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Home seismometer for earthquake early warning

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[1] The Japan Meteorological Agency (JMA) has started the practical service of Earthquake Early Warning (EEW) and a very dense deployment of receiving units is expected in the near future. The receiving/alarm unit of an EEW system is equipped with a CPU and memory and is on-line via the internet. By adding an inexpensive seismometer and A/D converter, this unit is transformed into a real-time seismic observatory, which we are calling a home seismometer. If the home seismometer is incorporated in the standard receiving unit of EEW, then the number of seismic observatories will be drastically increased. Since the background noise inside a house caused by human activity may be very large, we have developed specialized software for on-site warning using the home seismometer. We tested our software and found that our algorithm can correctly distinguish between noise and earthquakes for nearly all the events. **Citation:** Horiuchi, S., Y. Horiuchi, S. Yamamoto, H. Nakamura, C. Wu, P. A. Rydelek, and M. Kachi (2009), Home seismometer for earthquake early warning, *Geophys. Res. Lett.*, *36*, L00B04, doi:10.1029/2008GL036572.

1. Introduction

[2] It is pointed out that three great events, called the Tokai, Tonankai and Nankai earthquakes, of magnitude ~8.0 will occur near the most industrially developed areas in Japan. These destructive events will occur at areas along the subduction zone of the Philippine Sea Plate, and thus their locations are more than several tens of km away from metropolitan cities, such as Tokyo, Nagoya, Osaka, Kyoto, etc. Therefore, installation of an Earthquake Early Warning (EEW) system makes it possible for these cities to have a few to tens of seconds of warning time before the strong shaking from the S-wave arrives.

[3] An EEW system, called UrEDAS, was developed in the late 1980's by *Nakamura* [1988] for the railroads in Japan. More recently, *Odaka et al.* [2003] has developed an EEW system using a method similar to *Nakamura* [1988]. Other warning systems have been developed by *Espinosa-Aranda et al.* [1995] for Mexico City, and by *Wenzel et al.* [1999] for Bucharest, Romania. The recent installation of nation-wide dense seismic networks makes it now possible to develop an EEW covering a wide area, e.g., the system in Taiwan developed by *Teng et al.* [1997] and *Wu et al.* [1998, 2001].

[4] Japan developed an EEW using the Hi-net seismic network and started a practical service to issue an EEW, mainly owing to successful planning and implementation of a national research project devoted to EEW and its applications [*Horiuchi et al.*, 2005, 2007; *Yamamoto et al.*, 2008; *Motosaka et al.*, 2006] (http://www.bosai.go.jp/kenkyu/sokuji/index.htm).

[5] Because of limitations imposed by station spacing and the determination and transmission of earthquake source parameters in real-time, our automatic system cannot issue an EEW to areas within ~30 km of the earthquake's epicenter. It is estimated that about ~10 times the number of stations would be needed to issue an effective EEW near focal areas; however, this is cost prohibitive for government agencies.

[6] The practical service of the EEW in Japan was started on October 2007 and the receiving unit of EEW will soon be available to the general public for home/office installation. This warning unit, which contains a CPU and chip memory, is connected to the internet and receives real-time information regarding earthquake source parameters. The addition of an inexpensive seismometer and A/D converter would transform the receiver into a real-time seismic observatory, which we are calling a home seismometer; these additions are estimated to cost only about twenty dollars.

[7] The continual spread of home seismometers will provide an extremely dense network that will benefit not only EEW but many other seismological studies. The customer, however, is required to bear any additional costs and therefore the benefits of having a home seismometer must be emphasized. The major benefit is that a tuned house-specific warning may be worth the additional small cost; the present study develops the ability of on-site warning using the data from the home seismometer, which can even be installed at a noisy location inside the house.

2. Home Seismometer

[8] We have developed a home seismometer. The specifications of the MEMS sensor accelerometer are; 3 component; observation range, ±2000 Gal; sensitivity, 0.666 mv/Gal; and peak-to peak electrical noise, 3 Gal (vertical), 2 Gal (horizontal). The A/D converter has a resolution of 24 bits and can record 4 channels at 500 Hz.

[9] Upon receiving the EEW earthquake source parameters, the home seismometer can estimate the seismic intensity from an empirical relation between magnitude and shaking intensity [*Si and Midorikawa*, 1999] and will sound a voice alarm if the estimate is greater than a threshold level. We added the ability of an on-site warning to the above

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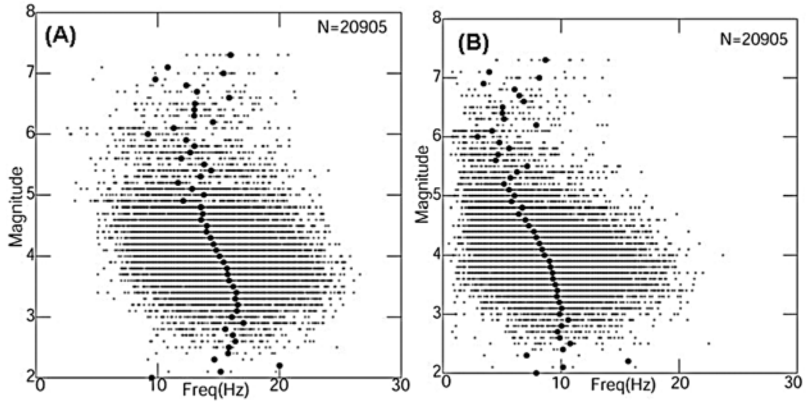

Figure 1. Plot of magnitude versus predominant frequency as determined from K-NET strong motion data. Predominant frequency is calculated by the amplitude ratio between (a) acceleration and jerk and (b) velocity and acceleration using 2-seconds of waveform data from the P-wave onset. Large circles are the average predominant frequencies in magnitude ranges of 0.1.

function. *Horiuchi et al.* [2005] developed an automatic processing system for the EEW, which is called REIS. REIS relies on the waveform data from the Hi-net array, which uses highly sensitive seismometers installed in bore-holes deeper than 100m to reduce ground noise. In comparison, a home seismometer is intended to be installed inside a house where there are high levels of background noise caused by daily household activities. Thus a special algorithm was developed that could discriminate between seismic events and noise background, which was based solely on the data obtained from the build-in seismometer.

3. Event Detection

[10] Figure 1 shows a plot of the predominant frequencies of P-waves versus earthquake magnitudes determined from the data of the strong-motion K-NET seismic network. We calculated predominant frequency, which is the reciprocal of average period, by applying equations similar to those used by *Wu and Kanamori* [2005] to two seconds of P-wave waveform data with hypocentral distance less than 50 km. Whereas *Wu and Kanamori* [2005] use displacement and velocity, we have used waveforms of acceleration and jerk, which is the derivative of acceleration, (Figure 1a) and of velocity and acceleration (Figure 1b). The analysis indicates that all the waveform data have predominant frequencies less than about 25 Hz. *Wu and Kanamori* [2005] and *Allen and Kanamori* [2003] suggested that the final magnitude can be estimated by the average period. As shown by *Rydelek and Horiuchi* [2006], we find no clear tendency between values of predominant frequencies and magnitudes for events with magnitude larger than about 5.0, albeit the scatter is large.

[11] We obtained four weeks of continuous waveform data by installing a home seismometer on the floor of a research room at NIED. We calculated predominant frequencies for noise events, which were identified as signals having amplitudes three times larger than the average background. We use acceleration and jerk for analysis because the integral of acceleration becomes unstable owing to large electric noise. The total number of noise data is 3661, which is plotted in Figure 2 against the predominant frequencies. Most of the events have predominant frequencies higher than 40 Hz, but there are also events with frequency less than 20 Hz. Comparison between Figures 1 and 2 shows that predominant frequency is an effective parameter for the discrimination between a seismic event and noise. Figure 2 includes a few ten's of low frequency events that were generated by a trigger test, in which we manually shook the home seismometer.

[12] Most conventional seismic observations are made with a sampling frequency of 100 Hz or lower. Figure 2 shows that the largest numbers of noise events have a frequency in a bandwidth centered at about 100 Hz.

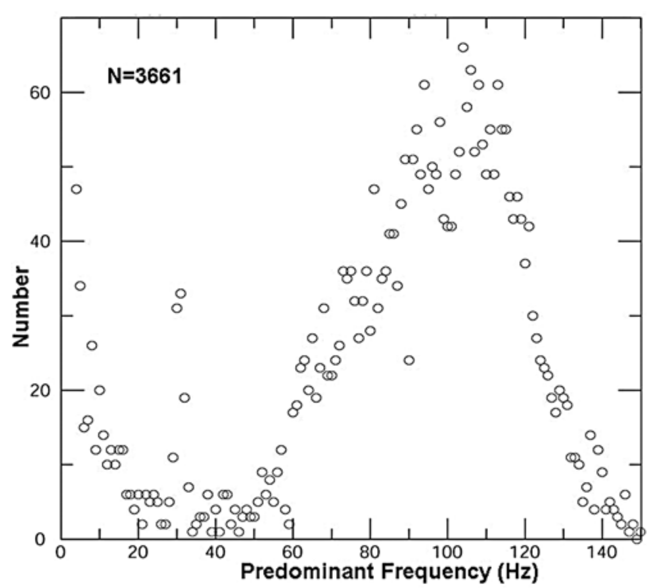

Figure 2. Number of noise events versus predominant frequency for data recorded from four weeks of observation at a NIED research room. Noise is considered an event if its amplitude becomes a factor of three larger than the time-average amplitude. Vertical axis shows the number of events in each 2 Hz interval. Events below 20 Hz are the result of a shift in the offset voltage of the sensor, which causes a large amplitude in the output of the filter used for event detection.

Table 1. Parameters for the Discrimination of Seismic Event From Noise

Parameter	Case A	Case B
1) Predominant frequency	40 Hz	40 Hz
2) Time duration larger than a threshold level	1.5 sec	0.6 sec
3) Number of zero crossings	5 times	5 times
4) Seismic intensity in JMA scale	2.0	4.5

Therefore it is difficult for data sampled at 100 Hz to accurately represent the spectral character of the noise, because the predominant frequency is above the Nyquist frequency of the digitizer. We designed the sampling frequency of the home seismometer to be 500 Hz in order to: (1) accurately collect waveform data of the noise; (2) be assured of sufficient bandwidth for reliable analysis; (3) discriminate seismic events from noise.

[13] Event detection is made by using the ratio of short (0.2 sec) and long-term (30 sec) averages of the absolute value of the amplitude of filtered accelerograms. We use a filter that has nearly the same amplitude response as the filter used to estimate shaking intensity from the JMA magnitude scale [*Yamamoto et al.*, 2008]. *Kunugi et al.* [2008] determined the coefficients of a digital filter having the approximate amplitude response of the JMA intensity filter, which we adapted for use with our 500 Hz sampling rate. This filter reduces the output amplitudes at frequencies of 20 Hz and 40 Hz by about 1/20 and 1/100, respectively, which helps to prevent triggers from small amplitude noise since most of these noise sources have predominant frequencies higher than 40 Hz.

4. Discrimination of Seismic Event From Noise Event

[14] In active regions of Japan, an earthquake is felt within a time interval of one month to a few months. Household activity, however, is a daily occurrence that will often result in cases of very strong noise events, e.g., small children playing near the home seismometer or the internet cable of the home seismometer moved during household cleaning. An on-site warning system should not issue false alarms even in such extreme situations.

[15] We developed an algorithm that uses the parameters shown in Table 1 to discriminate seismic events from noise. The corresponding values of filtered acceleration for shaking intensities of 1, 2, 3,4 on the JMA scale are 1, 3, 10, 30 Gal, respectively. Threshold levels for these parameters were determined from continuous waveform data: four weeks were recorded at NIED, and one week of data from 16 different rooms of large apartments located in the Tokyo area (16 weeks total).

[16] Because the frequency in Figure 2 becomes smallest at about 40 Hz, we assume a fixed value of 40 Hz as the cut-off for predominant frequency but consider two sets (Cases A and B) of threshold levels for the other parameters. When the home seismometer is located in a building with many apartments and an on-site warning is issued to all residents, false warnings can cause significant problems; therefore parameters should be chosen such that almost 100% of the noise is effectively discriminated. The testing of one week of continuous data from these 16 stations in Case A revealed that there was has no erroneous discrimination even if we reduced parameter (2) to be 1.0 sec. Case B is intended for the collection of earthquake data from the home seismometer network rather than for on-site warning; in this case, a discrimination as quickly as possible is necessary. We found that we will be able to calculate correct earthquake parameters, even if reports by a small number of stations are erroneous.

[17] As shown in Figure 3, we use a dedicated computer at the center of the home seismometer network, which acquires P-wave arrival times, shaking intensity, values of maximum acceleration, etc at times of earthquake occurrence through the internet. Parameters are revised every 0.2 sec and delay time for data transmission from the home seismometers is about 0.5 sec. The actual waveform data from each home seismometer is sent to this computer with a time delay of a few hours. In the future when the number of home seismometers becomes large, the central computer can quickly determine reliable earthquake parameters and relay these results back to the customers.

5. Testing Results

[18] During the 16 weeks of observations at Tokyo apartments there were no earthquakes that produced a shaking intensity larger than 2.0. The testing of Case A shows that no events were detected. We decreased the parameter (3) from 1.5 to 1.0 and parameter (4) from 4.5, to 4.0, but still no events were detected. We also made auxiliary tests by placing the home seismometer on the floor and generating different kinds of noise signals within 1m of the unit including movements of the internet cable. All the tests showed that Case A never registered an event by this noise, most of which have a predominant frequency higher than 40 Hz. The test result demonstrates that the parameters of Case A can discriminate almost 100% of the noise signals.

[19] Case B was unable to discriminate the noise from a seismic event in 48 instances and 46 of these were found in

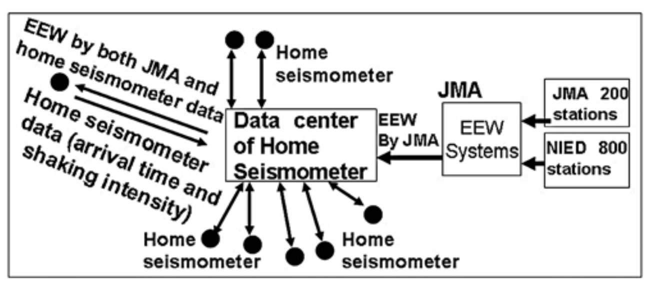

Figure 3. Block diagram of EEW system that includes the home seismometer network. Each home seismometer calculates P-wave arrival time, shaking intensity and maximum acceleration at the time of earthquake occurrence. These parameters are revised with an interval of 0.2 sec. Data center receives these parameters together with the EEW from JMA. It calculates hypocenter parameters and transmits computed result to each home seismometer; the calculations will start even without an EEW from JMA. Delay time for data transmission from the home seismometers to the data center is about 0.5 sec. The actual waveform data are returned with a time delay of a few hours.

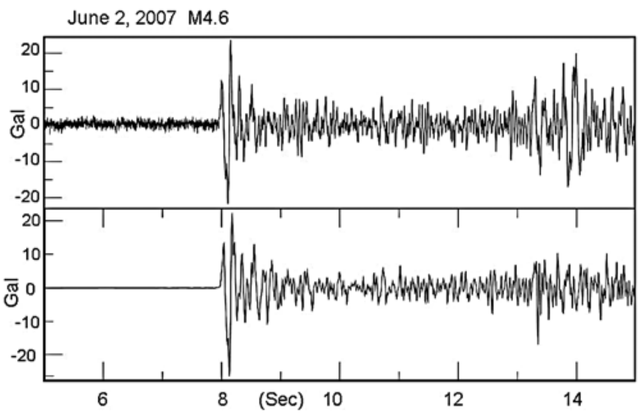

Figure 4. Comparison of accelerograms observed by a homeseismometer (top) and that by a K-NET station (bottom) set up at a same place for an event of magnitude 4.6 with epicentral distance of 47 km occurred on 2 June 2007.

the data from just two apartments. Observed predominant frequencies for this noise are about 15 Hz and the observed shaking intensities range from 0.8 to 1.3. It is suggest that this noise is probably generated by equipment at some larger-scale construction within hundreds of meters from the apartment. No events were detected that might have been generated by cars or some local source within or near the rooms of the apartment.

[20] We used a one dimensional shake table for a controlled testing of the home seismometer. The shaking was a sine-wave oscillation for three minutes with various amplitudes (5, 20, 100, 500, 1000, 1800 Gal) and frequencies (0.5, 1, 3, 6, 10 Hz). It is shown that the average measurement errors of the maximum acceleration and shaking intensity are 8.8% and 0.04, respectively. Figure 4 shows the comparison of accelerograms observed by a home seismometer and that by a K-NET station near the same place. The shaking test and the comparison demonstrate that the home seismometer is able to provide an accurate estimate of shaking intensity.

6. Discussion

[21] The EEW system in Japan uses the real-time waveform data from ~1000 seismic stations. The average distance of station spacing of about 25 km, combined with non-negligible time-delays in the EEW, means that there is an area within about 30 km from the earthquake's hypocenter where an EEW is not possible before the arrival of the damaging S-waves. Decreasing this region to less than 10 km would require about 10 times the number of seismic stations, which is cost prohibitive.

[22] JMA started practical service of EEW and a large population may be installing the receiving unit of EEW in the near future. If the home seismometer can be incorporated into the standard receiving unit of EEW, then the number of seismic observatories will be increased drastically. It is noted that even if the number of home seismometers becomes ~10,000 in the near future, a dedicated high-speed computer in the data center of the home seismometer network could calculate hypocenter parameters within 0.1 sec, since 2400 channels of 100 Hz sampling waveform data is presently being processed for the EEW system in Japan.

[23] Tests using a shake table and in-situ observations at 16 different apartments show that the home seismometer can detect seismic waves if the JMA shaking intensities are larger than about 2.0, thus demonstrating that the home seismometer can function as a seismic observatory for the EEW. The adaptation of the system to other environmental conditions will be a task of future work.

[24] The present EEW in Japan uses the seismic data from national arrays, all of which are installed by the government. On the contrary, home seismometer stations are installed by private enterprise. The present study has developed special software to provide an on-site warning and the customer only has to bear the additional cost of adding the seismometer to the EEW receiving unit. Immediate benefit to customers of the home seismometer will be an on-situ estimate of the amplification factor in the sedimentary layers. This results in a site-specific correction of the expected shaking intensity by a comparison between the waveform data from the home seismometer and those from closely located Hi-net or K-NET stations. This amplification factor will form an important safety index for houses and buildings at a time of large earthquake occurrence, since sites with large seismic amplifications may be more susceptible to heavy damage than those with small amplification factors. We believe that the addition of a seismometer to the EEW will produce valuable information to customers and the resulting ultra-dense seismic array will be of great value in many other earthquake related studies.

[25] **Acknowledgments.** PAR is thankful for support from the Korea Meteorological Administration Research and Development Program under grant CATER 2006-5101.

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