Background atmospheric acoustic waves from 0.01 to 0.1 Hz

K. Nishida(1), Y. Fukao (2), S. Watada (1), N. Kobayashi(3)

(1)Earthquake Research Inst., Univ. of Tokyo, Japapn

(2)IFREE, JAMSTEC, Japan

(3)Earth and Planetary Sciences, Tokyo Inst. of Tech., Japan

Abstract

Recently some groups reported Earth's background free oscillations even on seismically quiet days. Statistical features of them and annual variations of their amplitudes suggest that atmospheric disturbance is the most probable excitation source for this phenomenon. If the atmospheric excitation mechanism is effective, atmospheric acoustic free oscillations must be also excited persistently. In fact there is evidence of acoustic resonance between seismic free oscillations and the atmospheric acoustic free oscillations at around 3.7 and 4.4 mHz but there is no direct observation of them. In attempt to detect the long period acoustic waves, we installed a cross array of barometers in a 10 km–wide University Forest in Central Honshu from 2002 to 2004. The array has 28 micro–barometers employing quartz crystal resonator technology with station spacing of about 500 m. We analyzed 1-second continuous sampling records in a time period. Acoustic waves traveled from around northwest direction from 0.01 to 0.1 Hz with phase velocity of about 400 m/s at 0.1 Hz and about 800m/s at 0.01. These waves are often associated with mountain region. Our array size is still not large enough to detect the expected acoustic free oscillations at around 3.7 and 4.4 mHz. For the detection, we have developed more precision barometers and network data collection system for expansion of the array. Now we have started test observation at 8 stations.

1 Introduction

It has long been believed that only large earthquakes excite free oscillations of the solid Earth. Recently, however, a few groups reported Earth's background free oscillations even on seismically quiet days [15] [21] [11]. The excited modes are

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almost exclusively fundamental spheroidal modes, and they fluctuate persistently in little correlation with their neighboring modes [17]. These features suggest that the background free oscillations are excited incessantly by random disturbances globally distributed near the Earth' surface [17]. The intensities of these modes clearly show annual variations with a peak in July [18]. The observed amplitudes of some modes are anomalously large relative to the adjacent modes [18]. These are the modes that are theoretically expected to be coupled with the acoustic modes of the atmospheric free oscillations [23]. All of these features suggest that atmospheric disturbance is one of the most likely excitation sources of this phenomenon [17][18].

The aim of our installation is to find barometric evidence of background atmospheric acoustic free oscillations that must be excited persistently if the atmospheric excitation mechanism is effective. However, all of the past studies have been based on seismic observations and there are no direct comparable barometric observations. With the above aim we started a cross array observation of barometers.

2   An array observation from 2002 to 2004

2.1   Data and Instruments

The barometer system used in this study is composed of a pressure transducer, a data logger with a compact flash card, and a Quad-Disc static pressure probe designed to reduce undesired effects of dynamic pressure fluctuations [20]. High resolution observation of absolute atmospheric pressure is required to detect acoustic waves often hidden in the atmospheric turbulence of higher amplitudes. Low electric power consumption is also an important requirement because no power supply is available in our observation. These requirements are satisfied by an absolute pressure sensor employing quartz crystal resonator technology [16].

For a sampling interval of 1 sec, the practical resolution is then limited roughly to 0.1 Pa. The 1–sec continuous sampling records of pressure-related count numbers and temperature-related count numbers are written in a compact flash card. Upon recovery of the flash cards from the array, the pressure-related count numbers are converted into the absolute values of pressure compensated by the corresponding temperature-related count numbers.

We installed a cross array of these barometers in a 10 km–wide forest of the University of Tokyo in Chiba, which is expected to reduce dynamic pressure due to winds especially in a trough. The forest is located in the southern part of the Boso Peninsula, which is about 100 km southeast of Tokyo (Fig. 1: left). The Boso Peninsula has mild coastal weather with warm temperatures (the annual

mean temperature is around 14°C) and plenty of rainfall throughout a whole year (the annual precipitation is around 2000 mm) although their climate differs with changes in distance from the coast and in elevation. The forest belongs mostly to a warm-temperate, broad-leaved evergreen forest zone. The array has 28 micro–barometers with a station spacing of about 500 m. The left figure shows the locations of barometers used in this study. The cross array is composed of two linear arrays, the Goudai array and the Ippaimizu array. The Goudai array was installed in March 2002, which consists of 19 barometers in the NWN-SES direction. The Ippaimizu array was installed in September 2002, that has 7 barometers in the ENE-WSW direction. We also installed two barometers at Sengoku station in March 2002. In the present paper we use the records from the beginning to May 2004.
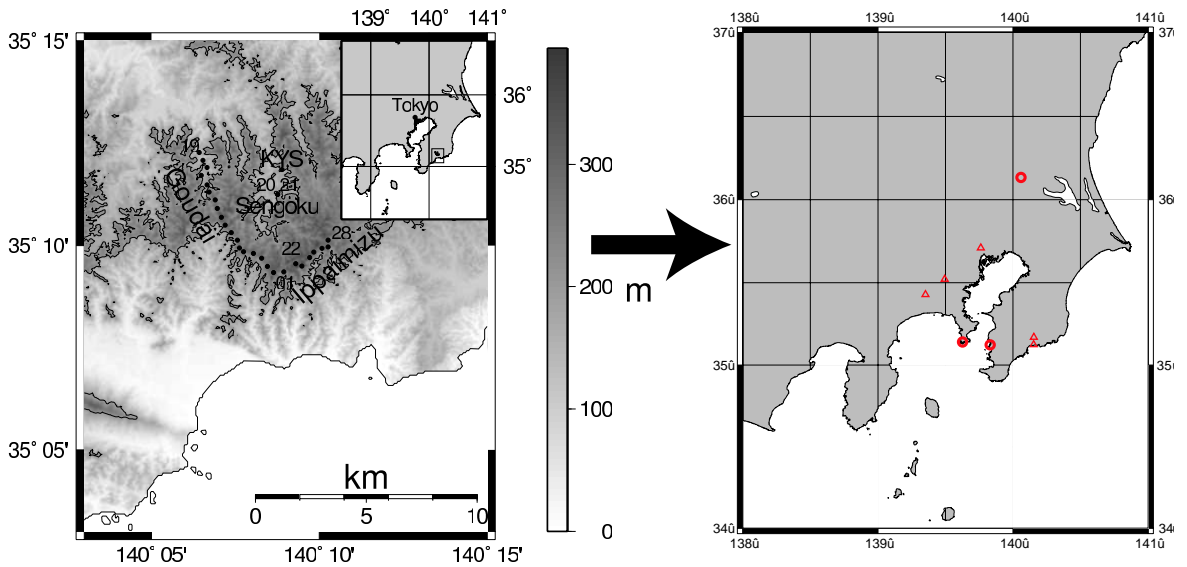

Figure 1: Left: location map of 28 barometers of the cross array. The array is composed of two linear arrays: (1) The Goudai array and (2) The Ippaimizu array. We also installed two barometers at Sengoku. Right: location map of 8 stations of a new observation. At three stations of broad band seismometers (circles) we installed new barometers.

2.2 Frequency–slowness spectra of background acoustic waves from 0.01 to 0.1 Hz

In order to determine temporal variations of their incident azimuths and amplitudes, we calculate two-dimensional frequency–slowness spectra [16], using the

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Goudai array and Ippaimizu array. Fig. 2 and 3 shows resultant temporal variations of 15 days average from April 2002 to May 2004. The left figure shows integration of frequency–slowness spectra from 0.02 to 0.03 Hz, and the right one shows that from 0.04 to 0.05 Hz. Most spectra show background acoustic waves traveling from northwest or west. The difference in spectral sharpness before and after 255/2002 can be explained by the difference in array response functions before and after the installation (15/09/2002) of the Ippaimizu array. In a time period of weak amplitudes of background acoustic waves from 140/2003 to 240/2003, we can also observed background acoustic waves traveling from southeast. The spectral maximum indicated by an open circle in each diagram does not show a significant temporal variation of incident angle of the acoustic waves within the error of slowness vector determination which is quite different before and after 255/2002. We calculate the rms amplitude of the acoustic wave signals [16]. This rms amplitude shows clearly an annual variation as in lower figures, with the minima around 3×10^{-3} Pa in summer and the maxima around 7×10^{-3} Pa in winter.

2.3   Dispersion curves of the background atmospheric waves

We have not detected acoustic waves below 0.02 Hz where the array response function is too broad in the slowness domain to identify their possible existence. However, with a strong assumption of unidirectional propagation of stochastic stationary waves [16], we could obtain a dispersion curve even below 0.02 Hz.

Fig. 4 plots the resultant phase velocity of the observed atmospheric waves with its solution error as a function of frequency. The phase velocity curves of gravity waves and microbaroms do not show significant dispersions, while the phase velocity curve of long-period acoustic waves exhibits a clear normal dispersion: the phase velocity is about 400 m/s at about 0.1 Hz and reaches about 800 m/s at 0.01 Hz.

The observed acoustic waves could be either internal waves or boundary waves trapped near the Earth's surface known as Lamb waves. Lamb waves are hydrostatically balanced in the vertical direction and propagates in horizontal direction around the Earth's surface. The phase speed of Lamb wave is known to be around 300 m/s [13]. The phase velocities of all the observed acoustic waves are faster than 350 m/s, so they are unlikely to be Lamb waves. Hereafter we regard the observed acoustic waves as internal waves.

Phase velocities of the observed acoustic waves at frequencies from 0.01 to 0.1 Hz are faster than 400 m/s so that they are most likely to be refracted in the stratopause (the boundary between the stratosphere and the mesosphere) or the thermosphere [5]. The dispersion characteristics of long-period acoustic waves may be explained by the frequency dependence of incident angle. Higher-frequency
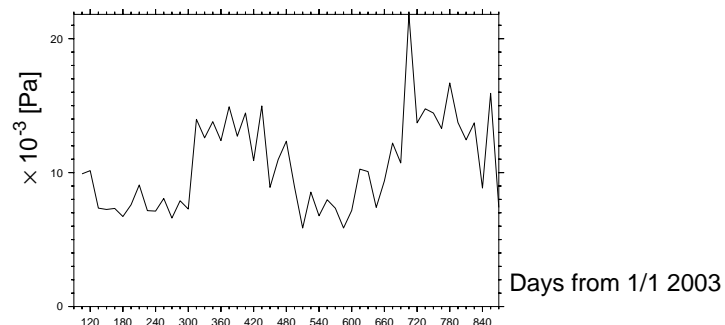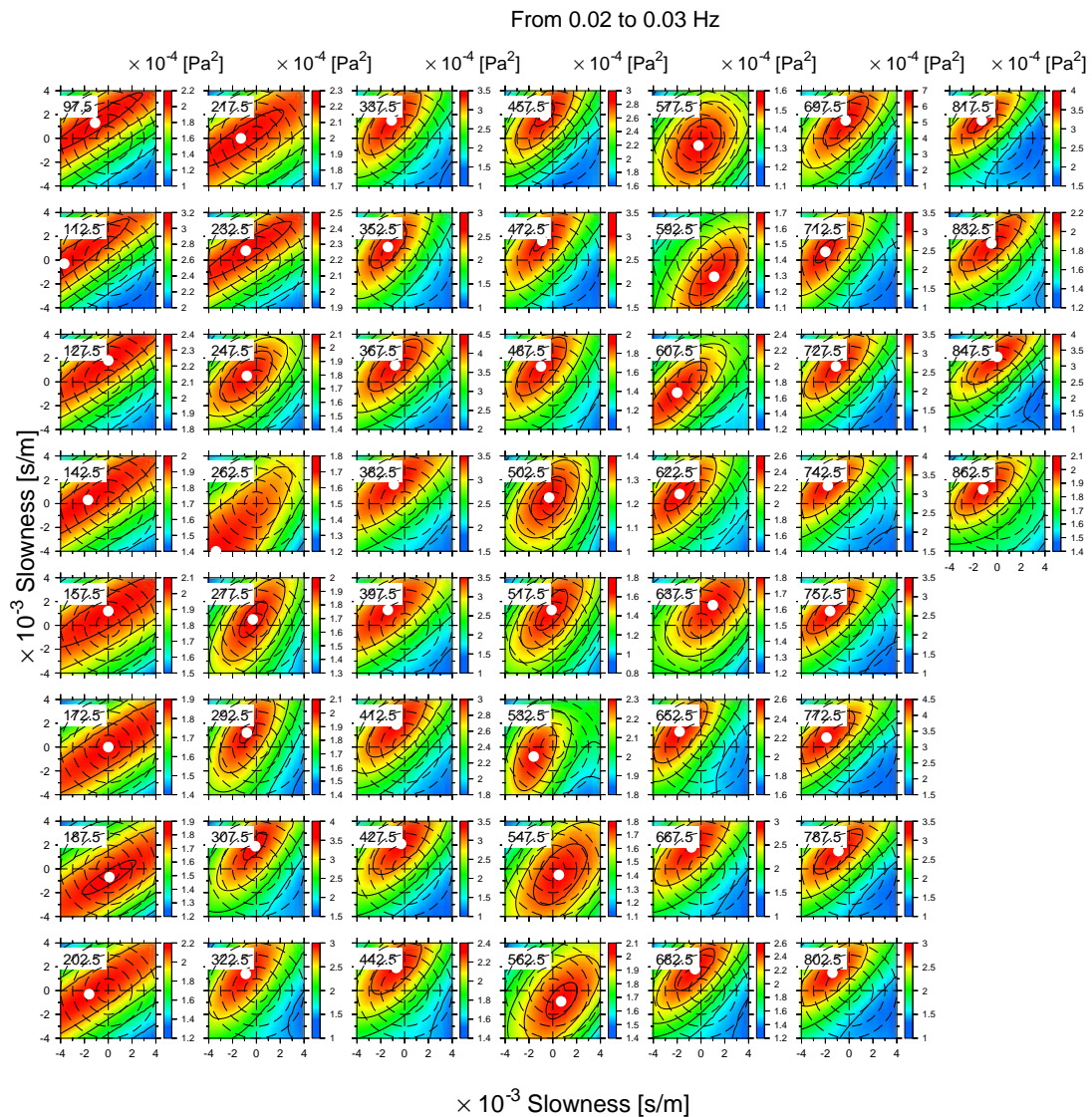
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From 0.02 to 0.03 Hz
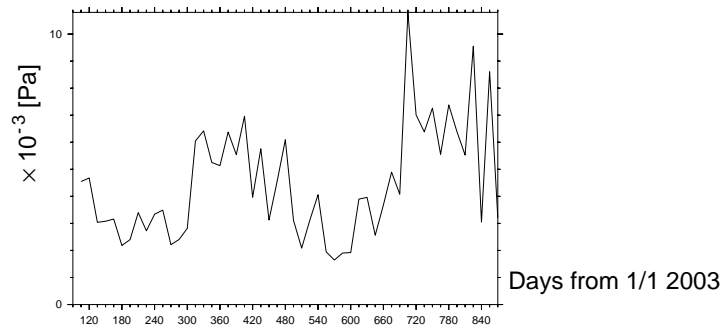

Figure 2: Temporal variation of 15 days average from April 2002 to May 2004. The left figure shows integration of frequency–slowness spectra from 0.02 to 0.03 Hz. White open circles indicate a phase velocity of about 500 m/s for these waves. Temporal variation of the amplitude of acoustic waves with the slowness vector given by small open circles in upper figure.
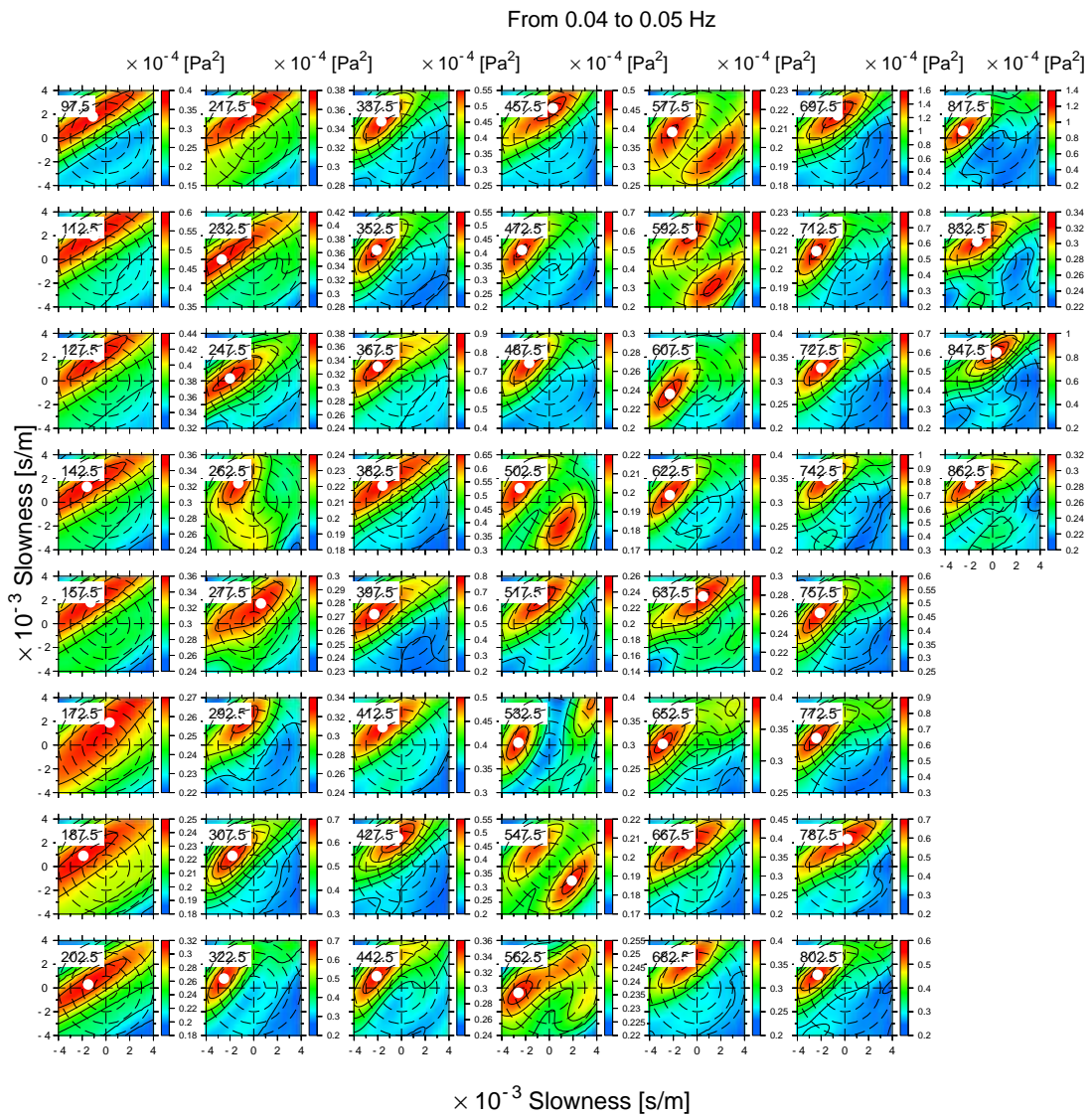
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From 0.04 to 0.05 Hz

Figure 3: Temporal variation of 15 days average from April 2002 to May 2004. The left figure shows integration of frequency–slowness spectra from 0.04 to 0.05 Hz. White open circles indicate a phase velocity of about 500 m/s for these waves. Temporal variation of the amplitude of acoustic waves with the slowness vector given by small open circles in upper figure.
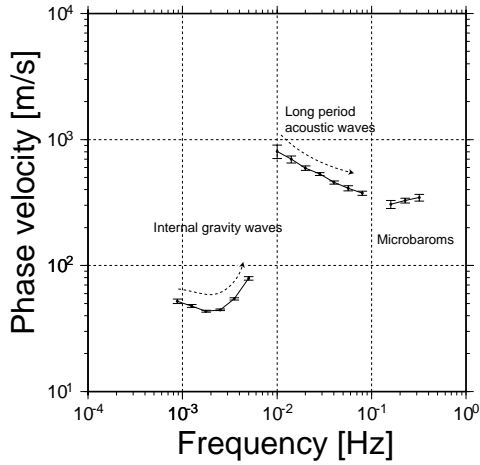
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Figure 4: Measured phase velocity with its solution error as a function of frequency from September 2003 to May 2003.

acoustic waves are radiated with lower angles from the ground and bounce in the stratopause to reach stations with lower angles and hence with lower horizontal phase velocities. On the other hand, lower-frequency acoustic waves are radiated with higher angles from the ground and undergone steep reflection in the thermosphere to reach stations with higher angles and hence with higher phase velocities.

When a source near the Earth's surface radiates internal acoustic waves refracted in the stratopause or the thermosphere, they cannot reach the Earth's surface over a certain distance range corresponding to the shadow zone. The zone typically starts about $50 \sim 100$ km from the source and extends out to about 175 ~ 200 km [5] [6]. In regions at middle and high latitudes, especially in winter, acoustic waves can travel eastward even in the shadow zone because tropospheric jet streams refract the acoustic waves in the troposphere [4]. However their horizontal apparent phase velocity of about 330 m/s [5] would be too slow to explain the phase velocities of the observed acoustic waves from 0.01 to 0.1 Hz in terms of the tropospheric refraction. We suggest that the excitation sources are either more than about 200 km far away from the array or within about 50 km if they are located near the Earth's surface.

2.4 Possible excitation mechanisms of the background atmospheric acoustic waves from 0.01 to 0.1 Hz

We discuss two possible excitation mechanisms of the observed acoustic waves from 0.01 to 0.1 Hz. The first mechanism is the excitation by severe weather [8], which has been proposed through the two kinds of observations. One is the

observation of infrasonic waves in a frequency range from 0.03 to 0.07 Hz with amplitudes of about 0.05 Pa recorded on ground barometers in a stormy period [7]. Another one is the observation of acoustic waves around 3.7 and 4.4 mHz detected as ionospheric waves by ground-based sounders associated with severe convective storms [9]. Georges (1973) suggested that both waves are different manifestations in different parts of the acoustic spectrum of the same emission mechanism. With this mechanism significant temporal changes of incident azimuths of acoustic waves in accordance with the motion of storm systems could be anticipated, yet our observation does not show such changes. We also find little correlation between the observed acoustic amplitudes and the storm activities. Severe weather is unlikely to be a dominant source for the long-period acoustic waves we observed.

The second mechanism is the aerodynamic excitation by atmospheric turbulence in mountain regions [1]. Turbulence on a curved boundary (mountain regions) excites a dipole field of acoustic waves [3], a mechanism more effective than a quadrapole field exited by turbulence on a plane boundary [12]. The observed mountain-associated infrasonic waves have several common features [1]: (1) wave periods from 30 to 70 s, (2) duration longer than 3 hours with amplitudes of about 0.05 Pa at a distance of 400 km [2], (3) fixed azimuths of arrivals from definite directions, (4) a strong tendency to be observed during winter months, and (5) group velocity of $325 \sim 425$ m/s. These features are consistent with our observations, suggesting that atmospheric disturbance in the mountain regions is the most likely source of the observed acoustic waves. If this mechanism is dominant, excitation sources in the mountain regions are about 200 km apart from our array in the west or northwest directions.

3   New observation for detection of background acoustic waves at 3.7 mHz and 4.4 mHz

We cannot detect background acoustic waves below 0.01 Hz using the above data set. The array size is still not large enough to detect background atmospheric acoustic waves possibly excited by the same sources as for the Earth's background free oscillations. In order to detect the oscillations, we expand the array (~ 10 km) to a larger scale (~ 100 km) this year. Fig. 1 shows location map of stations of an old array and those of a new array. We have installed barometers at three observatories, three stations of University and two stations of the University forest.For this observation we made a new data acquisition system via internet by a Linux box. The system time of the Linux box is synchronized with GPS. We show the block diagram of data acquisition in Fig. 5. Data acquisition is now underway.
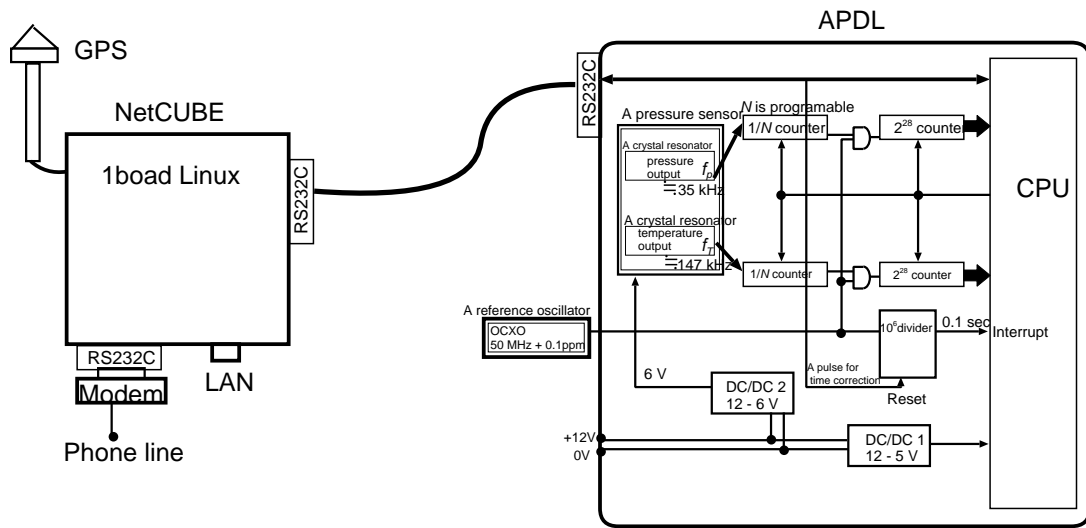
Figure 5: Block diagram of the observational system.

We also modify resolution of barometers (APDL in Fig.5). The pressure sensor measures atmospheric pressure using a precision quarts crystal resonator whose oscillation frequency of about 35 kHz is sensitive to pressure-induced stress. The guaranteed sensor accuracy and resolution are 0.01 % of reading and 10^{-8} of the full scale range, respectively. Sensor pulses are sent into the $1/N$ counter, where the gate opening and closing are synchronized with the onsets of the incoming 0-th pulse and N-th pulse, respectively. The integration time T from the gate opening to closing is measured by a high pression reference oscillator of 10 MHz in the case of past observation. The resonant period of a pressure sensor is then given by T/N with a measurement error of less than δt. Then frequency of the reference oscillator constrains resolution of this sensor. Now we can use oven controlled crystal oscillator of 50 MHz because of availability of power consumption. This clock up make an improvement from resolution of 0.125 Pa to that of 0.025 Pa. Fig. 6 shows comparison between data of an old barometer and that of a new one. Left figure shows typical barographs. The upper barograph of an old sensor shows digits of data, whereas the lower figure of a new sensor shows clear waveform. Discretization error of an old sensor increases noise level, which is shown by power spectra in the right figure. Thus, these figures show improvement of resolution.
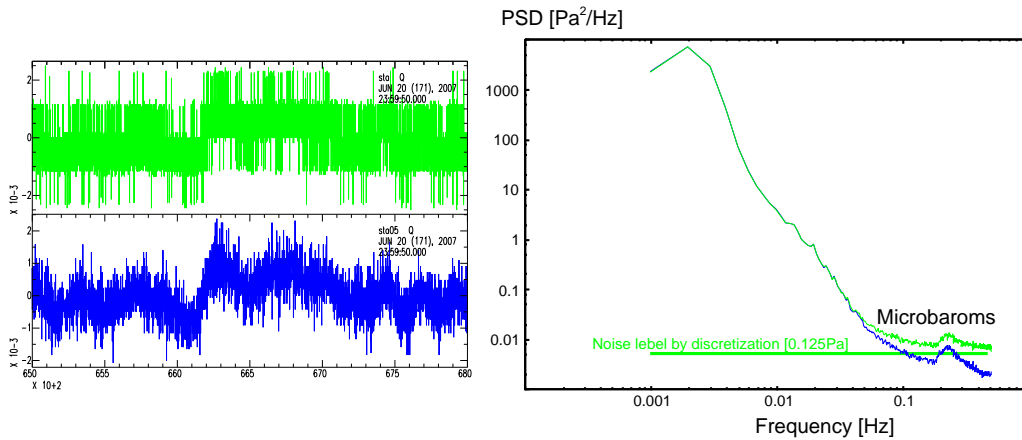
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Figure 6: Comparison between data of new system and data of old system.

4   Conclusions

We installed a cross array of about 30 barometers in the university forest. A special care of system designing was taken for accurate measurement of resonant frequency of a pressure-sensitive quartz resonator. The one-year records of the cross array were analyzed to calculate two-dimensional frequency–slowness spectra and to measure dispersion of atmospheric acoustic waves with an assumption of stochastic stationary plane waves. The analyses showed background acoustic waves traveling from northwest with a frequency-dependent phase velocity of 400 m/s at 0.1 Hz and 800 m/s at 0.01 Hz, which are interpreted as internal acoustic waves refracted in the stratopause and the thermosphere from distant sources more than 200 km away from the array. The observed features of infrasounds are consistent with those of mountain-associated waves but we still did not detect background atmospheric acoustic waves at 3.7 mHz and 4.4 mHz. In order to detect the background acoustic waves, we develop new barometers of higher resolution. In this year we expand the array ($\sim$ 10 km) to a larger scale ($\sim$ 100 km) this, now we are collecting data.

Acknowledgments

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