

## Portable infrasound monitoring device with multiple MEMS pressure sensors

Ryouichi NISHIMURA<sup>(1)</sup>, Zhenglie CUI<sup>(2)</sup>, Yôiti SUZUKI<sup>(2)</sup>

<sup>(1)</sup>Resilient ICT Research Center, National Institute of Information and Communications Technology, Japan, ryou@nict.go.jp

<sup>(2)</sup>Research Institute of Electrical Communication, Tohoku University, Japan, {sai@ais.,yoh@}riec.tohoku.ac.jp

### Abstract

Microelectromechanical system (MEMS) sensors are mass-produced and are therefore expected to be available to produce low-cost devices for infrasound monitoring. A low-cost device is useful in constructing a sensor network with various scales of a few to numerous sensors. To test its feasibility, we developed a device consisting of 32 MEMS barometric pressure sensors. A laboratory experiment revealed that internal noise increases as a signal frequency increases, but the noise can be reduced by simple averaging. Based on this fact, we stacked eight MEMS barometric pressure sensors on a single board to assemble an infrasound monitoring device that enables detection of a signal with amplitude of more than approximately 5 Pa. A field test was conducted, deploying them in areas surrounding an active volcano, Sakurajima in Japan. Signals associated with explosive eruptions were observed clearly in the frequency region of 0.1–5 Hz. The source position was also estimated using signals obtained at four observation points. The estimated source position showed generally good agreement with that of the volcano crater. Results confirmed that signals around the acoustic cut-off frequency can be obtained by the device.

Keywords: Infrasound, MEMS sensor, source localization

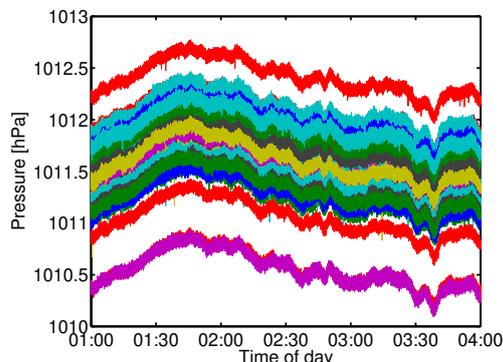
## 1 INTRODUCTION

Natural disasters all over the world have recently become frequent and devastating. Such disasters pose increasing threats to human life because they have devastating power and could damage wide areas. Monitoring meteorological conditions related to potential disasters is a promising method to mitigate resultant damage caused by disasters. Infrasound is known to be generated often when a strong geographical or meteorological event occurs on the earth [1]. Therefore, monitoring infrasound is useful to detect natural events that occur in remote areas because infrasound propagates long distances in the atmosphere. In fact, Arai et al. reported that infrasound signals were recorded at some inland observation points in Japan before large *tsunami* waves struck the northeast coasts of Japan at the 2011 Tohoku earthquake [2]. One observation point was approximately 270 km distant from the trench-axis side of the sub-fault, with the largest slip estimated by Fujii et al. [3]. The peak-to-peak amplitude of the infrasound signal received at the observation point was 64 Pa. Another observation point was IS30 (Infrasound Station of CTBTO), which was 430 km distant, where an infrasound signal with amplitude of 21–28 Pa was recorded. Le Pichon et al. also reported that infrasound signals associated with *tsunami* waves were recorded after the 2004–2005 large Sumatra earthquakes [4]. Considering these facts and their potential usefulness, infrasound monitoring continues to draw attention in many global research areas [5].

We are considering the use of infrasound especially for the early detection of natural events such as *tsunami* waves or explosive eruptions of volcanoes. It is desirable to distribute as many infrasound sensors as possible in such an application so that they can cover all the areas to be protected. The higher the resolution becomes with respect to both time and space, the better it is for the early detection of events occurring in an unknown remote area. However, dense monitoring is currently difficult to achieve because infrasound monitoring facilities need special equipment and thus expensive. For example, a microbarometer or a set of microphones for infrasound measurement, which has a precision of less than 1 Pa, costs approximately ten thousand US dollars in Japan. To circumvent this issue, we developed a measurement device for infrasound monitoring which can be produced



(a) Top view of the experimental device without cover.



(b) Raw data captured by 32 MEMS pressure sensors.

Figure 1. Experimental infrasound measurement device with multiple MEMS sensors.

at modest cost, especially anticipating its application to infrasound monitoring for the early detection of natural events that pose risks of disaster. We then evaluated the performance of the developed device using field tests and laboratory tests.

## 2 DEVELOPMENT OF AN INFRASOUND MEASUREMENT DEVICE

### 2.1 Experiment device

Microelectromechanical systems (MEMS) technology has made it possible to make smart and extremely compact sensors. In our daily lives, MEMS sensors are now pervasive. Partly because of that, they are available at low cost. In fact, on some smartphone models, a MEMS barometric pressure sensor is included together with other sensors to realize various smart functionalities on the telephone. Accordingly, some attempts have been made to use smartphones to monitor infrasound [6, 7]. Our earlier study found that a single MEMS barometric pressure sensor could not achieve satisfactory precision for monitoring infrasound that we particularly examine herein, such as that associated with a volcanic eruption or a *tsunami* [8]. Considering the infrasound wavelength is sufficiently long compared with human-audible sound, displacement of sensors by some centimeters can be ignored. Therefore, we first developed an experimental measurement device that consists of a single-board microcomputer, Raspberry Pi 3, combined with 32 MEMS barometric pressure sensors (BME280; Bosch GmbH). The host computer gathers sensor data using a serial peripheral interface (SPI). The experimental measurement device was manufactured by Toho Mercantile Co., Ltd. The top view of the developed experimental device is portrayed in Fig. 1(a). When multiple sensors are used simultaneously, data are first read sequentially from the memory of each sensor. They are then averaged and stored in the host computer.

A preliminary test was conducted to elucidate effects of using multiple sensors simultaneously. The experimental measurement device was placed on a desk in a meeting room on the fourth floor of the research institute. The building is located between downtown Sendai, Japan and its suburbs 10 km inland in a straight line from the Pacific coast. The device continuously records the pressure signal during a winter night. It has no function to take samples at precise constant intervals based on some reference clock signal. Therefore, the time information of each sampling was also recorded in UNIX time format. According to this information, the most frequent value of the sampling interval was 3.9 ms, i.e., 256 Hz, but sometimes with shorter or larger intervals. The empirical cumulative function of the sampling intervals indicates that approximately 80% of them were shorter than 5 ms and that more than 99% were shorter than 5.5 ms. Therefore, the observed data were resampled at a sampling rate of 200 Hz using the recorded time information with linear interpolation. Raw data accumulated

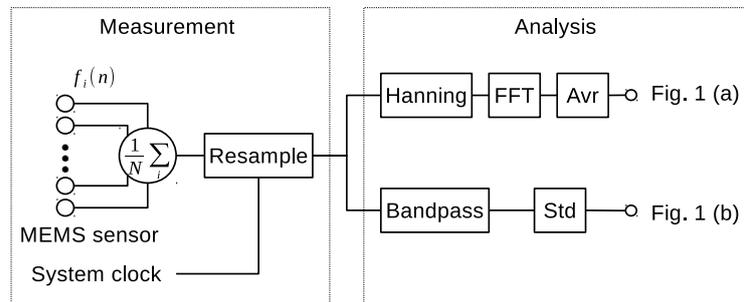


Figure 2. Block diagram of the measurement and analysis.

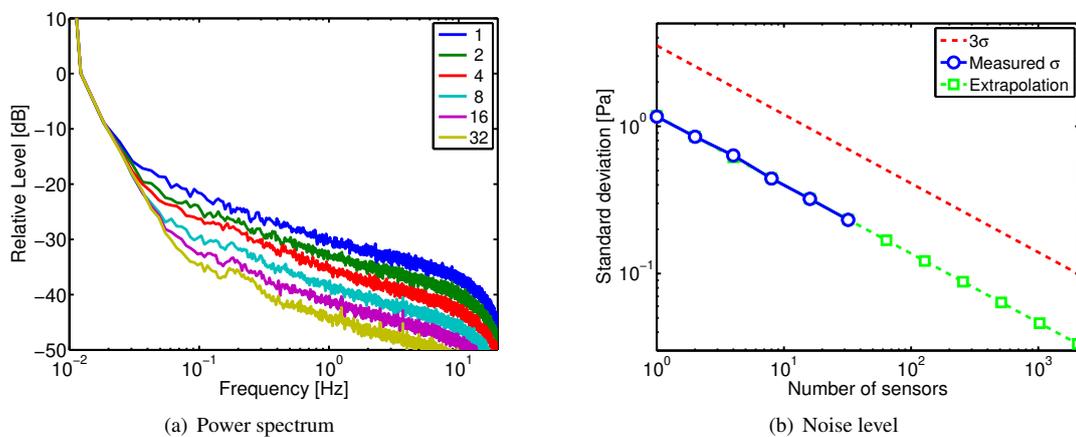


Figure 3. Effects of using multiple MEMS pressure sensors for infrasound measurement.

by each MEMS pressure sensor are shown in Fig. 1(b). As this figure shows, they have a considerable variance in their direct current components.

## 2.2 Data analysis

A block diagram of the whole analysis process is depicted in Fig. 2. Data recorded between 1:00 am and 4:00 am in the night were used for the analysis because it is expected that artificial noise is at the lowest level of the day. The extracted data were segmented into frames of 32,768 points with 50% overlap using a Hanning window. Frequency analysis was applied to each frame and then accumulated to derive the mean power spectrum of the data, which can be regarded as the mean power spectrum of ambient noise in the night. The total number of frames was 130. The number of MEMS pressure sensors involved in the measurement was varied: 1, 2, 4, 8, 16, and 32. The results are presented in Fig. 3(a). As this figure shows, the level of the power spectrum decreases as the number of involved MEMS sensors increases. Results suggest that uncorrelated system noise exists and that its remaining power can be reduced by arithmetic mean operation using multiple MEMS sensors. An increase near 0.2 Hz visible in the results of 32 MEMS sensors can be regarded as microbaroms.

This figure also implies that the spectrum curves are more or less parallel at frequencies above 0.2 Hz. The system noise can be regarded as dominant in this frequency region. Therefore, the noise level was evaluated quantitatively, assuming that the standard deviation of the signal extracted using a band-pass filter corresponding to this frequency band can be regarded as system noise. The cutoff frequency of the band-pass filter was set as

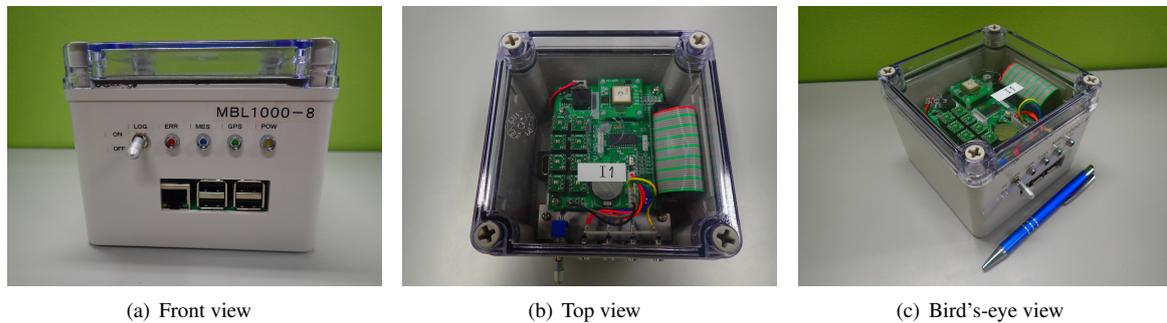


Figure 4. Appearance of the developed infrasound measurement device.

0.2 Hz for the lower side and 5 Hz for the higher side to exclude ambient noise effects. Actual measurements were taken by up to 32 MEMS sensors and extended to 1024 sensors using linear extrapolation based on the least squared error. The results are presented in Fig. 3(b), where the red dashed line represents  $3\sigma$ , which is regarded as the threshold level of a detectable signal in a noisy environment whose noise level is  $\sigma$ . Based on this result, eight MEMS sensors will be necessary to detect an infrasound signal having amplitude of approximately one pascal. Considering this finding obtained using the investigation with the experimental measurement device, we decided to use eight MEMS sensors to build an infrasound measurement device.

### 2.3 Developed infrasound measurement device

The shape of the developed device is presented in Fig. 4. An air inlet and a connector for the power supply are placed on the rear of the device. The box, which is 12 cm wide and deep and 10 cm high, consists of eight MEMS sensors (BME280; Bosch GmbH) combined with a single-board microcomputer (Raspberry Pi 3) and other IC chips. A global positioning system (GPS) module is mounted on the device for time correction. Sensor data are gathered at a sampling rate of approximately 85 Hz. The obtained data are resampled at a sampling rate of 40 Hz as post-processing to produce a set of data sampled at an equal interval. This resampling process was applied to the pooled data acquired by all measurement devices to make the sampling times equal among them. According to the BME280 specifications, it has a function to improve signal-to-noise ratio by averaging consecutive multiple samples at the sacrifice of sampling rate. Combining this function, one sample datum is obtained by averaging over four temporary consecutive samples using the function of each sensor and then averaging over all eight sensors on each device. Times of the devices are synchronized using GPS signals captured by the GPS module or using Network Time Protocol (NTP) over the internet, depending on the circumstances of the observation point. The time adjustment accuracy depends on the network condition when NTP is used. In a wired network, synchronization with an upper server is possible with an offset of less than a few milliseconds. If it is in a wireless environment, then the offset can increase by a digit, according to our preliminary test.

## 3 APPLICATION TO INFRASOUND MEASUREMENT

### 3.1 Field test setup

A field test was conducted using the developed infrasound measurement device. The objective of the test includes evaluation of practicality, usability, and endurance as well as acquisition of actual data for the following study of sound source localization. For the field test, the developed infrasound monitoring devices are distributed around an active volcano within 20 km distance to record infrasound generated by an explosive volcanic eruption. Sakurajima, an active volcano in Japan, is located in the southernmost part of Kyushu Island. Four devices were distributed as shown in Fig. 5. Information related to the four observation sites is presented in Table 1.

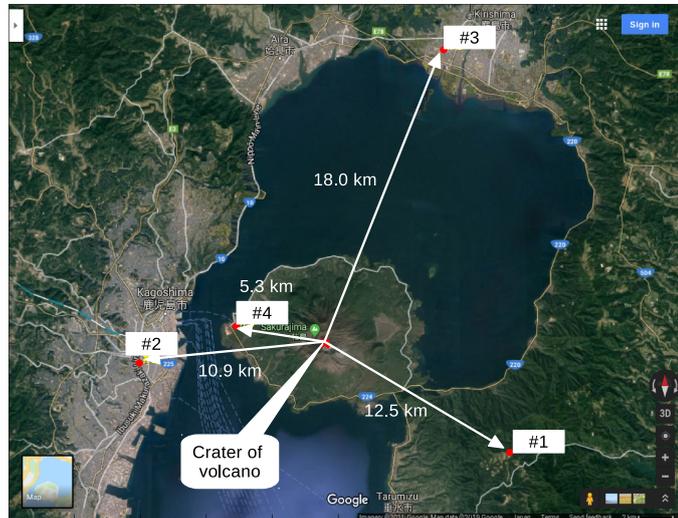


Figure 5. Placement of the measurement devices.

Time synchronization is realized using GPS on the device at Site #2 and NTP over a Long-Term Evolution

Table 1. Information for the four measurement sites

Site	Distance [km]	Device location	Time adjustment
#1	12.5	In the woods	NTP
#2	10.9	On top of a four-story building	NTP
#3	5.3	On top of a three-story building	GPS
#4	18.0	On top of a four-story building	NTP

(LTE) network at other sites. Each infrasound measurement device maintains continuous recording and periodically sends acquired data to the server to avoid data overflow of storage inside the device.

The arrival time difference was measured based on cross-correlation of signals acquired by each pair of observation sites. Calculation of the cross-correlation was performed only for the 180 s time frame where an infrasound signal associated with explosive eruption of Sakurajima volcano was apparently included. Information about Sakurajima eruptions is available from the Japan Meteorological Agency. Before calculation of cross-correlation, the signal was filtered by a band-pass filter with cut-off frequency of 0.1 Hz for the lower side and 5 Hz for the higher side to examine the frequency band in which an infrasound signal of volcanic eruption has dominant power. For this calculation, the speed of sound was assumed as 340 m/s.

### 3.2 Sound source localization

An example of the signals recorded using the deployed devices is presented in Fig. 6(a). For comparison, each signal is shifted so that the mean values are separated by 50 Pa. The sound arrival time differs in accordance with differences of the travel distances. Many studies have examined sound localization: some have examined infrasound [9]; others have investigated usual human audible sound [10]. An estimate of the exact source position can be obtained by application of these methods. However, to ease comprehension of the contributions of

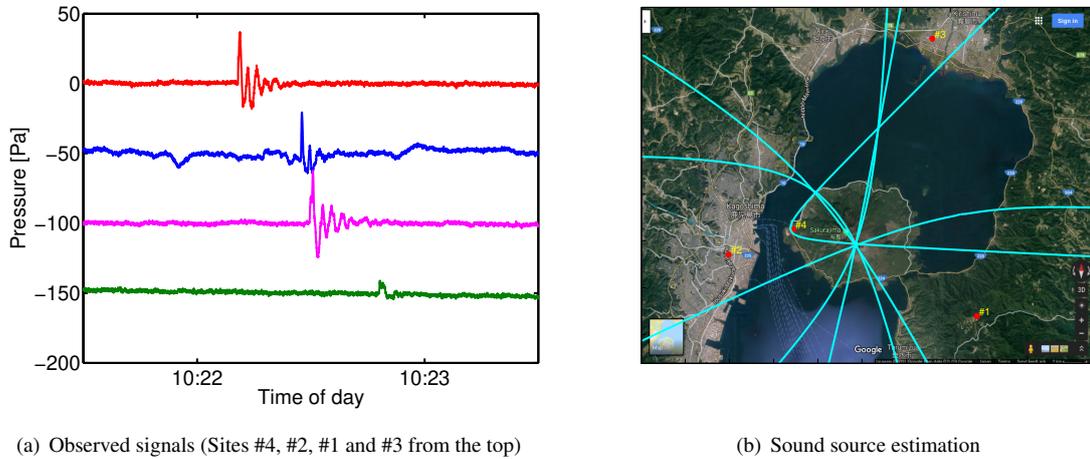


Figure 6. Source location estimation.

each sensor, we directly draw a hyperbola based on arrival time differences between pairs of sensors. Hyperbolae indicate equally distant places from a pair of devices. The canonical form of hyperbola on the x-y plane can be represented as

$$\frac{x^2}{a^2} - \frac{y^2}{b^2} = 1, \quad (1)$$

where  $(-a,0)$  and  $(a,0)$  are the intersection points on the x-axis and where  $(-\sqrt{a^2+b^2},0)$  and  $(\sqrt{a^2+b^2},0)$  are the foci. In our scenario,  $2a$  represents the distance that sound can travel in the time interval equivalent to the observed arrival time difference. Another parameter  $b$  is obtained such that the distance between the two measurement sites equals  $2\sqrt{a^2+b^2}$ . The intersection point of all the hyperbolae is regarded as an estimate of the source position. Results are presented in Fig. 6(b). As this figure shows, the source position is estimated using infrasound signals. Precision of the estimation depends on measurement conditions including wind and sound pressure level. If no disturbance exists, then all hyperbolae must intersect at a single point.

Assuming that infrasound measurement devices are placed on the coast, a source position more than a hundred kilometers distant from observation points is necessary for early warning of *tsunami* waves. Kuchinoerabujima Island is approximately 130 km distant from Sakurajima. Results for the eruption of the volcano located in Kuchinoerabujima Island are shown in Fig. 7. The estimated sound source position is not so far from the island. The epicenter of the 2011 Tohoku earthquake was estimated as 130 km distant from the coast. The distance of monitoring sensors from the sound source at Kuchinoerabujima Island is comparable to this distance. Sound pressure observed in this case is approximately 10 Pa peak-to-peak. This amplitude is smaller than that observed using a microbarometer placed in inland Japan when the 2011 Tohoku earthquake occurred. Therefore, the developed measurement device can be expected to be useful for monitoring infrasound associated with an event that might cause a natural disaster.

## 4 DISCUSSION

Wind is a loud noise that is invariably included in outdoor measurements. It has approximately the same frequency as infrasound. Therefore, separation of infrasound signals from wind noise is an important task for development of this method. A method based on the statistical characteristics of wind has been reported [7]. If multiple microphones are available, other methodologies can be applied to accumulate information from observation points that are mutually distant. Thereby, one can ascertain whether the signal is wind noise. Further investigation of this point must be undertaken in future works.

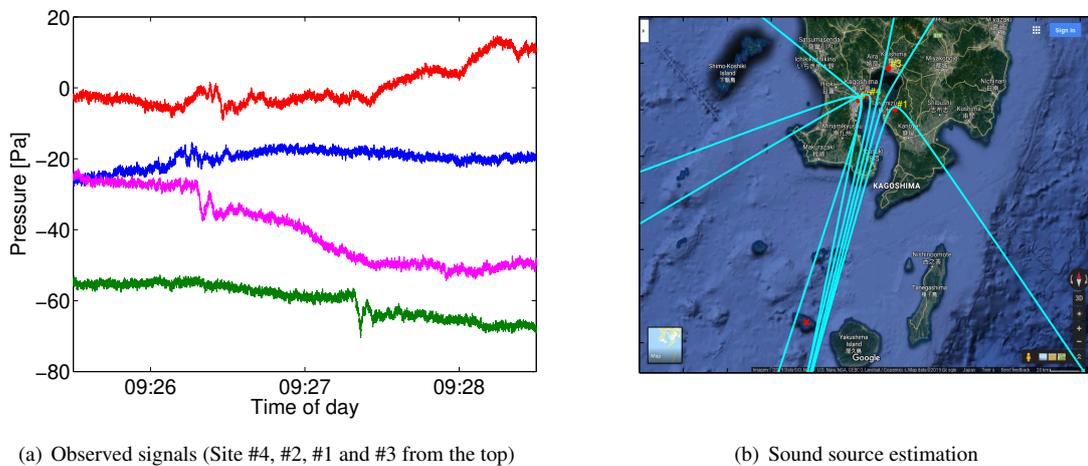


Figure 7. Estimation of a sound source distant from the sensors.

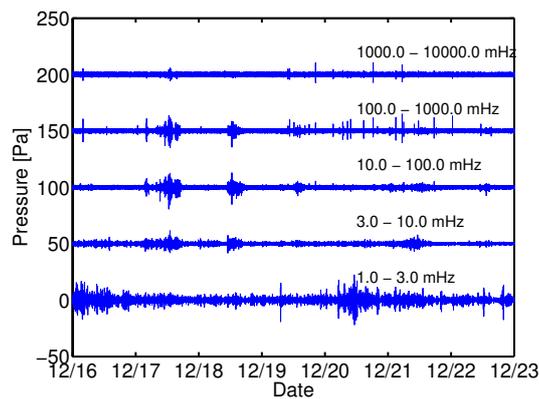


Figure 8. Frequency band decomposition of the signal recorded by the developed device.

Time synchronization among measuring devices is important especially because the arrival time difference is used for estimating the sound source position. As described above, the accuracy of time synchronization over wireless network is not good. For a wireless communication environment, a mobile network time protocol (MNTP) has been proposed to improve time synchronization performance [11]. Use of this technique might help when using GPS is difficult for some reason.

The frequency of infrasound generated by *tsunami* waves is reported as markedly lower than that of volcanic eruption. Figure 8 presents an example of the band-limited signals of the data acquired at Site #3. These signals are obtained through consecutive application of low-pass filtering and down-sampling. Spikes appearing in the two higher frequency bands are probably associated with volcanic eruptions. However, it seems that some signal exists in the lowest frequency band, although the signal origin is not clear.

## 5 CONCLUSIONS

We developed an infrasound measurement device combining MEMS barometric pressure sensors with a single-board microcomputer to make it available at a modest cost, aiming at a sensor network for infrasound mon-

itoring. Its practical usefulness was verified through a long-term operation test in which infrasound generated by volcanic eruptions was measured continuously in the field. Four devices distributed within 20 km around a volcano localized the estimated sound source to within a range of 1 km from the volcano crater, depending on the signal-to-noise ratio of observed signals. For its practical use in *tsunami* early warning systems, we expect that the developed device is capable of observing the generated infrasound with respect to the available range of sound source localization and detectable sound pressure of the signal. Estimation of sound source information using signal processing considering propagation characteristics specific to very low frequencies is a research topic in the future.

## ACKNOWLEDGEMENTS

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