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Rotation sensing without rotation sensors for land seismic

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Introduction

The use of rotation sensing has been a popular research topic over the last 15 years (Schmelzbach et al., 2018). The main application in land seismic is attenuation of coherent noise such as local attenuation of ground roll (Allouche et al., 2015) and scattered noise (Edme et al., 2013). Rotation sensing also allows characterization of local near-surface properties (Allouche and Øzdemir, 2019), and wavefield interpolation (Muyzert et al., 2012; Khatami and Ravasi, 2025).

Despite very promising field-test results, to date there have been no commercial land seismic survey using rotation sensing. The main obstacle is financial: the additional cost of rotation sensing using dedicated instruments is prohibitive as there are no readily available low-cost rotation sensors. Here, we review the different options for direct and indirect rotation sensing and explore whether the advent of small and cost-effective 1C accelerometer nodes can help make rotation sensing economically feasible for onshore seismic exploration.

Theory

As for the translational part of particle motion (V_x , V_Y and V_z), its rotational part can be decomposed in three orthogonal components: two in orthogonal vertical planes around the two horizontal axes (R_{XZ} and R_{YZ}) and one in the horizontal plane around the vertical axis (R_{XY}). This last component R_{XY} is only sensitive to SH and Love waves. Because of this, all the examples listed in the introduction only use the two rotation components in the vertical plane (R_{XZ} and R_{YZ}) in combination with V_Z , hence our focus here is on sensing these components of the seismic wavefield.

At or just below the land surface, taking the curl of the seismic wavefield leads to a relation between the rotation and spatial gradient of the translational wavefield (Robertsson and Curtis, 2002; Edme et Muyzert, 2013):

$$R_{XZ} = \frac{\delta V_Z}{\delta x}, \qquad R_{YZ} = -\frac{\delta V_Z}{\delta y}. \tag{1}$$

Rotation sensing is especially sensitive to waves with short wavelengths that are not properly sampled with standard acquisition geometries: the shorter the apparent wavelength at the surface of a seismic wave, the larger the spatial variation in V_z, and hence also the larger the rotation is.

For an inline V_z receiver interval of 25 m, this will be the case for apparent wavelengths smaller than 50 m (in consideration of the Nyquist criterion). In the crossline direction, if we have a receiver line spacing of 100 m, then it will be for apparent wavelengths smaller than 200 m. Figure 1a shows this aliasing limit in the apparent velocity vs frequency domain for these two cases. Every point above the limit lines will be spatially aliased, and this is where additional sensors are needed for unaliased wavefield recording. From Figure 1a, we can see that denser wavefield sampling is especially needed for wave modes with low apparent velocity, thus rotation is especially interesting for the characterization and attenuation of surface waves.

For a single plane wave, we can rewrite equation 1 following Edme et Muyzert (2013) as:

$$R_{XZ} = p_x \cdot A_Z, \qquad R_{YZ} = -p_Y \cdot A_z \tag{2}$$

with A_Z being the vertical component of acceleration and p the slowness of the wave or inverse of the apparent velocity along the surface.

As we want to combine rotation with translation data, we would like the resolution of rotation data to be comparable to the resolution of acceleration data. From equation 2, we can derive an equivalent rotational noise specification for different slowness or apparent velocities from an acceleration sensor noise specification, as shown in Figure 2b.

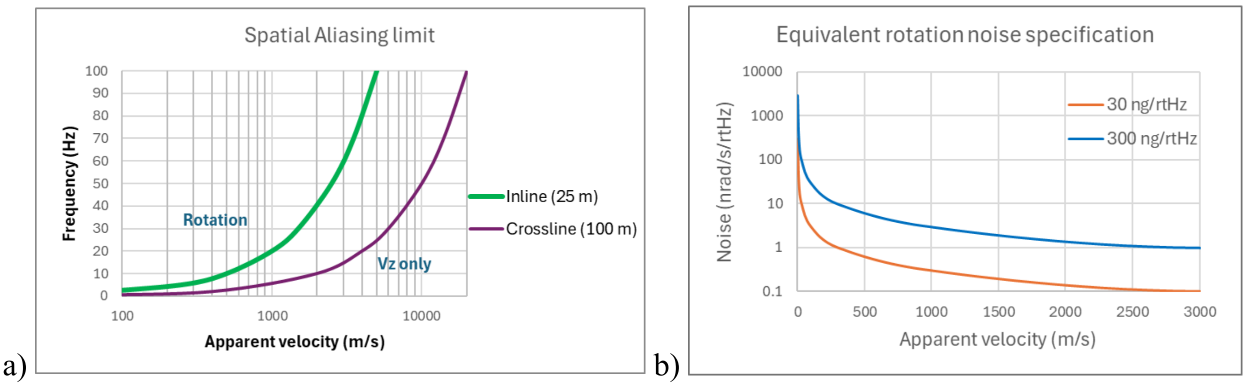

Figure 1 *a) Aliasing limit in frequency vs apparent velocity space for different receiver spacings*
b) Rotation noise level vs seismic wave apparent velocity, equivalent to acceleration noise

As expected, rotation sensing is more sensitive for very slow waves. However, for waves with apparent velocities of a few 100s of m/s, a noise level of few nrad/s/rtHz would be desirable.

Implementation

We have seen that at the land surface, rotation is equivalent to spatial gradients of the vertical translation component of the seismic wavefield. We will review the different options for measuring this quantity, using either dedicated sensors measuring rotation directly or indirectly, or using several standard seismic sensors to indirectly measure rotation.

Direct measurement: Rotation sensors

Rotation sensors are available and in use for seismological applications. These are large and expensive instruments which are not suitable for exploration seismic. Chen et al. (2025) have reviewed their performance and quote a typical noise floor level of 20 – 30 nrad/s/rtHz. There have also been developments of rotation sensors for exploration seismic (Schmelzbach et al., 2018). Eentec proposed a design based on electro-chemical MET technology 20 years ago. Projetti et al. (2014) designed and prototypes a MEMS rotation sensor for seismic. More recently, a 6C sensor was designed and tested in a seabed node (Pedersen et al., 2023). It seems however that we are still a long way from having a rotation sensor with a cost and performance level that is adequate for commercial land seismic operations.

Indirect measurement: wavefield gradiometry using dedicated instruments

Another solution is to measure the spatial gradient of the wavefield which can then be related back to rotation via equation 1. The finite difference between two relatively closely spaced seismic sensors is a good approximation of the spatial gradient. This wavefield gradient measurement can be made between two sensors inside a common instrument housing. The rotation is equivalent to the finite difference between the particle velocity measured at the two extremities of the package.

This approach has been successfully applied with the StiQ instrument (Muyzert et al, 2019), where two 3C MEMS were mounted at either end of a 20 cm tube, and their output finite differenced. However, the use of an integrated instrument for gradient measurement has some drawbacks. The small separation distance between the two sensors means that the recorded wavefield difference between the sensors is small, limiting the achievable resolution. This solution also requires dedicated hardware, requiring a significant capital investment to enable large scale data acquisition.

Indirect measurement: wavefield gradiometry using nodes

To overcome these drawbacks, a solution is to compute spatial wavefield gradients by differencing signals recorded using standalone nodal receivers deployed in a spatial pattern. Low-cost 1C accelerometer nodes that record translational motion in any orientation are suitable for such a purpose. Large inventories of such nodes already exist for use in conventional 1C seismic recording, eliminating the main economic obstacle to rotation sensing, as existing equipment can be used.

Three vertically-oriented seismic nodes offset in inline and crossline directions (Figure 2, left) can be used to record V_z and horizontal spatial wavefield gradients. Edme et al. (2014) tested this configuration, and demonstrated good potential for ground-roll attenuation.

The resolution of the gradient measurement can be increased by increasing the distance between the nodes, since a larger separation distance increases the amplitude of the wavefield difference between sensors, and attenuates errors introduced by variations in the node coupling, hence it is desirable to maximise the separation distance. However, if the distance between nodes is no longer small compared to the apparent wavelength of the wave, finite differencing of the sensor output is no longer a good approximation to the wavefield gradient and hence rotation. Some compensation for this can be applied, and a separation distance of several meters is still possible. Edme and Muyzert (2013) recommend a distance no larger than a third of the smallest wavelength of interest.

Figure 2 *Different nodes group configurations for rotation sensing*

An alternative node layout would be a stencil of 5 nodes (Figure 2, middle and right). This allows to compute two versions of the gradient in each direction, one on each side of the central node. You can then differentiate these two gradients to obtain in addition the second spatial derivatives of the wavefield, which can be very useful noise models. Such a layout is very similar to traditional land acquisition design using groups of sensors (e.g. cabled geophone arrays) which could be spaced every 25 m along a receiver line. Summing the outputs of the five nodes in a group would give an output equivalent to that of an analog array of geophones (Golikov et al., 2025), providing a standard vertical-component data set than can be processed conventionally.

The cost of a system with five nodes per group can be competitive with the cost of a cable system with geophone arrays, while the operational cost of deploying nodes will be lower than an equivalent number of cabled sensors. In addition, single-sensor acquisition with nodes delivers the individual trace data from each node, from which the spatial wavefield gradients (and hence rotations) can be computed via finite differencing. The noise attenuation methods referenced herein can be applied to this additional dataset, and the results compared to a straight sum of the vertical-component data, allowing experimentation with rotational acquisition at no additional acquisition cost compared to a conventional survey. This acquisition design also present opportunities to test other processing methods that use local groups of sensors.

Conclusion

Rotation sensing has proven potential for local noise attenuation and wavefield interpolation. It is unlikely that purpose-built rotation sensors and acquisition systems will become available soon at a scale and price-point that is acceptable for commercial land seismic acquisition. Because of the equivalence between rotation and spatial gradient of the wavefield at the land surface, it is however possible to obtain the benefits of rotational data processing methods by replacing analog geophone arrays with small groups of suitable 1C seismic nodes.

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