Low-Cost Cellular Accelerometer Node for Structural Health Monitoring

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Project context: Puerto Rico transmission tower structural health monitoring

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Abstract

Transmission towers in Puerto Rico are exposed to wind, corrosion, fatigue, and hurricane loading, but their wind-driven response dynamics are usually not measured continuously in the field. For tower research, these measurements can support fundamental understanding of drag loading, guy-wire restraint, line loads, baseline vibration behavior, and post-event changes, not only damage assessment. This report presents a low-cost cellular accelerometer node for structural health monitoring using the Nordic Thingy:91 X platform, its onboard ADXL367 accelerometer, LTE-M connectivity, and a Supabase/PostgREST cloud data path. The system samples triaxial acceleration as a continuous FIFO stream, packages readings into 100-sample batches, reports battery telemetry, and posts data over HTTPS to a cloud database and dashboard. A solar-assisted power architecture using a 2 W panel, BQ24074 charger/load-share, external 10 Ah LiPo buffer, and S7V8F5 regulated 5.0 V USB-C supply is specified to support unattended operation while keeping the Thingy:91 X hardware unmodified. Sensor viability was evaluated by benchmarking the Thingy accelerometer against a LORD S-200 reference sensor under the same excitation. Magnitude-based comparison reduced sensitivity to axis misalignment, while temporal alignment and calibration improved agreement between the prototype and reference signals. In the current validation dataset, raw magnitude correlation was approximately 0.939, calibrated magnitude correlation was approximately 0.955, magnitude RMSE was approximately 0.040 g, and FFT amplitude correlation was approximately 0.952 over 0 to 12.5 Hz. These results support the feasibility of using the integrated ADXL367 for prototype-level vibration monitoring and demonstrate an end-to-end sensor-to-cloud pipeline. A successful one-week outdoor run provided initial field-readiness evidence, while the planned three-week deployment remains future work; the remaining limitations are now more specific: the short reference-sensor validation window, tower-specific mounting and axis-alignment uncertainty, external-buffer state-of-charge telemetry, and additional validation on Puerto Rico tower sites.

Keywords

structural health monitoring; transmission towers; response dynamics; wind loads; wireless sensing; cellular IoT; LTE-M; triaxial accelerometer; ADXL367; Nordic Thingy:91 X; solar-assisted power; Supabase; reference-sensor validation; FFT analysis

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1. Broader Objective

1.1 Engineering Context

Electric transmission towers are distributed assets that must remain functional under wind, rain, corrosion, fatigue, and extreme storm loading. In Puerto Rico, this problem is especially important because transmission infrastructure is exposed to hurricane-season hazards, salt-laden coastal air, difficult access conditions, and long recovery timelines after major weather events. Traditional inspection is often periodic or event-driven, so the measured motion of a tower under wind, line loading, guy-wire restraint, and support conditions is rarely available as continuous field data.

Structural health monitoring addresses this gap by treating measured dynamic response as evidence of how the structure behaves under real loading, including changes in stiffness, looseness, connection condition, or boundary support [1], [2]. At the prototype stage, the immediate value is response-dynamics evidence: even a small number of reliable vibration measurements can establish baseline behavior, support post-event comparison, and show whether a site deserves closer inspection. For this reason, the critical engineering question is not only whether an accelerometer can record motion, but whether a low-cost field node can produce repeatable acceleration data, transmit it continuously, and retain enough power autonomy to be useful outside the laboratory.

The engineering constraints shape the system design. A practical node for remote tower monitoring should be low cost, physically simple, cellular rather than Wi-Fi dependent, and capable of operating from a solar-assisted power source. It should also avoid a custom circuit-board design unless the sensing, power, and data-pipeline assumptions are already proven. This project therefore uses the Nordic Thingy:91 X as an integrated sensor-node platform and evaluates whether its onboard ADXL367 accelerometer, LTE-M modem, and external solar/battery front end can support prototype-level structural monitoring with a constant stream of cloud-accessible data [3], [4].

1.2 Research Objective

The research objective of this project is to evaluate whether a low-cost cellular accelerometer node can provide useful prototype-level vibration measurements for remote tower response monitoring. The emphasis is on whether field data can support later study of response dynamics under wind and other service loads. Specifically, the project tests whether the Nordic Thingy:91 X platform can collect triaxial acceleration data with its onboard ADXL367 accelerometer, transmit that data over LTE-M to a cloud database, and operate within a solar-assisted power architecture suitable for controlled PR tower testing after outdoor validation.

The objective is also comparative: the onboard accelerometer is evaluated against a LORD S-200 reference sensor to determine whether the low-cost integrated sensor preserves the dominant time-domain and frequency-domain behavior of the measured response. Success is defined by an end-to-end feasibility result, not by full production readiness or final tower diagnosis: the node must demonstrate working sensing, data transmission, power plausibility, reference-sensor agreement, and outdoor operability well enough to justify controlled testing on Puerto Rico transmission towers.

1.3 Scope of This Report

This report argues that the tested Thingy:91 X platform is feasible as a prototype sensor-to-cloud node for tower response monitoring, while tower-site validation, external-buffer state-of-charge telemetry, and firmware duty-cycle optimization remain the next steps before production deployment.

This report covers a proof-of-concept sensor node and validation study for structural health monitoring, not a complete deployed monitoring network. The report focuses on the design and evidence needed to judge whether the selected low-cost platform can support PR tower field testing: the hardware architecture, firmware and cloud data path, power model, one-week outdoor deployment result, and comparison of the onboard accelerometer against a reference sensor.

The scope is intentionally limited to prototype feasibility. It does not claim production readiness, tower-level damage diagnosis, fleet-scale deployment, or environmental qualification. A successful one-week outdoor deployment demonstrated unattended operation under real weather, LTE, and solar exposure, but the planned three-week deployment was not completed. Remaining deployment work is tower-specific: final mounting and enclosure integration, direct verification of the solar charging path at tower sites, external-buffer state-of-charge monitoring, completion of a longer outdoor/tower-site run, and additional validation data under realistic Puerto Rico tower conditions.

2. Specific Goals

2.1 Goal Summary

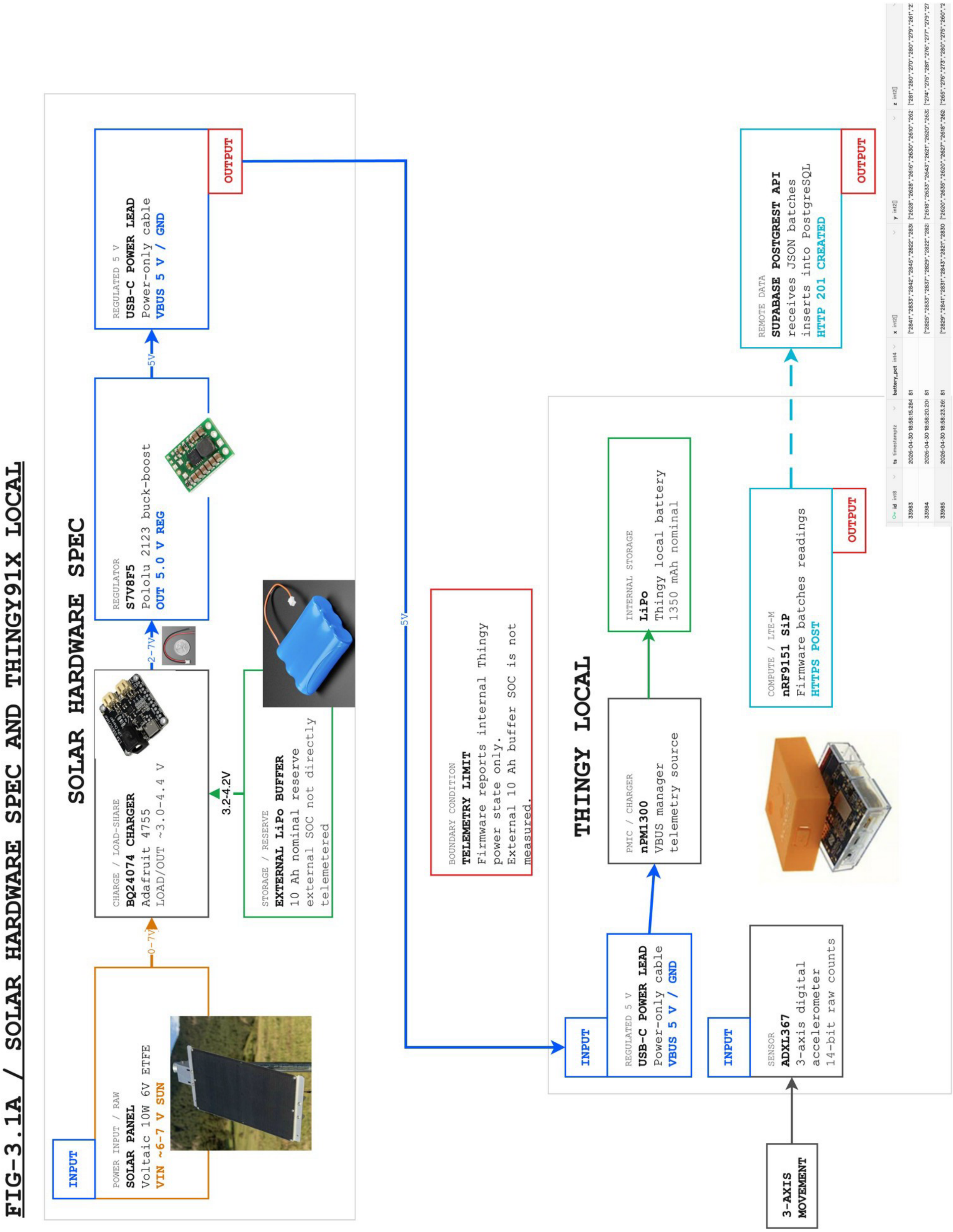
The project goals translate the broader structural-health-monitoring objective into six measurable prototype outcomes:

- Build a working sensing node using the Nordic Thingy:91 X and its onboard ADXL367 accelerometer, with raw triaxial acceleration available for analysis.
- Demonstrate continuous acceleration capture by sampling the ADXL367 FIFO stream and packaging readings into 100-sample batches without relying on manual data collection.
- Prove the LTE-M cloud data path by posting acceleration batches and battery-related telemetry to Supabase/PostgREST and making the data visible in the dashboard/export workflow.
- Evaluate power feasibility by separating the current continuous-post firmware behavior from the intended solar-assisted duty-cycled field architecture, including internal-battery and external-buffer autonomy estimates.
- Validate accelerometer usefulness by comparing the prototype data against a LORD S-200 reference sensor in time-domain magnitude behavior and frequency-domain amplitude content.
- Define the deployment envelope by identifying what the prototype already demonstrates through lab validation and a successful one-week outdoor run, and what remains for controlled PR tower testing, including tower mounting, enclosure integration, solar-path verification, and additional tower data.

3. Devices

This section documents the prototype as an integrated sensor-to-cloud system: the physical sensing node and external power chain, the firmware that reads and uploads acceleration data, and the cloud/dashboard path used for review and analysis. The emphasis is on what was assembled and tested, with remaining tower-rated enclosure and mounting work treated as future deployment work.

3.1 Hardware



id int8	ts timestamptz	battery_pct int4	x int2[]	y int2[]	z int2[]
33983	2026-04-30 18:58:15.284	81	["2841","2833","2842","2845","2822","283	["2628","2628","2616","2630","2610","262	["281","280","270","280","279","261","2
33984	2026-04-30 18:58:20.20	81	["2825","2833","2837","2829","2822","282	["2618","2633","2643","2621","2620","263	["274","275","281","276","277","279","27
33985	2026-04-30 18:58:23.26	81	["2829","2841","2831","2843","2821","2830	["2620","2635","2620","2627","2618","262	["265","276","273","280","275","260","2

Figure 3.1 summarizes the hardware architecture. The prototype uses an unmodified Nordic Thingy:91 X as the sensing, compute, local battery, and LTE-M communications node, with the

field power hardware kept external. The external chain harvests solar energy, buffers it in a separate LiPo battery, and presents the Thingy with a regulated 5.0 V USB-C input [3], [5]-[7].

Figure 3.1. Solar hardware architecture for the PR-SHM sensor node. The BQ24074 manages solar charging and the external LiPo; the S7V8F5 provides the regulated 5.0 V USB-C input to the Thingy:91 X. Firmware telemetry describes the Thingy internal battery/PMIC domain, not the external 10 Ah buffer state of charge.

Figure 3.2. Assembled prototype hardware used for integration testing. The photo shows the physical sensor node, solar panel, and external power hardware in the outdoor test configuration used before final tower-rated enclosure and rigid PR tower mounting are completed.

Figure 3.2 shows the assembled hardware used for integration testing. The main design boundary is telemetry: firmware battery and charger readings come from the Thingy internal nPM1300/stock-LiPo domain and confirm the local battery and USB input state, but they do not directly measure the external 10 Ah buffer state of charge. The onboard ADXL367 provides the prototype acceleration measurement [4], while the LORD S-200 is reference equipment used only for validation.

3.2 Firmware and Software

The firmware is written in C on Zephyr through the nRF Connect SDK for the Thingy:91 X nRF9151 target [8]. On boot, the application initializes the onboard ADXL367 accelerometer, the nPM1300 power interface, the cellular modem, and the TLS certificate used for HTTPS communication. The current firmware is a continuous-stream prototype: it prioritizes reliable sample capture and end-to-end upload rather than aggressive sleep scheduling.

Acceleration is captured from the ADXL367 FIFO at 25 Hz in the +/-2 g range [4]. The firmware reads the sensor directly over I2C as signed 14-bit raw counts, drains the FIFO into a RAM message queue, and groups readings into 100-sample batches. Each batch therefore represents about four seconds of triaxial acceleration data. The batch payload stores the x, y, and z arrays plus internal Thingy battery percentage, preserving raw data for later conversion, calibration, and frequency analysis off-device.

The transport layer posts each batch to Supabase/PostgREST over LTE-M using the nRF modem TLS store and Zephyr REST client [9]-[11]. A successful upload is indicated by an HTTP 201 or 200 response. If a batch POST fails, the firmware forces the modem offline, reconnects to LTE-M, and retries the batch once. Power firmware also exposes internal-battery voltage, current direction, VBUS presence, and charger-state reads for diagnostics; these readings describe the Thingy internal power domain, not the external solar buffer.

3.3 Cloud Data Pipeline

The cloud pipeline starts when the firmware sends an HTTPS POST to the Supabase PostgREST endpoint for the accel_batches table [10], [11]. Each database row represents one uploaded batch and contains the Supabase arrival timestamp, internal Thingy battery percentage, and three compact smallint arrays for x, y, and z acceleration counts. This compact row-per-batch format avoids the overhead of inserting one database row per accelerometer sample while preserving the raw triaxial data. Figure 3.3 summarizes this path.

FIG-3.3A / DATA PIPELINE

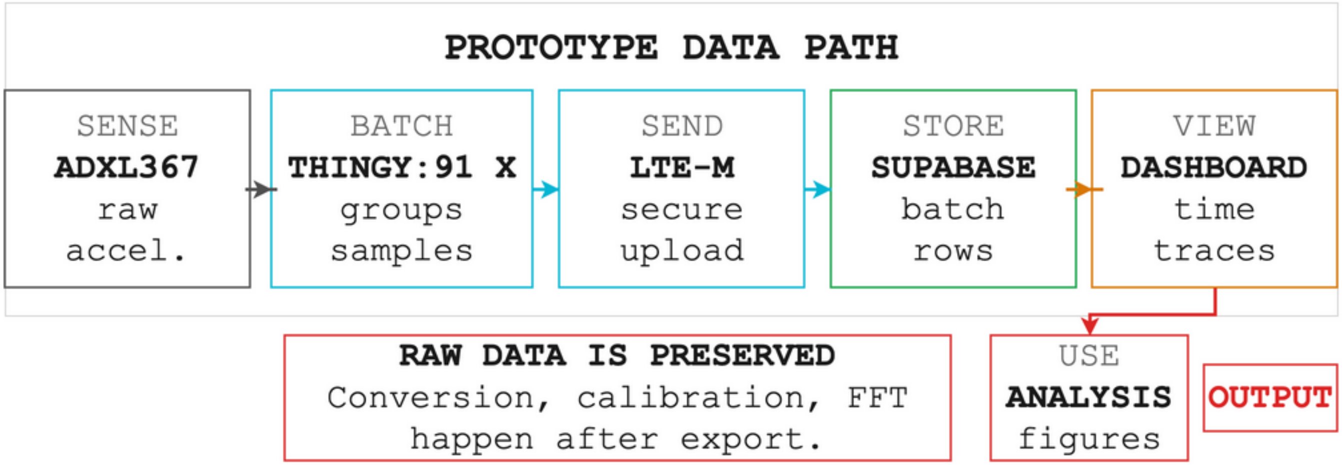


Figure 3.3. Minimal data pipeline for the PR-SHM prototype. Raw ADXL367 acceleration is batched on the Thingy:91 X, uploaded over LTE-M to Supabase, viewed in the dashboard, and exported for downstream calibration and FFT analysis.

For display and analysis, the database and frontend expand those batches back into a sample stream. The accel_samples_25hz SQL view unnests the x, y, and z arrays with ordinality and assigns 40 ms sample spacing for the 25 Hz stream; gaps longer than 15 seconds begin a new segment so outages remain visible. The React dashboard queries batch rows by time range, reconstructs per-sample traces for plotting, and uses a downsampled summary query for longer full-history views.

A deployed version of this dashboard is available at https://accelerometer-frontend.vercel.app/. It provides broad full-history and detail sample views for raw x/y/z acceleration, gravity-normalized acceleration, inclinometer outputs, and battery panels, using the same Supabase-backed data path [10].

The pipeline intentionally keeps the stored acceleration values as raw counts. Unit conversion to g, magnitude calculation, calibration against the LORD reference sensor, and FFT analysis are performed downstream from exported database/CSV data. The main evidence for this section is the successful HTTP 201 upload path, rows present in accel_batches, dashboard visibility, and exported datasets used in the validation plots.

4. Test Results and Success Criteria

The results are organized around feasibility claims rather than build chronology. For each test, the report states the measurement method, the comparison metric, the observed result, and the remaining limitation. The strongest quantitative evidence is the axis-calibrated accelerometer validation, while the strongest field-readiness evidence is the successful one-week outdoor deployment under real environmental exposure.

4.1 Constant-Stream Power and Solar Feasibility

The assembled node completed a successful one-week outdoor deployment before tower installation. A full three-week deployment was planned but was not completed because firmware power-cycling and charge-logic work remained in progress.

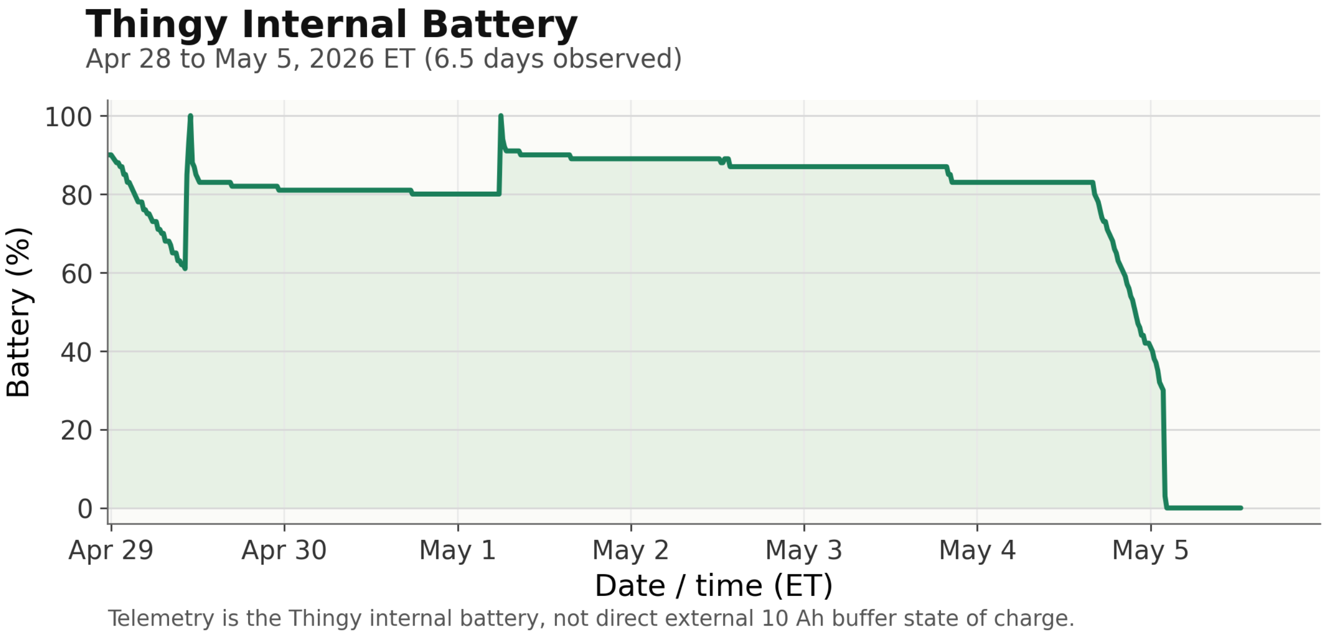


Figure 4.1. Thingy internal battery during the one-week outdoor deployment. The trace shows the battery telemetry recorded from Apr 28 to May 5, 2026 ET under the continuous-post firmware; it reflects the Thingy internal battery, not direct external 10 Ah buffer state of charge.

The current continuous-post firmware is intentionally more demanding than the final field target. It keeps the raw stream and LTE upload path active with frequent 100-sample batch posts, which is useful for validation but not optimized for battery life. The continuous model is closer to 20 mA at 5 V, or about 2.4 Wh/day. Under that behavior, the external 10 Ah buffer would last roughly 12 days ideal, about 10 days with conversion margin, and the internal battery alone would last only about 2.3 days. This difference is why duty-cycled sampling and upload remain firmware requirements before tower deployment.

The solar balance is favorable if the firmware is duty-cycled. A 2 W panel with a conservative

70 percent charge and regulation efficiency provides an estimated net harvest of about 7.7 Wh/day under the planning solar model, while the duty-cycled node consumes about 0.095 Wh/day. That is an approximate 81x daily energy surplus before site-specific shading and weather losses. The remaining hardware limitation is telemetry: the firmware reports the Thingy internal battery and VBUS domain, so an external-buffer voltage or state-of-charge measurement should be added before interpreting remote battery trends as true external reserve.

4.2 Accelerometer Viability Test

The accelerometer viability test compared the Thingy:91 X prototype against the reference accelerometer, with reference data exported through the SensorConnect workflow [12], over a 3,900-sample aligned window. The signals were first aligned by raw magnitude peaks, then the raw Thingy x, y, and z axes were mapped into the LORD g-frame using a three-axis affine calibration. Magnitude was computed after axis calibration, so the comparison evaluates a physically comparable acceleration magnitude rather than raw counts or unmatched device axes.

The calibrated magnitude trace closely followed the LORD reference during the impulsive event and subsequent ring-down. Across the validation window, the magnitude correlation was r = 0.955, RMSE was 0.040 g, and mean bias was -0.0089 g. This supports the prototype as a viable low-cost source for event and vibration-magnitude tracking under the tested mounting and sampling conditions.

Tilt was not reported as a validated result in this study. The ADXL367 comparison used dynamic acceleration magnitude after axis calibration, not a calibrated inclinometer output. Static or low-frequency tilt would require a stable gravity reference, mounting-angle calibration, and separate validation against a known tilt reference. The Thingy:91 X also includes a Bosch 6-axis inertial sensor that could potentially be enabled in future firmware for accelerometer/gyroscope fusion and tower tilt or inclination tracking.

Table 4.1. Summary metrics for the axis-calibrated accelerometer validation.

Metric	**Result**	**Interpretation**
Validation window and processing	3,900 samples; 30.46 s; peak aligned; 3-axis affine calibration	Magnitude was computed after mapping raw Thingy axes into the LORD g-frame.
Time-domain magnitude agreement	Pearson r = 0.955; RMSE = 0.040 g; bias = -0.0089 g	Calibrated Thingy magnitude closely follows the LORD reference trace.
Normalized magnitude error	3.8% of LORD RMS	Error is small relative to the observed reference response.
Frequency-domain agreement	Pearson r = 0.952; RMSE = 0.00258 g over 0-12.5 Hz	Primary spectral content is retained below the Thingy 25 Hz Nyquist limit.

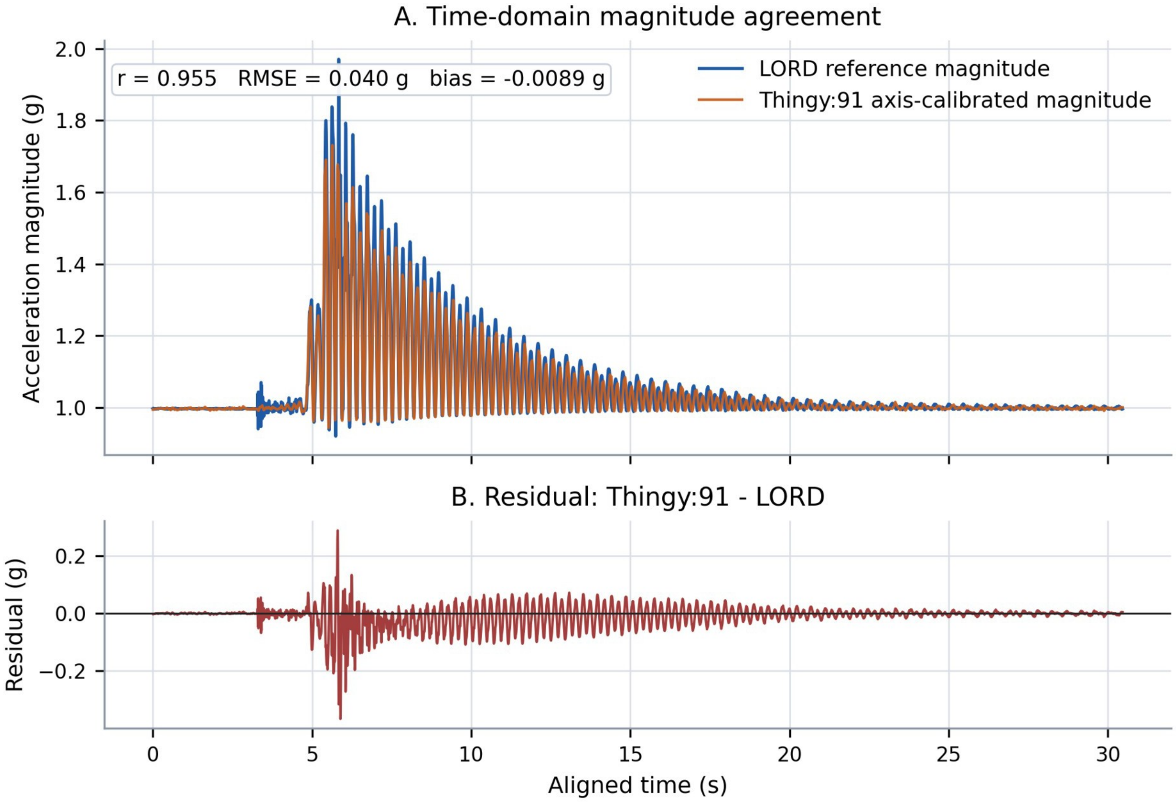


Figure 4.2. Time-domain validation of axis-calibrated magnitude. The upper panel compares LORD reference magnitude with Thingy:91 axis-calibrated magnitude over the aligned validation window; the lower panel shows residual error computed as Thingy:91 minus LORD.

Interactive time-series view: readers can inspect the aligned LORD and Thingy:91 magnitude traces in more detail at https://accelerometer-viability-axis-calibr.vercel.app/

Figure 4.2b zooms into two parts of the same aligned record. The largest mismatch is concentrated at the sharpest impulse near 5.9 s; during early ring-down, the calibrated Thingy:91 trace follows the LORD timing and decay with smaller residuals.

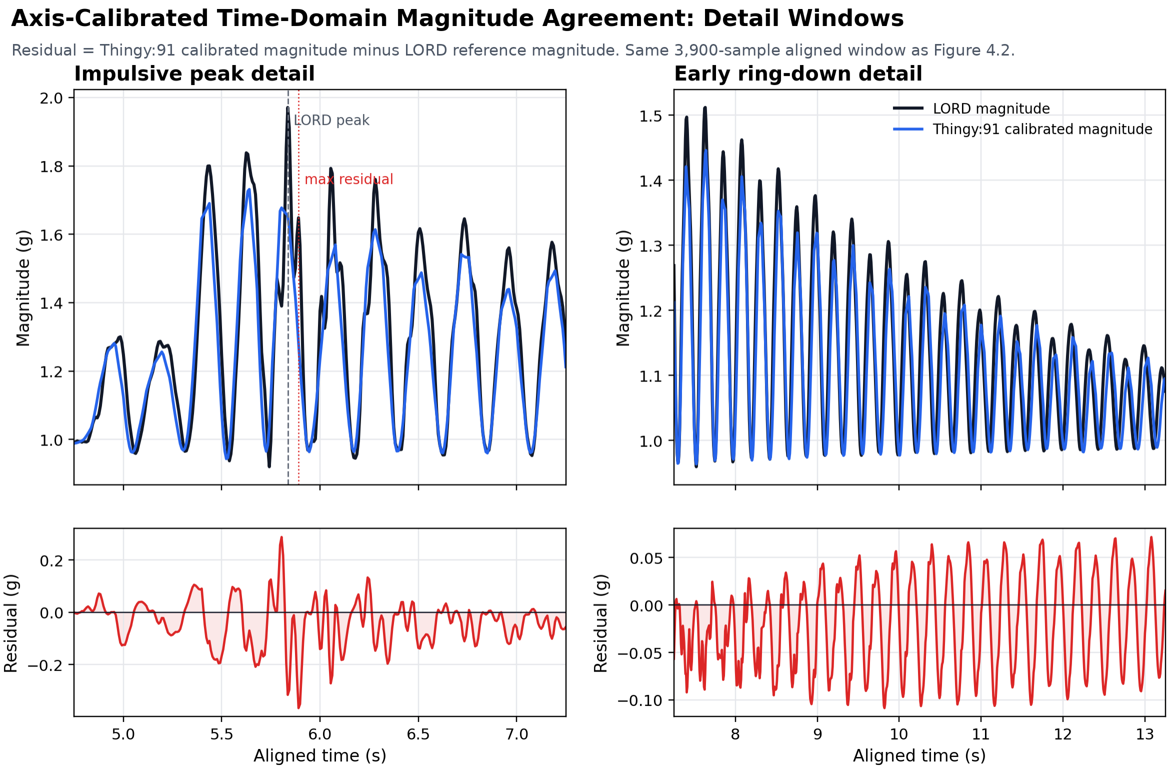


Figure 4.2b. Detail views of the time-domain magnitude agreement. The left panels isolate the impulsive peak and maximum residual; the right panels show early ring-down. Residual is Thingy:91 axis-calibrated magnitude minus LORD reference magnitude.

4.3 FFT Viability Test

The FFT viability test used the same aligned and axis-calibrated magnitude signals. Before transformation, each magnitude series was mean-removed and windowed with a Hann window. The comparison was limited to 0-12.5 Hz, which matches the Nyquist limit of the original 25 Hz Thingy:91 acceleration stream.

The frequency-domain result agrees with the time-domain result. FFT amplitude correlation was r = 0.952 with an amplitude RMSE of 0.00258 g over the 0-12.5 Hz band. The dominant mode occurred at approximately 4.50 Hz in the LORD spectrum and 4.46 Hz in the calibrated Thingy spectrum; both spectra also shared the secondary peak near 2.23 Hz. Smaller differences in low-amplitude peaks and the high-frequency floor remain, but the principal vibration content needed for feasibility analysis is retained.

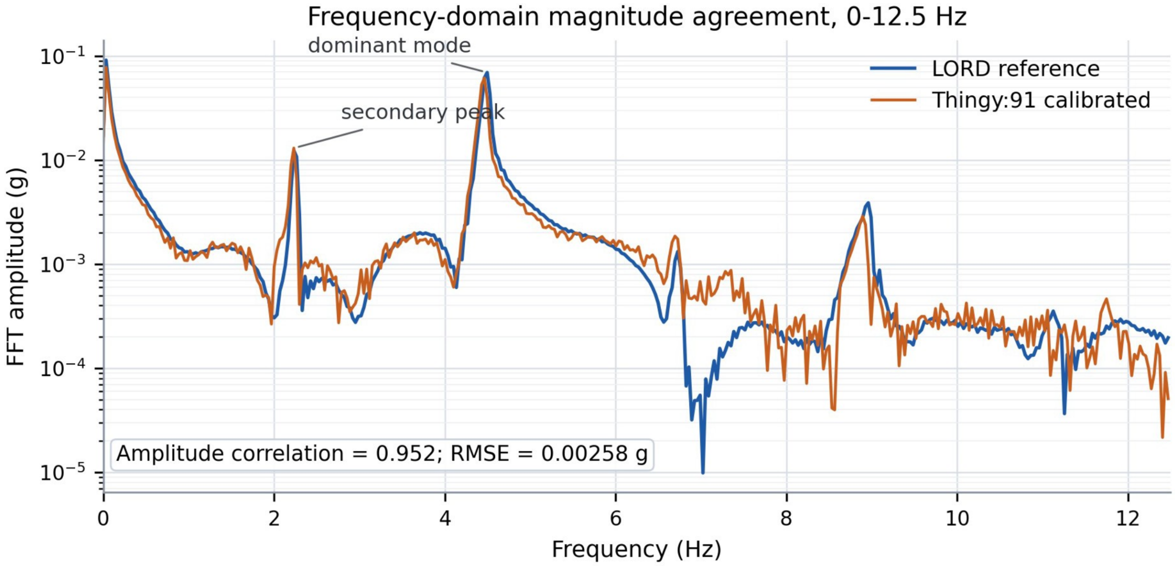


Figure 4.3. Frequency-domain validation of the calibrated magnitude signals. Mean-removed magnitudes were windowed with a Hann window before FFT comparison over 0-12.5 Hz.

4.4 End-to-End Pipeline Evidence

The end-to-end pipeline proof has four parts: the firmware must post complete 100-sample acceleration batches, Supabase must store those batches with battery telemetry, the dashboard must reconstruct the sample stream for inspection, and the same stored data must be exportable for validation analysis. In the tested path, transport_send_batch builds JSON arrays for x, y, and z raw counts plus battery_pct, posts them to /rest/v1/accel_batches, and treats HTTP 201 or 200 as success. The firmware also retries once after LTE-M reconnect if a batch POST fails. Progress logs documented stable cycles of acceleration POST -> HTTP 201, status POST -> HTTP 201, and configuration fetch.

Table 4.2. End-to-end pipeline evidence summary.

Pipeline stage	Success criterion	Evidence	Status
Firmware upload	A full acceleration batch reaches the cloud and returns a success code.	100-sample + battery POST -> HTTP 201/200; LTE retry.	Pass for prototype
Cloud storage and reconstruction	Stored rows preserve raw triaxial data and can be expanded back into a sample stream.	Raw arrays in accel_batches; 40 ms expansion; >15 s gap segmentation.	Pass for analysis
Dashboard visibility	Received data is visible without manual database inspection.	Vercel broad/detail views read batch, summary, and status data.	Pass for prototype

Export and validation use	The same data path supports downstream calibration and report figures.	Exports produced the validation datasets.	Pass for report evidence

The remaining pipeline refinement is sample-continuity metadata. Runtime logs showed the RAM queue preserving samples during reconnects with dropped=0, but Supabase currently reconstructs sample time from upload order and timestamps rather than explicit batch_seq, sample_seq_start, sample_count, and dropped_samples fields. Adding those fields would let the database independently prove continuity across LTE interruptions.

For reproducibility and future research, the machine-readable project source files are provided in the GitHub repository at https://github.com/gabe-kafka/accelerometer-easy. The repository includes the firmware, frontend dashboard, Supabase schema, and analysis/export scripts used for this report.

5. Discussion

The results show that the prototype is feasible as a sensor-to-cloud system and ready for controlled PR tower testing, while still short of production deployment. The Thingy:91 X captured triaxial acceleration, posted 100-sample batches over LTE-M, and preserved the main behavior of the LORD reference signal: calibrated magnitude correlation was 0.955, magnitude RMSE was 0.040 g, and FFT correlation was 0.952 over 0-12.5 Hz. The successful one-week outdoor deployment also shows that basic unattended operation outside the laboratory has already been demonstrated. The remaining power work is tower-site confirmation, external-buffer state-of-charge visibility, firmware duty-cycle optimization, and completion of a longer deployment run under realistic structural and solar conditions.

5.1 Limitations

The reference-sensor validation window was short and controlled, so the agreement should be treated as prototype evidence rather than a final accuracy claim. The completed one-week outdoor deployment reduces risk around basic unattended operation, but it does not replace tower-specific validation or the still-uncompleted three-week soak test. Mount stiffness, axis orientation, and calibration may change in a real tower installation. Tilt was not validated in this report; the reported results evaluate acceleration magnitude and spectral content, not calibrated tower inclination. LTE coverage and solar exposure will also vary by site, and firmware telemetry still describes the Thingy internal battery/PMIC domain instead of the external 10 Ah buffer. These limits do not invalidate the result, but they define the PR tower test conditions.

5.2 Future Work

Future work should keep the tested hardware platform and move from the completed one-week outdoor soak test to controlled PR tower validation. The sensing node and external power architecture have been assembled, checked, and successfully deployed outdoors for about one week; completing a longer three-week outdoor/tower-site run remains part of the next field step. Firmware work should continue in parallel through duty-cycled sampling/upload, watchdog confirmation, and clearer recovery after failed POSTs, while the tower test compares data gaps, battery trend, LTE signal, and vibration spectra under real structural conditions. Tilt/inclination is a separate future measurement path: the onboard Bosch 6-axis inertial sensor could potentially be enabled for sensor-fusion-based tilt estimates, then validated against a known inclinometer or controlled tower-mount reference.

6. Conclusion

This project demonstrates that a low-cost Thingy:91 X cellular accelerometer node can support prototype tower response monitoring. The tested hardware platform, LTE-M upload path, cloud pipeline, reference-sensor comparison, and successful one-week outdoor deployment are strong enough to justify moving from bench and outdoor validation to controlled PR tower testing. The system is not yet a production tower-monitoring deployment, but it has cleared the main feasibility question: the platform can collect useful vibration data for response-dynamics studies, transmit it reliably enough for analysis, and operate within a solar-assisted architecture that is ready for tower-site validation. The complete machine-readable source code for future research and reuse, including firmware, frontend, database, and analysis scripts, is available at https://github.com/gabe-kafka/accelerometer-easy.

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Appendix A. Hardware Specification

Appendix A summarizes the hardware specification and bill of materials, including the Thingy:91 X platform, ADXL367 sensor, solar charger/load-share, S7V8F5 regulator, external 10 Ah buffer, and Phase 1/Phase 2 mounting assumptions. The source documents are HARDWARE_SPEC.md and BOM.md.

Appendix B. Firmware and Cloud Configuration

Appendix B summarizes firmware and cloud configuration: Zephyr/nRF Connect SDK target, direct ADXL367 I2C reads, TLS/HTTPS upload, Supabase schema/views, remote sample-interval configuration, and dashboard query path. The source documents are FIRMWARE.md, ARCHITECTURE.md, and the Supabase SQL files.

Appendix C. Data Processing and Additional Plots

Appendix C summarizes processing details and additional plots, including SensorConnect exports, peak alignment, axis calibration, calibrated magnitude residuals, FFT validation, and raw/processed datasets in exports/.