

T.R.
GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

**DEVELOPING COST-EFFECTIVE DATA ACQUISITION
SYSTEMS BY USING MEMS ACCELEROMETERS AND
GEOPHONE SENSORS**

KAMER ÖZDEMİR
**A THESIS SUBMITTED FOR THE DEGREE OF
MASTER OF SCIENCE
DEPARTMENT OF CIVIL ENGINEERING
EARTHQUAKE AND STRUCTURAL
ENGINEERING DEPARTMENT**

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GEBZE TEKNİK ÜNİVERSİTESİ
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**İVMEÖLÇER VE JEOFON SENSÖRLERİ
İLE MALİYET-ETKİN VERİ TOPLAMA
SİSTEMLERİNİN GELİŞTİRİLMESİ**

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SUMMARY

In recent years, the use of practical and effective solutions has become more widespread in earthquake observation and structural health monitoring systems. This is due to the increasing availability of cost-effective and easy-to-install devices, which became possible with advances in technology. The aim of this study is to develop a cost-effective, standalone, open-source data acquisition device that is capable of measuring structural vibrations and ground motions which can be used in Earthquake Engineering applications. In order to conduct measurements for different applications such as structural vibrations and strong ground motions, a high dynamic range is required. Therefore, two different devices are developed by using a MEMS accelerometer sensor with 20-bit and geophone sensor with 24-bit digitizers running on a Raspberry Pi 4 single-board minicomputer. Devices have internet access thus they can synchronize their time from an NTP server and send stored MiniSEED files to databases. The devices are evaluated by offset, frequency response and noise tests with broadband GURALP 5TDE strong motion accelerometer as a reference device. Forced and ambient vibration tests are performed on three residential buildings. Modal parameters of the buildings subjected to ground motions and ambient vibrations are analyzed by a developed open-source software. In comparison to the Guralp reference sensor, the computed modal frequencies of buildings show a maximum difference of 1%, whereas the peak acceleration values deviate 7%.

Key Words: Structural Vibrations, Structural Health Monitoring, Earthquake Observations, Sensors, MEMS, Python.

ÖZET

Son yıllarda yapı sağlığı izleme sistemleri ve deprem gözlemlerinde pratik ve etkili çözümlerin kullanımı giderek yaygınlaşmaktadır. Bunun nedeni, teknolojiadaki ilerlemelerle mümkün olan uygun maliyetli ve kurulumu kolay cihazların sayılarının giderek artmasıdır. Bu çalışmanın amacı, Deprem Mühendisliği uygulamalarında kullanılabilecek, yapısal titreşimleri ve yer hareketlerini kaydedebilecek, uygun maliyetli, açık kaynaklı veri toplama cihazı geliştirmektir. Yapısal titreşimler ve kuvvetli yer hareketleri gibi farklı uygulamalar için ölçüm yapabilmek için geniş bir dinamik aralık gereklidir. Bu nedenle, 20-bit ve 24-bit sayısallaştırıcıya sahip MEMS ivmeölçer sensörü ve jeofon sensörü kullanılarak Raspberry Pi 4 minibilgisayar üzerinde çalışan iki farklı cihaz geliştirilmiştir. Cihazlar internet erişimine sahiptir, böylece NTP sunucusundan zamanlarını senkronize edebilir ve depolanan MiniSEED dosyalarını veritabanlarına gönderebilirler. Genişbant GURALP 5TDE ivmeölçeri referans sensör olarak kullanılarak cihazların offset, frekans tepkisi ve gürültü testleri gerçekleştirilmiştir. Üç farklı yapı üzerinden zorlanmış titreşim ve ortam titreşim testleri gerçekleştirilmiştir. Elde edilen veriler ile yapıların modal parametreleri geliştirilen açık kaynaklı yazılım ile analiz edilmiştir. Guralp referans sensörü ile karşılaştırıldığında yapıların hesaplanan modal frekansları maksimum %1, tepe ivme değerleri %7 farklılık göstermektedir.

Anahtar Kelimeler: Yapısal Titreşimler, Yapı Sağlığı İzleme, Deprem Gözlemleri, Sensors, MEMS, Python.

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LIST OF ABBREVIATIONS AND ACRONYMS

<u>Abbreviations</u>	<u>Explanations</u>
<u>and Acronyms</u>	
Ω	: Unit of electrical resistance
μg	: Micro-g
g	: Gravitational acceleration
Hz	: Hertz
mAh	: Milliampere-hour
mg	: Milli-g
s	: Second
T	: Period
V	: Voltage
AC	: Alternating current
ADC	: Analog-to-digital converter
ANSS	: Advanced National Seismic System
CEDAS	: Cost-effective Data Acquisition System
DAS	: Data Acquisition System
DRDY	: Data-Ready
DC	: Direct current
EW	: East-West Direction
GPIO	: General purpose input/output
GPS	: Global Positioning System
GTU-ESL	: Gebze Technical University Earthquake and Structure Laboratory
I2C	: Inter-Integrated Circuit
LSB	: Least Significant Bit
MEMS	: Microelectromechanical Systems
NS	: North-South Direction
NTP	: Network Time Protocol
ODR	: Output Data Rate
PGA	: Programmable Gain Amplifier
RECANA	: Record Analyzer Software
RMS	: Root mean square

RTOS	: Real-Time Operating System
SD	: Spectral Density
SHM	: Structural Health Monitoring
SNR	: Signal-to-Noise Ratio
SPI	: Serial Peripheral Interface
UBC	: Uniform Building Code



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1. INTRODUCTION

1.1. Motivation

The need for housing and infrastructure is always increasing along with the world population. Demand for megastructures, complex architectural and engineering projects such as high-rise buildings, bridges, dams and monumental structures are also growing. Together with the advantages of this type of structures, more caution is needed during their construction and operational time since they can be more hazardous and prone to human error. Furthermore, structural monitoring during and after earthquake events, as well as the examination of strong ground motion recordings plays a huge role in mitigation of seismic risk. By taking advantage of today's technology, Structural Health Monitoring (SHM) should address the need for safe and cost-effective operation of infrastructure [1].

With the advancements in silicon technologies over the past few decades, the utilization of both piezoresistive and Micro-Electro-Mechanical-Systems (MEMS) accelerometers have increased drastically [2]. Since the start of the 1990s, the word "MEMS" has been used in academic literature very frequently. In June 2023, according to Scopus database, over 33 thousand research items can be found with the keyword "MEMS". The number of indexed articles between the year 2000 and 2022 is shown in Figure 1.1. It is evident that the researches in this field has been increasing consistently since the beginning of 2000s.

MEMS accelerometer sensors brought Data Acquisition Systems (DAS) and data-loggers to exceedingly small sizes and low costs. Production of such cost-effective sensors with reasonable sensitivity and noise density contributed to the multiple disciplines and paved the way for the development of new devices [3]. By enabling the easy use of a large number of sensors, establishment of seismic networks at the building, regional, and even national scale have increased rapidly [4], [5], [6].

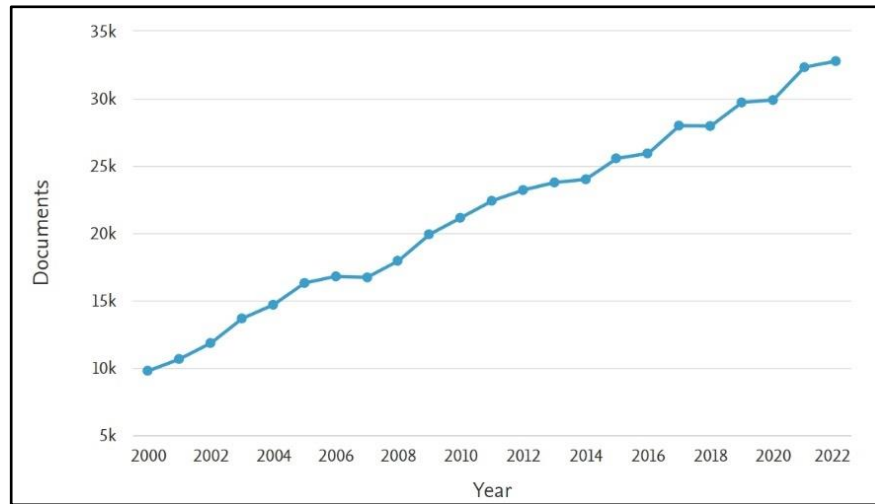


Figure 1.1: Number of scientific documents that contains the term “MEMS” according to Scopus analytics (accessed in June 2023).

The purpose of this study is to develop a standalone, cost-effective acceleration and velocity DAS, equipped with technical specification suitable for applications in Earthquake Engineering and Earth Sciences.

1.2. Objectives

The aim of this study is to develop a cost-effective, open-source DAS device that can measure structural vibrations and ground motions which can be used in Earthquake Engineering applications. It is anticipated that this thesis study will provide elucidation on the trade-off existing between the quality and cost considerations to devices featuring MEMS accelerometer and geophone sensors. In order to conduct measurements for different applications such as structural vibrations and strong ground motions, a high dynamic range is required. Therefore, the current research effort is to develop two Cost-Effective Data Acquisition Systems (CEDAS) with different types of sensors. Broadly, the device with MEMS accelerometer will measure high amplitude vibrations such as strong ground motions (CEDAS_acc), on the other hand, geophone device with high sensitivity will be capturing low amplitude ambient vibrations, and weak ground motions (CEDAS_geo). CEDAS devices running on Raspberry Pi 4 single-board minicomputer with wireless network connection. Thus, time synchronization from a Network Time Protocol (NTP) server and data storage in network database is possible. Software for sensor drivers and data analysis prepared

in a Python programming language. Validation and evaluation of the CEDAS devices involve offset, frequency response, shake table and noise tests for device characterization. Additionally, field tests conducted to validate the performance of the devices under forced vibration and ambient vibration conditions. CEDAS and Guralp reference devices are instrumented on three different residential buildings according to guidelines. Comparisons made among the devices based on time series and peak acceleration, velocity, displacement values, modal frequencies from estimated spectral densities and transfer functions. Record Analyzer (RECANA) software used for transforming raw data to desired unit of acceleration and trimming of the CEDAS devices MiniSEED file records. Processing the record is possible with baseline correction functions and Butterworth filters. Records can be exported to .txt, .csv and .xlsx formats for further processing.

1.3. Literature Review

The first pioneering demonstration of MEMS accelerometers dates back to 1979, at Stanford University an accelerometer device fabricated with 2x3x0.6 mm package and 0.02 gram weight, capable of measuring 10 mg over a 100 Hz bandwidth with measurement range up to 50g [7]. The manufacturing process of the accelerometer is called integrated-circuit fabrication, which represents one of the earliest applications of MEMS accelerometers, long before they became extremely popular products as today [7].

Over the years, MEMS accelerometers have found use in a wide range of fields, featuring extensive and widespread utilization in such areas as automotive, machinery, navigation systems, robotic and human exploration in space [8], [9]. Later with the necessities of these fields, sensors became more compact, sensitive, power efficient and suitable for earthquake monitoring applications [10].

Low-cost acceleration DAS are immensely popular in Earth Science and Earthquake Engineering related studies. D'Alessandro (2013) presented the suitability of low-cost MEMS accelerometer used in mobile phones and laptops for strong motion seismology. The device used in tests has a low sensitivity and high noise density. These types of devices are only usable for near field earthquakes with magnitude 5 or higher [11].

Sabato et al. (2016) prepared a review of studies with wireless MEMS accelerometer boards with better noise density and resolution for structural vibration monitoring and gave technical details and limiting factors about the designed devices [2]. Limiting factors for the given low noise devices are resolution of the analog to digital converter (ADC) used in the sensor boards. The latest advancements in MEMS sensors have demonstrated that they can achieve measurement accuracy and noise performance comparable to that of traditional wire-based Integral Electronics Piezoelectric (IEPE) accelerometers, especially when capturing micro vibrations characterized by amplitudes in the range of cm/s^2 and frequencies around 1 to 10 Hz [2].

However, these sensors are not appropriate for the current research effort due to not being cost-effective. Riberio and Lameiras (2019) tested multiple low-cost MEMS sensor boards on building models. Used boards have a maximum resolution of 16-bit, but the limitation factor for the used sensors is their high self-noise. Tested sensor boards are not capable of detecting modal frequencies of the building model under ambient vibration conditions [12]. Thus, these low-cost boards with built-in low resolution ADC's are suitable for forced vibration monitoring, local strong ground motions and for educational purposes [13].

By engaging citizens, utilizing low-cost MEMS sensors, and deploying networks in urban areas, these initiatives contribute to the broader goal of improving the understanding of earthquakes and enhancing early warning systems for the safety and resilience of infrastructures. The Community Seismic Network (CSN), QuakeCatcherNetwork (QCN), Urban Seismic Network, Self-organizing Seismic Early Warning Information Network (SOSEWIN), and ShakeNet are all notable initiatives in the field of seismic monitoring and earthquake research [4], [5], [6], [14], [15], [16]. Some of the networks use plug and play sensor solutions such as QCN. Phidget and O-Navi brands can be given as an example of these easy-to-use and versatile solutions [17], [18]. Evans et al. (2014) tested the multiple MEMS sensors including Phidget brand sensors according to guidelines [19]. These sensors found to be usable for regional seismicity and strong motion recordings.

Geophones, which are frequently chosen for local seismic applications, serve as weak ground motion recorder or velocity meters due to their exceptional reliability and high sensitivity. High sensitivity and low-cost makes them a great option for ambient

vibration monitoring of buildings and applicational geophysics such as microtremor measurements [20].

Ambrož (2017) showed an example for the possibility to use a Raspberry Pi single board computer as a low-cost data acquisition system for use in applications on human powered vehicles to measure acceleration, velocity and displacement [21]. Additionally, Raspberry Shake's devices use both MEMS accelerometer and geophone sensors with Raspberry computer as a processor [22]. Özcebe et al. (2022) investigated the use of Raspberry Shake RS4D model as a dynamic identification of structures [23].

1.4. Thesis Organization

This dissertation consists of five chapters. Brief information about the contents of the chapters are given below:

- Chapter 1 shortly summarizes the literature on existing data acquisition devices and seismic networks. The motivation and objectives of this study are discussed in this part.
- Chapter 2 gives the criteria to choose the right equipment for the considered applications, provides information about the hardware system used in the CEDAS devices. Provides information about the developed web based application where acceleration data from devices are processed.
- Chapter 3 presents the applications of different techniques conducted to evaluate the device performances and their suitability to desired applications.
- Chapter 4 includes field tests from instrumented residential buildings. CEDAS devices performance is evaluated under the ambient vibration and forced vibration by an earthquake.
- Chapter 5 summarizes the results of this study and gives information about the contributions that can be made in the future.

2. SYSTEM DESCRIPTION

2.1. Overview

Data acquisition refers to the essential process of sampling signals that capture various physical phenomena in the real world. Subsequently, these signals undergo a conversion process where they are translated into discrete digital numerical values. This transformation enables their manipulation and analysis by computers. For this study, transducer sensors convert acceleration and velocity parameters to electrical signals. By processing these signals in the circuitry, signals are converted to digital values by ADCs and processed by a computer. The outlined stages are shown in Figure 2.1.

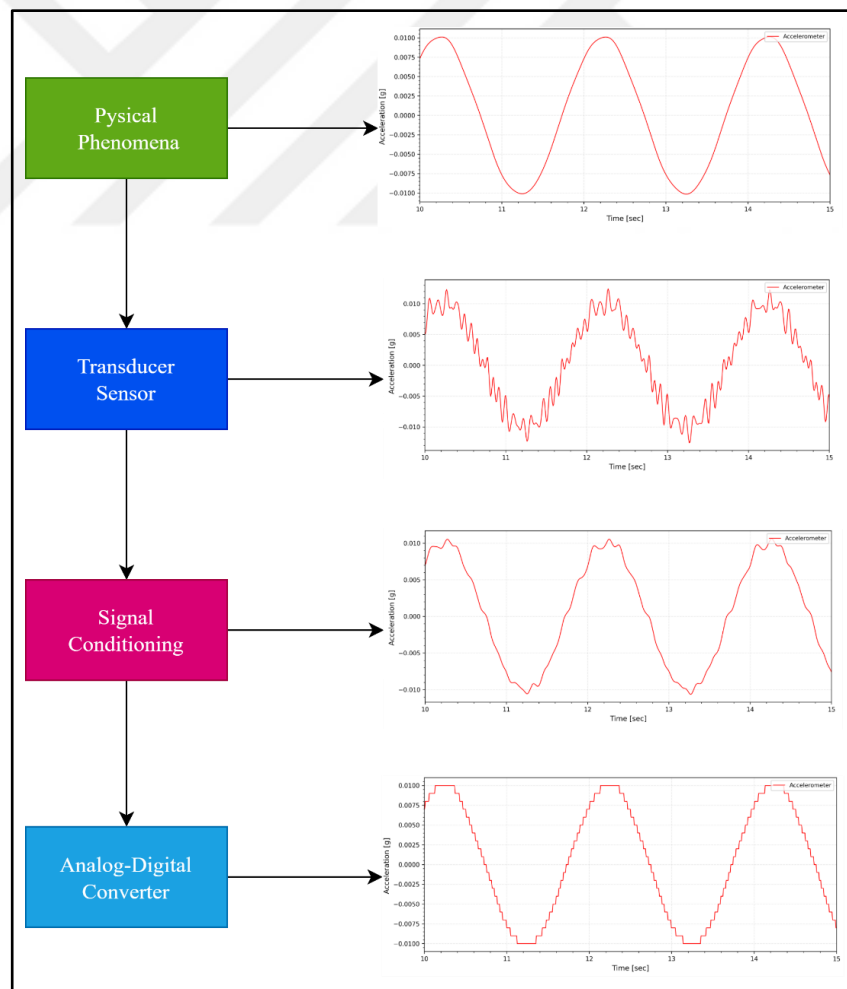


Figure 2.1: DAS operation sequence.

CEDAS devices are acceleration and velocity Data Acquisition Systems (DAS) or standalone data-loggers. Devices are a package of hardware and software that performs the mentioned processes. Hardware of the designed CEDAS devices consists of a single-board mini-computer, a sensor, an ADC and a microSD card. Devices are mounted on a protective casing with a flat surface. CEDAS devices are shown in Figure 2.2.

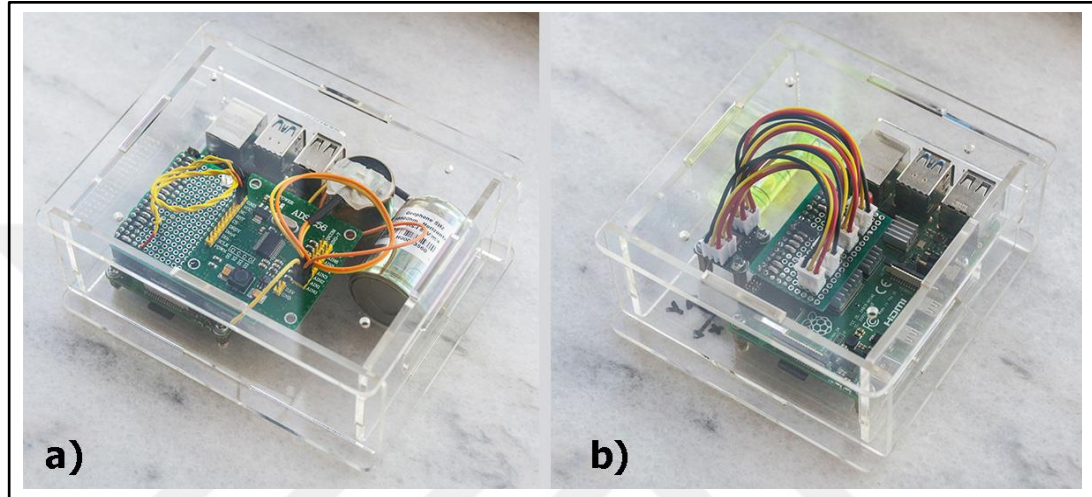


Figure 2.2: Views of (a) CEDAS_geo device (b) CEDAS_acc device.

Devices are using different sensors that aim to measure vibrations at different regions within the dynamic range. CEDAS_geo device uses horizontal and vertical geophone elements with an ADC board. CEDAS_acc has a triaxial MEMS accelerometer with 3 ADCs on sensor board. Geophones are targeted to measure low-amplitude vibrations while CEDAS_acc is more suitable for measuring strong ground motions.

Devices can be operated by connecting a keyboard and a monitor. However, it is possible to connect to the CEDAS devices from another computer wirelessly or by an ethernet port via RJ45 cable.

Single board computer communicates with the sensor board and ADC via SPI serial communication. SPI drivers for both devices are written with Python programming language according to device datasheets [24, 25].

Raspberry Pi 4 Model B GPIO pinout and CEDAS devices sensor and ADC board pinouts are shown in Figure 2.3, 2.4, 2.5. SPI serial communication connections

between slave MEMS accelerometer board and ADC board to master Raspberry Pi computer are listed in Table 2.1 and Table 2.2.

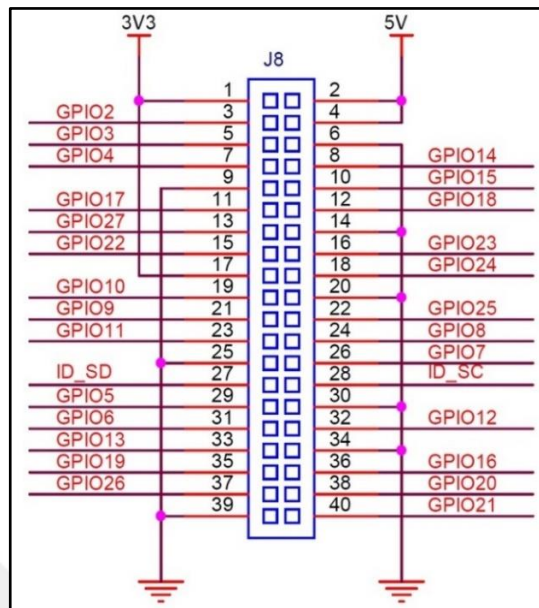


Figure 2.3: Raspberry Pi 4 Model B GPIO connector pinout.

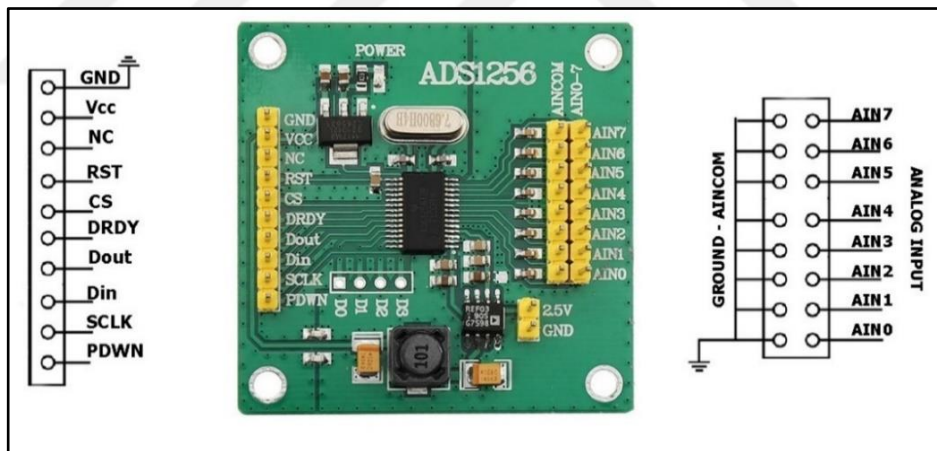


Figure 2.4: CEDAS_geo ADC board header pinout.



Figure 2.5: CEDAS_acc sensor board header pinout.

Table 2.1: SPI connection of CEDAS_geo ADS1256 ADC to Raspberry Pi.

Pin Description	ADS1256 Pinout	Raspberry Pi 4 Pinout
3.3V Power	VCC	1
Ground	GND	6
Data Ready	DRDY	11
Reset	RST	12
Power Down	PDWN	13
Chip Select	CS	15
Master Out Slave In	DIN	19
Master In Slave Out	DOUT	21
Serial Clock	SCLK	23

Table 2.2: SPI connection of CEDAS_acc ADXL355 sensor board to Raspberry Pi.

Pin Description	ADXL355 Pinout	Raspberry Pi 4 Pinout
3.3V Digital Power	VDDIO (1)	1
3.3V Digital Power	VDD (3)	1 or 17
Ground	GND (5)	9
Data Ready	DRDY (6)	11
Chip Select	CS (8)	24
Serial Clock	SCLK (10)	23
Master In Slave Out	MISO (11)	21
Master Out Slave In	MOSI (12)	19

2.2. Algorithm

In addition to the hardware of the device, effective and precise algorithm for the SPI and sensor driver is needed to control both ADXL355 MEMS sensor and ADS1256 ADC. Drivers have been prepared considering the datasheets of the hardware and other previously prepared resources. Drivers developed with the use of open-source Python modules such as SciPy for signal processing [27], Pandas for data storage and analysis [28], NumPy for mathematical functions and array computing [29], ObsPy for processing seismic data [30]. Drivers of CEDAS_acc and CEDAS_geo devices share a similar algorithm flowchart with slight changes. The flowchart is shown in Figure 2.6.

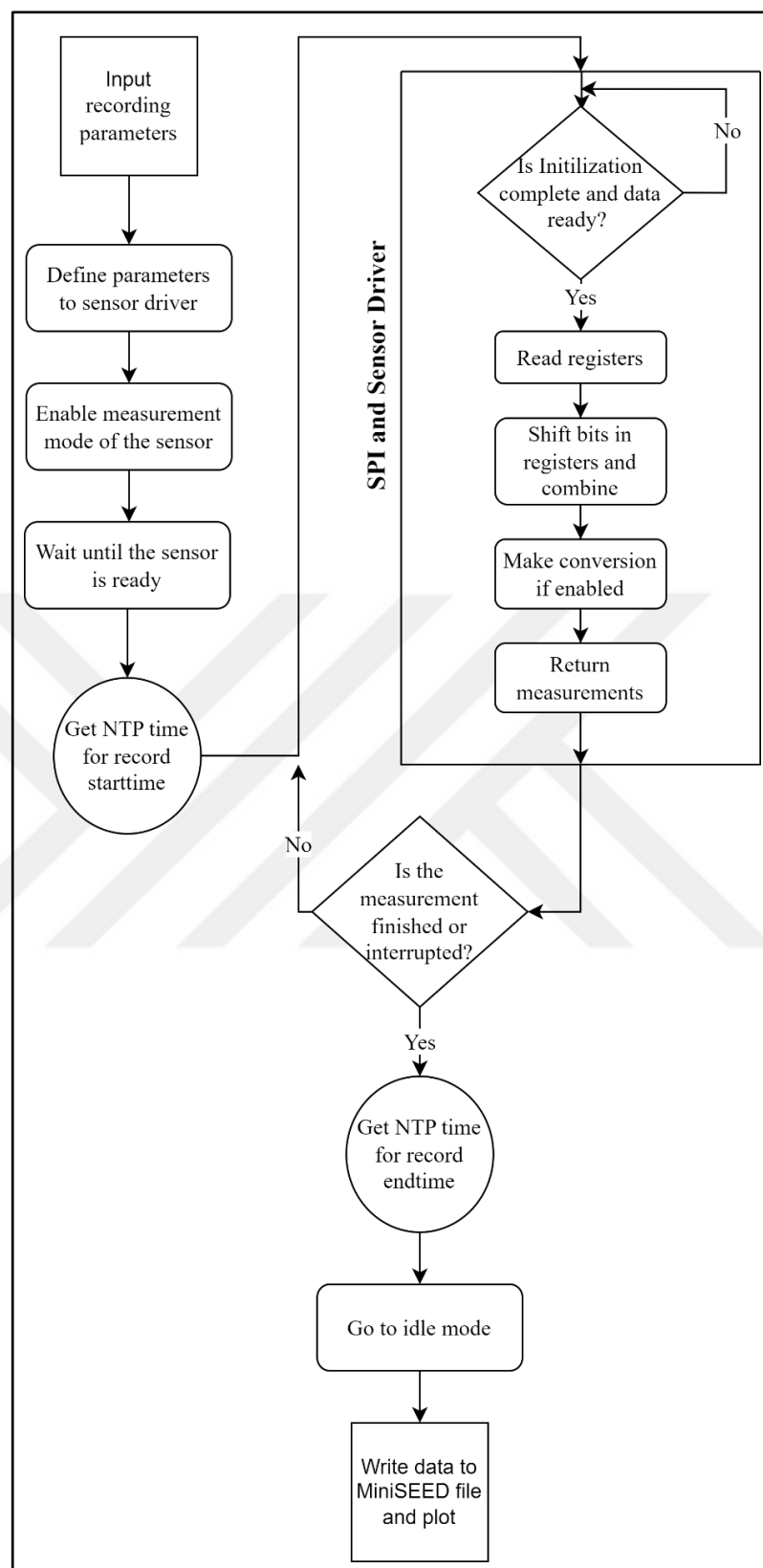


Figure 2.6: CEDAS_acc and CEDAS_geo device algorithm flowchart.

The algorithm starts with a user input. User need to set parameters to configure sensor and header information of the MiniSEED file. These parameters include sampling rate, number of data points and name of the network, station, location, and channel. Records start time and end time automatically added to headers as UTC datetime. Then, measurement range and sampling rate is defined to MEMS sensor driver. For the CEDAS_geo device, defined parameters to the ADC driver are sampling rate, input channel and programmable gain amplifier (PGA) value.

After the parameters are set, the algorithm restarts the conversion cycle and enables measurement mode from the driver. Algorithm delays due to the devices settling time. Delay of 50 millisecond is sufficient for both devices. Before starting the recording loop, the device turns on the recording light and gets NTP time as the start time of the measurement. Inside the recording loop, algorithm starts another polling loop to control Data Ready (DRDY) pin of the sensor board and ADC. Detailed information about the DRDY part of the algorithm given in Section 2.4.5. Readings from the ADC made by a continuous mode defined in the datasheet [24]. This mode enables to read data without waiting and synching for conversion cycle restart.

When a new measurement data is available, polling loop ends and data is read from the registers. Each device reads three bytes via the SPI bus, MEMS sensor returns 20-bit data for each axis, ADC returns 24-bit data. These bytes are merged and converted to integers values. Depending on the user input, conversion is made from raw data to acceleration or velocity. Lastly data is returned and saved into an array. If the recording duration is not completed or device is not interrupted, the recording loop continues. Otherwise, algorithm saves the measurements end time as a UTC datetime, device goes to idle or low power mode and recorded data inside the array is written to MiniSEED formatted file with the header information.

2.3. Application And Requirements

MEMS accelerometers and geophones find applications in various fields where the monitoring of motion, vibration and seismic activity are essential. CEDAS devices aim to be utilized in various applications. Accelerometers are employed to assess motions and vibrations of structures such as residential buildings, high-rise buildings, bridges, dams, and tunnels. They allow the evaluation of modal properties of the

structures, especially, CEDAS_acc device is suitable for forced vibration tests, shake table test and university laboratories for graduate/undergraduate education.

Geophones are particularly used in monitoring seismic activities. They form a backbone of seismograph networks for recording waveform of ground motion for seismology and early warning systems. CEDAS_geo is more suitable for ambient vibration and weak ground motion recordings.

Various guidelines exist, depending on the applications for different devices. The Advanced National Seismic System (ANSS) provides comprehensive instructions for the implementation of structural monitoring and the establishment of monitoring network stations at various scales, encompassing national, regional, and urban contexts. Guideline classifies instruments and gives expected performance specifications for the recommended instrument for the application [31], [32]. Additionally, Hutt et al. includes guidelines for performance testing of weak motion velocity sensors and strong motion accelerometers. Guidelines include the importance of tests or parameters for the type of sensors as a primary or secondary concern [33].

Standard characteristic definition terms used for sensors are specified and explained below. In addition, examples have been provided through CEDAS devices:

- Resolution

Resolution refers to the smallest detectable change in acceleration or velocity that the device can measure. Higher resolution means the device can detect smaller changes and provides more accurate and precise measurements if noise is not a concern. It is typically specified in terms of the number of bits. When selecting an accelerometer for a specific application, it is important to consider the required resolution based on the desired level of accuracy and the expected range of acceleration values to be measured.

As an example, CEDAS_acc device with a 20-bit resolution can assign 2^{20} (1,048,576) different acceleration value.

- Measurement Range

Measurement describes a level at which the output of a sensor deviates from the input signal. In other words, it is the minimum and maximum value that the sensor can accurately detect and measure.

CEDAS_geo devices use 5Hz geophone element with a measurement range of $\pm 1.6\text{mm/s}$ for the PGA level of 16 or below. By selecting higher gain levels, measurement range decreases while sensitivity increases. Example to clipping of CEDAS_geo shown in Figure 2.7. as an example.

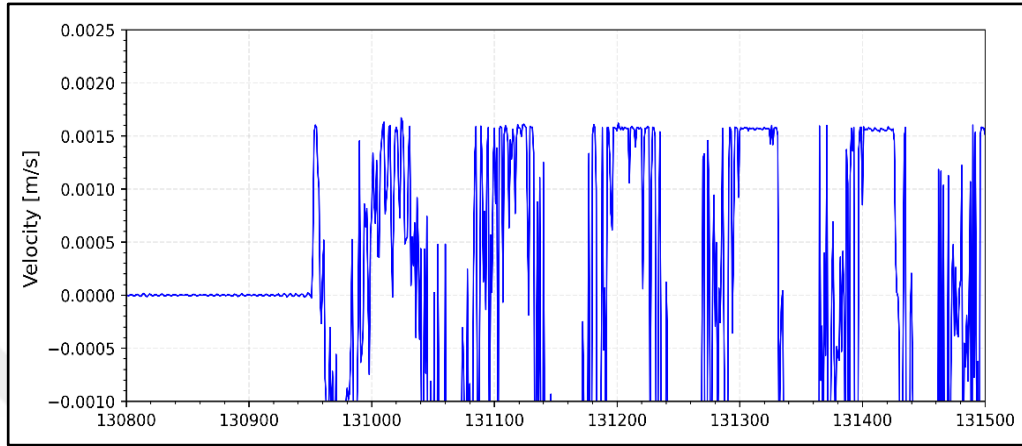


Figure 2.7: Clipping of CEDAS_geo device 5 Hz horizontal geophone element.

- Sensitivity

Sensitivity refers to the ability of a sensor to detect and respond to changes in the measured quantity.

Sensitivity for CEDAS_acc depends on measurement range and resolution. For the 20-bit CEDAS_acc device with $\pm 2.048\text{g}$ measurement range, sensitivity of the device given in equation 2.1:

$$2^{20} / 4.096 \text{ g} = 256,000 \text{ LSB/g} \quad (2.1)$$

Sensitivity values for different measurement ranges for CEDAS accelerometer are listed in Table 2.3.

Table 2.3: Sensitivity of the CEDAS_acc device for different measurement ranges.

Range (g)	Typical Sensitivity (LSB/g)	Scale Factor (g/LSB)
± 2.048	256,000	3.9062×10^{-6}
± 4.096	128,000	7.8125×10^{-6}
± 8.192	64,000	15.625×10^{-6}

- Frequency Response

Frequency response (Bandwidth) is defined as the lower and upper frequencies at which the magnitude drop is less than 3dB from the highest value.

Frequency response of the CEDAS_acc device's ADXL355 sensor board is shown in Figure 2.8. The response of the sensor stays in the 3dB in-band limit between DC to approximately 500 Hz [25].

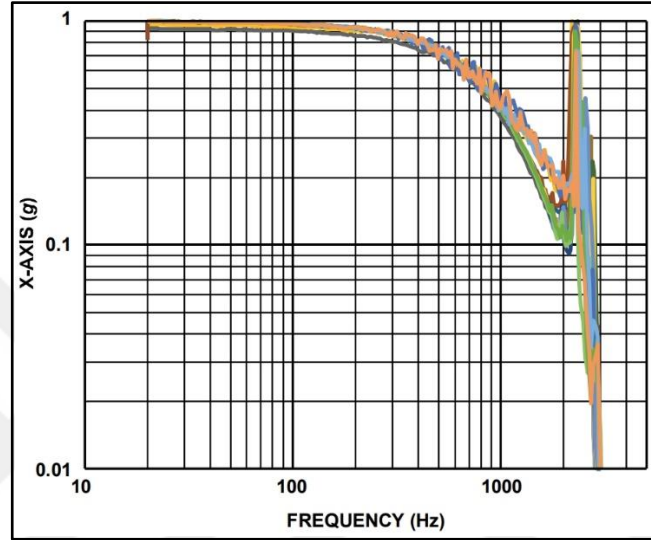


Figure 2.8: Frequency response of ADXL355 sensor.

For the CEDAS_geo, frequency response of the ADC drops by -3dB at 44.2 Hz for the 100 sample per second (SPS) [24]. Additionally, frequency response of a 5 Hz geophone element assessed in evaluation tests at section 3.3.

- Noise Density

The noise of a device is an unwanted output that does not represent real motion or vibration. Noise is specified as RMS or spectral density. In this thesis noise performance of the devices indicated as spectral noise density which assesses the noise characteristics of a sensor across its operating frequency range. CEDAS_acc has a noise density of $20 \mu g/\sqrt{Hz}$ between DC to 500 Hz frequency according to datasheet [25]. Noise density of the CEDAS_geo shown on a spectrum at the evaluation tests at next section in a Figure 3.21.

- Offset

Offset or bias represents the deviation of the sensor's output from the true or expected value when the input is supposed to be zero. It is important to compensate and correct the offset when using sensors to ensure accurate and reliable measurements regarding regulations.

2.4. Device Features

2.4.1. Raspberry Pi Single-Board Mini-Computer

CEDAS devices use a Raspberry Pi 4 Model B 4GB version model as a processor. The Raspberry Pi 4 is a versatile single-board computer. Platform offers a Raspbian real-time Linux or preemptive-kernel Linux operating system with support for many digital interfaces such as I2C, SPI and UART [26]. A 40-pin GPIO pinout enables direct interconnection of a sensor and an ADC to computer board. Secure Shell (SSH) and Virtual Network Computing (VNC) protocols enable the use of the device remotely by another computer. Wireless network connection offers an unlimited number of configurations and makes the device a standalone data-logger.

2.4.2. Sensors

CEDAS_geo uses a 5 Hz horizontal and 10 Hz vertical geophone element. Technical properties are only given for horizontal devices and the following tests include horizontal geophone element that has a 5 Hz natural frequency, 80 V/m/s sensitivity, 1850 Ω coil resistance and 0.6 open circuit damping. Additionally, vertical measurement can be made by an included 10 Hz vertical geophone element with 28.8 V/m/s sensitivity. Sensors used on CEDAS devices are listed with their technical properties in Table 2.4.

Table 2.4: CEDAS_geo and CEDAS_acc devices technical properties.

	CEDAS Geophone Device	CEDAS Accelerometer Device
Sensor	5 Hz Geophone Element	ADXL355
Measurement Range	± 1.6 mm/s (PGA=16)	$\pm 2g$, 4g, 8g
ADC Resolution	24-bit	20-bit
Noise Density	Figure 3.21.	$20 \mu g/\sqrt{Hz}$
Frequency Response	Figure 3.6.	0 – 500 Hz
Sampling Rate (SPS)	50,60,100,500,1000	62.5,125,250,500,1000
Supply Voltage	1.8V – 3.6V	2.25V – 3.6V

Prior to CEDAS_acc sensor selection, the performance of commonly utilized MEMS sensor boards in the research mentioned in the literature review were compared. The sensors are shown in Figure 2.9. with their general technical details in Table 2.5 [34], [35], [36], [25].

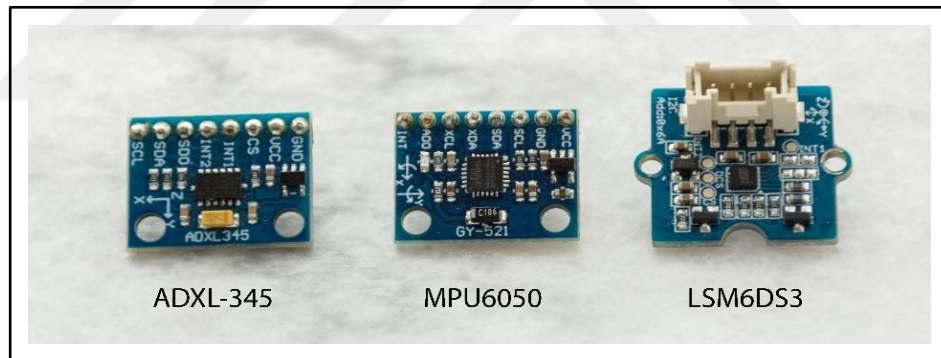


Figure 2.9: Tested MEMS evaluation boards for sensor selection.

Table 2.5: Tested MEMS evaluation boards.

MEMS Sensor Board	ADXL345	MPU-6050	LSM6DS3	ADXL355
Resolution	10-bit	16-bit	16-bit	20-bit
Measurement Range	$\pm 2g$	$\pm 2g$	$\pm 2g$	$\pm 2g$
Sensitivity (LSB/g)	256	16,384	16,384	256,000
Noise	0.75 (LSB RMS)	400 $\mu g/\sqrt{Hz}$	90 $\mu g/\sqrt{Hz}$	20 $\mu g/\sqrt{Hz}$

Sensor boards are assessed on a building model. Recordings were obtained synchronously with all devices on a structural model. Spectral density of the data shown in Figure 2.10.

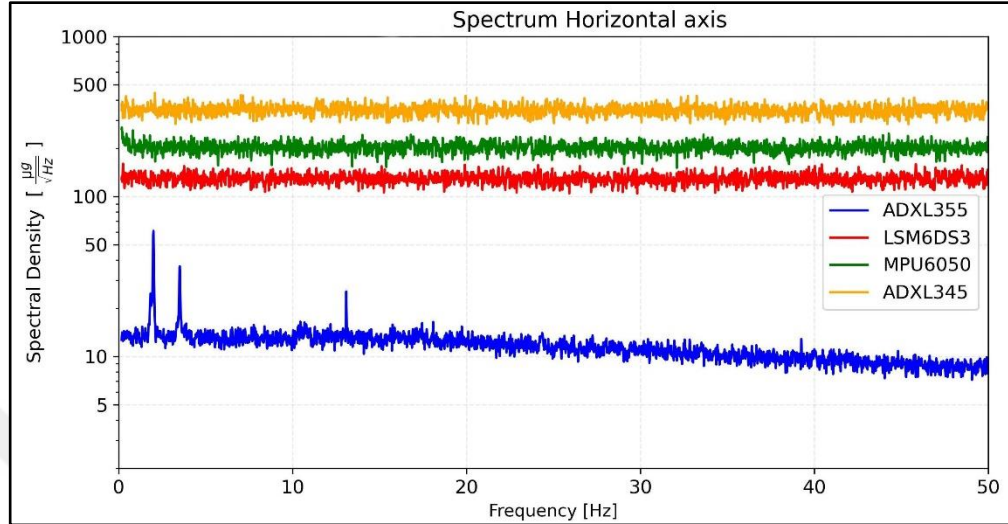


Figure 2.10: Spectral density of the MEMS sensor boards on a building model.

Sensors other than the ADXL355 can be classified as motion sensors which are not capable of vibration monitoring for buildings due to their noise levels. The only sensor capable of capturing modal frequencies of the building model is ADXL355 sensor. MPU6050 and LSM6DS3 sensor boards are limited by their noise level, ADXL345 is limited by a low resolution ADC used in the board.

2.4.3. Analog to Digital Converter

ADC is a component that is responsible for converting analog signal to a digital representation that can be processed and interpreted by a computer.

CEDAS_geo has a 24-bit ADC with 4th order delta-sigma modulator followed by a programmable digital filter. ADC board supports 2-wire differential connection for a total of 8 input channels. The device has a two geophone sensor connected to the two channels of the ADC. Desired sensor can be selected from the software without any physical interaction.

MEMS digital sensor board used in the CEDAS_acc has a three built-in 20-bit delta-sigma ADC with antialiasing filters. The board has an additional 12-bit ADC for its temperature sensor.

2.4.4. Power Supply

Accordingly, to Raspberry Pi 4 Model B datasheet, the device requires a decent quality USB-C power supply with capability of delivering 5V at 3A [15]. CEDAS devices consume approximately 800 mA when they are in the measurement mode with Wi-Fi enabled and connected to the network.

Devices can be powered by either plugging them into a wall outlet (AC) with a suitable adapter or by a battery (DC). The devices can record for 24-hours with 20000 mAh battery.

2.4.5. Network Synchronization and Sample Timing

CEDAS devices run on a Raspbian operating system. Raspberry Pi is configured to use the time sync servers provided by the NTP pool. This pool of servers maintains accurate time and will automatically boot servers that do not maintain an accurate time. While the CEDAS devices are connected to a network it maintains the accurate time and stays synchronized. Measurements can be done without an internet connection on the other hand MiniSEED file cannot get proper information about the record start and end time without synchronization.

Having a stable sample interval between each measurement from the sensors is crucial for obtaining accurate signals in frequency domain. Therefore, the internal clocks of ADXL355 and ADS1256 are used for stable sample rate. Flowchart of the algorithm shown in the Figure 2.11.

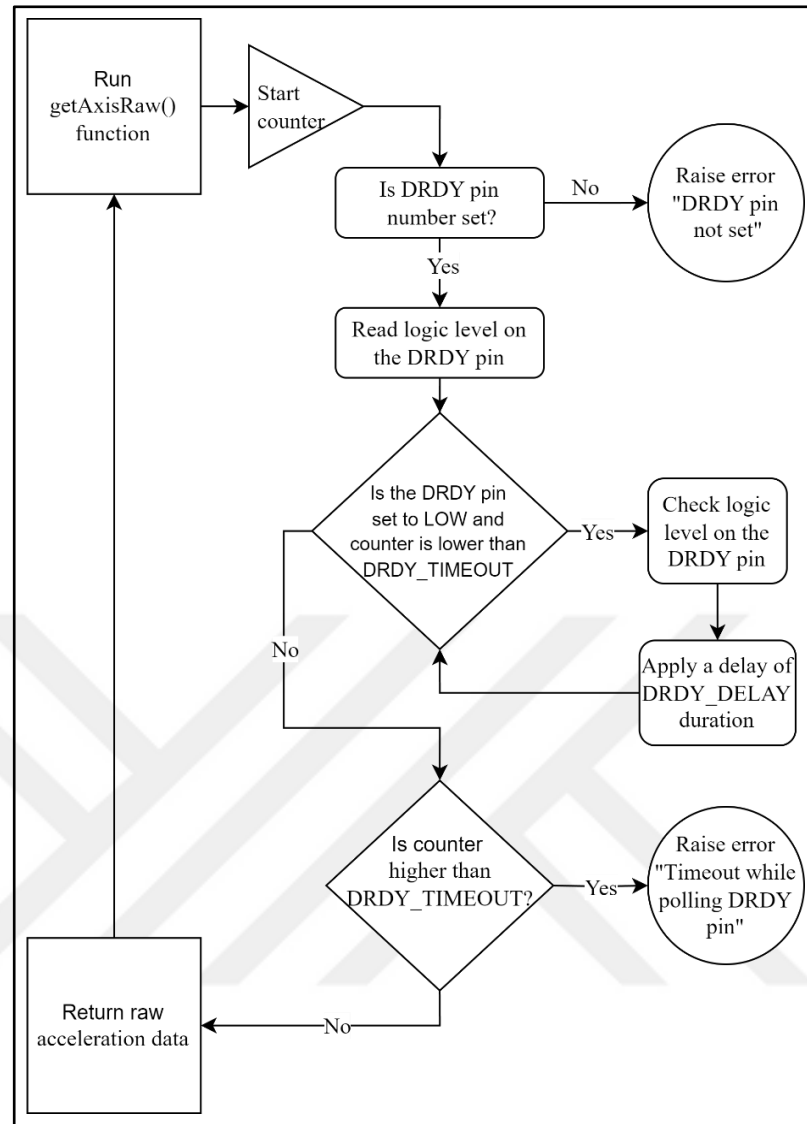


Figure 2.11: DRDY pin algorithm flowchart.

DRDY is an output indicator that signals sample being ready to read. When the new data is ready, DRDY pin is pulled to logic level of low to high, though, algorithm detects the new data is ready to be read. Figure 2.12. shows oscilloscope view of DRDY pin for ADXL355 sensor board with sampling rate set to 125 Hz. The wire is pulled low to high with 8000 microsecond intervals. Thus, the time between two samples is precisely adjusted via internal clock [24].

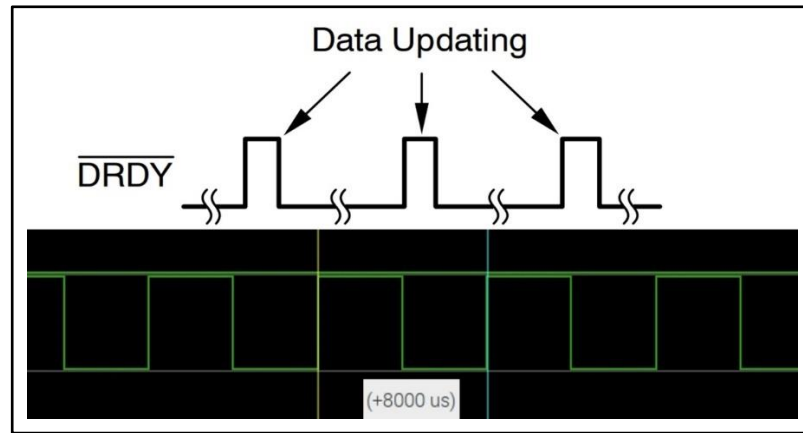


Figure 2.12: Oscilloscope view of CEDAS_acc device DRDY pin.

The frequency stability of the oscillator varies from sensor to sensor which introduces deviation at clock timing relative to each other [37]. The deviation is affected by environmental factors such as temperature, humidity, and aging. If the clock timing deviation is different than actual time delta, it will indicate that clock is slow or fast compared to real time and introduce a time drift. Deviation is represented in Figure 2.13.

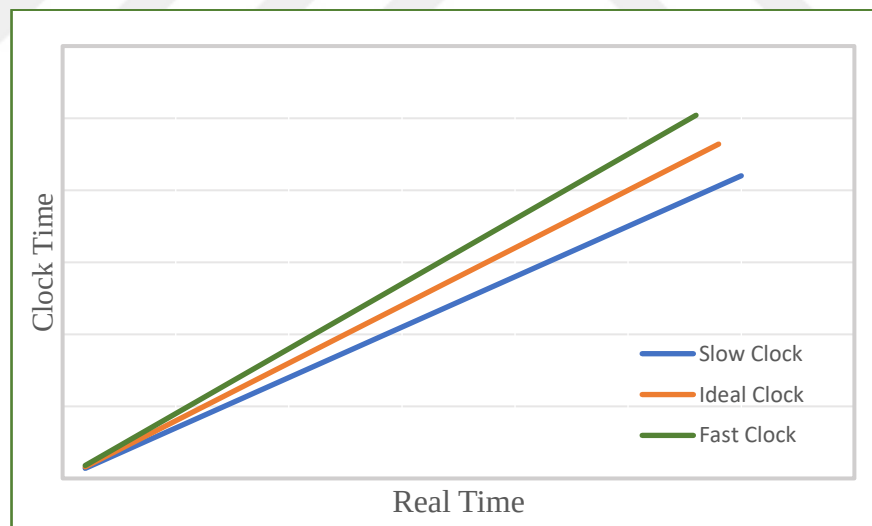


Figure 2.13: Clock delay illustration.

The frequency variation of internal clock used in ADXL355 sensor given in Figure 2.14 [25]. The clock of the sensor shows a frequency variation of 20% from the center frequency. This may introduce a frequency offset, causing a shift in measured signals center frequency. This can lead to inaccurate frequency measurements and affect the overall performance of the device [38].

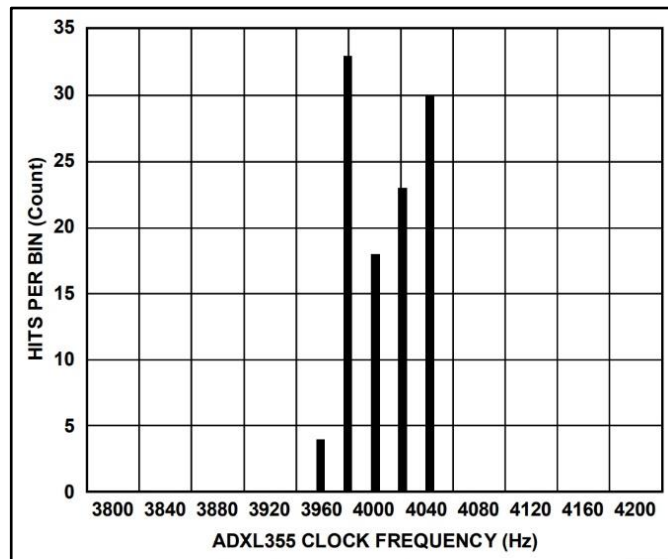


Figure 2.14: Histogram for ADXL355 internal clock frequency distribution.

2.4.6. Data Storage

CEDAS devices used in the tests store recorded acceleration and velocity data on the microSD card attached to it. SD card with minimum 8 gigabyte capacity and capability of writing minimum 10 megabytes per second is suggested. The daily capacity requirement for CEDAS_acc at default 125 SPS is 144 megabytes, for CEDAS_geo at default 100 SPS is 38 megabytes.

Recorded data stored in a MiniSEED file format. Along with the waveform data of the recording, following information stored in the file header:

- Network name,
- Station name,
- Location name,
- Channel name or names,
- Start time as a UTC Datetime,
- End time as a UTC Datetime,
- Sampling rate,
- Time delta between samples,
- Total number of data points,

2.4.7. Data Processing

Data processing of CEDAS devices involves conversion of raw data, filtering, time domain and frequency domain analysis.

Conversion of raw data to a desired unit of acceleration or velocity depends on the hardware of the device and user selected inputs. Formula of raw data to velocity conversion factor $K_{conversion}$ for the CEDAS_geo given below:

$$K_{conversion} = \frac{2 \times Reference\ Voltage}{Geophone\ sensitivity \times ADC\ Gain \times ADC\ bit\ count} \quad (2.2)$$

For all the tests made in the dissertation, 5 Hz horizontal geophone element is used with 80 V/m/s sensitivity, 24-bit ADC and PGA parameter set to 16. Reference voltage of the ADC board is 2.5V. Raw data converted to velocity unit of m/s with a factor calculated below:

$$K_{conversion} = \frac{2 \times 2.5V}{80 \frac{V}{m/s} \times 16 \times 2^{24}} = 2.328 \times 10^{-10} m/s \quad (2.3)$$

CEDAS_acc has a default $\pm 2.048g$ measurement range with 20-bit ADC. Raw sensor data can be converted to acceleration unit of g by multiplying raw data with the given value below:

$$K_{conversion} = \frac{Total\ Range}{ADC\ bit\ count} = \frac{2 \times 2.048g}{2^{20}} = 3.9 \times 10^{-6} g \quad (2.4)$$

For processing of the data, the Butterworth filter is used. The filter is based on the Butterworth polynomial, which defines the transfer function of the filter. The order of the Butterworth filter determines the steepness of the roll-off and the sharpness of the transition band. Throughout the conducted tests, low-pass Butterworth filters are used [39].

Welch's method, also known as the Welch periodogram, is a popular technique used for estimating the spectral density of a signal [40]. It is a modification of the traditional periodogram method and is designed to reduce the variance of the spectral

estimate by dividing the signal into overlapping segments. It provides a trade-off between frequency resolution and variance reduction [40].

$X(j)$ is a stationary sequence from $j = 0$ to $N - 1$ sample. Let $X(j)$ have a spectral density of $P(f)$. Overlapping segments with a length of L and the starting points of these segments is D units apart. With the total of K number of segments, Fourier transforms these sequences calculated by [40]:

$$A_k(n) = \frac{1}{L} \sum_{j=0}^{L-1} X_k(j) W(j) e^{-2\pi k i j n / L} \quad (2.5)$$

Total of K modified periodogram $A_k(n)$ is calculated by:

$$I_k(f_n) = \frac{L}{U} |A_k(n)|^2 \quad (2.6)$$

Where U is:

$$U = \frac{1}{L} \sum_{j=0}^{L-1} W^2(j) \quad (2.7)$$

And f_n is calculated with an n between 0 to $L/2$.

$$f_n = \frac{n}{L} \quad (2.8)$$

The estimate of the average of these periodograms is calculated by:

$$P(f_n) = \frac{1}{K} \sum_{k=1}^K I_k(f_n) \quad (2.9)$$

Segmentation is illustrated in Figure 2.15.

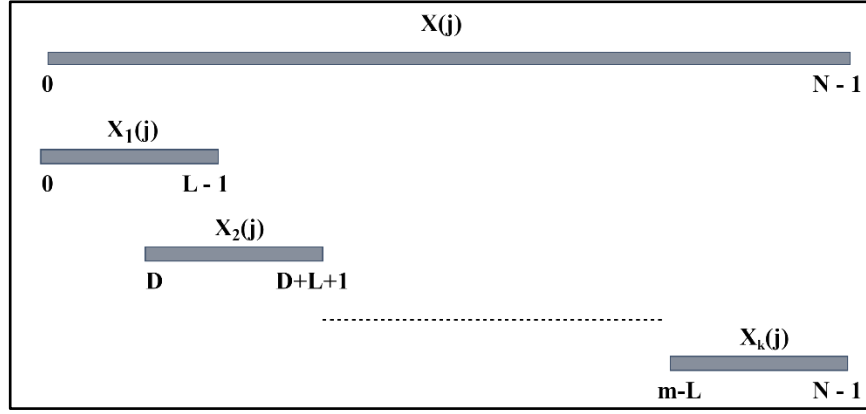


Figure 2.15: Illustration of record segmentation.

Different window sizes are used for spectral analysis in the following sections. Windows are averaged by %50 overlap with Hanning window. The Tukey type window is used in spectrogram calculations to maintain statistical independence between segments compared to Welch's method. Spectrogram is a way of visualizing the change of a signal's frequency content over time.

Transfer function is used for identifying response of a building by making comparison of input and outputs. It is defined as a correlation between the estimation of Spectral Density (SD) of input and output signals. It can be expressed as below:

$$H = \frac{SD \text{ of output signal}}{SD \text{ of input signal}} \quad (2.10)$$

2.4.8. Record Analyzer Software (RECANA)

A part of data analysis for CEDAS devices can be managed by the developed Record Analyzer (RECANA) web application. The RECANA software can be accessed through any web browser, or it can be installed locally by the executable version. MSEED, SAC or GCF formatted data is supported by the software.

Web application consists of two sections. In the import section, uploaded data can be read, and time series can be viewed with the header file information. Time series are automatically created by using header information. Data can be calibrated, the user needs to input calibration factor and unit of acceleration. Trimming of the time series is made by redefining the start and end of the record as seconds by a slider.

Filter and export section includes baseline correction, filtering and exporting of the data. Time series can be detrended by subtracting constant offset value or polynomial trend. When polynomial option selected, user need to select the order of the polynomial to fit. In the next part, an interactive filter kernel can be designed and applied to data. Low-pass, High-pass and Band-pass filters can be applied by user selectable corner frequencies. Lastly, data can be exported to .txt, .csv or .xlsx file formats for further analysis with desired software by the user. The algorithm flowchart of the web application is given in Figure 2.16.

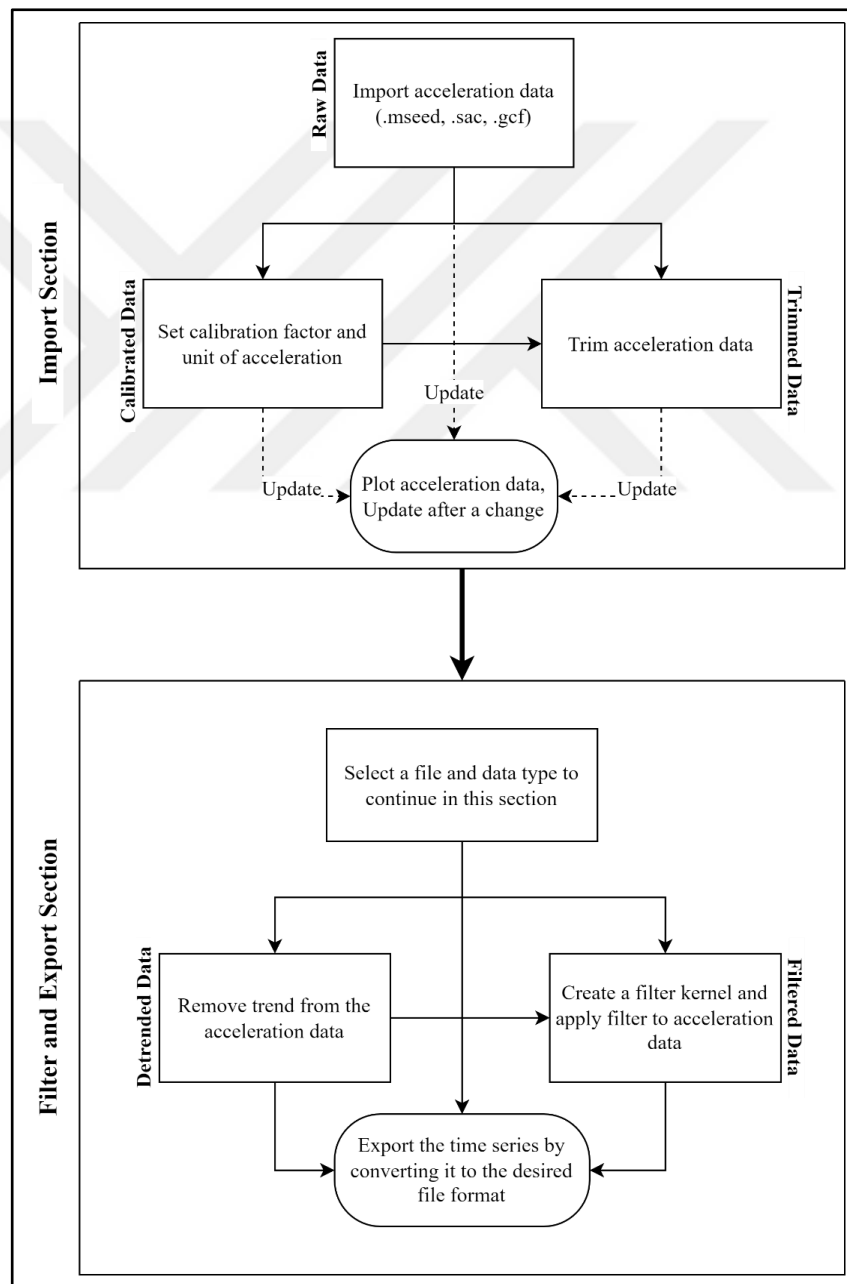


Figure 2.16: Record analyzer web application algorithm flowchart.

3. PERFORMANCE EVALUATION TESTS

3.1. Overview and Testing Methodology

The performance of the CEDAS_acc and CEDAS_geo devices are evaluated through three types of tests: offset test for CEDAS_acc, ambient vibration test to acquire frequency response of the CEDAS_geo, high-level excitation test with shake table for to obtain frequency response of CEDAS_acc device and lastly the noise test from a low noise environment. In these tests, Guralp CMG-5TDE strong motion accelerometer is used as a reference device. Guralp CMG-5TDE is a widely used broadband sensor for seismic data observations. Technical properties such as flat response between DC to 200 Hz makes it a great reference device for these series of tests [41].

Data processing and the analyses methods are conducted via the Python algorithms. The data processing steps for this section are given in the following list:

- Reading MiniSEED files of CEDAS devices and GCF files of Guralp device and getting the parameters of instrument calibration factor, record start time, record end time, sampling rate, number of data points information from the header of the files.
- Conversion of raw data to desired unit of acceleration. g, mg, or micro-g unit are used throughout the section.
- Trimming of the record for shake table analysis.
- Applying a baseline correction by fitting a linear function and subtracting from the signal. Baseline correction is not applied for offset test.
- Filtering by a 6th order low-pass Butterworth filter with 20 Hz cut-off frequency for offset and shake table test. Time series for remaining tests are not filtered.
- Calculation of spectral density and frequency domain filtering by applying Welch's method.

Measurements throughout the tests are executed with ± 2 g measurement range and 125 SPS for CEDAS_acc, ± 1.6 mm/s measurement range, PGA set to 16 and 100 SPS for CEDAS_geo device unless otherwise noted. Differently from CEDAS_acc

and Guralp, velocity records of CEDAS_geo are converted to acceleration before the analyses.

3.2. Offset Test

Offset refers to the DC (0 Hz) output level of the sensor when no motion is acting on it. The offset test is conducted by attaching the sensor to an accurately rectilinear cubic box. Then, box placed on a carefully levelled flat surface and records taken for six possible orientations [19]. Orientations are shown in Figure 3.1 [34].

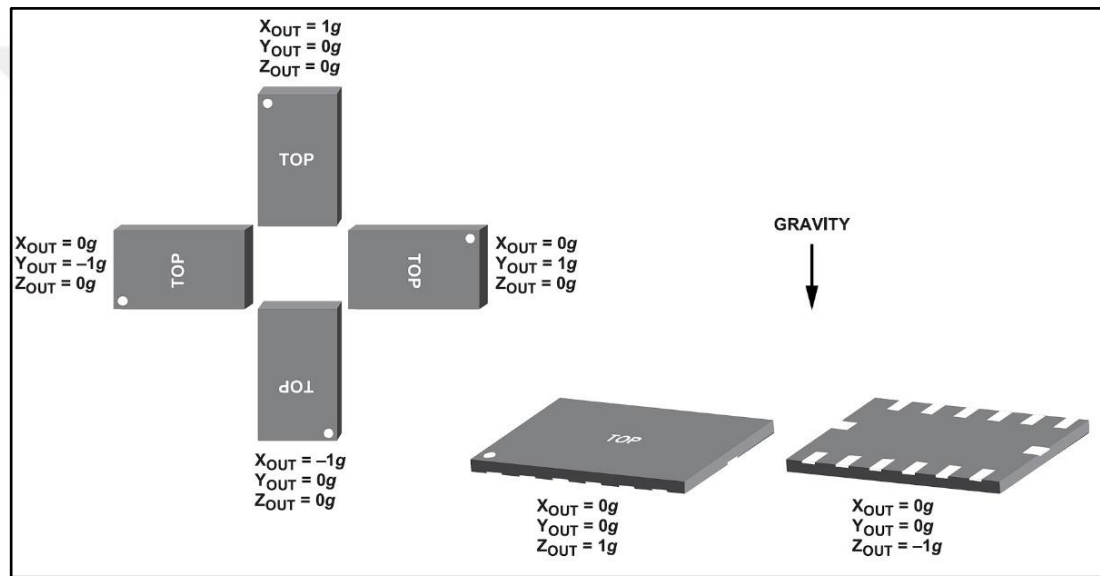


Figure 3.1: Sensor orientations used in the offset calibration test.

The accelerometer used in the device has a flat frequency response between DC to approximately 500 Hz [25]. Generally, accelerometers have this advantageous behavior which helps to evaluate the device by using gravity as a reference input. However, geophones have a low response at frequencies below their natural frequency. Also, it is not possible to use horizontal geophone element against gravity. Thus, this motionless test can only be conducted with an accelerometer device.

For each orientation, 60 seconds of data is averaged and offset values for each axis is calculated by the given formula:

$$\begin{aligned}
X_{Measurement} - X_{Actual} &= X_{Offset} \\
Y_{Measurement} - Y_{Actual} &= Y_{Offset} \\
Z_{Measurement} - Z_{Actual} &= Z_{Offset}
\end{aligned}
\tag{3.1}$$

Depending on the orientation, actual measurement is equal to +1g or -1g. By subtracting the actual measurement from the average of 60 seconds of measured data, offset value for the regarding axis and orientation is calculated. Test data is shown in Figure 3.2.

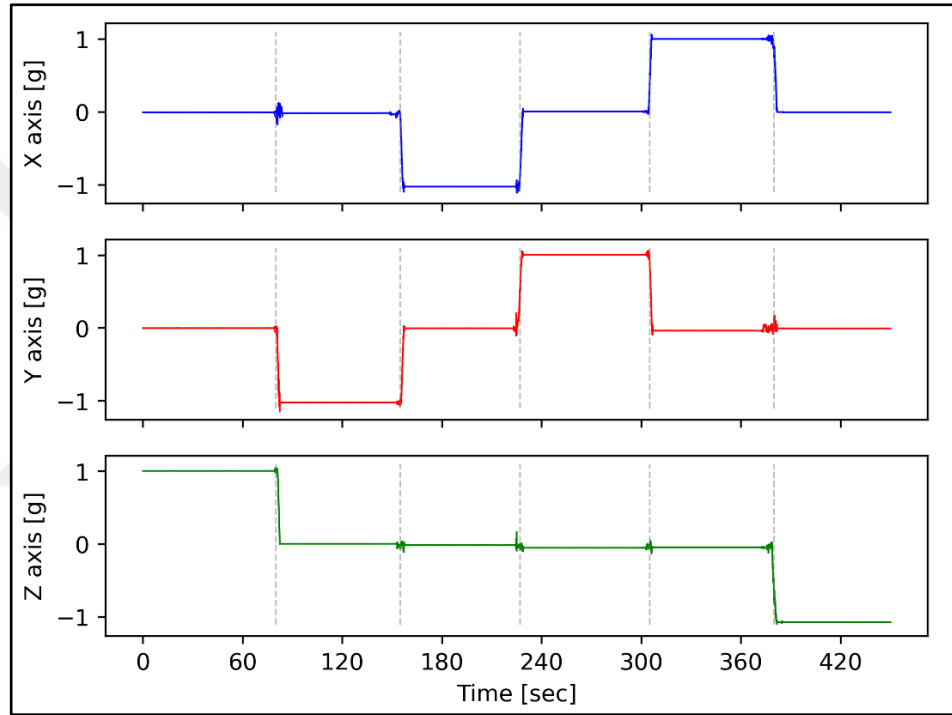


Figure 3.2: Time series from CEDAS_acc offset test, showing total of 6 orientations. Segments divided by dashed lines represent each flip.

As a result, offsets and static sensitivity of each axis is obtained for the accelerometer device. Each axis has sensitivity errors under 1% level which is ANSS instrumentation guidance for Class A and Class B accelerometers [31]. Maximum offset found 2% for horizontal axis and 6% for vertical axis. Found values are lower than the maximum offset values given in sensor datasheet [25]. These offsets are calibrated before the following tests by simply subtracting the measured errors from the sensor outputs and redefining the calibration factor of the device [42].

3.3. Frequency Response Tests

Frequency response tests for the CEDAS_acc and CEDAS_geo devices are conducted in Gebze Technical University Earthquake and Structure Laboratory (GTU-ESL). Different methods are used to determine devices' frequency response. Geophone device is evaluated by using ambient vibration recordings of Guralp sensor from the same location simultaneously. Accelerometer device is evaluated by a shake table with generated sine wave signals at various amplitude and frequencies.

Frequency response test of geophone device is performed by comparing recordings of Guralp reference device and CEDAS devices from the same position simultaneously. Figure 3.3 shows the location where the devices recorded ambient vibration data.

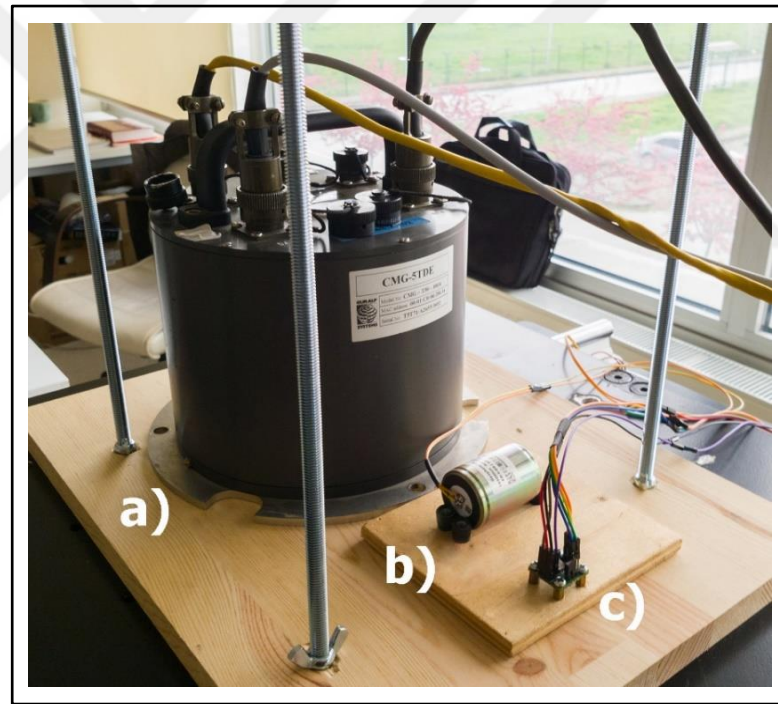


Figure 3.3: Sensor placements for frequency response test of (a) GURALP CMG-5TDE reference sensor with (b) CEDAS_geo and (c) CEDAS_acc devices.

CEDAS_geo, CEDAS_acc devices and Guralp reference device captured data at the GTU-ESL for 16-hours. Acceleration time series of records given in Figure 3.4.

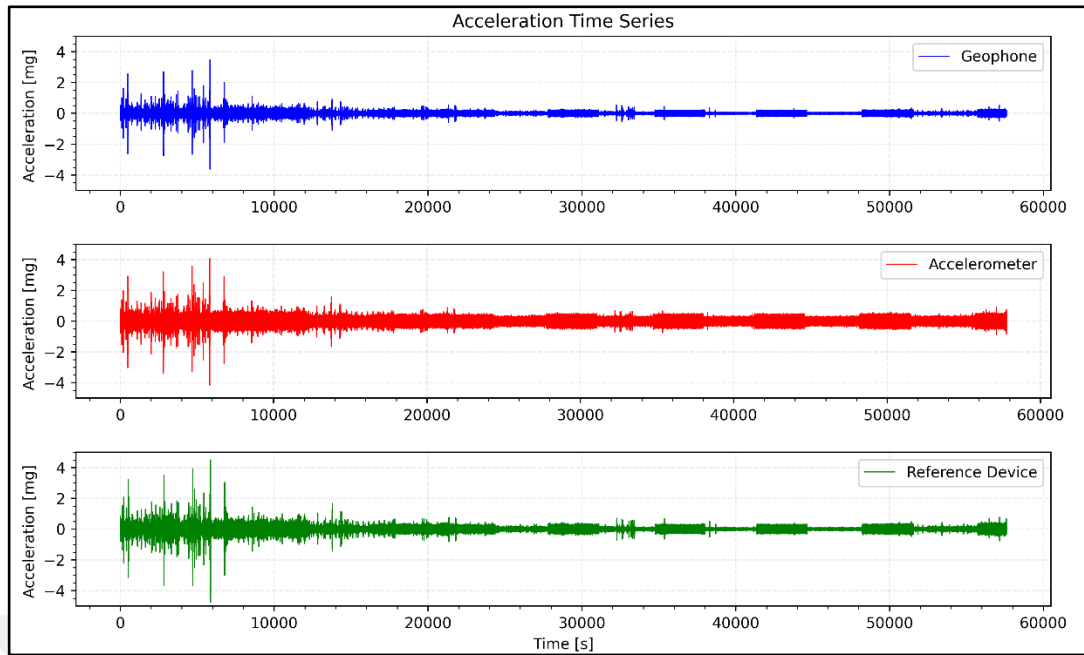


Figure 3.4: Time series of 16-hour synchronous environmental noise recording from CEDAS devices and reference sensor from same location.

Spectral density functions are calculated for the devices in a horizontal direction shown in Figure 3.5.

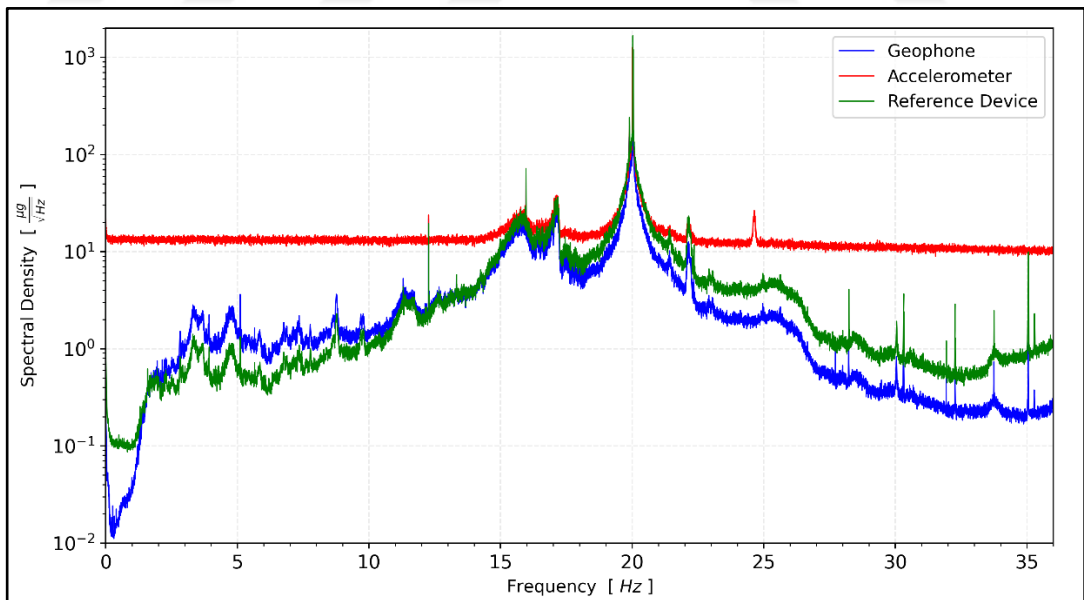


Figure 3.5: Spectral density of synchronous environmental noise recording from CEDAS devices and reference sensor at same location.

Reference sensor shows the actual spectral amplitudes of the ambient vibrations at the laboratory. Relative to other sensors, MEMS accelerometer device has higher

noise density, and it is unable to capture signals with lower than $15 \mu g/\sqrt{Hz}$ spectral density. Thus, this test is not appropriate to evaluate frequency response of accelerometer device in these conditions. However, CEDAS_geo is not limited by instrumental noise and can be evaluated.

Transfer function of the CEDAS_geo is calculated. The spectral density of Guralp reference device is used as an input, and the CEDAS_geo is considered as the output motion. Frequency response or transfer function of the device shown in Figure 3.6.

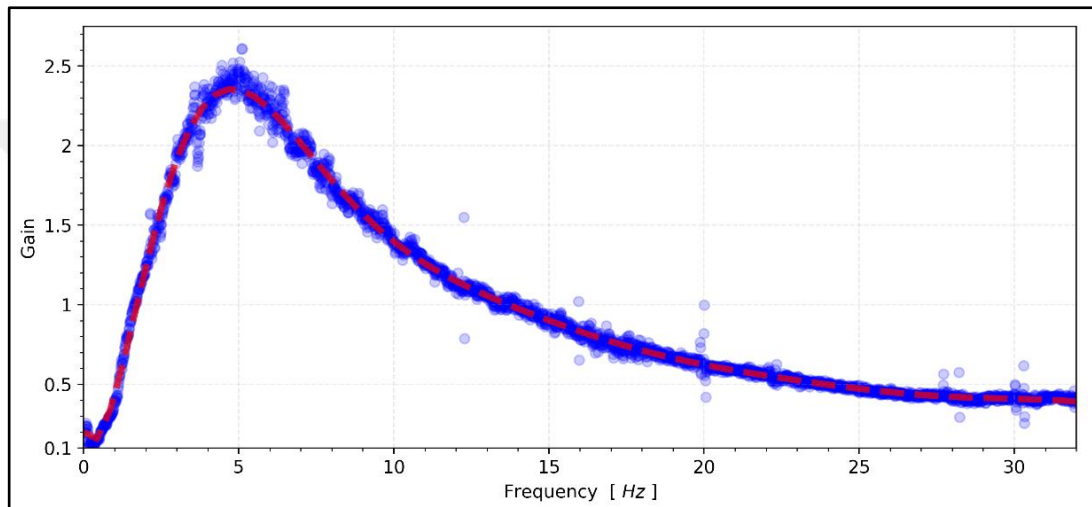


Figure 3.6: Response curve (transfer function) of the CEDAS_geo.

CEDAS_geo device has a response above the 3dB in-band limit at frequencies close to its 5 Hz natural frequency and response falls below 3dB in-band limit at the edges of the frequency range. Result shows geophone cannot be used without scaling the signal appropriately to transfer function. In the following tests, transfer function is applied to all data obtained from the CEDAS_geo device.

In this series of tests, frequency response of CEDAS_acc is tested by using Guralp device as a reference sensor. Tests are conducted on a single-axis shake table located at GTU-ESL, which has an operational frequency of up to 30 Hz. The shake table is shown in Figure 3.7.

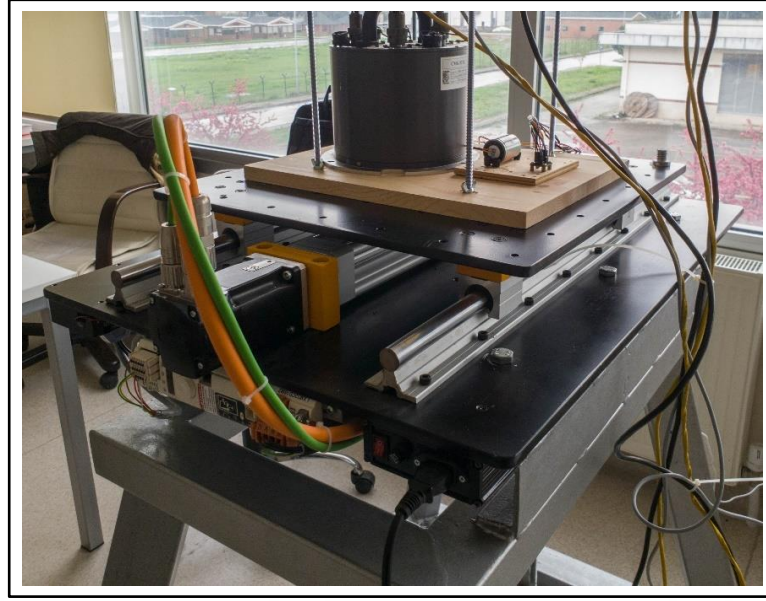


Figure 3.7: Shake table that used for frequency response test of CEDAS_acc.

For each test, five sinusoidal waves with constant frequency and variable amplitude (0.5Hz, 1Hz, 2Hz, 3Hz, 4Hz, 5Hz, 6Hz, 8Hz, 10Hz) are created and recorded simultaneously using the CEDAS_acc and the Guralp device. CEDAS_geo is not included in this test due to its insufficient measurement range for the shake table.

Filtered time series of each shake is overlapped with the Guralp reference device shown in Figure 3.8. The spectral density of the time series, which includes all shake tests, is presented in the Figure 3.9.

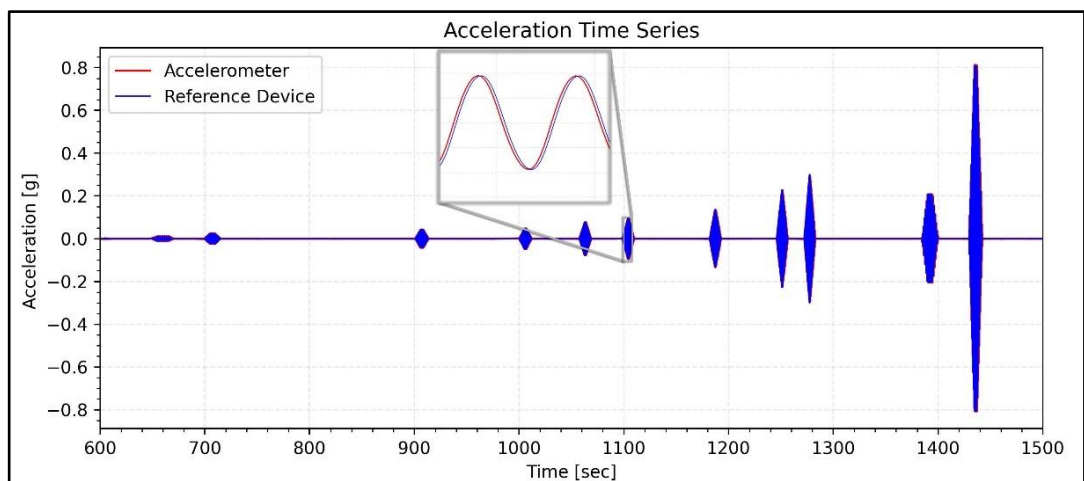


Figure 3.8: Time series of the shake tests.

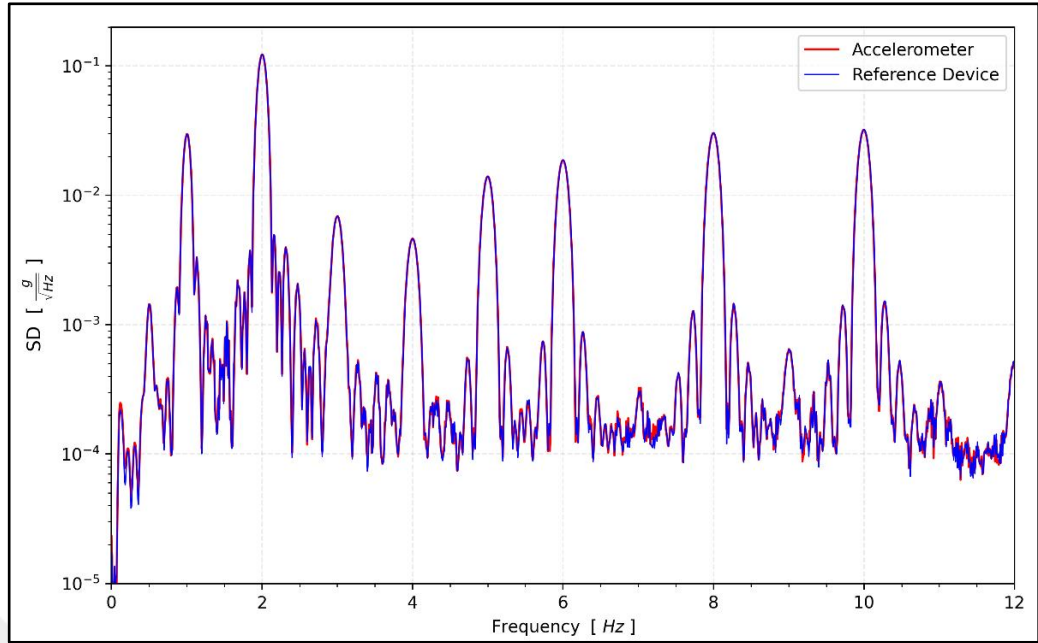


Figure 3.9: Spectral density of the shake tests.

Frequencies where the amplitude has peaked for both devices are shown in spectral density figures. Frequency values corresponding to peak amplitudes of each shake are overlapping with the reference sensor. This shows CEDAS_acc has an accurate and stable sampling rate. Time series and spectral density estimates for the shake tests are given in the figures between 3.10 to 3.18.

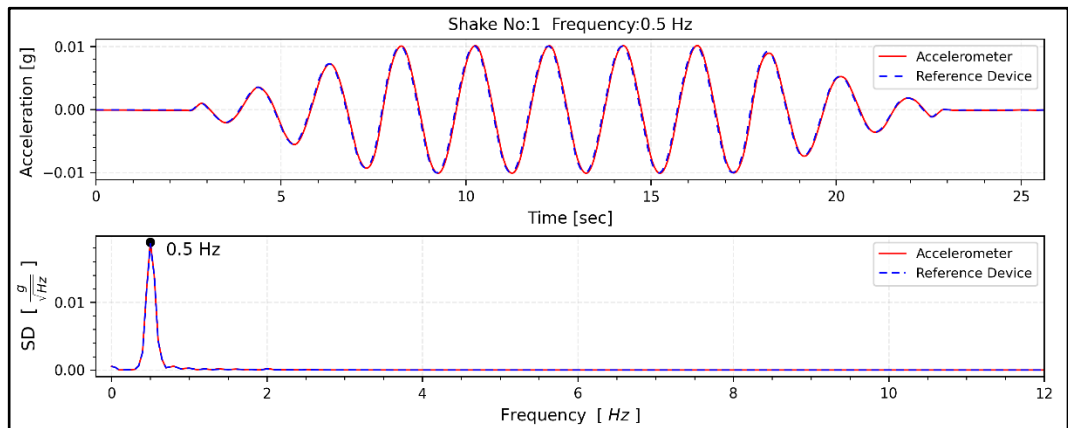


Figure 3.10: Time series and spectral density of the 0.5 Hz frequency sinusoidal signal.

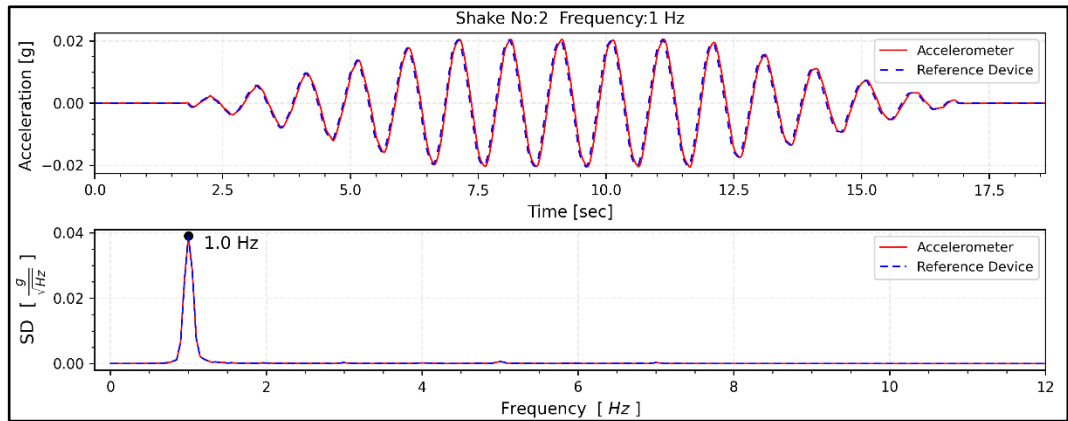


Figure 3.11: Time series and spectral density of the 1 Hz frequency sinusoidal signal.

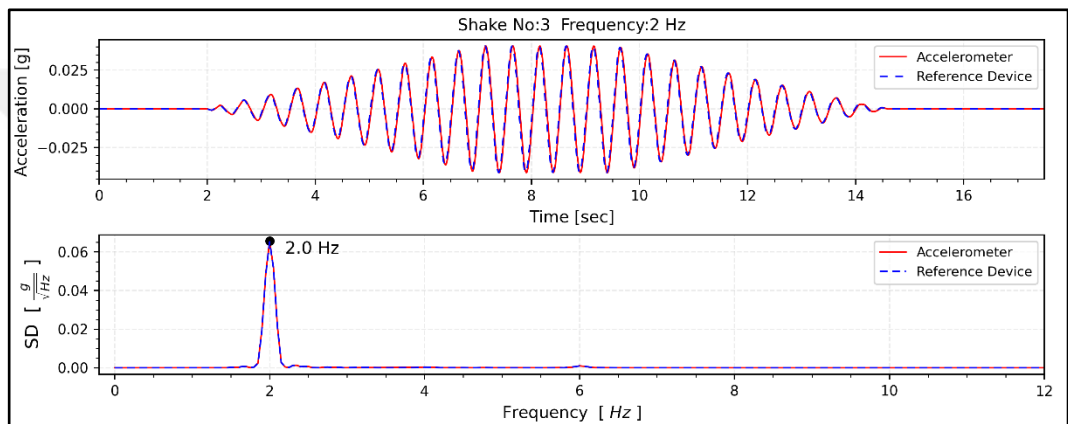


Figure 3.12: Time series and spectral density of the 2 Hz frequency sinusoidal signal.

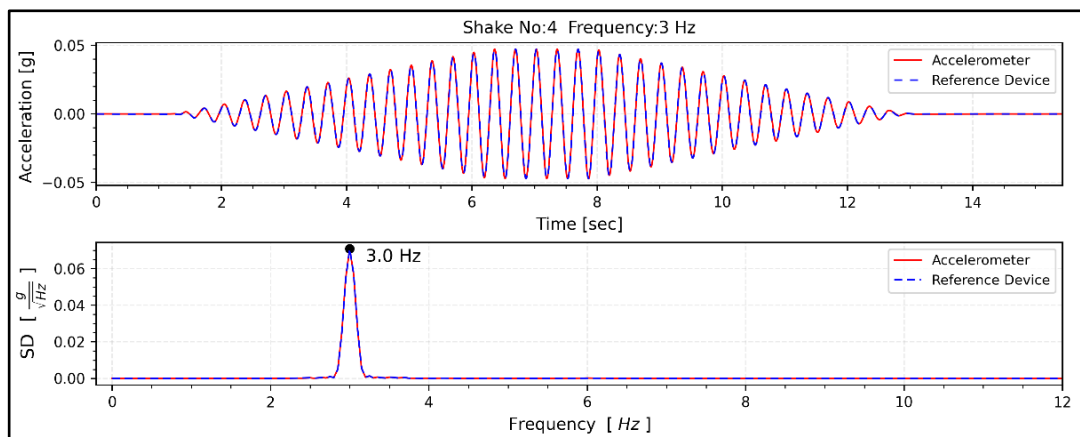


Figure 3.13: Time series and spectral density of the 3 Hz frequency sinusoidal signal.

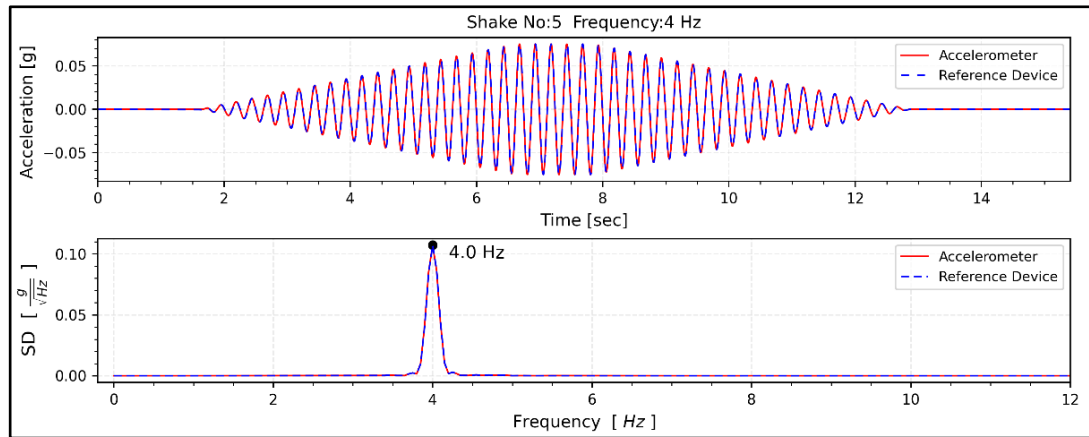


Figure 3.14: Time series and spectral density of the 4 Hz frequency sinusoidal signal.

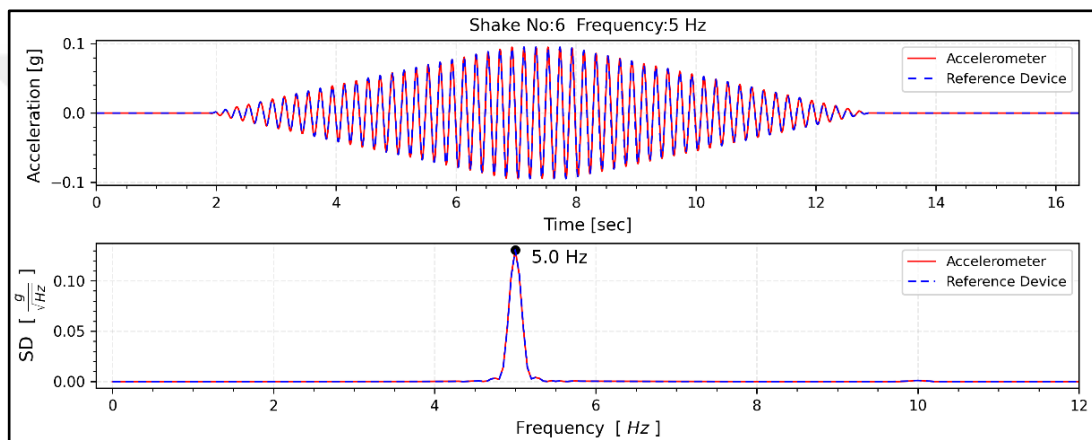


Figure 3.15: Time series and spectral density of the 5 Hz frequency sinusoidal signal.

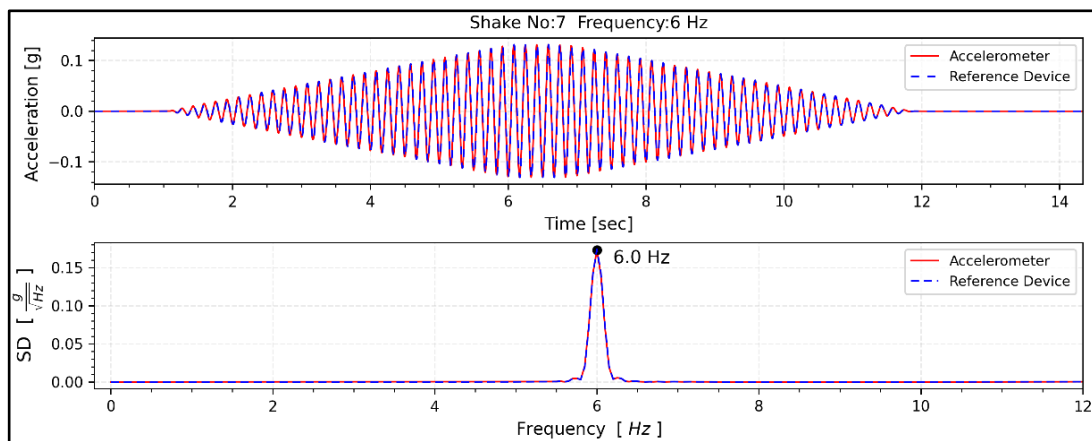


Figure 3.16: Time series and spectral density of the 6 Hz frequency sinusoidal signal.

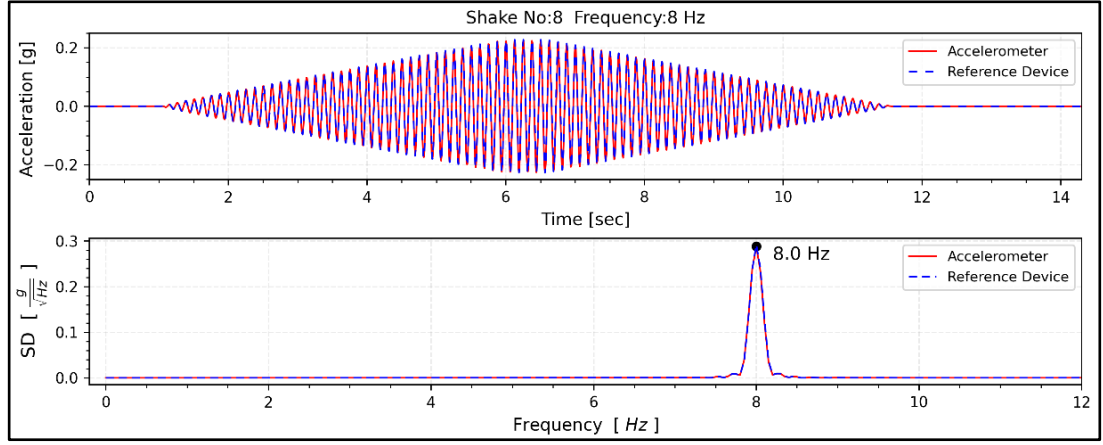


Figure 3.17: Time series and spectral density of the 8 Hz frequency sinusoidal signal.

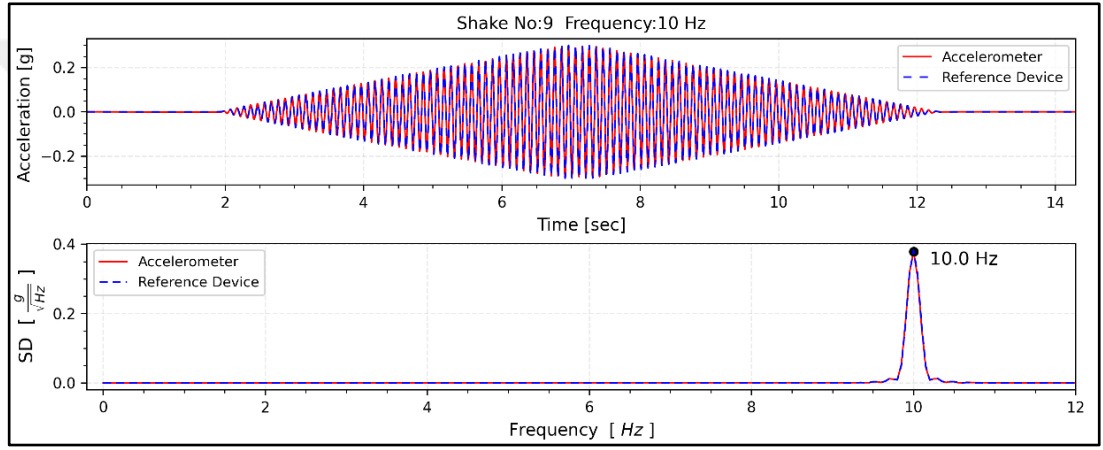


Figure 3.18: Time series and spectral density of the 10 Hz frequency sinusoidal signal.

Flat response of the reference device gives an opportunity to obtain frequency response of CEDAS_acc by comparing with the reference device. The error rates (amplitude deviations) R_{error} are calculated by comparing spectral density amplitudes corresponding to frequency of sinusoidal by using the formula given below:

$$R_{error} = \frac{a_{device} - a_{reference}}{a_{reference}} \times 100\% \quad (3.2)$$

Amplitude deviations between 0.5Hz-10 Hz shows maximum of 1.5% difference. Peak amplitude values and error rates for CEDAS_ACC and Guralp device are listed in Table 3.1 and visualized in Figure 3.19. Result shows the CEDAS_acc is in the 3dB limit and has a flat response between the tested frequency range.

Table 3.1: Frequency and amplitude values of each shake and spectral density amplitude deviation of CEDAS_acc regards to reference device.

Test No	Reference Device		Accelerometer Device		Amplitude Deviation (%)
	Frequency (Hz)	Amplitude (g/ $\sqrt{\text{Hz}}$)	Frequency (Hz)	Amplitude (g/ $\sqrt{\text{Hz}}$)	
1	0.5	0.01867	0.5	0.01886	1.01
2	1.0	0.03879	1.0	0.03904	0.64
3	2.0	0.06525	2.0	0.06561	0.55
4	3.0	0.07091	3.0	0.07098	0.10
5	4.0	0.11071	4.0	0.11068	0.03
6	5.0	0.13171	5.0	0.13155	0.12
7	6.0	0.17955	6.0	0.17816	0.78
8	8.0	0.29111	8.0	0.28752	1.25
9	10.0	0.38097	10.0	0.37702	1.05

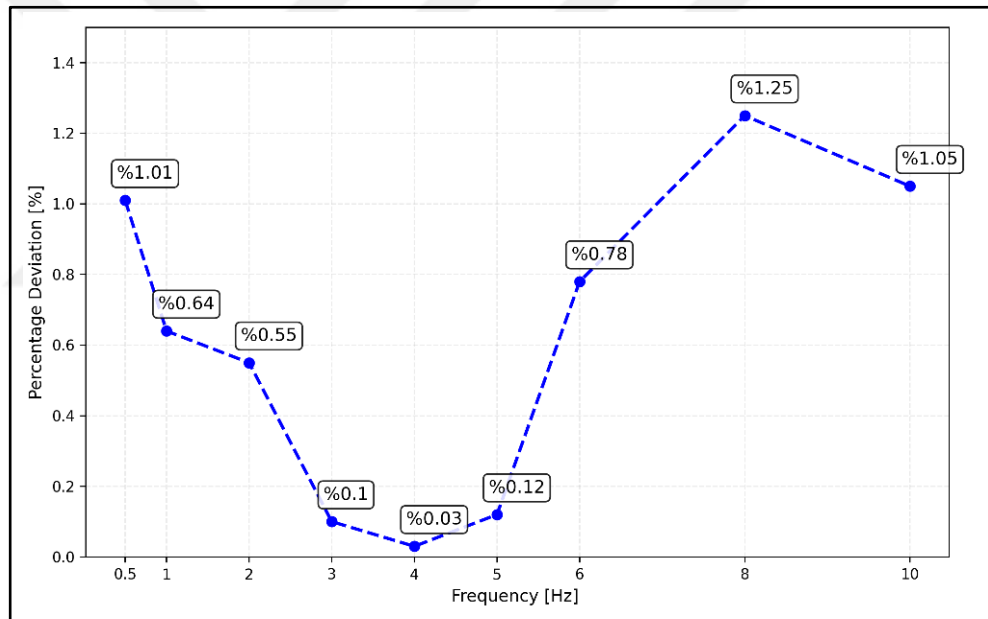


Figure 3.19: Spectral density amplitude deviation of CEDAS_acc regards to reference device.

3.4. Noise Test

In this test, noise level of the CEDAS devices given as spectral noise which provides noise level for various frequencies. The test is conducted in a rural area with low background noise level during the night. However, these conditions do not required to obtain noise level of CEDAS_acc, because the noise of the MEMS sensor

is well above from the ambient noise of the site. Thus, this test is focused to find out noise density of the CEDAS_geo.

The single-sensor method used with the assumption of the site noise is well below the self-noise of the device [43]. Records are taken from the mentioned site for a total of 45 minutes with a 5 Hz horizontal geophone element. Result is compared with the Cauzzi and Clinton (2013) high-noise and low-noise model for accelerometers [44]. Raw velocity time series from the low-noise site are shown in Figure 3.20.

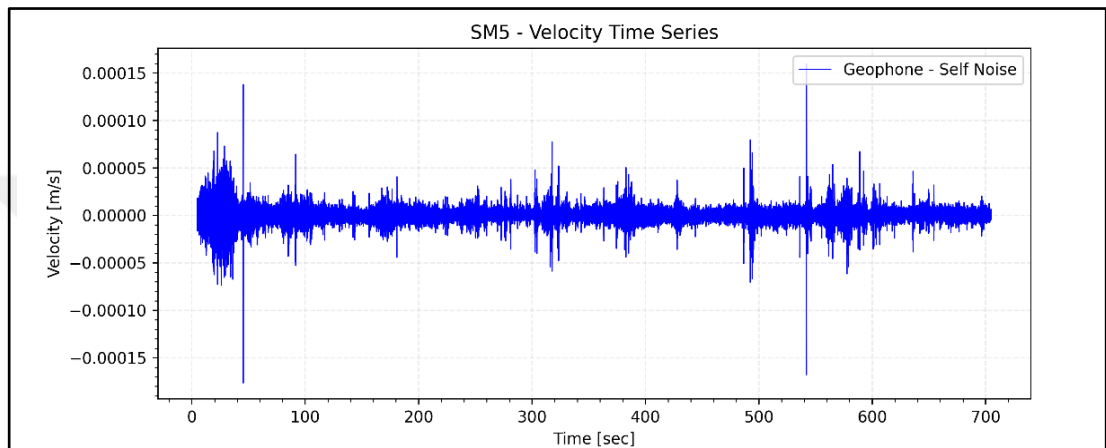


Figure 3.20: Time series of CEDAS_geo device from low noise environment.

Recorded raw velocity data is converted to acceleration and response of the device is corrected. For the CEDAS_geo, spectral noise density was found between the low and high noise models. Spectral density of the CEDAS devices with low and high noise models are shown in Figure 3.21 [44].

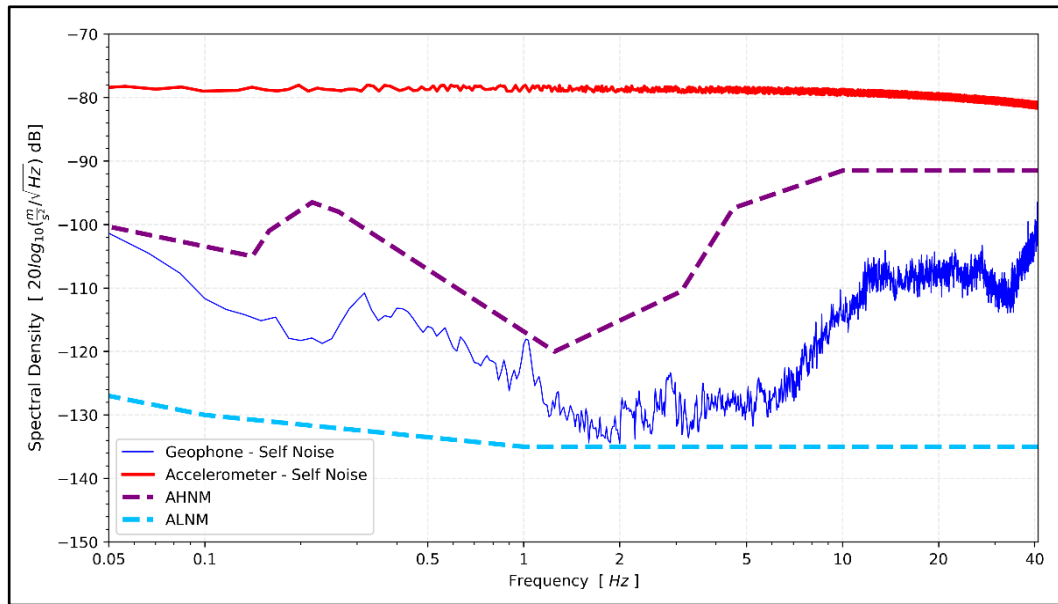


Figure 3.21: Spectral noise density of CEDAS_geo and CEDAS_acc devices from low noise environment compared to low and high noise models.

The spectral density of the CEDAS_geo indicates that the device has the potential to record vibrations lower than ambient noise of the site. Further tests are needed to find absolute instrument noise.

4. FIELD TESTS

4.1. Overview

After acquiring the characteristic parameters of CEDAS devices, a series of tests have been made on 3 different buildings. Selected buildings are 6 to 10 story reinforced concrete structures which, in general represents Turkey's common residential building stock.

Building 1 is located in a much more crowded area compared to Building 2 and 3. Which is exposed to higher level of environmental noise. Analyses on Building 1 aims to determine the capabilities of CEDAS devices for tracking modal frequencies from continuous ambient vibration data.

Building 2 and 3 are located in Gaziantep/Turkey has been temporarily instrumented between 6 April 2023 and 15 April 2023. Two months after the devastating 6 February 2023, M7.8 and M7.6 earthquakes, the region was still experiencing around 150 aftershocks daily. In conjunction with the effect of this situation, the responses of Building 2 and 3 under the influence of forced vibration by an earthquake are evaluated along with the ambient vibration analyses. The purpose of these tests is to evaluate the CEDAS devices performance under real environmental conditions, specifically when a building is subjected to a ground motion.

The devices were placed in accordance with the recommended instrumentation schemes from codes and regulations. Uniform Building Code (UBC) volume 2 recommends three triaxial devices at basement or ground floor, mid-floor, and top floor of the structure [45]. Celebi (2000) remarks UBC recommendations are suitable for monitoring rather than analyzing the structure. The instrumentation scheme should be sufficient to reconstruct the response of the structure [46]. Even though the aim of this thesis is not modeling of buildings and improving responses of the models, by considering future work, instrumentation made accordingly. Thus, free-field and ground floor recordings are important to understand soil-structure interaction. Sensor should be located at a distance greater than 1.5-2 times the height of the structure for free-field time series. To evaluate the effect of torsion, two parallel sensors at a maximum distance apart from each other should be placed. Extra sensors should be

placed on floors where the higher modes contribute the most and change of stiffness occurs [46].

Building 2 and 3 are instrumented with 8 CEDAS_acc devices in respect to mentioned guidelines. Guralp 5TDE strong motion accelerometers were placed at the most critical locations, which are the basement as a free-field and the top floor. Due to security concerns, free-field sensors are placed in the basement or ground floor of the structures. Next to Guralp devices at basement and top floor, CEDAS_acc devices are placed for a direct comparison. The remaining CEDAS devices are placed on the mid-floors and near the top of the building in the most out-of-center position possible on a plan. Additionally, a CEDAS_acc device is mounted to the center of the top floor on an elevator tower on both buildings in order to easily distinguish the translational and torsional modes without further process. Devices are placed in small, seldom-used rooms, cellars or closets near a shear wall or column. Instruments are placed on a clean, horizontally even surfaces.

Guralp devices are connected to AC power while CEDAS_acc devices powered by DC power from batteries due to inaccessibility to power at some locations and for the protection against power outages. CEDAS_acc devices record data throughout the night for approximately 18 hours a day. The remaining hours of the day are used to charge batteries and to control the sensors and integrity of the gathered data. Data processing and the analyses methods are carried out via the Python programming language. The data processing steps for this section are given in the following steps:

- Definition of sensor locations and orientations.
- Reading MiniSEED and GCF file formats of the devices and defining the parameters of instrument calibration factor, start datetime, end datetime, sampling rate, number of data points information from the header of the files.
- Conversion of raw data to desired unit of acceleration. Milli-g (mg) and micro-g (μ g) unit is used throughout the section.
- Trimming of the record according to the necessary analysis, earthquake or ambient vibration.
- Resampling of devices to 100 Hz sampling rate.
- Applying a baseline correction by fitting a linear function and subtracting from the signal.

- Filtering by a 6th order low-pass Butterworth filter with 20 Hz cut-off frequency for Building 1, 12 Hz cut-off frequency for Building 2 and 3.
- Estimation of spectral density, spectrogram, transfer function for the analyses.

Welch's method is applied with Hanning window with 50% overlap for the frequency domain filtering. Window size used in analyses changes between 20 to 120 seconds.

Integration from acceleration to velocity and displacement computed by approximating integral of the time series via trapezoidal method with delta unit spacing.

Building locations and earthquake epicenter maps are created with Python, PyGMT module [47]. Earthquake parameters are taken from Kandilli Observatory and Earthquake Research Center (KOERI) and Regional Earthquake-Tsunami Monitoring Center (RETMC) [48].

4.2. Building 1

4.2.1. Overview of the Building 1 and Instrumentation

In this part of the field tests, CEDAS devices are placed on a 6-story reinforced concrete building located in Safranbolu/Turkey. Measurements are made by a single horizontal geophone therefore, analysis results include the ambient vibration data only for EW direction of the building. CEDAS_acc and CEDAS_geo devices are located on the edge of the top floor. Instrument location and measurement direction is shown in Figure 4.1.

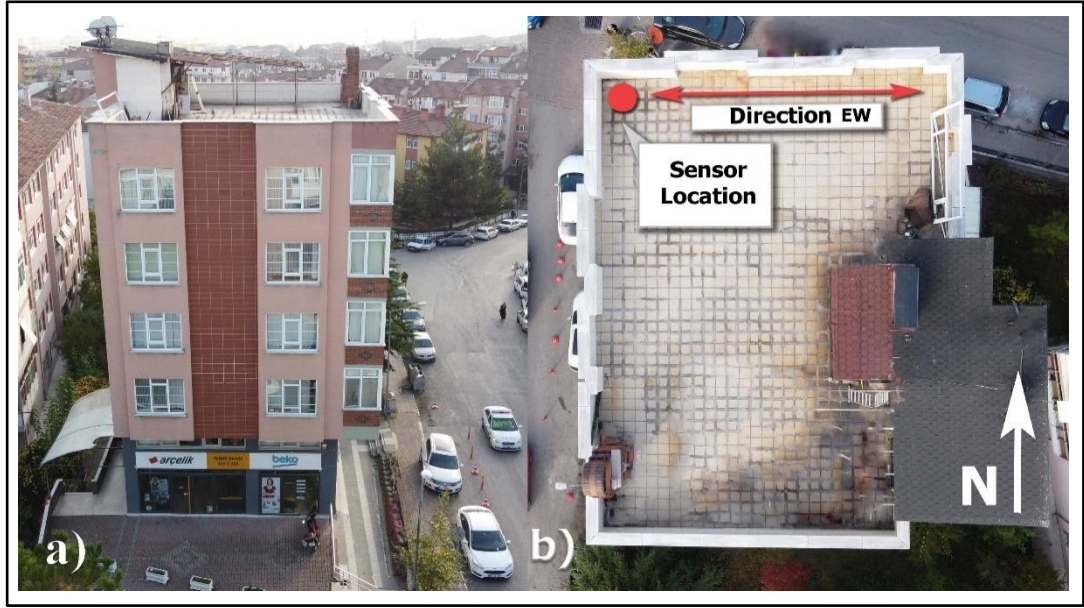


Figure 4.1: (a) Front view of Building, (b) sensor location and measurement direction from top view.

4.2.2. Ambient Vibration Analysis

The analysis aims to measure the capabilities of CEDAS devices for tracking modal frequencies from continuous structural ambient vibration data. An algorithm designed for finding peaks from calculated spectral density to track fundamental frequencies of the building. Algorithms find all local maxima values by comparing neighboring values. Additionally, updates peak properties for dynamically changing conditions on calculated spectral density. Parameters are given below:

- Threshold: Minimum amplitude or required threshold value for the peak.
- Prominence: Amplitude value that describes how much a peak stands out from the surrounding baseline.
- Frequency Distance: Required minimum frequency difference between two peaks.

Devices recorded structural ambient vibrations for 24 hours. 6th order low-pass Butterworth filtered time series with 20 Hz cut-off frequency are shown in Figure 4.2.

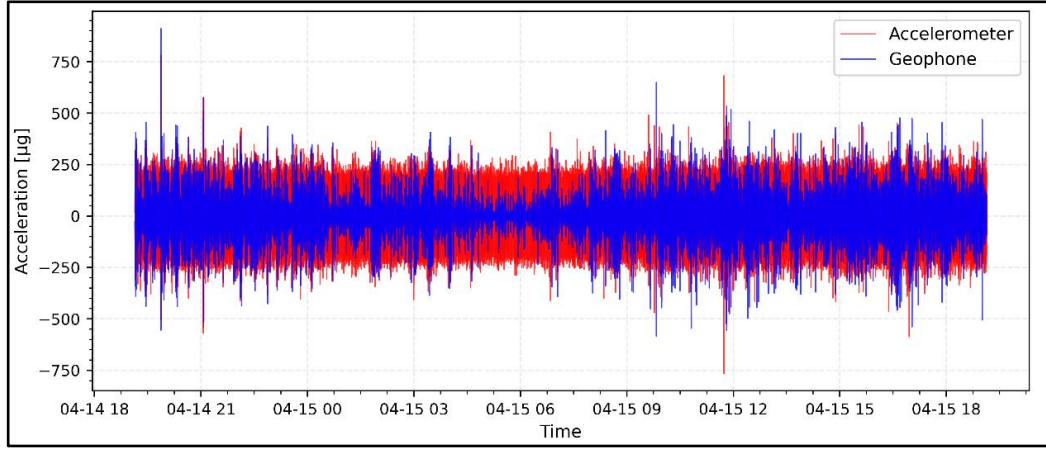


Figure 4.2: Overall look to 24 hours ambient vibration time series of CEDAS devices from Building 1 in EW direction.

Spectral densities of the 24-hour records are shown in Figure 4.3. The first three modal frequencies of the building for EW direction are observable at approximately 2 Hz, 3.5 Hz and 7.75 Hz, respectively. Frequencies are matched for both devices. The amplitude of the first mode matches however, second and third modes have different amplitude peaks. This circumstance was caused due to high noise of the CEDAS_acc.

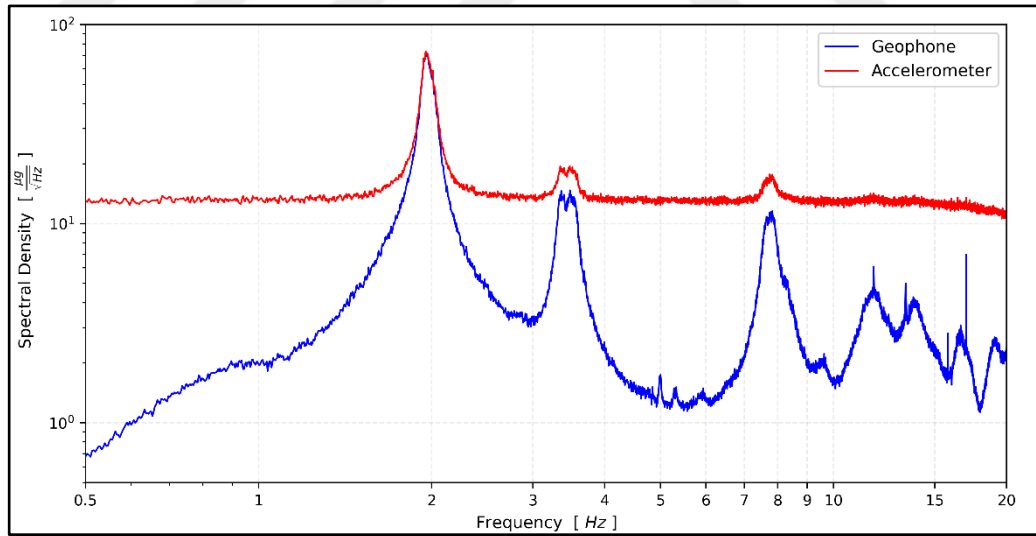


Figure 4.3: Spectral Density of 24 hours ambient vibration time series of CEDAS devices from Building 1 in EW direction

Peak picking algorithm is calculated with 3-minute running windows. Spectral density is calculated by applying Welch's method with 60 second time window with 33% overlapping to reduce noise in frequency domain. The first three peaks corresponding to maximum amplitudes are estimated. Analysis is recalculated five

times a second. Estimated modal frequencies are shown in Figure 4.4 and a more detailed view of modes in Figure 4.5. After each run, three dots are added to the figure which represents modal frequency estimation of the algorithm.

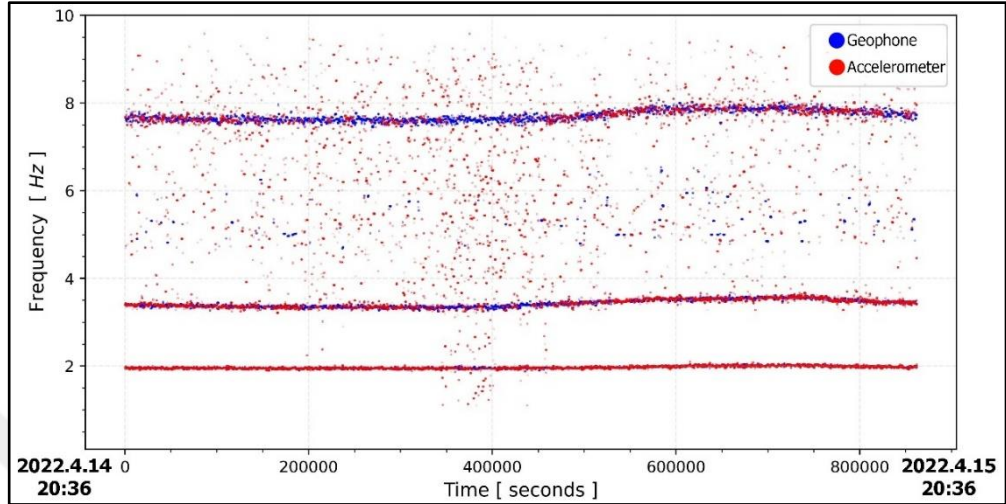


Figure 4.4: Detected natural frequencies with the peak picking algorithm for the first 3 mode of the Building 1 in EW direction.

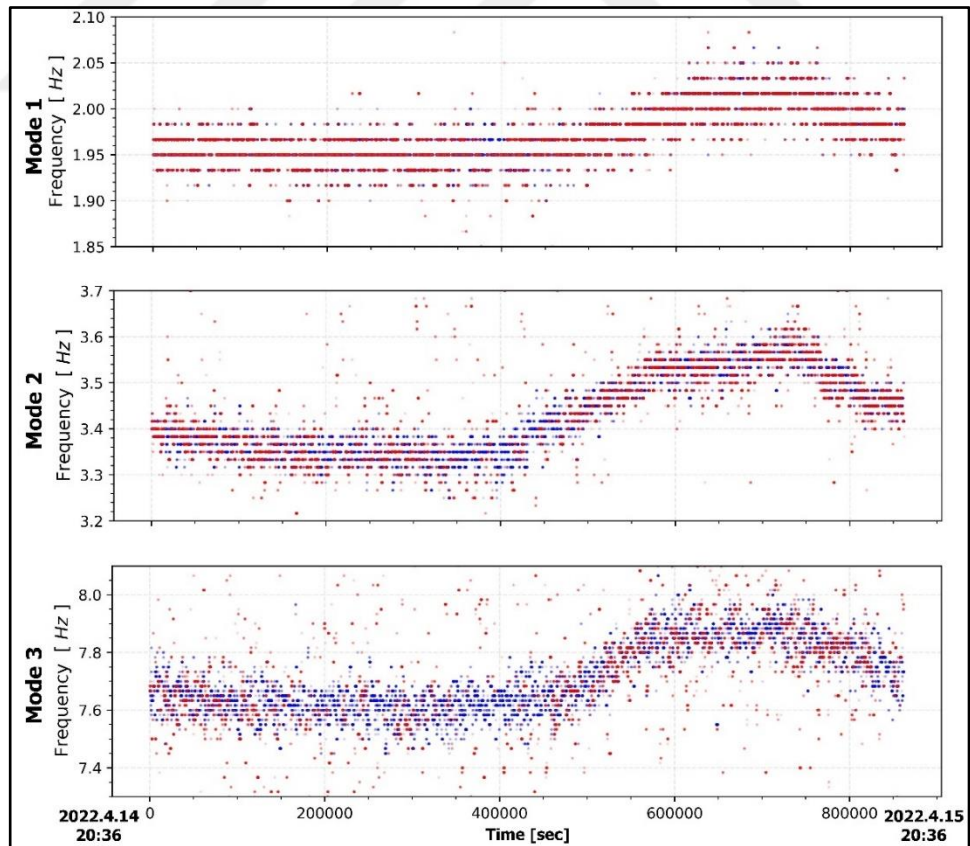


Figure 4.5: Cropped and detailed look to detected natural frequencies with the peak picking algorithm for the first 3 mode of the Building 1 in EW direction.

Results show a variation in each modal frequencies during the 24 hours of recording. To evaluate the accuracy rate of modal frequency estimation of the algorithm, a range has been determined for each mode. The ranges for the first, second, and third modes are as follows: 1.9-2.05 Hz, 3.3-3.6 Hz, and 7.7-8.0 Hz, respectively. The accuracy rate is calculated based on the occurrence of the estimated peak within these ranges. Accuracy rates for CEDAS_geo are 100%, 99%, 91%. For CEDAS_acc, accuracy rates are 96%, 69%, and 45% for the first, second, and third modes, respectively. Results are listed in Table 4.1.

Table 4.1: Accuracy rate of peak picking algorithm for the first 3 mode of the Building 1 in EW direction.

Mode No	Accuracy Rate (%)	
	CEDAS_acc	CEDAS_geo
1 (1.9Hz - 2.05Hz)	96.35	100
2 (3.3Hz - 3.6Hz)	69.41	99.75
3 (7.5Hz - 8.0Hz)	45.45	91.55

Due to the second and third mode of the building generating lower amplitude vibration than CEDAS_acc self-noise, the device loses track of the second and third modal frequencies compared to CEDAS_geo.

Similarly, modal frequencies and difference at noise levels for the CEDAS devices can be observed from the spectrograms shown in Figure 4.6 and 4.7.

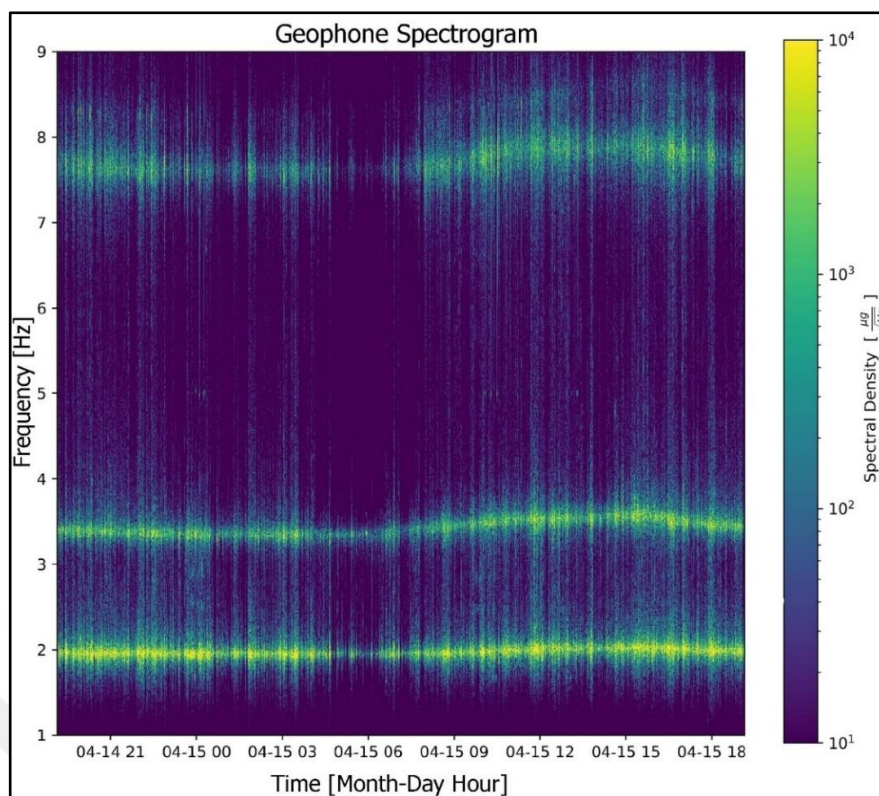


Figure 4.6: Spectrogram of the 24-hours CEDAS_geo recording.

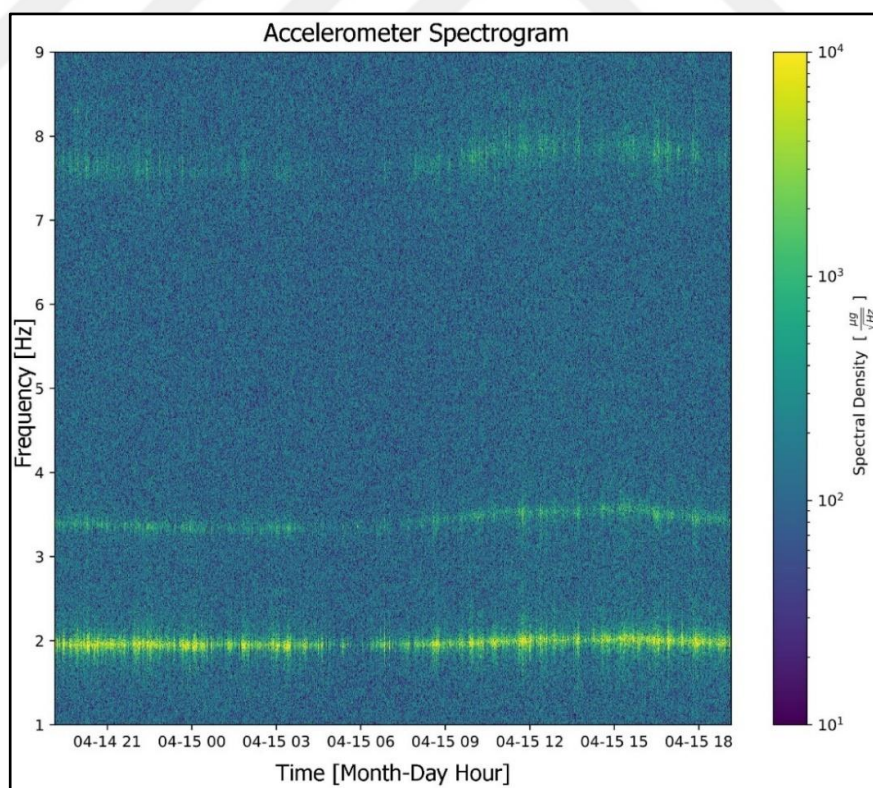


Figure 4.7: Spectrogram of the 24 hours CEDAS_acc recording.

4.3. Building 2

4.3.1. Overview of the Building 2 and Instrumentation

A 7-story residential building, shown in Figure 4.8, located in Gaziantep city center has been instrumented for 4 days.



Figure 4.8: Aerial photos of the Building 2 from (a) side and (b) top.

Due to the presence of people living in the Building 2 during the instrumented period, the device placements were arranged in the most suitable locations possible. Building 2 is instrumented with a 9 CEDAS_acc. Guralp 5TDE strong motion accelerometers are placed in the basement and top floor of the building as a reference sensor. Next to Guralp devices at basement and top floor, CEDAS_acc devices are

placed for a direct comparison. Placements of the devices at west side of top floor and basement shown in Figure 4.9.

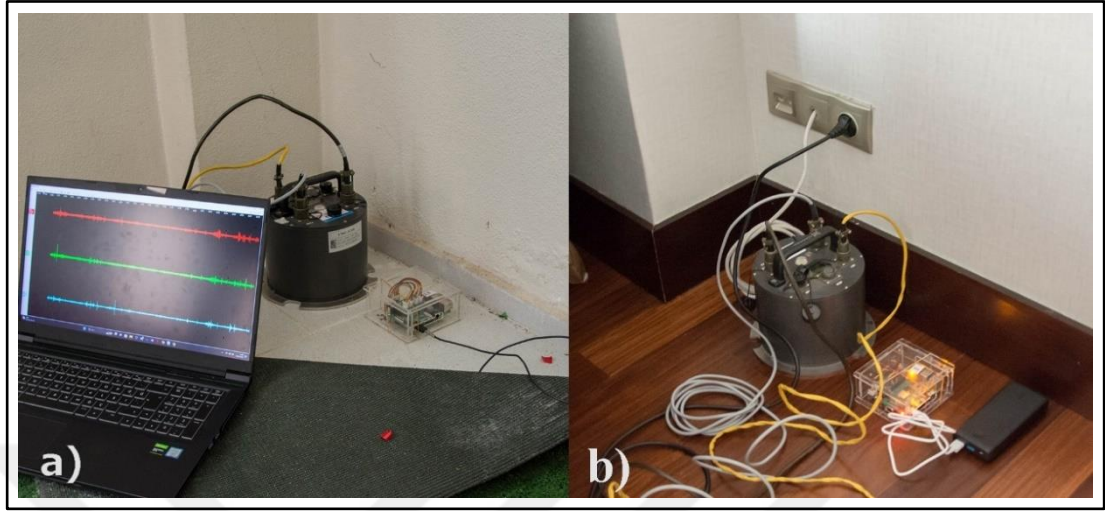


Figure 4.9: Guralp and CEDAS devices mounted locations at (a) ground floor and (b) top floor of the Building 2.

As a free-field recorder, devices are placed in the basement. The remaining 7 CEDAS_acc devices are placed on the Ground floor, 2nd, 4th, 6th, and top floor of the building. A total of 6 CEDAS_acc mounted to the uttermost points of the western facade of the building and the last device is mounted to the center of the top story on an elevator tower to easily distinguish the translational modes from torsional modes. Detailed locations of the devices on a plan view and cross section illustration of the building shown in Figure 4.10.

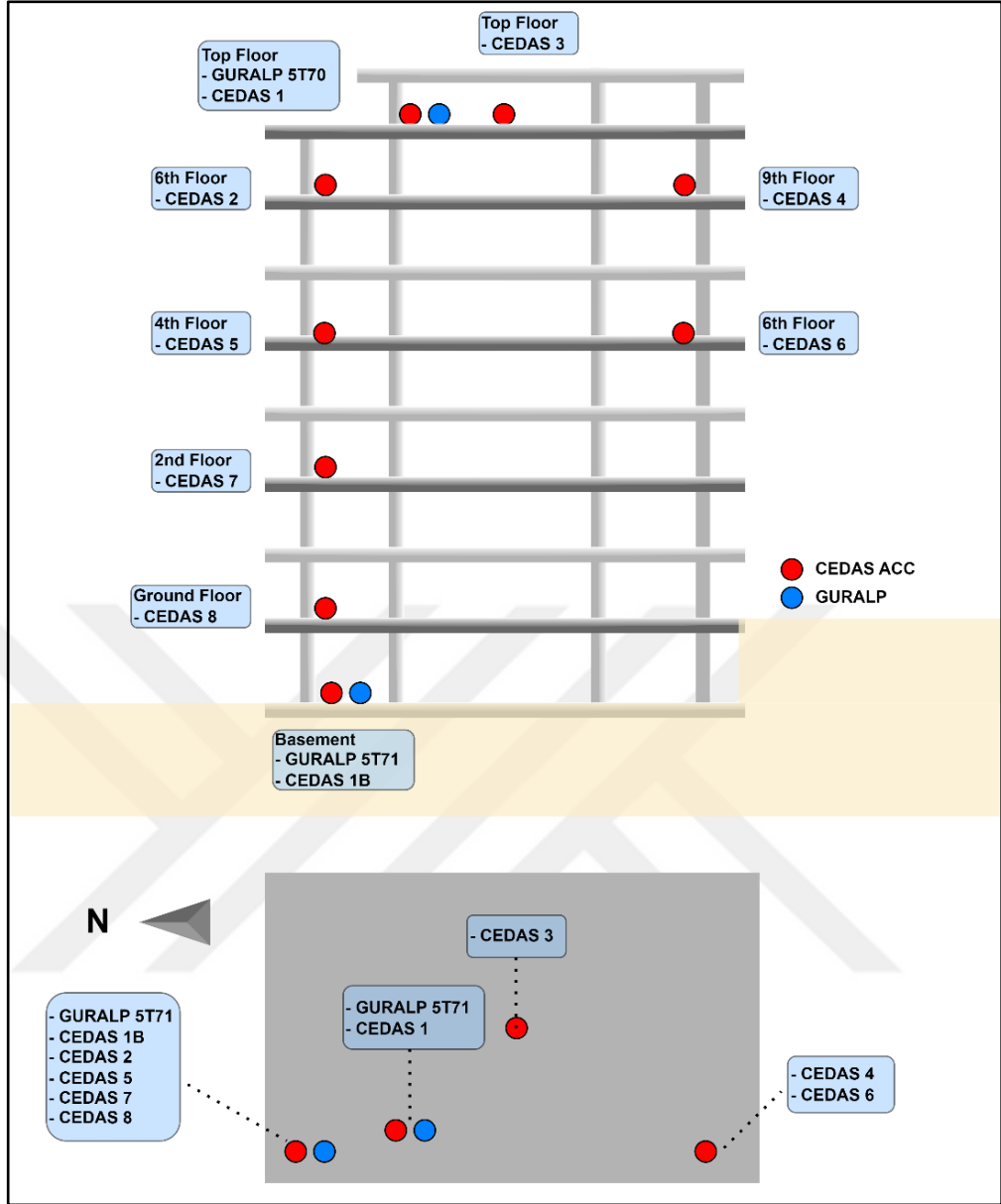


Figure 4.10: The locations of the sensors on the Building 2.

4.3.2. Forced Vibration Analysis

In this section, response of the building affected by a M3.9 earthquake with an epicentral distance of 48 km is analyzed. An earthquake occurred on April 10, 2023, at 22:45:08 in Kahramanmaraş/Pazarcık is shown in Figure 4.11 with the location of Building 2.

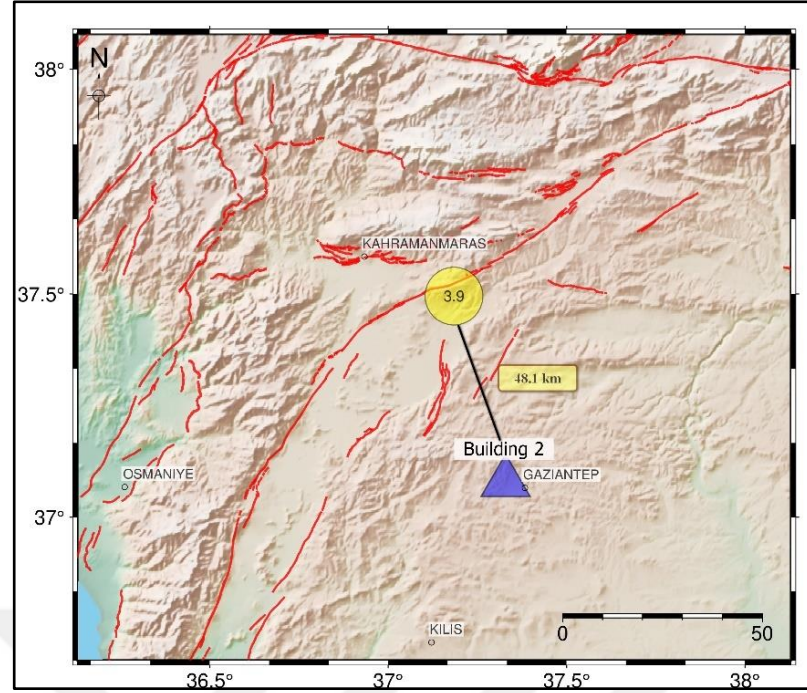


Figure 4.11: The Epicenter of the M3.9 Earthquake excited the Building 2 (Triangle refers to Building 2 location).

Filtered time series from all devices located on the building for both NS and EW directions are shown in Figure 4.12. In addition, peak acceleration value for the devices are given in the same figure. A total of 100 seconds of time series data analyzed for each device. Time series includes approximately 10 seconds of ground motion data, followed by a free vibration of the building.

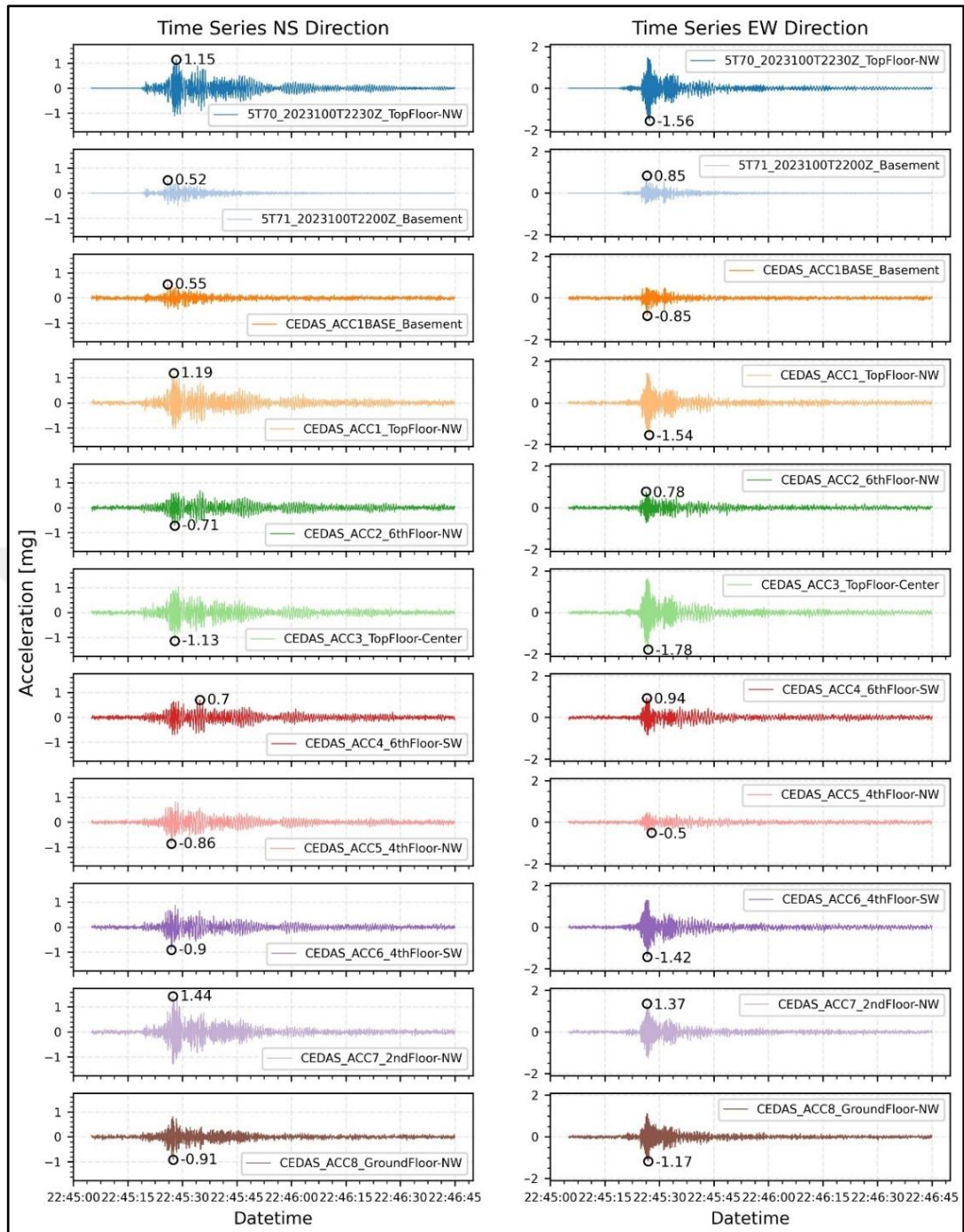


Figure 4.12: Time series of the response of the Building 2 in NS and EW directions.

Peak acceleration values for the devices in the NS and EW directions are listed in Table 4.2. From the Guralp and CEDAS_acc devices placed side by side, similar peak acceleration values are found. Peak acceleration for Guralp device at basement is found 0.52 mg in NS direction, 0.85 mg in EW direction while for CEDAS_acc it is 0.55 mg in NS direction, 0.85 mg in EW direction. Peak acceleration for Guralp device

at top floor is found 1.15 mg in NS direction, 1.56 mg in EW direction while for CEDAS_acc it is 1.19 mg in NS direction, 1.54 mg in EW direction.

Table 4.2: Recorded peak acceleration values of Guralp and CEDAS_acc from the Building 2.

Device Name	Location	Peak Acceleration (mg)	
		NS Direction	EW Direction
Guralp 5T71	Basement	0.52	0.85
Guralp 5T70	Top Floor-NW	1.15	1.56
CEDAS_acc1b	Basement	0.55	0.85
CEDAS_acc8	Ground Floor	0.91	1.17
CEDAS_acc7	2nd Floor-NW	1.44	1.37
CEDAS_acc6	4th Floor-SW	0.9	1.42
CEDAS_acc5	4th Floor-NW	0.86	0.5
CEDAS_acc4	6th Floor-SW	0.7	0.94
CEDAS_acc2	6th Floor-NW	0.71	0.78
CEDAS_acc1	Top Floor-NW	1.19	1.54
CEDAS_acc3	Top Floor-Center	1.13	1.78

A detailed look for acceleration time series from top floor and basement of both devices shown in Figure 4.13 for NS direction, Figure 4.14 for EW direction. Overlapping of the time series indicates both devices are synchronized.

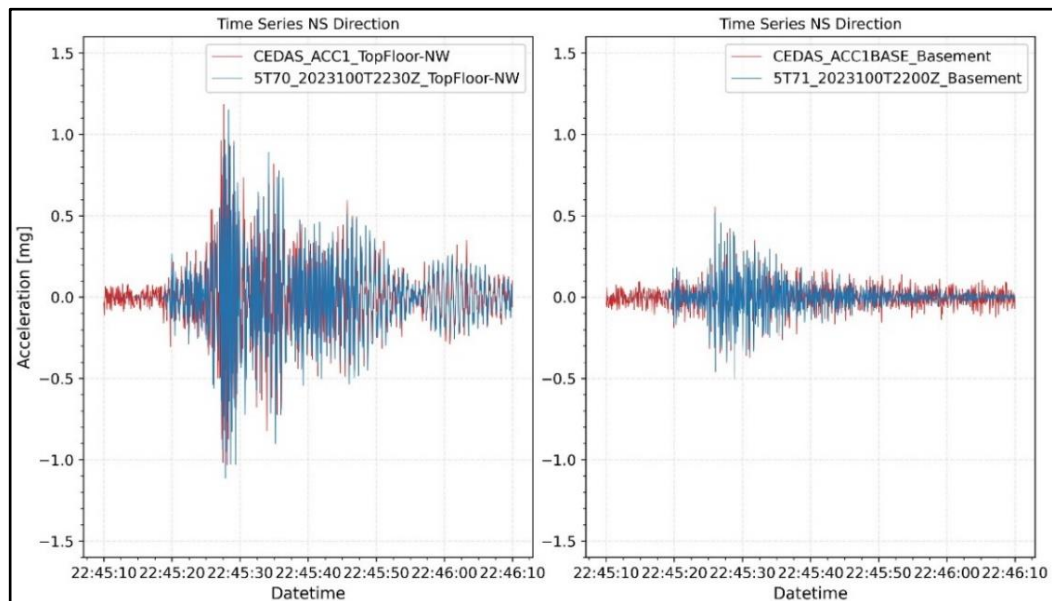


Figure 4.13: Time series of Guralp and CEDAS_acc from top floor and basement of Building 2 in NS direction.

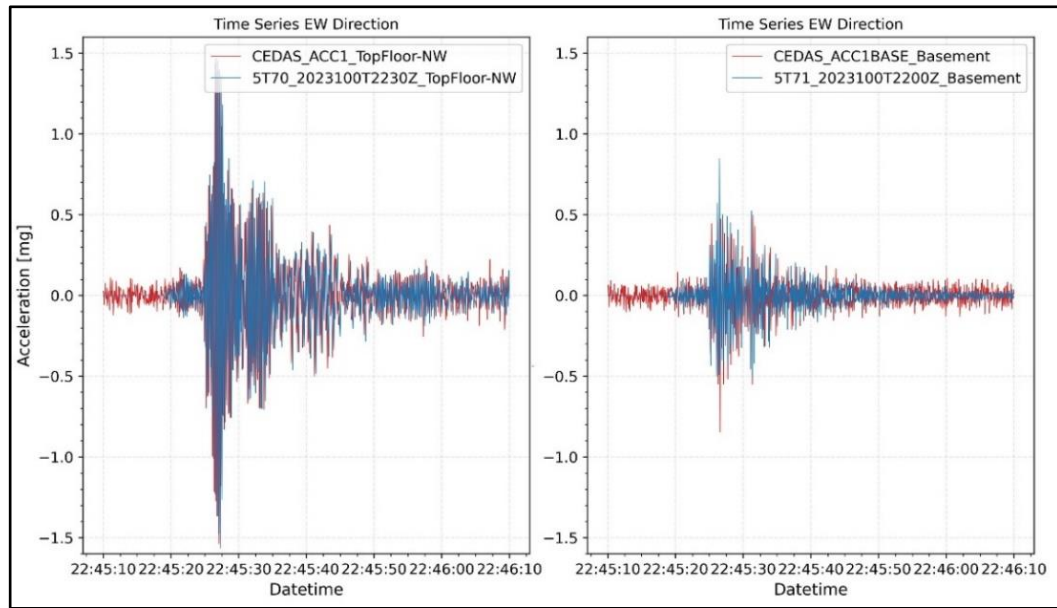


Figure 4.14: Time series of Guralp and CEDAS_acc from top floor and basement of Building 2 in EW direction.

By integrating the acceleration data, velocity and displacement time series for the devices located side by side at basement and top floor are calculated and shown in Figure 4.15 for NS direction, Figure 4.16 for EW direction. After each integration, filtering and baseline correction is applied to time series. A 3th order polynomial is fitted and subtracted from the time series. Secondly, 6th order low-pass Butterworth filter with 20Hz cut-off frequency is applied to velocity and displacement time series.

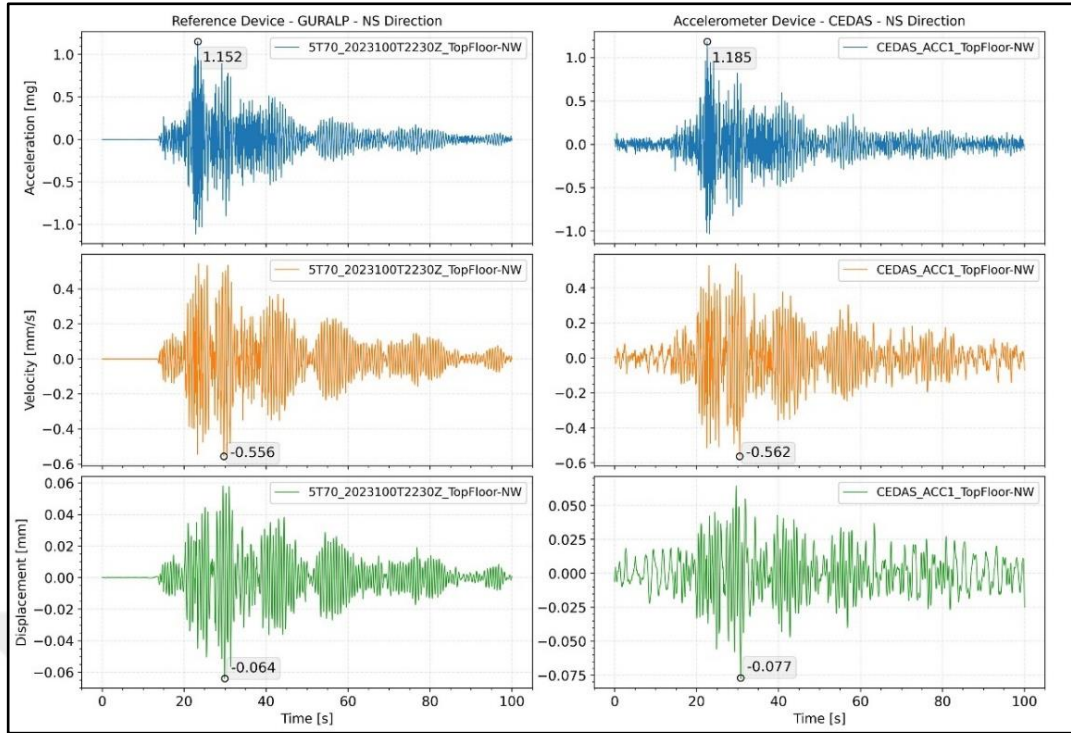


Figure 4.15: Acceleration, velocity, and displacement time series of Guralp and CEDAS_acc from Building 2 in NS direction.

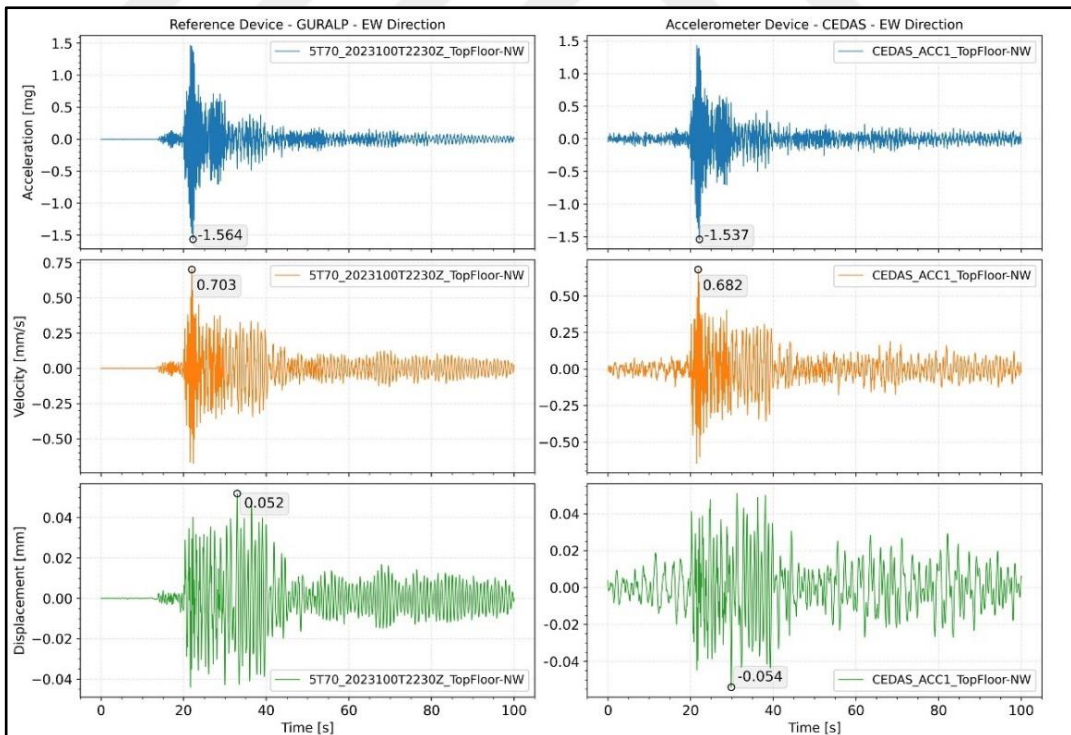


Figure 4.16: Acceleration, velocity, and displacement time series of Guralp and CEDAS_acc device from Building 2 in EW direction.

Table 4.3 shows peak acceleration, velocity, and displacement values. The percentage deviation in NS direction of CEDAS_acc in reference to Guralp device for absolute peak acceleration, velocity, and displacement were found to be 2.8%, 1.1%, and 20.3%, respectively. For EW direction, percentage deviations are 1.7%, 3.1% and 3.8% respectively. By each integration, error rate increases due to low signal-to-noise ratio (SNR) of the CEDAS_acc.

Table 4.3: Recorded acceleration, velocity and displacement peak values of Guralp and CEDAS_acc from Building 2 in both directions.

Device	Direction	Absolute Peak Values		
		Acceleration (mg)	Velocity (mm/s)	Displacement (mm)
Guralp	NS	1.152	0.556	0.064
	EW	1.564	0.703	0.052
CEDAS acc	NS	1.185	0.562	0.077
	EW	1.537	0.682	0.054

Calculated spectral density functions for all devices located on the building for both NS and EW directions are shown in Figure 4.17. Additionally, modal frequencies of the 1st and 2nd translational modes are shown in the figure.

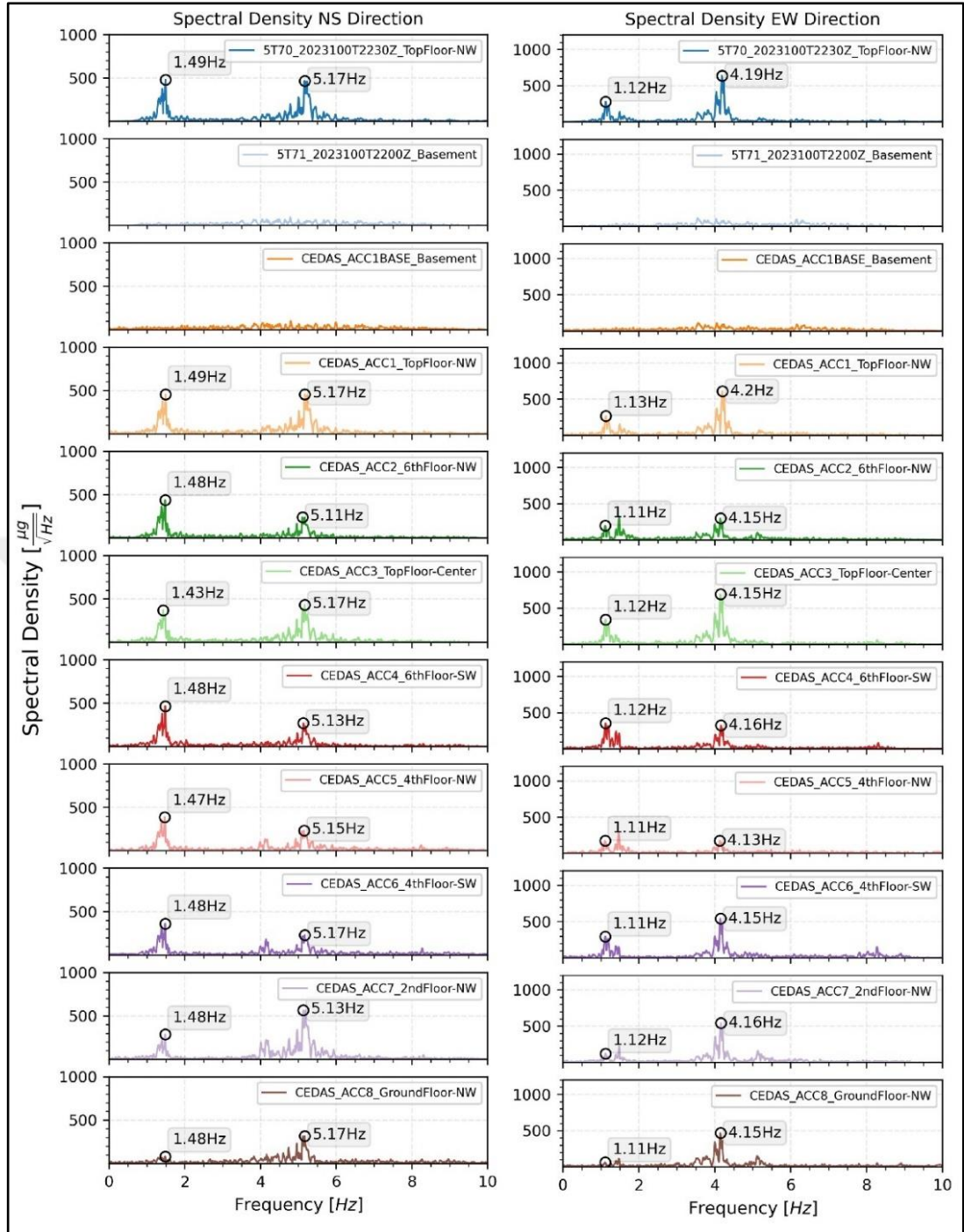


Figure 4.17: Spectral Density of the response of the Building 2 in NS and EW directions.

Modal periods of 1st and 2nd translational modes of Building 2 for both NS and EW directions are listed in Table 4.4. Response of the building during earthquake is analyzed by spectral density method. According to analysis results, 1st and 2nd translational modes were found to be 0.67s and 0.19s for NS direction, 0.89s and 0.24s

for EW direction, respectively. Calculated values are consistent when different devices and various locations are considered.

Table 4.4: First and second mode periods of the Building 2 in both directions.

Device Name	Location	Modal Periods (s)			
		NS	NS	EW	EW
		1st Mode	2nd Mode	1st Mode	2nd Mode
Guralp 5T70	Top Floor-NW	0.67	0.193	0.89	0.238
CEDAS_acc8	Ground Floor	0.67	0.193	0.90	0.240
CEDAS_acc7	2nd Floor-NW	0.67	0.195	0.89	0.240
CEDAS_acc6	4th Floor-SW	0.67	0.193	0.90	0.240
CEDAS_acc5	4th Floor-NW	0.67	0.194	0.90	0.240
CEDAS_acc4	6th Floor-SW	0.67	0.195	0.89	0.240
CEDAS_acc2	6th Floor-NW	0.67	0.195	0.90	0.240
CEDAS_acc1	Top Floor-NW	0.67	0.193	0.89	0.238
CEDAS_acc3	Top Floor-Center	0.7	0.193	0.89	0.240

Detailed comparisons of Guralp and CEDAS_acc device located at top floor and basement are shown in Figure 4.18 and Figure 4.19.

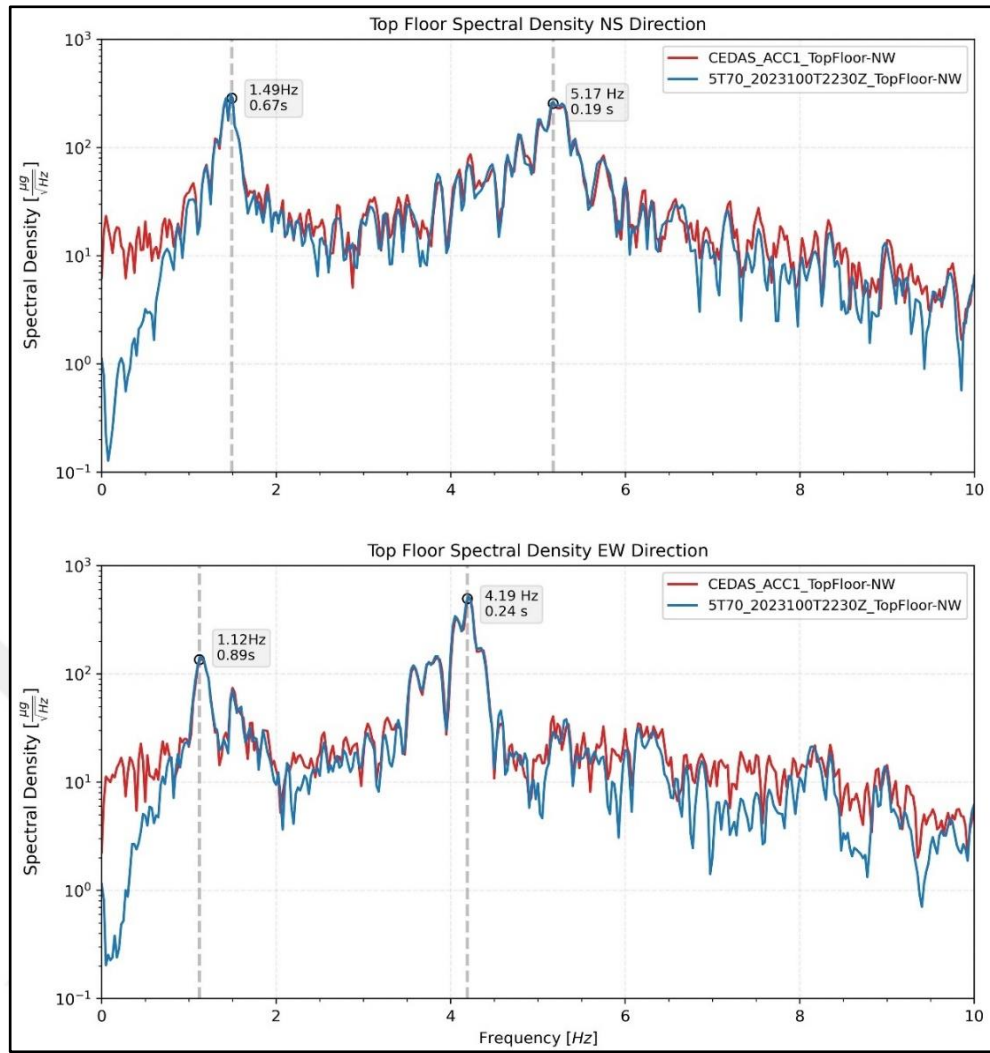


Figure 4.18: Modal frequencies and periods of Guralp and CEDAS devices from top floor of Building 2 in NS and EW directions.

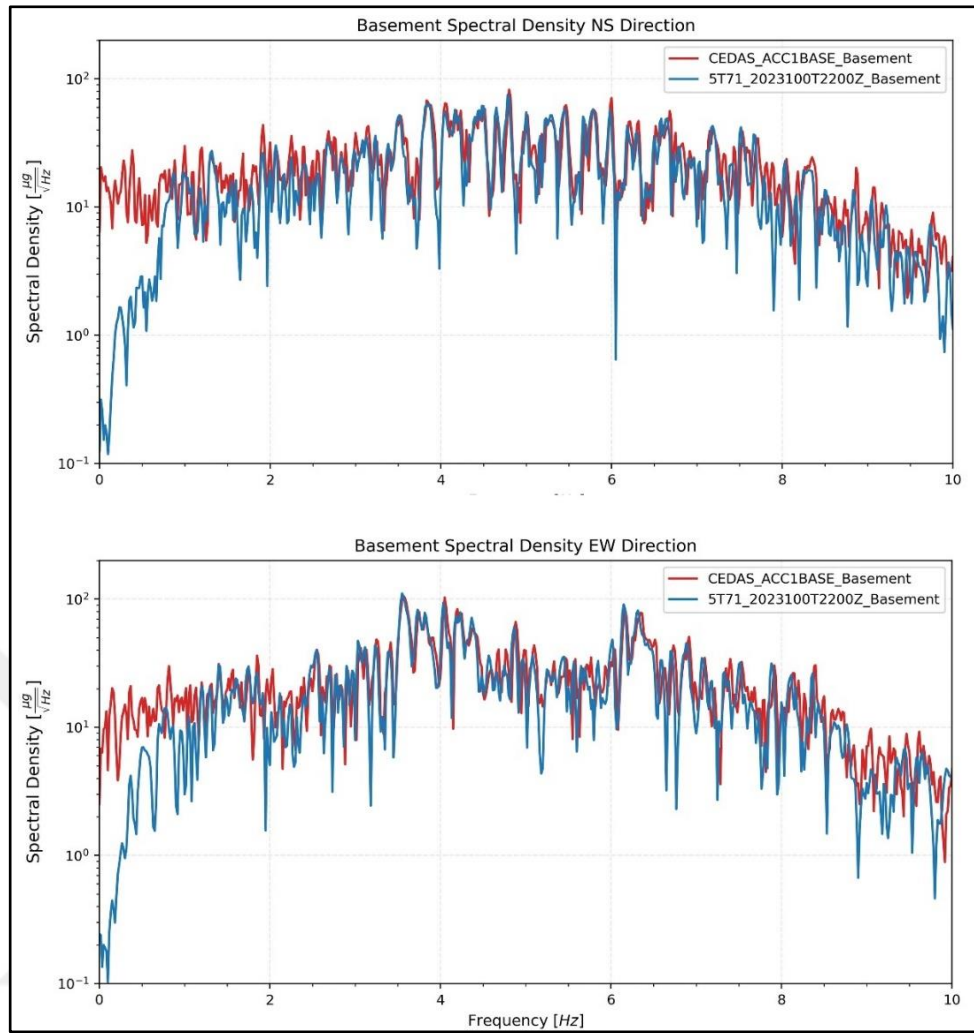


Figure 4.19: Spectral Density of Guralp and CEDAS devices from basement of Building 2 in NS and EW directions.

Transfer functions are generated by using basement recording of Guralp device as an input. As an output, devices located at 2nd, 4th, 6th and top floor NW location and top floor center are used. Estimated transfer functions are shown in Figure 4.20 for NS and EW directions of recordings.

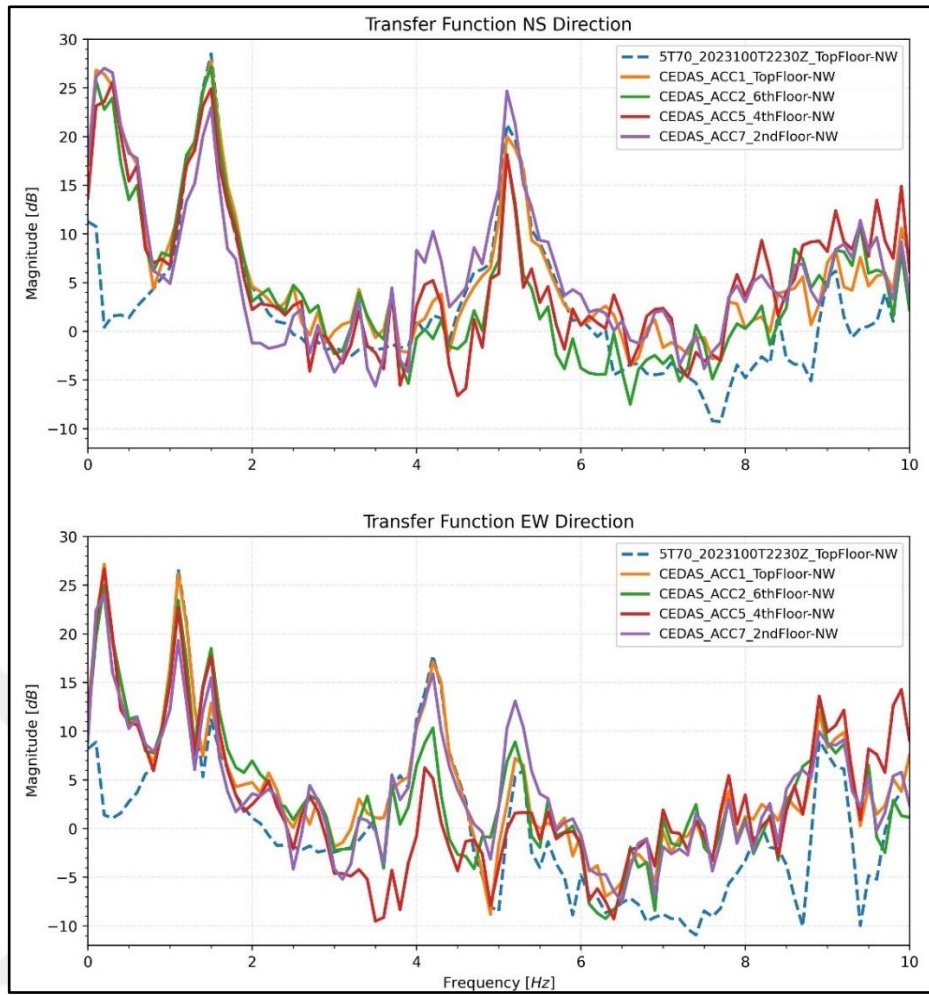


Figure 4.20: Transfer functions of devices from different floors of Building 2 in NS and EW directions.

4.3.3. Ambient Vibration Analysis

Ambient vibration of the Building 2 is recorded between 06.04.2023 and 11.04.2023. Recordings are gathered in the night time for the duration of approximately 18 hours a day. A total of 5 ambient vibration recordings are selected with the least contamination from aftershocks, environmental noise due to residents and traffic.

Representative ambient vibration time series are shown in Figure 4.21 for both NS and EW directions.

Recordings are analyzed by calculating spectral density. First and second modal frequencies for devices located at same location at top floor are shown in Figure 4.22 for both NS and EW directions.

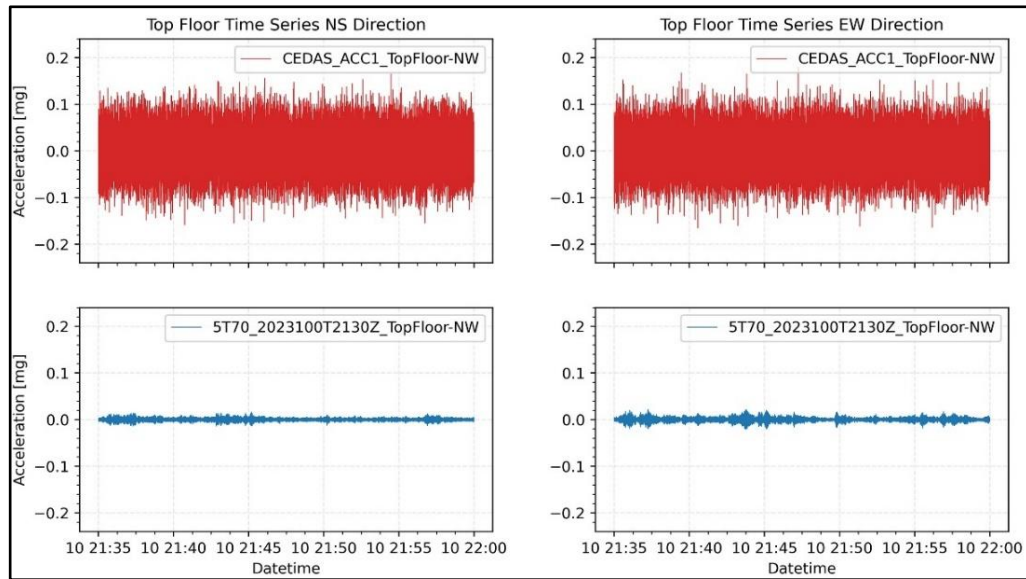


Figure 4.21: Representative ambient vibration time series of Guralp and CEDAS devices from top floor of the Building 2 in NS and EW directions.

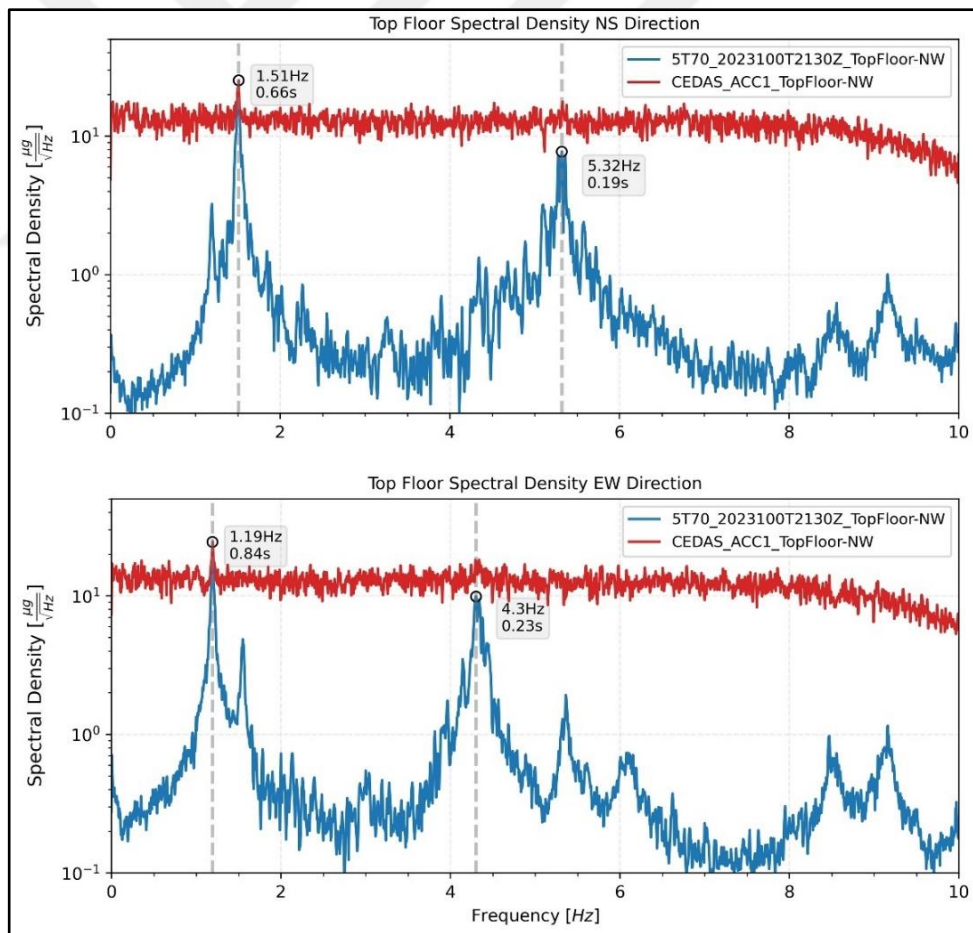


Figure 4.22: Spectral Density and modal frequencies of representative ambient vibration data of Guralp and CEDAS devices from top floor of Building 2 in NS and EW directions.

The results and details of all ambient vibration recordings from the top floor are listed in Table 4.5.

Table 4.5: First mode periods of other 5 ambient vibrations from the Building 2 in both directions.

No	Date	Start Time (UTC)	Duration (min)	Modal Periods (s)			
				NS Direction		EW Direction	
				Guralp	CEDAS	Guralp	CEDAS
1	07.04.2023	01:30	30	0.67	0.67	0.87	0.87
2	08.04.2023	00:00	20	0.67	0.67	0.86	0.86
3	08.04.2023	23:30	20	0.67	0.67	0.86	0.86
4	10.04.2023	21:30	30	0.66	0.66	0.84	0.84
5	11.04.2023	01:30	30	0.67	0.67	0.85	0.85

4.4. Building 3

4.4.1. Overview of the Building 3 and Instrumentation

A recently constructed 10-story residential building, shown in Figure 4.23, located in Gaziantep city center has been instrumented for 4 days.

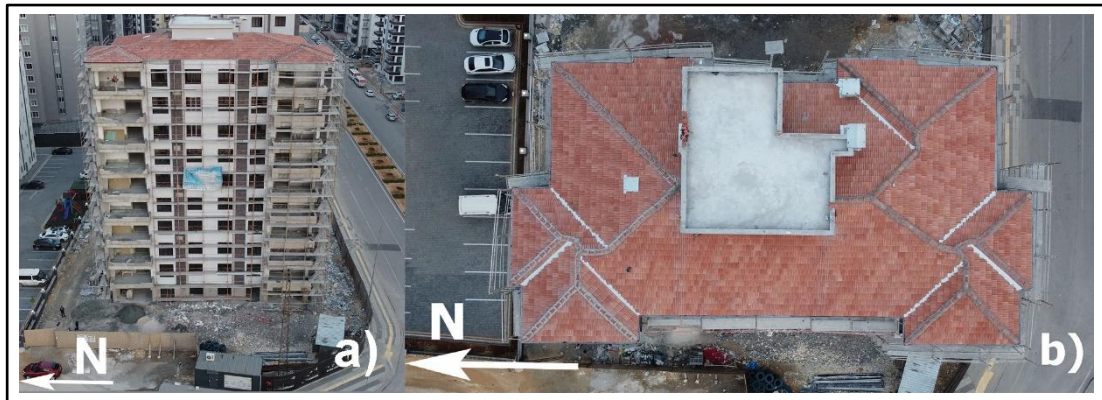


Figure 4.23: Aerial photos of the Building 3 from (a) side and (b) top.

Due to the absence of human occupants, Building 3 was more accessible, which enabled more optimized sensor placement compared to Building 2. Building 3 is instrumented with an 8 CEDAS_acc and 1 CEDAS_geo device. Guralp 5TDE strong motion accelerometers are placed on the ground floor and 9th floor of the building as

a reference sensor. Single CEDAS_geo device is located on the 9th floor of the building besides Guralp and CEDAS_acc. Next to each Guralp accelerometer, CEDAS_acc devices are placed for a direct comparison. Placements of the devices at east side of 9th floor and ground floor given in Figure 4.24.

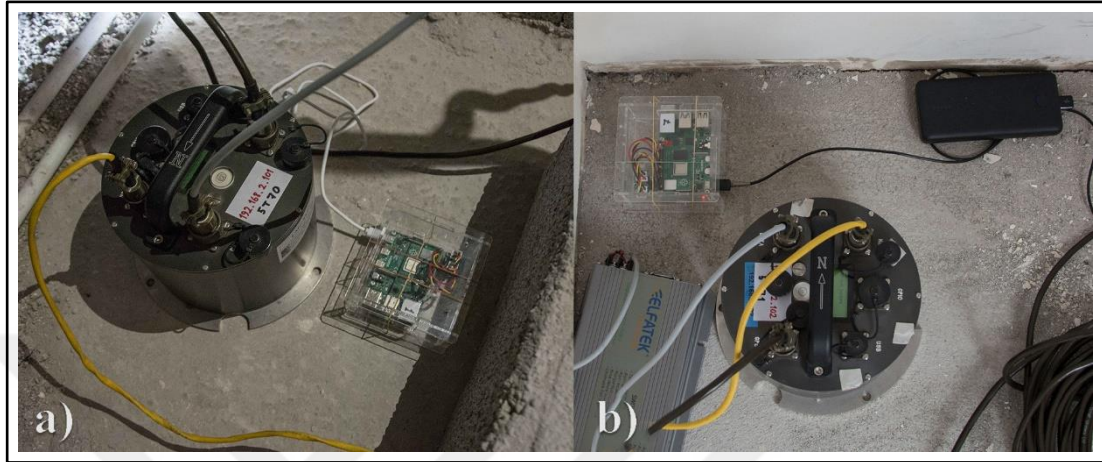


Figure 4.24: Guralp and CEDAS devices mounted locations at (a) ground floor and (b) 9th floor of the Building 3.

As a free-field recorder, devices are placed to ground floor instead of basement due to security concerns. The remaining 6 CEDAS_acc devices are placed on the 3rd, 6th, 9th, and top floor of the building. A total of 5 CEDAS_acc mounted to the uttermost points of the western facade of the building and the last device is mounted to the center of the top story on an elevator tower to easily distinguish the translational and torsional modes. Detailed locations of the devices on a plan view and cross section illustration of the building shown in Figure 4.25.

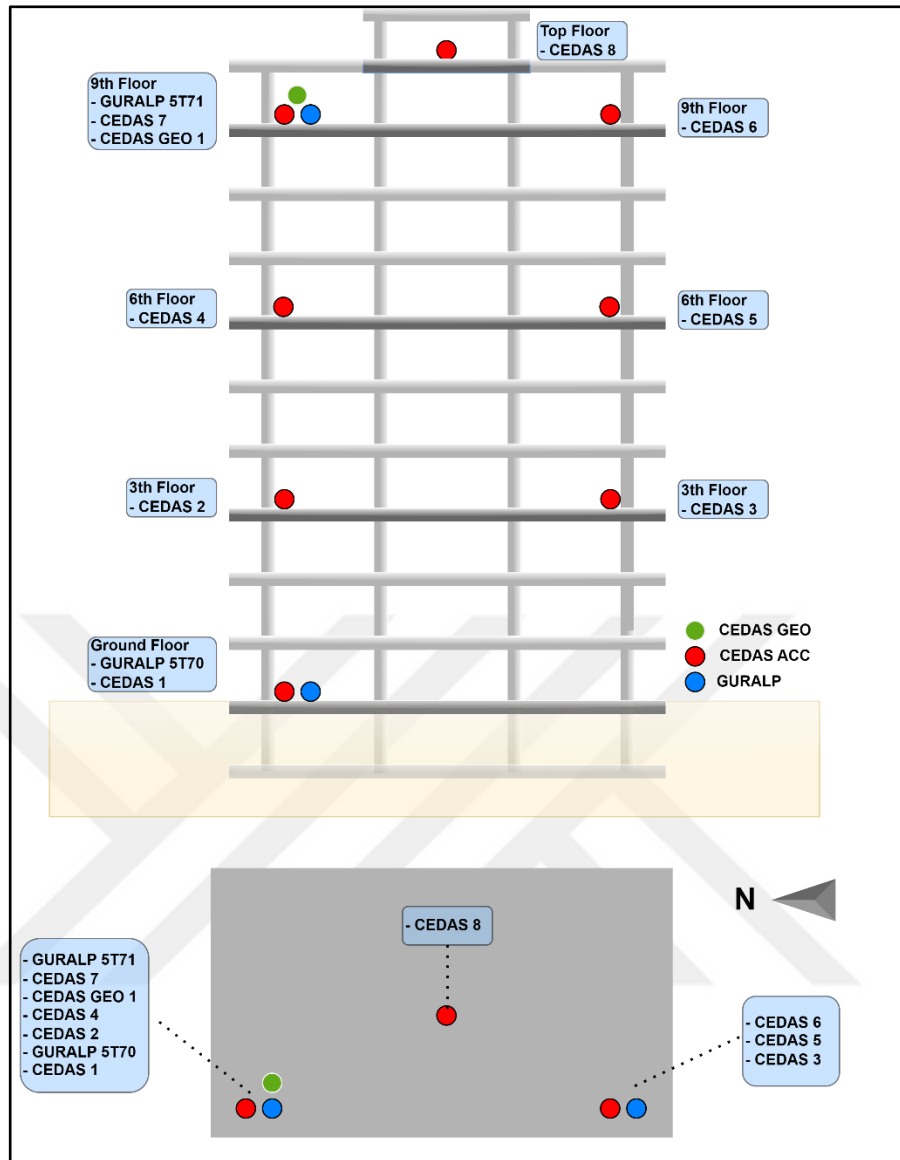


Figure 4.25: The locations of the sensors on the Building 3.

4.4.2. Forced Vibration Analysis

In this section, the response of the building affected by a M3.2 earthquake with an epicentral distance of 39 km is analyzed. An earthquake occurred on April 13, 2023, at 03:36:05 in Gaziantep/Nurdağı is shown in Figure 4.26. with the location of Building 3.

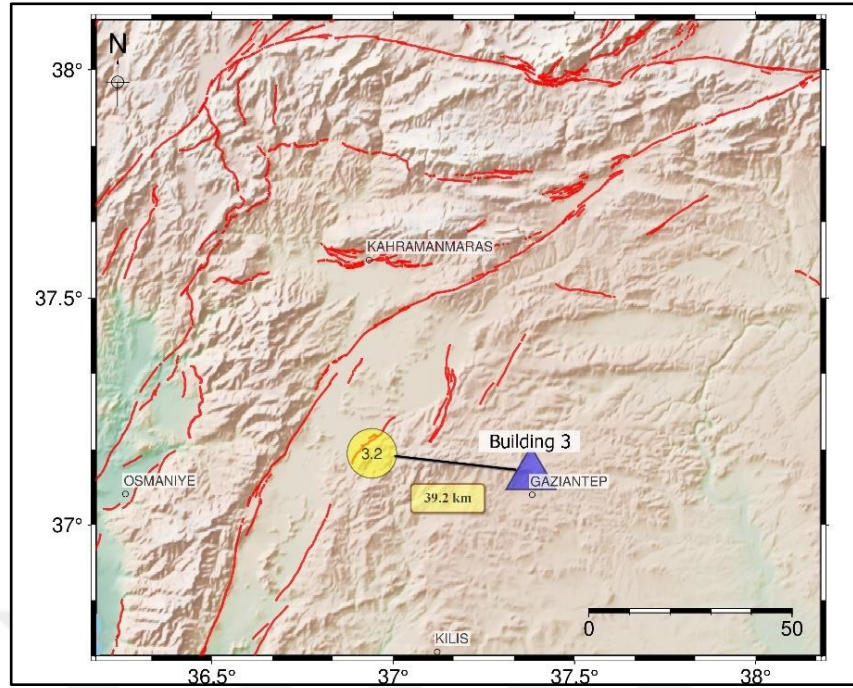


Figure 4.26: The Epicenter and other parameters of the M3.2 Earthquake excited the Building 3 (Triangle refers to location of Building 3).

Filtered time series from the devices located on the building for both NS and EW directions are shown in Figure 4.27. Also, peak acceleration values for the devices are given in the figure. A total of 100 seconds time series are analyzed for each device. Time series includes approximately 10 seconds of ground motion data, followed by a free vibration of the building.

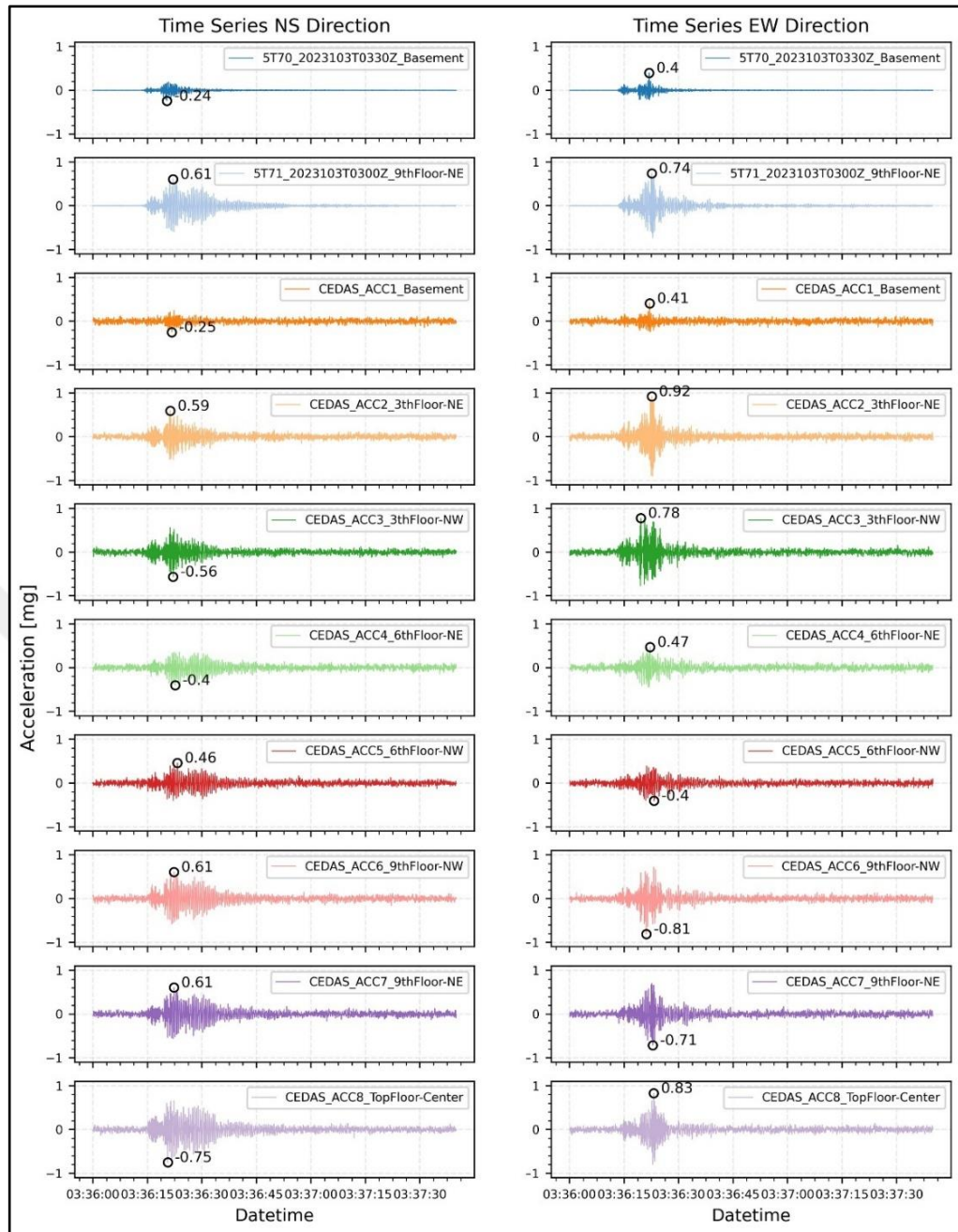


Figure 4.27: Time series of the response of the Building 3 in NS and EW directions.

Peak acceleration values for the devices in the NS and EW directions are listed in Table 4.6. From the Guralp and CEDAS_acc devices placed side by side, similar peak acceleration values are found. Peak acceleration for Guralp device at basement is found 0.24 mg in NS direction, 0.4 mg in EW direction while for CEDAS_acc it is 0.25 mg in NS direction, 0.41 mg in EW direction. Similarly, minor differences are observable for the devices located at 9th floor-NE as well.

Table 4.6: Recorded peak acceleration values of Guralp and CEDAS devices from the Building 1.

Device Name	Location	Peak Acceleration (mg)	
		NS Direction	EW Direction
Guralp 5T70	Basement	0.24	0.4
Guralp 5T71	9th Floor-NE	0.61	0.74
CEDAS_acc1	Basement	0.25	0.41
CEDAS_acc2	3rd Floor-NE	0.59	0.92
CEDAS_acc3	3rd Floor-NW	0.56	0.78
CEDAS_acc4	6th Floor-NE	0.4	0.47
CEDAS_acc5	6th Floor-NW	0.61	0.81
CEDAS_acc7	9th Floor-NE	0.61	0.71
CEDAS_acc6	9th Floor-NW	0.71	0.78
CEDAS_acc8	Top Floor-Center	0.75	0.83

A detailed look for acceleration time series from 9th floor and basement of both devices shown in Figure 4.28 for NS direction, Figure 4.29 for EW direction. Overlapping of the time series indicates both devices are synchronized.

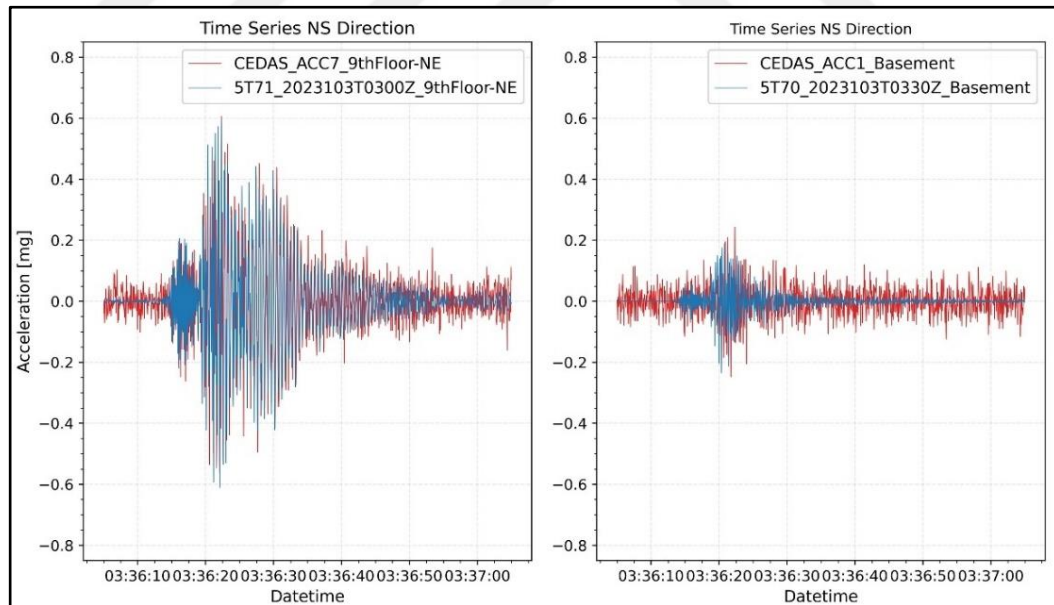


Figure 4.28: Time series of Guralp and CEDAS devices from top floor and basement of Building 3 in NS direction.

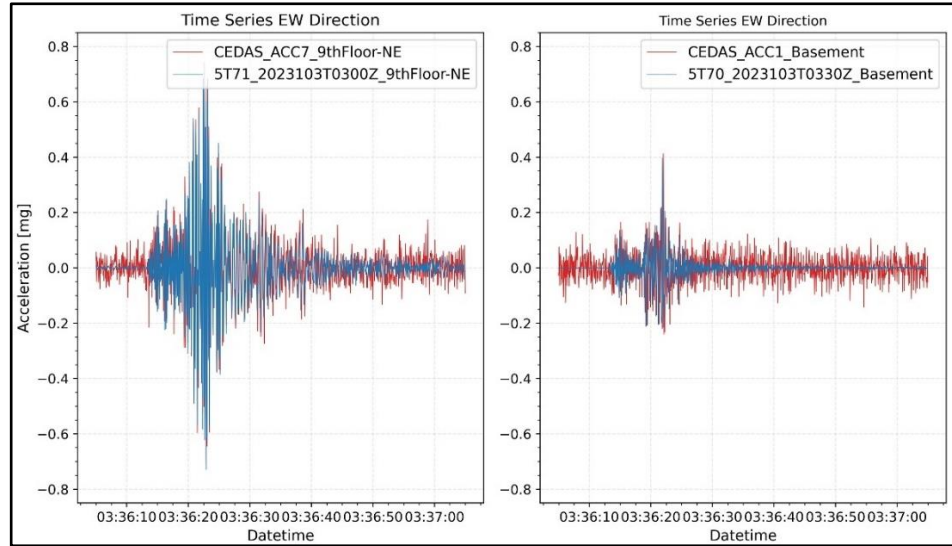


Figure 4.29: Time series of Guralp and CEDAS devices from top floor and basement of Building 3 in EW direction.

By integrating the acceleration data, velocity and displacement time series for the devices located side by side at basement and 9th floor are calculated and shown in Figure 4.30 for NS direction, Figure 4.31 for EW direction. After each integration filtering and baseline correction is applied to time series. A 4th order polynomial fitted and subtracted from the time series. Secondly, the 4th order Butterworth low-pass filter with 20Hz cut-off frequency is applied.

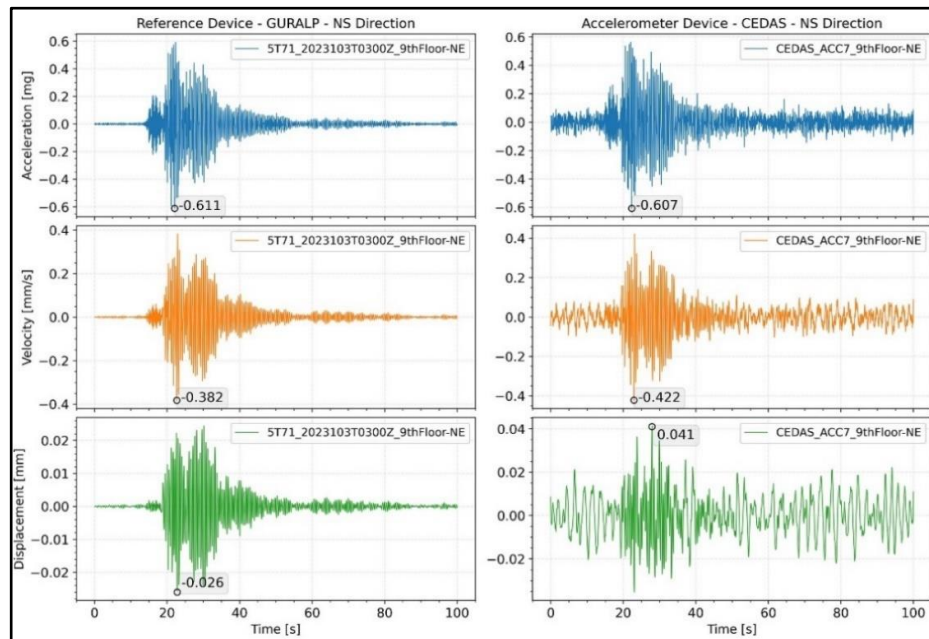


Figure 4.30: Acceleration, velocity and displacement time series of Guralp and CEDAS devices from Building 3 in NS direction.

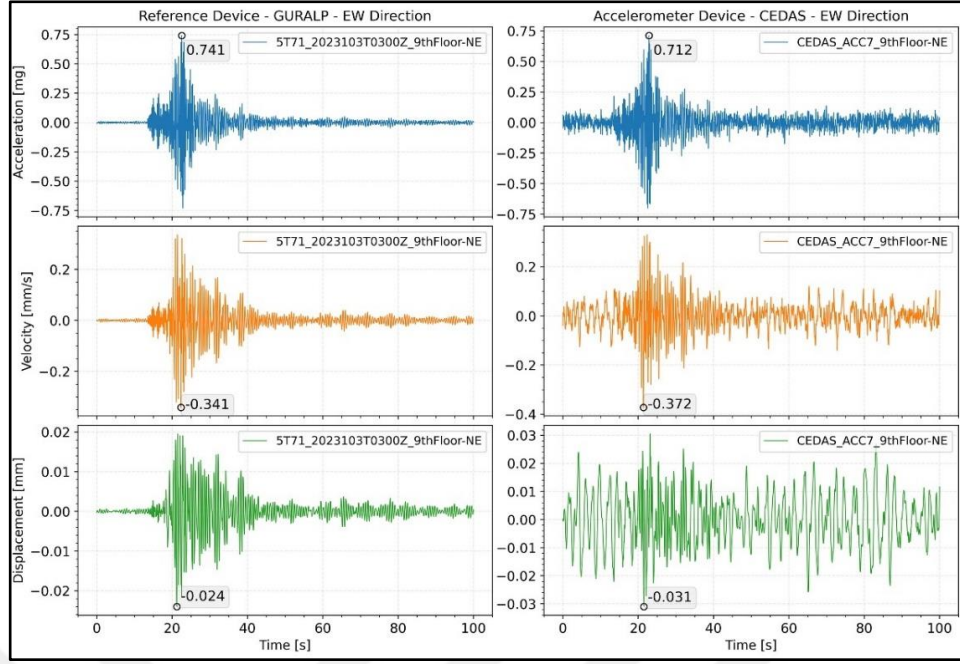


Figure 4.31: Acceleration, velocity and displacement time series of Guralp and CEDAS devices from Building 3 in EW direction.

Table 4.7 shows peak acceleration, velocity and displacement values. The percentage deviation in NS direction of CEDAS_acc in reference to Guralp device for absolute peak acceleration, velocity, and displacement were found to be %0.6, %9.5, and %36, respectively. For EW direction, percentage deviation is %4.1, %8.3 and %22.6 respectively. By each integration, error rate increases due to low SNR of the CEDAS_acc.

Table 4.7: Recorded acceleration, velocity and displacement peak values of Guralp and CEDAS_acc from Building 3 in both directions.

Device	Direction	Absolute Peak Values		
		Acceleration (mg)	Velocity (mm/s)	Displacement (mm)
Guralp	NS	0.611	0.382	0.026
	EW	0.741	0.341	0.024
CEDAS	NS	0.607	0.422	0.041
	EW	0.712	0.372	0.031

Calculated spectral density for all devices located on the building for both NS and EW directions are shown in Figure 4.32. Also, modal frequencies of the 1st and 2nd translational modes are shown in the figure.

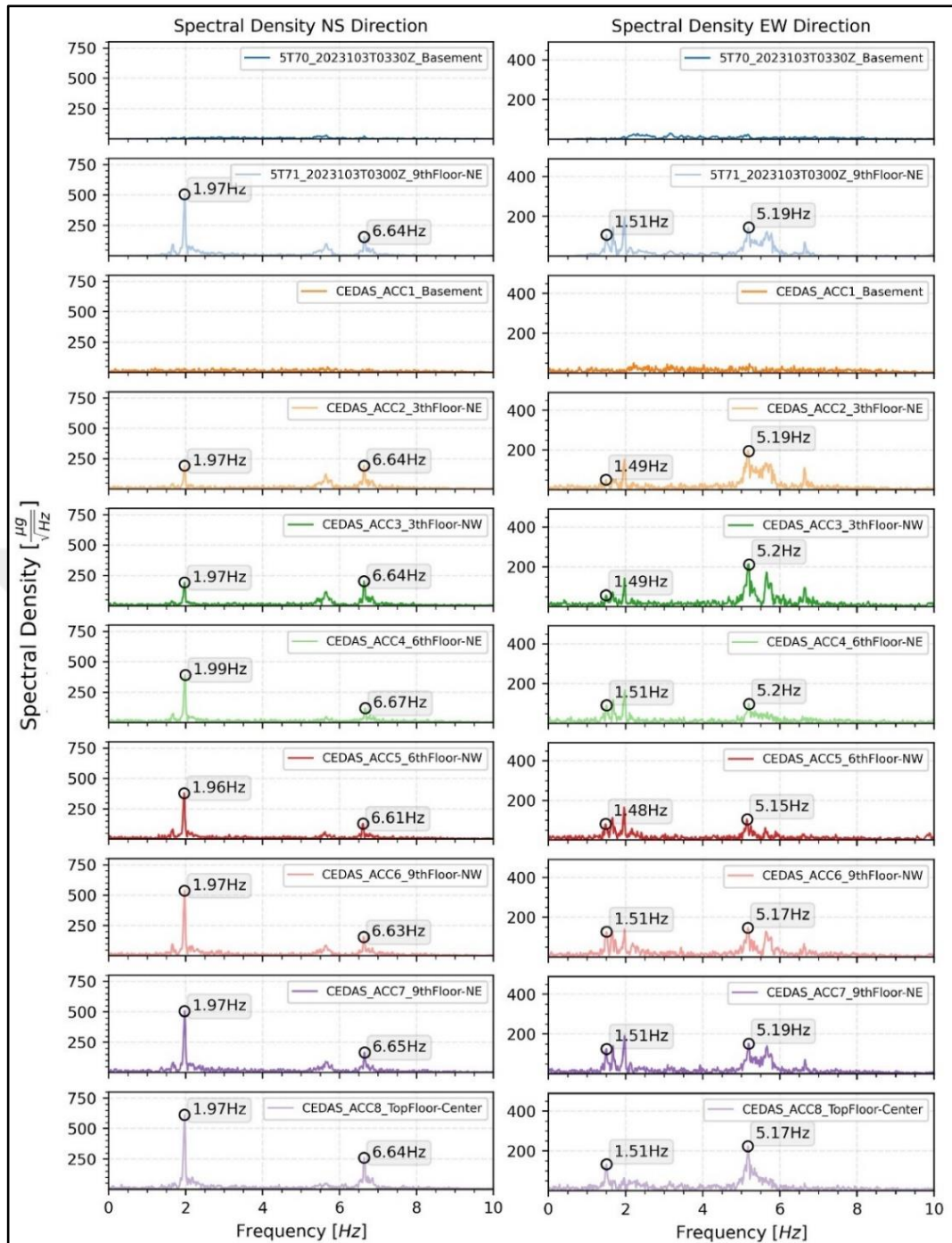


Figure 4.32: Spectral density of the response of the Building 3 in NS and EW directions.

The modal periods of 1st and 2nd translational modes of Building 3 for both NS and EW directions are listed in Table 4.8. Response of the building during earthquake is analyzed by Spectral Density method. According to analysis, 1st and 2nd translational modes were found to be 0.51s and 0.15s for NS direction, 0.66s and 0.19s for EW direction, respectively. Additionally, torsional modes are observable with 0.6

s and 0.17s periods. Calculated values are consistent when devices from separate locations are considered.

Table 4.8: First and second mode periods of the Building 3 in both directions.

Device Name	Location	Modal Periods (s)			
		NS	NS	EW	EW
		1st Mode	2nd Mode	1st Mode	2nd Mode
Guralp 5T71	9th Floor-NE	0.51	0.151	0.66	0.193
CEDAS_acc2	3rd Floor-NE	0.51	0.151	0.67	0.193
CEDAS_acc3	3rd Floor-NW	0.51	0.151	0.67	0.192
CEDAS_acc4	6th Floor-NE	0.50	0.150	0.66	0.193
CEDAS_acc5	6th Floor-NW	0.51	0.151	0.67	0.194
CEDAS_acc7	9th Floor-NE	0.51	0.150	0.66	0.193
CEDAS_acc6	9th Floor-NW	0.51	0.151	0.66	0.193
CEDAS_acc8	Top Floor-Center	0.51	0.151	0.66	0.193

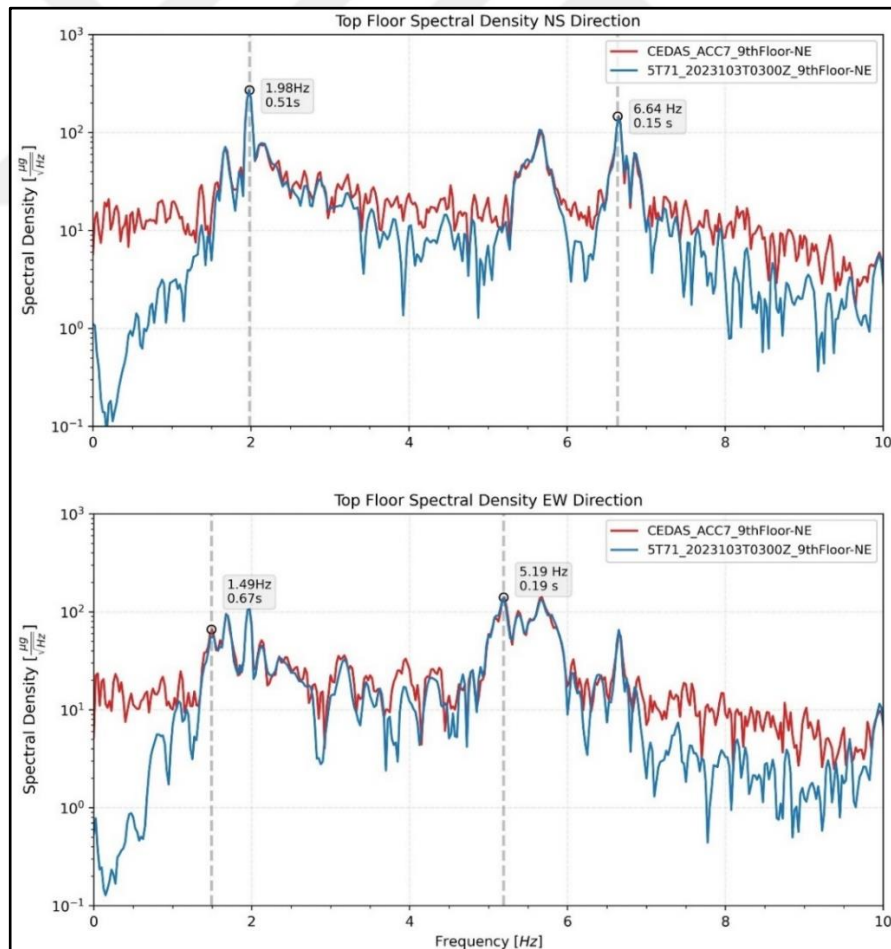


Figure 4.33: Modal frequencies and periods of Guralp and CEDAS devices from top floor of Building 3 in NS and EW directions.

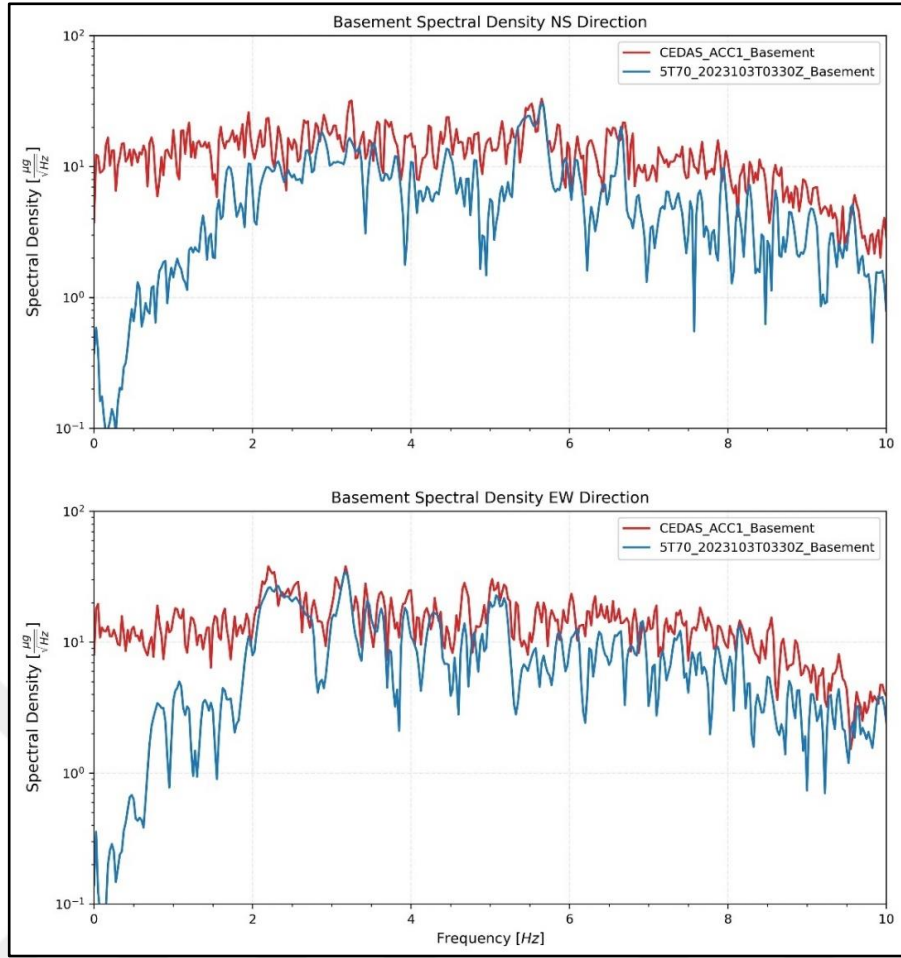


Figure 4.34: Spectral density of Guralp and CEDAS devices from basement of Building 3 in NS and EW directions.

Transfer functions are generated by using basement recording of Guralp device as an input. As an output, devices located at 3rd, 6th, 9th floor NE location and top floor center are used. Estimated transfer functions are shown in Figure 4.35 for NS and EW directions of recordings.

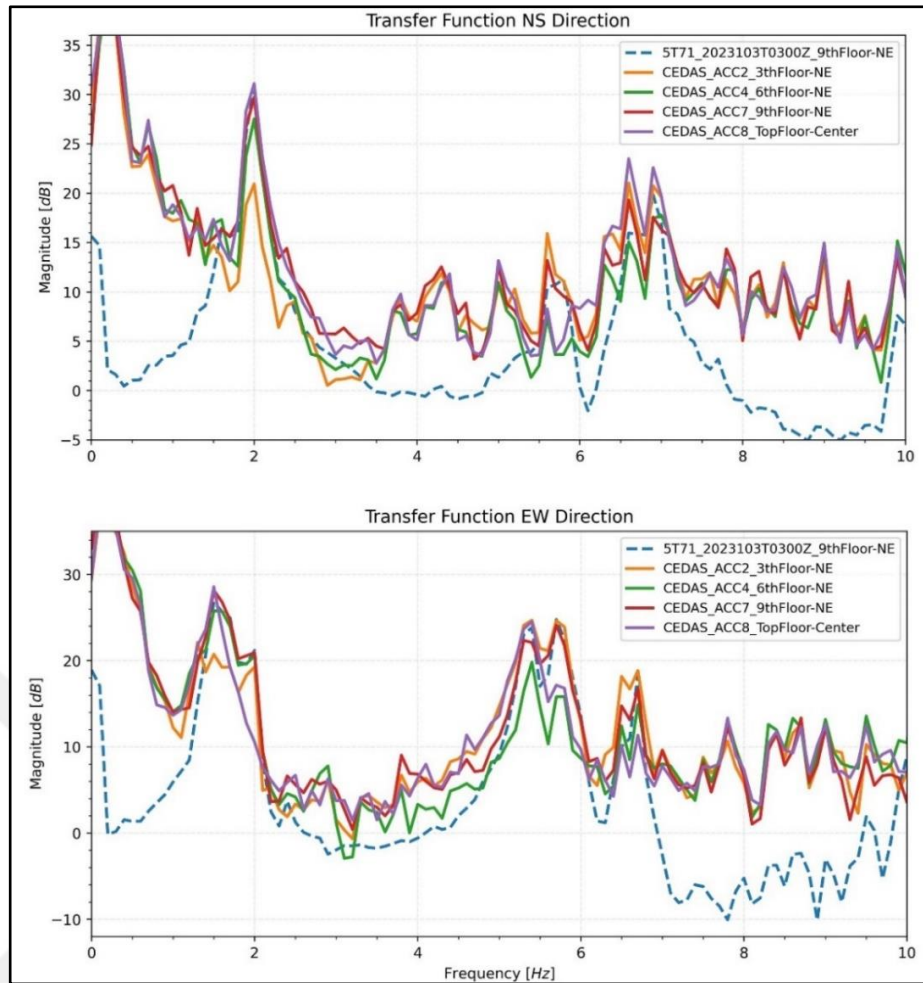


Figure 4.35: Transfer functions of devices from different floors of Building 3 in NS and EW directions.

4.4.3. Ambient Vibration Analysis

Ambient vibration of the Building 3 is recorded between 11.04.2023 and 15.04.2023. Recordings are gathered during the night for the duration of approximately 18 hours a day. A total of 5 different ambient vibration recordings are selected with the least contamination from aftershocks and currently ongoing construction work, traffic, and mechanical equipment noise. Representative ambient vibration time series are shown in Figure 4.36 for both NS and EW directions.

Recordings are analyzed with Spectral Density method. First and second modal frequencies for devices located at 9th floor NE are shown in Figure 4.37 for both NS and EW directions.

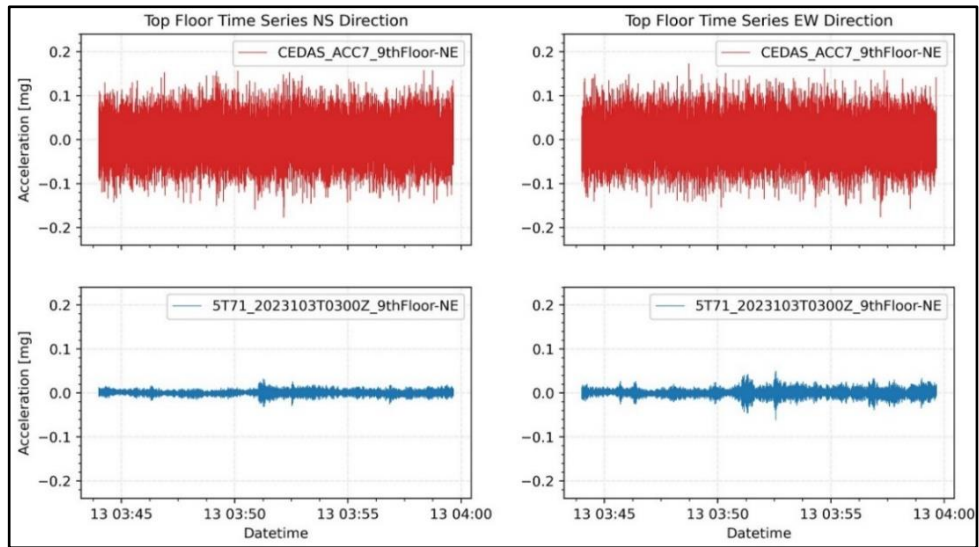


Figure 4.36: Representative ambient vibration time series of Guralp and CEDAS devices from 9th floor of the Building 3 in NS and EW directions.

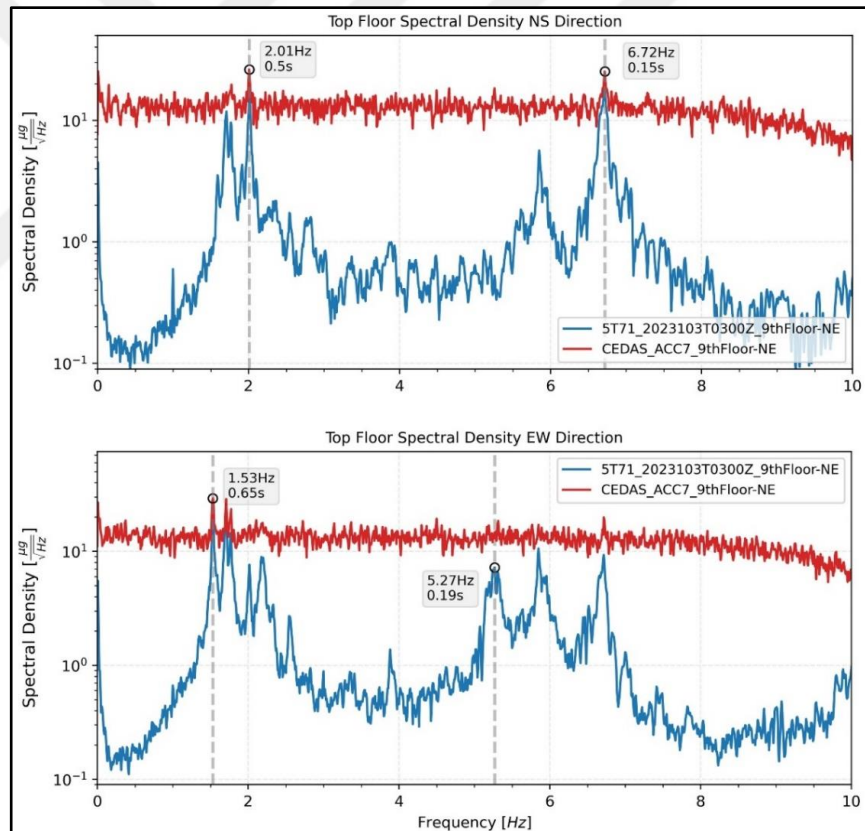


Figure 4.37: Spectral density and modal frequencies of representative ambient vibration data of Guralp and CEDAS devices from top floor of Building 3 in NS and EW directions.

The results and details of all ambient vibration recordings are listed in Table 4.9.

Table 4.9: First mode periods of 5 ambient vibrations from the Building 3 in both directions.

No	Date	Start Time (UTC)	Duration (min)	Modal Periods (s)			
				NS Direction		EW Direction	
				Guralp	CEDAS	Guralp	CEDAS
1	12.04.2023	00:30	30	0.49	0.49	0.63	0.63
2	13.04.2023	00:30	30	0.50	0.50	0.64	0.64
3	13.04.2023	03:45	20	0.50	0.50	0.65	0.65
4	14.04.2023	21:00	20	0.49	0.49	0.65	0.65
5	14.04.2023	23:05	20	0.49	0.49	0.64	0.64

4.4.4. Forced and Ambient Vibration Analyses with CEDAS_geo

In this section, CEDAS_geo device is analyzed, and results are compared with the Guralp accelerometer and CEDAS_acc. Test is made while single horizontal geophone element connected to the device, thus, analysis results for this section only includes EW direction of the building.

Response of the Building 3 affected by a M4.2 earthquake with an epicentral distance of 133.5 km is analyzed. An earthquake occurred on April 14, 2023, at 23:01:33 in Kahramanmaraş/Göksun is shown in Figure 4.38. with the location of Building 3.

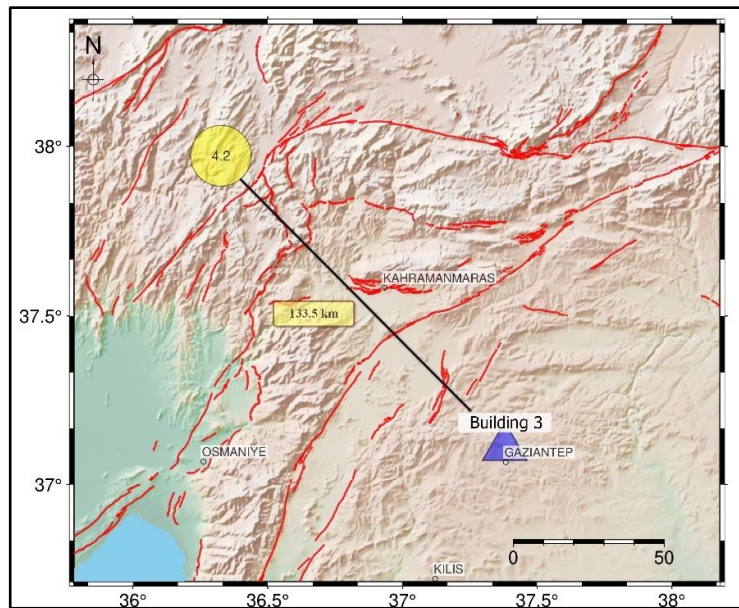


Figure 4.38: The Epicenter and other parameters of the M4.2 Earthquake excited the Building 3 (Triangle refers to location of Building 3).

A detailed look of acceleration time series from 9th floor of the building for Guralp and CEDAS_geo device is shown in Figure 4.39.

Acceleration and integrated velocity and displacement time series for the devices located side by side at 9th floor are calculated and shown in Figure 4.40 for EW direction.

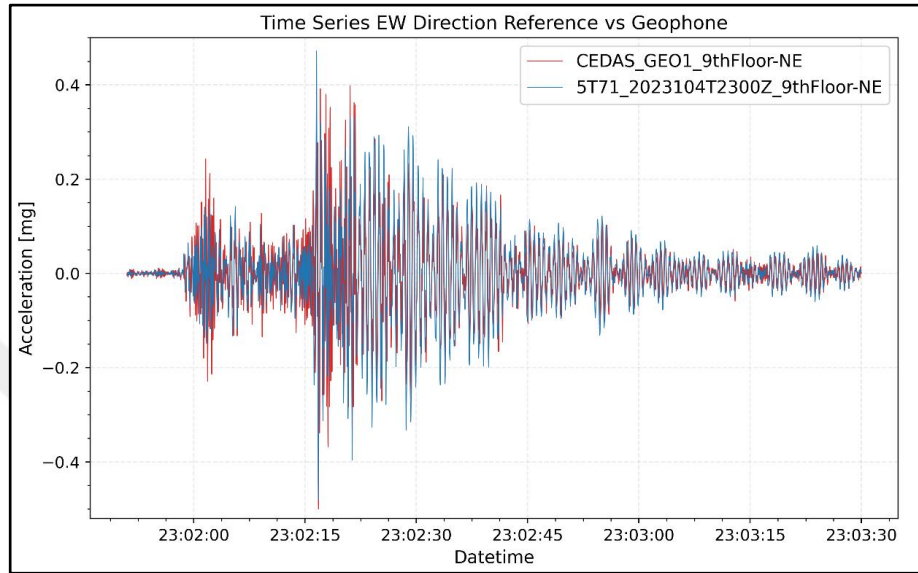


Figure 4.39: Time series of Guralp and CEDAS_geo devices from 9th floor of Building 3 in EW direction.

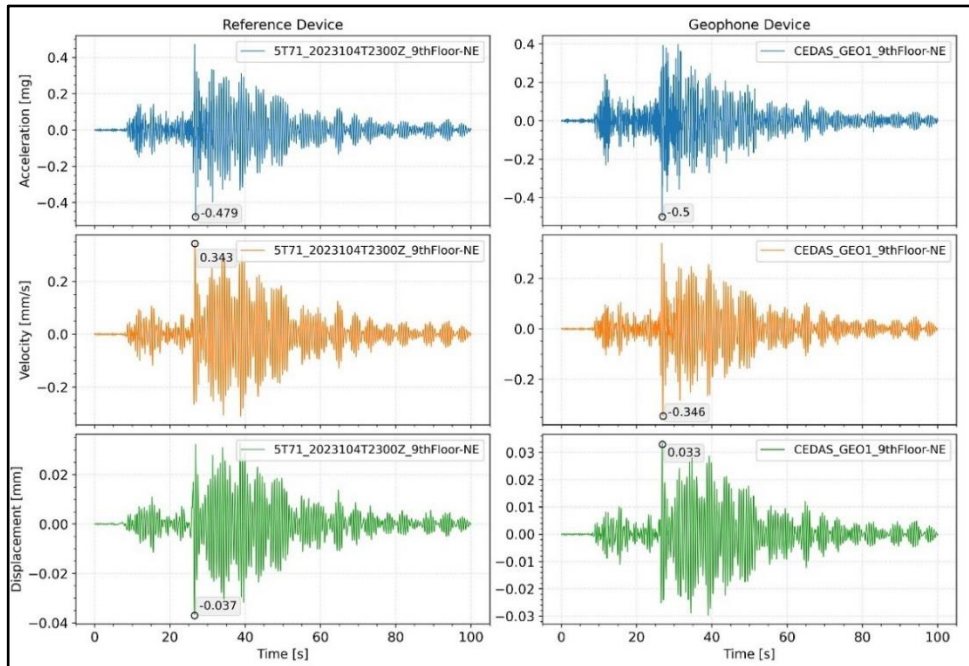


Figure 4.40: Acceleration, velocity and displacement time series of Guralp and CEDAS_geo devices from Building 3 in EW direction.

Table 4.10 shows peak acceleration, velocity and displacement values. The percentage deviation in EW direction of CEDAS_geo in reference to Guralp device for absolute peak acceleration, velocity, and displacement were found to be 4.2%, 0.8%, and 10.8%, respectively. For CEDAS_acc, percentage deviation is 6.8%, 4.4% and 13.5% respectively.

Table 4.10: Recorded acceleration, velocity, and displacement peak values of Guralp and CEDAS devices from Building 3 in EW direction.

Device	Direction	Absolute Peak Values		
		Acceleration (mg)	Velocity (mm/s)	Displacement (mm)
Guralp	EW	0.479	0.343	0.037
CEDAS_geo	EW	0.5	0.346	0.033
CEDAS_acc	EW	0.446	0.328	0.042

Spectral density of Guralp device and CEDAS devices located at 9th floor are given in Figure 4.41. Modal frequencies and periods of 1st and 2nd translational modes of Building 3 for EW direction shown in the figure.

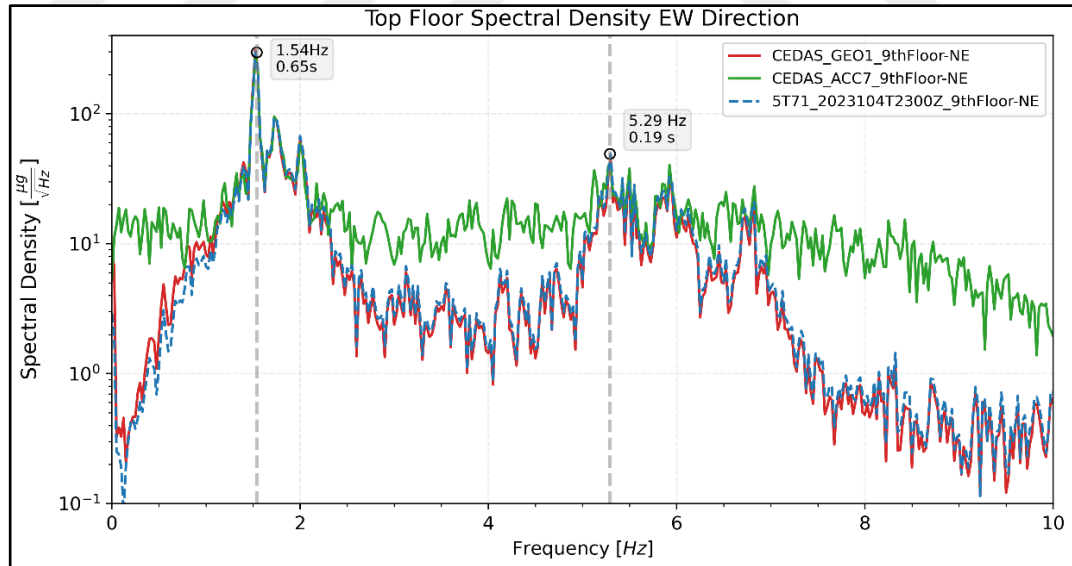


Figure 4.41: Modal frequencies and periods of Guralp and CEDAS devices from 9th floor of Building 3 in EW direction.

Ambient vibration time series of Guralp and CEDAS_geo devices are given in Figure 4.42. Time series include recordings from the 9th floor and basement of the building. Throughout the record, both devices are able capture natural frequencies of the building. Spectrogram for both devices is shown in Figure 4.43.

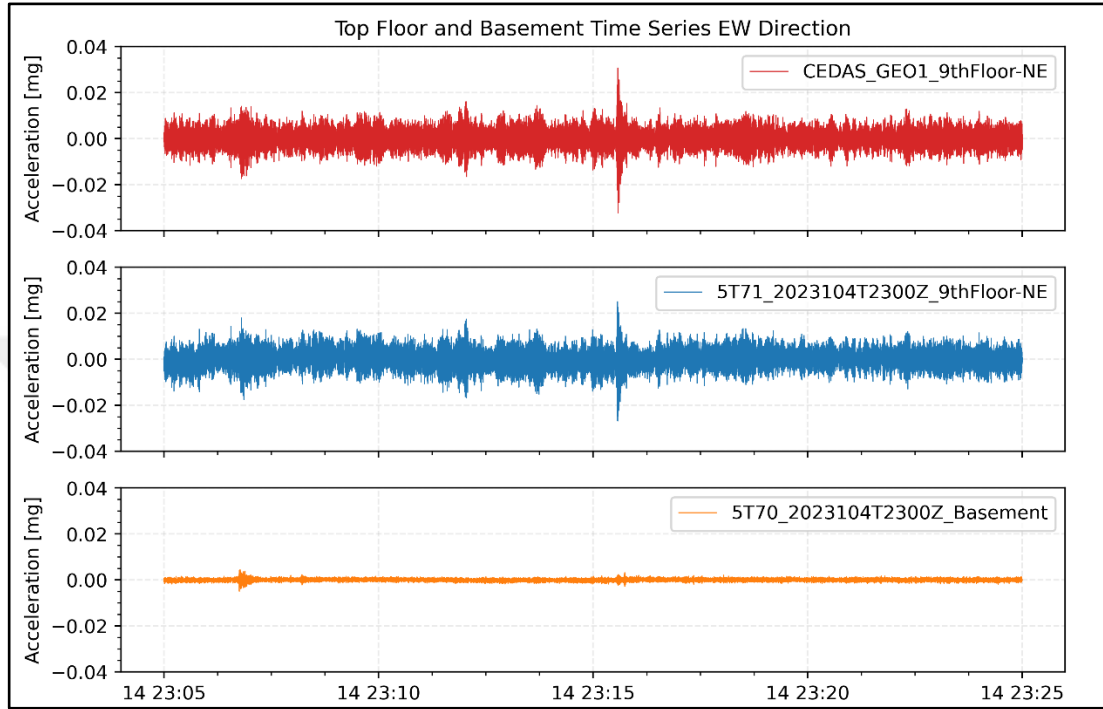


Figure 4.42: Ambient vibration time series of Guralp and CEDAS_geo from 9th floor and basement of Building 3 in EW direction.

Calculated spectral density of the 20 minute ambient vibration records shown in Figure 4.44. First and second translational modal frequencies and periods are marked on the figure. Results show, along the 0 to 10 Hz range shown in figure, devices are overlapped.

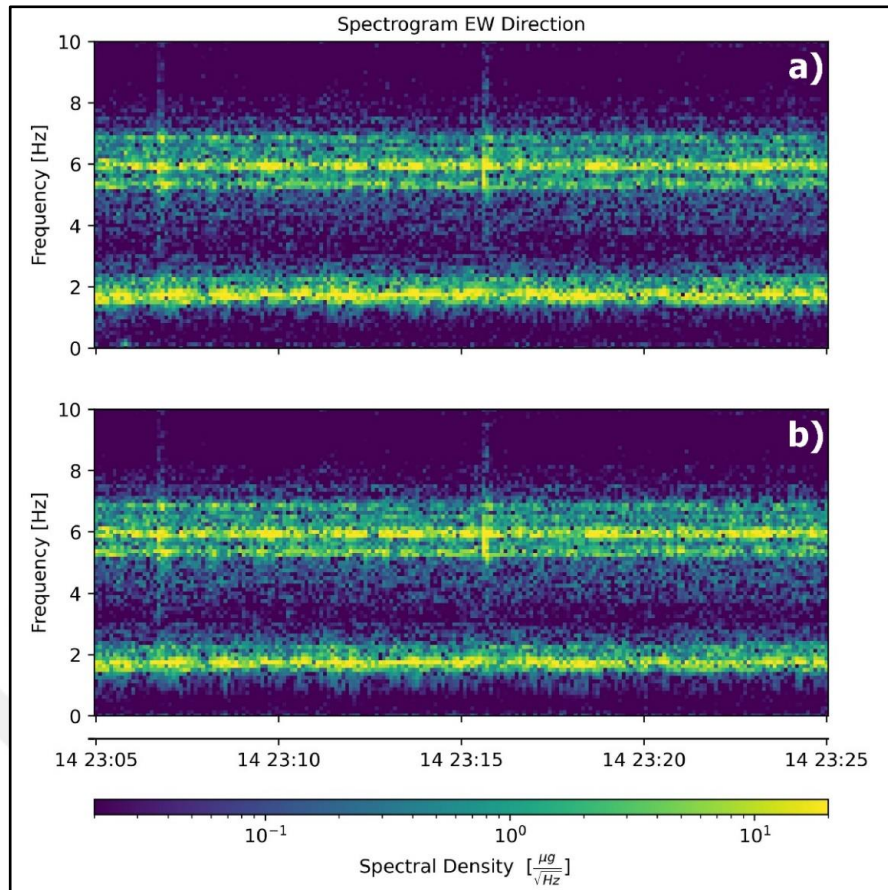


Figure 4.43: Spectrogram of ambient vibration data from (a) Guralp and (b) CEDAS_geo device in EW direction of Building 3.

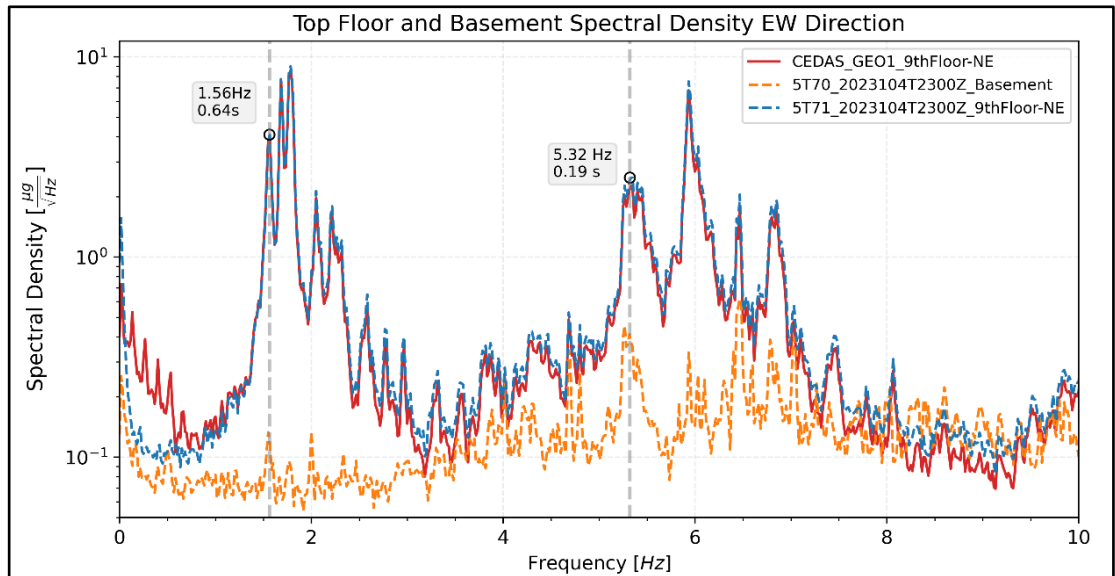


Figure 4.44: Spectral density and modal frequencies of ambient vibration data of Guralp and CEDAS_geo device in EW direction of Building 3.

5. CONCLUSION AND FUTURE WORK

5.1. Conclusion

This dissertation reviewed low-cost sensor options and prepared an acceleration and velocity DAS using open-source Python software for applications in Earthquake Engineering and Earth Sciences. Validation tests and field tests have been conducted for both CEDAS devices that use MEMS accelerometer sensor board and analog geophone sensor.

The thesis can be categorized into three sections:

The first section includes the details of software and hardware of prepared CEDAS devices. Devices run on a Raspberry Pi single-board minicomputer with a network connection. CEDAS are two separate devices with features that compensate for each other's limitations. Appropriate sensor selection is made regarding the literature review and guidelines. Different sensors are tested for the MEMS accelerometer and geophone selection. CEDAS_acc consists of triaxial MEMS sensor with $\pm 2g$ measurement range, 20-bit resolution, spectral noise density of $15 \mu g/\sqrt{Hz}$ as tested. CEDAS_geo device consists of 5Hz horizontal geophone element with 80V/m/s sensitivity, 24-bit resolution and nano-g level noise density. When CEDAS devices used together, they cover a wide dynamic range.

In the second section, CEDAS devices are evaluated by offset, frequency response, shake table and spectral noise density tests. Offsets of the CEDAS_acc devices are calibrated. Sensitivity error is found lower than %1 for each axis, which is lower than ANSS guidance for strong ground motion accelerometers. Frequency response of the CEDAS_geo device is evaluated by calculating the transfer function with GURALP CMG 5TDE reference sensor. Frequency response of the device is flattened by designing a digital filter by using the transfer function. CEDAS_acc is tested on a shake table with GURALP reference sensor. Waveforms in the time domain show the signals are overlapping. This indicated the timing and frequency response of the CEDAS_acc is accurate regards to reference sensor. Amplitudes of the spectral density estimates deviates by 1.5% maximum, compared to Guralp reference device. Results indicate that CEDAS_acc has a flat response, and it is in the -3dB in-band limit between the tested 0.5Hz to 10Hz frequency range. Finally, noise density of the

CEDAS devices is estimated. CEDAS_acc has a flat self-noise at -78 dB or $15 \mu g/\sqrt{Hz}$. CEDAS_geo has a noise density between low and high noise models [44]. As a result, CEDAS_acc can be classified as Class B accelerometer per ANSS instrumentation guidance, sensor performance specifications according to number of components, clip-level, resolution, flat response, sensitivity accuracy performance metrics. CEDAS_acc can be used as primary sensor in dense strong motion array for urban monitoring and for structural monitoring with a reference device according to ANSS guidance. Also, it can be used as an optional device for regional, urban monitoring and structural monitoring with a reference device. Measurement range and frequency response of CEDAS_geo is unacceptable per general ANSS guidance. Nevertheless, frequency response is corrected by a designed digital filter. Further tests are needed for noise density with the provided technics in appropriate conditions.

In the third section, CEDAS devices are tested on a multiple residential reinforced concrete structure. Building 1 is monitored for modal frequency tracking from continuous ambient vibration data. With the developed algorithm, the first, second and third mode of the building are tracked for 24-hours. CEDAS_geo successfully identified the modal frequencies from the background noise by a accuracy rate of 100%, 99%, 91% for first, second and third modes, respectively. CEDAS_acc tracked by 96%, 69%, and 45% accuracy rate. Building 2 and 3 are investigated under the forced vibration and ambient vibration. Peak values obtained from forced vibration acceleration time series and modal frequencies calculated from spectral density estimates are nearly the same compared to Guralp reference sensor. First and second mode for buildings both directions are given in Table 5.1. CEDAS_acc has time drifts at a level of seconds. This issue is not observed in the CEDAS_geo device. The internal clock of the MEMS sensor is not running at the center frequency which introduces time drifts and small shifts in frequency domain. However, this problem did not affect the results.

Table 5.1: First and second mode periods of the buildings in both directions for forced vibration analysis.

	Device Name	Location	Modal Periods (s)			
			NS Direction		EW Direction	
			1st Mode	2nd Mode	1st Mode	2nd Mode
Building 2	Guralp 5T70	Top Floor	0.67	0.193	0.89	0.238
	CEDAS acc1	Top Floor	0.67	0.193	0.89	0.238
Building 3	Guralp 5T71	9th Floor	0.51	0.151	0.66	0.193
	CEDAS acc6	9th Floor	0.51	0.151	0.66	0.193

The natural frequencies of the buildings slightly change when the ambient and forced vibration data is compared, which is the indication of linear behavior of the building during the earthquake.

Field tests showed CEDAS_acc is capable for the forced vibration analysis of the low to mid rise buildings. Founded modal frequencies show a maximum of 1% difference compared to the Guralp reference device. Similarly, maximum deviation of peak acceleration values is 7% for Building 1 and 2. However, when velocity and displacement series are calculated by integrating, the impact of the noise increases, waveform and peak values differ more from reference device. When SNR exceeds a certain level, velocity and displacement time series becomes unusable. CEDAS_geo offers much more SNR. Thus, acceleration, velocity and displacement time series are highly correlated with the Guralp reference device. The results are summarized for both buildings in Table 5.2.

Table 5.2. Recorded acceleration, velocity, and displacement peak values of Guralp and CEDAS_acc and CEDAS_geo devices from buildings in both directions.

	Device	Direction	Absolute Peak Values		
			Acceleration (mg)	Velocity (mm/s)	Displacement (mm)
Building 2	Guralp	NS	1.152	0.556	0.064
		EW	1.564	0.703	0.052
	CEDAS_acc	NS	1.185	0.562	0.077
		EW	1.537	0.682	0.054
Building 3	Guralp	NS	0.611	0.382	0.026
		EW	0.741	0.341	0.024
	CEDAS_acc	NS	0.607	0.422	0.041
		EW	0.712	0.372	0.031
Building 3_2	Guralp	EW	0.479	0.343	0.037
	CEDAS_geo	EW	0.500	0.346	0.033
	CEDAS_acc	EW	0.446	0.328	0.042

As a result, field tests demonstrate the potential of cost-effective CEDAS devices. When the CEDAS_acc is used in conjunction with a Guralp reference sensor or a CEDAS_geo device, valuable and supportive information is obtained from a highly affordable device against its equivalents. CEDAS devices are designed to encompass a wide dynamic range when used together. Compared with its peers, CEDAS devices offer a much more affordable and flexible solution for a wide range of applications such as SHM for low to high rise buildings, seismic measurements, and monitoring networks. Low-cost is an important issue for enabling widespread deployment of devices. In general, cost of CEDAS_acc is around 200 USD and CEDAS_geo with single geophone element is 250 USD as in 2023. Hopefully, this thesis study helps to clarify the recent trade-offs between the quality and the cost of the MEMS accelerometer and geophone sensor based devices.

5.2. Future Work

In future work, the development and enhancement of the CEDAS devices can focus on incorporating advanced signal processing techniques, exploring new sensors, and optimizing data storage and retrieval mechanisms for improved performance and usability.

Using external synchronization is possible for CEDAS devices. By full external synchronization or with interpolation method sampling rate can be more accurate and better synchronization can be achieved [26]. Thus, problems such as minor time drift and frequency domain offsets can be solved especially for CEDAS_acc device.

Further improvements to timing can be made by using a faster programming language than Python for sensor and ADC drivers. Real-time operating system (RTOS) and real time kernel for Raspberry computer can allow for the execution of tasks and processes with more precise timing compared to the operating system of current device.

CEDAS devices can serve web pages for the sensor readings, e-mail an alarm for any given condition, and FTP (File Transfer Protocol) the waveforms or analyzed results into databases or direct to the clients. These functionalities can be implemented on the RECANA web application.

Further processing with the obtained data from Building 2 and 3 from field tests will be done. Mode shapes and natural periods of the buildings will be extracted by Frequency Domain Decomposition technique and algorithms are going to be implemented to the RECANA software [49]. By using plans of the building, finite element models of the buildings will be created and corrected by using monitored data.

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BIOGRAPHY

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APPENDICES

Appendix A: Publications within the Scope of the Thesis Study

Özdemir K., Kömeç A., (2022), “Cost-Effective Data Acquisition System for Structural Health Monitoring and Earthquake Observations”, 6th GTU Graduate Research Symposium, Kocaeli, Türkiye.

Appendix B: Device Connection Diagrams

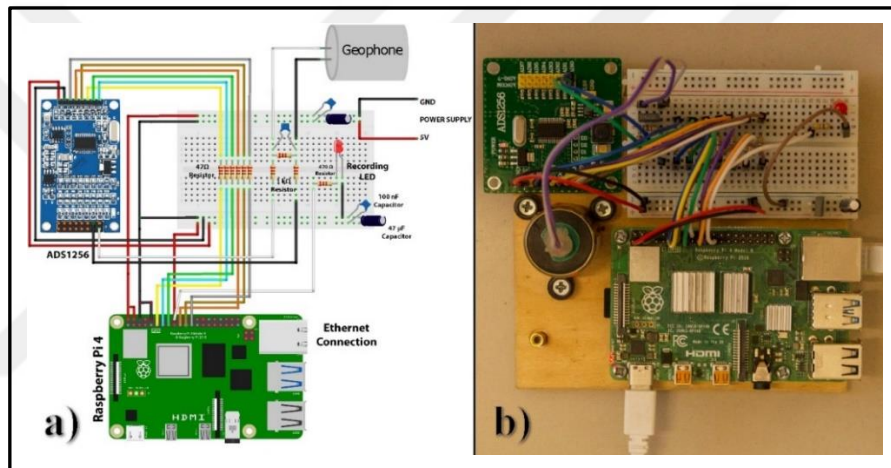


Figure B1.1: (a) CEDAS_geo connection diagram (b) circuit connection of prototype device for example visualization.

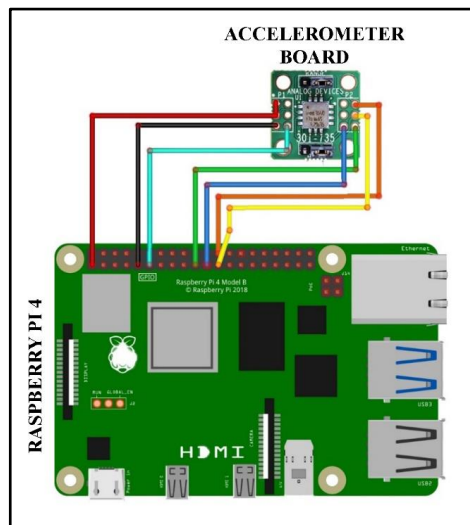


Figure B1.2: CEDAS_acc connection diagram.

Appendix C: Data Ready Function Code Snippet

```
def wait_drdy(self):
    # Counter
    start = time.time()
    elapsed = time.time() - start
    # Wait DRDY pin to go low or DRDY_TIMEOUT seconds to pass
    if self.drdy_pin is not None:
        drdy_level = wp.digitalRead(self.drdy_pin)
        while (drdy_level == wp.LOW) and (elapsed < self.drdy_timeout):
            elapsed = time.time() - start
            drdy_level = wp.digitalRead(self.drdy_pin)
            # Use delay to avoid busy wait and reduce CPU load.
            time.sleep(self.drdy_delay)
        if elapsed >= self.drdy_timeout:
            print("\nTimeout while polling DRDY pin")
    else:
        time.sleep(self.drdy_timeout)
        print("\nDRDY pin did not connected")
```

Appendix D: Record Analyzer (RECANA) Web Application

GitHub Repository of RECANA Web Application:

<https://github.com/kamerozdmr/RECANA>

GitHub Repository of RECANA Executable Packing:

https://github.com/kamerozdmr/RECANA_Executable

Web Application Link:

<https://recana.streamlit.app/>

Import and Trim

Select a file to analyze.

Import acceleration data

Drag and drop files here
Limit 200MB per file • MSED, SAC, GCF

Browse files

2023105T0000Z.gcf 0.8MB X

20230206102447_4612_01.SAC 41.6KB X

20230206011732_3139_N.mseed 151.5KB X

Read Records

Ready

Record properties							
	filename	fileformat	tracename	npts	delta	starttime	endtime
0	20230206102447_4612_01	SAC	Trace1-E	10,501.0000	0.0100	2023-02-06T10:24:33	2023-02-06T10:24:33
1	20230206011732_3139_N	mseed	Trace1-HNE	21,315.0000	0.0100	2023-02-06T01:16:46	2023-02-06T01:16:46
2	20230206011732_3139_N	mseed	Trace2-HNN	21,313.0000	0.0100	2023-02-06T01:16:46	2023-02-06T01:16:46
3	20230206011732_3139_N	mseed	Trace3-HNZ	21,294.0000	0.0100	2023-02-06T01:16:46	2023-02-06T01:16:46
4	2023105T0000Z	gcf	Trace1-HHE	131,000.0000	0.0050	2023-04-15T00:00:00	2023-04-15T00:00:00
5	2023105T0000Z	gcf	Trace2-HHN	130,800.0000	0.0050	2023-04-15T00:00:00	2023-04-15T00:00:00
6	2023105T0000Z	gcf	Trace3-HHZ	131,200.0000	0.0050	2023-04-15T00:00:00	2023-04-15T00:00:00

Figure D1.1: RECANA web application filtering section.

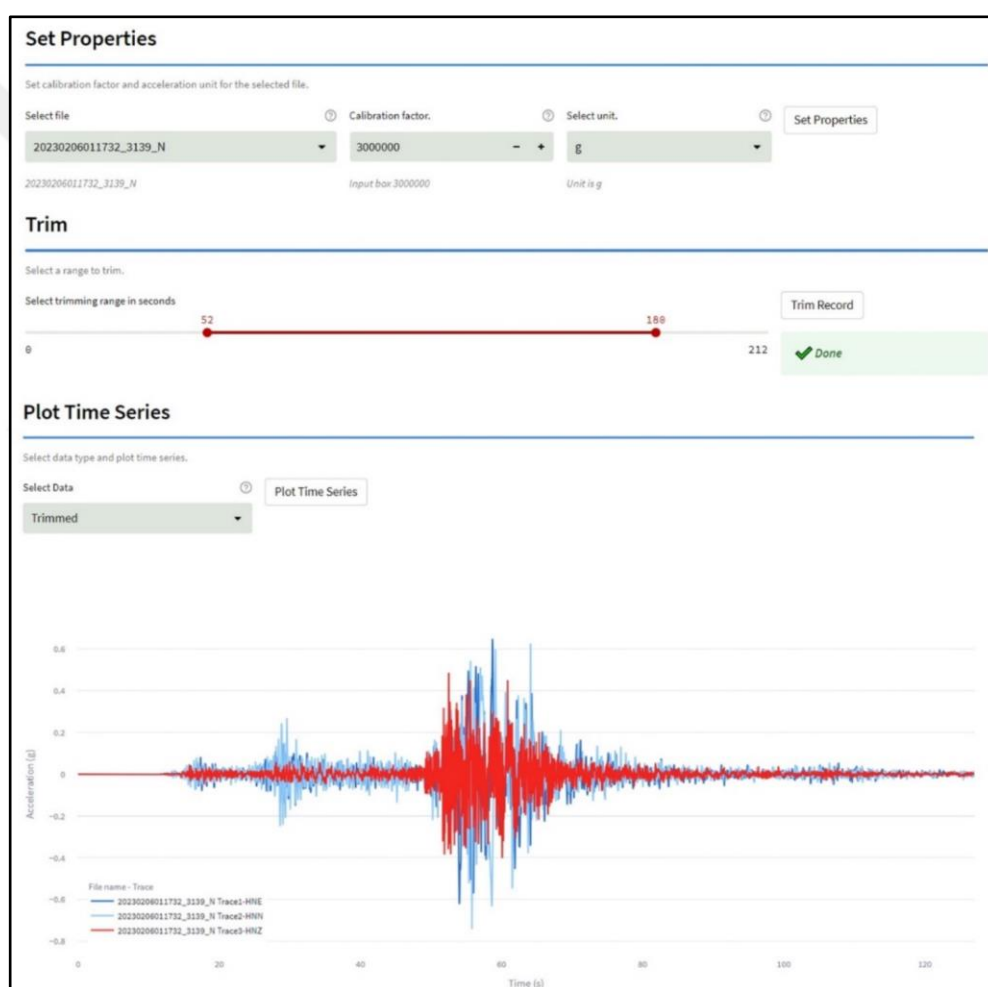


Figure D1.2: RECANA web application calibration, trimming and visualization section.

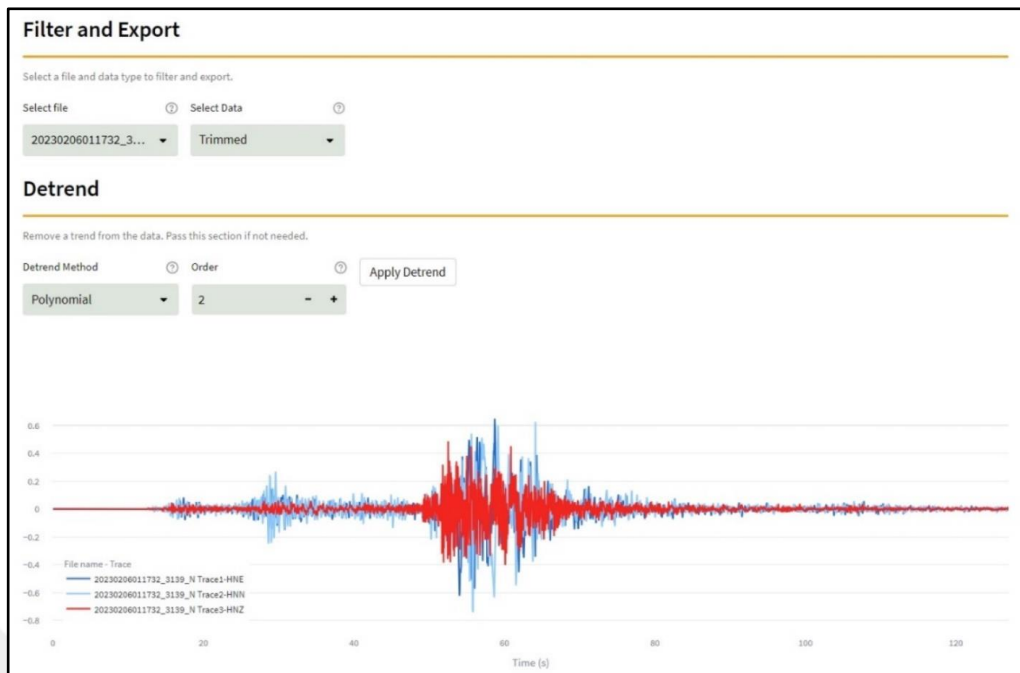


Figure D1.3: RECANA web application detrending section.

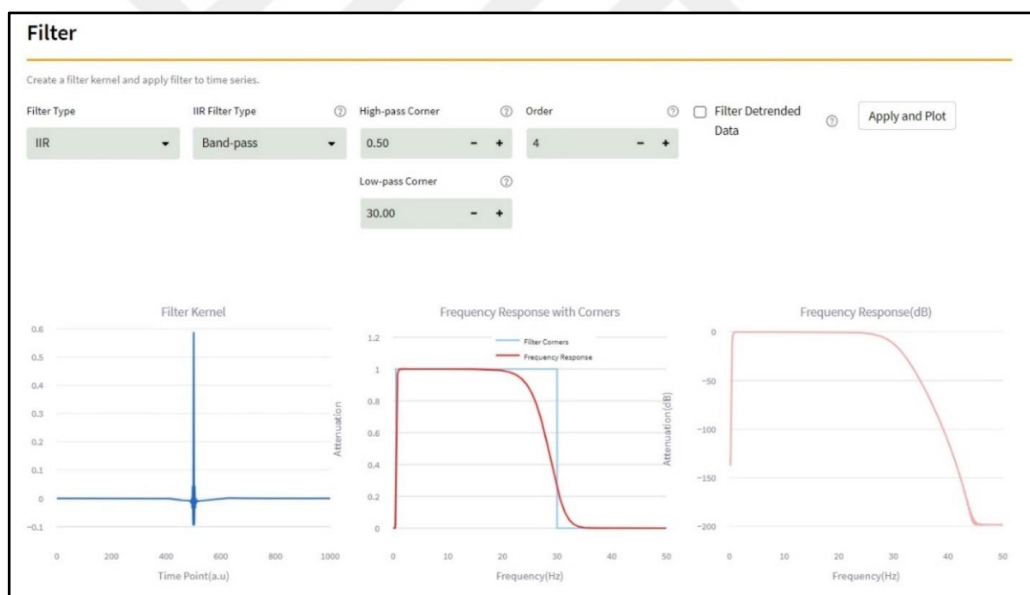


Figure D1.4: RECANA web application filtering section.

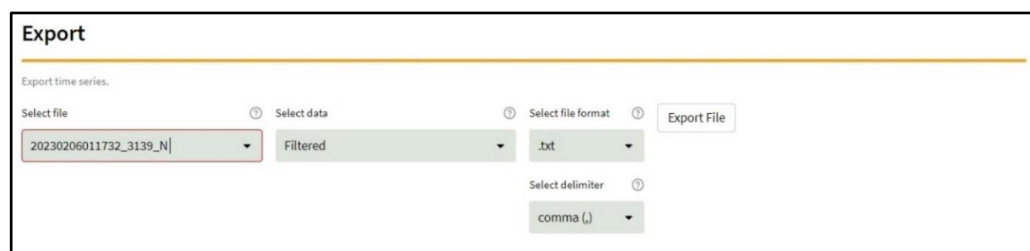


Figure D1.5: RECANA web application exporting section.

Appendix E: Animation for Peak Picking Algorithm

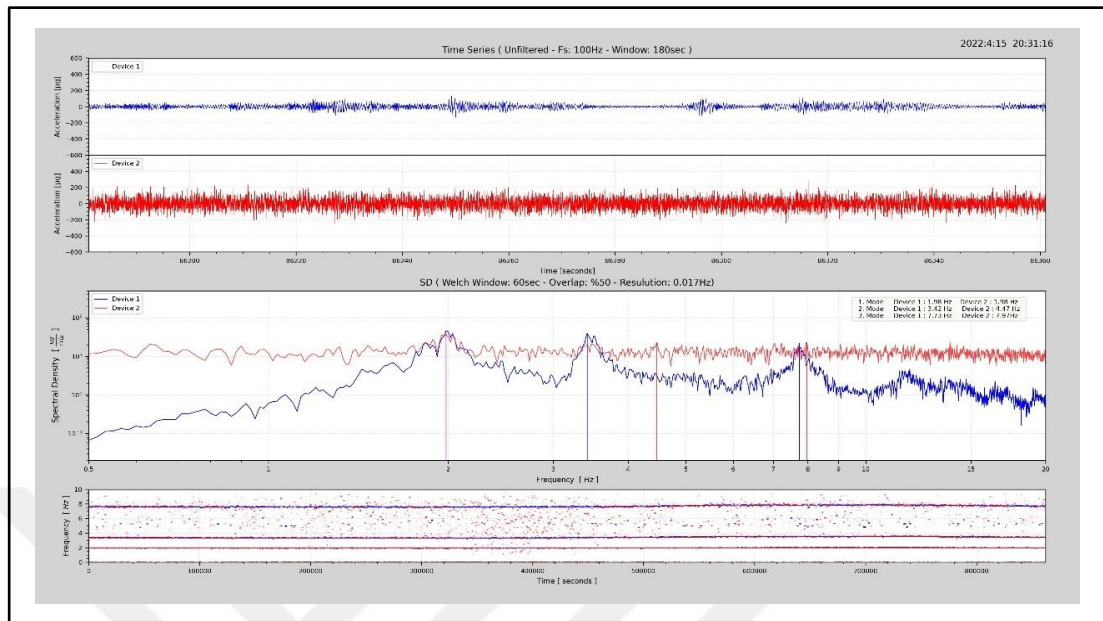


Figure E1.1: Time series, spectral density and fundamental frequency tracking algorithm animation screen.

Animation video links:

https://www.youtube.com/watch?v=I7ved_or6vo

https://www.youtube.com/watch?v=dejl7_i7Lyg