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DATA AND EXPERIMENT DESCRIPTIONS

A case study of detecting the triplet of $_3S_1$ using superconducting gravimeter records with an alternative data preprocessing technique

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ABSTRACT

Due to their very low noise levels in the low frequency band (<1 mHz), superconducting gravimeters (SGs) are particularly suitable to observe long-period free oscillations of the Earth. This case study is dedicated to the detection of the triplet of the seismic normal mode $_3S_1$ that was excited by the December 26, 2004, Sumatra-Andaman earthquake (Mw = 9.3). Using SG records, the Hilbert-Huang transformation is used as an alternative data preprocessing technique, instead of the traditional detiding method. After removal of atmospheric pressure effects from the original SG records, we applied the Hilbert-Huang transformation to the SG residues, to select the signals that included the frequency band of interest, and to construct a new data series. Then, by applying the multi-station experimental technique to five 273-h-long common new data series recorded at different SG stations, we clearly observed all of the three singlets of the mode $_3S_1$, with the central singlet more evident compared to previous studies. Observations of the low-frequency modes $_3S_1$ (n = 0, 1, 2, …; l = = 1,2, …) provide constraints on the inner and outer core structure. This case study provides an alternative data-preprocessing approach to observe the splitting frequencies of the low-frequency mode type $_3S_1$ (n = 0, 1, 2, …).

1. Introduction

After a large earthquake, various seismic normal modes (free oscillations) of the Earth are excited for several days to months (e.g., Alterman et al. 1974, Widmer-Schnidrig 2003). The typical length of the time that a seismic normal mode lasts for depends on its quality factor Q (which is inversely proportional to the ratio of the energy loss per cycle to peak strain energy), whereby the larger the Q, the longer the vibration of the normal mode (e.g., Aki and Richards 1980, Chao and Gilbert 1980). The frequencies of the modes are closely related to the structure of the Earth. For instance, the triplet of the seismic normal mode $_3S_1$ (generally the normal modes below 3 mHz) is sensitive to the density, compressibility, and velocity of P-waves in the mantle and core [e.g., Ritzwoller and Lavely 1995, Resovsky and Ritzwoller 1998, see also http://phys-geophys.colorado.edu/geophysics/nm.dir/3s/3s1.kerplot.gif].

Theoretically, if the Earth is taken as an idealized spherically symmetric, non-rotating, purely elastic, isotropic body, modes $_nS_l^m$ with the same n and l have the same eigenfrequency, which is referred to as degeneracy [Dahlen and Tromp 1998]. Here n is the radial overtone number, l the angular degree, and m the azimuthal order. However, for the real Earth, its rotation, ellipticity and lateral heterogeneity remove the degeneracy, which results in the appearances of split peaks [e.g., Alterman et al. 1974, Dahlen and Sailor 1979, Rogister 2003]. The splitting of the modes below 1 mHz is highly sensitive to the three-dimensional density structure of the Earth mantle and core [e.g., Okal 1978, Ritzwoller and Lavely 1995, Widmer-Schnidrig 2003], and therefore, observations of the splitting of modes below 1 mHz might help to constrain Earth models.

Due to the Global Geodynamics Project (GGP) [e.g., Crossley et al. 1999, Crossley and Hinderer 2008], superconducting gravimeters (SGs) are extremely sensitive to gravity variations that are related to various geophysical processes (e.g., tides, inner core wobble, tectonic activity, Earth free oscillations). They also have very low noise levels in the low frequency band, and thus they are particularly suitable for the observation of long-period signals of interest.

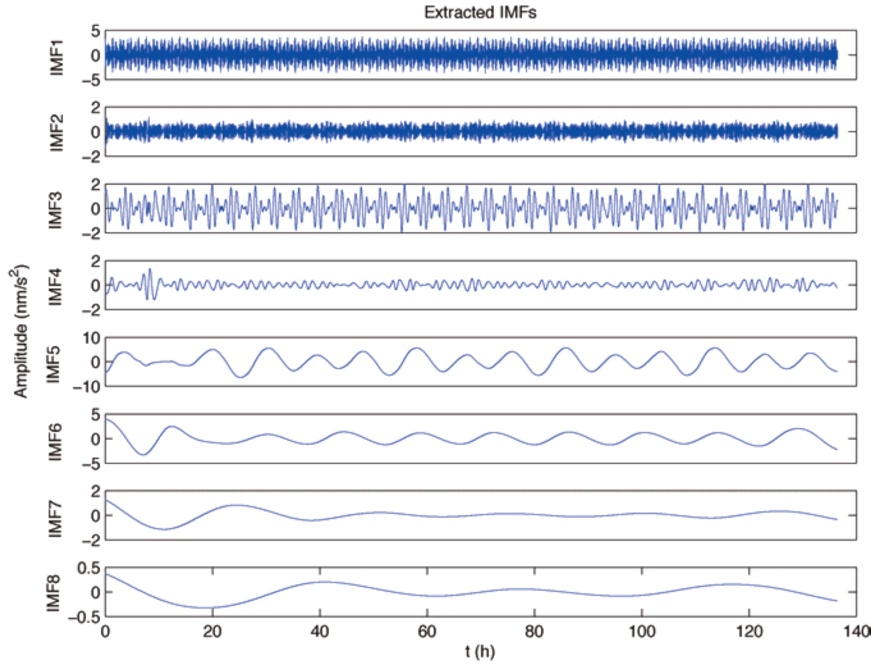
Previous studies [e.g., Rosat et al. 2003a, 2004; Hu et al. 2006a, b, Xu and Sun 2009] have shown that for frequencies below 1 mHz, the SGs can reach a better signal-to-noise ratio than most of the broadband seismometers. Hence, SGs have specific advantages for the study of the gravest normal modes.

The $_3S_1$ multiplet was first observed by Chao and Gilbert [1980], using seven records at the International Deployment Accelerometer spring gravimeter stations after the 1977

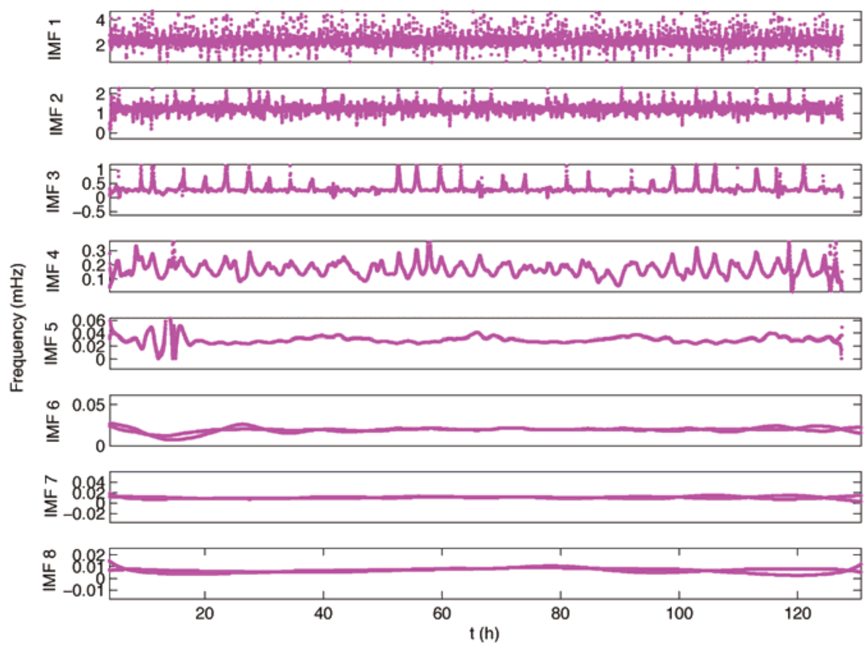
Indonesia earthquake (Mw = 7.8) and then by Roult et al. (2010) using 247 recordings at 157 Federation of Digital Seismograph Networks broadband seismometer stations after the 2004 Sumatra earthquake (Mw = 9.3). However, following a closer examination of the spectra shown in Figure 10 of Roult et al. (2010), we find that the middle spectrum line ($m = 0$) of the mode ${}_3S_1$ is very weak and cannot be easily observed. Here, it will be shown that by combining only five SG records at three stations after the 2004 Sumatra-Andaman earthquake with an alternative analysis technique, instead of traditional detiding process for data preprocessing, we can clearly resolve all three singlets of the seismic normal mode ${}_3S_1$.

2. Methods

The preprocessing of the SG raw data generally involves tides removal and air correction (necessary for better observation of low frequency modes below 1 mHz), in addition to correcting for instrumental errors, such as spikes, gaps, and abrupt offsets. The detiding process is usually done



(a)



(b)

Figure 1. Illustration of the Hilbert-Huang transformation using synthetic data. (a) Eight IMFs labeled by the sequences they are sifted, which are decomposed from the synthetic signal with frequencies IMF1-8 (2.5, 2.1, 1.92, 1.2, 0.31, 0.24, 0.03, 0.02) mHz, and amplitudes (1.5, 1.3, 0.8, 0.55, 0.7, 1.0, 4.0, 3.0) nm/s^2, respectively. (b) Instantaneous frequencies corresponding to each of IMF1-8 according to time.

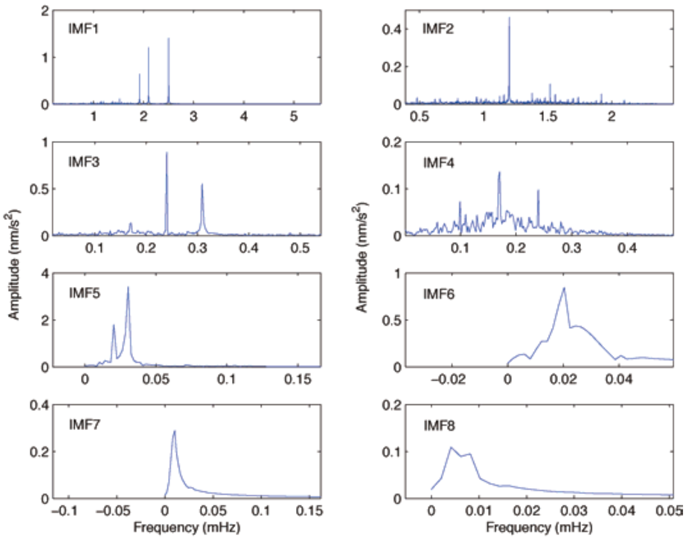


Figure 1. (c) Fourier amplitude spectra for the corresponding IMF1-8, demonstrating that each IMF in Figure 1a indeed contains certain frequencies, as can be seen from Figure 1b. Therefore certain IMFs can be selected to study the signal of interest.

by subtracting syntheses computed from certain tide models, although removing the tides by this method is not very thorough, as tidal effects on the records can be different for individual places, and the tidal factors used to compute synthetic tides are just average values obtained over several years.

Alternatively, the SG data can be bandpassed to a certain frequency range of interest, although it must be noted that the presence of Gibbs phenomenon and marginal effects might result in some undesired effects in the original observations. While wavelet-based detection for weak signals [Hu et al. 2006a, b, Rosat et al. 2007] has great potential, the uniform frequency resolution will show inferior resolution in time and frequency compared to the Hilbert analysis representation [see Figure 1 of Huang et al. 1999].

Herein, the Hilbert-Huang transformation (HHT) analysis is used to locate our desired frequency band directly, which will generate a new data series that will be naturally free from influences of long-period signals, e.g., tidal effects and some other possible influences. To enhance each singlet peak, the multi-station experiment (MSE) technique [Cummins et al. 1991] will be applied. The following two paragraphs are short descriptions of these two techniques.

The HHT analysis technique was first proposed by Huang et al. [1998], to decompose a complicated data series into a finite, and often small number of, intrinsic mode functions (IMFs) that are based on empirical mode decomposition (EMD) (i.e., the sifting process) [see details in Huang et al. 1998]. The essence of the method is to empirically identify the intrinsic oscillatory modes by their characteristic time scales in the data, and then to decompose the data accordingly. When the first IMF is obtained, the sifting process will be repeated again to find the next IMF in the residue. If the last residue becomes a monotonic function from which no more IMFs can be extracted, the sifting process stops. By virtue of the definition of IMF, the earlier sifted IMFs (signals) generally have higher frequencies. Figure 1 illustrates the method with synthetic data. Figure 1a shows the extracted IMFs based on EMD, and the corresponding instantaneous frequency of each IMF is shown in Figure 1b. Using these, by zooming in (horizontal or vertical zoom), we can roughly determine the frequency range of each IMF. By this criterion, with concentration on one or a few frequency bands of interest, we can select certain IMFs for further study. Figure 1c shows the corresponding Fourier amplitude spectrum of each IMF in Figure 1a, and is just a verification of our judgment from Figure 1b.

The MSE technique was first proposed by Cummins et al. [1991], and used by Courtier et al. [2000] to detect the triplet of the Slichter mode ${}_1S_1$ [Slichter 1961; see also e.g. Smylie 1992]. It was also used by Rosat et al. [2003b] to detect the mode ${}_2S_1$ and by Rosat et al. [2006] and Guo et al. [2006] to search for the ${}_1S_1$ triplet. This method takes into account the temporal and spatial properties of degree-one spheroidal modes to generate three new time series, each of which contains only one of the prograde equatorial (m=–1), retrograde equatorial (m=1) and axial (m=0) signals. Spectral analysis is then applied to every time series. In the present study, the MSE technique is used to effectively isolate and enhance the three singlets that correspond to the mode ${}_nS_l^m$ (m=–1, 0, 1).

3. Data and data analysis

The datasets are corrected minute data (gaps and disturbances filled with synthetic signals by station operator after decimation to 1 min), downloaded from the GGP data centre (http://www.eas.slu.edu/GGP/ggphome.html), and corrected for the local atmospheric pressure effect using a nominal constant admittance of –3 nms^{-2}/hPa. The air pressure correction is necessary to better detect the frequencies less than 1 mHz [Zürn and Widmer 1995]. As a case study, five records from three SG stations, Canberra (C1), Bad Homburg (H1, H2), Sutherland (S1, S2), are used in the present study. The length of the records is 273 h, about one Q-cycle, as the length suggested by Dahlen [1982] for better frequency estimation of a certain mode.

After correction of the local atmospheric pressure effect, the gravity residues are decomposed into a series of IMFs, as shown by Figure 2a, based on the EMD [Huang et al. 1998], and after applying Hilbert transformation to every IMF and by examining the variation of the instantaneous frequencies with time of the IMFs (see Figure 2b), we chose the correct IMFs that included the signal of the mode ${}_3S_1$. In the present study, we chose the first three IMFs of all of the records, and accordingly constructed five common new data series, which

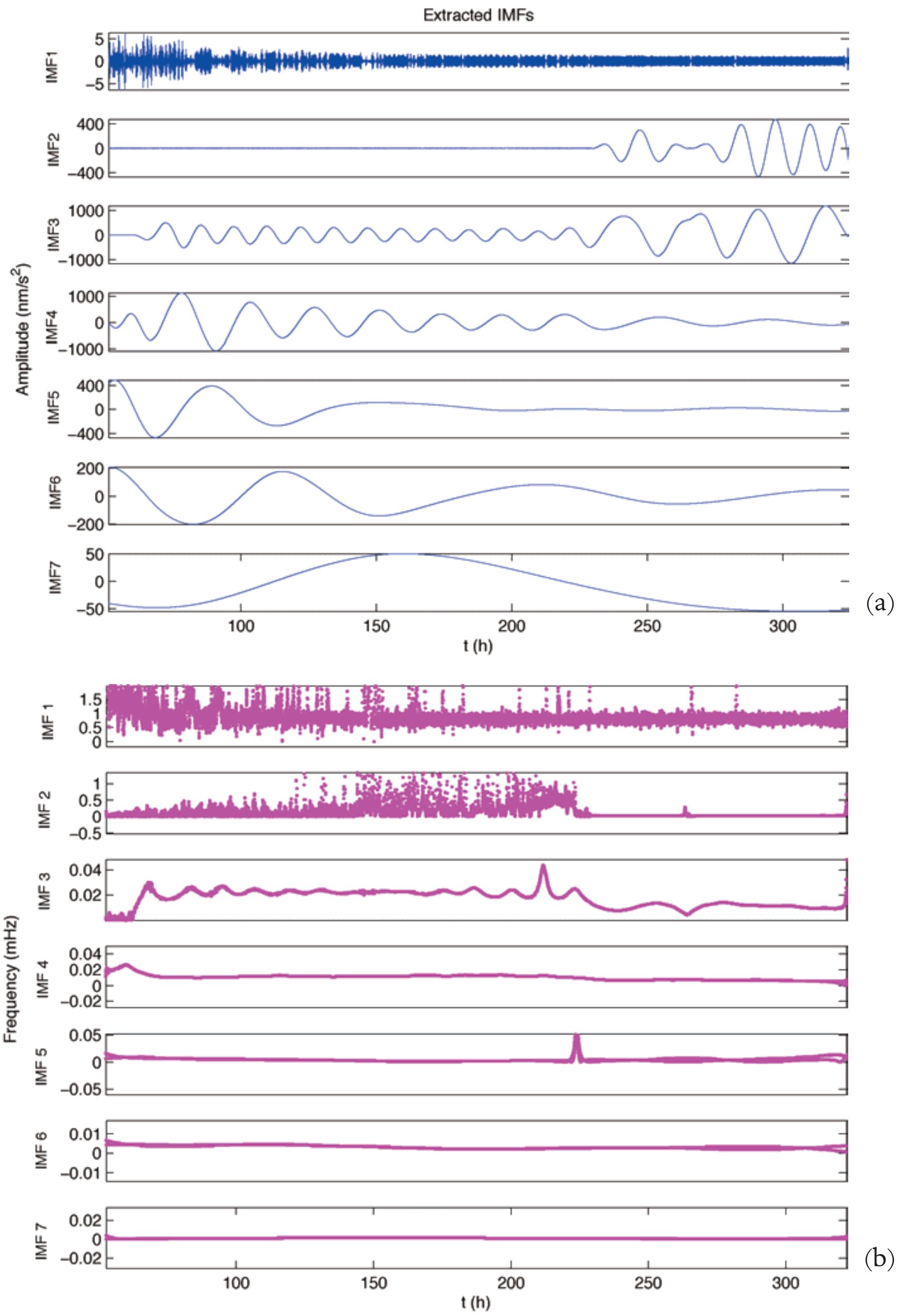


Figure 2. The Hilbert-Huang transformation applied to the SG data following correction for pressure, as recorded at Bad Homberg (H2). (a) Extracted IMFs (1-7) of the SG data based on EMD. (b) Instantaneous frequencies corresponding to each of IMF1-7 of panel (a).

included the signal of the mode ${}_3S_1$, which will be further used to detect the ${}_3S_1$ triplet based on the MSE technique. As the typical frequency of ${}_3S_1$ is very close to that of ${}_1S_3$, and as it also obeys certain selection rules [Alterman et al. 1974], the splitting frequencies of ${}_3S_1$ might be seriously contaminated by those of ${}_1S_3$, because the typical frequencies ($m = 0$) of ${}_1S_3$ and ${}_3S_1$ are 0.944139 mHz and 0.944364 mHz, respectively [Resovsky and Ritzwoller 1998]. However, as the quality factor Q of ${}_3S_1$ (826.9) is almost three times of that of ${}_1S_3$ (282.7) [Dziwonski and Anderson 1981], we can consider the Earth as a filter and use the records with a later starting point after the earthquake, to weaken the influence of ${}_1S_3$. As shown by Figure 3, we find that about 56 h after the Sumatra-Andaman event, the amplitude of ${}_1S_3$ is largely reduced compared to that of five hours after the event. Indeed, based on the decay law $A(t)=A(t_0)\exp[-\pi(t-t_0)f/Q]$ [Aki and Richards 1980], 56 h after the event, the amplitudes of the ${}_1S_3$ and ${}_3S_1$ decay to 14.7% and 51.8%, respectively, of those standing 5 h after the event.

4. Results

We applied the MSE technique to the five common new data series (i.e., the new data series constructed by the HHT technique, as indicated above), and we obtain three time-series, each of which contains only one of the

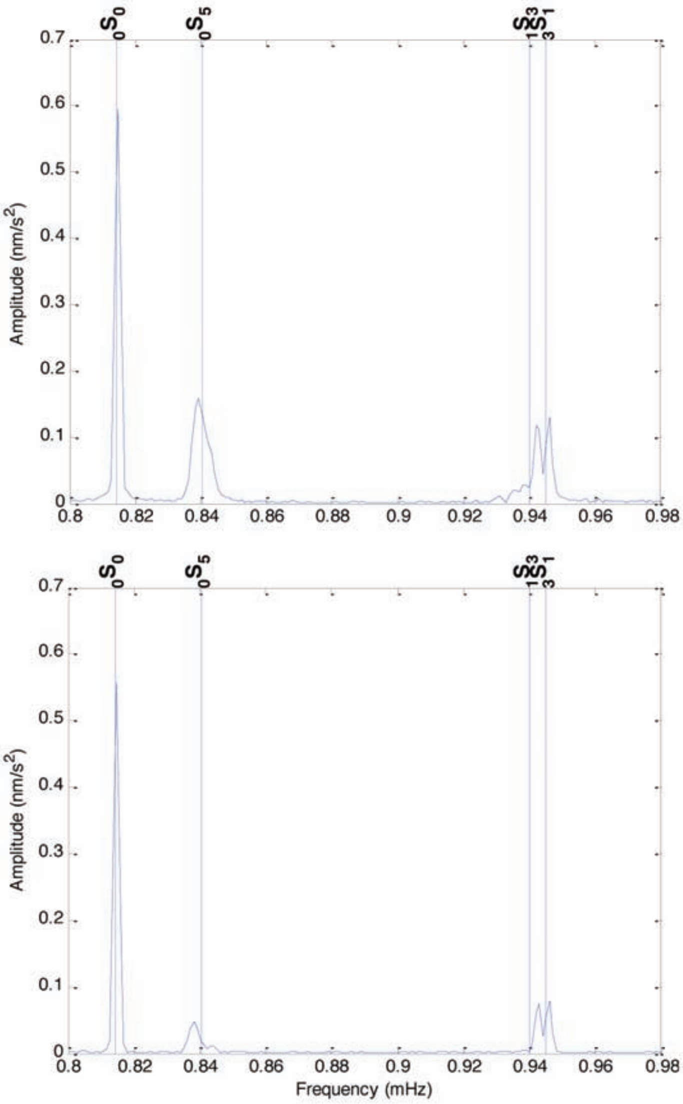


Figure 3. Comparison of the Fourier amplitude spectrum of the 273-h SG record from Bad Homburg (H2) starting 5 h (top slot) and 56 h (bottom slot) after the earthquake. The spectra were performed on the first two IMFs, after corrections for pressure. The vertical dotted lines denote degenerate frequencies for the model PREM.

prograde, retrograde and axial modes that have been successfully enhanced in the corresponding amplitude spectra, as shown in Figure 4a (m=–1), b (m=1), and c (m=0), respectively. Hence, all of the three singlets of $_3S_1$ have been clearly extracted and are close to the frequencies computed from PREM. By fitting a synthetic Lorentzian resonance function [e.g., Dahlen and Tromp 1998] to each singlet of the spectrum, we obtained the three splitting frequencies, as listed in Table 1. The errors given in the present study are standard deviations of the estimated frequencies obtained by least-square fitting with five to eight points. The exact number of points used for estimation of a certain singlet might vary, depending upon how many points around the peak fit the Lorentzian resonance function best.

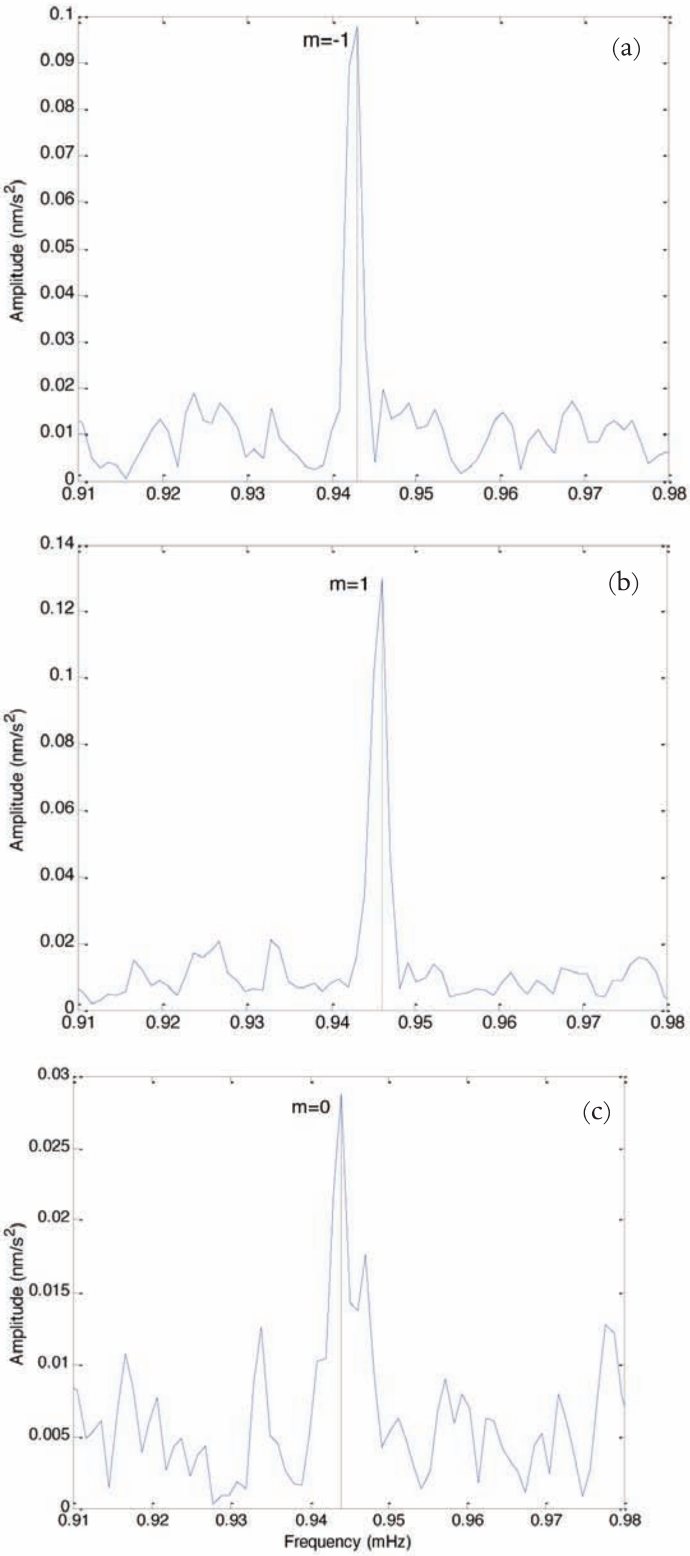


Figure 4. Amplitude spectra of the three singlets of the mode 3S1 obtained from the multi-station experimental analysis technique. (a) m=–1. (b) m=1. (c) m=0.

In Table 1, the theoretical predictions are based on the model PREM-re [Roult et al. 2010] and the model PREM-re+SAW12D [Li and Romanowicz 1996, He and Tromp, 1996], respectively. Both models are based on PREM, but the former includes only the Earth rotation and ellipticity, and the

Model or author(s)	m=–1 (mHz)	m=0 (mHz)	m=1 (mHz)
PREM-re	0.942267	0.944215	0.945472
PREM-re + SAW12D	0.942925	0.944914	0.946144
Chao and Gilbert (1980)	0.94270 $\pm 5.5\times10^{-5}$	0.94535 $\pm 9.0\times10^{-5}$	0.94563 $\pm 4.0\times10^{-5}$
Resovsky and Ritzwoller (1998)[a]	–	0.944364$\pm 1.0\times10^{-4}$	–
Roult et al. (2010)	0.94256 $\pm 1.241\times10^{-4}$	0.94419 $\pm 3.444\times10^{-4}$	0.94579 $\pm 1.493\times10^{-4}$
Present study	0.942598 $\pm 4.25\times10^{-5}$	0.944113 $\pm 2.65\times10^{-4}$	0.945864 $\pm 2.13\times10^{-4}$

[a] As a reference, the observation of the frequency (m = 0) of ${}_3S_1$ given by Resovsky and Ritzwoller [1998], who did not provide the triplet ${}_3S_1$.

Table 1. Comparison of the observed triplet frequencies of ${}_3S_1$ from previous studies with the present study, according to the model predictions.

Differences	Author(s)	m=–1 (mHz)	m=0 (mHz)	m=1 (mHz)
Obs - PREM-re	Chao and Gilbert (1980)	4.33×10^{-4}	1.14×10^{-3}	1.58×10^{-4}
	Resovsky and Ritzwoller (1998)	–	1.49×10^{-4}	–
	Roult et al. (2010)	2.93×10^{-4}	-2.50×10^{-5}	3.18×10^{-4}
	Present study	3.31×10^{-4}	-1.02×10^{-4}	3.92×10^{-4}
Obs - PREM-re + SAW12D	Chao and Gilbert (1980)	-2.25×10^{-4}	4.36×10^{-4}	-5.14×10^{-4}
	Resovsky and Ritzwoller (1998)	–	-5.50×10^{-4}	–
	Roult et al. (2010)	-3.65×10^{-4}	-7.24×10^{-4}	-3.54×10^{-4}
	Present study	-3.27×10^{-4}	-8.01×10^{-4}	-2.80×10^{-4}

Table 2. Differences between the observations and the model predictions for the ${}_3S_1$ triplet.

latter includes not only the rotation and ellipticity, but also the three-dimensional elastic structure heterogeneity of the mantle. Chao and Gilbert [1980] first observed the triplet frequencies of ${}_3S_1$ by applying the spherical harmonic stacking technique [Buland et al. 1978] to seven spring gravimeters records, Roult et al. [2010] also observed the triplet frequencies of the mode ${}_3S_1$ based on 247 seismic records by taking simply the average value of the frequencies corresponding to the mode of interest. We note that, the triplet frequencies of the mode ${}_3S_1$ were observed by only the two above-mentioned studies, to our present knowledge. For instance, although Resovsky and Ritzwoller [1998] observed the frequency of ${}_3S_1$ (m = 0) using a dataset of more than 4,500 seismograms, they did not provide the frequencies of ${}_3S_1$ ($m = \pm 1$). As a comment here, we note that in the study of Roult et al. [2010], the middle spectrum line (m = 0) of the mode ${}_3S_1$ is very weak. In our study, the middle spectrum line (m = 0) of ${}_3S_1$ was clearly extracted from the records due to the combination of the HHT and MSE techniques.

As can be noted from Table 2, the observed ${}_3S_1$ triplet in the present study are very close to the model PREM-re+SAW12D predictions, except that the central singlet deviates from the theoretical value a little more, as do the results of Chao and Gilbert [1980] and Roult et al. [2010]. The causes for this are not clear. Besides, all of the observed frequencies [given by Chao and Gilbert 1980, Roult et al. 2010, and the present study] corresponding to $m=\pm 1$ are higher than the model PREM-re predictions, and smaller than the model PREM-re + SAW12D predictions. This implies that the mode ${}_3S_1$ is very sensitive to the physical parameters of the mantle and core, and the observed triplet of ${}_3S_1$ might provide significant constraints on the three-dimensional structure of the Earth. We can preliminarily conclude that based on the observations of the ${}_3S_1$ triplet (by previous studies and the present study, see Tables 1 and 2), both the models PREM-re and PREM-re + SAW12D might need to be adjusted as the predictions based on these models deviate from the «most likely real values» (the observations given by different authors) by slightly systematic shifts of about –3.0 μHz and about 3.0 μHz in the frequency-decreasing and -increasing directions, respectively. In addition, from Table 1 we note that as model PREM-re + SAW12D predicted, the splitting width of the mode ${}_3S_1$ is 3.22 μHz, close to the estimate (3.21 μHz) given by He and Tromp (1996), of 3.21 μHz, and the observed splitting widths given by Chao and Gilbert [1980], Roult et al. [2010], and the present study are 2.90 μHz, 3.23 μHz, and 3.26 μHz, respectively.

5. Conclusions

As the mode ${}_3S_1$ is quite sensitive to the mantle and outer core, the observation of the splitting frequencies of the mode ${}_3S_1$ can provide significant information of the deep interior of the Earth, and consequently can improve the Earth model.

The application of the HHT and MSE analysis techniques to five common SG records leads to a clear observation of the triplet frequencies of the mode $_3S_1$. The observed $_3S_1$ triplet frequencies from the SG records at the Canberra (CB), Sutherland (S1, S2) and Bad Homburg (H1, H2) stations are in close agreements with the theoretical predictions provided by the model PREM-re, and especially by the model PREM-re + SAW12D. The present study shows that the approaches (i.e., a combination of the HHT and MSE analysis techniques) proposed here are effective for the detection of the splitting frequencies of the mode $_3S_1$, as only five SG records were used, and consequently, it can potentially be applied to the detection of the Slichter triplet $_1S_1^m$ (m=–1, 0, 1), of which the claimed observations are still controversial.

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