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Characteristics of Seismic Wave Propagation of Harmonic Tremors Observed at the Margin in the Lützow-Holm Bay, East Antarctica

Masaki Kanao

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Abstract

Several kinds of seismic signals involving physical interactions within the shallow atmosphere—ocean—cryosphere—solid earth system have been detected in continental margins of Antarctica and surrounding Southern Ocean. In this study, characteristic features of seismic tremors with harmonic overtones recorded at Syowa Station, the Lützow-Holm Bay (LHB), East Antarctica, are demonstrated for the period from October 2014 to March 2015. A few tens of tremors ($N = 81$) are identified in both the short-period and broadband seismographs. The characteristic tremors with harmonic overtones can be explained by a repetitive source, suggesting the existence of several interglacial asperities. It implies that the tremors might be involved in local origins, presumably be the dynamics of cryosphere, including discharge of sea-ices from bay, collision of icebergs and fast-ices, calving of glaciers, and the other origins. The strong harmonic tremors with frequency overtones found in LHB are mostly generated by collisions between icebergs and the edge of fast sea-ice by comparison with satellite data. Seismic tremors in terms of cryosphere dynamics, therefore, are likely to be associated with variation of surface environment in the Antarctic, and continuous monitoring of their time-space variability provides indirect evidence of climate change.

Keywords: cryosphere dynamics, seismic tremors, harmonic overtones, sea-ice, icebergs, Syowa Station, East Antarctica

1. Introduction

During the International Polar Year (IPY2007-2008), the “Polar Earth Observing Network (POLENET)” was the largest contributions to establishing seismic network in the whole

Antarctic continent [1]. Several kinds of seismic signals associated with surface environmental variations within the shallow atmosphere–ocean–cryosphere–solid earth system have been detected in continental margins and surrounding Southern Ocean (**Figure 1**). Ice-related seismic motions for small magnitude events are generally named ice-quakes (ice-shocks) and can be generated by glacially related dynamics. Such kinds of cryoseismic sources have been classified into several kinds: movements of ice-sheets, sea-ice, oceanic tide-cracks, oceanic gravity waves, icebergs, and the calving fronts of ice-caps [2–4].

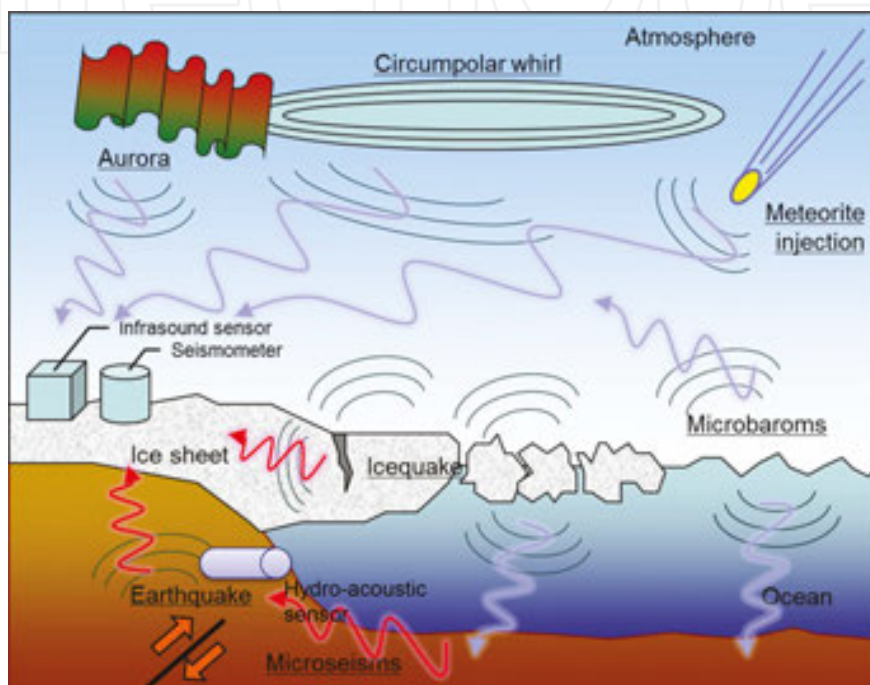


Figure 1. Schematic illustration of interdisciplinary physical interaction within multi-spheres in polar region. Several kind of seismic waves, infrasonic waves, as well as hydro-acoustic waves are generated by surface environmental sources, which are affected by time-space variations of these spheres in polar region.

Hypocenters of local seismic events nearby Syowa Station (SYO; 69S, 39E) were previously identified in both along the coast and edges of fast-ice in the Lützow-Holm Bay (LHB) region (**Figure 2**), Eastern Dronning Maud Land, East Antarctica [4]. These seismic sources were estimated to be the calving of glaciers and/or the discharge of sea-ice, together with the collision between icebergs and sea-ices around the Bay. Some parts of cryoseismic events, however, have a possibility that they include tectonic local events associated with the faulting systems, volcanic activities, as well as glacial isostatic rebound crustal movement. Cryoseismic dynamics, as mentioned in this chapter, are mostly involved in environmental changes, and their space-time variability provide a new proxy for monitoring climate change in polar region.

In this chapter, characteristic features of recently identifying seismic tremors observed around the LHB are demonstrated for 6 months from October 2014 to March 2015, by considering a relationship between surface environmental changes in vicinity of the area, in particular cryosphere evolution and dynamics.

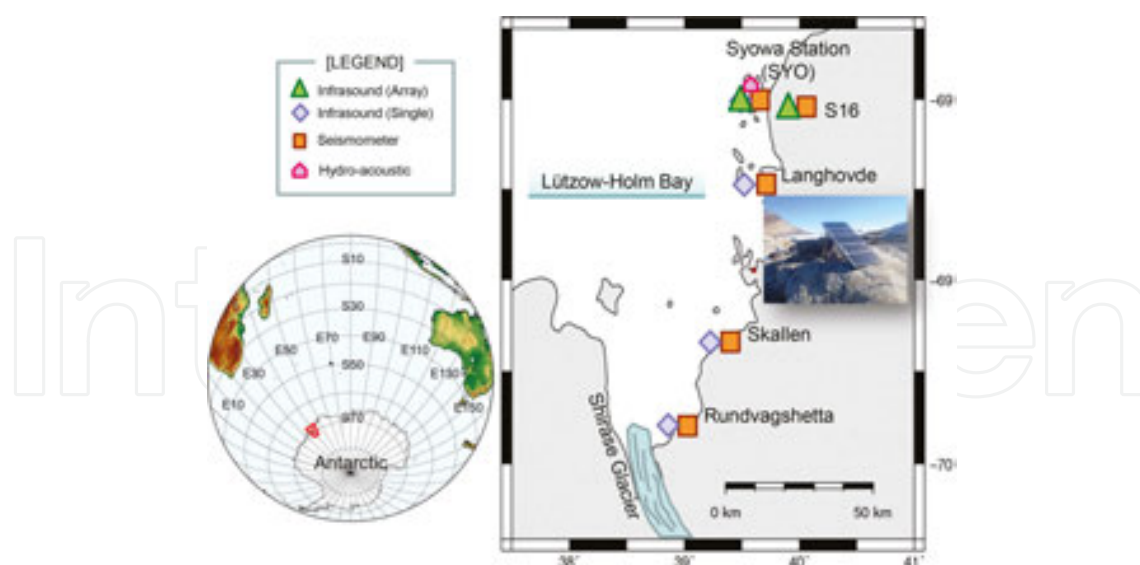


Figure 2. Distribution of seismic stations around the LHB, East Antarctica. A three-component short-period and broadband seismographs have been operated at Syowa Station (SYO). In addition, three-component portable broadband seismographs (CMG-40T type) have been deployed at several stations around the LHB. Photo of the “Langhovde” station on an outcrop is inserted in the map.

2. Seismic tremors with harmonic overtones

By this study, a few tens of seismic tremors ($N = 81$) are newly recognized in both three-component short-period seismographs (HES) and broadband seismographs (STS-1) deploying at Syowa Station (SYO) during the period from October 2014 to March 2015. Details of seismic observation at SYO and teleseismic detectability are written by [5]; auto-monitoring systems for both the seismographs at SYO are traced in [6]. Some of the newly found tremors attribute characteristics of strong harmonic overtones, in their frequency content over the 1 Hz, representing nonlinear features having upward and/or downward frequency contents with duration times from few minutes till few hours. These tremors occur independently against the arrivals of teleseismic phases, as well as are recorded by both types of seismic sensors (HES and STS-1) simultaneously. Therefore, the generating sources of these harmonic tremors are assumed to be local or regional origins.

Since the time-series number of tremors including small and weak signal events are assumed to be increased when the large storms visit to the area around LHB. At that time, oceanic swells energy in southern Indian Ocean was enhanced [7], followed by the occurrence of crashing phenomenon among the pack-ices surrounding the Bay. Then the nonlinear and weak seismic tremors (as well as infrasound and hydro-acoustic signals) are illuminated to some extent. However, in this study, we focus on the harmonic tremors with relatively large seismic energy, which are attributed by frequency overtones with nonlinear time-line features appeared in the power spectral densities, as shown in this chapter.

Figure 3a and **b** are one of the clear examples of the harmonic tremor with frequency overtones recorded at SYO on 05 November 2014. A total of six component seismograms by both short-

period and broadband are shown in **Figure 3a**. Selected pictures for two-component short-period seismographs are also represented in **Figure 3b**. For this harmonic tremor event, downward dipping frequency content is significantly identified with duration of about 90 min. Moreover, seismograms of the same event for other seismic station surrounding [LangHovde (LNG) station, which is 15 km southward from SYO; **Figure 2**] is indicated in **Figure 4a** and **b**. For this station, similar duration time around 90 min is recognized as appeared in the SYO's seismograms. Power spectral densities of the harmonic tremor recorded at LNG are presented in **Figure 4b**. Identical frequency peaks corresponding to harmonic overtones are indicated by five arrows, which have almost the similar frequency contents between three components of seismographs.

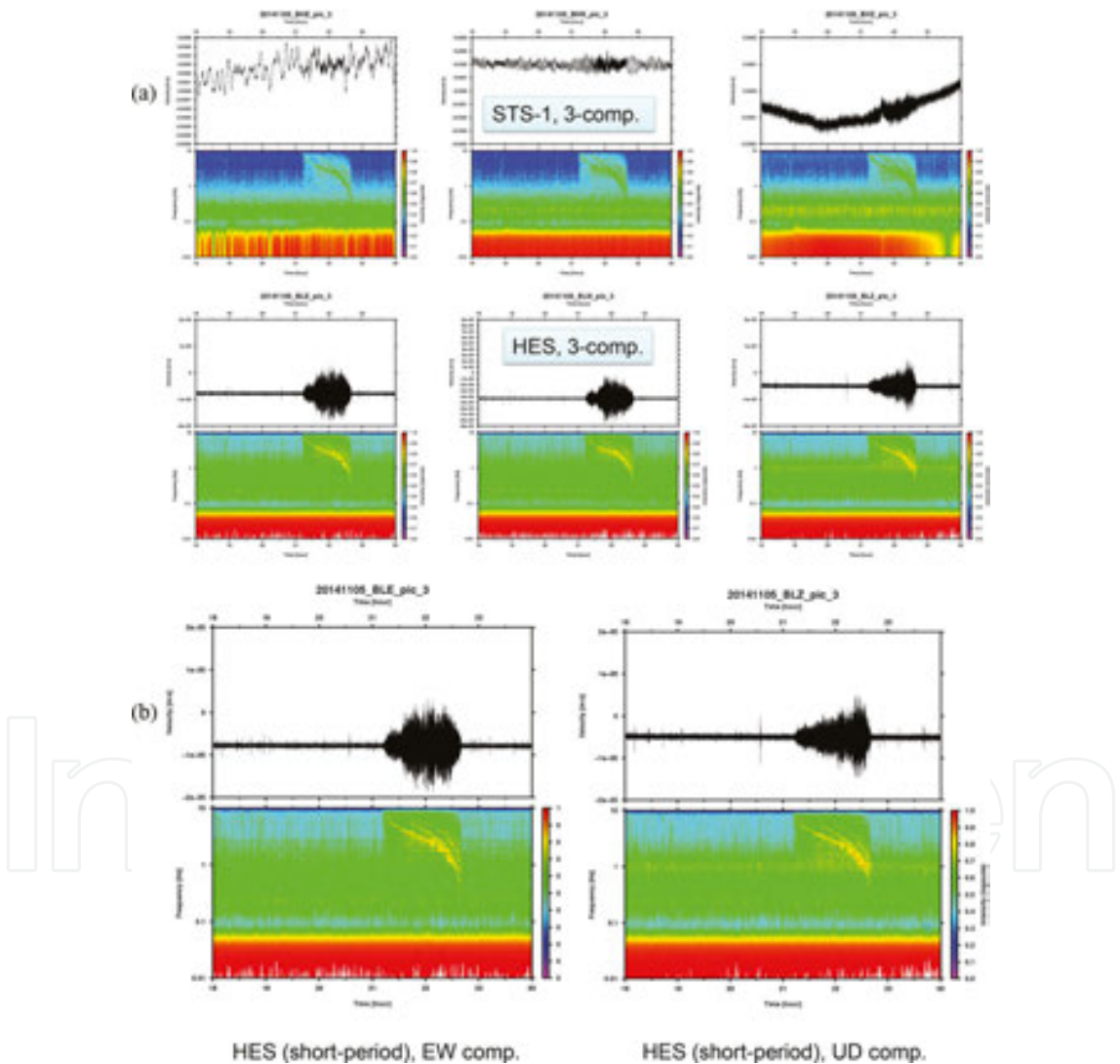


Figure 3. (a) Seismic waveforms and their power spectral densities of the harmonic tremor with harmonic overtones recorded at SYO (18-24 Universal Time, Coordinated (UTC), 05 November 2014) for both three-component short-period seismographs (HES; lower panels) and broadband seismographs (STS-1; upper panels), respectively. (b) Seismic waveforms and their power spectral densities of the harmonic tremor recorded at SYO (18-24 UTC, 05 November 2014; the same event in **Figure 3(a)** for the two-component short-period seismographs (HES).

Figures 5a, b and **6a, b** are the second example of characteristic harmonic tremors recorded at SYO in a few days of mid-February, 2015. A series of nonlinear harmonic tremors with frequency overtones can be identified. They have several pattern of time evolution in their frequency content in a duration time between 2 and 6 h. Some of them have downward dipping frequency contents (i.e., the decrease in frequency of each harmonic overtone). In contrast, the others are characterized by upward dipping frequency contents (i.e., the increase in frequency of each harmonic overtone). Addition, very nonlinear fluctuation in frequency contents are also identified in several harmonic tremor events. Four major tremors are identically observed on 16 February 2016 and the last tremor around 22 UTC is overrapped by teleseismic arrival phases (**Figure 6a** and **b**).

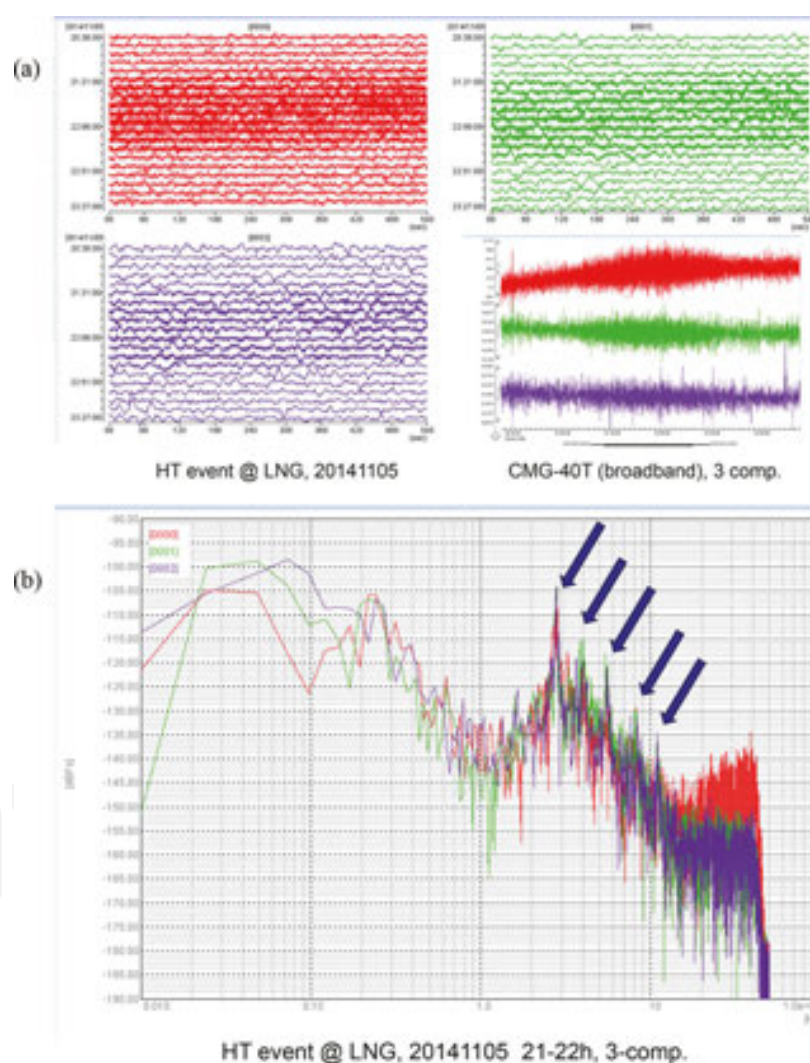


Figure 4. (a) Seismic waveforms of the harmonic tremor with harmonic overtones recorded at LangHovde (LNG) station (20-24 UTC, 05 November 2014) for three-component broadband seismographs (CMG-40T). The lower-right panel shows the three component seismographs with the same time axis. (b) Power spectral densities of the harmonic tremor with harmonic overtones recorded at LangHovde (LNG) station (21-22 UTC, 05 November 2014) for three-component broadband seismographs (CMG-40T). Five arrows represent individual frequency peaks of the identical harmonic overtones.

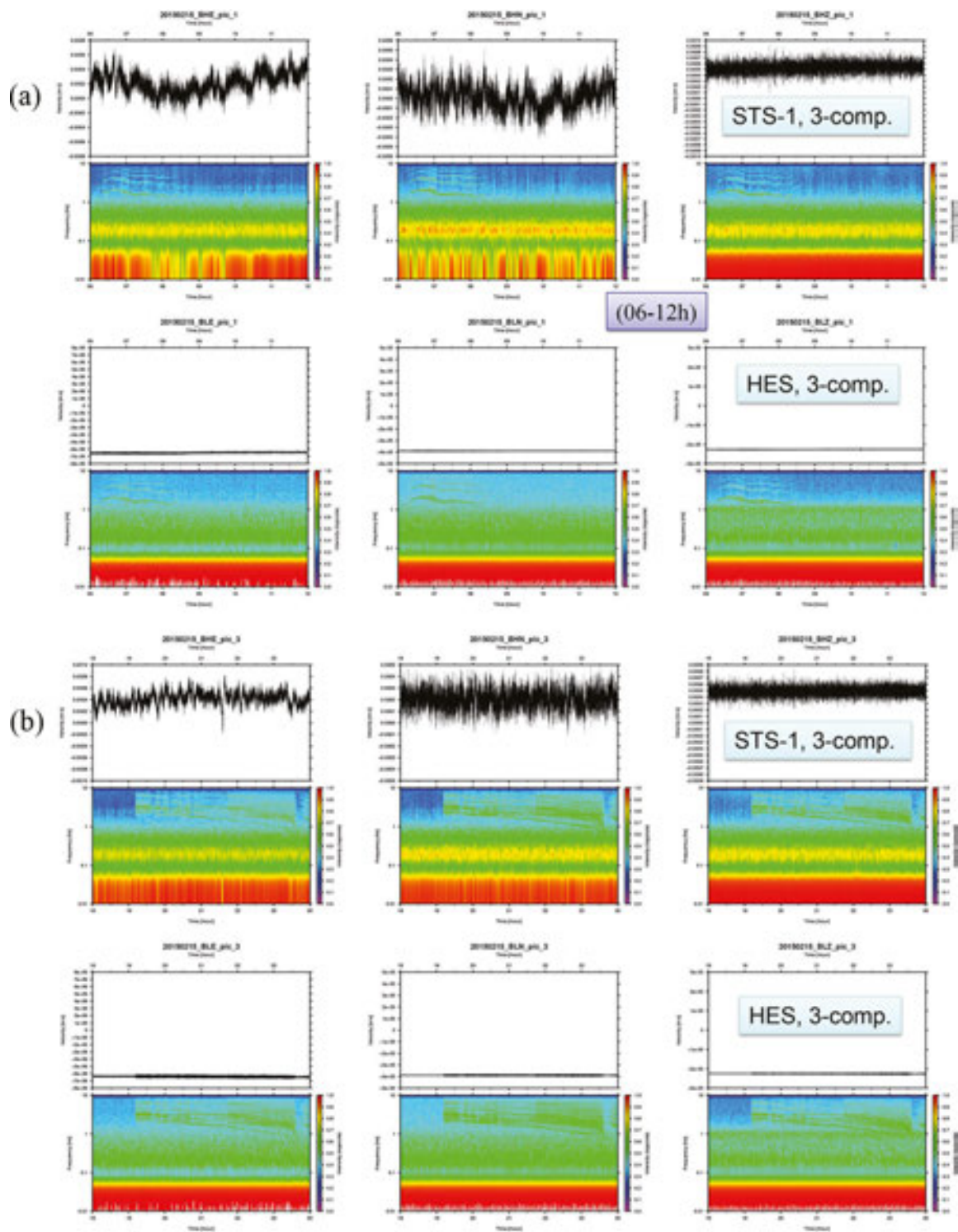


Figure 5. (a) Seismic waveforms and their power spectral densities of the harmonic tremor with harmonic overtones recorded at SYO (06-12 UTC, 15 February 2015) for both three-component short-period seismographs (HES; lower panels) and broadband seismographs (STS-1; upper panels), respectively. (b) Seismic waveforms and their power spectral densities of the harmonic tremor with harmonic overtones recorded at SYO (18-24 UTC, 15 February 2015) for both three-component short-period seismographs (HES; lower panels) and broadband seismographs (STS-1; upper panels), respectively.

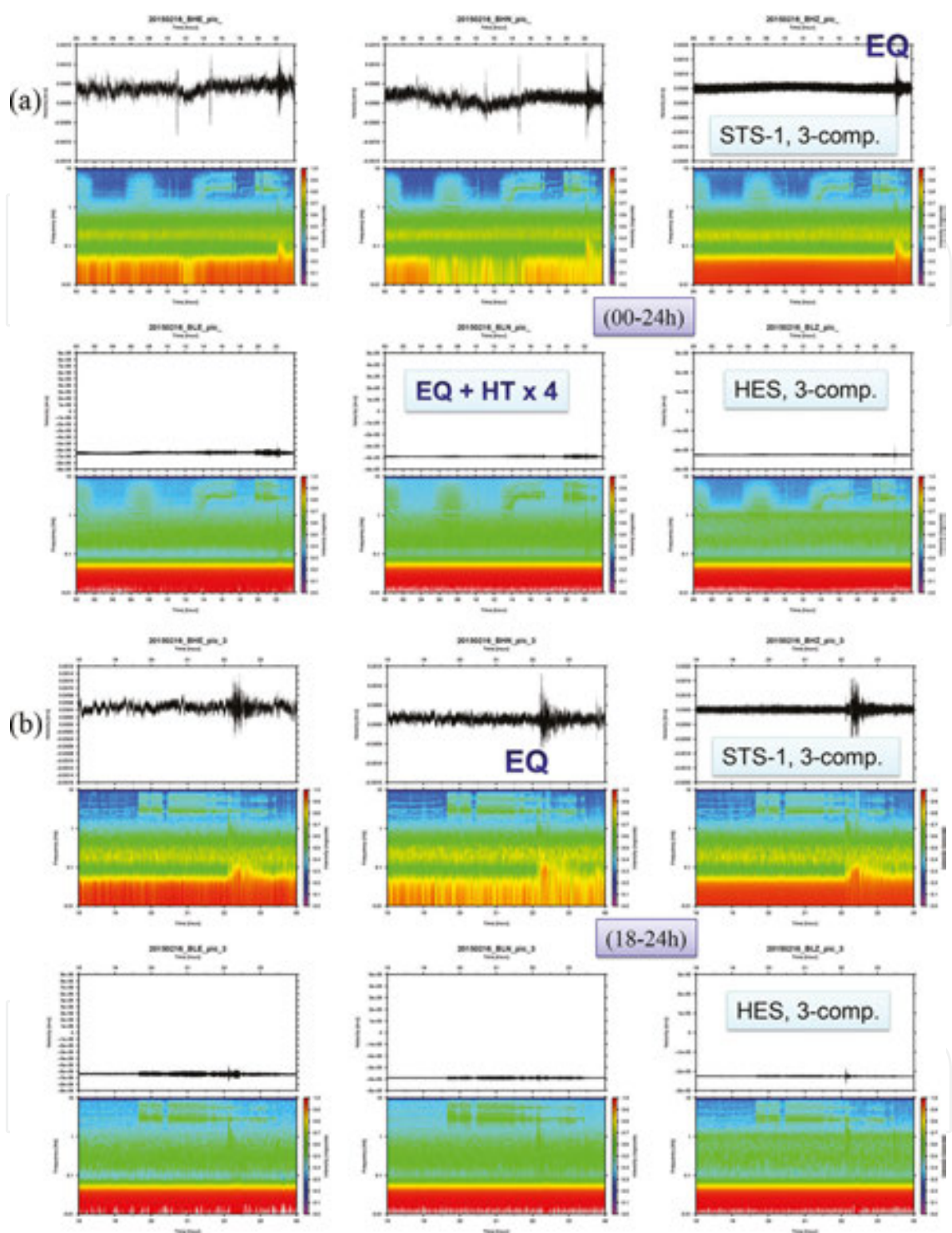


Figure 6. (a) Seismic waveforms and their power spectral densities of the harmonic tremor with harmonic overtones recorded at SYO (00-24 UTC, 16 February 2015) for both three-component short-period seismographs (HES; lower panels) and broadband seismographs (STS-1; upper panels), respectively. Four major harmonic tremors are identically observed with overlapped by teleseismic phases on the last tremor around 22 UTC. (b) Horizontal axis expanding panel of **Figure 6a**. (18-24 UTC, 16 February 2015). The nonlinear harmonic tremor are overlapped by teleseismic phases around 22 UTC and later time.

3. Plausible sources of harmonic tremors

Several kind of cryoseismic signals have been reported in many areas of Antarctic margins: the Ross Sea [8, 9], the Antarctic Peninsula [10, 11], the Dronning Maud Land [12], and the others. Similar to the tremor events treating in this chapter, the harmonic tremors by collision of two tabular icebergs were reported by locally deployed seismic stations [8]. The characteristic tremor signals were consisted of extended episodes of stick-slip ice-quakes occurred when the ice-cliff edges of two tabular icebergs rubbed together during glancing, which is explained by the “strike-slip” iceberg collisions. Source mechanisms of such harmonic tremors might provide useful information for the study of iceberg behavior, and a possible method for remotely monitoring the iceberg activity and evolution.

Moreover, similar nonlinear harmonic tremors associated with glacial dynamics have been reported at Whillans Ice Stream, West Antarctica [13, 14]. Simultaneous observation with geodetic measurement such as GPS and tide-gauge represent a strong collation with the occurrence time and generating procedure of these harmonic tremors. The harmonic overtones of seismic tremors can be explained by a repetitive source [15], suggesting existence of several interglacial asperities which generate the characteristic tremors. It strongly implies the tremor signals might be involved in the local origins, presumably the cryosphere dynamics: discharge of fast-ice from the Bay, collision of icebergs and fast-ices, and calving of glaciers in vicinity of the stations.

On the basis of above evidence of cryoseismic signals appeared in the Antarctic outside LHB, we utilize an adequate satellite image to focus on spacial distribution and time variability of cryosphere dynamics around LHB, so as to compare with the seismic data studied here. **Figure 7** indicates the MODIS satellite image around the LHB on 13 February 2015 (from NASA). A large iceberg flowed at the offshore of LHB in southern Indian Ocean from the east to the west during 13–19 February 2015. The nonlinear harmonic tremors with frequency overtones as shown in **Figures 5–6** could presumably be related with the collision procedure between the large iceberg and the northern edge of the fast sea-ice surrounding the LHB.

Figure 8 represents the other example of harmonic tremor with harmonic overtones recorded at SYO on 15 December 2014 for two-component broadband seismographs. Three major harmonic tremors are identically observed and the strongest one is found between 2300 and 2330 UTC. **Figure 9** shows the MODIS satellite image around the LHB on the same day as 15 December 2014. A large iceberg flow along the offshore of LHB in southern Indian Ocean from the east to the west, followed by a collision between the northern edge of the fast-ice (NE direction from SYO, about 100 km distance) during 13–18 December 2014. Then the iceberg rotated anti-clockwise and flowed off into the Southern Ocean to the westward. The harmonic tremors as shown in **Figure 8** could presumably be generated by the collision procedure between the iceberg and the northern edge of the fast sea-ice.

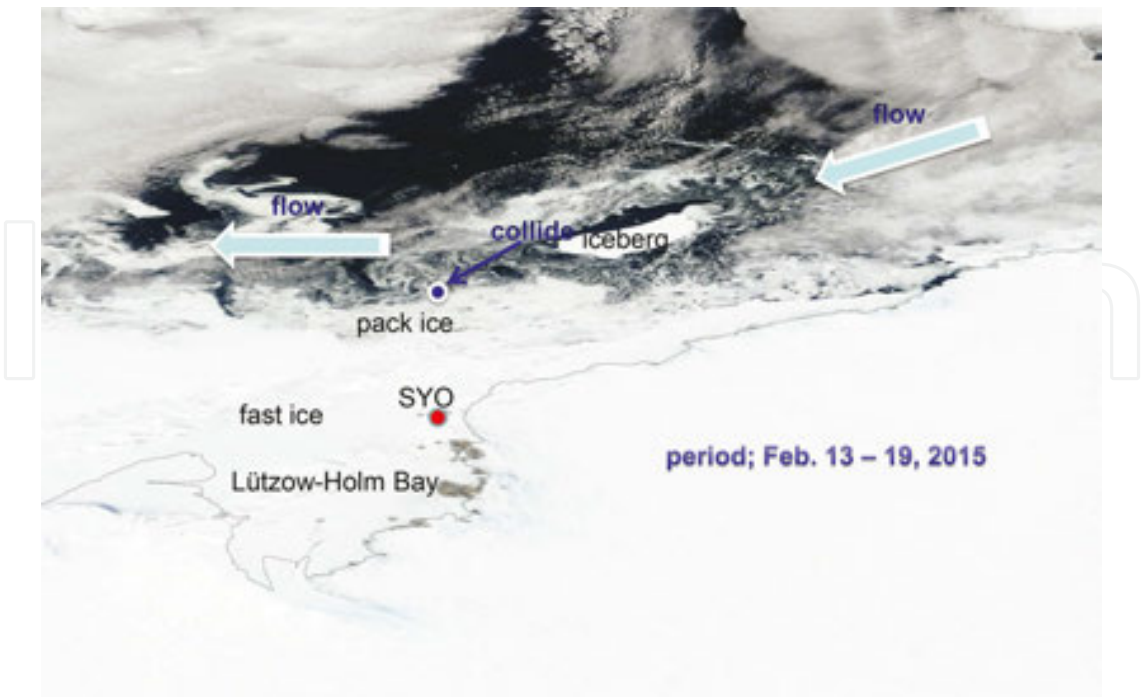


Figure 7. Moderate resolution Imaging Spectroradiometer (MODIS) satellite image around the LHB on 13 February 2015. A large iceberg flow at the offshore in southern Indian Ocean from the east to the west during 13–19 February 2015.

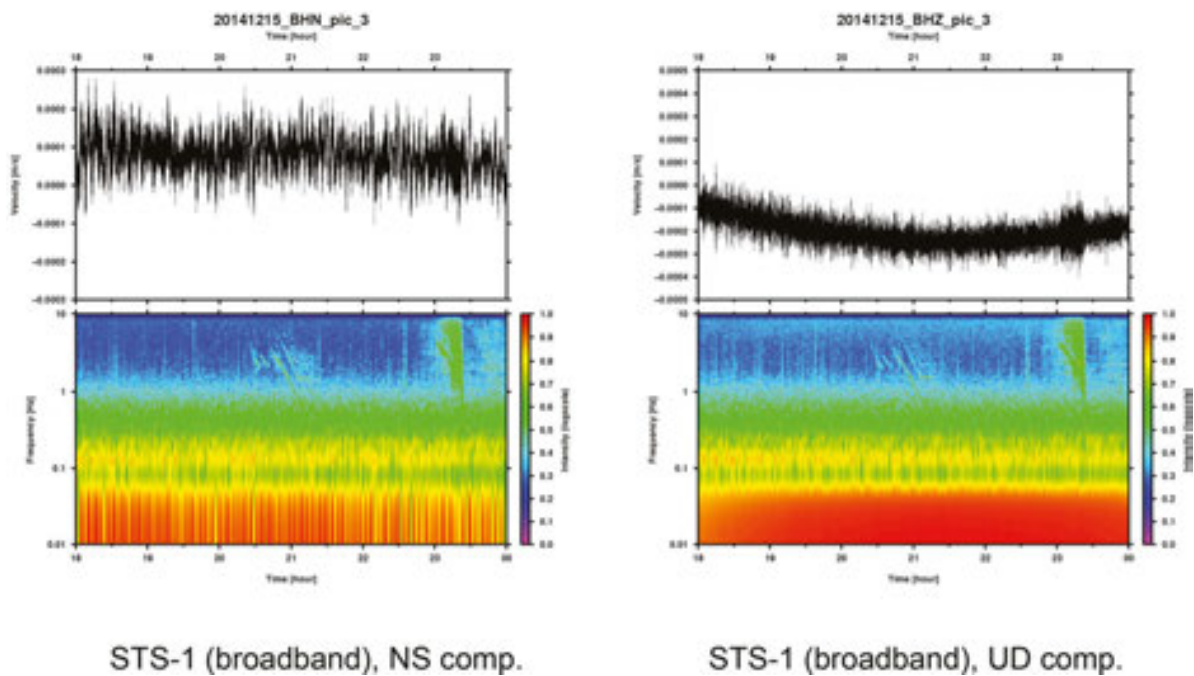


Figure 8. Seismic waveforms and their power spectral densities of the harmonic tremor with harmonic overtones recorded at SYO (18–24 UTC, 15 December 2014) for two-component broadband seismographs (STS-1). Three major harmonic tremors are identically observed and the strongest signal is found between 2300 and 2330.

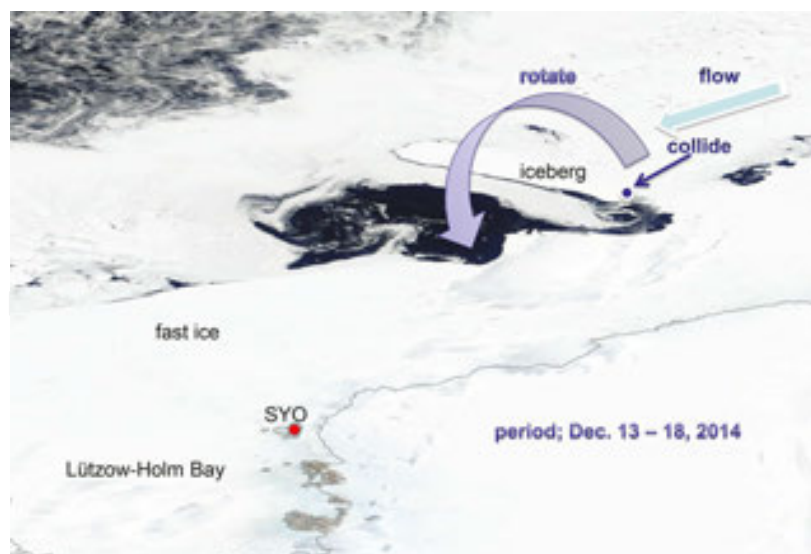


Figure 9. MODIS satellite image around the LHB on 15 December 2014. A large iceberg flow at the offshore in southern Indian Ocean from the east to the west, followed by a collision between the northern edge of the fast-ice (NE direction from SYO, about 100 km distance) during 13–18 December 2014. Then the iceberg rotated anti-clockwise and flowed off into the Southern Ocean again to the westward.

4. Discussion

Over the past few decades, seismic network deployments in many regions of polar region have been detected the local seismicity. Bannister and Kennett [16] demonstrated that a majority of seismicity around McMurdo Station, the Ross Sea, was located along the coast, particularly near large glaciers. Eckstaller [12] deployed local seismic network around Neumayer Station, the Dronning Maud Land and determined hypocenters of local events, locating along the coast and surrounding bay. Seismic events involving cryosphere dynamic phenomena are in generally “ice-quakes,” and are most frequently occurred by glacially dynamic movements of the ice-sheets, ice-caps, sea-ices, icebergs, and tide-cracks in other region of Antarctica [17–19]. Icemicity (ice-quake activities) around the Bransfield Strait detected by hydrophone arrays illustrated clearly dynamic behavior of the sea-ice in the strait [11].

Around the LHB, on the other hand, local seismicity was previously reported for the dataset from 1987 to 2003 [4] (**Figure 10**). A total number of 17 seismicity were determined by a local network deployed at LHB. Majority events locate along the coast and northern edge of the continental shelf, which almost coincide with the edge of the fast sea-ice in LHB. According to the discussion in this chapter, several numbers of the local events could possibly be relatively large ice-quakes associated with sea-ice, iceberg, and glacier dynamics around the LHB. However, it should also be pointed out that several small to middle magnitude tectonic events could not be located accurately, since they have ambiguous arrivals in the waveforms recorded by the present station network, particularly around Antarctica.

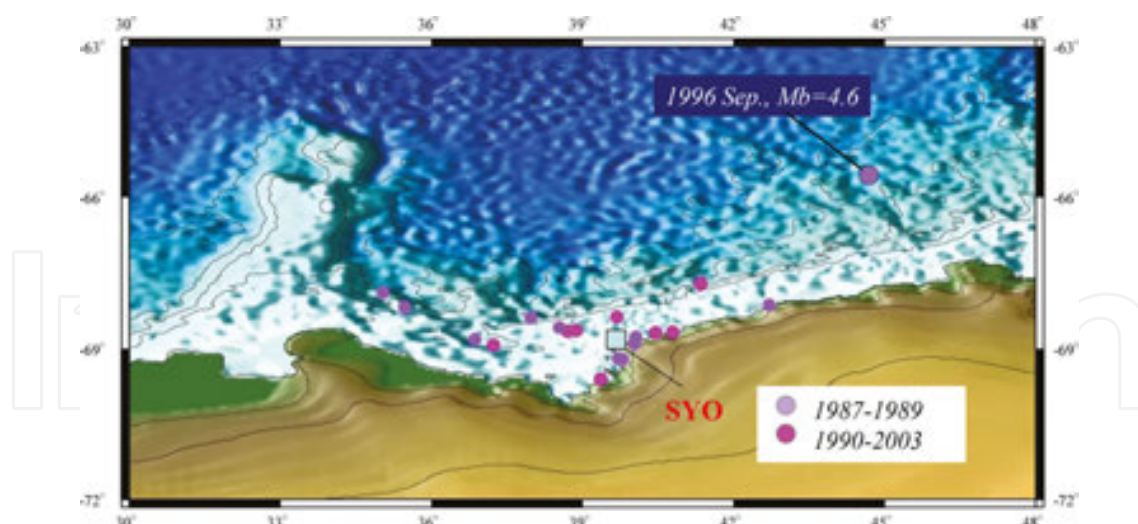


Figure 10. Local seismicity around LHB from 1987 to 2003 determined by local network (modified after [4]). It is noticed that the September 1996 $M_b = 4.6$ event in Indian Ocean was from United States Geological Survey (USGS).

Moreover, dynamics of the sea-ices (both fast-ices and pack-ices) around the Bay affect the occurrence of cryoseismic harmonic tremors. A large volume of fast sea-ice was discharged from LHB in 1997 austral winter, and the discharge event was clearly imaged by the National Oceanic and Atmospheric Administration (NOAA) satellite [20]. The broadband seismometer (STS-1) at SYO recorded significant harmonic overtones associated with the discharge events (**Figure 11**; [21]). At the time, a few tens of hours long tremors were strikingly observed. The long-duration nonlinear tremors had spectral characteristics that distinguished them clearly from teleseismic or local tectonic events. Several sequences of harmonic overtone signals, presumably associated with the merging of multiple ice volumes, appeared on the power spectral densities. Power spectral densities also represented surge events that seem more closely related to the breakup process of the sea-ice mass.

In contrast to long-duration and high-amplitude harmonic tremors treated in this chapter, relatively small and short-period tremors are also observed with duration times of few seconds to tens of few seconds. The events can be more clearly identified during the austral autumn, such as in October and November in 2014. They are estimated to have significantly near-field origins, such as by ice-shocks in relation to the sea-ice level changes in relation to oceanic tide variation in LHB. The opening of the tide-cracks when the sea-ice level decrease could generate the seismic shocks, which can be recorded only nearby the cracks. One week of dataset at SYO in late December season was already investigated by Kaminuma [22], which demonstrated a clear relationship between the tide level change and the occurrence of small ice-shocks. Recently, tide-modulated ice flow variations enhance the seismicity near the calving front of Bowdoin Glacier, Greenland in the Arctic [23]. Characteristics of these tide level relating events near SYO are expected to be examined more detail in future by precise and long-duration measurement, together with a combination to other physical observational parameters such as meteorological data surrounding the LHB.

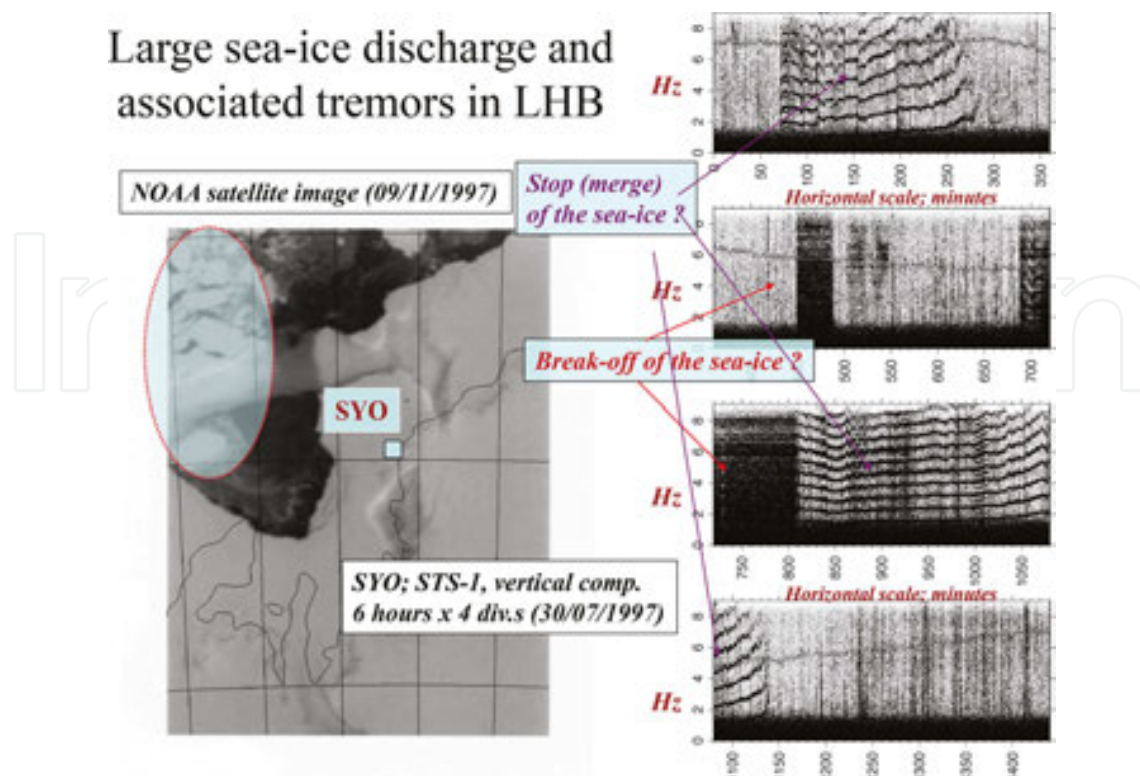


Figure 11. A large sea-ice discharged from LHB in 1997 austral winter (Modified after Ref. [21]). Left: NOAA image in 11 September 1997. The broken red circle with light-blue shading highlights the estimated residuals of the discharged sea-ice volume. Right: Power spectral densities of the broadband seismometer (STS-1) at SYO in 30 July 1997, in four successive time-periods of individual 6 h. Characteristic harmonic overtones were identified.

It is also noticed that the laming signals against the fast sea-ice in LHB by a huge ice-breaker vessel “Shirase” (weight of 11,000 ton) are clearly identified around 11–13 January 2015 within the analyzed period, when the vessel approached to the point very close to the SYO (within a few kilometer of distance). The laming signals hold frequency contents over few hertz with 10–15 min intervals. Identification of these sources generated by human activities has not yet been completed in methodology; therefore, theoretical modeling would most likely be required in order to explain physical processes of the source mechanism.

5. Conclusion

In summary, characteristic features of seismic harmonic tremors recorded at LHB, East Antarctica are demonstrated for the period from October 2014 to March 2015. A few tens of tremors ($N = 81$) are recognized in both the short-period and broadband seismographs at SYO. The characteristic tremors with harmonic overtones can be explained by a repetitive source, suggesting existence of several interglacial asperities. It implies that the tremors might be involved in local origins, presumably be the dynamics of cryosphere; that is, the discharge of fast-ice from the Bay, collision of icebergs and fast-ices, calving of glaciers, etc. The strong harmonic tremors with frequency overtones in LHB could mostly be generated by collisions

between icebergs and the edge of the fast sea-ice, on the basis of comparison with satellite image data.

The seismic tremors in terms of cryosphere dynamics, therefore, are likely to be associated with variations in surface environments in the Antarctic, and continuous monitoring of their time-space variability provides indirect evidence of climate change. There are still a lot to be learned about physical mechanisms of the harmonic tremors and interactive procedure between cryosphere and the solid earth in polar region. Continuous observation by a sufficiently large number of high-quality stations, as well as theoretical work, will probably be necessary to make progress in this new branch of interdisciplinary science "Cryoseismology." Given the high cost and technical difficulties of continuous observation in polar region, such works require successive international collaboration beyond the International Polar Year.

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