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A geophone-based and low-cost data acquisition and analysis system designed to microtremor measurements

Ozkan Kafadar[1]

[1]Department of Computer Programming, Kocaeli University, 41000 Kocaeli, Turkey

Correspondence: Ozkan Kafadar (okafadar@kocaeli.edu.tr)

Abstract. The commercial data acquisition instruments designed for three-component microtremor measurements are usually very expensive devices. In this paper, a low-cost, computer-aided and geophone-based system designed to record, monitor and analyze the three-component microtremor data, is presented. This proposed system is not a simple data acquisition system. It is also an integrated system developed to interpret the microtermor data without any external software. Therefore, the predominant frequency and ground amplification factor of survey area can be easily estimated by using this system. The proposed system has several features such as 200 Hz sampling frequency, approximately 72 dB dynamic range, text data format and data analysis tools. This system consists of a graphical user interface developed by using .NET Framework 4.5.2 and an external hardware that includes signal conditioning circuits, voltage converter circuit, external analog-to-digital converter and Arduino Uno board. The proposed system uses the low-cost and high gain geophones with 4.5 Hz natural frequency to measure three-component microtremor data. The developed software undertakes many tasks such as communication between the external hardware and computer, transferring, monitoring and recording the seismic data to computer, and interpretation of the recorded data using the Nakamura method. To demonstrate the accuracy and precision of the proposed system, the channel consistency and internal noise measurement tests are performed. Besides, the proposed system is compared to a commercial digitizer and the obtained results are presented in this study.

1 Introduction

The fundamental of the seismic methods is based on the recording of the seismic waves generated by the natural or synthetic sources. Various sensors with different frequencies, called as seismometer, accelerometer or geophone, are used to measure these seismic oscillations. Geophones are often preferred sensors in seismic applications because of their large bandwidths, excellent reliabilities and low costs. These devices convert the ground motion into a measurable electrical signal. Data acquisition systems are needed to digitize the analog signals detected by these sensors and to store them in a data storage device. Recently, many studies have been performed to design seismic data acquisition systems. In a study by Khan et al. (2012), a software component has developed to digitize the analog seismic signals using the computer sound card. Llorens et al. (2016) have

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designed a simple data acquisition system for recording the seismic data detected by the vertical geophone to an external SD card. In our previous study, we have developed a hardware and software for seismic refraction method (Kafadar and Sertcelik, 2016). In another study, a hardware has been designed for recording the seismic noise (Llorens et al., 2018).

In this paper, a low-cost, computer-aided and Arduino-based three-component microtremor measurement and analysis system (MicDAC) is presented. In the literature, there are many data acquisition and analysis systems developed with using the Arduino boards for scientific purposes (Llorens et al., 2016; Fisher and Gould, 2012; Huang et al., 2018; Puente et al., 2017). The MicDAC is controlled through a user-friendly graphical interface (MicDAC-GUI) developed by using the Microsoft .NET Framework 4.5.2 platform and C# language. The MicDAC is not a simple digitizer. Moreover, it is an analysis tool that it can interpret the recorded ambient noise using the Nakamura (horizontal-to-vertical spectral ratio) method (Nakamura, 1989) and it can calculate the two parameters (predominant frequency and ground amplification factor), which are too important to design earthquake-resistant structures. This study is completely different from the literature that the proposed system does not require any external software. On the other hand, it can display the calculated Fourier spectra for three-component ambient noise in real-time. This feature provides a pre-information about the frequencies of ambient noise in the survey area before starting the measurement to the user.

2 Microtremor Survey Method

Except for earthquakes and seismic explosions, the vibrational movements of the earth that occur the natural (winds, oceanic waves and geothermal reactions) or artificial (traffic and industrial machines) causes and whose periods do not exceed a few minutes, are called microseism (Katz, 1976). The microtremor term is used for periods range between 0.05 and 2 seconds. In other words, microtremors are low-amplitude (1-10 microns) and low-frequency (0.5-20 Hz) oscillations. Therefore, long-period seismometers are used to measure these seismic waves.

Microtremors have been classified by some researchers. According to Aki (1957) and Frantti (1963), microtremors are surface waves. Other researchers claim that microtremors are body waves (Kanai, 1962; Douze, 1964). In general, surface sources such as wind, ocean waves and cultural noise generate the surface waves, whereas naturally occurring earth tremors with extremely small amplitude generate the body waves (Weller, 1974).

The horizontal-to-vertical spectral ratio (H/V) technique proposed by Nakamura (1989) is one of the most popular methods developed for analysis of the microtremor data. This method based on the single-station microtremor data analysis can easily minimize the source effect by normalizing the horizontal spectral amplitude with the vertical spectral amplitude. The first step to evaluate the microtremor data using the H/V technique is to remove the offsets for each seismic component. This process is performed by subtracting the mean value of signals from each time-domain signal in seismic data. Optionally, low-pass filter can be applied to the recorded signal to remove the high-frequency components. Then the tapering and Fast Fourier Transform operations are applied to each selected time windows. The recorded microtremor data are generally split into shorter time windows before starting the analysis process. It is a standard practice to multiply these windows by a taper before performing a Fourier spectrum. The cosine tapers are usually preferred in seismic data analysis. They minimize the discontinuity effect

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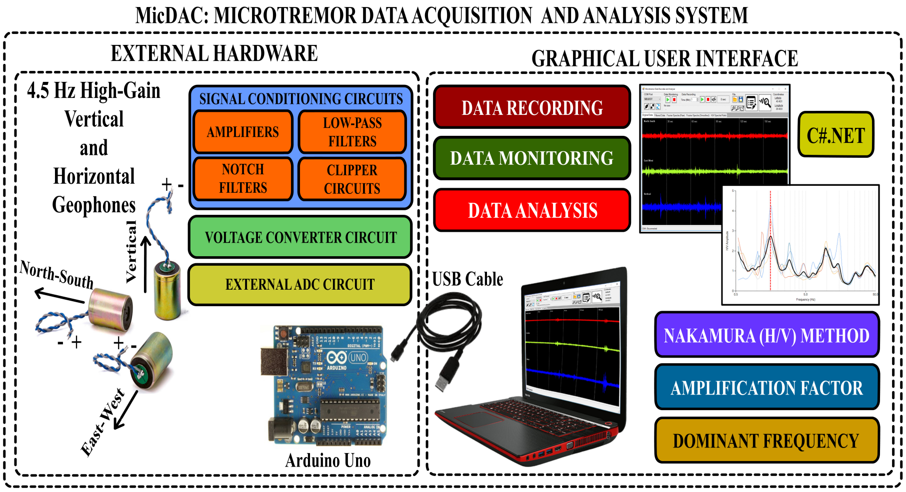

Figure 1. Graphical abstract of proposed system for measurement and analysis of three-component microtremor data.

between the ends of the time series (Percival and Walden, 1993). Raw spectra contain many frequency samples. The Konno-Ohmachi smoothing is widely used to smooth the Fourier spectrum (Konno and Ohmachi, 1998). This process is not mandatory, but strongly recommended. In this study, the quadratic mean is used to calculate the average of two horizontal components. The SESAME (Site effects assessment using ambient excitations) project is the most comprehensive study performed to interpret the H/V curves (SESAME, 2004). In the SESAME report, required conditions to interpret the H/V curves correctly is described in details.

3 System Architecture and Design

The MicDAC consists of a developed graphical user interface and an external hardware that includes amplifiers, low-pass and notch filter circuits, clipper circuits, voltage converter circuit, external analog-to-digital converter and Arduino Uno board. The graphical abstract of the MicDAC is shown in Fig. 1. The designed external hardware is connected to the computer via the USB bus. It utilizes the USB port as power supply. Thus, no external battery is required.

3.1 Hardware implementation

The vertical and horizontal geophones manufactured by Sara Electronic Instruments were used to measure three-component microtremor data. They have some characteristic features such as 4.5 Hz natural frequency, 0.2-240 Hz usable band and 78 V/m/s sensitivity. There are also geophones with lower frequency on market, but the price of these instruments increases exponentially with decreasing frequencies. Moreover, cost of the high-quality broadband seismometers can reach a mid-level car price. For this reason, in this paper a low-cost hardware-software device is presented to both measure and interpret the three-component microtremor data.

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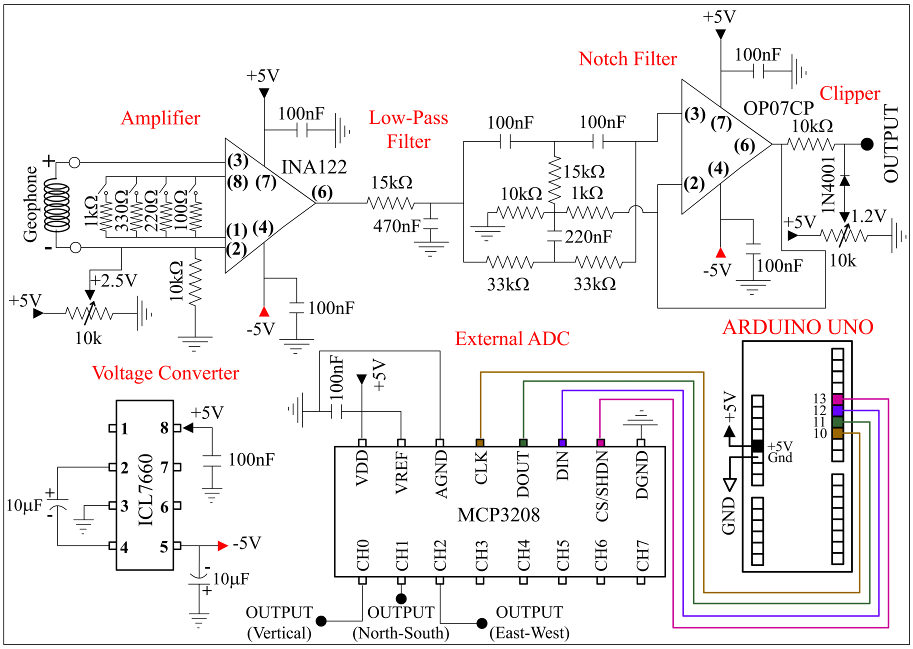

Figure 2. Schematics of external hardware and pin connections.

The output of a geophone consists of two poles and its output voltage is too weak to be recorded without amplification. The voltage difference between these poles can be measured by using various operational amplifiers. The first stage of this signal conditioning circuits consists of differential input and single output INA122 amplifiers Texas Instruments (1997). These amplifiers are instrumentation amplifiers with very important properties such as low-noise (60 nV/$\sqrt{Hz}$), high quality and rail-to-rail output, wide power supply range (single supply: 2.2 V to 36 V, dual supply: -0.9/+1.3 V to -18/+18 V), low offset voltage (250 μA max) and low quiescent current (60 μA).

In this study, symmetrical power supplies (±5 V) were used to supply these amplifiers. Arduino Uno board can only provide 3.3 V and 5 V positive outputs. For this reason, the ICL7660 integrated circuit was used to obtain the negative power supply (-5 V) from the positive power supply (+5 V). The pin connections of ICL7660 voltage converter and INA122 amplifier are shown in Fig. 2. It can be set four different gain levels (46 dB, 56 dB, 60 dB and 66 dB) for each channel thanks to the DIP switch and resistors connected to the pins 1 and 8 of INA122 amplifiers.

The next step in the external hardware is a passive RC (Resistor-Capacitor) low-pass circuit, which is used to attenuate the high-frequency components in the amplified signal and to avoid the aliasing phenomenon. Cutoff frequency of the low-pass filter was set approximately 22 Hz because the corresponding frequency range in microtremor studies is 0-20 Hz. In the last stage of the signal conditioning circuits, the Twin-T notch filters and clipper circuits were used to remove the 50 Hz interferences and to clip the negative voltage in the output signal, respectively (Fig. 2). Instead of the internal 10-bit analog-to-

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digital converter on the Arduino board, the MCP3208 12-bit external analog-to-digital converter was preferred to assure higher resolution signals.

3.2 Software implementation

The MicDAC sketch (Arduino uses the sketch term for a program) is compiled with Arduino 1.8.8 version and stored as a file, called MicDAC.ino. This sketch digitizes the seismic data with 200 Hz sampling frequency and it transfers the digitized data to the computer via USB bus. The second program (MicDAC-GUI), developed by using .NET Framework 4.5.2 in C# language, is a user-friendly and Windows operating system-based software (Fig. 4). The MicDAC-GUI consists of data monitoring mode, data recording mode and analysis tools. It detects the available COM ports automatically. The data monitoring mode is used to display three-component microtremor data in real-time and to test the geophones before starting the recording operation. In addition, this mode is also used to adjust the offset needed to see signals symmetrically through the 10K potentiometer, a component of the external hardware (Fig. 2). The data recording mode is used to record three-component microtremor data during the desired time.

The MicDAC-GUI allows performing records of maximum 180 minutes. When the recording operation ends, the user is alert with an alarm and the temporary data is saved into a file called “datam.txt”. The microtremor data are stored in a text file. This data file consists of three columns: V (vertical), NS (north-south) and EW (east-west) components. The recorded signal values vary in the range of between 0 and 4095 because the analog-to-digital converter is 12-bit. Besides, the coordinates of survey area and descriptions are stored in a file with info extension.

The MicDAC-GUI allows many operations such as low-pass filtering, tapering, windowing and smoothing on the recorded data. It can be selected the desired signals thanks to the windowing feature of the MicDAC-GUI. The window length (10.24, 20.48, 40.96, 81.92 and 163.83 seconds) is a user-defined parameter. The duration of the analyze process increases or decreases depending on the number of enabled time windows and data length. The frequency distribution of each window is displayed separately. This feature gives an idea about the windows that will be used in the analysis. Finally, the horizontal-to-vertical spectral ratios for each selected time window are calculated. The calculated H/V spectral ratios are also numerically displayed using a grid component. After the analysis process ends, the parameters (cutoff frequency of low-pass filter, taper ratio, length of time window, bandwidth of Konno-Ohmachi smoothing function), raw data, low-pass filtered data, Fourier amplitude spectra data, smoothed Fourier amplitude spectra data and H/V spectra data are saved into a text file with "soln" extension.

3.3 The reliability and accuracy tests of MicDAC

In this section, three tests were performed in order to demonstrate the accuracy and precision of the MicDAC: (1) channel consistency tests using synthetic and real data; (2) internal noise measurement test and (3) comparison of the characteristics and frequency contents of recorded signals using the proposed system and a commercial microtremor measurement device.

The channel consistency test was performed to evaluate the time-amplitude differences for each channel. Firstly, a 1 Hz sinusoidal signal of 15 mV amplitude generated by the Model FG-8002 function generator manufactured by EZ Digital company was connected to each input channel and these signals were recorded over a period of 60 seconds with a 46 dB gain. After

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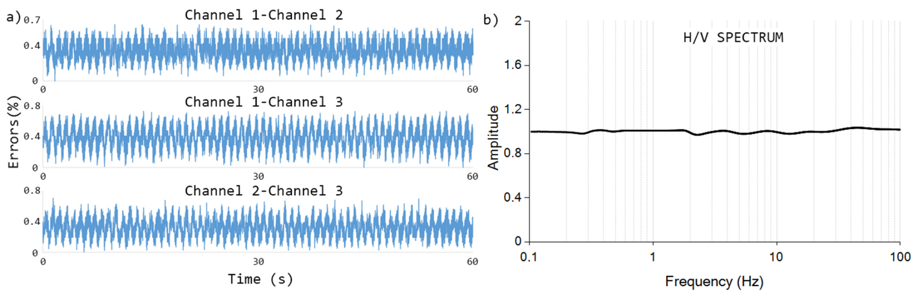

Figure 3. a) Error percentages of difference signals. b) H/V spectral ratio.

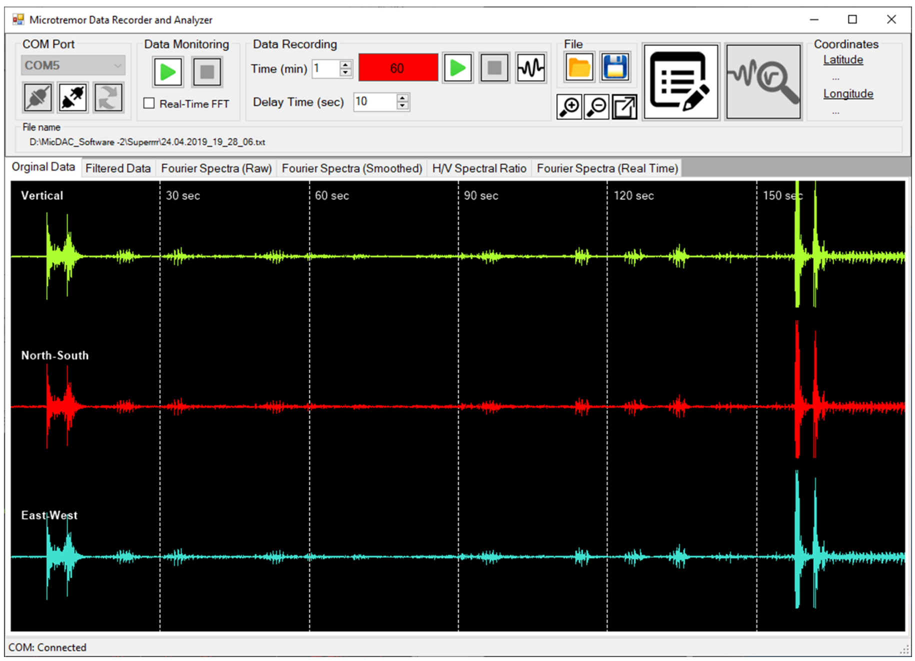

Figure 4. Screenshot of MicDAC-GUI and detected signals using a 4.5 Hz vertical geophone connected to each channel inputs.

that, the differences of the recorded signals for each channel were calculated. As shown in Fig. 3a, the error percentages (amplitudes of difference signals x 100/4096) of the difference signals (Channel 1-Channel 2, Channel 1-Channel 3 and Channel 2-Channel 3) are lower than 1%. The H/V ratio were calculated using the same sinusoidal signals recorded by three channels and presented in Fig. 3b. The H/V ratio will be equal 1 because the same sinusoidal signals were applied to each channel input.

Secondly, channel consistency test was conducted with using real sensors. For this purpose, same vertical geophone, placed on the table in a building, was connected to the inputs of each channel and the ambient noise is recorded over a period of 180 seconds (Fig. 4). In this test, the calculated Fourier spectra were utilized to demonstrate the frequency contents of three channels. The calculated Fourier spectra and H/V ratio are shown in Fig. 5a and 5b, respectively.

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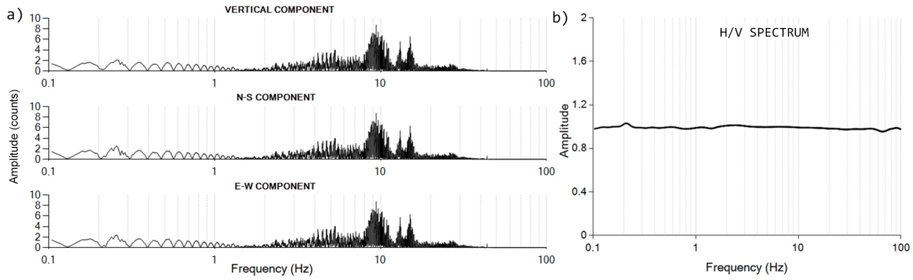

Figure 5. a) Fourier spectra for three-component data shown in Fig. 4. b) H/V spectral ratio.

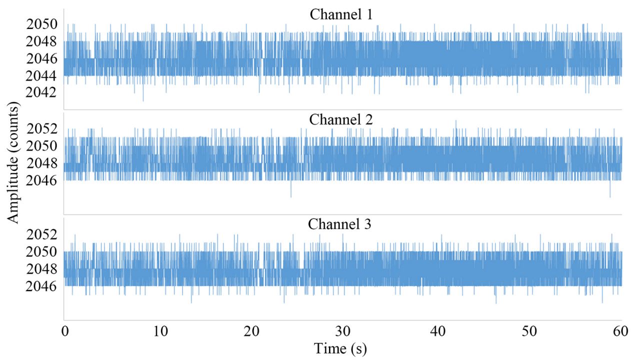

Figure 6. Internal noise measurements for each channel.

In the next test, the internal noise of MicDAC was recorded during a time period of 60 seconds with 200 Hz sampling frequency and standard deviations for each channel were calculated (Fig. 6). The noise levels of three channels were observed as approximately ± 3 counts (7.3242 mV, 9.39x10^{-5} m/s).

Finally, the MicDAC was compared with a commercial digitizer called as Geobox manufactured by SARA Electronic Instruments. Different versions of the Geobox with sensors of 0.5, 1, 2 and 4.5 Hz, are available in the market. We used the 4.5 Hz version Geobox (SR04HS) to make a comparison with MicDAC because MicDAC uses 4.5 Hz horizontal and vertical geophones. The Geobox uses 24-bit digitizer while the MicDAC uses a 12-bit digitizer.

Three-component microtremor data shown in Fig. 7a and Fig. 7b were recorded simultaneously with each device. Seismolog-MT software was used to monitor and to record the data with Geobox. As a result of this comparison in the time domain, the peaks observed in the signals indicated that each component had the same characteristics. Despite this similarity in the signal characteristics, the same result could not be obtained for the signal amplitudes. Because both devices have different gain levels. For three-component microtremor data recorded with MicDAC, 46 dB and 60 dB gains were used, respectively. This similarity in the signal characteristics was also confirmed by frequency contents (Fig. 7c).

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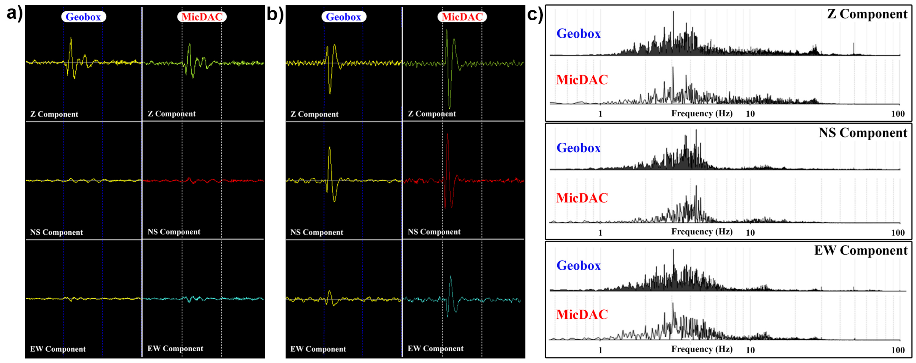

Figure 7. Three-component seismic data recorded simultaneously using both devices a) MicDAC with 46 dB gain b) MicDAC with 60 dB gain c) Comparison of Fourier spectra of recorded three-component microtremor data using Geobox and MicDAC.

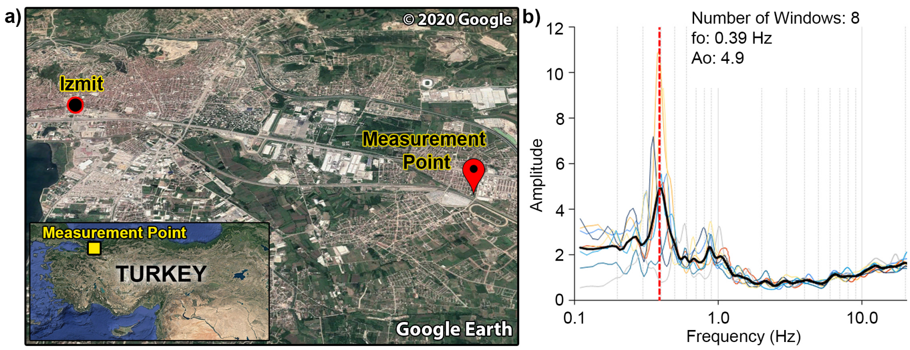

Figure 8. a) Location of test measurement point on Google Earth© view b) H/V spectral ratio.

4 Experimental Study

In this section, another test measurement was performed to test the performance of MicDAC in field conditions and to compare the obtained results with a previous study. For this purpose, a previously measured area was selected for recording the ambient noise. The measurement point is located in Kartepe district in Marmara region, Turkey (Fig. 8a).

This region is in the middle of Izmit basin and the upper strata of this basin composed of alluvium deposits consisting of silt, sand, gravel and clay. In this region, a large-scale study for site classification and seismic hazard assessment was already conducted by Marmara Research Center of TÜBİTAK and Greater Metropolitan Municipality of Kocaeli (Özalaybey et al., 2008, 2011). According to their study, the thickness of the sediments of the Izmit basin was calculated as approximately 715 meters in the area. Especially, in the regions located in the middle of Izmit Basin, it was obtained that the predominant frequency varies between 0.2 and 1.0 Hz and the corresponding magnification values are between 5-6 times (Özalaybey et al., 2008).

The ambient noise was recorded during a period of 20 minutes. The relation between the expected minimum frequency and recording duration is explained SESAME report in details (SESAME, 2004). The recorded signal was split into 14 time windows of 81.92 seconds and 8 of them were used to analysis. 5% cosine tapering and 10 Hz low-pass filtering operations were applied to the selected windows, and Fourier spectra for each window were calculated. The Konno-Ohmachi filter with bandwidth 40 was applied to the obtained Fourier spectra. Then H/V spectral ratio was calculated. Finally, the predominant frequency and amplification factor for the measurement point were determined as 0.39 Hz and 4.9, respectively (Fig. 8b). These findings showed that the obtained results are consistent with the literature (Özalaybey et al., 2008).

5 Conclusions

The aim of this study is to develop a low-cost, computer-aided and Arduino-based three-component microtremor data acquisition and analysis system using basic electronic components, integrated circuits and Microsoft .NET Framework 4.5.2 application development platform. The designed external hardware can be easily assembled by readers and controlled through a developed graphical user interface using C# language. This software allows monitoring and recording three-component microtremor data, and analyzing the recorded data using the horizontal to vertical spectral ratio technique (H/V). Finally, the predominant frequency and amplification factor of the survey area can be estimated. The performed tests (channel consistency, internal noise measurement and comparison with a commercial digitizer) to demonstrate the accuracy and precision preformances of the proposed system indicated that this system can be an inexpensive alternative to microtremor studies. The proposed system is completely an open-source and open-hardware system, and researchers and university students interested in the microtremor survey method can use the MicDAC system in their academic studies.

Code availability. The MicDAC software folder with the size of 10 MB, contains an Arduino sketch program, sample data folder, executable file folder, MicDAC open-source software files and readme file. The MicDAC software was developed by using the C#.NET language. It is based on Microsoft Windows OS and Framework 4.5.2. The developed graphical user interface, device firmware and other supplementary files can be supplied from the author or downloaded from GitHub, a web-based repository hosting service: https://github.com/ozkankafadar/MicDAC.

Author contributions. All stages of this work were carried out by the author

Competing interests. The author declares that there are no conflicts of interest

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