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Anomalous signals before 2011 Tohoku-oki *M*w9.1 earthquake, detected by superconducting gravimeters and broadband seismometers

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Abstract: The 2011 Tohoku-oki earthquake, occurred on 11 March, 2011, is a great earthquake with a seismic magnitude *M*w9. 1, before which an *M*w7. 5 earthquake occurred. Focusing on this great earthquake event, we applied Hilbert-Huang transform (HHT) analysis method to the one-second interval records at seven superconducting gravimeter (SG) stations and seven broadband seismic (BS) stations to carry out spectrum analysis and compute the energy-frequency-time distribution. Tidal effects are removed from SG data by T-soft software before the data series are transformed by HHT method. Based on HHT spectra and the marginal spectra from the records at selected seven SG stations and seven BS stations we found anomalous signals in terms of energy. The dominant frequencies of the anomalous signals are respectively about 0. 13 Hz in SG records and 0. 2 Hz in seismic data, and the anomalous signals occurred one week or two to three days prior to the event. Taking into account that in this period no typhoon event occurred, we may conclude that these anomalous signals might be related to the great earthquake event.

Key words: earthquake; anomalous signals; superconducting gravity data; broadband seismic data; Hilbert-Huang Transform

1 Introduction

Some anomaly signals may appear before a large earthquake event. Various studies[1-7] were aimed to detect the anomalous signals and obtain possible clues to earthquake prediction. Some studies[8-10] suggested that superconducting gravimeter (SG) data and broadband seismometer (BS) data might detect anomalous signals prior to some large earthquakes, and research on these signals could contribute to better understanding earthquake mechanism.

At 5:46, on Mach 11, 2011 (UTC), a great earthquake with a seismic magnitude *M*w9. 1 occurred in the offshore area of eastern Japan, Tohoku-oki. Before this main shock, an *M*w7. 5 earthquake occurred at 2 : 45, on March 9 (UTC) and after the main shock, several medium-large earthquakes occurred. On March 12, there still occurred several earthquakes with magnitudes being larger than 6. 5. Since seismic signals are nonlinear and non-stationary series, for the present purpose, the conventional Fourier transform and wavelet transform are not suitable for seismic data processing, whereas the Hilbert-Huang Transform (HHT) time-frequency-energy analysis technique is demonstrated to be more suitable for this task[9]. Thus, we use HHT method to process SG data and BS data before and after the 2011 Tohoku-oki *M*w9. 1 earthquake.

2 Data and processing

We examined the data sets spanned in March 2011,

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sampled at one-second interval at 16 SG stations distributed globally under the Global Geodynamics Project (GGP). But not all of the data provided by the stations are in good quality because the data from some stations have many breaks or long breaks and thus they are not suitable for usage. Here, we chose the good-quality data from seven SG stations. The distribution of all of the SG stations is shown in figure 1.

GGP provides only 1 Hz SG data one month before and one month after an earthquake with its seismic magnitude larger than 9.1. As a contrast, a plenty of globally distributed BS data are released by IRIS (Incorporated Research Institutions for Seismology, http://www.iris.edu/data/). We chose seismic data at stations located within the range that the epicenter distances of the stations are smaller than 2000 km. Figure 2 shows the distribution of the chosen seven seismic stations.

The original SG data and BS data should be preprocessed for further analysis. We removed the tidal effects from the SG data using the T-soft software provided by the International Center for Earth Tides (ICET, http://www.astro.oma.be/ICET). Based on the rdseed software (transferring the seismic records from seed format to binary sac format) and SAC (processing seismic data in sac format), BS data were transferred to accelerations after removing the mean and trend. Then,

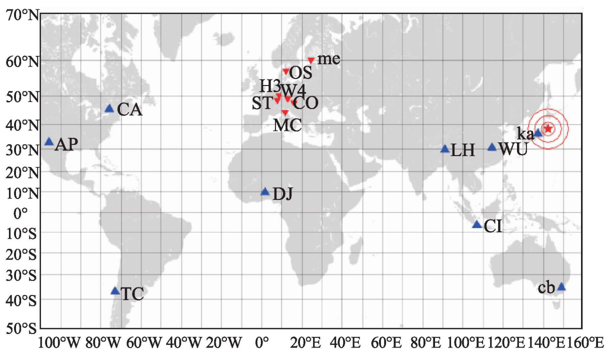


Figure 1 Distribution of superconducting gravimeter (SG) stations (Red triangles represent 7 selected SG stations and blue triangles represent the ones that are not used. The red star represents the location of the earthquake event. The selected seven SG stations are: CO (Conrad Observatory, Austria); H3 (BadHomburg, Germany); MC (Medicina, Italy); me (Metsahovi, Finland); OS (Onsala, Sweden); ST (Strasbourg, France); W4 (Wettzell, Germany))

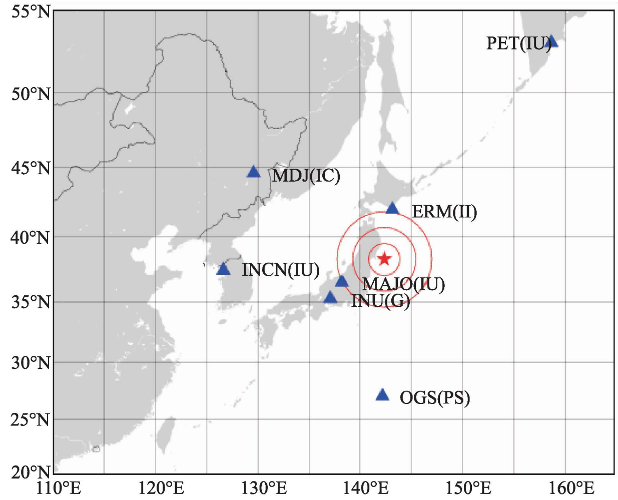


Figure 2 Distribution of broadband seismic (BS) stations (Blue triangles represent the stations and the red star represents the location of the earthquake event. The seven stations are listed as: INCN (Inchon, Republic of Korea, IU network); MAJO (Matsushiro, Japan, IU network); ERM (Erimo, Hokkaido Island, Japan, II network, GSN-IRIS/IDA); PET (Petropavlovsk, Russia, IU network); MDJ (Mudanjiang, Heilongjiang Province, China, IC network, New China Digital Seismograph Network); INU (Inuyama, Japan, G network, Geoscope); OGS (Chichijima, Bonin Islands, Japan, PS network, Pacific21))

we applied Hilbert-Huang Transform method to the preprocessed data.

The key part of the method is the Empirical Mode Decomposition (EMD) which decomposed complicated data set into a finite and often a small number of intrinsic mode functions (IMFs), which are arrayed from high frequency to low frequency[11].

Having obtained the IMF components, one can apply Hilbert transform to each component and compute the instantaneous frequency and amplitude at any moment[12,13], thus construct the energy-frequency-time distribution, designated as HHT spectrum[14,15]. To obtain a more accurate energy-frequency-time distribution, in this study we directly plotted discrete points of HHT spectra without using interpolation methods (different amplitude values were marked by different colors). Records at each station can be decomposed into about 20 IMF components. For HHT spectrum, the spectrum of IMF1 (the first IMF, which has the highest frequency) is similar to that of the composition of all of the IMFs, because the amplitudes of the anomalous signals in IMFs, except for IMF1, are so small that they are submerged in the background noises in the HHT spectra. Thus, HHT spectrum of each IMF1 is enough in this study.

To get more clear relationship between the amplitude and frequency of anomalous signal, we further investigate the marginal spectrum. It represents the total amplitude contribution from each frequency value in a certain time period. If HHT spectrum is $H(t,f)$, where t is time, f is frequency, H is amplitude, then the marginal spectrum is defined as $h(f)=\int H\ (t,f)\ dt$. It is necessary to compare the marginal spectrum of different time periods, but the lengths of time periods tend to be different. So we divide the marginal spectrum by the length of the time period T, as $h(t)=(\int H(t,f)\mathrm{d}t)/T$. Strictly speaking, what we compute and apply here is actually the average marginal spectrum (called marginal spectrum hereafter).

3 Results and analysis

Figure 3 shows HHT spectra of SG data at each station. The time and intensity of the earthquake event are evident, and we can easily find anomalous signals before the great earthquake.

From figure 3, we found that in March 1 – 3 and March 9–10, the signals around 0.1 Hz appeared and in March 4–5 and March 7–8, the amplitudes of HHT spectra are relatively small and steady. In March 9 – 12, a few other earthquakes are also clearly seen.

According to the earthquake catalog (http://www.iris.edu/seismon/) and typhoon catalog (http://www.ncdc.noaa.gov/oa/ibtracs/), there was no typhoon event in March 1 – 12 and no earthquake event with magnitude larger than 6.0 in March 1–3. The anomalous signals in March 1 – 3 are possibly the anomalous signals related to the large earthquake[4,16]. To find out the dominant frequency of the signals, we chose two time windows: March 4–5 as the quiet days and March 1–3 as the anomalous days. Then, we computed the marginal spectra in the two periods, respectively. The comparison is shown in figure 4.

Figure 4 suggests that the dominant frequency of the signals in the anomalous days is around 0.13 Hz. Note that even in the quiet days, the marginal spectra show an obvious common peak around 0.13 Hz at some certain stations. We selected the identical period as the quiet days, the definition of which is in a relative sense. In the chosen quiet days, there are possibly some anomalous signals mixed in the marginal spectra at some certain stations while the marginal spectra around 0.13 Hz are smooth at other stations. In fact, the result presented in figure 4 is consistent with the HHT spectra of the SG records as shown by figure 3.

Figures 3 and 4 show that there is gravity anomaly in March 1–3 in some areas that has a dominant frequency around 0.13 Hz. Since no typhoon and earthquake event with magnitude larger than 6.0 occurred in this period, we may conclude that the gravity anomaly prior to 2011 Tohoku-oki *M*w9.1 earthquake is related to the great earthquake.

Therefore, if the anomalous signals during the period in March 9 – 10 are also related to the great earthquake, then the marginal spectra should also show a peak around 0.13 Hz in this period. The result is shown in figure 5.

The energy-frequency distributions of data at different stations are very similar (Fig.5), and the marginal spectra have obvious peaks around 0.13 Hz and around 0.05 Hz. The peaks around 0.13 Hz are inerratic but the patterns of peaks around 0.05 Hz are diverse and rather complex. These results can be explained by the occurrences of other earthquakes with seismic magnitudes larger than 6.0 in this period. The marginal spectra during March 9–10 play little role in discerning the dominant frequency of the anomalous signals during March 9 – 10 that are related to the great earthquake. To further analysis, we computed the segmented marginal spectra.

The data series from 5 : 30 March 9 to 5 : 30 March 11 at ST station were divided into four records, with all durations are all six hours, and their marginal spectra were studied respectively. Figure 6 shows the results.

Based on figure 6(a), during the time 1–6 h, the marginal spectra have two peaks around 0.13 Hz and around 0.05 Hz; during the time 7–12 h, there is only one peak, around 0.13 Hz; during the time 13–18 h, the peak value around 0.05 Hz is much bigger than that around 0.13 Hz; during the time 19–24 h, the energy in the marginal spectra looks relatively steady.

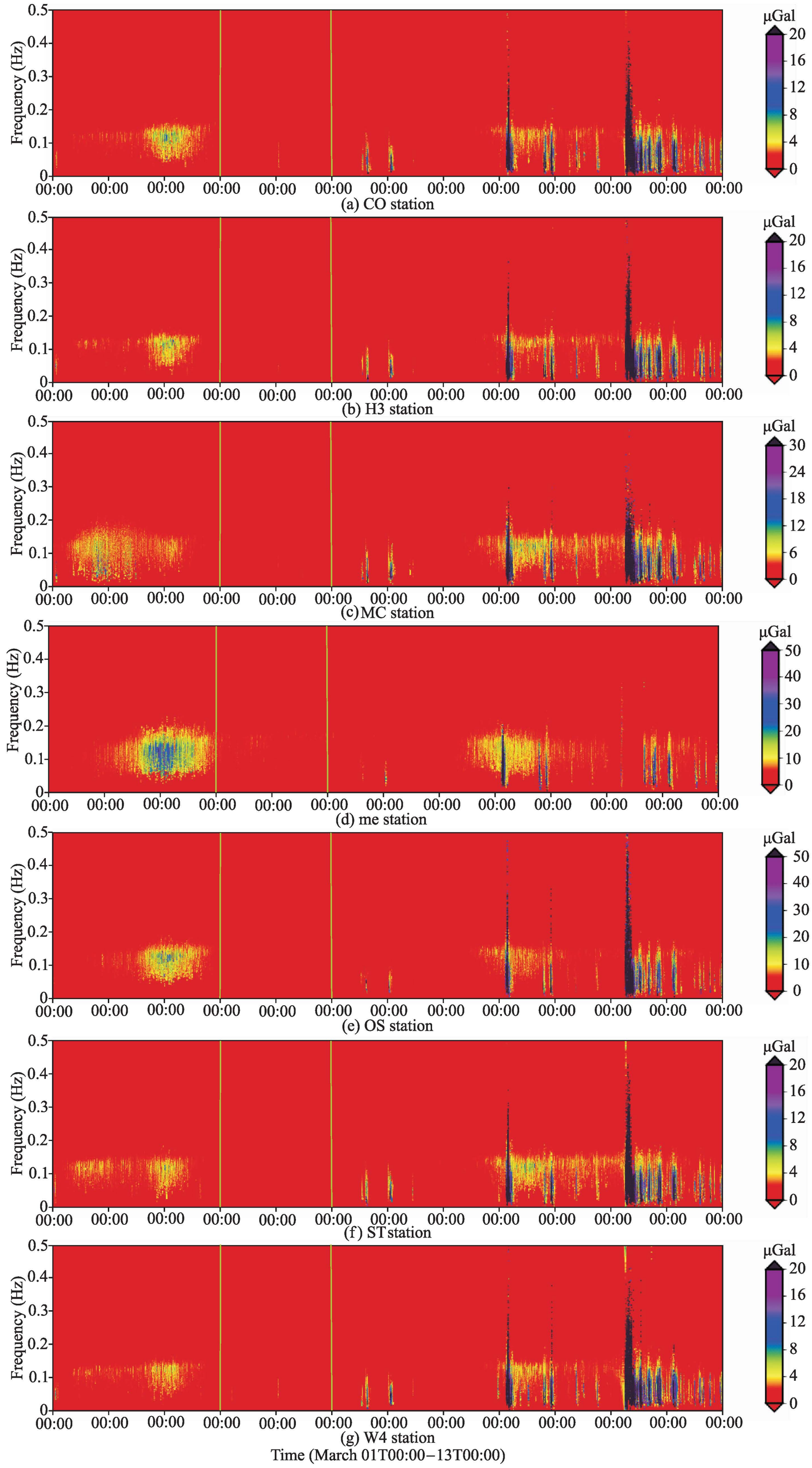
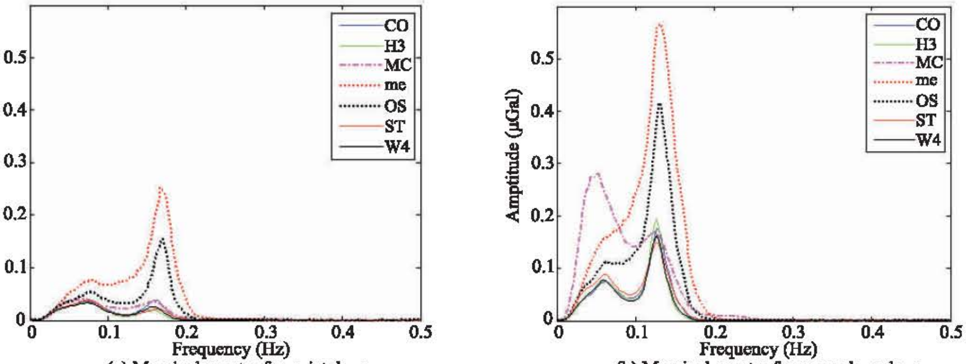


Figure 3 HHT spectra of SG data series after removing tidal effects, March 1–12, 2011 at 7 chosen stations. In March 1–3 and March 9–10, the signals around 0.1 Hz in the frequency domain have an obvious increase in their amplitudes. The two vertical green solid lines demonstrate the quiet days when the amplitudes are small and steady. (a) Conrad Observatory, Austria, (b) Bad Homburg, Germany, (c) Medicina, Italy, (d) Metsahovi, Finland, (e) Onsala, Sweden, (f) Strasbourg, France, and (g) Wettzell, Germany.



(a) Marginal spectra for quiet days (b) Marginal spectra for anomalous days

Figure 4 Marginal spectra of SG data series at 7 stations in the quiet days (denoted by two vertical green solid lines in figure 3) and anomalous days (denoted by the left vertical axis and the left vertical green solid line in figure 3)

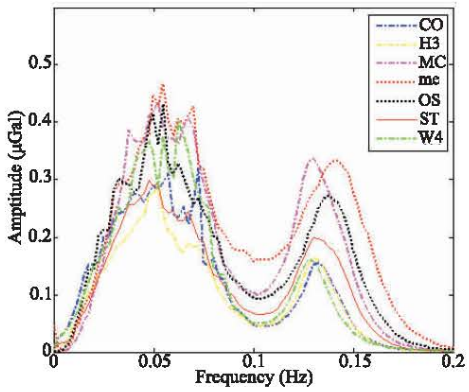
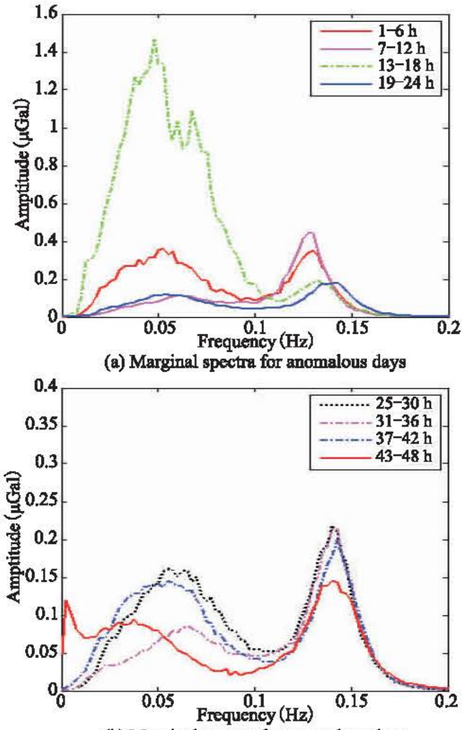


Figure 5 Marginal spectra of SG data series during March 9–10 in 2011 at seven stations



(b) Marginal spectra for anomalous days

Figure 6 Eight segmented marginal spectra of SG data series during the time 5 : 30 March 9 to 5 : 30 March 11.

To summarize, the values of energy around 0.05 Hz is not constant among the eight time periods and the change is consistent with the time of the other earthquakes occurrence with a seismic magnitudes larger than 6.0. At 2 : 45(UTC), March 9, 2011, an earthquake with magnitude 7.5 occurred, thus, the peak around 0.05 Hz during the time 1–6 h is probably the post-earthquake effects, which disappeared during the time 7–12 h. The situation during the time 13–18 h and 19–24 h is related to the earthquake with magnitude 6.6 during the time 13–18 h. The energy around 0.13 Hz is fairly steady, which only decreased after the energy release of other earthquakes. This is exactly the feature of anomalous signals related to the large earthquake. Thus, the detected anomalous signals in gravity records with the dominant frequency around 0.13 Hz is what we aim to find.

In addition to SG data, similar anomalous signals can be detected in BS data. Figures 7 and 8 show the results.

HHT spectra in figure 7 clearly show the intermittent anomalous signals with an obvious increase in amplitude prior to the great earthquake occurrence on March 11. We roughly classified the duration of the anomalous signals into two periods, around March 3 and March 7–10, and further analyzed the anomalous signals via the marginal spectra, as shown in figures 8 and 9.

From figure 7, the quiet periods are relatively scattered at ODJ (IC), INU (G) and OGS (PS) stations, thus the data at these three stations were not used when we computed the marginal spectra of the quiet days. The anomalous days around March 3 at different stations vary according to the duration of the anomalous

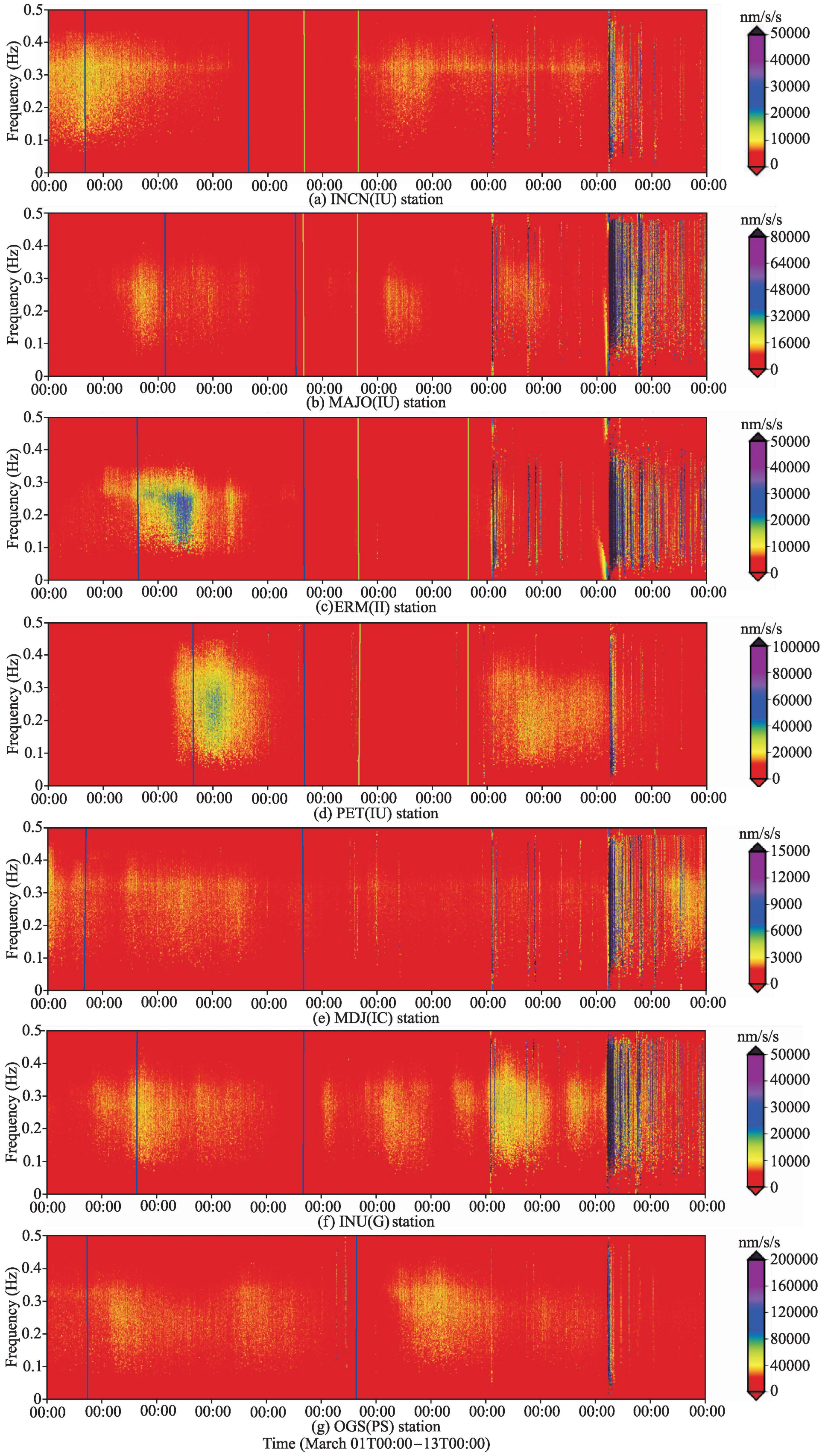
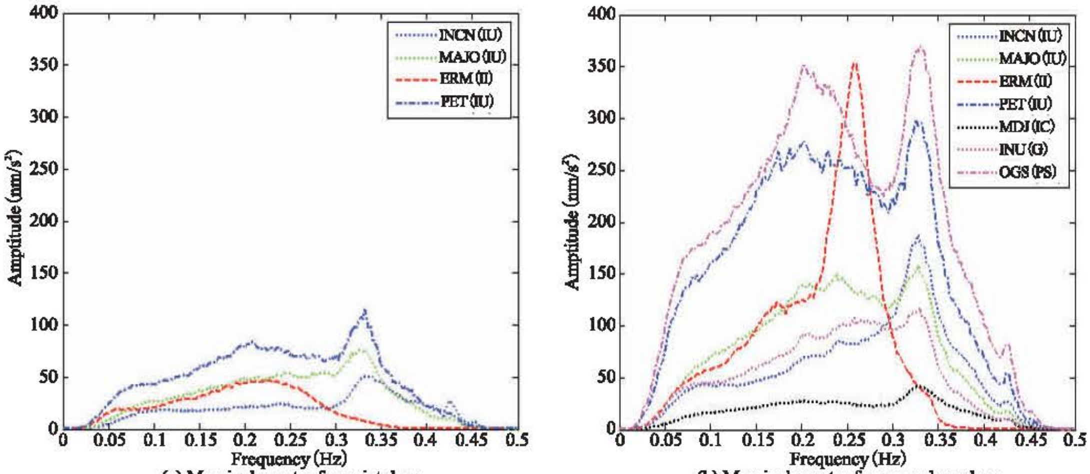


Figure 7 HHT spectra of BS data series that cover the period March 1−12, 2011 at 7 stations. (c) and (d) show obvious increases in amplitudes in the frequency domain around 0.2 Hz to 0.28 Hz, around March 3.



(a) Marginal spectra for quiet days (b) Marginal spectra for anomalous days

Figure 8 Marginal spectra of BS data series at different stations (The quiet days at each station are listed below: NCN: March 5; MAJO: March 5; ERM: March 6–7; PET: March 6–7 (denoted by two vertical green solid lines in figure 7). The anomalous days at each station are listed below: NCN: March 1–3; MAJO: from 12:00 March 2 to March 4; ERM: March 2–4; PET: March 3–4; MDJ: March 1–4; INU: March 2–4; OGS: March 1–5 (denoted by two vertical blue solid lines in figure 7))

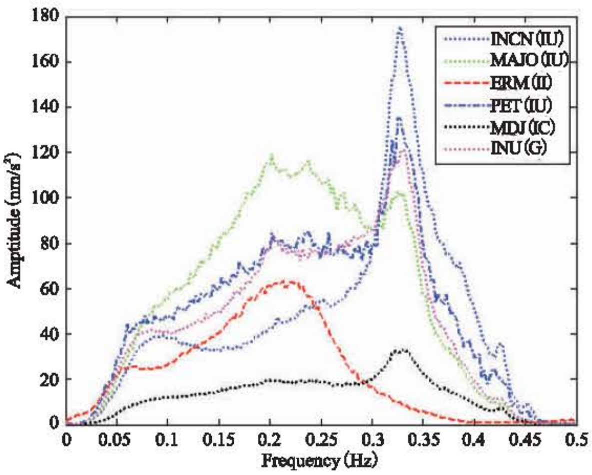


Figure 9 Marginal spectra of BS data series at different stations for anomalous days (00 : 00, March 7 to 2 : 00, March 9, 2011)

signals. Due to several large earthquakes on March 9, we chose the time period from March 7 to a few minutes prior to the earthquake with the magnitude 7.5 on March 9 as the latter anomalous days.

As shown in figures 8 and 9, the marginal spectra in the quiet days have obvious peaks around 0.33 Hz and the energy is fairly steady around 0.17–0.3 Hz. The energy-frequency distributions in the anomalous days at different stations are not very similar. According to previous study[9], the energy-frequency distributions can be divided into two categories. One is that the marginal spectra in the anomalous days have only one peak around 0.33 Hz and have an obvious increase in the range 0.17–0.3 Hz compared to the quiet days, similar to the spectrum at INCN (IU) station. Such anomalous signals correspond to the anomalous signals detected by inland seismic stations prior to Wenchuan earthquake in previous study[9]. And the other is that the marginal spectra in the anomalous days have one broad peak in the range from 0.17 Hz to 0.3 Hz, even exceeds the peak value around 0.33 Hz, and the energy has obvious increase in the range 0.17–0.3 Hz compared to the quiet days such as the spectrum at MAJO (IU) station. Such anomalous signals correspond to the anomalous signals detected by coastal seismic stations prior to Wenchuan earthquake in previous study of Shen et al[9].

The energy-frequency distributions in the two anomalous periods are very similar, so it can be concluded that the anomalous signals have the same nature. However, since the energy of the signal 0.2 Hz in the anomalous days is much bigger than that in the quiet days, we infer that this signal is anomalous signal related to the great earthquake.

As for ERM (II) station, there is no dominant frequency band around 0.33 Hz in the marginal spectrum. This may have something to do with the station itself but not the earthquake event. The dominant frequency band in the range 0.17–0.3 Hz still exists, which further sustains the argument that the energy concentrated on the dominant frequency band in the range from 0.2 Hz to 0.3 Hz in the anomalous days is related to the great earthquake.

4 Conclusion

Based on the study of SG data and BS data in March 1−12, we find that about one day to one week before 2011 Tohoku-oki *M*w9.1 earthquake, records at seven SG stations and seven BS stations detected the anomalous signals which are obvious in data amplitude. In data preprocessing, we removed the tidal effects which are long-term and relatively steady from the original gravity data. There are no typhoon events in this period; hence the anomalous signals should be related to the earthquake event.

According to the distribution of these seven SG stations and seven BS stations, the factor that leads to this kind of anomalous signals has wide influence on the Earth. Also, the time duration of the anomalous signals is often several days prior to the large earthquake. Besides, the characteristics in frequency spectrum of the anomalous signals prior to this great earthquake are very similar to those of the Wenchuan earthquake[9]. Therefore, it is reasonable to conclude that the dominant frequency band around 0.13 Hz in SG data and the dominant frequency band in the range 0.17−0.3 Hz in BS data in March 1−3 and around March 9 are anomalous signals prior to 2011 Tohoku-oki *M*w9.1 earthquake.

The anomalous signals have relatively steady frequency bands and energy before the large earthquake and they diminish very quickly after the earthquake. We may infer that before the large earthquake occurs, the anomalous signals, result from gravity anomaly and propagation of seismic waves, are induced by the ground vibration in the process of the slow slip and extrusion of faults when the stress on the faults reaches a critical state. The quick decrease of the anomalous signals is the result of the stress release in earthquake occurrence.

There are anomalous signals in both March 1−3 and around March 9. Based on this, we may conclude that the stress in the interior of the Earth is so large that the slow slip of faults starts around March 1−3. The faults enter into a relatively steady state in the following several days, and the second slow slip of faults occurs around March 9, and the slip stops gradually with the occurrence of the great earthquake on March 11.

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