Rotational Signals In The P Coda

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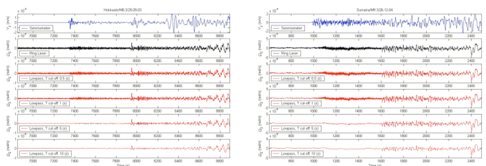
1 Introduction

The collocated observations of rotations around a vertical axis and translations obtained by a 4x4m ring laser and traditional broad band seismometer recently opened opportunities to find out additional information that may not be contained in classical three-component recordings. By investigating the cross correlation between transverse acceleration and rotation rate around a vertical axis we recognized that there is significant rotational motion component in the P coda of seismic signals. Theoretically, in spherically symmetric isotropic media we should not observe a vertical component of rotation before the onset of SH waves. Two possible explanations for this phenomenon are: (1) Tilt of the Earth's surface caused by P waves polluted the ring laser measurements; (2) P-SH converted energy (because of 3D effects) close to the receiver. In this study, tilt in the P coda of the seismic signal as well as its effects on the Ring Laser records have been calculated from translation data of a 3-component-seismometer. These estimates indicate that the P coda rotations are due to both P-SH scattering and ring laser – tilt coupling, however, P-SH scattering being orders of magnitude stronger. The result may eventually provide a means to estimate near receiver P-SH scattering in a quantitative way, thereby separating out the SH contribution in the scattering field.

Keywords: cross correlation, transversal acceleration, rotation, tilt, tilt coupling, scattering

2 Observations

Figure 1 & 2: Observations of translational and rotational ground motions induced by earthquakes. Two top traces: Vertical component of ground velocity recorded by broadband seismometer and rotation rate (vertical axis) recorded by a ring laser sensor. Four bottom traces: rotation rate low-pass filtered with different cut-off periods 0.5 s, 1 s, 5 s, 10 s. **Significant energy in rotational motions in the P coda is visible.** The connection between the decrease of the rotation amplitude and the increase of the cut-off period implies that **the P coda rotations are predominantly in the high frequency range. Left:** Hokkaido event 25/09/2003, M8.3; **Right:** Sumatra event 26/12/2004, M9.3.



Theoretically, assuming plane wave propagation in horizontal direction with transverse polarization, rotation rate and transverse acceleration should have the same waveform and their amplitudes should scale proportional to phase velocity (Cochard et al., 2005; Igel et al., 2005, 2006)

⇨

The zero lag normalized cross correlation coefficients - defined between 0 (no similarity) and 1 (perfect match) - between rotation rate and transversal acceleration (after applying high pass filter) were calculated for sliding time windows (length of twice as long as the cut off period of the high pass filter applied before) along the time series

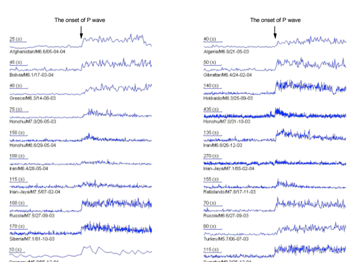
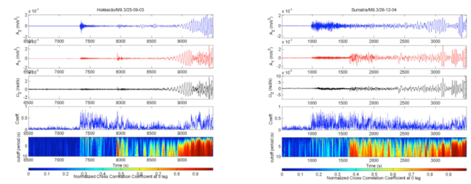


Figure 3. The normalized cross correlation coefficients between rotation rate and transverse acceleration (after applying high pass filter with cut-off period 1s) calculated for sliding time windows of 2s. **The coefficients increase at the onset of P waves in all observed events indicating correlated energy in SH type motions.**

3 Observations



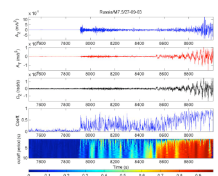


Figure 4, 5 & 6. Top three traces: Vertical acceleration, transverse acceleration and rotation rate, respectively. The fourth trace: zero lag normalized cross correlation coefficients calculated for time windows of 2 s between rotation rate and transverse acceleration after applying high pass filter with cut-off period 1 s. Bottom: the correlation coefficients as a function of time and cut-off period (length of sliding time window twice as long as high pass cut off period applied before correlating). **There is a sharp increase in correlation at and following the direct P – wave. This correlation smears out and becomes less pronounced with increasing period, while the corresponding correlation of SH – type signals and Love waves increases with period.**

The observations indicate that there are significant rotational motion components in the P coda. Theoretically, in spherically symmetric isotropic media we should not observe vertical component of rotation before the onset of SH waves. So the main questions to address here are: What is the cause of rotational motions in the P coda? Can we extract additional information of the wave field from this phenomenon?

4 Possible Causes – Tilt Coupling

The Sagnac equation (e.g., Schreiber et al., 2005) reads :

$$\Delta f = \frac{4\mathbf{A}}{\lambda P}\left[\dot{\Omega}_{E0}\cos(\alpha_1) + \dot{\Omega}_Z\cos(\alpha_2) + \dot{\Omega}_{NS}\cos(\alpha_3) + \dot{\Omega}_{EW}\cos(\alpha_4)\right] \quad (1)$$

Here Δf is the Sagnac frequency the ring laser sensor records; A and P are area and perimeter of the ring laser, λ is laser wavelength; $\dot{\Omega}_{E0}$ is rotation rate of the Earth around its rotation axis; $\dot{\Omega}_Z$ is earthquake-induced rotation rate around the vertical axis; $\dot{\Omega}_{NS}$ and $\dot{\Omega}_{EW}$ are tilt rates around NS and EW axes, respectively; α_1, α_2, α_3 and α_4 are angles between the normal unit vector of the ring laser and unit base vectors of the Earth's rotation axis, vertical axis and horizontal axes in NS, EW directions at ring laser location, respectively. These angles can be calculated if tilt components and latitude of ring laser position are known.

The rotation rate presented in the observation ignored a possible tilt contribution in equation (1). In fact, when seismic waves arrive they do generate tilt at the Earth's surface (i.e. rotational motions around the horizontal axes). This will pollute the ring laser measurements through changes of α_1, α_2, α_3 and α_4. This phenomenon is called "tilt coupling". Since the mechanical instrument was made as rigid and stable as possible, two possible explanations for the P coda rotation are: 1) Tilt coupling; 2) 3D effects (P-SH scattering close to the receiver location).

Using (1) the rotation rate due to tilt coupling can only be estimated. With theoretical tilt calculations, such kind of rotation rate is insignificant compared to the theoretical rotation rate (Fig. 7). Of the two tilts (i.e. NS tilt and EW tilt), the effects of EW tilt is much stronger (Fig. 8).

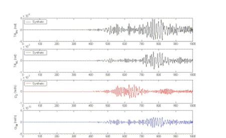


Figure 7. Top 3 traces: theoretical EW, NS tilts and rotation rate around a vertical axis for Gibraltar event 24/02/2004, M6.4 and Wettzell station. Bottom: Calculated rotation rate due to tilt coupling only.

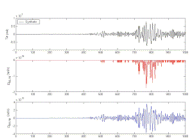


Figure 8. Top: theoretical tilt; Middle and bottom: calculated rotation rate due to the top theoretical tilt in different directions. Middle: effects of NS tilt; Bottom: effects of EW tilt.

5 Li's tilt and tilt coupling in the P coda rotation

To estimate whether the tilt coupling contributes to the observed rotational signal in the P-coda, tilt data is indispensable. However, tiltmeters – sensors that measure the horizontal components of rotational motions at the Earth's surface - are sensitive to translational motions, and thus do not provide the correct signals of tilt. A solution for getting tilt in P coda here is Li's method (Li et al., 2001), an approach that allows to obtain tilt (under certain conditions) from translation data.

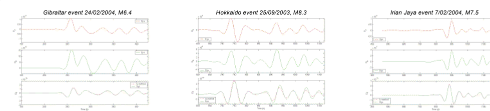


Figure 9, 10 & 11. D_Z and D_R are vertical and radial components of theoretical displacements; Bottom: Superimposed the theoretical tilt with Li-tilt.

The fit between theoretical tilt and Li's tilt (derived from theoretical translation data) in the P coda (Figure 9, 10 and 11) revealed the suitability of Li's method for our applications.

Observed translation data ⇨ **Li's tilt (in P coda)** ⇨ **Tilt coupling & corrected rotation rate (in P coda)**

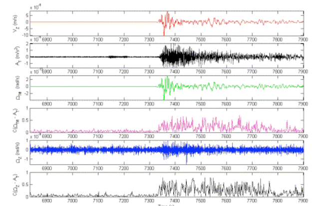


Figure 12. Hokkaido event 25/9/2003, M8.3. (From top to bottom): V_Z: vertical component of velocity; A_T: transverse acceleration; Ω_{Tilt}: calculated tilt coupling; $C(\Omega_{Tilt}-A_T)$: Normalized cross correlation coefficients between Ω_{Tilt} and A_T; Ω_Z: vertical rotation rate after subtracting the tilt coupling; $C(\Omega_Z-A_T)$: Normalized cross correlation coefficients between Ω_Z and A_T.

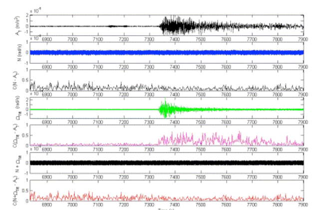


Figure 13. Hokkaido event 25/9/2003, M8.3. (From top to bottom): A_T: transverse acceleration; N: Random noise which has no similarity with A_T and its maximum amplitude is the same with that of the rotation rate; $C(N-A_T)$: Normalized cross correlation coefficients between N and A_T; Ω_{Tilt}: the calculated tilt coupling; $C(\Omega_{Tilt}-A_T)$: Normalized cross correlation coefficients between Ω_{Tilt} and A_T; $N+\Omega_{Tilt}$: Random noise N added Ω_{Tilt}; $C(N+\Omega_{Tilt}-A_T)$: Normalized cross correlation coefficients between $N + \Omega_{Tilt}$ and A_T.

We cannot reproduce the increase in correlation between transverse acceleration and rotation rate with tilt-coupling. This result indicates the negligible contribution of tilt coupling in the observed P coda rotation.

6 Conclusions

- **The main cause for observed P coda rotation is due to 3D effects (P-SH scattering).**
- **The observations may provide a means to estimate near receiver P-SH scattering in a quantitative way, thereby separating out SH motions from the scattering field.**
- **We will now proceed to quantify the observed P-SH scattering with 3D modeling.**

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