

Design and Calibration of an Affordable Seismic Monitoring System

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Abstract— This paper presents the design, calibration, and validation of a low-cost seismic monitoring system using an ADXL335 Micro-Electro-Mechanical Systems (MEMS) accelerometer, ADS1115 16-bit Analog-to-Digital Converter (ADC), Raspberry Pi 4 Model B, and Long Range (LoRa) SX1278 transceiver. A standardized one-dimensional shake table, which simulates controlled ground motion, was used to calibrate the system, providing a safe and repeatable environment for evaluating the system. The monitoring system was validated using the 2010 Chile (M8.8) and 2015 Gorkha (M7.3) aftershock records, achieving Pearson correlation coefficients of 0.8911 and 0.9010, respectively. A 4th-order Butterworth bandpass filter (0.1–2.0 Hz) reduced out-of-band noise, while LoRa communication achieved 100% packet delivery with Received Signal Strength Indicator (RSSI) values between –31 and –34 dBm at 10m distance. Costing under 20 USD per node, the proposed system provides an affordable and scalable solution for dense seismic monitoring in earthquake-prone developing regions.

Keywords — MEMS accelerometer, ADXL335, ADS1115, LoRa, Raspberry Pi, seismic monitoring, shake table, Nepal, earthquake early warning, low-cost sensor network.

I. INTRODUCTION

Nepal sits at the boundary of the Indian and Eurasian plates, making it highly earthquake-prone. The 2015 Gorkha Earthquake (Mw 7.8) alone killed over 8,800 people, underscoring the need for dense, real-time seismic monitoring for early warning and hazard response [1]. MEMS accelerometers provide an affordable route to this, given their small size and low cost [2], and have already been used in early-warning systems [3]. The ADXL335 (GY-61), a three-axis analog MEMS accelerometer (± 3 g range, ~ 300 mV/g sensitivity) [4], has shown reasonable accuracy against reference seismometers in prior low-cost deployments [5,6], though at costs and performance levels this work aims to improve on — the proposed system reaches $r = 0.89$ – 0.90 against shake-table references at under 20 USD per node.

The proposed system combines the ADXL335 with an ADS1115 16-bit ADC and Raspberry Pi 4 Model B for data acquisition and processing. The ADS1115 provides 16-bit resolution, I²C communication, programmable gain, and data rates up to 860 samples/s [7]. Raspberry-Pi-based seismic

monitoring, such as RaspMI with its 72 dB dynamic range and 100 Hz sampling, has previously been demonstrated [8]. MEMS-based urban seismic networks [9] and low-cost Arduino-based structural vibration systems reporting up to $14\times$ lower cost than conventional monitoring equipment [10] further demonstrate the potential of affordable sensing technologies, positioning the present system's sub-20 USD per-node cost favorably within this landscape.

This paper presents a MEMS-based seismic monitoring system with GPS timing, standardized shake-table calibration, waveform validation, and 433 MHz LoRa telemetry, demonstrating reliable performance for strong-motion monitoring in Nepal. Moreover, it also opens new avenues for deployment of affordable vibration monitoring systems for civil engineering structures.

II. SYSTEM DESIGN AND METHODOLOGY

A. System Model

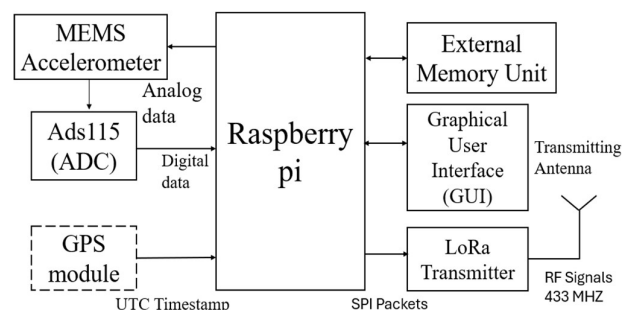


Fig. 1. System Architecture of Transmitting Section.

Fig. 1 shows the transmitting section of the proposed seismic monitoring system. The ADXL335 accelerometer senses ground vibrations and generates analog signals, which are converted into digital data by the ADS1115 ADC. The Raspberry Pi 4B processes the data, adds the GPS-based UTC timestamp, stores it in the external memory, and displays it on the GUI for real-time monitoring. Finally, the processed data is sent to the LoRa transmitter via SPI and wirelessly transmitted through a 433 MHz antenna to the receiving station. The entire system is powered by a 3.3 V supply for stable operation.

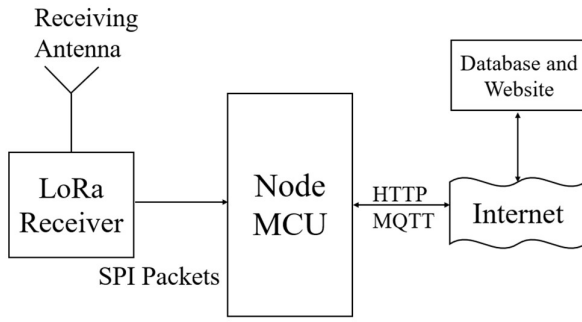


Fig. 2. System Architecture of Receiving Section

Fig. 2 illustrates the receiving section of the proposed seismic monitoring system. The LoRa receiver captures the wireless data transmitted from the sensing unit and forwards it to the Node MCU ESP32 through SPI communication. The ESP32 processes the received data and sends it to the database and website via the Internet using the HTTP POST protocol. This enables the seismic data to be stored securely and displayed on a web interface for remote, real-time monitoring.

B. Sensing Chain: ADXL335 and ADS1115

The ADXL335 accelerometer produces analog voltage outputs corresponding to vibrations along the X, Y, and Z axes [4]. Since the Raspberry Pi 4B does not include built-in analog input pins, the ADS1115 is interfaced to convert these analog signals into digital data that can be processed by the Raspberry Pi. This interface enables accurate acquisition of vibration measurements while providing a simple and reliable connection between the sensor and the processing unit summarized in Table I.

TABLE I. ADS1115 KEY SPECIFICATION [7]

Feature	Specification
Resolution	16-bit (15-bit effective with sign)
Interface	I ² C (up to 4 configurable addresses)
Sampling Rate	8–860 SPS (programmable)
Programmable Gain	Built-in PGA (± 0.256 V to ± 6.144 V)
Operating Voltage	2.0 V – 5.5 V

C. STATIC CALIBRATION

The raw ADS1115 count N is converted to voltage using:

$$V = \left(\frac{N}{32768} \right) \times V_{PGA}$$

where $V_{PGA} = 4.096$ V (PGA FS range). The zero-g offset $V_{0g} = 1.65$ V is measured empirically by averaging 1000 static ADC samples. Acceleration in g is:

$$a_g = \frac{(V - V_{0g})}{S}$$

where $S = 0.3$ V/g is the nominal ADXL335 sensitivity. For engineering units (cm/s^2):

$$a_{\text{cm/s}^2} = a_g \times 980.665$$

D. Digital Filtering

A 4th-order Butterworth bandpass filter (0.1–2.0 Hz) using SciPy `sosfiltfilt` was applied to both signals to remove drift, tilt errors, and high-frequency noise while retaining the

seismic frequency range. Zero-phase filtering prevents phase distortion and preserves Pearson correlation accuracy [11].

E. LoRa Wireless Telemetry

Processed data are packed into 12-byte binary packets containing elapsed time and acceleration values, then transmitted using the SX1278 LoRa module at 433 MHz via SPI [12]. LoRa provides long-range, low-power communication, making it suitable for remote seismic monitoring in Nepal's hilly regions without cellular networks. Similar LoRa systems have been used for environmental monitoring. At the base station, an ESP32 receives and decodes the packets before sending the data via Wi-Fi to a web server for real-time display.

F. Shake-Table Validation Protocol

Dynamic calibration was performed using a laboratory 1D shake table at the Earthquake Laboratory of Khwopa Engineering College, as shown in Fig. 3. The platform generates controlled horizontal vibrations that simulate earthquake-like ground motion. A previous real-time seismic monitoring system using low-cost instrumentation has also been reported [13], while a low-cost MEMS accelerometer has been experimentally evaluated using a 1D shake table at Khwopa Engineering College [14].

Official displacement records from the 2010 Chile Earthquake (Mw 8.8, ± 0.61 g peak) and the 2015 Gorkha Earthquake (Mw 7.8, ± 0.056 g peak) were replayed, with the records numerically double-differentiated to obtain reference acceleration time series. The ADXL335 was rigidly mounted on the table platform, and data were acquired at 100 Hz with UTC timestamps assigned in software (no dedicated hardware GPS or real-time-clock module was used), as shown in Fig. 4. Sensor and reference records were time-aligned using cross-correlation and evaluated using Pearson correlation coefficients and log-log FFT spectral comparison. Python-based seismic signal-processing approaches provide additional support for waveform and frequency-domain analysis [15].



Fig. 3. Standard shake table of khwopa engineering college



Fig. 4. System setup in shake table surface

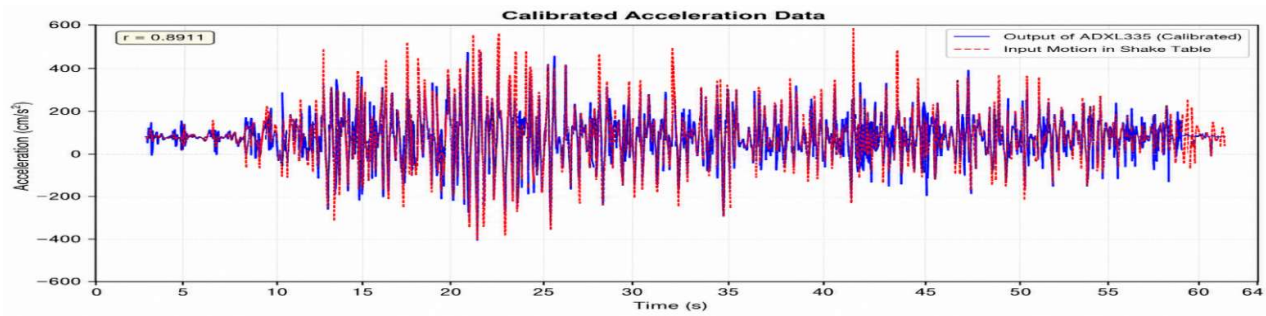


Fig. 5. Full time-domain waveform – Chile earthquake — Chile Earthquake. Solid: filtered ADXL335 output; Dashed: shake-table reference.

III. RESULT AND DISCUSSION

The ADXL335 was mounted on the 1D laboratory shake table, and the complete sensing system was acquired and was transmitted vibration data during replay of historical earthquake records. The measured signals were then compared with the reference records after time alignment and filtering.

A Chile Earthquake - Time-Domain Analysis

The Chile earthquake record was used to evaluate the system under strong ground motion conditions. The record spans approximately 65s at a sampling rate of 100 Hz (~6,500 samples) and consists of three distinct phases: rapid onset, sustained strong motion (14:02:39–14:03:09), and decaying coda. As shown in Fig. 5, the measured waveform (solid line) closely follows the reference waveform (dashed line) throughout all three phases, showing close agreement with the reference signal even at peak accelerations of approximately $\pm 600 \text{ cm/s}^2$ ($\pm 0.61 \text{ g}$) without noticeable saturation. This close agreement is further quantified by the Pearson correlation analysis summarized in Table II. The system achieved a full-record correlation of $r = 0.8911$, while the peak strong-motion segment (Segment A) reached $r = 0.9264$, indicating the highly agreement during the most critical period of the earthquake. Furthermore, the sustained (Segment B) and decay (Segment C) phases achieved correlations of $r = 0.8595$ and $r = 0.8225$, respectively, confirming consistent tracking performance throughout the entire record. Moreover, the measured peak acceleration utilized only 31% of the sensor's $\pm 2 \text{ g}$ measurement range, indicating sufficient headroom for recording stronger seismic events.

TABLE II. SEGMENTAL PEARSON CORRELATION – CHILE EARTHQUAKE./

Segment	Time Window	r	Assessment
A – Peak motion	14:02:40–14:02:53	0.9264	Excellent
B – Sustained	14:02:53–14:03:09	0.8595	Good–Excellent
C – Decay	14:03:09–14:03:27	0.8225	Good
Full record	14:02:23–14:03:27	0.8911	Excellent

B Chile Earthquake - Frequency-Domain Analysis

Fig. 6 presents a log-log FFT comparison across the full recorded bandwidth (approximately 0.02–50 Hz) between the ADXL335 sensor output (solid blue) and the shake table's

input motion (dashed red), evaluated without normalization or band-limiting. Below roughly 0.1 Hz, the sensor output sits consistently above the input curve, reflecting low-frequency noise and drift inherent to the accelerometer rather than genuine table motion, since the physical excitation in this range is negligible. Between approximately 0.15 Hz and 3 Hz, the two traces converge closely, tracking nearly identical peak and dip structure. This band captures the shake table's dominant mechanical excitation, including its primary drive frequency near 3 Hz. Beyond roughly 3–5 Hz, the two curves diverge: the sensor output's noise floor rolls off and drops below the input curve, while the input trace retains higher broadband energy up to the Nyquist limit, likely reflecting quantization or controller-signal noise in the shake table's reference input rather than physical motion. Overall, the comparison indicates good fidelity between sensor and table motion in the physically relevant excitation band, with divergence at higher frequencies attributable to sensor bandwidth/noise-floor limitations rather than a modeling or gain error.

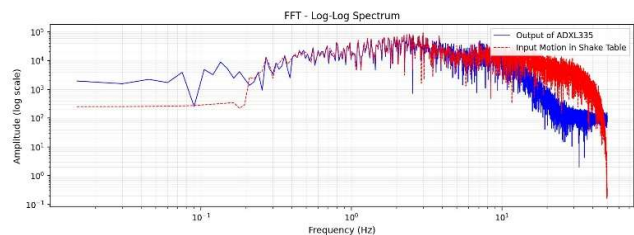


Fig. 6. Chile Earthquake, Broadband Frequency-Domain Comparison

C. Gorkha Earthquake 2015 - Time-Domain Analysis

The Gorkha Earthquake 2015 record was used to evaluate the proposed system under moderate ground motion conditions. The record is 110 s at a sampling rate of 100 Hz (~11,000 samples), with peak accelerations of approximately $\pm 55 \text{ cm/s}^2$ ($\pm 0.056 \text{ g}$). As shown in Fig. 7, the measured waveform (solid line) closely follows the reference waveform (dashed line) throughout the record, demonstrating accurate tracking even for low-amplitude seismic motions. This agreement is further quantified by the Pearson correlation analysis summarized in Table III. The peak-motion segment (Segment B) achieved the highest correlation among all experiments ($r = 0.9751$), while the full-record correlation remained significant at $r = 0.9010$. Although the coda segment (Segment D) yielded a lower correlation ($r = 0.4473$), this is primarily attributed to the low signal-to-noise

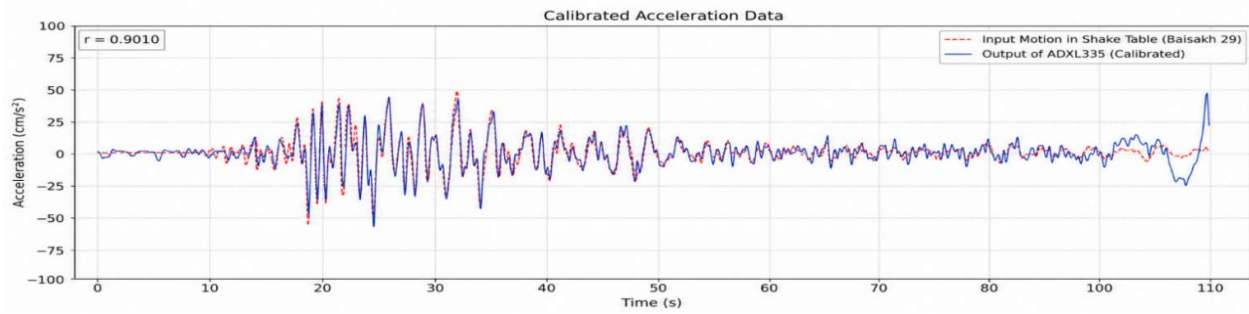


Fig. 7. Full time-domain waveform – Gorkha Earthquake (2015) Solid: filtered ADXL335 output; Dashed: shake-table reference.

ratio during the noise-dominated decay phase rather than limitations of the sensor. Moreover, the recorded peak acceleration utilized only 2.8% of the sensor's ± 2 g measurement range, demonstrating the system's ability to accurately resolve low-amplitude ground motions while retaining substantial dynamic range for stronger seismic events.

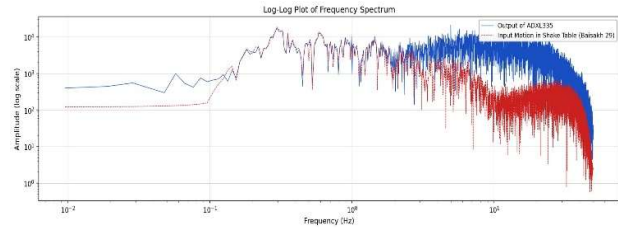


Fig. 8. Baisakh 29 Earthquake, Broadband Frequency-Domain Comparison

TABLE III. SEGMENTAL PEARSON CORRELATION – GORKHA EARTHQUAKE.

Segment	Time Window	r	Assessment
A – Early strong motion	10:07:10–10:07:37	0.9692	Excellent
B – Sustained strong motion	10:07:36–10:08:03	0.9751	Peak Excellent
C – Decay phase	10:08:03–10:08:30	0.7421	Good
D – Coda (low SNR)	10:08:29–10:08:56	0.4473	Expected
Full record	10:07:10–10:09:00	0.9010	Excellent

D. Gorkha Earthquake - Frequency-Domain Analysis

Fig. 8 presents a log-log FFT comparison across the full recorded bandwidth (approximately 0.01–50 Hz) between the ADXL335 sensor output (solid blue) and the shake table's input motion (dashed red) for the Baisakh 29 event, evaluated without normalization or band-limiting. Below roughly 0.1 Hz, the sensor output sits noticeably above the input curve (on the order of 400–800 versus ~120–150), reflecting low-frequency sensor noise and drift rather than genuine table motion, since physical excitation in this range is minimal. Between approximately 0.1 Hz and 3 Hz, the two traces rise sharply and converge closely, tracking nearly identical peak and dip structure that includes a shared dominant peak near 0.3 Hz reaching roughly 2×10^4 indicating this band captures the shake table's actual mechanical excitation with high fidelity between sensor and reference. Beyond roughly 3 Hz, the two curves diverge: the sensor output maintains a higher, noisier amplitude envelope extending out to approximately 30 Hz before rolling off toward the Nyquist limit, while the input trace drops to a lower noise floor (roughly one to two orders of magnitude below the sensor output) over the same range. This high-frequency divergence is attributable to sensor-side broadband noise rather than a modeling or calibration error, since the well-matched mid-band confirms accurate sensor response in the physically relevant excitation range.

E. Cross-Event Performance Summary

Table IV summarizes the overall performance of the proposed seismic monitoring system under two earthquake scenarios with significantly different amplitudes and frequency characteristics. Despite the Chile earthquake exhibiting nearly ten times the peak acceleration of the Gorkha earthquake, the system maintained excellent full-record correlations of $r = 0.8911$ and $r = 0.9010$, respectively, confirming linear and reliable sensor tracking across a wide range of seismic intensities. Furthermore, the peak-motion segments achieved correlations exceeding $r = 0.92$ for both events ($r = 0.9264$ for Chile and $r = 0.9751$ for Gorkha), demonstrating the highest accuracy during the most critical phases of ground motion. No sensor saturation or measurable frequency-shift error was observed in either experiment, indicating that the system accurately preserved both the amplitude and frequency characteristics of the recorded signals. Although low-amplitude coda segments were more susceptible to the estimated 5–10 cm/s^2 noise floor, primarily due to ADC quantization and electromagnetic interference, this limitation had negligible impact on strong-motion monitoring performance.

TABLE IV. CROSS-EVENT PERFORMANCE COMPARISON

Parameter	Chile Earthquake	Gorkha 2015
Peak Acceleration	$\pm 600 \text{ cm/s}^2$ ($\pm 0.61 \text{ g}$)	$\pm 55 \text{ cm/s}^2$ ($\pm 0.056 \text{ g}$)
Fraction of Sensor Range	$\sim 31\%$ of $\pm 2 \text{ g}$	$\sim 2.8\%$ of $\pm 2 \text{ g}$
Frequency Character	Broadband 0.3–10 Hz	Narrowband $f_0 = 0.2958 \text{ Hz}$
Frequency Shift Error	None detected	Zero error
Full-Record Pearson r	0.8911	0.9010
Peak Segment Pearson r	0.9264 (Seg. A)	0.9751 (Seg. B)
Sensor Saturation	None	None
LoRa Delivery Rate	100%	Not performed

F. LoRa Wireless Telemetry Results

To evaluate wireless data transmission, calibrated Chile earthquake data were sent packet-by-packet from the Raspberry Pi to a Node MCU base station via an SX1278 LoRa transceiver pair at 433 MHz over a single 10 m indoor bench link. Each 12-byte packet carried elapsed time and acceleration values in g and cm/s². As summarized in Table V, all packets were received without loss over this short range, with RSSI values of -31 to -34 dBm (well above the SX1278's -148 dBm sensitivity) and SNR values of +2.25 to +12.00 dB confirming stable demodulation; decoded packet contents matched the sender log exactly, verifying data integrity. It should be noted that this test covers only a single short-range, short-duration transmission using the Chile record, the longer Gorkha record (110 s, ~11,000 samples) was not transmitted over LoRa, hence its delivery rate is listed as "Not performed" in Table IV. Longer-duration streaming, extended and obstructed ranges typical of Nepal's hilly terrain, and multi-node/multi-hop performance therefore remain unvalidated, and these results should be read as a proof-of-concept rather than a deployment-ready demonstration. Since the 433 MHz band is license-free in Nepal, the system can be deployed without spectrum licensing, and future work will extend testing to longer-range, longer-duration, and multi-node scenarios, including packet-loss, RSSI, and SNR as a function of distance and terrain, along with communication security.

TABLE V. LoRa LINK QUALITY METRICS - CHILE EARTHQUAKE TRANSMISSION

Packet No.	Time s (s)	RSSI (dBm)	SNR (dB)
1	0.0000	-34	10.75
2	0.0111	-31	4.00
3	0.0217	-33	2.25
4	0.0322	-33	12.00

IV. CONCLUSION

This paper presented the design, calibration, and experimental validation of a low-cost IoT-enabled seismic monitoring system integrating the ADXL335 MEMS accelerometer, ADS1115 16-bit ADC, Raspberry Pi 4B, and SX1278 LoRa transceiver. Experimental evaluation using the Chile 2010 and Gorkha 2015 earthquake records demonstrated accurate time and frequency-domain response and consistent performance under both strong and moderate seismic motions, along with proof-of-concept validation of LoRa-based wireless transmission over a short-range link. Owing to its low cost, scalability, and satisfactory measurement accuracy, the proposed system offers a promising foundation for dense seismic monitoring networks in Nepal and other earthquake-prone developing regions, pending further validation of long-range and multi-node communication performance.

V. FUTURE WORK

Future work will extend the system from single-axis shake-table validation to real-world testing in civil engineering structures like buildings and bridges to compare the result with standard commercial seismometers. We will add complementary validation metrics (RMSE, cross-correlation

lag, spectral coherence) alongside Pearson's r and also introduce hardware-based GPS/RTC timestamping to eliminate manual jitter correction. The further work will encompass secure LoRa transmissions with lightweight AES-128 encryption and CRC/HMAC integrity checks and evaluate network scalability and range and packet-loss/RSSI/SNR performance under Nepal's hilly terrain conditions.

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