Estimated Green's function extracted from superconducting gravimeters and seismometers*

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Abstract Estimated Green's function (EGF) between stations has been extracted from ambient seismic noise, direct surface wave and coda waves. It is also confirmed by laboratory experiments on ultrasonics and theoretical derivations assuming diffusive wave field, equi-partition of modes or random sources on an enclosed surface. This method provides a new approach to study the crust and mantle structure at regional scale, continental scale and global scale. Following the achievements with seismometer records, the records of infrasonic station, hydrophone and microphone were also used to obtain the EGFs of different wave fields. Since superconducting gravimeter is a better long period instrument than regular seismometer, EGF at longer period is expected to be obtained with the cross correlation of gravity data. In this paper, we will show the EGFs extracted by cross-correlations between the superconducting gravimeters and the seismometers. Both the travel times and dispersion curves obtained from different data types are consistent. The result shows that it is possible to retrieve the deep structure by the cross correlation of gravity data.

Key words: superconducting gravimeter; noise cross-correlation; estimated Green's function

CLC number: P315.72⁺6 **Document code:** A

1 Introduction

In the last decade, seismology community made important progress in studying diffusive wave field. Both the theory and experiment have proven the feasibility of extracting EGF between receivers from cross correlations of ambient seismic noise or seismic coda wave (Weaver and Lobkis, 2001; Derode et al., 2003a, b; Snieder, 2004). This new approach can provide dispersion curve at shorter period and better coverage than the traditional methods which are based on the earthquake signals. Also the ambient noise method has the advantage of accurate source location and origin

time in contrast to unknown location and origin time of natural earthquakes. The research scale extends from crustal scale into continental and global scales (Shapiro et al., 2005; Yang et al., 2007; Nishida et al., 2009). This method is also applicable in other wave fields such as infrasonic, acoustic waves. The recent studies have reported some interesting results obtained from hydrophone and microphone records (Burov et al., 2008; Haney, 2009). Even in the electromagnetic fields, the Green's function could be retrieved by cross-correlation and cross-convolution (Slob and Wapenaar, 2007).

The natural seismic background noise is proposed to be generated by nonlinear interactions between atmosphere, ocean and solid earth and its period ranges from 10^{-5} Hz to 1 Hz (Tanimoto and Artru-Lambin, 2006). Seismometers are designed to record the earthquake signals, so the instrument response of modern broadband seismometer is flat between 10^{-3} Hz and 10 Hz.

* Received 13 November 2010; accepted in revised form 1 March 2011; published 10 April 2011.

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In contrast, the free oscillations excited by large earthquake and tide are strong in longer periods (>100 s) which are useful in deep structure studies. The superconducting gravimeter data has been widely used in geodynamic, seismic normal modes and earthquake rupture process study (Ishii and Tromp, 1999; Park et al., 2005; Sun et al., 2006). Compared with the traditional spring gravimeter, the superconducting gravimeter (SG) is considered to be more precise and have lower drift rate. So the superconducting gravimeter can provide absolute acceleration records which can be compared from year to year. Although it is designed to study the tide, it also clearly records the earthquake signals from normal modes to body waves. Such advantage makes it possible to obtain broader band EGF and to monitor temporal changes with Green's function from SG. So it is also necessary to investigate the feasibility of extracting EGF from cross-correlation between superconducting gravimeter and seismometer.

In this paper, we demonstrate that EGFs could be retrieved from the cross correlation (CC) between gravity and ground motion measurements. The EGFs are extracted by stacking one-year's noise cross correlation functions (NCFs) at different frequency bands and station-pairs. The results are also compared with EGFs

obtained from seismic NCFs in dispersion curve. The similarity confirms the validity of EGF from new data type.

2 Data and method

We used data from four superconducting gravimeters of the Ocean Hemisphere Project (<http://ohpdm.eri.u-tokyo.ac.jp>, Figure 1). The gravimeters were deployed in Japan, Australia, Norway, Antarctic and most of the sample rates are 1 Hz (part of SYO data was sampled by 0.5 Hz and interpolated into 1Hz). The superconducting gravimeter is designed to monitor the tide and the frequency response is uniform. The air pressure correction is important for tidal studies, and the admittance is about $-3 \times 10^{-11} \text{ m} \cdot \text{s}^{-2} \cdot \text{Pa}^{-1}$ in the frequency band of 0.001 Hz and less, and it is dominated by the local atmosphere (Sun et al., 2006). But atmosphere effects are negligible for the frequency band of 100–1 s where oceanic waves are the dominant sources of ambient noise (Tanimoto and Artru-Lambin, 2006), so we do not apply atmosphere correction to SG noise data for NCF studies. Even though atmosphere corrections are necessary at longer periods, the random nature of atmosphere effects may help to obtain EGF (Snieder, 2004).

Figure 1 Seismic (open triangle) and gravimeter (solid triangle) station used in this study. ESA: Esashi, NRA: Ny-Alesund; CAN: Canberra; SYO: Syowa.

Five GSN stations installed through the Eurasia provide continuous data of LHZ channel with sampling rate of 1 Hz. This dataset are recorded by Strecheisen STS-1V/VBB seismometers whose response is flat in the range from 0.01 Hz to 1 Hz (Figure 2). The data

recorded by seismic station CAN (STS-1), SYO (STS-1), KSN (STS-2, operated by F-net) close to the respective SGs are also used to do comparison (Figure 1). Linear trend and mean values are removed from the raw data, and then a deconvolution is applied to removing

Figure 2 (a) The instrument response of STS-1 seismometer LHZ channel at station BFO. (b) Spectrum of acceleration record at ESA. (c) Spectrum of acceleration record at KSN.

the instrument response.

We compare the spectrum of ESA (SG) and KSN on March 23, 2002 which is an earthquake silent day (Figure 2). The response of STS-2 is quite similar to STS-1. The secondary peak of microseism spectrum in 2.5–10 s is the strongest one in whole spectra. The sharp decrease nearby 2 s is caused by the deconvolution for removing instrument response. The primary peak of microseism spectrum is much weaker in this spectrum. The hum (>100 s) which is related to nonlinear interactions between atmosphere, ocean, seafloor is also visible (Tanimoto and Artru-Lambin, 2006). But the dominant spectral signature of tide (6–24 hours) was not included in the deconvolution procedure. The shape of this noise spectrum is quite similar to the USGS New Low Noise Model (NLNM, Peterson, 1993).

The spectrum of ESA is obviously different from KSN's although the separation is only about 20 km. The strongest peak is around the period of 12 hours that is in the tidal band. This peak did not appear in a previous result at same seismic station (Banka and Crossley, 1999) while the power spectral distribution of other SG stations showed it. The peak of sphere reso-

nance of SG (around 10 mHz) disappears in our result (Banka and Crossley, 1999). The peaks of microseism are weaker than the ones on station KSN. In the intermediate period (100–1000 s), the SG spectrum has a linear increase with period without the bump of the Earth hum in seismometer's record.

The noise data preprocessing follows the one proposed by Bensen et al. (2007), the raw continuous data was cut into daily segments first. Then a running absolute average procedure was employed to reduce the effect of earthquake and instrument irregularities. After spectral whitening, the daily cross correlation is calculated in frequency domain and converted into temporal domain. The temporal normalized stacking of daily cross correlations produces the long time series NCF.

3 Results and discussion

We first calculate the cross correlation between two superconducting gravimeters: CAN (Canberra, Australia), SYO (Syowa, Antarctic) (Figure 3). The frequency band is chosen as 0.003 to 0.02 Hz considering the longest effective period is about 500 s for a distance

Figure 3 The SG and seismic NCFs between CAN-SYO. The last public available data of SG SYO is 2000, so we used NCFs in different time periods. Since the annually NCF is considered be stable, it won't take much error into comparison.

of 7000 km because the distance has to be three time longer than wave length of surface waves for valid surface wave analysis. In the one-year stacked NCFs, the Rayleigh waves propagating along the great circle linking the two stations arrives at about 2000 s in both positive and negative legs and the SNRs range from 0.85 to 1.13. Here the noise is defined as the mess waveform behind the inter-station Rayleigh wave segment while signal is defined as the ± 50 s segment between the arrival with 3.5 km/s.

Two years' and three years' NCFs have higher SNRs (2.03 for NCF of 1999–2000, 3.14 for NCF of 1998–2000). There are two seismic stations close to the superconducting gravimeters, which are helpful to verify NCFs from SG stations (Figure 3). The arrival time difference is very small, suggesting that NCF from SG stations are valid. The Rayleigh waves emerging in the

SGs' NCF appear to contain longer period signal than NCF from seismometers.

The global seismic networks cover most continents and their good maintenance makes the continuous data of more than ten years available. Several years' records of GSN stations have been successfully used to extract broadband (10–400 s) EGFs (Nishida et al., 2009). Combining the signal detection capability of cross correlation, the NCF of SG-seismometers has the potential of extracting longer period EGF, even at the period that is longer than the corner frequency of instrument response of regular seismometers.

We calculate the NCF between seismic station INCN (Inchon, Korea) and SG station ESA (Esashi, Japan) to demonstrate the feasibility of NCF between seismometers and SG station (Figure 4). The distance between INCN and ESA is 1298 km, and the maximum

Figure 4 (a) The NCFs of ESA-INCN and KSN-INCN. (b) The respective dispersion curves.

effective period is about 100 s and frequency band is set as 0.01–0.2 Hz. The one-year noise cross correlations are similar during 1999–2002. Station KSN, which is about 26 km far away from ESA, is used as a reference seismic station to compute NCFs between seismic stations. The Rayleigh wave SNR (3.55 while $v=2.7$ km/s) of one-year NCF between KSN-INCN is higher than the one (1.74) of between ESA-INCN. This phenomenon is the same as the above example for CAN-SYO. To quantify the difference between seismic NCF and gravimeter NCF, we compare dispersion curves obtained by multiple filter method (Herrmann and Ammon, 2002). The two dispersion curves of NCFs for year 2002 fit each other well in short period. At longer period, the dispersion curves cannot be retrieved from the NCF of INCN-KSN which may due to the limited instrument capability. The dispersion curves of one-year and four-year NCFs agree

with each other even better in short period (<20 s). The difference of group velocity in longer period (>20 s) is less than 0.1 km/s. But the spectra of two types cross-correlation functions show a arrival difference of about 20 s in positive leg that is caused by the different spectra. The long period components (~ 20 s) of inter-station Rayleigh wave of KSN-INCN dominates the waveform, so the peak arrives before the ESA-INCN whose long period component is relative weaker and the Rayleigh wave group velocity measurement with multiple filter method is not affected.

Since the lowest frequency of NCF of INCN-ESA is limited by the inter-station distance (three times longer than surface wave length), we calculate the NCFs of ULN-ESA (at much longer distance) to demonstrate behavior at different frequency bands. Figure 5 shows the four-year (1999–2002) NCFs of ULN-ESA at 0.01–

Figure 5 (a) The 1999–2002 ESA-ULN NCFs at different frequency bands. (b) 1999–2002 NCFs at different stations separations.

0.2 Hz, 0.008–0.03 Hz, 0.003–0.02 Hz bands. As expected, the Rayleigh wave in longest period arrives before others in the shorter periods and the SNR (3.58 with $v=3.9$ km/s) is also the highest. Another station pair (BFO-ULN) also shows similar behavior. The SNR of short period decreases more quickly than long period one as the separation of stations increase. It is well known that the high frequency signal is strongly attenuated and scattered in the crust, so the coherence of high frequency signal is worse than that of the low frequency one. This may be the reason for the difference in SNR in different frequency bands.

At the long period (>100 s), the microseismic signal is incoherent especially for SG even after stacking four years daily cross correlations. Figure 5 shows four-year (1999–2002) NCFs calculating in 0.003–0.02 Hz of seismic stations in Eurasia and ESA. The station separation ranges from 2 908 to 9 264 km. The group velocity is about 3.7–3.9 km/s which is close to the estimation from NCFs of seismometers. Although temporal normalization is applied to the raw data to reduce the effect of instrument difference, the SNR of SG-seismometer NCF is obviously lower than one of between seismometers.

4 Conclusions

Two series of NCFs have been obtained from stacking years of daily cross correlation among superconducting gravimeters and between superconducting gravimeter and seismometer. The NCFs of two new instrument combinations are comparable with the traditional ones of seismometers in arrival time and dispersion. Although the difference in instrument responses reduces the SNR of NCF, the temporal stacking of longer time range can suppress this undesirable effect. Another candidate approach is using the cross correlation of data with shorter segments instead of one day long segment. The SNR also depends on stations distance and frequency band used in spectral whitening. The records of distant stations rarely produce strong signals in NCFs at short periods. The uniform response of superconducting gravimeter theoretically provides EGF in very long period which is helpful to understand the deeper structure of the Earth. Our result demonstrates the feasibility of this approach.

Acknowledgements This research is supported jointly by Chinese Academy of Sciences Fund (No. KZCX-YW-116-1) and Joint Seismological Science

Foundation of China (Nos. 20080818 and 200708035). The data was provided by OHP DMC and IRIS DMC.

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