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# New determinations of $Q$ quality factors and eigenfrequencies for the whole set of singlets of the Earth's normal modes $_0S_0$, $_0S_2$, $_0S_3$ and $_2S_1$ using superconducting gravimeter data from the GGP network

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**Abstract**

We present new modal $Q$ measurements of the $_0S_0$ and $_0S_2$ modes, and first modal frequencies and $Q$ measurements of $_2S_1$ and $_0S_3$ modes.

The high quality of the GGP (Global Geodynamics Project) superconducting gravimeters (SGs) contributes to the clear observation of seismic normal modes at frequencies lower than 1 mHz and offers a good opportunity for studying the behaviour of these modes.

The interest of scientists in the gravest normal modes is due to the fact that they do contribute to a better knowledge of the density profile in the Earth, helping to constrain Earth's models.

These modes have been clearly identified after some large recent events recorded with superconducting gravimeters, particularly well-suited for low-frequency investigations. The Ms = 8.1 (Mw = 8.4) Peruvian earthquake of June 2001 and the Ms = 9.0 (Mw = 9.3) Sumatra-Andaman earthquake of December 2004 provide us with individual spectra which exhibit a clear splitting of the spheroidal modes $_0S_2$, $_0S_3$ and $_2S_1$, and a clear identification of each of the individual singlets, with a resolution never obtained from broad-band seismometers records.

The $Q$ quality factors have been determined from the apparent decrease of the amplitude of each singlet with time, according to a well-suited technique [Roult, G., Clévédé, E., 2000. New refinements in attenuation measurements from free-oscillation and surface-wave observations. Phys. Earth Planet. Inter. 121, 1–37]. The results are compared to the theoretical frequencies and $Q$ quality factors computed for the PREM and 1066A models, taking into account both rotation and ellipticity effects of the Earth. The two observed datasets (frequencies and $Q$ quality factors) exhibit a splitting on the observed values different from the predicted one. That seems to point out that some parameters as density or attenuation values used in the theoretical models do not explain the observations.

A new dataset of frequencies and $Q$ quality factors of the whole set of singlets of the gravest spheroidal modes is thus under construction. That dataset includes the five individual singlets of the $_0S_2$ mode clearly identified on the SG records, the three singlets of the $_2S_1$ mode recently observed for the first time by [Rosat, S., Hinderer, J., Rivera, L., 2003b. First observation of $_2S_1$ and study

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of the splitting of the football mode ${}_0S_2$ after the June 2001 Peru earthquake of magnitude 8.4. Geophys. Res. Lett. 30, 21211, doi:10-1029/2003L018304], the ${}_0S_0$ radial mode, and the seven individual singlets of the ${}_0S_3$ mode.


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## 1. Introduction

The degenerate frequencies and damping values of normal modes in the seismic frequency-range (100–1000 s) clearly depend on the lateral heterogeneities of the Earth. These modes allowed the construction of numerous Earth's models in the last decades. However if the 3D velocity models and the 1D density models are now relatively well constrained, the 3D attenuation and density models still remain unclear due to inherent difficulties in processing amplitude data (Smith, 1971; Durek et al., 1993; Romanowicz, 1995; Durek and Ekström, 1996; Widmer-Schnidrig et al., 1991; Kenneth, 1998; Masters and Gubbins, 2003).

Nevertheless some modes are rarely observed, because the current earthquakes' magnitude doesn't allow a sufficient excitation of these modes. The information included in the not well-known gravest modes is very rich (Masters and Gilbert, 1983; Masters and Ritzwoller, 1988; Resovsky and Ritzwoller, 1998; Widmer-Schnidrig, 2003); these modes are related to the whole Earth and they can improve our knowledge of the 3D density profile. The former literature shows the great difficulty of good damping measurements of the amplitudes due to the inherent problem of amplitudes determination and to the fact that several modes are interfering (Roult, 1975; Roult and Romanowicz, 1984; Roult et al., 1990).

The FDSN seismological stations (GEOSCOPE, IRIS, etc.) are well adapted for surface waves tomographic studies or for normal modes free oscillations analysis at frequencies down to 2 mHz due to the STS1 Streckeisen seismometers flat response in velocity at periods down to 360 s (Wielandt and Streckeisen, 1982) and to their low noise level in that frequency-band (Ekström et al., 2001; Roult et al., 1999; Roult and the Geoscope group, 2002; Stutzmann et al., 2000). However superconducting gravimeters appear to be more adapted for the study of modes at lowest frequencies.

The Global Geodynamics Project (GGP) is operating a worldwide network of 20 stations equipped with superconducting gravimeters (Crossley et al., 1999; Goodkind, 1999) and microbarometers, as shown in Fig. 1. The high signal to noise ratio of these sensors (after correction for the atmospheric pressure effect) has been compared to classical broad-band seismometers (Freybourger et al., 1997; Van Camp, 1999; Rosat et al., 2002; Widmer-Schnidrig, 2003). The GGP stations evidently exhibit a lower noise level (Fig. 2) in the sub-seismic band (frequencies lower than 1000 s). Some low-frequency modes ($f < 1$ mHz) are rarely observed, except after major earthquakes as Chile 1960 or Sumbawan 1979 events. Some of them are vibrating in a very unique and original way, involving a translation of the inner core and the outer core in the same direction, as the ${}_2S_1$ mode that had never been strictly observed until the recent work of Rosat et al. (2003b), or the so-called Slichter mode ${}_1S_1$, which consists of a translational motion of the inner core (Slichter, 1961), the observed and theoretical frequencies of which are still controversial (Hinderer et al., 1995; Jensen et al., 1995; Courtier et al., 2000; Rieutord, 2002; Rosat et al., 2003a).

The high quality of the SG records allows the identification of the five singlets of the gravest spheroidal ${}_0S_2$ mode with one single record without any doubt. In the past, the IDA gravimeters helped us to observe, after the Sumbawan earthquake of 1979, the evident splitting of this mode (Buland et al., 1979; Tanimoto, 1990), with 4 over 5 distinct singlets well identified at RAR station. But the observation and comprehensive identification of the seven singlets of the spheroidal fundamental ${}_0S_3$ mode from a single record has never been noticed in previous studies. So we decided to perform, as well as a frequency analysis, a $Q$ quality factor analysis, by following the amplitude decrease of one particular singlet with time, according to our $Q$-determination method (Roult and Clévédé, 2000).

There are two different classical ways for measuring attenuation. Some authors performed extensive analyses of free oscillation spectra resonance peaks based on long time series (Widmer et al., 1991) and others analyse the amplitudes of surface waves (Romanowicz, 1995; Durek and Ekström, 1996).

The gravest spheroidal modes are clearly identified on each individual spectrum from SG records of some GGP stations after the large Peruvian earthquake (2001 June 23rd, Ms = 8.1). The duration of available data (more than 10 days) is long enough to clearly see the splitting due to the Earth's rotation and ellipticity. That duration helps in distinguishing the radial mode ${}_0S_0$ and the spheroidal fundamental mode ${}_0S_5$, as shown in Fig. 3 in the frequency-band