Dynamic Bridge Monitoring in Chile - First Field Experience with the RIEGL VZ-600i Profile Scanning Mode at Puente Las Cucharas

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SUMMARY

Recent developments in terrestrial laser scanning (TLS) technology enable measurements at unprecedented temporal resolutions, extending its application from static surveys towards dynamic monitoring of engineering structures. A key innovation is the profile scanning mode of the *RIEGL* VZ-600i terrestrial laser scanner, which allows the continuous acquisition of a single scan line at rates of up to 420 profiles per second. This high-frequency operation opens new possibilities for contactless observation of vibrations, transient deformations, and other short-term structural phenomena.

In September 2025, this functionality was tested for the first time under real-world conditions during a field experiment at the Puente Las Cucharas railway bridge of Metro Valparaíso, Chile (officially called EFE Valparaíso, S.A.). The objective was to evaluate the performance, stability, and operational feasibility of the profile scanning mode in a complex outdoor environment. Continuous profile sequences were recorded during regular train passages over several minutes, capturing the bridge under realistic dynamic excitation. The setup included synchronized time referencing, reference scans, and stable mounting to ensure geometric consistency and precise temporal control.

The acquired datasets allow for an initial assessment of achievable precision, signal stability, and data completeness under dynamic conditions. The experiment focused on testing the measurement concept and data characteristics rather than on the interpretation of the bridge response. Early findings demonstrate that the system delivers stable, dense, and geometrically consistent range data even under varying environmental and motion conditions.

This contribution presents the experimental setup, acquisition strategy, and first technical observations from the Chilean field deployment. The results highlight the potential of the profile scanning mode as a valuable extension to existing monitoring concepts, complementing traditional sensor-based approaches such as accelerometers, GNSS, or fiber-optic systems. By combining the strengths of geodetic and structural monitoring methods, high-rate laser line scanning can significantly enhance the capability for detailed, non-invasive, and temporally dense observations in Structural Health Monitoring (SHM).

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1. INTRODUCTION

The monitoring of civil infrastructure has become an essential component of modern maintenance and risk management strategies. Ageing structures, increasing traffic demands, and limited resources require approaches that go beyond periodic visual inspections and allow an assessment of the actual structural behavior under operational conditions. In this context, Structural Health Monitoring (SHM) is commonly understood as a decision-support tool that complements conventional inspection strategies and contributes to risk-based maintenance planning and service-life management (Novák et al., 2024; Wedel et al., 2025).

From a monitoring perspective, different temporal scales must be considered. Long-term or quasi-static observations focus on slowly varying effects (e.g., temperature-induced deformations). In contrast, dynamic monitoring addresses structural responses induced by traffic and other operational excitations. Dynamic displacements provide valuable insight into stiffness, load transfer mechanisms, and overall system behavior, but their observation under real operating conditions places increased demands on sensor technology, particularly with respect to temporal resolution, stability, and synchronization (Lienhart et al., 2023; Novák et al., 2024; Wedel et al., 2025).

Traditionally, dynamic bridge monitoring has been dominated by contact-based sensor systems. Accelerometers, strain gauges, inclinometers, and displacement transducers provide high temporal resolution but require physical installation on the structure. As a result, spatially distributed observations of dynamic behavior are often limited (Lienhart et al., 2023; Schill & Eichhorn, 2019; Schill et al., 2022). Driven by advances in sensor technology and data processing, contactless and remote sensing techniques have increasingly been investigated. Geodetic sensors such as robotic total stations (e.g., Lienhart, 2017), GNSS receivers (e.g., Schöneberger et al., 2022), image-assisted total stations (e.g., Zschiesche et al., 2022), terrestrial laser scanners (e.g., Wujanz et al., 2018), and radar-based instruments (e.g., Baumann-Ouyang et al., 2022) enable measurements without direct physical interaction with the structure.

Different geodetic sensing techniques exhibit complementary characteristics with respect to spatial resolution, temporal resolution, and sensitivity direction. Point-based sensors such as GNSS or robotic total stations allow three-dimensional displacement measurements at selected locations, whereas image-based systems enable spatially distributed observations. Terrestrial laser scanning (TLS) is particularly attractive in this context, as it allows dense geometric measurements without the need for physical target installation on the structure. By adapting the acquisition strategy and restricting data acquisition to a single scan line, TLS can be used to observe a single line with high temporal resolution, enabling the observation of dynamic structural responses along defined structural sections (Schill & Eichhorn, 2019). Numerous studies demonstrate the potential of laser-based approaches for dynamic bridge monitoring in laboratory investigations, controlled field experiments, and selected operational deployments (e.g., Meyer et al., 2022; Kostjak & Neuner, 2023), and show that contactless methods can complement established sensor-based monitoring concepts (Schill et al., 2022).

TLS from *RIEGL* have become well established in monitoring applications, particularly in the context of permanent laser scanning (PLS). In such configurations, scanners are operated continuously over extended periods to capture quasi-static structural changes, enabling the observation of slow deformations and long-term trends with high geometric stability (Lindenbergh et al., 2025). Building upon this established monitoring framework, recent developments now allow the same scanner platform to be operated in a dedicated high-rate line scanning mode, extending its application from quasi-static observations towards dynamic bridge monitoring. This paper presents first field experience with the VZ-600i focusing on practical implementation aspects, data acquisition strategies, and operational behavior during regular railway operation.

2. STUDY AREA AND EXPERIMENTAL CONTEXT

The experiment was conducted on 11 September 2025 at the Puente Las Cucharas railway bridge in central Chile. The bridge is part of the interurban railway network operated by the Empresa de Ferrocarriles del Estado (EFE) and serves as a key link within the Metro Valparaíso system, connecting the cities of Valparaíso and Limache. The reliable operation of this infrastructure is essential for regional mobility, as the bridge is subjected to regular bidirectional metro traffic under continuous service conditions. An overview of the geographic setting, the alignment of the metro line, and the location of the bridge is shown in Figure 1.

Puente Las Cucharas is a railway bridge with a total length of approximately 175 m, comprising concrete arch sections of about 70 m and metallic truss sections totaling approximately 145 m. The bridge has a width of 7.5 m, accommodates two railway tracks with a gauge of 1.7 m, and rises approximately 17 m above its base. It was designed for continuous bidirectional train operation. Construction took place between 1908 and 1913 under the supervision of engineer Manuel Trucco and involved the assembly of a prefabricated steel structure manufactured in France by Schneider & Le Creusot and transported to Chile by ship. The current structure replaced earlier bridge constructions at the same location, including an initial wooden bridge built in 1855 and a subsequent metallic structure, reflecting the progressive adaptation of the crossing to increasing rail traffic demands. With an operational age exceeding 110 years, the bridge remains in service within the Metro Valparaíso system, supporting daily metro operations and occasional freight traffic and thus representing a typical operational load scenario for interurban railway bridges in the region (Sepúlveda Orbenes, 2005).

Over its service life, Puente Las Cucharas has undergone several maintenance and repair measures to ensure structural integrity. Historical records from the period 1912–1914 document cracking in the concrete arch sections, attributed to foundation conditions on sandy soil and possibly influenced by seismic activity (Sepúlveda Orbenes, 2005). These issues were addressed through extensive load testing using heavy trains at different speeds, additional temporary loading, and subsequent injection of liquid cement under pressure to seal the cracks, with railway traffic temporarily suspended during repair works. In the early 2000s, further structural assessments were conducted in the context of the Merval IV Etapa project. These investigations included numerical modelling and normative load evaluations to verify the suitability of the bridge for modern metro rolling stock, leading to targeted reinforcement measures on selected structural elements while maintaining ongoing railway operation.

From the perspective of EFE as the national railway operator, Puente Las Cucharas represents a critical asset within the regional transport network. Continued interest in monitoring the structure arises from its strategic role, its advanced age, and the need to accommodate increasing operational demands without service interruptions (EFE Trenes de Chile, 2024). The bridge was selected as a test site due to its continuous operation, favorable accessibility of the surrounding area, and its suitability for non-contact monitoring under real traffic conditions. Against this background, Puente Las Cucharas provided a suitable test site for evaluating the practical implementation of laser-based line scanning for dynamic bridge monitoring under real operating conditions.

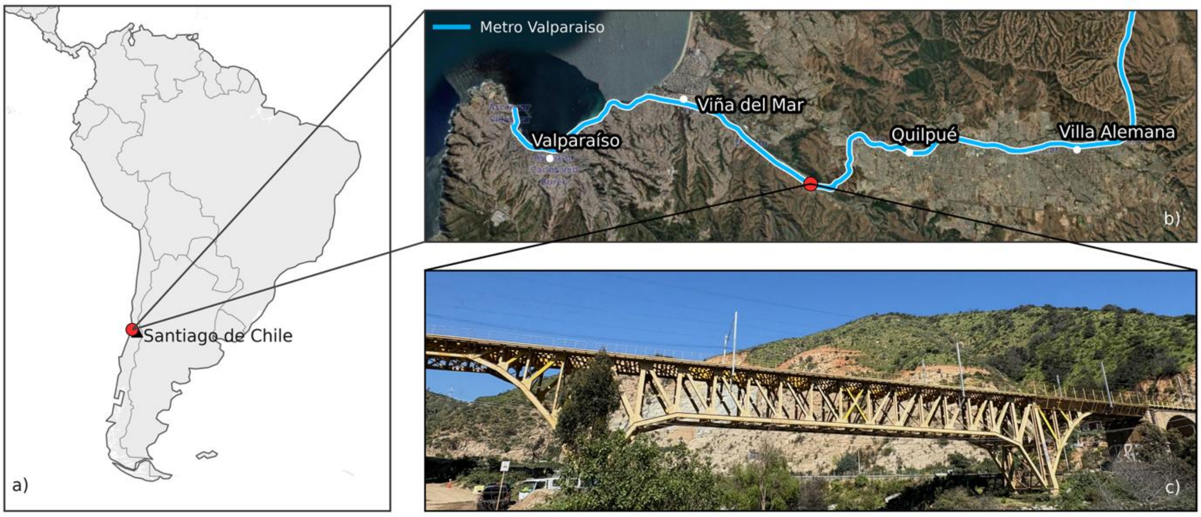

Figure 1: Location and context of the Puente Las Cucharas railway bridge. (a) Geographic location of Valparaíso in central Chile, approx. 150 km west of Santiago de Chile (base map: Natural Earth). (b) Alignment of the Metro Valparaíso railway line connecting Valparaíso and Limache, with the location of Puente Las Cucharas indicated (imagery: Esri World Imagery; railway overlay: OpenRailwayMap tiles and railway vectors derived from OpenStreetMap via Overpass API; © OpenStreetMap contributors, Open Data Commons Open Database License (ODbL); OpenRailwayMap, CC-BY-SA 2.0). (c) Photograph of Puente Las Cucharas taken in September 2025 from a position northeast of the bridge.

3. MEASUREMENT SYSTEM AND LINE SCANNING CONCEPT

3.1 *RIEGL* VZ-600i – System Overview

A 3D terrestrial laser scanner, operated statically on a tripod or measuring pillar, captures the geometry of the environment by emitting laser pulses and recording the return signal after the laser pulse hits a surface where it is diffusely reflected. In time-of-flight light detection and ranging (LiDAR), the travel time of the signal is measured, and together with the laser beam direction precise 3D coordinates are calculated for each target. The 3D laser scanner emits a large number of laser pulses, while at the same time varying both the horizontal angle through rotation of the scanner frame around its vertical axis, and the vertical angle using a scanning mechanism which deflects the laser beam using e.g., a mirror. Through this process, the laser scanner generates a point cloud which digitally represents the geometry of the surrounding environment. This 3D point cloud serves as the foundation for further processing and downstream tasks, such as deriving 3D models from the point cloud or performing change-detection between point clouds acquired at different epochs.

Table 1: Specifications of the *RIEGL* VZ-600i laser scanner (RIEGL, 2025a)

Measurement rate **Scan speed**	2.2 MHz pulse repetition rate (PRR) Min.: 4 scan lines per second; Max.: 420 scan lines per second Scan time <30 seconds for standard panorama scan (~30 Mio. measurements, 6 mm resolution @ 10 m distance)
Scanning mechanism	Rotating multi-facet mirror (with 4 facets)
Precision	3 mm (1-sigma value, at 100 m range, under *RIEGL* test conditions)
3D accuracy	3 mm @ 50 m; 5 mm @ 100 m (1-sigma value, based on target modelling, under *RIEGL* test conditions)
Scan angle range: **horizontal x vertical**	360° x 105° (-40° to +65°)
Measurement range **(2,2 MHz PRR)**	0.5 - 220 m (90% reflectivity) 0.5 - 100 m (20% reflectivity) (typical values)
Weight	< 6 kg
GNSS receiver	internal (L1), optional: *RIEGL* RTK-GNSS receiver (L1/L2)
Orientation sensors	integrated 3-axis accelerometer, 3-axis gyroscope, 3-axis magnetometer (compass), barometer
Laser class	1 (eyesafe)
Protection class	IP64, dust-tight and splash-proof

In typical applications, the user is interested in the 3D point cloud. If instead of 3D coverage repeat scans of a linear feature are desired, a 3D laser scanner can be used as a 2D line scanner by keeping the scanner frame (i.e., the rotating scanner head) fixed w.r.t. its horizontal angle.

In this article, the *RIEGL* VZ-600i laser scanner is used (see Table 1). The VZ-600i is a fast and highly performant laser scanner; with a scan time of 30 seconds for the default 3D scan pattern of 6 mm point resolution at 10 m distance. The device scans with a pulse repetition rate of 2.2 MHz. It uses a rotating multi-facet mirror with 4 mirror facets, rotating at up to 105 revolutions per second, to generate up to 420 scan lines per second with a vertical field of view of 105 degrees.

3.2 Operating Modes

The VZ-600i can be used in different operating modes: It is foremost a TLS to be used statically on e.g., a tripod or in stop-and-go mode on a vehicle. In these cases, the laser scanner is static during data acquisition (i.e., during scanning), and performs 3D sampling of the environment by changing the direction of the emitted laser pulse both horizontally (frame rotation) and vertically (deflection of laser beam by the rotating multi-facet mirror). In-between data acquisition, the scanner is moved to the next scan position. Accurate georeferencing of the scan data is achieved using integrated GNSS and inertial sensors in addition to a block adjustment which optimizes individual scan positions both with respect to each other as well as with respect to external survey control.

In monitoring applications, the scanner is fixed on a permanent measurement pillar, or in a protective housing. In this setup, measurements are made continuously and repeatedly, allowing for analysis of temporal phenomena using scans made in pre-defined intervals according to a pre-defined schedule.

The VZ-600i can also be operated kinematically, where the scanner is mounted on a moving platform, such as a car. Scanning occurs during movement, and can be performed either in 3D mode (with rotation of the scanner head, thus creating repeat 3D scans) or in 2D mode (lateral looking and not rotating the scanner head, where the 3D sampling is achieved through the motion of the carrier platform). In this article, the focus is on static usage of the laser scanner in both the default 3D mode (to create an initial 3D model of the environment including the bridge), and in the 2D mode (for the monitoring of specific linear features over time).

3.3 Operating Principles of the Line Scan Mode

The line scan mode is fundamentally a standard scan, with the frame rotation disabled. In this mode, the scanner performs a 2D scan with the given pulse repetition rate and line speed. The pulse repetition rate directly relates to the point measurement rate, and lower pulse repetition rates enable higher maximum measurement range (RIEGL, 2025a).

The line speed is proportional to the speed of rotation of the multi-facet polygon mirror and determines the number of scan lines per second (one per facet and revolution of the polygon mirror). The facets of the polygon mirror are not perfectly orthogonal due to manufacturing imprecisions, and their actual geometry is precisely determined during calibration. In consequence, scan lines from different facets generally do not coincide exactly, and thus four consecutive scan lines are not necessarily identical although the points from all scan lines are themselves geometrically correct. The number of lines per second (LPS) and pulse repetition rate (PRR) together determine the angular spacing between points in the same scan line, the socalled theta increment. For a scan mechanism consisting of a multi-facet mirror with four facets, the theta increment is given by

$$\Delta\theta = \frac{LPS \cdot 360°}{4} \cdot \frac{2}{PRR} \quad (1)$$

At the maximum PRR of 2200 kHz and the maximum LPS of 420, the corresponding theta increment is thus 34 mdeg. In other words, each second 420 scan lines are acquired, where consecutive points within a scan line are vertically offset from each other with an angular increment of 34 mdeg.

3.4 Data Output: 3D Point Cloud and 2D Line Scan Data

The acquired data is post-processed in *RIEGL's* RiSCAN PRO software. This software performs conversion of the scanner's raw data into point cloud data, including georeferencing of the point cloud and multi station adjustment (i.e., co-registration of multiple scan positions or registration w.r.t. survey control). The point clouds themselves can be exported in several point cloud formats (e.g., LAS/LAZ, e57, ...) or accessed in their "native" *RIEGL* database (RDB) format via the RDBLib library (RIEGL, 2025b). The RDBLib is a freely available software library for reading and writing various data types (e.g., point clouds, trajectories, voxels) to and from *RIEGL*'s proprietary RDB (*RIEGL* Data Base) file format. The RDBLib provides easy and straightforward access to the stored data from different programming languages (e.g., Python), thus eliminating the need to manually decode and handle a proprietary data format. This facilitates seamless integration and data processing for advanced applications and analyses.

An RDB file can store arbitrary secondary attributes together with a primary attribute, usually a point's XYZ coordinates. For point clouds, the RDB format provides an efficient spatial index for fast spatial queries of the database and enables visualization of large point clouds within the RiSCAN PRO software. Where standard RDB point clouds typically contain the timestamp of each point only as a secondary attribute, the timestamp is of primary interest for line scan data. To allow efficient analysis of temporal characteristics of the acquired data, line scan data is stored with timestamps as primary attributes and thus not with a spatial index but rather with a temporal index by default, although conversion between spatial and temporal index is possible.

4. EXPERIMENTAL SETUP AND MEASUREMENT CONCEPT

4.1 Field Deployment and Measurement Geometry

The TLS was set up and operated on the eastern side of the Puente Las Cucharas bridge, as a highway on the western side prevents an unobstructed line of sight to the structure. The eastern side provided clear visibility of the relevant structural components and sufficient space for stable deployment.

The observation geometry was verified in situ to ensure that the scan line intersected a defined structural cross-section of the bridge and remained stable during the measurements. A consistent Project Coordinate System (PRCS) was established using six scan positions. The first five positions were operated upright on a tripod and used to define the local reference frame; inter-position distances were less than 10 m, allowing linkage to discrete GNSS measurements. Data from each position are initially provided in the Scanner's Own Coordinate System (SOCS). The transformation to the PRCS is described by the Scanner Orientation and Position (SOP) matrix, defining scanner position and orientation within the project frame. The PRCS is defined as a local tangential plane to the Earth's ellipsoid, with axes oriented east (X), north (Y), and vertically (Z, antiparallel to the gravity vector), yielding a levelled XY-plane.

The sixth scan position was used for line scanning and operated with a 45° Tilt Mount. A full 360° scan was acquired and automatically registered to determine the SOP matrix of the tilted configuration and integrate it into the PRCS. The scanner alignment was refined iteratively until positioned centrally beneath the selected girder. The scan line orientation was set via the scanner's graphical user interface using a preview image. The final setup and scan configuration are shown in Figure 2.

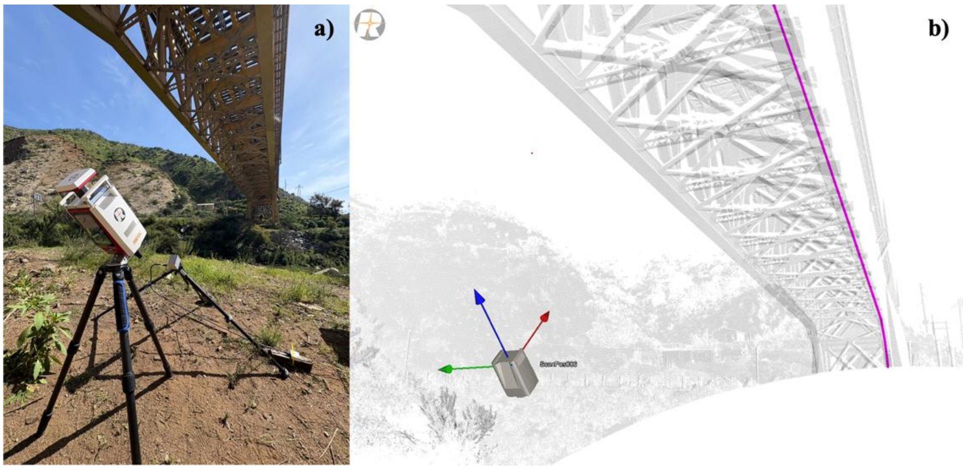

Figure 2: Field setup at the Puente Las Cucharas bridge. (a) Final scan position with the terrestrial laser scanner mounted in the 45° Tilt Mount for VZ-600i. (b) Screenshot from RiSCAN PRO showing the registered 360° overview scan (dark colour) and the corresponding high-rate line scan (magenta) aligned with the girder on the northern side of the bridge.

4.2 Data acquisition

The data acquisition focused on the collection of time-resolved line scan measurements during regular train operation. The line scan mode was initiated directly on the scanner using the device application. Line scan data were recorded between 15:15:19 and 15:43:16 local time, corresponding to UTC - 3 h. During this period, five individual RDBX data files were acquired, with recording durations ranging from approx. 40 s to 15 min. Resulting file sizes varied between approx. 350 MB and 7.6 GB, depending on the recording duration.

The scanner was operated with a PRR of 2200 kHz and a fixed angular increment of $\Delta\theta = 10$ mdeg. Based on the selected system parameters, this configuration resulted in an effective LPS of approx. 124 lines per second, following the relationship described in Equation 1.

Time stamping of the data was based on the scanner's internal GPS receiver, providing timestamps in UTC. All measurements therefore share a common absolute time reference. Train passages occurred at regular intervals of approx. 12 min per direction, with opposing train movements typically separated by 90 s to 2 min. Line scan data include train passages in both travel directions.

Data acquisition was manually controlled, without the use of external triggers. To support the identification and temporal assignment of train passages, a low-cost camera system was operated in parallel. The camera recorded image sequences, from a slightly different position, with GPS-based timestamps and was adapted for this measurement campaign based on the approach described by Blanch et al. (2024). The camera data were used exclusively for temporal referencing of train events and are not part of the laser-based displacement analysis.

Each start–stop sequence of the line scan mode resulted in an individual RDBX file, which forms the basic unit for subsequent data processing. The primary objective of the data acquisition was to obtain datasets containing clearly identifiable train passages to evaluate the practical functionality and stability of the line scanning approach under real operating conditions.

4.3 Data processing and Analysis Concept

The data processing workflow presented in this study represents an adapted analysis routine developed specifically for the evaluation of high-rate line scan data. It is not a standardized processing pipeline available within the *RIEGL* software environment. Instead, it demonstrates the flexibility provided by direct access to raw scanner data and metadata, allowing custom, application-specific analysis workflows to be implemented.

All line scan data were accessed directly from the native RDBX format using the *RIEGL* library. Each measurement point was first transformed from the SOCS into the established PRCS using the corresponding SOP matrix, ensuring a consistent spatial reference and a uniquely defined vertical direction.

To align the analysis strictly with the geometry of the monitored structure, a Locally Levelled Coordinate System (LLCS) was introduced for the selected girder. The origin of the LLCS was defined at the eastern end of the girder, at its connection to the concrete foundation. The z-axis of the LLCS coincides with the z-axis of the PRCS and thus represents the vertical direction. The x-axis of the LLCS is aligned along the longitudinal axis of the girder and oriented towards its western end, also defined by the connection to the concrete foundation. The y-axis completes the right-handed coordinate system and is oriented transversely to the bridge axis, perpendicular to the longitudinal profile of the structure.

The transformation from the PRCS into the LLCS was defined by a Local Orientation and Positioning (LOP) matrix. The effective transformation applied to the measurement points can thus be expressed as:

$$X_{LLCS} = \underbrace{T_{PRCS \to LLCS}}_{=LOP^{-1}} \cdot \underbrace{T_{SOCS \to PRCS}}_{=SOP} \cdot X_{SOCS} \tag{2}$$

The smallest physically meaningful temporal unit of the measurement is the scan line, as each scan line corresponds to one mirror facet of the rotating four-facet mirror system. To obtain temporally smoothed observations, four consecutive scan lines corresponding to one complete mirror rotation were aggregated into a frame. Each frame therefore represents one full mirror cycle. The timestamp of a frame was defined by the first scan line of the respective cycle, resulting in an effective temporal sampling rate of approximately 31 Hz (mean frame duration 0.032204 s).

For each frame, points belonging to the monitored girder were selected based on their spatial location within the LLCS. Along the longitudinal direction (LLCS x-axis), a fixed spatial binning of 0.10 m was applied. This simplified discretization was considered sufficient for the selected structural element and avoids additional complexity associated with geometry-dependent segmentation.

For each spatial bin and frame, the mean vertical coordinate (LLCS z-axis) was computed, yielding time-resolved vertical profiles of the girder. A reference profile was defined as the temporal mean of all frame-based profiles. Relative deformations were then expressed as deviations from this reference profile. To analyze the temporal behavior, displacement time series were extracted at selected reference positions along the girder. These time series typically exhibit non-linear trends. Trend components were approximated using B-spline regression following the approach of Harmening and Neuner (2016), with the number of spline knots selected by minimization of the Bayesian Information Criterion (BIC).

As a first estimate of the achievable measurement precision, the Median Absolute Deviation (MAD) was computed for each reference position based on the detrended ΔZ time series. After subtraction of a spline-based trend $\hat{s}(t)$, the residuals were obtained as

$$r(t_i) = \Delta Z(t_i) - \hat{s}(t_i) \tag{3}$$

The MAD was evaluated in the temporal domain according to

$$\mathrm{MAD} = \mathrm{median}(|\, r_i - \mathrm{median}(r)\, |) \tag{4}$$

and converted to an equivalent standard deviation under the assumption of a normal distribution using

$$\sigma_{\text{MAD}} = \frac{\text{MAD}}{0.6745} \tag{5}$$

This provides a robust estimate of the achievable measurement precision.

5. RESULTS

The results are presented for a train passage recorded during regular metro operation. The selected event corresponds to a west–eastbound train travelling towards Limache. The train entered the bridge at 18:38:09 UTC (15:38:09 local time, LT) and left the bridge at 18:38:23 UTC (15:38:23 LT).

Figure 3(a) illustrates the monitored line scan profile along the selected girder. For the analysis, only the segment of the girder running parallel to the track alignment was considered, corresponding to LLCS x-coordinates between 11 m and 64 m. The scanner position is indicated in the same coordinate system at x = 2.409 m, y = 0.036 m, and z = −1.574 m. The observed measurement profile corresponds to the scanner's vertical field of view of 105°, which is fully utilized by the applied 45° tilt mount, enabling a continuous intersection of the scan line with the girder over the entire monitored segment and ensuring a stable measurement geometry.

Figure 3(b) shows the measured points along the line scan for a single time instant (18:38:02 UTC) during the train passage. Variations in measurement precision are already visible at this level. Increasing dispersion with growing distance from the scanner and very shallow incidence angles can be observed. The reference position at x = 23 m used for the subsequent time-series analysis is indicated in the same plot.

The temporal evolution of the vertical displacement at the reference position is shown in Figure 3(c). The time series covers the interval from 18:38:01 to 18:38:53 UTC, including the undisturbed state prior to train arrival, the loading phase during passage, and the subsequent recovery. The raw observations (blue) are shown together with a B-spline approximation representing the underlying trend. The spline model was selected in a data-driven manner, resulting in a configuration with 12 knots. During the train passage, a clear downward movement of the bridge is observed, reaching a minimum vertical displacement of approximately 2.4 mm. After the train leaves the bridge, the deformation reverses and gradually returns towards the initial level. A short period of counteracting motion is visible for approximately 25 s before the displacement stabilizes again. The time of maximum deformation coincides with the train position captured by the camera system, as shown in Figure 4. The time axis of the line scan data is based on the scanner's internal GPS time reference; for comparison with the camera images, all timestamps were consistently expressed in UTC, accounting for the GPS–UTC offset of 18 s.

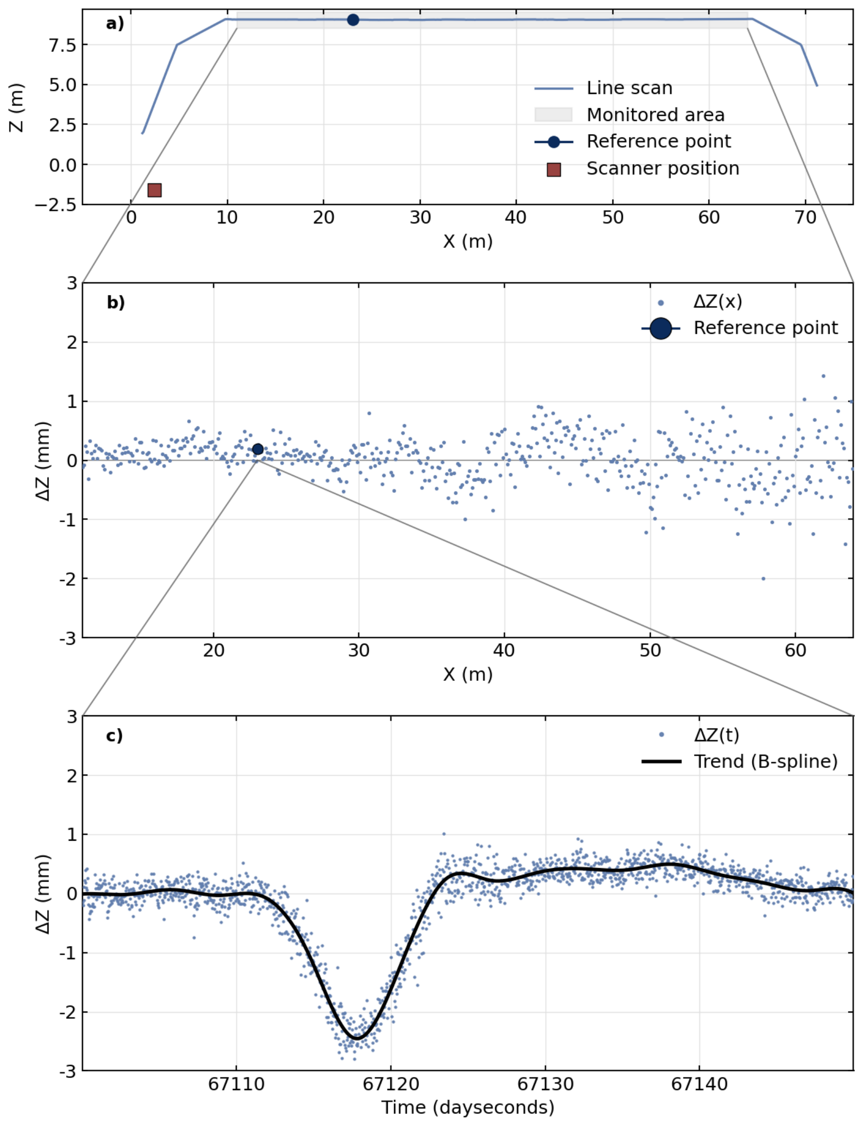

Figure 3: Line scan results for a representative train passage. (a) Longitudinal profile of the monitored girder in the LLCS (x = 11–64 m) with scanner position. (b) Spatial ΔZ profile at 18:38:02 UTC, including the reference position. (c) ΔZ time series at the reference position (x = 23 m) with B-spline trend.

Figure 4: Camera image used for temporal verification of the train passage on Puente Las Cucharas at 18:38:16 UTC.

To assess the achievable measurement precision, the dispersion of the detrended time series was evaluated using the MAD. Figure 5 shows the resulting σ_{MAD} values as a function of the reference position along the profile. For reference positions up to approximately 26 m, σ_{MAD} values remain below 0.2 mm. With increasing distance, the dispersion increases markedly, reaching approximately 0.4 mm at 40 m and about 0.6 mm at 50 m. The observed increase follows an approximately exponential trend with distance from the scanner (and thus, in this setup, with angle of incidence). This behavior is consistent with previously reported characteristics of terrestrial laser scanning data and reflects the influence of acquisition geometry on measurement precision (e.g., Soudarissanane et al., 2009).

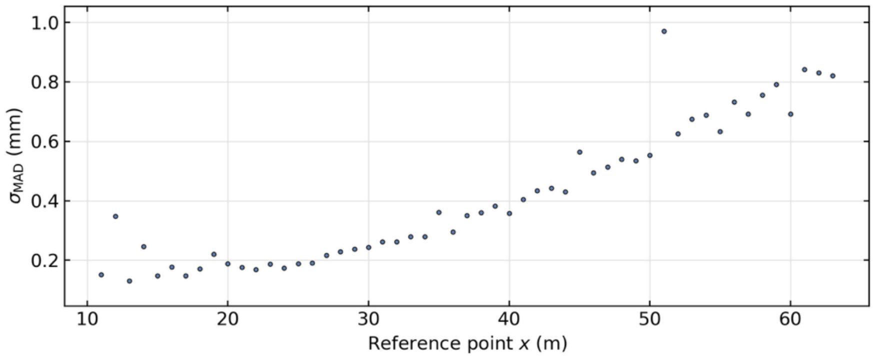

Figure 5: σ_{MAD} values of the detrended ΔZ time series as a function of the reference position along the girder.

6. DISCUSSION AND CONCLUSION

This study reports first field experience with the *RIEGL* VZ-600i operated in a high-rate line scan mode for dynamic bridge monitoring under real operational conditions. The results show that this configuration enables the contactless observation of time-dependent vertical deformations induced by regular train traffic. The contribution focuses on the practical implementation and robustness of the measurement and processing workflow.

Consistent with previous studies by Schill et al. (2022), the analysis confirms that the measurement uncertainty of individual laser points is not sufficient for reliable dynamic deformation assessment. Meaningful results require spatial aggregation of neighboring points along the monitored profile. The adopted frame-based processing and spatial binning strategy proved effective in extracting reproducible deformation signals from line scan data under field conditions.

The achievable temporal resolution is closely linked to the selected spatial resolution. Higher spatial resolution (smaller point spacing within each line) inevitably leads to reduced temporal resolution (reduced line scan rate). Reported scan rates of different laser scanning systems in the literature, such as those for Z+F scanners presented by Schill et al. (2022), therefore cannot be directly compared without accounting for spatial resolution and acquisition geometry. In this experiment, an effective sampling rate of approximately 31 Hz was deliberately chosen to ensure a stable and robust measurement configuration.

From a methodological perspective, the presented results indicate that the obtained measurement precision is sufficient to resolve dynamic structural responses. While the achievable precision is inherently influenced by acquisition geometry, the study demonstrates that stable and interpretable deformation signals can be derived when appropriate spatial aggregation and processing strategies are applied.

One limitation identified during the field deployment relates to the measurement geometry. Despite the use of a 45° tilt mount, the effective vertical field of view of the scanner restricts the optimization of incidence angles compared to systems with substantially larger vertical fields of view. This may limit geometric flexibility for certain bridge configurations but could be solved with adaptable tilt mounts.

From an application perspective, laser-based line scanning offers several promising use cases. One potential application is the preliminary assessment of bridges prior to the installation of permanently mounted sensors, providing rapid insight into dynamic behavior using mobile equipment. Furthermore, line scanning can be integrated into longer-term monitoring concepts, where PLS is used for quasi-static observation of bridges and adjacent terrain, complemented by temporary high-rate measurements.

Overall, the field experiment demonstrates that high-rate laser-based line scanning can be implemented with comparatively low effort on site. In the context of SHM, where demands for reliable, contactless, and spatially distributed measurements are expected to increase due to ageing infrastructure and growing traffic loads, line scan–based TLS represents a valuable complementary approach for supporting informed maintenance and risk management decisions.

REFERENCES

Baumann-Ouyang, A., Butt, J., & Wieser, A. (2022). Bridge deformations during train passage: monitoring multiple profiles using concurrently operating MIMO-SAR sensors. In 5th Joint International Symposium on Deformation Monitoring (JISDM 2022) (pp. 11-19). Editorial Universitat Politècnica de València. https://doi.org/10.4995/jisdm2022.2022.13620

Blanch, X., Guinau, M., Eltner, A., & Abellán, A. (2024). A cost-effective image-based system for 3D geomorphic monitoring: An application to rockfalls. Geomorphology, 449, 109065. https://doi.org/10.1016/j.geomorph.2024.109065

EFE Trenes de Chile. (2024). Sensores e inteligencia artificial al servicio del monitoreo y mantenimiento del Puente Las Cucharas. https://www.efe.cl/sensores-e-inteligencia-artificial-al-servicio-del-monitoreo-y-mantenimiento-del-puente-las-cucharas/

Harmening, C. & Neuner, H. (2016). Choosing the Optimal Number of B-spline Control Points (Part 1: Methodology and Approximation of Curves). Journal of Applied Geodesy, 10(3), 139-157. https://doi.org/10.1515/jag-2016-0003

Kostjak, V., & Neuner, H. B. (2023). Investigation of Systematic Influences on the Distance Measurement and Sensitivity of a Profile Laser Scanner. Allgemeine Vermessungs-Nachrichten, 4, 99-108.

Lienhart, W., Ehrhart, M. & Grick, M. (2017). High frequent total station measurements for the monitoring of bridge vibrations. Journal of Applied Geodesy, 11(1), 1-8. https://doi.org/10.1515/jag-2016-0028

Lienhart, W., Schill, F., & Moser, T. (2023). Dynamic Bridge Monitoring with Remote Sensing Techniques. In Structural Health Monitoring 2023: Designing SHM for Sustainibility, Maintainability and Reliability (pp. 184-191). DEStech Publications, Inc. https://doi.org/10.12783/shm2023/36736

Lindenbergh, R., Anders, K., Campos, M., Czerwonka-Schröder, D., Höfle, B., Kuschnerus, M., Puttonen, E., Prinz, R., Rutzinger, M., Voordendag, A., & Vos, S. (2025). Permanent terrestrial laser scanning for near-continuous environmental observations: Systems, methods, challenges and applications. ISPRS Open Journal of Photogrammetry and Remote Sensing, 17, 100094. https://doi.org/10.1016/j.ophoto.2025.100094

Meyer, N.; Schmid, L.; Wieser, A.; Medic, T. (2022). Vibration monitoring of a bridge using 2D profile laser scanning: Lessons learned from the comparison of two spatio-temporal processing strategies. En 5th Joint International Symposium on Deformation Monitoring (JISDM 2022). Editorial Universitat Politècnica de València. 177-184. https://doi.org/10.4995/JISDM2022.2022.13813

Novák, B., Stein, F., Farouk, A., Thomas, L., Reinhard, J., Zeller, T., & Koster, G. (2024). Erfahrungssammlung Monitoring für Brückenbauwerke – Dokumentation 2021. Bundesanstalt für Straßenwesen. https://doi.org/10.60850/bericht-b197

RIEGL Laser Measurement Systems GmbH (2025a). Datasheet RIEGL VZ-600i. https://www.riegl.com/fileadmin/media/Products/01_Terrestrial_Scanning/RIEGL_VZ-600i/RIEGL_VZ-600i_Datasheet_2025-10-03.pdf

RIEGL Laser Measurement Systems GmbH (2025b). rdblib (RIEGL database library) [Software library]. https://www.riegl.com/en-austria/products/detail/rdblib

Schill, F., & Eichhorn, A. (2019). Deformation monitoring of railway bridges with a profile laser scanner. ZFV – Zeitschrift für Geodäsie, Geoinformation und Landmanagement, 144, 109–118. https://doi.org/10.12902/zfv-0248-2018

Schill, F., Michel, C., & Firus, A. (2022). Contactless Deformation Monitoring of Bridges with Spatio-Temporal Resolution: Profile Scanning and Microwave Interferometry. *Sensors*, *22*(23), 9562. https://doi.org/10.3390/s22239562

Schönberger, C., Lienhart, W., & Moser, T. (2022). Dynamic monitoring of civil infrastructures with geodetic sensors. In Proceedings 5th Joint International Symposium on Deformation Monitoring JISDM 2022 (pp. 537-543) https://doi.org/10.4995/JISDM2022.2022.16057

Sepúlveda Orbenes, R. (2005). Análisis estructural Puente Las Cucharas (Master's thesis). Pontificia Universidad Católica de Valparaíso, Valparaíso, Chile.

Soudarissanane, SS., Lindenbergh, RC., Menenti, M., & Teunissen, PJG. (2009). Incidence angle influence on the quality of terrestrial laser scanning points. In F. Bretar, M. Pierrot-Deseilligny, & MG. Vosselman (Eds.), Proceedings ISPRS workshop laserscanning 2009 (pp. 183-188). ISPRS.

Wedel, F., Pitters, S., Hille, F., Herrmann, R., & Schneider, R. (2025). Leitfaden – Strategischer Einsatz von Monitoring für Ingenieurbauwerke. Bundesanstalt für Straßenwesen. https://doi.org/10.60850/bericht-b210

Wujanz, D., Burger, M., Neitzel, F., Lichtenberger, R., Schill, F., Eichhorn, A., Stenz, U., Neumann, I. and Paffenholz, J. (2018). Belastungsversuche an einer Mauerwerksbrücke: Terrestrisches Laserscanning zur Verformungsmessung. In Mauerwerk Kalender 2018, W. Jäger (Ed.). https://doi.org/10.1002/9783433608050.ch10

Zschiesche, K., Fitzke, M. & Schlüter, M. (2022). Self-Calibration and Crosshair Tracking with Modular Digital Imaging Total Station. PFG 90, 543–557. https://doi.org/10.1007/s41064-022-00220-0

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