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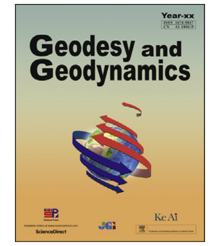

Feasibility analysis of searching for the Slichter triplet in superconducting gravimeter records

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ABSTRACT

The search for the elusive Slichter triplet requires elaborate analysis of the elastic-gravitational mode characters and the non-stationary behavior of noisy time-series. A typical question is that it is difficult to characterize the excitations with attenuation by diffusion when their intensity is low compared to noise. Thus the theory for deriving the modes' frequencies is still controversial, and various scholars tried to search for the Slichter triplet in superconducting gravimeter (SG) records, but failed. One of the main causes might be due to the inappropriate use of datasets. We present in this paper synthetic experiments on the selection of record length, sampling rate and number of SG records under the Global Geodynamics Project (GGP) to detect the damped harmonic signals hidden in noises based on the optimal sequence estimation (OSE) method. Moreover, our results show that the existing observation conditions arouse restrictions and it might be impossible to detect the Slichter triplet excited by single excitation source based on Fourier spectrum analysis. Thus we suggest a stacking way of combining several seismic events in the case that the excitation mechanism has so far been unclear.

1. Introduction

As one of the largest challenges in fundamental geophysics, the search for the translational motion of the solid inner core, also referred to as Slichter modes (or Slichter triplet) [1], is still open despite various efforts devoted by many scholars [2–15]. The difficulty in detecting the Slichter triplet lies in that they are extremely weak, weaker than the Earth's background noise, so the interested signals are likely to be buried in stronger noises [13]. The identification of the Slichter triplet might depend on sufficient accumulation of

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high-quality data, improvement of data preprocessing techniques for providing high-quality residual gravity time series after removing 'known' modeled signals and effectively reducing or canceling the noises. The superconducting gravimeter (SG) has high sensitivity and continuity, and is very stable and superior over the best seismometer in the frequency band of 0.3–0.8 mHz [6]. Moreover, SG has high signal-to-noise ratio (SNR) in the long-period seismic and sub-seismic frequency bands, and is particularly suitable for observing long-period signals, such as the Slichter modes [4,8,16]. Since the main restoring force is the Archimedean force, the periods of the Slichter triplet are directly related to the value of the density jump at the inner core boundary (ICB) [17]. Therefore, the detection and characterization of the oscillation (time of excitation, frequency and decay rate) may help constrain the density jump and the viscosity at the ICB, and consequently constrain the Earth's 3D structure [17,18].

The Slichter modes are a natural possible result of the response of the inner core to the geodynamic excitation process which is still not observably confirmed [9,10]. Various scholars have studied the excitation mechanism of the Slichter modes, mainly attributed to the surficial pressure flow acting in the core, the seismic excitation, surface load, or meteoroid impact [19–23]. A sufficient excitation source is fundamental because, the source should excite the Slichter modes to a detectable level, say the nanoGal level (1 nGal = 0.01 nm/s^2) for the SGs to detect the induced surface gravity effect, just as Rosat [24] has demonstrated that a vertical deep-slip seismic event with magnitude Mw = 9.7 is required to excite the Slichter modes to a detectable level obtained from the PREM model [25]. Unfortunately, it seems that the past major seismic events are too small to excite the interested signals to the detectable level of SG. Therefore, Rosat and Rogister [22] suggested that a combination of several possible sources might excite the Slichter mode triplet to an observable level.

Moreover, some damping sources of the Slichter modes have been considered previously, including the anelastic deformations of the inner core, the viscous dissipation and the magnetic dissipation [9,10]. Based on the excitation by earthquakes and the seismic anelasticity of the inner core and mantle, Crossley [20] and Crossley et al. [21] showed that the quality factor Q is in the order of 5000, with a corresponding decay time on the order of 400 days. The damping due to the outer core viscosity has been formulated by Smylie and McMillan [26] and also by Rieutord [27]. To estimate the dynamic viscosity of the outer core near the inner core boundary, Mathews and Guo [28] proposed an upper limit of 1.7×10^5 Pa for outer core viscosity using nutation data corresponding to Q of 5000, implying a decay time on the order of 400 days (Cf. also Guo et al. [10]). The magnetic damping of the inner core oscillation has been studied by Buffett and Goertz [29]. They have shown that the Q value should be between 5.8×10^5 and 2200 for a magnetic field ranging from 0.0005 to 0.002 T corresponding to a decay time of 108 yr to 150 d for a nominal period of 5.2 h as Guo et al. [10] suggested, assuming the magnetic field at the ICB on the order of 0.002 T, a Q value on the order of 2000 and a decay time on the order of 100 days.

This paper focuses on illustrating the detectability of the damped and weak Slichter modes excited by a specific excitation source, such as an earthquake source, occurring in synthetic SG time series, which are generated based on the SG stations from the GGP (http://www.eas.slu.edu/GGP/ggpstations.html), and attempts to provide theoretical and experimental references to search for the Slichter triplet in practice.

2. Synthetic data and method

The Earth's free oscillation signals excited by an earthquake source recorded by a gravimeter at the surface of a spherically symmetric, rotating, ellipsoidal Earth, is given by a superposition of spheroidal and toroidal modes [30,31],

$$s_j(t) = \sum_l \sum_{m=-l}^{l} A_l^m Y_l^m\left(\theta_j, \phi_j\right) exp\left[i\left(\omega_l^m + i\alpha_l^m\right)t\right] \tag{1}$$

where θ_j and ϕ_j are the colatitude and longitude of the jth station, respectively. Since the medium is three-dimensional, each mode is described by its radial order n, and two surface orders l and m, where the azimuthal order, m, varies over $-l \le m \le l$ ($m = -l, -l+1, \dots, 0, 1, \dots, l$) [18]. Here we drop the radial order n. The coefficients A_l^m are the excitation amplitudes determined by the centroid moment tensor and mode eigenfunctions [31], and ω_l^m are the corresponding eigenfrequencies, which are determined by the Earth's density distribution and structure. The attenuation factors are described by $\alpha_l^m = \omega_l^m / 2Q_l^m$, which measure the rate at which the mode's seismic energy loses due to friction [10,21]. $Y_l^m(\theta_i, \phi_i)$ is a fully normalized surface spherical harmonic function consisting of the azimuthal functions $e^{im\phi_j}$ and the associated Legendre functions $P_l^m(\cos\theta_j)$,

$$Y_l^m\left(\theta_j, \phi_j\right) = (-1)^m \left[\left(\frac{2l+1}{4\pi}\right)\frac{(l-m)!}{(l+m)!}\right]^{1/2} P_l^m(\cos\theta_j) e^{im\phi_j} \tag{2}$$

$$P_l^m(x) = \left(\frac{(1-x^2)^{m/2}}{2^l l!}\right)\left[\frac{d^{l+m}}{dx^{l+m}}(x^2-1)^l\right] \tag{3}$$

Since we focus on the detection of the Slichter triplet (with degree one) in the sub-seismic frequency band, the real-valued residual gravity time series considering background noise at the jth station from equations (1)–(3) can be written as:

$$g_j(t) = \sum_{m=-1}^{1} a_m \sin\theta_j \cos\left(\omega_m t + m\phi_j\right) \exp\left(-\frac{\omega_m t}{2Q_m}\right) + n_j(t) \tag{4}$$

where a_{-1}, a_0 and a_1 are constants, denoting the amplitudes corresponding to the prograde equatorial mode, axial mode, and retrograde equatorial mode, respectively.

In a spherical, non-rotating, elastic, isotropic (SENRI) Earth model, the degenerate Slichter eigenperiod is about 5.42 h based on PREM [32,33]. If non-spherical corrections due to the rotation and ellipticity are considered in this degree-one case [34], a 5-term coupling chain defined by Smith [19] is truncated to calculate the eigenperiods of the spherical equivalent-rock PREM, where the surface ocean is replaced by a solid crust