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First observation of ${}_2S_1$ and study of the splitting of the football mode ${}_0S_2$ after the June 2001 Peru earthquake of magnitude 8.4

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[1] The recent Peru earthquake with a moment magnitude $M_w = 8.4$ on June 23, 2001 presents a good opportunity for the observation of the seismic gravest normal modes. For the longest periods, below 1 mHz Superconducting Gravimeters (SGs) have been shown to be less noisy than long-period seismometers. A stack based on the spatial and temporal properties of the modes of degree one in a spherical harmonic development applied to 164 h of common records at the Cantley, Canberra, Strasbourg, Sutherland and Vienna SG stations has led to the first clear observation of the ${}_2S_1$ long-period seismic modes with a central frequency close to 0.4 mHz. Moreover the spectrum of the SG record at the Strasbourg station confirms the benefit SGs can provide to normal mode seismology with the clear observation of the splitting of the fundamental mode ${}_0S_2$ into 5 fairly well resolved singlets with only one record. **INDEX TERMS:** 1213 Geodesy and Gravity: Earth's interior—dynamics (8115, 8120); 1294 Geodesy and Gravity: Instruments and techniques; 7255 Seismology: Surface waves and free oscillations. **Citation:** Rosat, S., J. Hinderer, and L. Rivera, First observation of ${}_2S_1$ and study of the splitting of the football mode ${}_0S_2$ after the June 2001 Peru earthquake of magnitude 8.4, *Geophys. Res. Lett.*, 30(21), 2111, doi:10.1029/2003GL018304, 2003.

1. Introduction

[2] Presently 20 superconducting gravimeters (SGs) are measuring the temporal variations of the Earth's gravity and their measurements are collected under the framework of the GGP (Global Geodynamics Project) global network [Crossley *et al.*, 1999]. Earthquakes are a source of vibration of the Earth that cause high-frequency variations (normal modes) of the Earth's gravity field. These modes are excited after an earthquake of magnitude greater than $M_w = 6.5$ [Widmer-Schmidrig, 2003] and can be observed from long-period seismometers and also from relative gravimeter data [Richter *et al.*, 1995]. A study of the noise levels of the SGs in the GGP network has shown [Rosat *et al.*, 2002] that for frequencies less than 1 mHz, SGs can reach better noise levels than most of the long-period seismometers. SGs can therefore contribute successfully to the study of the gravest normal modes [Freybourger *et al.*, 1997; Van Camp, 1999; Widmer-Schmidrig, 2003]. We highlight the unique contribution of SGs to long-period seismology through 1/the detection of the long-period seismic mode ${}_2S_1$ by combining five SGs data following the June 23, 2001 $M_w = 8.4$ Peru earthquake and 2/the

study of the splitting of the gravest fundamental normal mode ${}_0S_2$ at the French station in Strasbourg. ${}_0S_2$ and ${}_2S_1$ are the gravest spheroidal seismic normal modes. ${}_0S_2$ is called the football mode as the deformed shape alternates between that of an American football and a pumpkin. The entire Earth partakes in the motion. ${}_2S_1$ is the first overtone of ${}_1S_1$, the so-called Slichter mode [Slichter, 1961] which consists essentially of a rigid translation of the solid inner core relative to the fluid outer core and mantle. ${}_2S_1$ is a peculiar mode because it involves almost a rigid body translation of both the inner core and the outer core in the same direction.

[3] The improvement of 1D-density models can be achieved by the observation of Zeeman splitting (splitting due to rotation) of individual multiplets and Coriolis coupling between spheroidal and toroidal multiplets [Widmer-Schmidrig, 2003]. Zeeman splitting and Coriolis coupling are small signals which constrain the 1D-density profile much like the Earth's mass and moment of inertia. Rotational splitting is largest for low-frequency multiplets because of their vicinity to the Earth's rotation frequency. Zürn *et al.* [2000] pointed out that Coriolis coupling provides linear constraints on the density profile, very similar to Zeeman splitting. Incidentally, the SGs have contributed some of the best detections of the fundamental toroidal mode ${}_0T_2$ [Widmer-Schmidrig, 2003]. Besides, splitting of modes below 1 mHz is highly sensitive to the 3D-density structure of the Earth's mantle and core. Therefore, SGs are particularly suited to the study of the gravest seismic normal modes.

[4] The datasets are raw gravity records taken 5 hours after the earthquake and corrected for the tides by subtracting synthetic local tides, and for the local atmospheric pressure effect using a nominal constant admittance of $-3 \text{ nm/s}^2/\text{hPa}$. The pressure correction is necessary to improve the signal to noise ratio for frequencies less than 1 mHz [Zürn and Widmer, 1995; Van Camp, 1999; Rosat *et al.*, 2002].

2. The Degree One Mode ${}_2S_1$

[5] The normal spheroidal elastic mode ${}_2S_1$ has not yet been observed [e.g., Table 1 in Dahlen and Sailor, 1979; Table 2 in Crossley, 2003; the Reference Earth Model web site, <http://mahi.ucsd.edu/Gabi/rem.html>]. A close look at the spectra from Zürn *et al.* [1991, Figure 6] and Widmer-Schmidrig [2003, Figure 5] also reveals a small peak at the ${}_2S_1$ frequency. However, the authors did not discuss its possible presence and did not investigate the splitting. We use a stacking method, called the multi-station experiment, dedicated to the degree-one modes which was proposed by Courtier *et al.* [2000] for

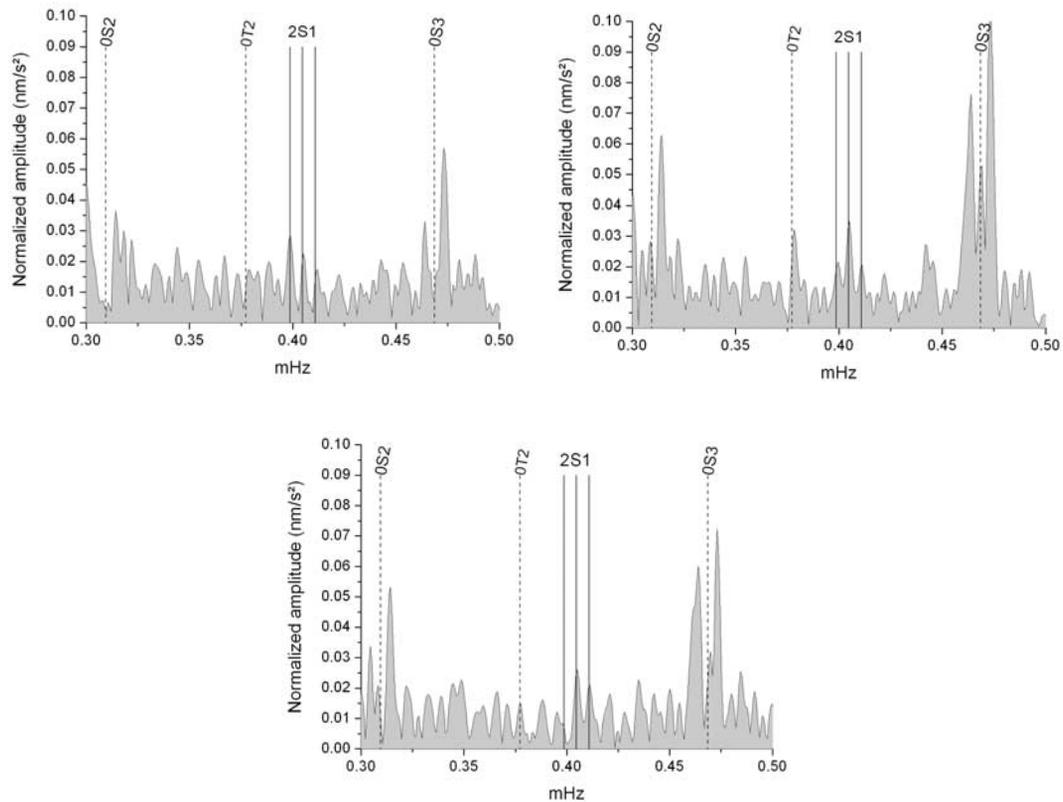


Figure 1. Amplitude spectra of the a) $m = -1$, b) $m = 0$ and c) $m = 1$ modes obtained from the multi-station analysis technique.

enhancing the search for the ${}_1S_1$ triplet (translation of the inner core) [Slichter, 1961] and recently used by Rosat *et al.* [2003]. This method is a specialization to the degree-one mode of a more general technique carried out by Cummins *et al.* [1991] which consists of a stack according to surface spherical harmonics.

3. The Multi-Station Analysis Technique

[6] The multi-station experiment takes into account the temporal and spatial properties of a degree-one spheroidal mode. The method was proposed in the search for the sub-seismic ${}_1S_1$ Slichter mode but can be applied to any mode of degree one in a spherical harmonic development. This stacking method leads to the enhancement of three modes which correspond to the three splitting modes of order $m = -1$, $m = 0$ and $m = 1$ which are respectively the prograde equatorial, axial and retrograde equatorial modes.

[7] Five records from the GGP SG stations, Cantley, Canberra, Strasbourg, Sutherland and Vienna, 164 h-long decimated to 10 s, have been used for the stack because of their low-noise levels in this band [Rosat *et al.*, 2002].

4. Results of the Stack

[8] The prograde, axial and retrograde modes extracted from the multi-station analysis are clearly enhanced in the amplitude spectra shown in Figures 1a ($m = -1$), 1b ($m = 0$) and 1c ($m = 1$). The peaks observed are at the predicted frequencies of the ${}_2S_1$ triplet. The axial combination enhances also the toroidal mode ${}_0T_2$ already observed by Zürn *et al.* [2000] and which is caused by Coriolis coupling between spheroidal modes.

[9] The observed eigenfrequencies of ${}_2S_1$ are in good agreement with the values we computed using a perturbation method to the first order in ellipticity and to the second order in rotation as Dahlen and Sailor [1979] did for PREM and 1066 A Earth models (cf. Table 1). Our computation uses

Table 1. Comparison of the Observed Frequencies of ${}_2S_1$ After The Multi-Station Experiment With the Predicted Values for the Earth Models PREM and 1066 A

	Observations and errors (mHz)	Model PREM (computed values in mHz) (this paper)	Model 1066 A (computed values in mHz) (this paper)
$m = -1$	$0.3986 \pm 5.5 \cdot 10^{-5}$	0.39875	0.398708
$m = 0$	$0.4049 \pm 7.3 \cdot 10^{-5}$	0.404727	0.404690
$m = 1$	$0.4111 \pm 5.9 \cdot 10^{-5}$	0.410948	0.410880

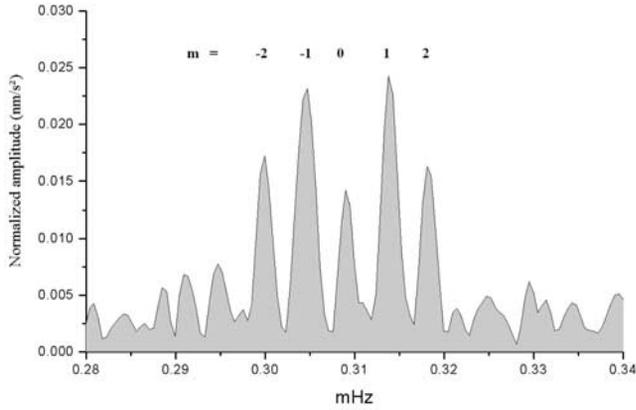


Figure 2. Observation of the 5 singlets of the fundamental mode ${}_0S_2$ with the SG C026 gravimeter at Strasbourg. The spectrum was performed using 274 h of SG data corrected for tides and pressure.

eigenfunctions obtained from MINOS code [Woodhouse, 1988].

5. Splitting of ${}_0S_2$

[10] Figure 2 corresponds to the amplitude spectrum using a 274 h-long signal which we found to be optimal for the study of ${}_0S_2$. Dahlen [1982] suggests that the optimal window length for frequency estimates is one Q-cycle. In our case the length of the window was limited by a second earthquake occurring 13 days after the main event. Notice the high resolution reached by the GWR C026 SG of Strasbourg sampled at 2 s: the 5 peaks of the fundamental mode of degree 2 ${}_0S_2$ are well separated.

[11] By fitting a synthetic Lorentzian resonance function [e.g., pp. 234–235 in Dahlen and Tromp, 1998] to each singlet of the spectrum, we can determine the 5 frequencies and their error bars. The observed frequencies with the SG C026 at Strasbourg are compared in Table 2 with the predicted values of ${}_0S_2$ computed for the Earth model 1066 A [Gilbert and Dziewonski, 1975] by Dahlen and Sailor [1979] following a perturbation method and by Rogister [2003] by integration of the equations to the second order in rotation and ellipticity. They are also compared with the values we computed for Earth model PREM [Dziewonski and Anderson, 1981] using the same method as for ${}_2S_1$ (paragraph 3), as well as with the values observed by Lindberg [1986] from 7 IDA records of the 1977 Indonesian event and Ritzwoller et al. [1986] after combining more than

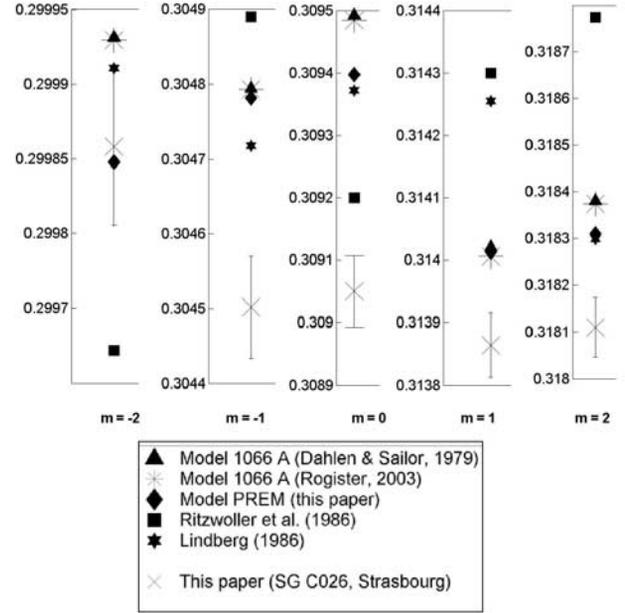


Figure 3. Comparison of the observed singlets of ${}_0S_2$ and their error bars from the SG C026 gravimeter at Strasbourg with the values observed by Ritzwoller et al. [1986], by Lindberg [1986] and with the predicted values for Earth models 1066A and PREM from various authors.

100 records. Notice on Figure 3 that the formal error bars obtained from our observations (see Table 2) are small and agree with the PREM values for $m = -2$ and 1. For $m = -1$, $m = 0$ and $m = 2$, our observations are smaller than the predicted and previously observed values. However, before concluding that the existing models need to be improved, a stack involving more SG records for this particular earthquake has to be investigated.

[12] We conclude that the splitting frequencies observed with the SG C026 at the Strasbourg station are in close agreement with the theoretical values computed for the Earth's models PREM and 1066 A either by a perturbation method or by a direct integration. This implies that SG data after a strong seismic event could help in constraining the lateral density structure of the Earth from the observations of long-period seismic modes [Ritzwoller and Lavelly, 1995].

6. Conclusion

[13] By a combination of five gravity records using an adapted stacking method, SGs have led to the detection of

Table 2. Comparison of the Observations With the Predicted Periods for the ${}_0S_2$ Multiplet

Model	1066 A Dahlen & Sailor (perturbation)	1066 A Rogister (2003) (integration)	PREM This paper (perturbation)	Ritzwoller et al. [1986] (Multiple event stripping using more than 100 records)	Lindberg [1986] (Stacking of 7 IDA records of 1977 Indonesian event)	This paper (Estimates from one SG C026 record at Strasbourg)
$m = -2$	0.2999310	0.2999293	0.2998479	$0.299722 \pm 1.4 \cdot 10^{-4}$	$0.299911 \pm 6.1 \cdot 10^{-5}$	$0.299858 \pm 5.3 \cdot 10^{-5}$
$m = -1$	0.3047944	0.3047935	0.3047817	$0.304890 \pm 4.1 \cdot 10^{-4}$	$0.304718 \pm 4.14 \cdot 10^{-4}$	$0.304502 \pm 6.8 \cdot 10^{-5}$
$m = 0$	0.3094921	0.3094837	0.3093972	$0.309200 \pm 2.7 \cdot 10^{-4}$	$0.309372 \pm 9.5 \cdot 10^{-5}$	$0.309050 \pm 5.7 \cdot 10^{-5}$
$m = 1$	0.3140210	0.3140058	0.3140127	$0.314300 \pm 2.7 \cdot 10^{-4}$	$0.314255 \pm 1.21 \cdot 10^{-3}$	$0.313864 \pm 5.1 \cdot 10^{-5}$
$m = 2$	0.3183800	0.3183734	0.3183099	$0.318774 \pm 1.0 \cdot 10^{-4}$	$0.318298 \pm 7.5 \cdot 10^{-5}$	$0.318110 \pm 6.4 \cdot 10^{-5}$

The frequencies are given in mHz.

the long-period seismic mode ${}_2S_1$. This first observational evidence of ${}_2S_1$ and its splitting will help to constrain Earth's models in the outer core and mantle. SGs also demonstrated their high resolution in the long-period seismic band through the observation of the 5 singlets of the gravest fundamental mode ${}_0S_2$ at a single station with the example of the Strasbourg instrument. A study including more records should be carried out to improve Earth's models. SGs are clearly useful instruments for the studies of long-period normal modes and thus are complementary to the long-period seismometers.

[14] **Acknowledgments.** The authors are grateful to the GGP station managers who have provided their datasets of the Peruvian earthquake. This study was supported by CNRS (Intérieur de la Terre). This is EOST contribution N°2003.39-UMR 7516.

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