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# Small-aperture-array translational and rotational seismograms from distant sources – An example of the Jan Mayen Mw 6.8 of 30 August 2012 earthquake

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ABSTRACT

We present the seismic rotation rate due to the earthquake of Mw 6.7 at the Jan Mayen island, obtained from broad-band seismograms at a distance of about 2740 km. The order of magnitude of the rotation rate amplitude is only $10^{-9}$ rad/s in this case. It is studied with a focus on rotation-to-translation relations. A joint analysis of the rotational and translational data allowed us to determine the true backazimuth and phase velocity of S- and Rayleigh waves. For the surface waves, we studied the frequency dependence of both the backazimuth and phase velocity (wave dispersion). The results are independently confirmed by a method based on time delays between translational records within a small-aperture array. Both methods revealed an unusual velocity drop in the dispersion curve between the periods of 18 and 22 s. This feature may be an indication of a low-velocity zone in the lower crust.



## 1. Introduction

Seismic rotation, the curl of the seismic wavefield, represents a new observable which started being studied and analyzed mainly in the past decade (Igel et al., 2012). Rotational ground motions represent linear combinations of spatial ground motion gradients, and thus they fall into seismic gradiometry (e.g., Langston (2007)) as a special case. Although it has been shown recently that collocated rotational and translational seismograms may provide information on subsurface structure, rotational seismology is still accepted with certain skepticism. It is partly because the measured ground rotations are usually very small to be widely considered as interpretable quantities, especially when induced by distant earthquakes. Measurements of rotational ground motions are becoming relevant in a wide range of fields as it is documented also in two special issues devoted to advances in rotational seismology (Bull. Seis. Soc. Am, Vol 99, No. 2B, 2009; J. Seismol, Vol 16, No. 4, 2012).

In this paper we focus mainly on relations between certain rotational and translational components of the ground motion induced by distant earthquakes. Assume the Cartesian coordinate system $\xi,\ \eta,\ z$ with the $\xi$-axis (radial) pointing from the epicenter to the observation point, $z$-axis (vertical) pointing upwards and the $\eta$-axis (transverse) completing the coordinates to create a right-handed system. Under translational components we understand ground velocity components $v_\xi,\ v_\eta,\ v_z$. These translational components are measured by classical seismometers. By rotational components $\Omega_\xi,\ \Omega_\eta$ and $\Omega_z$ we mean here components of the vector equal to a half, with a minus sign, of the curl of ground velocity. They represent rotation rates around the given Cartesian axis. At the Earth's surface, thanks to stress-free boundary conditions, the expressions for them simplify to

$$\Omega_\xi = \frac{\partial v_z}{\partial \eta} \tag{1}$$

$$\Omega_\eta = -\frac{\partial v_z}{\partial \xi} \tag{2}$$

$$\Omega_z = \frac{1}{2}\left(\frac{\partial v_\xi}{\partial \eta} - \frac{\partial v_\eta}{\partial \xi}\right), \tag{3}$$

where the vertical-axis component $\Omega_z$ is called torsion rate, and the two horizontal-axis components, $\Omega_\xi,\ \Omega_\eta$, are called tilt rates.

The rotational components induced by distant earthquakes can be measured by a suitable broad-band rotational sensor with a sensitivity sufficiently high to detect very small ground motion rotation. For example, ring-laser gyroscopes based on the Sagnac effect (e.g., Schreiber et al. (2009)) meet these requirements. An alternative approach is to derive spatial ground velocity gradients

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in Eqs. (1)–(3) by differencing seismograms across a small-aperture (with respect to the wavelength) array, see below.

Various papers report a similarity in waveforms between torsion rate and transverse acceleration teleseismic records (e.g., Igel et al., 2005, 2007). Note that the torsion rate is measured by most of the ring lasers around the world as they are usually installed in a horizontal plane. The matching of the above mentioned waveforms can even be used to retrieve the apparent phase velocity along the surface from their amplitude ratio. Kurrle et al. (2010) reported the possibility of estimating Love wave dispersion curves from amplitude ratios between transverse acceleration and torsion rate. In this paper, as we determine all three rotational components and not the torsion rate alone, we show that for distant earthquakes the phase velocity can be also retrieved by matching vertical acceleration and transverse tilt rate and taking their amplitude ratio. Even the Rayleigh wave dispersion can be determined in this way.

Another quantity retrievable from matching rotational and translational data is the real backazimuth, i.e., the real propagation direction. Igel et al. (2007) again used torsion rate and transverse acceleration and determined the backazimuth by maximizing the correlation coefficient between them. For the same purpose, we use here a more accurate method based on minimizing the radial tilt rate.

We demonstrate all the discussed rotation-to-translation relations on an example of the Mw 6.7 earthquake that occurred near the Jan Mayen island in the North Atlantic (see Fig. 1a) on 30 August 2012. Since that time for almost twenty-one following months it was the strongest earthquake with the epicenter in the European plate (71.44N, 10.60W, ANSS catalog). We recorded it at a distance of about 2740 km at seven stations of a small-aperture array around the gas storage Příbram-Háje (Fig. 1b). The distance between the individual stations is up to about 2 km, the array area is approximately 14 km$^2$. The elevation varies from 548 m (JER) to 572 m (BUK). The stations are equipped with three-component Guralp CMG-40T seismometers with flat frequency response between 0.03 and 30 Hz.

## 2. Translational seismograms

Fig. 2 shows the three-component ground velocity and its amplitude spectrum as recorded at the KON station (see Fig. 1b) which we choose as a reference station in the array. The radial axis points from the source to the station, i.e., against the direction of geometrical backazimuth (341°). Note that the radial direction as defined above roughly corresponds to the true propagation direction of the P-wave group as its amplitude on the transverse component is much lower than that on the other two components. Fig. 3 provides a detailed view of the wave groups most relevant with respect to seismic rotations, S- and surface waves (including the Airy phase), recorded within the array. From the records themselves, without further analysis (see below), it is not possible to ascertain the true propagation direction of these wave groups. Waveforms from the individual stations are very similar and their mutual time shifts are clearly seen. The amplitude spectra of the specified wave groups are shown on the right, in order to see the prevailing frequencies/periods.

## 3. Array-derived rotations

As we do not have a suitable long-period point rotational sensor, we used the ADR (Array Derived Rotation) method to determine rotational components (1)–(3) at the KON station of the Příbram-Háje array. The method, proposed by Spudich et al. (1995), has been applied in the classic paper by Huang (2003) at a close distance from the earthquake fault surface trace. Suryanto et al. (2006) compared array-derived rotations with direct ring-laser measurements of an earthquake at a comparable distance as that used in our study. The ADR method is based on the Taylor's expansion up to the first order of the seismic wavefield from the reference station in the array. Let us denote the reference station position vector $\mathbf{r}^0$, and the position vector of the n-th station as $\mathbf{r}^n$ ($n$ goes up to $N-1$, where $N$ is the total number of stations in the array). Assume the stations are distributed at a close distance

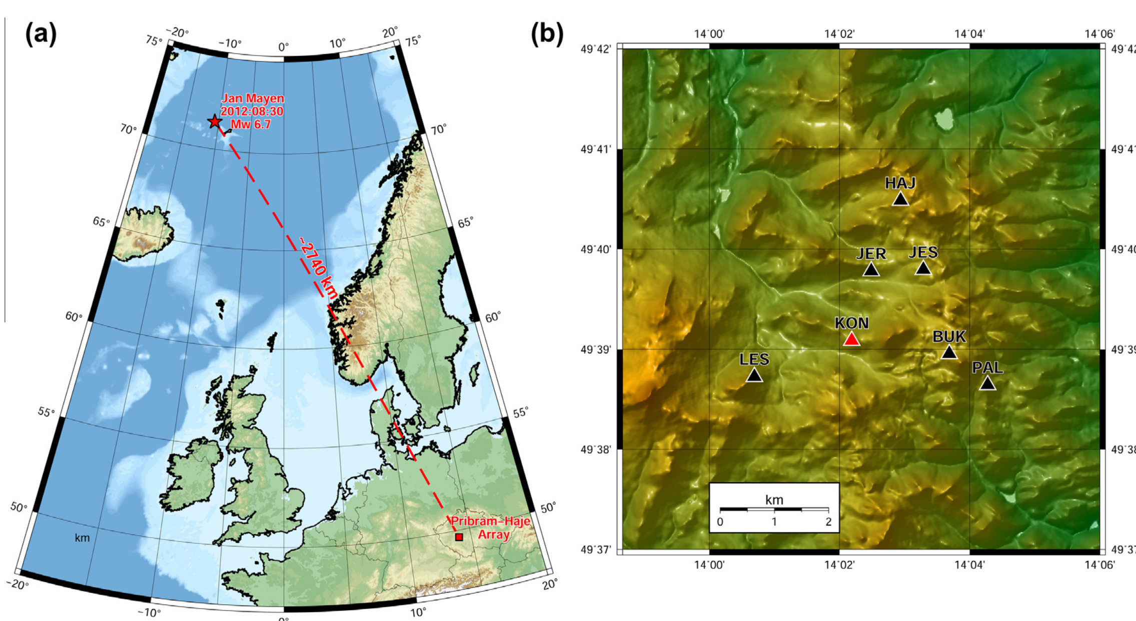


**Fig. 1.** (a) Epicenter of the Jan Mayen earthquake, Mw 6.7, 30 August 2012 (red star) and the location of the Příbram-Háje array (red square). (b) a map of the Příbram-Háje array area in geographic coordinates. Station positions shown as triangles. The red filled triangle denotes the KON station which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