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## High-resolution analysis of the gravest seismic normal modes after the 2004 $M_w = 9$ Sumatra earthquake using superconducting gravimeter data

S. Rosat,<sup>1</sup> T. Sato,<sup>1</sup> Y. Imanishi,<sup>2</sup> J. Hinderer,<sup>3</sup> Y. Tamura,<sup>1</sup> H. McQueen,<sup>4</sup> and M. Ohashi<sup>5</sup>

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[1] The  $M_w > 9$  Sumatra-Andaman earthquake on December 26, 2004 has strongly excited the low-frequency seismic modes and is a unique opportunity to improve the frequency and damping measurements of the gravest seismic modes. The precise estimation of the frequency splitting of the seismic modes below 1 mHz is needed to improve 1D-density models of the Earth. From this event,  ${}_2S_1$  is observed for the first time without any stacking on both SG (Superconducting Gravimeter) and seismic records. We report here analyses of SG data obtained from 11 sites. The spectra of SG records clearly show the splitting of  ${}_0S_2$  into 5 completely resolved singlets and the splitting of  ${}_0S_3$  into 7 singlets at individual stations. The present results demonstrate that SGs provide high quality data for a precise analysis of the low-frequency seismic modes. **Citation:** Rosat, S., T. Sato, Y. Imanishi, J. Hinderer, Y. Tamura, H. McQueen, and M. Ohashi (2005), High-resolution analysis of the gravest seismic normal modes after the 2004  $M_w = 9$  Sumatra earthquake using superconducting gravimeter data, *Geophys. Res. Lett.*, 32, L13304, doi:10.1029/2005GL023128.

### 1. Introduction

[2] Under the framework of the GGP project (Global Geodynamics Project [Crossley *et al.*, 1999]), SGs are continuously recording surface time-varying gravity. The high resolution, low noise level and stability of SGs at frequencies below 1 mHz [Van Camp, 1999; Widmer-Schmidrig, 2003; Rosat *et al.*, 2003a, 2004] make these instruments suitable for the analysis of the low-frequency seismic normal modes of the Earth. The precise determination of the frequency splitting of seismic modes below 1 mHz is a way to improve 1D density models without any trade-off with elastic parameters, as they are directly linked to the 1D-density profile [Widmer-Schmidrig, 2003]. The splitting of the gravest modes also possesses high sensitivity to the 3D-density structure in the Earth's mantle and core, so their observation can constrain the Earth's lateral density structure [Ritzwoller and Lavelly, 1995]. The recent Sumatra-Andaman earthquake on 2004 December 26

is a rare opportunity to improve Earth's models, as this huge event has strongly excited the low-frequency seismic modes both on SG and seismic records.

[3] SGs have allowed the high quality observation of the harmonic degree two seismic mode  ${}_0S_2$ , the so-called "football mode," and the first detection, by stacking 5 SG records, of the degree one seismic mode  ${}_2S_1$  after the  $M_w = 8.4$  Peru earthquake that occurred on 2001 June 23 [Rosat *et al.*, 2003b]. These two modes are the gravest seismic spheroidal modes and  ${}_2S_1$  corresponds to a translation of the core with respect to the mantle. After Sumatra earthquake,  ${}_2S_1$ , the core-sensitive mode  ${}_3S_2$  and the fundamental radial mode  ${}_0S_0$  were strongly excited. This means that the earthquake radiated much energy towards the core.

[4] In the following, SG data from Esashi (ES), Kamioka (KA), Matsushiro (MA) in Japan, Canberra (CB) in Australia, Strasbourg (ST) in France, Bad-Homburg (BH), Moxa (MO), Wettzell (WE) in Germany, Medicina (MC) in Italy, Vienna (VI) in Austria and Sutherland (SU) in South Africa have been corrected for solid and oceanic tides and atmospheric pressure effects using a nominal admittance of  $-3 \text{ nm.s}^{-2} \text{ hPa}^{-1}$ . The necessity to correct seismometer and SG data for local atmospheric pressure at frequencies below 1 mHz has been demonstrated by many authors [e.g., Zürn and Widmer, 1995; Freybourger *et al.*, 1997; Rosat *et al.*, 2003a]. We first compare this earthquake to the 2001 Peruvian event. Then we show the high-resolution frequency splitting of  ${}_0S_2$  and  ${}_0S_3$ . Finally, we compute new frequency estimates for  ${}_2S_1$ .

### 2. Comparison With the 2001 $M_w = 8.4$ Peru Event

[5] The analysis by Rosat *et al.* [2003b] for the Peru event was limited to 274 hours because of the occurrence of a second large quake 13 days after the main event. For the Sumatra event, the analysis using SG can be performed on much longer records (e.g., 25 days) and the amplitude of the gravest seismic modes is about 10 times larger than after the Peru earthquake (Figure 1). The data length is enough to resolve the  ${}_0S_3$  singlets (Figure 2) and the  ${}_0S_2$  singlets are completely isolated (Figure 3). Besides,  ${}_2S_1$  is observed without any stacking (Figure 4) at individual stations.

[6] A notable characteristic of the Sumatra earthquake is the strong excitation of  ${}_0S_0$ . A preliminary analysis using 37 days of data from CB gives a Q-value of  $5601 \pm 36$  and a frequency of  $0.8146627 \pm 4.2 \cdot 10^{-6}$  mHz, while the predicted quality factor and frequency for the PREM [Dziewonski and Anderson, 1981] model are respectively

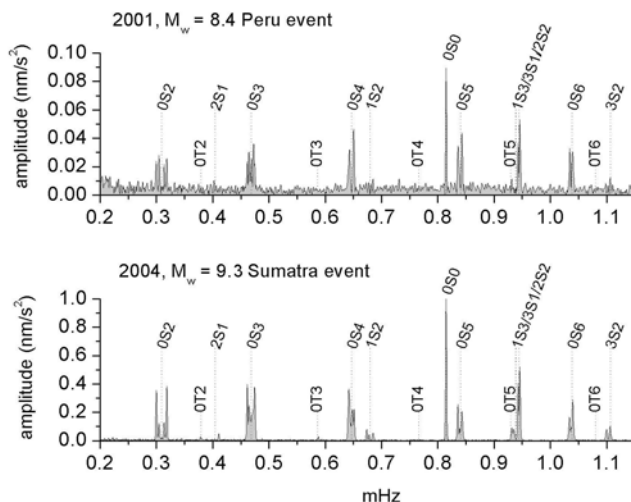
<sup>1</sup>National Astronomical Observatory of Japan, Iwate, Japan.

<sup>2</sup>Ocean Research Institute, University of Tokyo, Tokyo, Japan.

<sup>3</sup>UMR 7516 CNRS-ULP, Institut de Physique du Globe de Strasbourg (IPGS-EOST), Strasbourg, France.

<sup>4</sup>Research School of Earth Sciences, Australian National University, Canberra, ACT, Australia.

<sup>5</sup>Institute for Cosmic Ray Research, University of Tokyo, Tokyo, Japan.

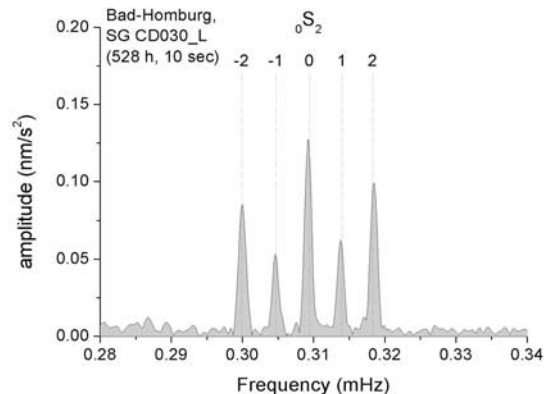


**Figure 1.** Amplitude spectra of SG data at Canberra (240 hours) (top) after the 2001  $M_w = 8.4$  Peru event and (bottom) after the 2004  $M_w = 9$  Sumatra earthquake.

5327 and 0.8146639 mHz after correcting for second order effects of rotation and ellipticity.

### 3. High-Resolution Frequency Splitting of ${}_0S_2$ and ${}_0S_3$

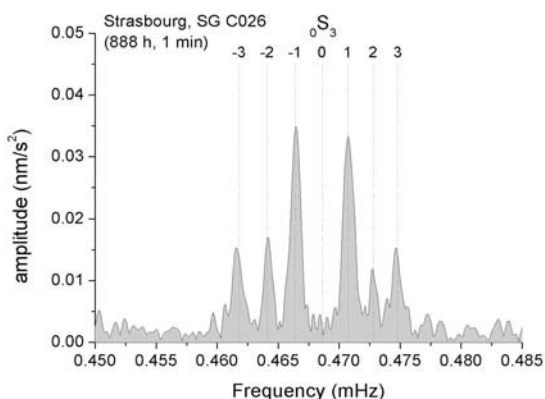
[7] The data for the Sumatra event are available at the GGP website for 12 sites (<http://www.eas.slu.edu/GGP/sumatra.html>). We also used the data obtained from two Japanese sites, MA and KA. Choosing the best quality records, we have performed frequency analyses of  ${}_0S_2$  using 528 hours of data at stations CB, MA, ST, BH (Figure 3), MO, MC, WE, VI and SU, 408 h at KA and 240 hours at ES. The noise level at ES is too high to justify a longer time series. Usually a good compromise between frequency resolution and signal-to-noise ratio (SNR) can be obtained for a record length of one Q-cycle [Dahlen, 1982]. The SNR of the modes after the Sumatra event are so high that we can easily use a series of several Q-cycles to increase the frequency resolution. The results for  ${}_0S_2$  are compared with



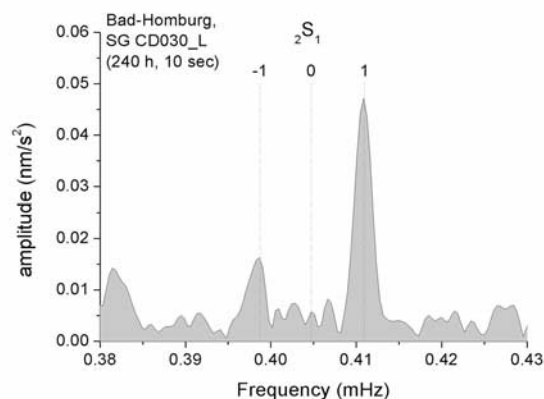
**Figure 3.** Observation of the five singlets of  ${}_0S_2$  at Bad-Homburg using 528 hours of data after the 2004 Sumatra event. The predicted frequencies for PREM are indicated by the vertical dotted lines.

previous estimates and with predicted values in Table 1. Our error bars and those for the Peru estimates have both been computed using the method proposed by Dahlen [1982], which considers the SNR of the singlet and the windowing effect. Our predictions for PREM model have been computed using the perturbation method of Dahlen and Sailor [1979] and the eigenfunctions computed with MINOS [Woodhouse, 1988]. We can see that individual record estimates often have smaller errors than previous estimates using a multiple event stripping technique [Ritzwoller et al., 1986] of more than 100 IDA gravimeter records or multiple taper and stacking of 7 IDA records of the 1977 Indonesian event [Lindberg, 1986]. The mean of the five singlet frequencies at ST and KA has smaller errors than the value obtained by Buland et al. [1979] using a stack of 6 IDA records of the 1977 Indonesian event. The mean frequency obtained here from the analysis of SG data is smaller than the PREM value while the mean frequencies obtained by Buland et al. [1979], Lindberg [1986] and Ritzwoller et al. [1986] are greater than PREM prediction.

[8] The singlets of  ${}_0S_3$  are also well resolved, as shown for example in the ST record with 37 days of data (Figure 2).



**Figure 2.** Observation of the well-resolved singlets of  ${}_0S_3$  at Strasbourg after the 2004 Sumatra earthquake. The single  $m = 0$  was not excited at Strasbourg.



**Figure 4.** Observation of  ${}_2S_1$  at Bad-Homburg using 240 hours of data after the 2004 Sumatra event.

**Table 1.** Observed and Predicted Frequencies of  ${}_0S_2^a$ 

	${}_0S_2$ Frequencies, mHz					Mean Frequency
	m = -2	m = -1	m = 0	m = 1	m = 2	
Canberra	0.29996 $\pm 1.3 \cdot 10^{-4}$	0.30458 $\pm 2 \cdot 10^{-4}$	-	0.31379 $\pm 3.2 \cdot 10^{-4}$	0.31844 $\pm 3.8 \cdot 10^{-5}$	0.30919 $\pm 1.7 \cdot 10^{-4}$
Esashi	0.29983 $\pm 2.5 \cdot 10^{-4}$	0.30472 $\pm 5.5 \cdot 10^{-4}$	-	0.31383 $\pm 8.9 \cdot 10^{-4}$	0.31853 $\pm 7.2 \cdot 10^{-4}$	0.30923 $\pm 6.0 \cdot 10^{-4}$
Kamioka	0.29996 $\pm 3.9 \cdot 10^{-5}$	0.30458 $\pm 8.7 \cdot 10^{-6}$	-	0.31383 $\pm 2.6 \cdot 10^{-5}$	0.31848 $\pm 5.1 \cdot 10^{-5}$	0.30921 $\pm 3.1 \cdot 10^{-5}$
Matsushiro	0.29992 $\pm 7.5 \cdot 10^{-5}$	0.30465 $\pm 1.2 \cdot 10^{-4}$	-	0.31373 $\pm 2.2 \cdot 10^{-4}$	0.31842 $\pm 2.0 \cdot 10^{-4}$	0.30918 $\pm 1.5 \cdot 10^{-4}$
Strasbourg	0.29997 $\pm 6.6 \cdot 10^{-5}$	0.30462 $\pm 1.1 \cdot 10^{-4}$	0.30929 $\pm 6.1 \cdot 10^{-5}$	0.31389 $\pm 9.6 \cdot 10^{-5}$	0.31845 $\pm 3.3 \cdot 10^{-5}$	0.30924 $\pm 9.7 \cdot 10^{-5}$
Bad-Homburg	0.29998 $\pm 2.0 \cdot 10^{-5}$	0.30467 $\pm 1.1 \cdot 10^{-4}$	0.30924 $\pm 6.4 \cdot 10^{-6}$	0.31378 $\pm 3.5 \cdot 10^{-5}$	0.31844 $\pm 2.4 \cdot 10^{-5}$	0.30922 $\pm 3.9 \cdot 10^{-5}$
Moxa	0.30001 $\pm 5.3 \cdot 10^{-5}$	0.30452 $\pm 8.8 \cdot 10^{-5}$	0.30925 $\pm 8.1 \cdot 10^{-5}$	0.31383 $\pm 3.2 \cdot 10^{-5}$	0.31843 $\pm 5.2 \cdot 10^{-6}$	0.30921 $\pm 5.2 \cdot 10^{-5}$
Wetzell	0.29999 $\pm 5.1 \cdot 10^{-5}$	0.30433 $\pm 3.4 \cdot 10^{-4}$	0.30918 $\pm 2.2 \cdot 10^{-5}$	0.31388 $\pm 4.6 \cdot 10^{-5}$	0.31840 $\pm 1.0 \cdot 10^{-4}$	0.30916 $\pm 1.1 \cdot 10^{-4}$
Vienna	0.29994 $\pm 1.6 \cdot 10^{-5}$	0.30469 $\pm 1.4 \cdot 10^{-4}$	0.30928 $\pm 5.7 \cdot 10^{-5}$	0.31393 $\pm 5.3 \cdot 10^{-5}$	0.31848 $\pm 4.2 \cdot 10^{-5}$	0.30926 $\pm 6.2 \cdot 10^{-5}$
Medicina	0.29999 $\pm 1.2 \cdot 10^{-5}$	0.30459 $\pm 5.9 \cdot 10^{-6}$	0.30929 $\pm 1.1 \cdot 10^{-4}$	0.31378 $\pm 1.5 \cdot 10^{-5}$	0.31842 $\pm 4.1 \cdot 10^{-5}$	0.30921 $\pm 3.7 \cdot 10^{-5}$
Sutherland	0.29996 $\pm 9.9 \cdot 10^{-6}$	0.30480 $\pm 6.3 \cdot 10^{-5}$	0.30904 $\pm 1.7 \cdot 10^{-4}$	0.31377 $\pm 8.9 \cdot 10^{-5}$	0.31840 $\pm 1.3 \cdot 10^{-5}$	0.30919 $\pm 6.9 \cdot 10^{-5}$
Weighted mean	0.29997 $\pm 6.3 \cdot 10^{-6}$	0.30458 $\pm 4.7 \cdot 10^{-6}$	0.30924 $\pm 6.0 \cdot 10^{-6}$	0.31381 $\pm 1.1 \cdot 10^{-5}$	0.31843 $\pm 4.6 \cdot 10^{-6}$	0.30921 $\pm 1.6 \cdot 10^{-5}$
<i>Rosat et al.</i> [2003b] (one SG record at Strasbourg of 2001 Peru event)	0.29987 $\pm 1.9 \cdot 10^{-4}$	0.30455 $\pm 8.9 \cdot 10^{-5}$	0.30911 $\pm 2.9 \cdot 10^{-4}$	0.31389 $\pm 1.3 \cdot 10^{-4}$	0.31821 $\pm 6.6 \cdot 10^{-5}$	0.30913 $\pm 1.5 \cdot 10^{-4}$
<i>Buland et al.</i> [1979] (stack of 6 IDA records of 1977 Indonesian event)	0.30001	0.304799	0.30949	0.31399	0.31849	0.30936 $\pm 9.8 \cdot 10^{-5}$
<i>Ritzwoller et al.</i> [1986] (multiple event stripping using more than 100 records)	0.299722 $\pm 1.4 \cdot 10^{-4}$	0.304890 $\pm 4.1 \cdot 10^{-4}$	0.309200 $\pm 2.7 \cdot 10^{-4}$	0.314300 $\pm 2.7 \cdot 10^{-4}$	0.318774 $\pm 1.0 \cdot 10^{-4}$	0.309377 $\pm 2.4 \cdot 10^{-4}$
<i>Lindberg</i> [1986] (multiple taper and stack of 7 IDA records of 1977 Indonesian event)	0.2999911 $\pm 6.1 \cdot 10^{-5}$	0.304718 $\pm 4.14 \cdot 10^{-4}$	0.309372 $\pm 9.5 \cdot 10^{-5}$	0.314255 $\pm 1.21 \cdot 10^{-3}$	0.318298 $\pm 7.5 \cdot 10^{-5}$	0.309311 $\pm 3.7 \cdot 10^{-4}$
PREM	0.2998479	0.3047817	0.3093972	0.3140127	0.3183099	0.3092699

<sup>a</sup>The observations based on SG records after the 2004 Sumatra event are compared to previous estimates and to the PREM predictions.

The high-precision analysis of  ${}_0S_3$  frequencies is compared in Table 2 with PREM predictions and previous estimates by *Buland et al.* [1979]. The estimates at ST are in good agreement with theoretical predictions. Our results indicate that, with a single SG record, we can reach high frequency resolution in  ${}_0S_2$  and  ${}_0S_3$  estimates.

#### 4. New Observation of ${}_2S_1$

[9] The Sumatra earthquake has strongly excited  ${}_2S_1$ , and the singlet m = 1 is particularly clearly observed on individual SG spectra (e.g. BH, Figure 4). This is the first time this mode has been observed directly. Unluckily only the singlet m = 1 seems to be observed on most SGs (except

BH and ST where m = -1 appears faintly). The frequency analysis of  ${}_2S_1$  is compared in Table 3 to PREM predictions and to the stack of 5 SGs done by *Rosat et al.* [2003b] after the Peru event. The error bars at individual stations are large, except for BH, MO, WE and VI, where they are smaller than those obtained for the Peru event.

#### 5. Conclusion

[10] The 2004  $M_w > 9$  Sumatra-Andaman earthquake confirms the results obtained with the Peru event, demonstrating the contribution of SGs for high-resolution frequency splitting analysis of the gravest seismic modes. The combination of the SG data with other seismic data, in particular

**Table 2.** Observed and Predicted Frequencies of  ${}_0S_3$ 

	${}_0S_3$ Frequencies, mHz						
	m = -3	m = -2	m = -1	m = 0	m = 1	m = 2	m = 3
Strasbourg	0.46167 $\pm 3.0 \cdot 10^{-5}$	0.46424 $\pm 2.0 \cdot 10^{-4}$	0.46639 $\pm 1.8 \cdot 10^{-5}$	-	0.47084 $\pm 1.1 \cdot 10^{-5}$	0.47266 $\pm 4.8 \cdot 10^{-5}$	0.47474 $\pm 2.1 \cdot 10^{-5}$
<i>Buland et al.</i> [1979]	0.46167	0.46408	0.46617	0.46883	0.47091	0.47317	0.47450
PREM	0.4618	0.4641	0.4664	0.4686	0.4707	0.4728	0.4748

**Table 3.** Observed and Predicted Frequencies of  ${}_2S_1$ 

	${}_2S_1$ Frequencies, mHz		
	m = -1	m = 0	m = 1
Canberra	-	-	$0.41072 \pm 5.4 \cdot 10^{-4}$
Kamioka	-	-	$0.41033 \pm 1.8 \cdot 10^{-4}$
Matsushiro	-	-	$0.41078 \pm 4.9 \cdot 10^{-4}$
Strasbourg	$0.39801 \pm 3.7 \cdot 10^{-4}$	-	$0.41082 \pm 2.5 \cdot 10^{-4}$
Bad-Homburg	$0.39822 \pm 6.1 \cdot 10^{-5}$	-	$0.41081 \pm 1.1 \cdot 10^{-4}$
Moxa	-	-	$0.41077 \pm 7.8 \cdot 10^{-5}$
Wetzell	-	-	$0.41082 \pm 1.1 \cdot 10^{-4}$
Vienna	-	-	$0.41081 \pm 9.9 \cdot 10^{-5}$
Medicina	-	-	$0.41074 \pm 1.9 \cdot 10^{-4}$
Sutherland	-	-	$0.41126 \pm 1.6 \cdot 10^{-4}$
Weighted mean	$0.39821 \pm 6.0 \cdot 10^{-5}$	-	$0.41080 \pm 4.2 \cdot 10^{-5}$
Rosat <i>et al.</i> [2003b] (stack of 5 SG records of 2001 Peru event)	$0.3986 \pm 1.9 \cdot 10^{-4}$	$0.4049 \pm 2.1 \cdot 10^{-4}$	$0.4111 \pm 1.8 \cdot 10^{-4}$
PREM	0.39875	0.404727	0.410948

horizontal records, after the Sumatra earthquake will further help to precisely estimate the  ${}_2S_1$  frequencies and its splitting. This precise frequency splitting analysis is essential to constrain the 1D density profile in the mantle and core independently of the elastic parameters.

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- H. Hinderer, UMR 7516 CNRS-ULP, (IPGS-EOST), Strasbourg, France.
- Y. Imanishi, Ocean Research Institute, University of Tokyo, Tokyo, Japan.
- H. McQueen, Research School of Earth Sciences, Australian National University, Canberra, ACT, Australia.
- M. Ohashi, Institute for Cosmic Ray Research, University of Tokyo, Tokyo, Japan.
- S. Rosat, T. Sato, and Y. Tamura, National Astronomical Observatory of Japan, 2-12 Hoshigaoka, Mizusawa, Iwate 023-081, Japan. (rosat@miz.nao.ac.jp)