5b>.

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