

D.3.1.2: Final Report and presentation of the results from the pilot tests to consortium, expert council and external stakeholders

Work package 3



Project Information

Project ID	CE0100439
Project Acronym	BIM4CE
Project Full Title	Bridge monitoring using real-time data and digital twins for Central Europe
Starting Date	30.03.2023
Duration	3 years
Topic	Strengthening innovation capacities in central Europe
Project Website	https://www.interreg-central.eu/projects/bim4ce/
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Document Information

Work Package	3
Deliverable Title	Final Report and presentation of the results from the pilot tests to consortium, expert council and external stakeholders
Version	8.0
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Reviewer(s)	Ilia Lashkov
Citation(s)	D.1.2.1: Report of State of the Art of Bridge Monitoring in Central Europe D.1.3.1: Report on existing bridge types in CE including criteria for selection for target bridge type D.1.4.2: Conceptual Framework for Application of Digital Monitoring System D.2.4.1: Report & Presentation on effectiveness of Measurement system & calibration based on the pilot action D.2.5.1: Final report including comments of the expert panel in which requirements are documented D.3.1.1: Midterm review of implemented solution and presentation to consortium



Document Classification:

Draft		Final	x	Confidential		Restricted		Public	
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History			
Version	Issue Date	Status	Distribution
1	16.02.2026	Draft	SINA
2	18.03.2026	Draft	TUD
3	27.03.2026	Draft	SINA
4	30.03.2026	Draft	ZAG
5	21.04.2026	Draft	Cestel
6	27.04.2026	Draft	SPD
7	07.05.2026	Draft	ZAG
8	19.05.2026	Final	SINA

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List of Abbreviations

ABBREVIATION	DESCRIPTION
ACC	Accelerometer
ANPSD	Average Normalized Power Spectral Density
BIM	Building Information Modeling
DT	Digital Twin
GVW	Gross Vehicle Weight
HGV	Heavy Goods Vehicle
IDA-KI	Infrastructure Data Analysis with Artificial Intelligence
IoT	Internet of Things
MEMS	Micro Electro-Mechanical Systems
SHM	Structural Health Monitoring
SPD	Schüßler-Plan Digital GmbH
TUD	Technische Universität Dresden
WIM	Weigh-in-Motion
ZAG	Slovenian National Building and Civil Engineering Institute



1. Introduction

The Deliverable 3.1.2: "Final Report and presentation of the results from the pilot tests to consortium, expert council and external stakeholders" shows the results of the project in order to create a report which can be presented to a larger group of stakeholders. The idea is to foster customer engagement and ideally begin negotiations about future sites where the solution should be implemented.

This report begins with a general overview that describes the project, its objectives, and the partners involved, along with the roles they played. It then proceeds with a description of the main phases into which the project was divided, in order to proceed in successive steps. The identified phases are foundations and requirements, development with pilots, and adaptation/upscaling. In particular, this report focuses on the third phase and the presentation of the results obtained, with the aim of disseminating them to stakeholders.

2. BIM4CE Project

Bridges are critical transport infrastructure and significant monitoring and maintenance activities are required to ensure their safety. Bridge monitoring is a process that involves observing and collecting data not only on structural conditions, but also on the more operational and functional aspects of a bridge.

BIM4CE is a project co-funded by the second call of the Interreg Central Europe program, which focuses on cooperation between Central European countries to improve sustainable development. Interreg Central Europe supports projects involving partnerships between public bodies, universities, companies, and non-governmental organizations from different member states.

Figure 1. Project logo

BIM4CE involves the participation of eight partners from three different European countries (Germany, Italy and Slovenia) who are working together to offer a digital, accessible, and scalable bridge monitoring solution for the benefit of all countries and citizens of the European Union.

The team active on the BIM4CE Project consists of the eight partners shown in the Figure 2.



Figure 2. BIM4CE Partners

Germany

- **Technische Universität Dresden** (Dresden) - *Lead Partner*: Collaboration in the design of innovative technological sensors for bridge monitoring solutions.
- **Schüßler-Plan Digital GmbH** (Düsseldorf): Develop a data management platform, and design and creation of BIM-based Digital twins for bridges.

Italy

- **FOS S.p.A.** (Genoa): Co-leader of the project and coordinator of social media communication and management.
- **CSP ICT Innovation** (Turin): Design and realization of IoT architectures and communication infrastructure between sensors, data analysis and visualization.
- **SINA** (Milan): Participation in the investigation of state-of-the-art monitoring systems in the Central European region.

Slovenia

- **BP Akademija** (Murska Sobota): Research activities for data analysis and preparation results in the form of stakeholder maps, reports, presentations and whitepapers.
- **Cestel** (Trzin): Measurement system design by providing strain gauge -based sensors and other data collection tools. Software development with feedback and consultation.
- **ZAG** (Ljubljana): Provide access to the data on Slovenian bridge infrastructure, design of monitoring, analysis and interpretation of the bridge weigh-in-motion data (B-WIM) and monitoring data.



2.1 The challenge

In Central Europe, bridge monitoring systems typically have to be developed individually for each specific use case, making them complex and cost intensive. As a result, the EU-wide adoption of smart maintenance systems for bridge monitoring is hindered. This highlights the need for a standardized, cost-effective digital bridge monitoring and management solution for Central Europe.

2.2 Project objective

The use of appropriate monitoring systems allows for the identification of any anomalies or situations of material degradation, ensuring structural safety and efficiency, as well as the durability of the work overtime. Within this context, it can be said that smart systems (sensors, digital tools – Building Information Modeling, and IoT systems) can be of great support to technicians and experts in the field for monitoring purposes; in fact, they allow maintenance processes to be optimized, but at the same time their use requires high investments.

An example of a bridge monitoring system based on IoT and BIM technologies involves the use of sensors connected to a communication network to collect data on structural conditions, such as deformation, vibration, temperature, and corrosion. This data is then integrated into the BIM model of the bridge, which allows the information to be analysed in real time and supports the management and maintenance of the infrastructure.

The BIM4CE project aims to design an innovative solution for bridge management that aspires to be both effective and economical compared to the solutions listed above. In fact, the solution will be based on existing technologies, the use of which will be extended to various types of contexts to ensure scalability. The solution will pave the way not only for more cost-effective and safer intelligent systems for bridge monitoring, but also for interesting applications in other sectors where monitoring is a key factor.

The goal of the project is to offer a bridge monitoring solution that is digital, affordable and scalable, benefiting all countries and citizens in the European Union, thus enabling a more cost-efficient, and safer asset management. Starting from bridges in central Europe, in the future other important buildings and assets will be equipped with similar smart systems for equal reasons. The approach and solution proposed in BIM4CE can be a blueprint for these endeavours.

2.3 Implementation

BIM4CE is designing a more generalized solution for bridge management that is effective enough to assist operators with maintenance decisions yet not too complex or cost intensive. It consists of hardware and software for data gathering, connectivity infrastructure, data analysis, data storage, and decision management.

BIM4CE builds on knowledge generated in previous projects. Therefore, the solution is a mix of proven technology and innovative technology including sensor foils developed at TU Dresden and, digital twin models that best meet the needs of bridge owners and operators in Central Europe.

The project [1] is organized into three phases—foundations and requirements, development with pilots, and adaptation/upscaling—culminating in a validated, standardized bridge monitoring solution ready for broader deployment across Central Europe.



The work starts by convening stakeholders through workshops to establish an expert council, review the state of the art, document owner/operator needs, define target bridge types, shortlist pilot sites, and agree letters of commitment. It then develops and tests both the digital twin approach and a cost-effective measurement system—including printed sensor foils—through transnational pilot actions, followed by multi-country implementation, comparative evaluation, and reporting as is listed below.

- Stakeholder workshops, expert council setup, needs assessment, target bridge selection, pilot site list, concept video, and letters of commitment.
- Selection of BIM/digital twin methods, design of the measurement system, sensor foil specification, and pilot validation (including calibration on a research bridge).
- Implementation on bridges in Germany, Slovenia, and Italy; midterm review; comparison with existing methods; final report and stakeholder presentations.

In particular from an operational standpoint, the work was organized according to the following phases:

- **Phase 1:** lays foundations and defines requirements via transnational engagement, a meta-study of monitoring practices, and a Central Europe strategy.
- **Phase 2:** develops and pilots the digital twin and measurement system, including data sheets and whitepapers.
- **Phase 3:** adapts and upscales the combined solution on pilot bridges in three countries with midterm and final evaluations.

Phases of the project has been thoroughly covered and described in separate reports, to which the reader is referred. The following chapters, however, focus extensively on Phase 2 with a short description of the development of the BIM-based Digital Twin, and on Phase 3, presenting and discussing the results obtained at the pilot sites.



3. Pilot sites applications

Based on Cestel and ZAG's experience with in-service measurements on bridges and bridge assessments, the bridges to be considered as pilot sites were selected from among those that meet the following criteria [2]:

Item	Description
Bridge types	Slab bridges
	Beam-deck bridges
Material	Concrete
Span length	Between 6m and 20m
Deck thickness	Up to 80cm (slab bridges)
	Up to 150cm (beam/deck combination)
Number of lanes	Up to four
Other parameters	No skew
	Smooth approach
	Road surface in good condition

Table 1. General characteristics of bridges

Based on the data presented in Table 1, the following pilot sites were selected:

- Tomačevno Bridge
- IDA-KI openLAB Bridge
- Sant'Ambrogio Bridge

The main objectives of the BIM4CE project are to design a long-term digital monitoring system for bridges in Central Europe, with the aim of ensuring the serviceability, safety, and sustainability of bridges, as well as keeping operational costs low.

The following diagram [3] outlines the subsystems and underlying logic of how Structural Health Monitoring (SHM) operates, to provide a comprehensive understanding of the innovative pilot methods to be applied in digital monitoring systems.

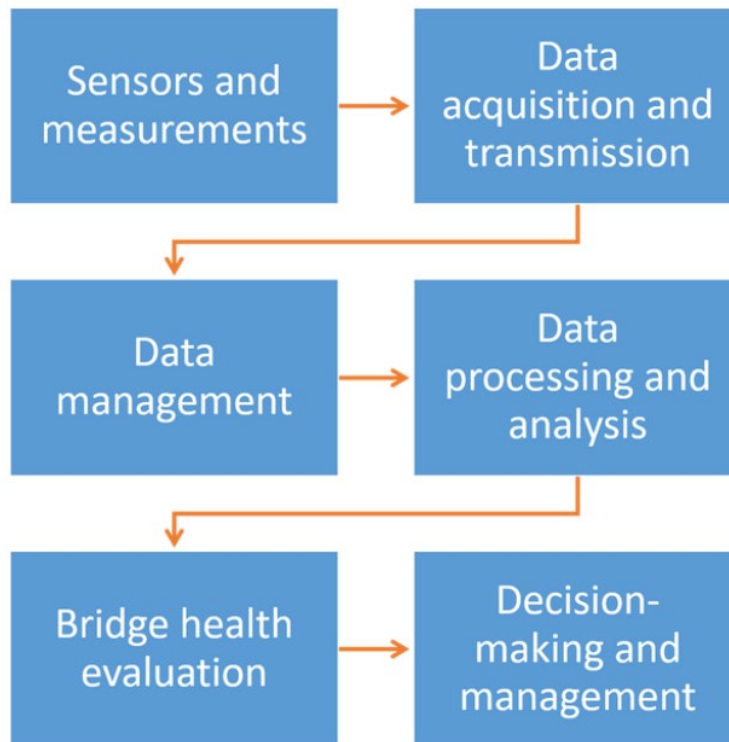


Figure 3. Structural health monitoring (SHM) framework

Following an initial phase in which various sensors and data acquisition systems for monitoring were evaluated, and a subsequent phase in which the methods for acquiring and transmitting data to the platform developed for the BIM digital model were assessed, it was possible to proceed with the design of the most suitable monitoring system for each bridge.

In its final configuration [4], the bridge monitoring system will include sensors for measuring accelerations, strains, water ingress and temperature, both under natural conditions and under operational traffic conditions, which can be grouped as follows:

- **Accelerometers** (*Dewesoft IOLITE 3xMEMS*)
- **Strain-based Bridge Weigh-in-motion** (*Cestel SiWIM MkIV*)
- **Leakage** (*TUD Flexible Leakage Sensor Foil*)
- **Temperature** (*PT100*)

Finally, all the data measured by the sensors are sent and stored in a cloud-based platform called InfoHub, where is possible to visualize data and integrate them with the bridge's BIM digital twin model.

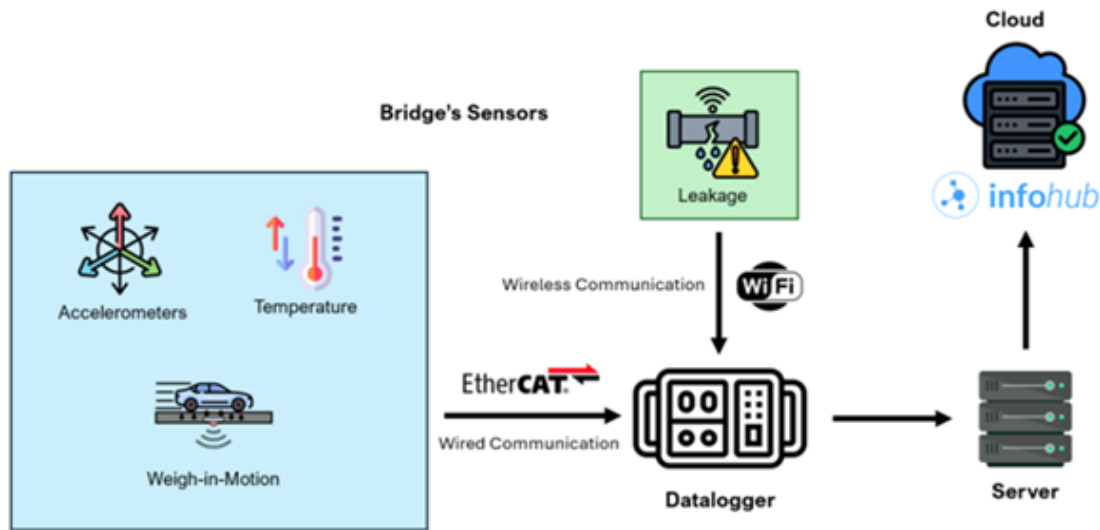


Figure 4. Final monitoring system [4]

3.1 Tomačev Bridge

3.1.1. Structural description

The Tomačev roadway bridge is a multi-span concrete road bridge near Ljubljana, Slovenia, crossing the Sava River (Figure 5). It was built in 1982. The bridge has a seven-span continuous superstructure made as a post-tensioned double-T concrete section, supported by circular piers on deep foundations.



Figure 5. Aerial view of the Tomačev bridge – view towards Ljubljana



The bridge is composed of two parallel independent structures. The right one carries traffic toward Ljubljana, while the left carries traffic in the opposite direction. Experimental campaign focused on the right structure, shown in Figure 6.



Figure 6. View under the superstructure of the Tomačev bridge – view towards Ljubljana

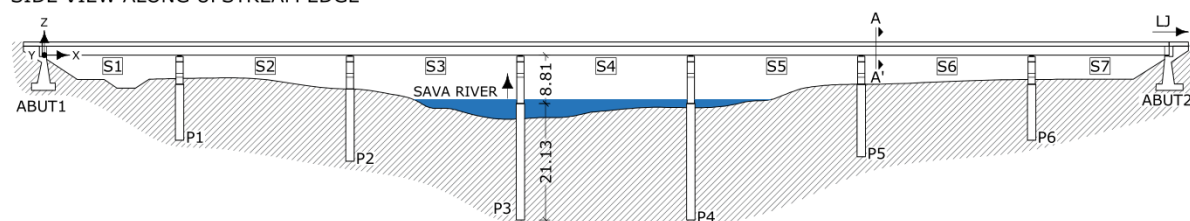
Structurally, the superstructure was cast in place using sliding formwork technology. At the abutments, cross girders connect the main longitudinal girders. The bridge has modular expansion joints at both abutments. At these ends, the deck is supported by guided unidirectional pot bearings, while above the piers it is supported by round elastomeric bearings.

In terms of condition and interventions, no major rehabilitation was carried out after construction, except for replacement of the expansion joints in 1990 and replacement of the asphalt layer and steel safety barrier in 2018. The bridge is generally in good condition, although it has typical ageing-related defects such as local concrete spalling from insufficient cover, clogged expansion joints, corroded bearings, and drainage-related deterioration near the abutments.

Figure 7 and Figure 8 show side, plan and cross-section view of the Tomačev bridge.



SIDE VIEW ALONG UPSTREAM EDGE



PLAN VIEW

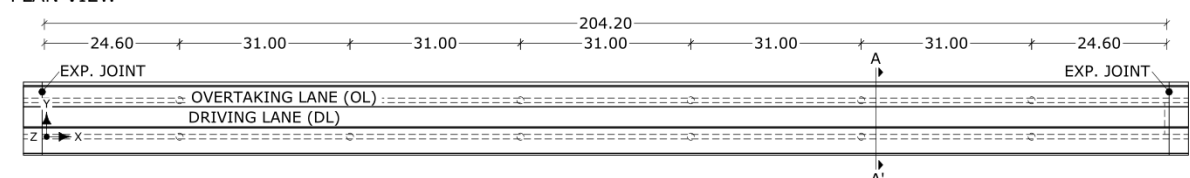


Figure 7. Side and plan view of the Tomačevo bridge with marked A-A' cross section cut position

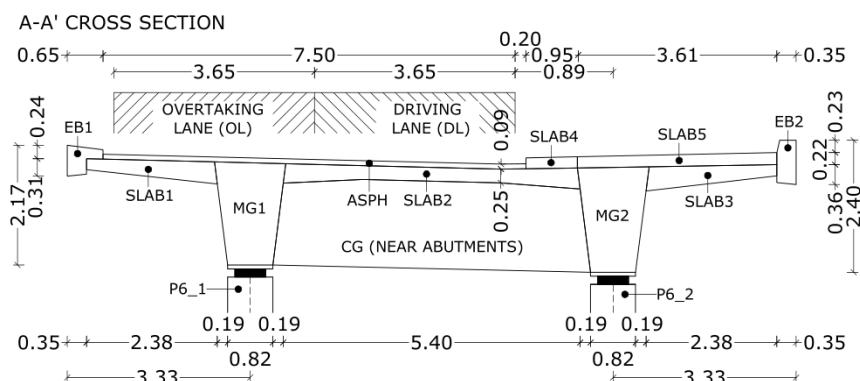


Figure 8. A-A' cross-section cut view of the Tomačevo bridge

3.1.2. Bridge monitoring system

The measurement systems installed on the Tomačevo bridge allow for the measurement of the following parameters:

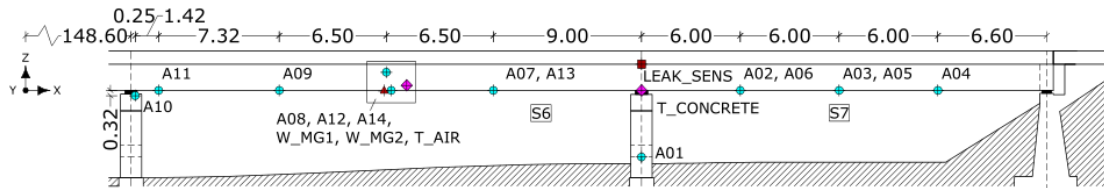
- gross vehicle weight of heavy vehicles (over 3,5 t)
- air and concrete temperature
- accelerations of the bridge in horizontal and vertical directions
- natural frequencies of the bridge, extracted from the acceleration measurements
- leakage

To measure these, the following sensors have been installed, shown in Figure 9:

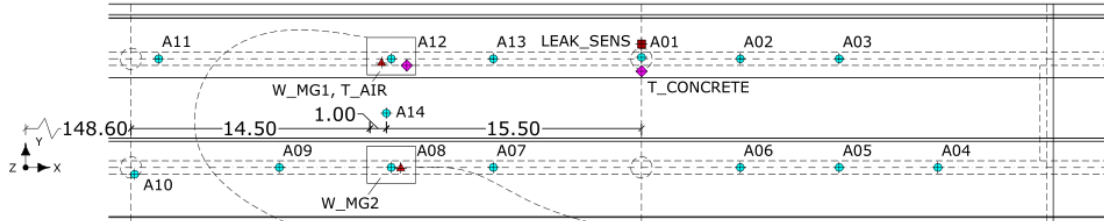
- 3-axial accelerometers
- strain-based weigh-in-motion sensors
- temperature sensors
- leakage sensor



SIDE VIEW ALONG UPSTREAM EDGE WITH SENSOR DISPOSITION: SPANS S6 & S7

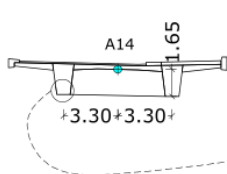


PLAN VIEW WITH SENSOR DISPOSITION: SPANS S6 & S7



DETAILED VIEWS NEAR MID-SPAN

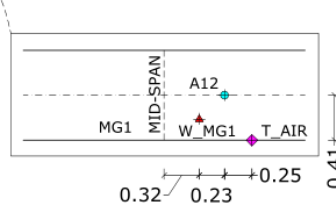
POSITION OF A14 IN
CROSS-SECTION VIEW



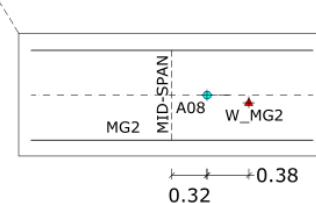
MG1: CROSS-SECTION



MG1: PLAN VIEW



MG2: PLAN VIEW



LEGEND

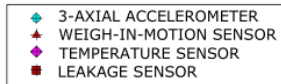


Figure 9. Sensor disposition of the Tomačevro bridge

The overall architecture of the bridge monitoring system, including different sensor types and data transmission pathways, is illustrated in Figure 10. Most sensors were connected to the datalogger through a wired EtherCAT communication system, while the leakage sensors represented the only exception, transmitting data wirelessly.

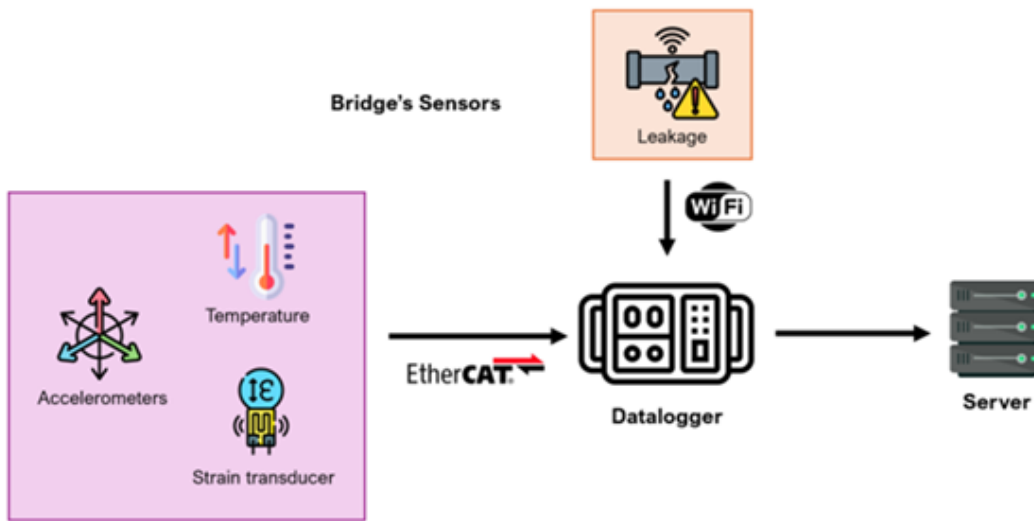


Figure 10. Bridge monitoring system on Tomačevo bridge [4]

3.2 IDA-KI openLAB Bridge

3.2.1. Structural description

The openLAB research bridge, located in Germany and built as part of the IDA-KI (Infrastructure Data Analysis with Artificial Intelligence) project [5],[6], is a prestressed concrete bridge with a total length of 45 meters and a width of 4.5 meters, built at the Hentschke Bau GmbH facilities in Bautzen (Figure 11) [8].

The bridge combines different construction methods to provide a broad range of common structural types. Each of the three spans has its own research focus. The openLAB is used to assess the suitability of the evaluation algorithms to be developed and to facilitate their practical transfer. The bridge is equipped with tracks and a movable bogie, which are used to simulate the effect of traffic loads.



Figure 11. openLAB research bridge

An illustration of the characteristic cross-sections of the openLAB bridge is presented Figure 12. The bridge combines different construction methods to provide a broad range of common structural types. Each of the three spans has its own research focus. Spans 1 and 2 consist of three parallel precast prestressed concrete girders with a cast-in-place concrete slab, whereas Span 3 showcases a rapid-construction concept. Each span is associated with a distinct research focus, addressing typical deficiencies of older prestressed concrete bridges, contemporary construction solutions, and innovative structural details. The openLAB is used to assess the suitability of the evaluation algorithms to be developed and to facilitate their practical transfer. The bridge is equipped with tracks and a movable bogie, which are used to simulate the effect of traffic loads.

The openLAB bridge is designed as a full-scale open laboratory to test different monitoring solutions and, as such, offers a unique opportunity for testing and validating equipment under real-world conditions. The openLAB research bridge was constructed in the summer of 2022 near the lead partner, the Dresden Integrated Center for Applied Physics and Photonic Materials, as part of a project funded by mFUND and the German Federal Ministry of Transport and Digital Infrastructure (BMVI). All relevant stakeholders have agreed to use the bridge for testing, including the builder, Hentschke Group, which has close ties to TU Dresden.

The aim of the IDA-KI research project is to develop methods for the automated analysis and evaluation of monitoring data. The validation is carried out using real measurement data recorded on the research bridge.

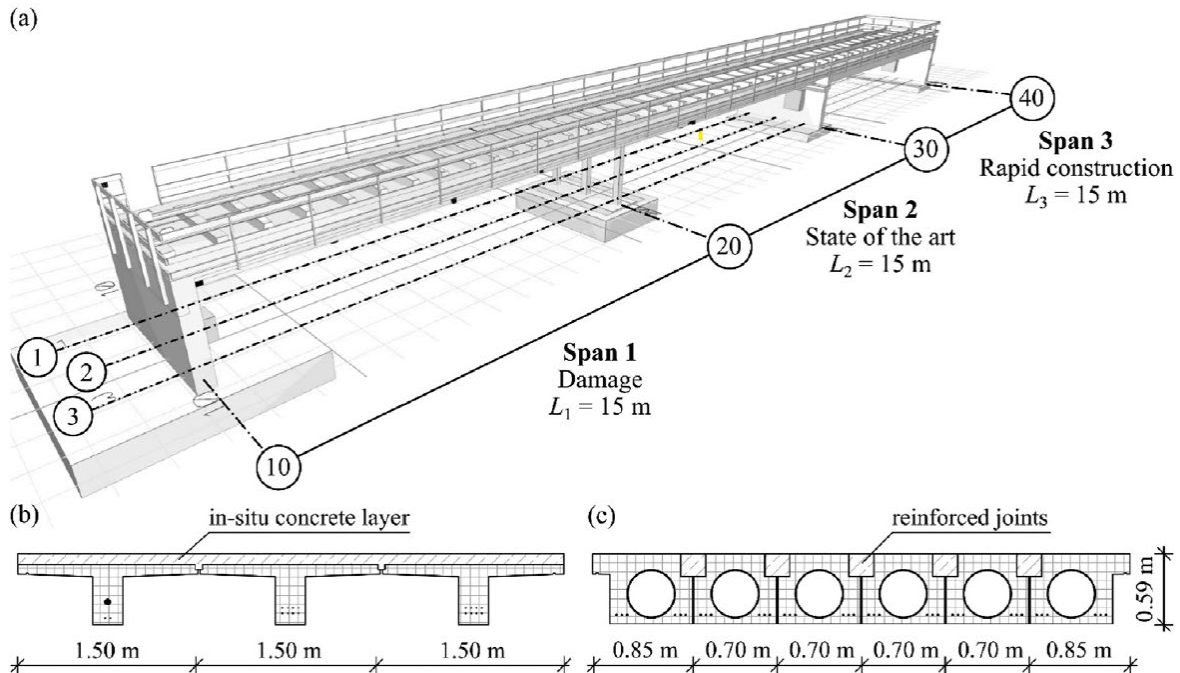


Figure 12. Illustration of the openLAB bridge: (a) overview (b) cross-section of span 1 (c) cross-section of span 3 (after [7]).

3.2.2. Bridge monitoring system

The openLAB research bridge is equipped with a comprehensive permanent monitoring system as part of the openLAB research infrastructure. This overall system allows the measurement of a wide range of parameters:

- air temperature
- acceleration vertical direction
- natural frequencies of the bridge, extracted from the acceleration measurements
- inclination
- displacement
- solar radiation
- precipitation

Within the BIM4CE project, the existing monitoring system was complemented with an additional sensor, distributed over the bridge as indicated in Figure 13:

- weigh-in-motion sensors for measuring the gross vehicle weight of the bogie
- 3 extensometers (strain transducers)
- 12 3-axial accelerometers (A01-A02)
- concrete temperature (T)

The installed sensors enabled participation in two test campaigns conducted within the openLAB project.

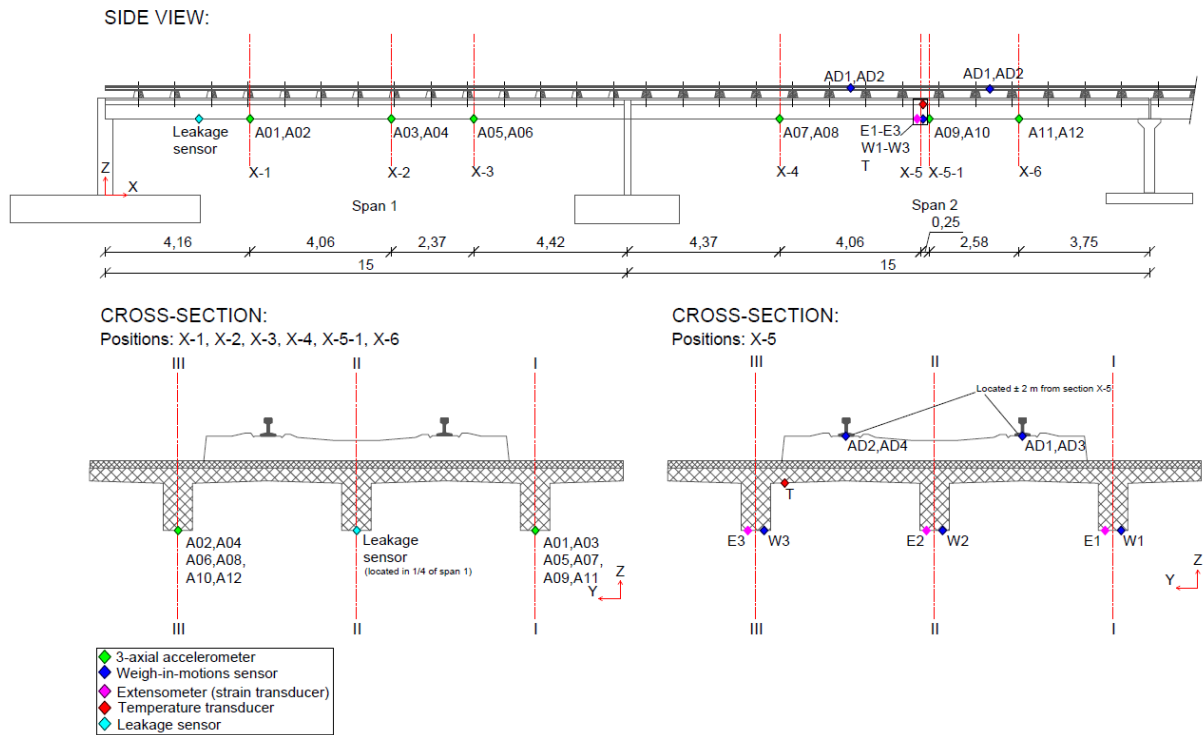


Figure 13. Sensor disposition of the openLAB bridge

The weigh-in-motion system consists of three weighing sensors (W1–W3) installed on the underside of the girders at the midspan of Span 2, and four axle and speed detection sensors mounted on the underside of the rails above the bridge.

In addition, three strain transducers (extensometers) were installed adjacent to the weighing sensors to provide supplementary benchmarking data.

The accelerometers were distributed approximately uniformly along the lengths of the first two spans, with six accelerometers installed per span. They were mounted on the underside of the left and right girders. The concrete temperature was also measured in Span 2. Furthermore, a leakage sensor was installed at one-quarter of the first span, near the drainage hole, to detect potential leakage problems.

As the bridge is part of an openLAB research initiative, results from other installed sensors can also be readily obtained. A scheme of the installed sensors within BIM4CE is presented in Figure 14.

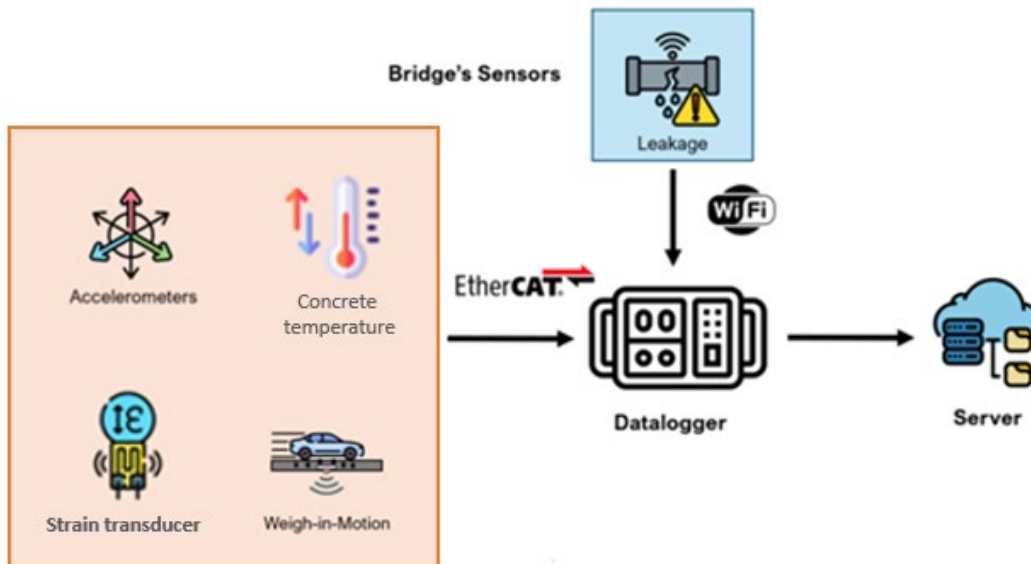


Figure 14. Bridge monitoring system on openLAB bridge

3.3 Sant'Ambrogio Bridge

3.3.1. Structural description

The viaduct [9] was built in the early 1990s and is located between Avigliana Ovest and Borgone, along the A32 Turin-Bardonecchia highway in Italy. The structure serves only the downhill lane and consists of a post-tensioned reinforced concrete slab deck with simple supports and a continuous slab, extending over a total of 5 spans, each with a span of approximately 20 m, for a total length of approximately 99 m and a total width of 12.50 m for the single carriageway.



Figure 15. Sant'Ambrogio bridge

The deck, cast in place on a precast formwork, is longitudinally prestressed with two rows of 10 parabolic cables, each composed of 12 strands of 0.6-inch diameter.

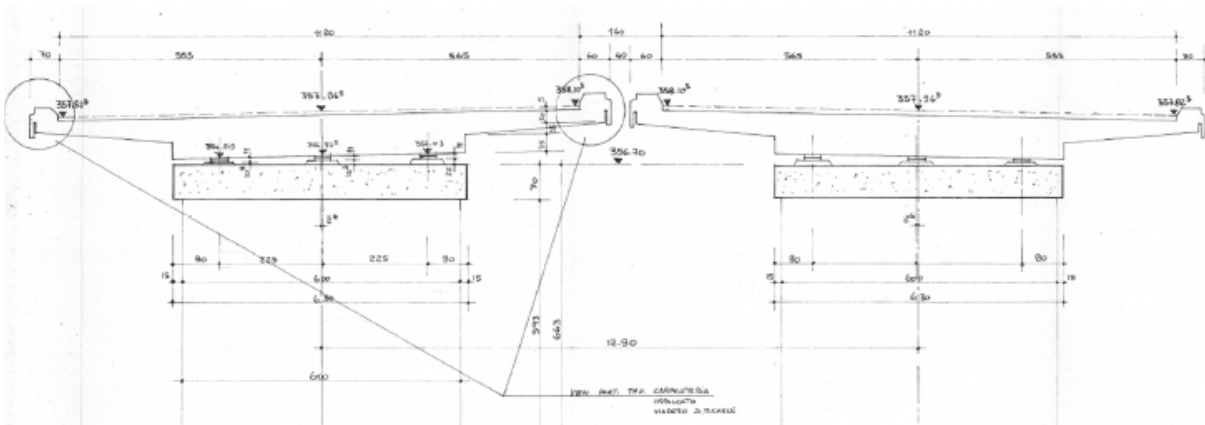


Figure 16. Cross-section of the structure (left carriageway towards Torino)

The piers have a rectangular cross-section of 6 m x 1 m with deep foundations consisting of 59 piles with a diameter of 600 mm and a depth of 16 m, constructed using jet grouting with reinforcement consisting, for the 38 outer piles only, of metal pipes with a diameter of approximately 90 mm and a thickness of 10 mm, connected by a circular plinth with a diameter of 7.10 m and a total thickness of 1.80 m.

The two abutments (serving both carriageways) also have deep foundations of the same type with a rectangular connecting plinth measuring 6.30 x 26.00 m and 1.80 m thick.



3.3.2. Bridge monitoring systems

The Sant'Ambrogio Bridge is equipped with an existing monitoring system that enables the measurement of several parameters, including:

- air temperature & relative humidity
- acceleration in vertical direction
- inclination along the length of the deck
- relative displacement between the deck and the supports

To measure these, the following devices are installed:

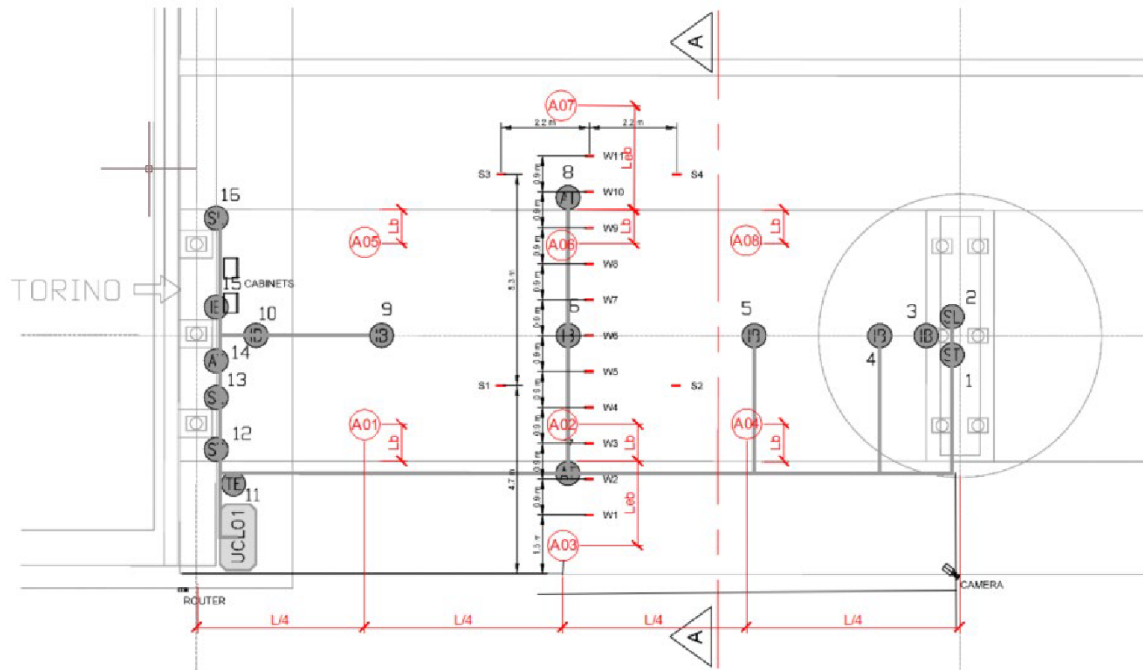
- air temperature and relative humidity sensor
- uniaxial accelerometers
- inclination sensors
- displacement transducers

In the existing monitoring system, all sensors communicate and transmit data via a wired system, first to a microcontroller and only then to the Datalogger.

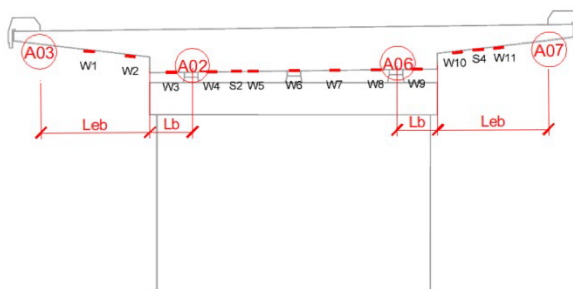
Within the BIM4CE project, the bridge was equipped with additional sensors, distributed over the bridge as indicated in Figure 17.



Plan view:



Cross-section:



A0X 3-axial MEMS accel.

LEGEND:

- L – span length
- Lb – distance from web edge to centre of bearing
- Leb – distance from web edge to beginning of edge beam
- W – Weighing sensor – ST-504
- S – Speed measuring sensor – ST-504
- AT – Triaxial accelerometer
- IB – Biaxial inclinometer
- SL – Longitudinal horizontal relative displacement transducer
- ST – Transverse horizontal relative displacement transducer

Figure 17. Sensor disposition Sant'Ambrogio bridge

The weigh-in-motion system was designed to monitor traffic in both lanes. It consists of 11 weighing sensors (W1-W11) installed at the midspan section and distributed approximately uniformly across the width of the deck. In addition, each traffic lane is equipped with two axle and speed detection sensors (S1-S4) spaced about 4 m apart.

The bridge was also instrumented with eight triaxial accelerometers (A01-A08). Two were installed at approximately one-quarter and three-quarters of the span length, while the remaining sensors were arranged across the width of the deck at midspan, with four sensors distributed uniformly at this section. Additional measurements included air and concrete temperature.

The architecture of the installed system at the Sant'Ambrogio bridge is shown in Figure 18.

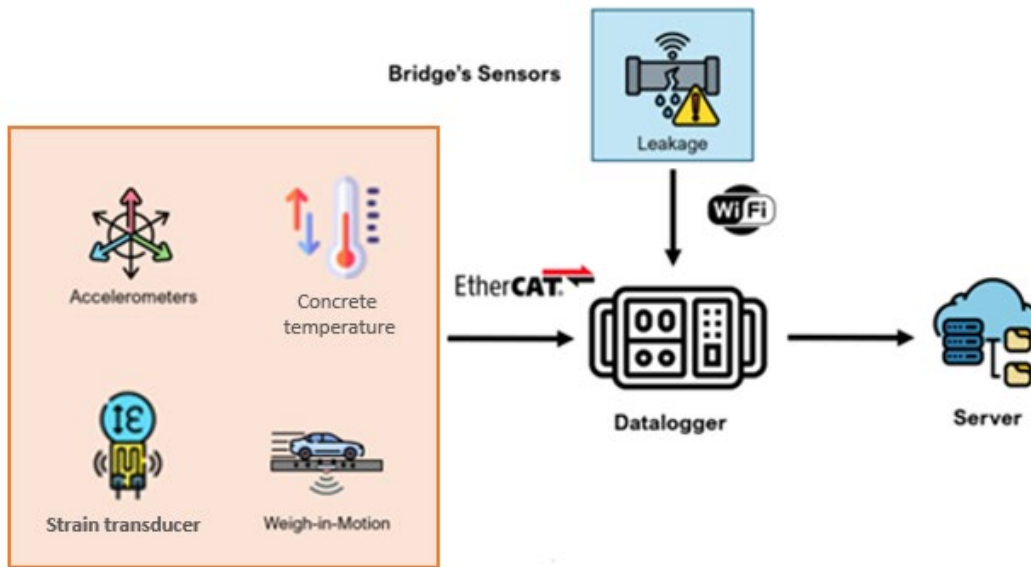


Figure 18. Bridge monitoring system on Sant'Ambrogio bridge [4]

In detail, the installed instrumentations are as follows:

- N.15 Cestel strain transducers for the SiWIM (weigh-in-motion) system, wired to two 8-channel junction boxes and then to an acquisition panel located on the abutment, which also provides the power supply.
- N.1 wireless leakage sensor, powered at 12 V DC.
- N.8 Dewesoft IoLITEiw 3xMEMS-ACC triaxial accelerometers with a dedicated communication and power network based on the EtherCAT standard, connected to a dedicated acquisition panel.
- N.1 camera for visual monitoring of vehicles crossing the bridge.
- N.3 electrical/control panels: one for power distribution, one for operating the Cestel SiWIM system, and one for the remaining sensors and the camera.

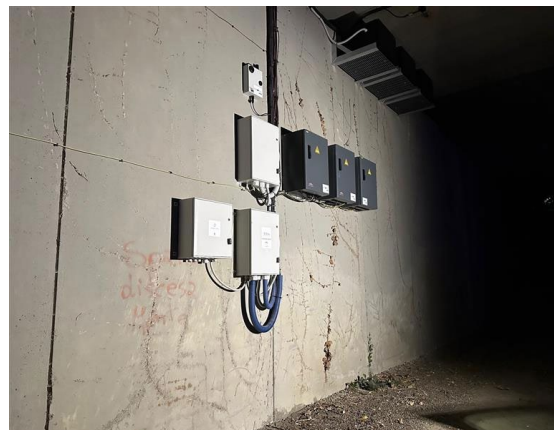
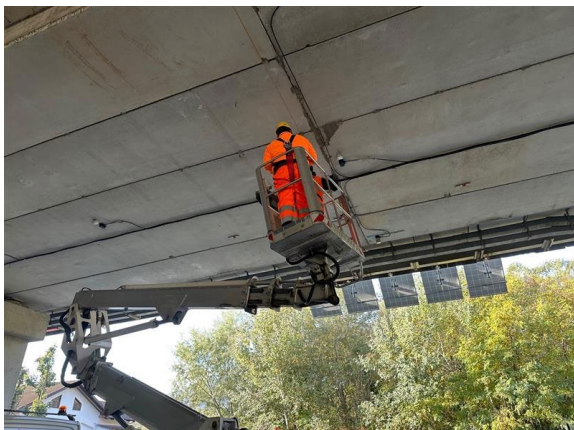




Figure 19. Installation of instrumentation on Sant'Ambrogio bridge

The entire monitoring system was installed in three days, with two operational teams working approximately six hours per day and using an aerial platform to access the deck.

System commissioning required the execution of a dynamic load test, involving two heavy vehicles and the closure of one traffic lane for approximately six hours during nighttime. The two 4-axle vehicles had masses of approximately 20 tons and 42 tons, respectively.

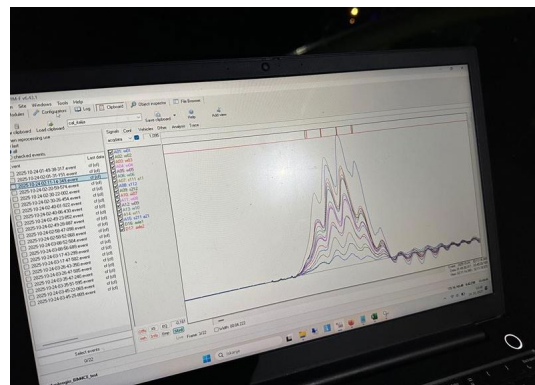


Figure 20. Dynamic load test on Sant'Ambrogio bridge



The monitoring system is powered entirely by a photovoltaic energy supply, consisting of 5×280 W solar panels, 5×200 Ah batteries for energy storage and nighttime operation, and a 60 A charge controller.

The power supply system requires additional three days of work, with one operational team working approximately six hours per day and using an aerial platform to access the deck.



Figure 21. Power supply system on Sant'Ambrogio bridge

4. BIM-based digital twin platform

This chapter presents the development and implementation of the BIM-based Digital Twin (DT) platform developed within the BIM4CE project to support the structural health monitoring (SHM) of bridge infrastructure. The primary objective is to demonstrate a scalable and interoperable approach that integrates Building Information Modeling, sensor-based monitoring data, and openBIM standards into a unified digital environment for continuous bridge assessment.

The work focuses on the practical integration of geometric, semantic, and time-dependent data, illustrating how measurement data can be contextualized within a BIM model to enable effective visualization, analysis, and data-driven decision-making. The implemented solution is designed not only as a technical monitoring system but also as a communication tool for infrastructure owners, engineers, and public authorities.

To support this integration, a structured and standardized BIM model is required. Therefore, the technical requirements and specifications for model development are defined to ensure compatibility with sensor data integration, interoperability between systems, and alignment with relevant international standards.

4.1 BIM model requirements

The BIM model is defined as the central digital asset underpinning the Digital Twin. Model development follows the Level of Information Need (LOIN) framework in accordance with BS EN ISO 7817-1:2024 and ISO 19650, fully replacing traditional LOD-based approaches. LOIN enables the specification of only the geometric, semantic, and documentary information strictly required to support sensor integration, data visualization, and interoperability.



To ensure data exchange, the following industry-standard file formats are used:

- Point Cloud Data: E57 – Compatible with CloudCompare for pre-processing
- BIM Model Data: IFC (Industry Foundation Classes) – openBIM-compliant, ensures compatibility with
- DESITE BIM md and Infohub
- Sensor Data: CSV – Compatible with DEWESoft X for integration with Infohub
- Metadata and Naming Conventions: CSV and JSON.

Naming Convention: Consistent naming conventions and attribute definitions and classifications are applied to organize data within the model. This ensures clear identification and management of key structural elements. The naming convention is structured into ten hierarchical levels to ensure clarity, traceability, and consistency across all project files.

The first three levels pertain to geographic identification:

- Level 01 contains a four-character code representing the bridge name.
- Level 02 uses a two-character code for the country of the bridge.
- Level 03 includes a three-character code denoting the city where the bridge is located.

The following levels define the document's content and origin:

- Level 04 identifies the file creator.
- Level 05 specifies the responsible project partner.
- Level 06 indicates the trade or discipline model (e.g., structural, sensor data).
- Levels 07 and 08 define the general and specific document types, respectively.
- Level 09 provides space for additional metadata, such as the date of data collection.
- Level 10 assigns a unique sequential number for version control.

For example, the file name TOMA_SN_LJU_PP_PP6_MD_SD_VDA_250423_000.csv can be interpreted as follows:

- **TOMA:** The project name, referring to the Tomačevo Bridge.
- **SN:** The country code, indicating Slovenia.
- **LJU:** The city code, representing Ljubljana.
- **PP:** The file was created by a project partner.
- **PP6:** The specific partner responsible for the file, in this case, Cestel.
- **MD:** The document type, indicating bridge monitoring data.
- **SD:** A detailed classification, specifying that the file contains sensor data.
- **VDA:** The type of sensor data—Vehicle Data Acceleration.
- **250423:** The date the data was collected, in DDMMYY format (23 April 2025).
- **000:** A sequential number identifying this as the first version of the file.

Attribute definition and classification: To enable efficient monitoring and seamless data integration, each bridge element and sensor is assigned a set of clearly defined attributes aligned with the project's monitoring objectives.



Elements are organized into two main groups: *Bridge* and *BridgeSens*. Within these, subgroups are specified to refine classification:

- For the Bridge group, the subgroups include Substructure and Super-structure.
- For the BridgeSens group, the Sensor subgroup is defined, which includes the following key elements:
 - 3AxialAccelerometer
 - WeighInMotion
 - Leakage

Each of these elements is further described using specific PropertySets, categorized as:

- General – for metadata and identification
- Structure – for physical and geometric properties
- Measurement – for monitoring and sensor data

Additionally, each property is classified as either mandatory or optional, establishing a clear hierarchy and scope for data processing. The attribute structure and classification hierarchy are illustrated in the figure below.

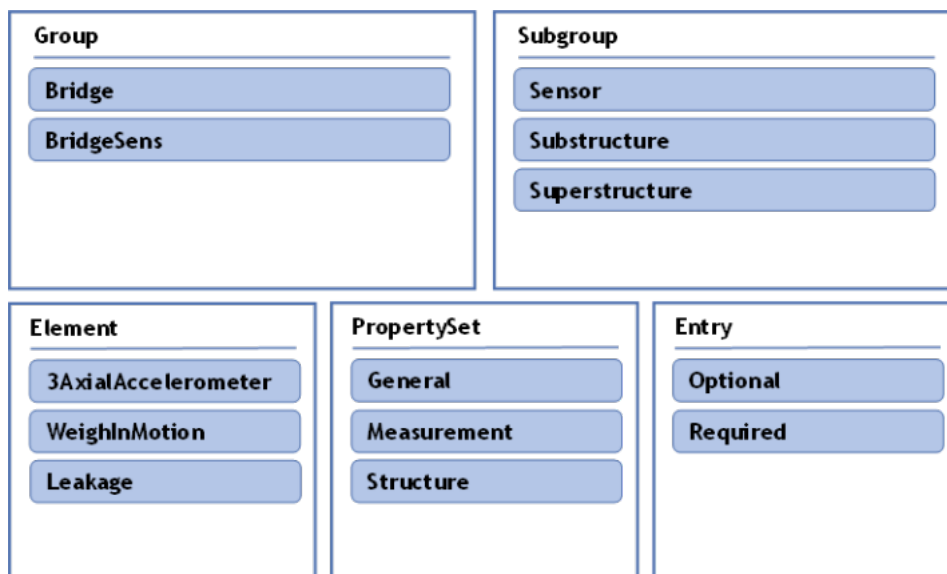


Figure 22. Attribute classification hierarchy

4.2 BIM model development

The development of the BIM model forms the foundation of the Digital Twin demonstrator, enabling the integration of geometric data with monitoring information for visualization and analysis. The modeling process combine existing CAD documentation and newly acquired point cloud data to create a simplified yet accurate representation of the bridge, focusing on essential structural elements relevant for sensor integration and aligned with the defined Level of Information Need (LOIN).

Where available, CAD drawings are used as reference data to support the modeling process and assist in determining sensor locations, particularly in areas where scan data is limited. In parallel, high-resolution point cloud data is collected using LiDAR technology to capture



the bridge's as-is condition. The point cloud is processed in CloudCompare, where it is cleaned, aligned, and segmented into key structural components. These components are then converted into simplified mesh geometries and structured using Python scripts into a hierarchically organized model, which is exported as a geo-referenced IFC file and stored on Infohub. In some cases, an existing IFC model of the bridge may already be available; in such situations, the workflow can proceed directly to the next stage.

Building on the prepared geometric model - whether newly generated or already available - the next step involves semantic enrichment to transform it into a data-driven BIM model suitable for Digital Twin integration. Model elements are classified into structural components (Bridge) and sensor-related elements (BridgeSens), with sensors such as accelerometers, weigh-in-motion systems, and leakage detectors incorporated into the model. Each element is enriched with standardized PropertySets, including general metadata, structural characteristics, and measurement-related attributes. These attributes are defined based on the LOIN framework and structured using external data sources such as .csv and .json files.

Sensor objects are instantiated at their real-world positions and linked to their corresponding data streams, ensuring consistency between the physical system and its digital representation. The final model, stored in IFC format, ensures interoperability and seamless integration with the Infohub platform and DESITE BIM md. Through this process, the BIM model evolves from a geometric representation into an intelligent Digital Twin foundation, enabling structured data management, real-time visualization, and informed decision-making for bridge monitoring.

4.3 Data acquisition and Digital Twin development pipeline

Sensor outputs are processed using a combination of software tools and custom Python scripts, generating parameter-specific CSV files containing standardized timestamps, sensor identifiers, coordinates, values, and units. Data are automatically uploaded to Infohub on a daily basis, ensuring structured storage, consistency, and seamless integration into the Digital Twin environment.

A structured Digital Twin development pipeline is implemented to transform raw sensor data and spatial information into an interactive, semantically enriched DT environment. The pipeline is divided into five key phases:

1. Acquisition of raw sensor data
2. Collection and organization of raw 3D data and BIM semantic data
3. Pre-processing of spatial and sensor data
4. Generation of processed BIM and sensor data models
5. Development of the interactive Digital Twin platform

This workflow ensures that all data components - geometry, semantics, and time-dependent measurements - are aligned, interoperable, and accessible through a single platform. The pipeline is designed to be modular and extensible, supporting future integration of additional sensor types and analytical processes.



4.4 Digital twin platform development and data visualization

The Digital Twin interface is deployed within DESITE BIM md, providing an interactive environment for exploring the 3D bridge model and associated sensor data. Access to the platform is provided through the Infohub environment, where users log in and select the relevant scope, project, and bridge.

Figure 23. User login and selection of scope, project, and bridge within the DT platform

The bridge model is imported as an IFC file from Infohub and subsequently semantically enriched using the Level of Information Need (LOIN) dataset. This process links the geometric model with structured attribute data, resulting in a fully integrated and information-rich BIM model within the platform.

Figure 24. Interface buttons for importing the IFC bridge model into the DT platform and initiating semantic enrichment

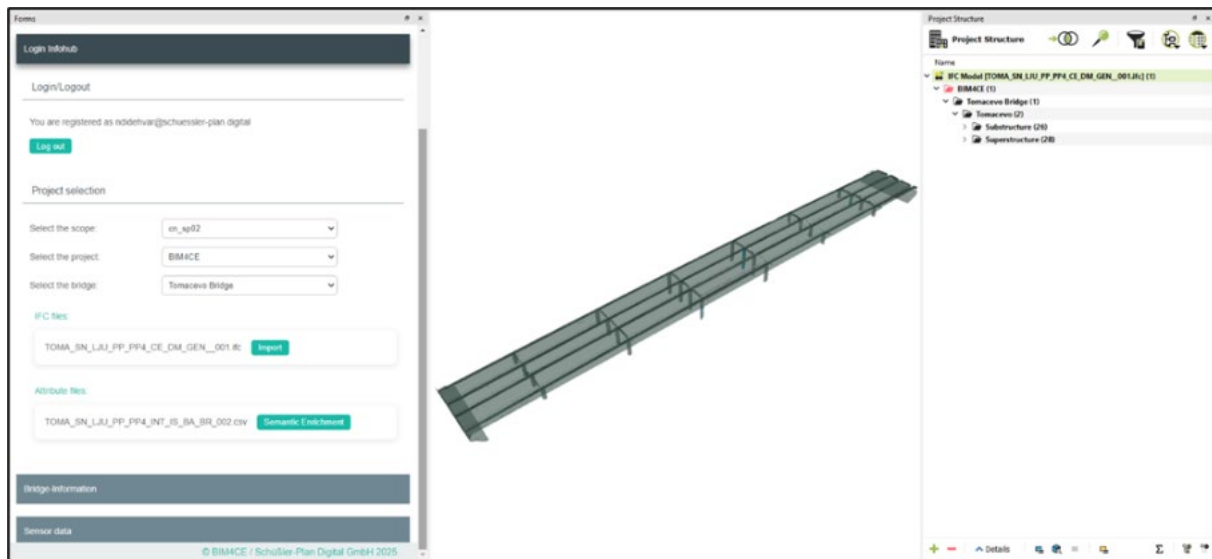


Figure 25. Imported and semantically enriched IFC model of the bridge displayed on the platform

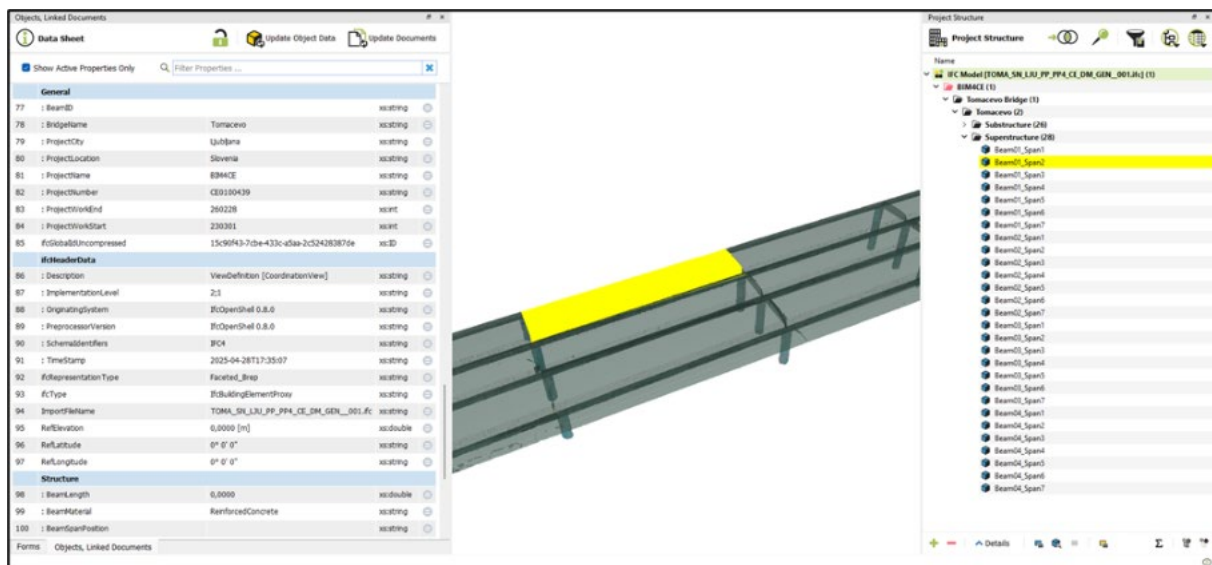


Figure 26. Example of a semantically enriched structural element with assigned attributes

General bridge information is also retrieved from predefined data files and displayed in the interface.



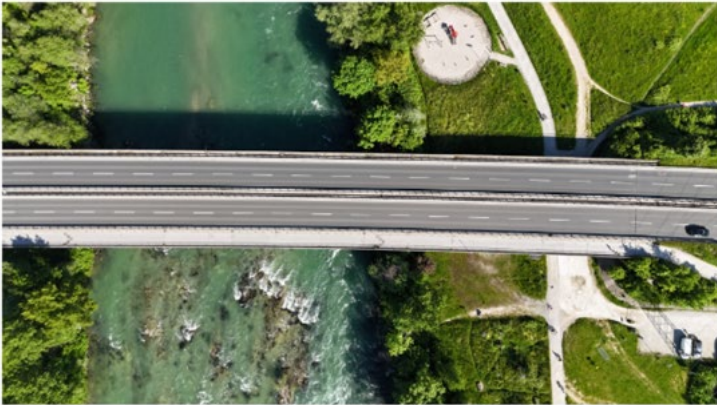
Bridge-Information	
Information about the bridge	
Bridge ID/name:	Tomacevo bridge
Date:	Friday, May 16, 2025
Country:	Slovenia
City:	Ljubljana
Construction year:	1982
Road section:	104
Total length:	204.5 m
Construction type:	Cast-in-place prestressed concrete girder bridge with cantilever RC circular piers
Material:	Reinforced concrete
Height:	From 5.1 m to 8.6 m
Number of spans:	7
Typical span length:	31 m
Number of traffic lanes:	2 (in each direction)
Average monthly number of HGVs (vehicles over 3,5 t):	21.141 (direction Ljubljana)
	
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Figure 27. General bridge information visualized on the DT platform

Sensor objects are then generated within the model using predefined positions and structured according to the IFC hierarchy. These objects are semantically enriched based on the LOIN definitions, ensuring consistent linkage between physical sensors and their corresponding digital representations.



Create Sensors

Create sensors as generic objects:

Create Sensors

Attribute files:

TOMA_SN_LJU_PP_PP4_INT_IS_BA_BS_002.csv Semantic Enrichment

Figure 28. Buttons for creating the generic IFC sensor objects into the DT platform and semantically enrich them

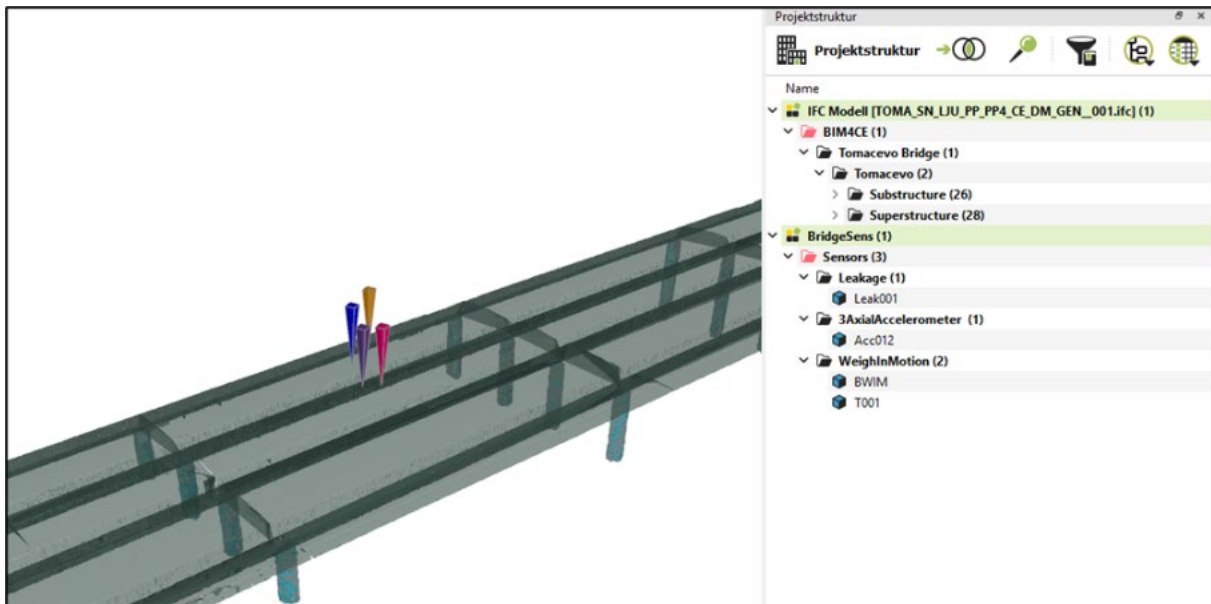


Figure 29. Sensor objects instantiated at correct positions with corresponding IFC hierarchy

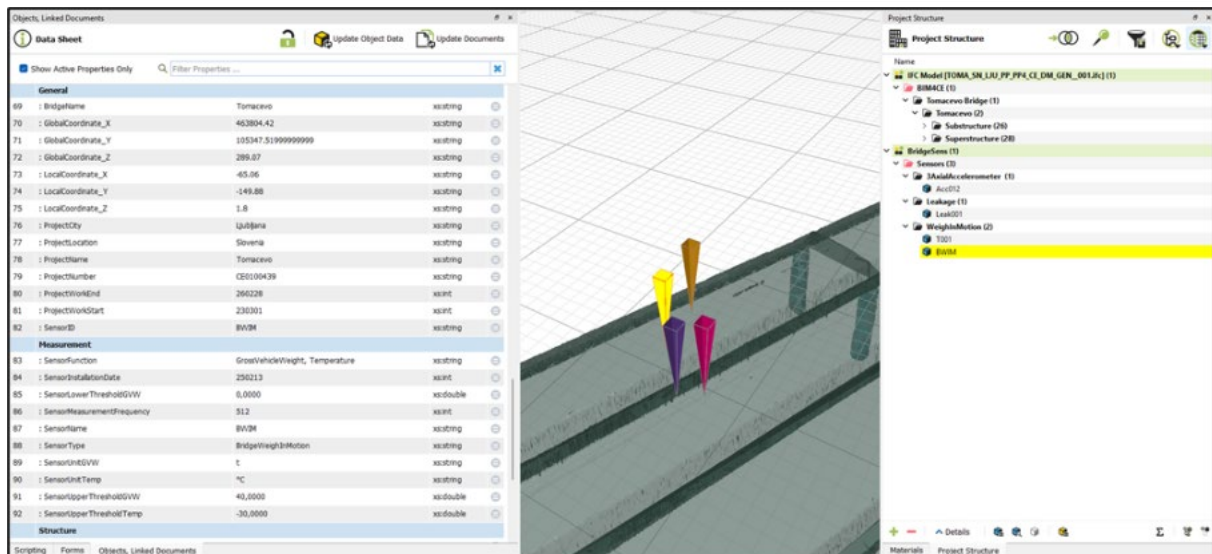


Figure 30. Example of a semantically enriched sensor object with assigned attributes

To visualize monitoring data, users select a specific observation period and data category (e.g., bridge-related or vehicle-related data). Sensor data can be accessed interactively by selecting individual sensors within the 3D model or interface, allowing real-time visualization and analysis through charts and diagrams.

Select observation period

Select observation period...

Select observation period...

Last 24 Hours

Last Week

Last Month

Last Three Months

Last Six Months

Last Year

Last Two Years

Bridge-related data - Select Sensor

Bridge weigh-in-motion sensors

T001 (Temperature)

3Axial Accelerometers

Acc012 (Frequency)

Acc012 (Acceleration)

Bridge-related sensor data

Vehicle-related data - Select Sensor

Bridge weigh-in-motion sensors

BWIM (Gross Vehicle Weight)

Leakage sensors

Leak001 (Leakage)

Vehicle-related sensor data

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Figure 31. Selection of observation period and categorization of sensor data types on the platform



For parameters with defined thresholds, exceedances are automatically highlighted, enabling quick identification of critical conditions. This functionality supports efficient decision-making for maintenance and monitoring.

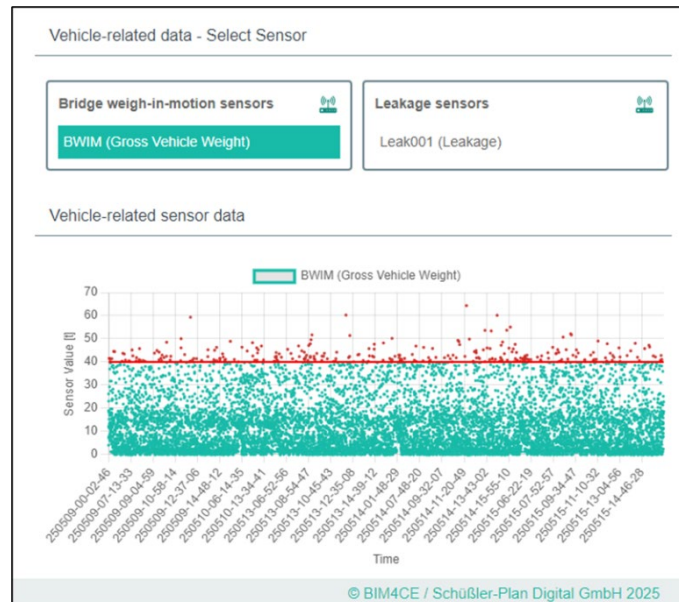


Figure 32. Sample visualization of BWIM sensor data showing threshold exceedances highlighted in red

4.5 Digital twin of the pilot sites

The developed concept was first implemented on the Tomačev Bridge, serving as the primary pilot bridge within the BIM4CE project. As no IFC model of the bridge was initially available, the structure was captured using 3D scanning, and the resulting point cloud data was used to generate the IFC-based geometric model. Subsequently, the workflow described in the previous sections of Chapter 4 was applied to develop the semantically enriched BIM model and integrate it into the Digital Twin platform.

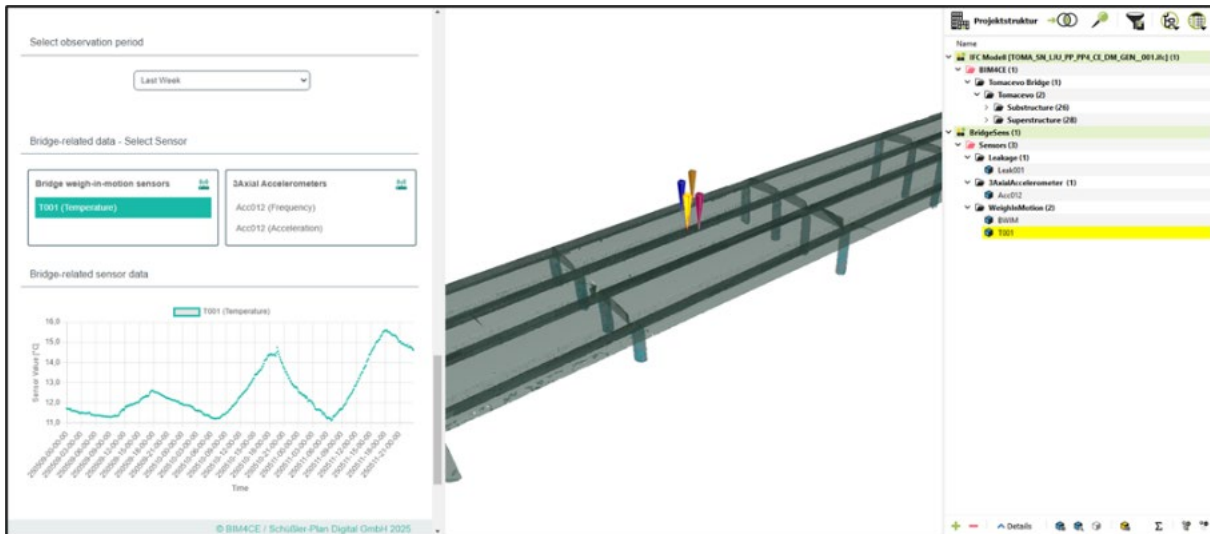


Figure 33. Interactive visualization of temperature sensor data and the 3D bridge model for Tomačevó Bridge

For the other two pilot sites - the openLAB Bridge in Germany and the Sant'Ambrogio Bridge in Italy - existing IFC models were already available. Therefore, the initial geometric modeling step required for the Tomačevó Bridge was not necessary. Instead, the process continued directly with semantic enrichment, sensor integration, and implementation within the Digital Twin platform. The following figures illustrate the application of the developed concept for these two bridges.



Figure 34. General bridge information visualized on the DT platform for openLAB Bridge

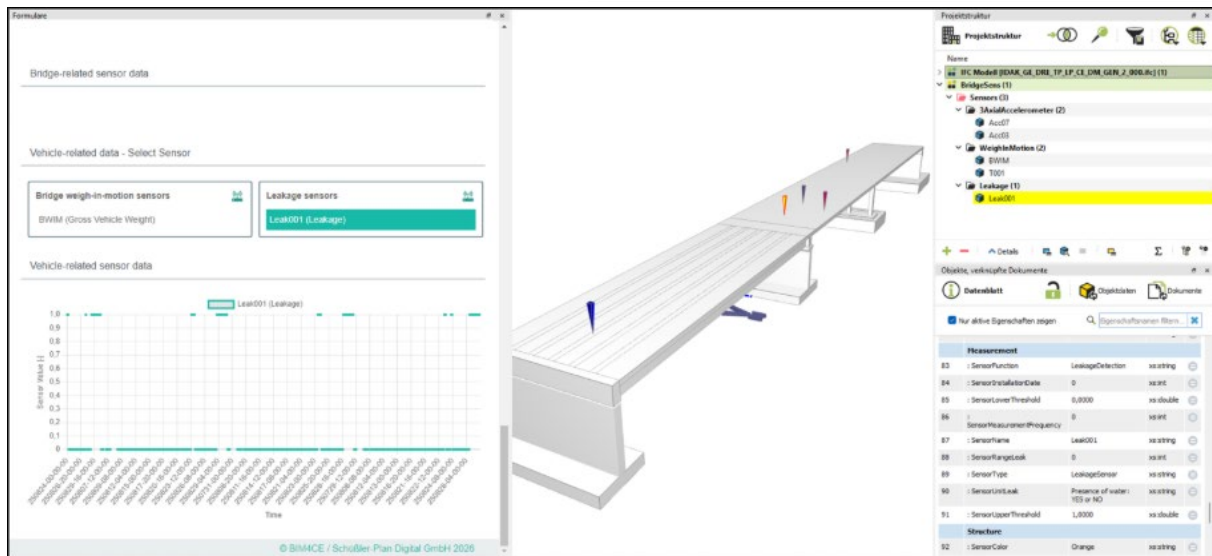


Figure 35. Interactive visualization of leakage sensor data and the 3D bridge model for openLAB Bridge

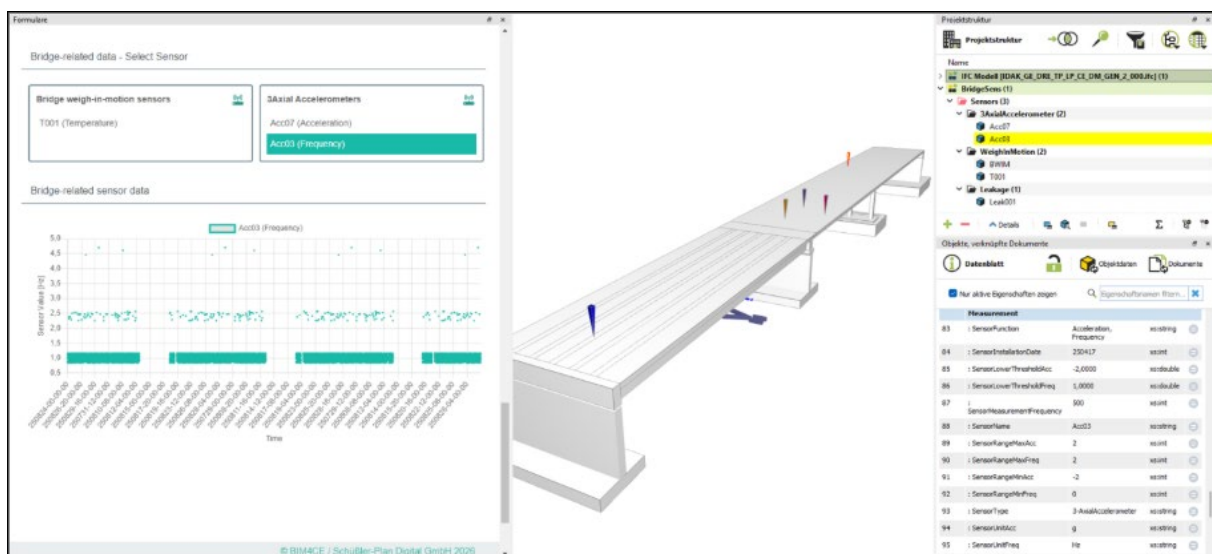


Figure 36. Interactive visualization of frequency sensor data and the 3D bridge model for openLAB Bridge

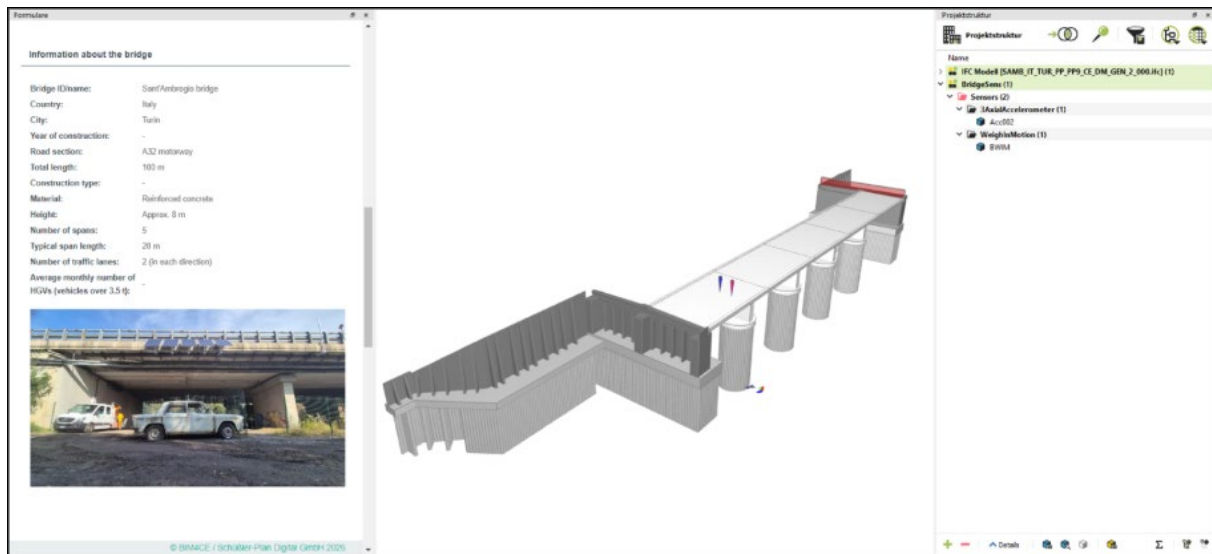


Figure 37. General bridge information visualized on the DT platform for Sant'Ambrogio Bridge

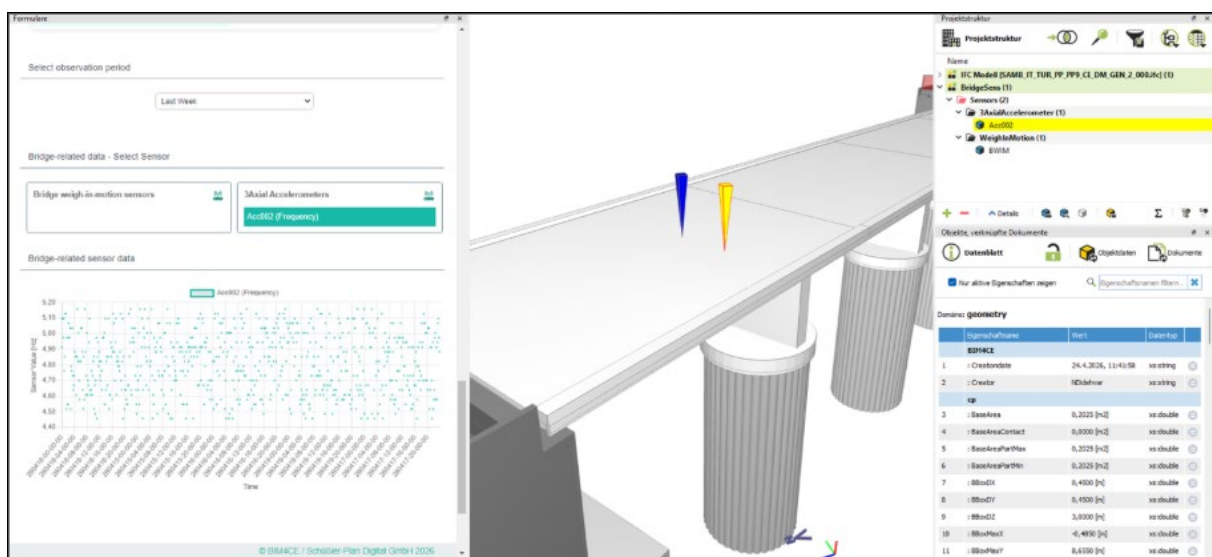


Figure 38. Interactive visualization of frequency sensor data and the 3D bridge model for Sant'Ambrogio Bridge

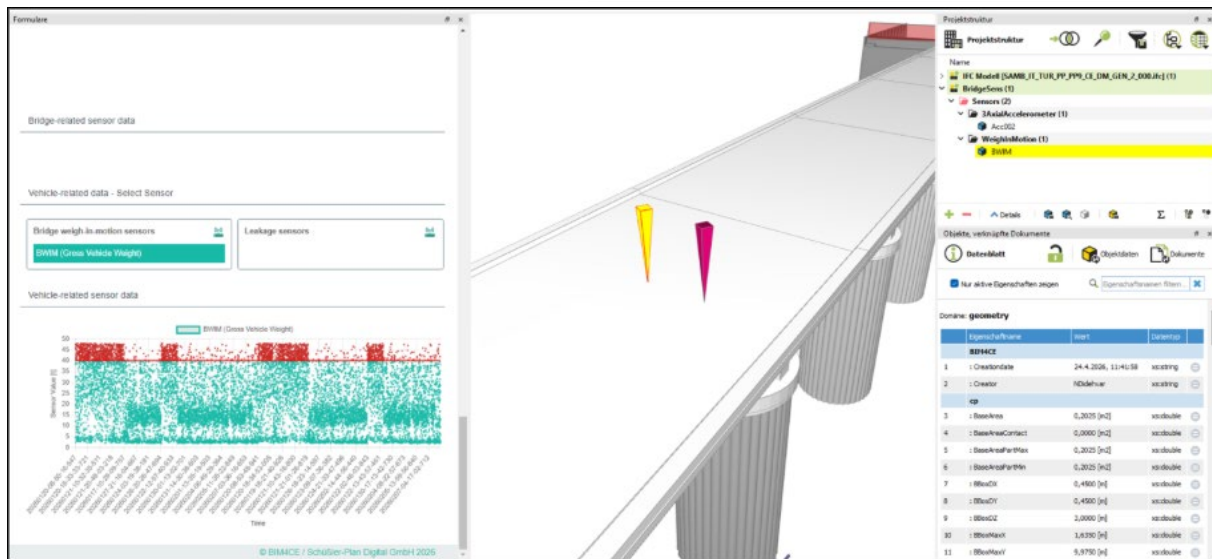


Figure 39. Interactive visualization of bridge WIM sensor data and the 3D bridge model for Sant'Ambrogio Bridge

5. Results

5.1 Tomačevko Bridge

5.1.1. Long-term monitoring

This chapter shows the results of the acceleration-based long-term monitoring in the period from 21. 2. 2025 to 14. 1. 2026, together with B-WIM and temperature data. The average normalized power spectral density (ANPSD) method, introduced by [13] was used to identify the natural frequencies and mode shapes. All acceleration sensors except A01 and A10 were used in calculation of the ANPSD.

Additionally, the frequency tracking algorithm was developed to tracks the natural frequencies in the considered time period. Figure 40 shows the ANPSD graph for the frequency range from 0 to 25 Hz and for the signals in X and Y direction. Green-yellow trajectories indicate the variation of natural frequencies through time.

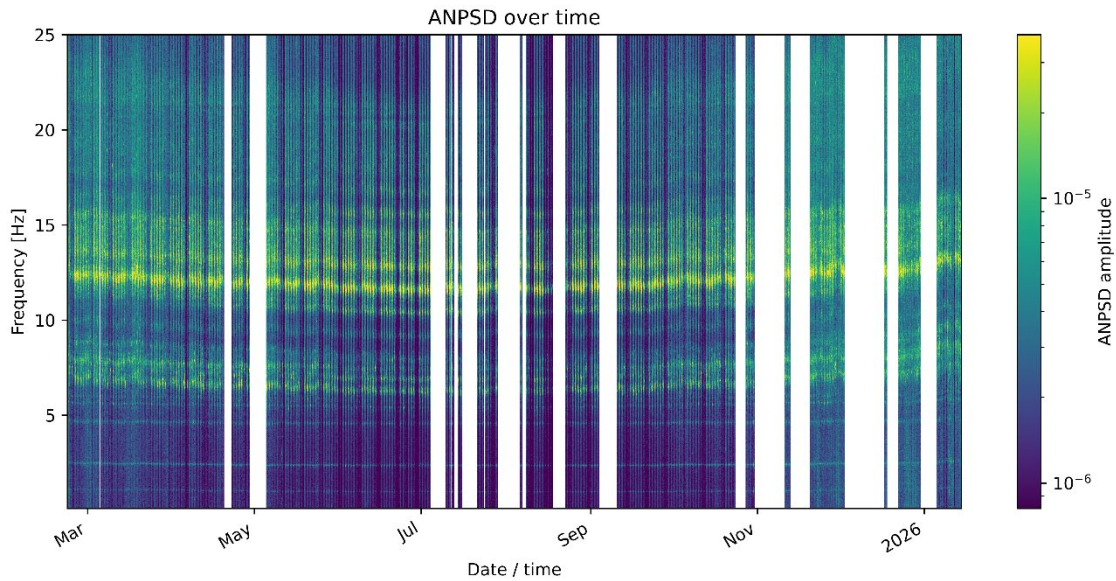


Figure 40. Average normalized power spectral density (ANPSD) graph for acceleration signals in X and Y directions for the time period 21. 2. 2025 – 14. 1. 2026

Similarly, Figure 41 shows the ANPSD graph for the frequency range from 0 to 25 Hz and for the signals in Z direction. Yellow trajectories indicate the variation of natural frequencies through time.

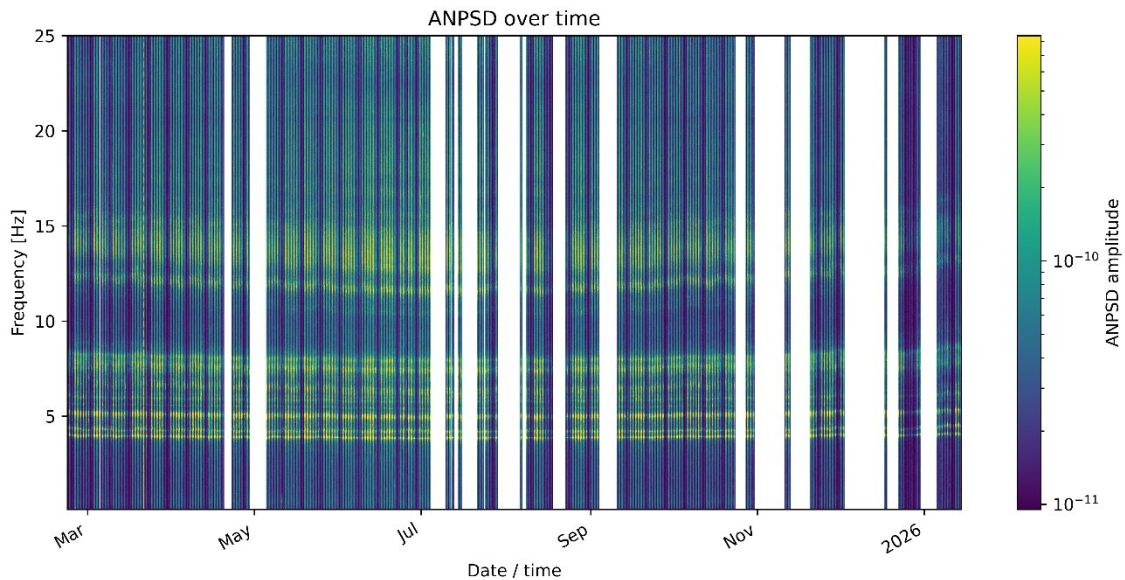


Figure 41. ANPSD graph for acceleration signals in Z directions for the time period 21. 2. 2025 – 14. 1. 2026

Figure 42 and Figure 43 show the four natural modes, which were tracked in the considered time period: B-Y-1, B-Y-2, B-Z-2 and B-Z-3. First two represent the primary movement in the transverse direction while other two represent the primary bending movement in vertical direction.

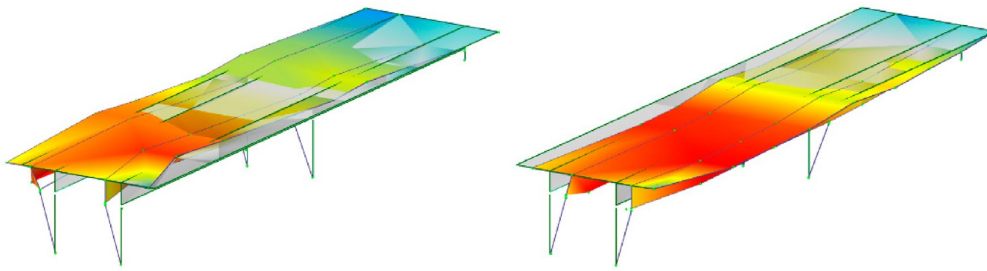


Figure 42. B-Y-1 (left) and B-Y-2 (right) mode shapes (adapted from [10])

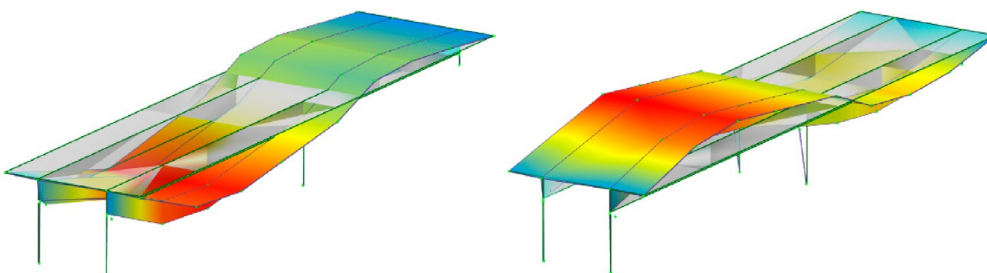


Figure 43. B-Z-2 (left) and B-Z-3 (right) mode shapes (adapted from [10])

Figure 44 shows the ANPSD graph for the signals in X and Y direction. Two yellow trajectories indicate the variation of natural frequencies B-Y-1 and B-Y-2 through time. Below the ANPSD graph, the variation of the air and concrete temperature is shown.

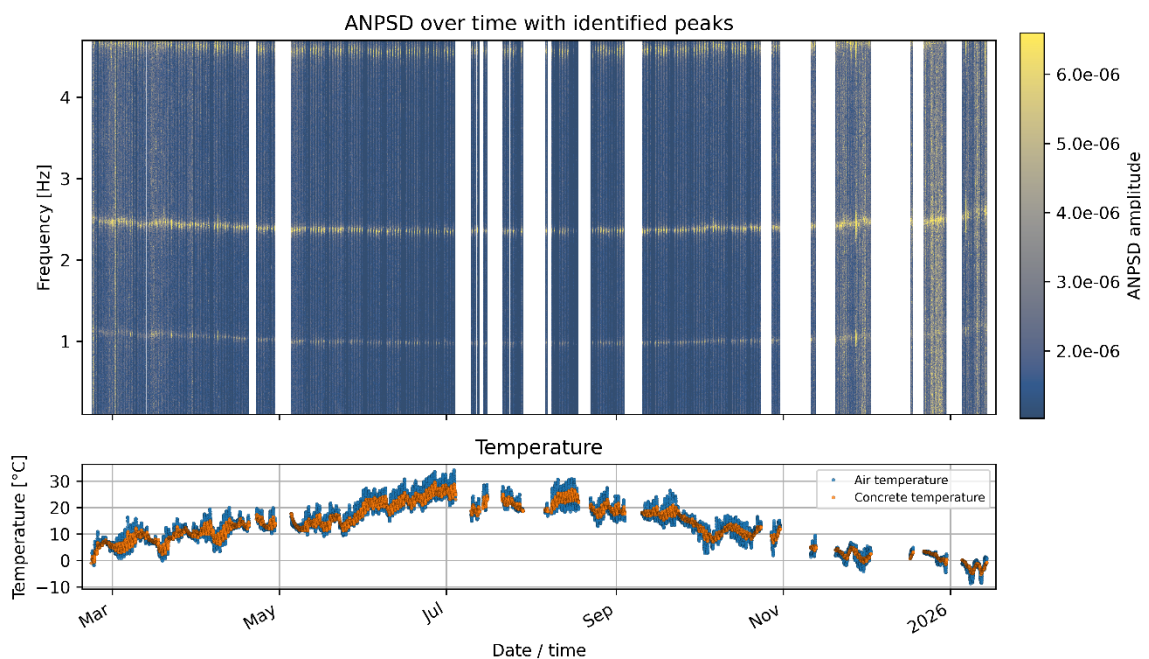


Figure 44. ANPSD graph for acceleration signals in X and Y direction and temperature variation graph



Figure 45 shows the ANPSD graph for the signals in Z direction. Two yellow trajectories indicate the variation of natural frequencies B-Z-2 and B-Z-3 through time. Below the ANPSD graph, the variation of the air and concrete temperature is shown.

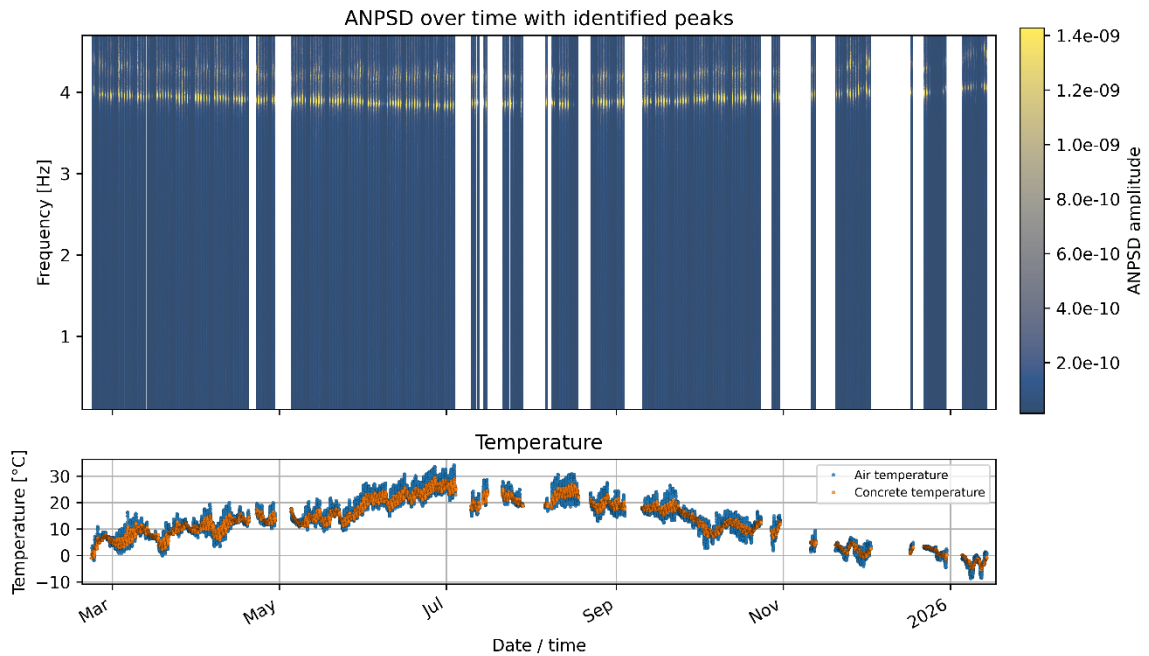


Figure 45. ANPSD graph for acceleration signals in Z direction and temperature variation graph

Figure 46 shows the tracked frequencies B-Y-1, B-Y-2, B-Z-2, B-Z-3 on top of the ANPSD graph for the signals in X and Y direction. Four different colours indicate the variation of natural frequencies B-Y-1, B-Y-2, B-Z-2 and B-Z-3 through time. Below the ANPSD graph, the GVW data for individual vehicles over 3.5t, captured with B-WIM system is shown. At the bottom, the variation of the air and concrete temperature is shown. Note that, due to establishment of the B-WIM system, the observed period is slightly shorter: from 26. 2. 2025 to 14. 1. 2026.

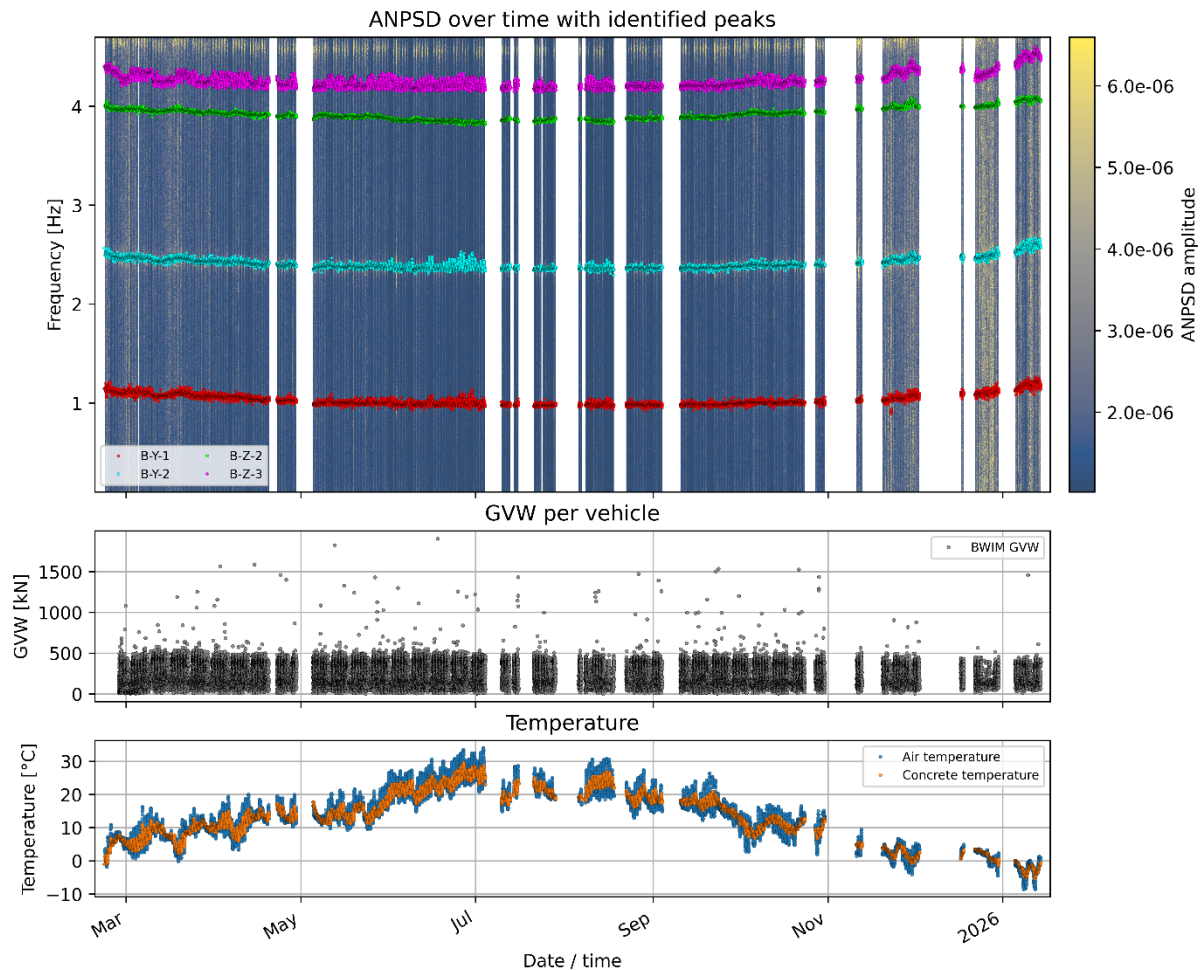


Figure 46. ANPSD graph for acceleration signals in X and Y direction with tracked frequencies B-Y-1, B-Y-2, B-Z-2, B-Z-3, B-WIM weighted gross vehicle weights (GVWs) for individual vehicles over 3.5 t and temperature variation graph

Tracked frequencies show a consistent temperature-dependent behaviour, as reported for example by [11]; lower temperatures cause increase of the elastic modulus of concrete and consequently increase in natural frequencies. Similarly, higher temperatures cause decrease of the elastic modulus and consequently lower natural frequencies. B-WIM data shows expected trend as the maximum GVW load allowance in Slovenia is 40 t without a special permit, 60 t with a special permit and more than 60 t under special conditions such as escort etc. Number of vehicles with GVW higher than 60 t is a consequence of a bridge's location. Close to the bridge a factory produces heavy components and therefore exceptional transport is present on the bridge on a daily to weekly basis.

5.1.2. Leakage sensor

The leakage monitoring system at the Tomačev Bridge pilot site was operated continuously over the period from 9 May to 20 August 2025, corresponding to 104 days of observation. During this period, seven sensing channels were evaluated in order to detect moisture penetration and leakage activity at the monitored location. The recorded data indicate that the system generally captured distinct wet and dry states and made it possible to compare the behavior of the individual sensing channels over time.



A short-term operational pattern observed between 19 July and 20 August 2025 shows that on 19 July only Sensors 4 and 5 indicated leakage, corresponding to the pattern 0,0,0,1,1,0,0. From 22 July onward, the pattern changed to 0,1,1,1,1,0,0, meaning that Sensors 2, 3, 4, and 5 indicated leakage, while Sensors 1, 6, and 7 remained inactive in this period. This shift suggests that the leakage indication expanded from a localized response in Sensors 4 and 5 to a broader cluster involving Sensors 2 and 3 after a delay of approximately three days.

Over the full monitoring period, the leakage classification frequency differed noticeably between the channels. Channel 3 showed 16,988 leaking events and a leakage share of 16.42%, while Channel 4 showed 15,717 leaking events and 14.57%, making these the most responsive channels in the monitored setup. Channel 5 also showed elevated activity with 14,244 leaking events and a leakage share of 13.78%, and Channel 6 showed a nearly identical level with 14,088 leaking events and 13.65%. Channel 1 recorded 10,179 leaking events corresponding to 9.85%, while Channel 2 recorded 7,565 leaking events corresponding to 7.32%. Channel 7 showed the lowest activity, with 5,052 leaking events and a leakage share of 4.89%, and therefore served as the most stable reference channel during the observation period.

The raw signal statistics also show clear differences in baseline response and variability among the sensors. Sensor 1 had a mean raw value of 56,847.33 with a standard deviation of 21,345.67, while Sensor 6 had a mean of 68,234.12 with a standard deviation of 18,923.44. Sensor 7 showed the highest average raw value at 90,512.88 and the lowest variability among the high-baseline sensors, with a standard deviation of 15,234.22. In contrast, Sensors 2, 3, 4, and 5 had substantially lower mean values, ranging from 56,234.50 to 67,891.34, and relatively high standard deviations between 12,456.78 and 19,876.54, which is consistent with stronger fluctuation and more frequent switching behavior in the channels most associated with leakage indications.

The operational data further indicate that the system was able to distinguish between channels with consistently low activity and channels with repeated wet-state responses. In particular, Channels 3 and 4 can be considered the principal monitoring channels within this pilot setup because they combined the highest number of leakage events with sustained activity over the total monitoring window. Channels 1, 2, 5, and 6 provided supporting information on the spatial distribution and temporal progression of moisture influence, whereas Channel 7 functioned as a low-activity reference with clearly reduced leakage indication frequency.

An abnormal sensor behavior was observed in early August, when several sensors indicated continuous leakage for an extended period. Based on site observation and interpretation of the measurement behavior, this continuous indication was likely not caused solely by actual water ingress but by water condensation trapped beneath the adhesive tape used in the sensor installation. This explanation is consistent with the sudden persistence of leakage signals across multiple adjacent sensors and should therefore be considered when interpreting the early August data. The abnormal behavior does not invalidate the monitoring campaign as a whole, but it indicates that the early August interval should be treated with caution because environmental and installation-related effects likely influenced the measured response.

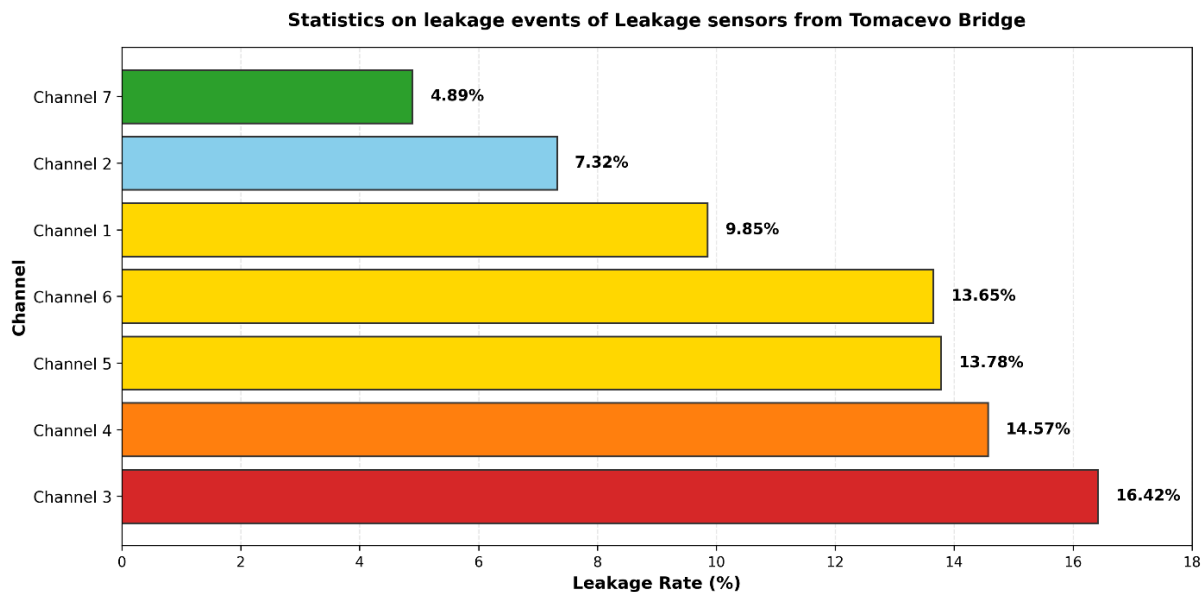


Figure 47. Statistics on leakage events of Leakage sensors from Tomačevu Bridge, where Channel indicates the Sensors Number

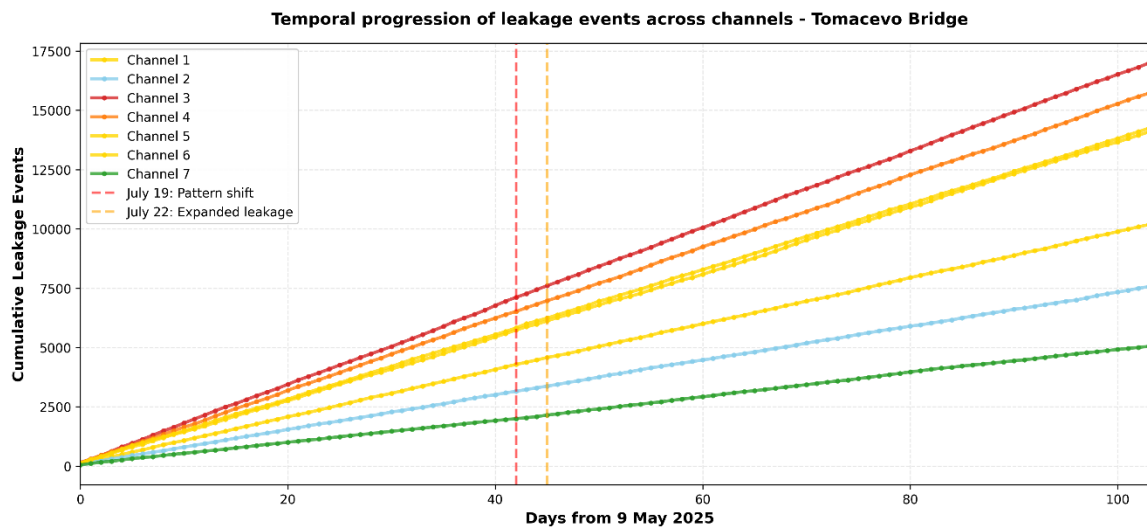


Figure 48. Sensor's leakage rate depending on the sensor position and temporal progression



Channel	Leaking Events	Leakage Share	Status
Channel 1	10,179	9.85%	Supporting reference
Channel 2	7,565	7.32%	Low activity reference
Channel 3	16,988	16.42%	PRIMARY MONITOR
Channel 4	15,717	14.57%	Primary monitoring
Channel 5	14,244	13.78%	Supporting information
Channel 6	14,088	13.65%	Supporting information
Channel 7	5,052	4.89%	STABLE REFERENCE

Table 2. Summary of leakage classification frequency across all channels during 104-day monitoring period

Sensor	Mean Raw Value	Std. Deviation
Sensor 1	56,847.33	21,345.67
Sensor 2	57,234.50	18,976.54
Sensor 3	58,901.34	19,876.54
Sensor 4	59,123.67	18,234.22
Sensor 5	60,456.78	19,234.56
Sensor 6	68,234.12	18,923.44
Sensor 7	90,512.88	15,234.22

Table 3. Raw signal statistics showing baseline response and variability among sensors

The pilot application at the Tomačev Bridge confirmed the potential of the leakage-monitoring approach to track moisture-related behaviour over time and to reveal spatial differences in sensor responses within the observed area. The results also emphasized that the reliability of long-term measurements depends strongly on installation quality, particularly regarding sealing and protection against condensation effects. In this sense, the pilot not only validated the monitoring concept under real-world conditions but also provided important lessons for the further refinement of sensor installation procedures and overall system durability in future deployments.

5.1.3. Traffic data

The B-WIM system was installed on the road section G2-104, which connects the following settlements: Ljubljana (Črnuče)–Litija–Hrastnik–Zidani Most. The designation G2 is used to mark state roads intended for traffic connection between regional centers and for linking traffic to public roads of the same or higher category in the country [12].

The instrumented structure carries two lanes of traffic towards Ljubljana: on average, approximately 1.000 HGVs per day were detected on the slow lane and approximately 150 HGVs per day on the passing lane.



The heaviest vehicles passing over the structure are exceptional transports, which can weigh over 100 t. Figure 49 shows such transport weighing 117 t, which carries an electrical generator. On average, five such vehicles are detected by the B-WIM system each month.



Figure 49. An exceptional transport (GVW: 117 t) which passed over the bridge on 18 March

When it comes to the number of axles, the most common type of HGV in regular traffic is a 2-axle rigid vehicle, followed by 5-axle articulated vehicle, 4-axle rigid vehicle and 3-axle rigid vehicle (Table 4). Vehicles with 6 or more axles are exceptional transport vehicles and the present a small fraction of the whole traffic composition.

Number of axles	Number of HGVs (March, 2026)
2	40938
3	10116
4	18540
5	25765

Table 4. Composition of heavy traffic based on the number of axles

The vehicles weighing between 10 t and 20 t present the largest share of heavy traffic, which corresponds to 2-axle HGVs, whose maximum allowed GVW in Slovenia is 18 t (Table 5). The maximum allowed GVW in normal traffic (ie. Vehicles without exceptional transport permits) is 40 t. Vehicles over 40 t present 2,8 % of all of the vehicles, with vehicles over 50 t presenting just a fraction of all of the vehicles (0,1%).



GVW	Percentage of HGVs
<10 t	29,6%
10 t - 20 t	42,6%
20 t - 40 t	14,1%
30 t - 40 t	10,8%
40 t - 50 t	2,8%
> 50 t	0,1%

Table 5. An overview of GVW classes

Among the rigid HGVs, there is a large number of HGVs carrying construction material due to the fact that there are construction companies and cement factories located in the area north of Ljubljana. These types of vehicles can be problematic from the point of view of traffic loads, as the vehicles themselves can structurally carry a much heavier load than what is legally allowed. For example, Figure 50 shows a 3-axle rigid vehicle that can legally have a GVW of 26 t. Its GVW is 28,6 t, which represents a 10 percent overload, and the axle load of the tandem axle is 22,8 t, which is 14 percent over the legal limit.



Figure 50. A typical 3-axle vehicle carrying construction material



5.2 IDA-KI openLAB Bridge

5.2.1. Long-term monitoring

This chapter shows the results of the acceleration-based long-term monitoring in the period from 19. 4. 2025 to 5. 5. 2025. The average normalized power spectral density (ANPSD) method, introduced by [13] was used to identify the natural frequencies and mode shapes. All acceleration sensors (A01-A12) were used in calculation of the ANPSD, however only accelerations in vertical (Z) direction were considered.

Additionally, the frequency tracking algorithm was developed to tracks the natural frequencies in the considered time period, similarly as for the Tomačevó bridge. Figure 51 shows the ANPSD graph for the frequency range from 0 to 25 Hz. Horizontal yellow trajectories indicate the variation of natural frequencies through time, while yellow vertical lines indicate periods of activities performed on the bridge or in the surrounding are near the bridge (industrial facilities) that excited the vibrations of the bridge.

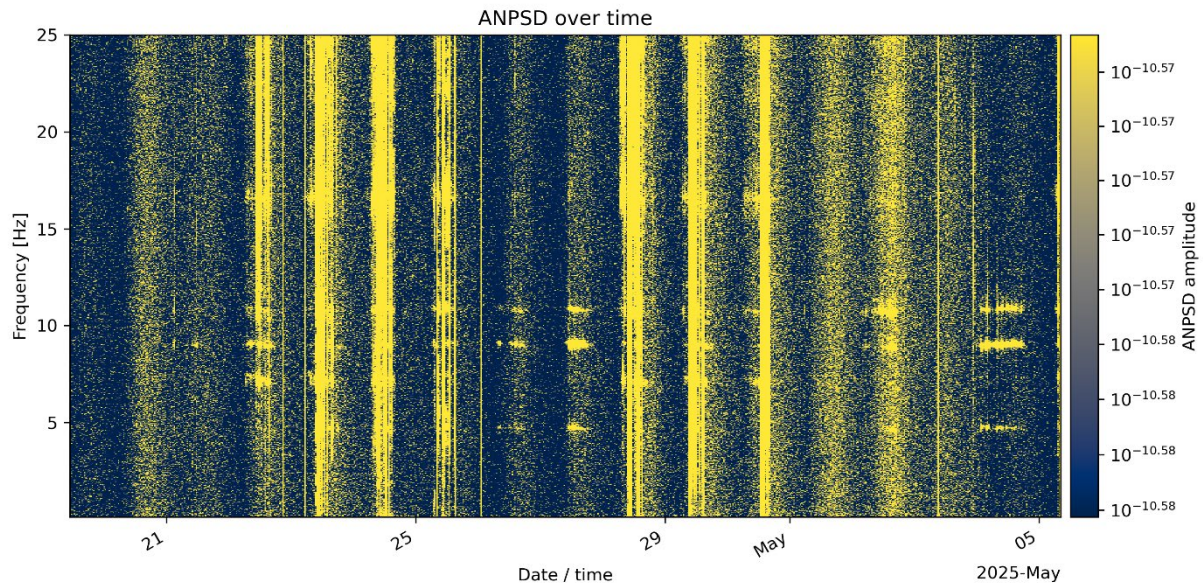


Figure 51. Average normalized power spectral density (ANPSD) graph for acceleration signals in Z direction for the time period 19. 4. 2025 – 5. 5. 2025

Figure 52, Figure 53 and Figure 54 show five natural modes, which were tracked in the considered time period: B-Z-1, B-Z-2, B-Z-3, T-1 and T-2. The description of the mode shapes is as follows:

- B-Z-1 Asymmetric bending over both spans
- B-Z-2 Symmetric bending over both spans - largest amplitude in span 2
- B-Z-3 Symmetric bending over both spans - largest amplitude in span 1
- T-1 Torsional mode – largest amplitude in span 2
- T-1 Torsional mode – largest amplitude in span 2

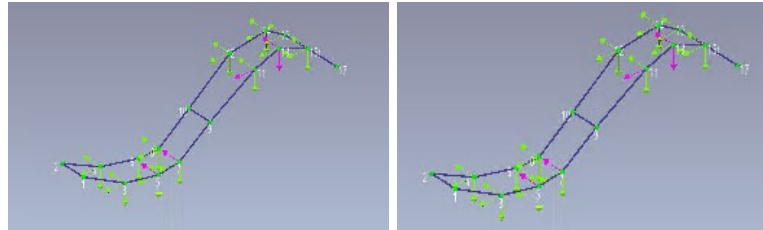


Figure 52. B-Z-1 (left) and B-Z-2 (right) mode shapes

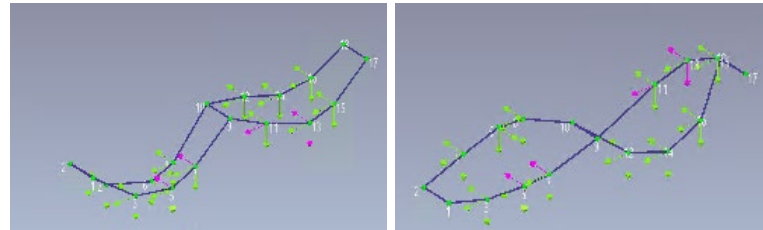


Figure 53. B-Z-3 (left) and T-1 (right) mode shapes

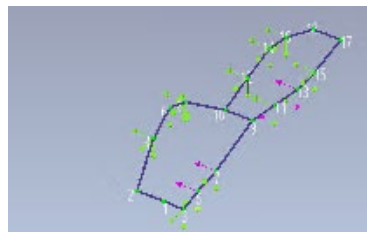


Figure 54. T-2 mode shape

Figure 55 shows the tracked frequencies B-Z-1, B-Z-2, B-Z-3, T-1 and T-2 on top of the ANPSD graph for the signals in Z direction. Five different colours indicate the variation of natural frequencies through time. Below the ANPSD graph, the variation of the concrete temperature is shown.

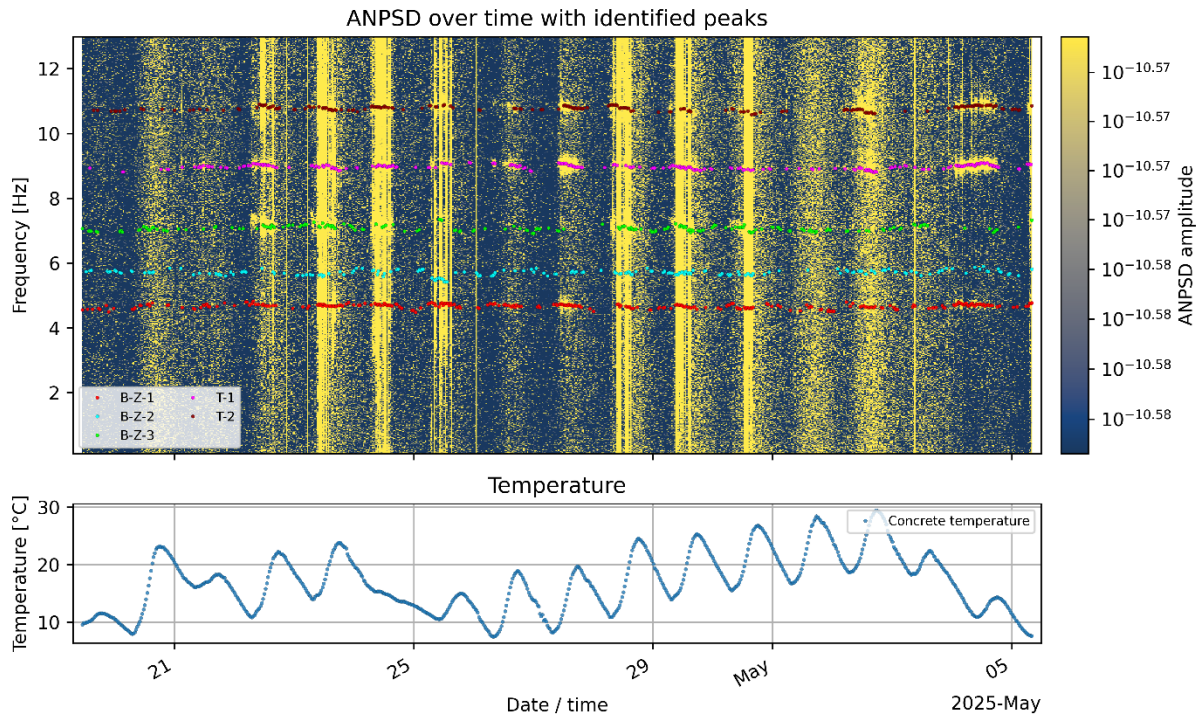


Figure 55. ANPSD graph for acceleration signals in Z direction with tracked frequencies B-Z-1, B-Z-2, B-Z-3, T-1, T-2 and concrete temperature variation graph

Tracked frequencies show a consistent temperature-dependent behaviour, as reported for example by [11]; lower temperatures cause increase of the elastic modulus of concrete and consequently increase in natural frequencies. Similarly, higher temperatures cause decrease of the elastic modulus and consequently lower natural frequencies.

5.2.2. Leakage sensor

The leakage monitoring system at the openLAB bridge pilot site was operated continuously over the period from 5 May to 11 September 2025, corresponding to 129 days of observation as shown in Figure 56. During this period, seven sensing channels were evaluated in order to detect moisture penetration and leakage activity at the monitored location. The recorded data indicate that the system generally captured distinct wet and dry states and made it possible to compare the behavior of the individual sensing channels over time as shown in the Figure 57.



Figure 56. Photo of leakage foil installation on openLAB bridge.

Channel	Leakage_Events	No_Leakage	Leakage_%	Status
Channel 1	10042	87710	10.27%	GOOD
Channel 2	7430	90322	7.60%	GOOD
Channel 3	14938	82814	15.28%	GOOD
Channel 4	14245	83507	14.57%	GOOD
Channel 5	13857	83895	14.18%	GOOD
Channel 6	13864	83888	14.18%	GOOD
Channel 7	4524	93228	4.63%	GOOD

Figure 57. Statistics on leakage events of Leakage sensors from IDA Ki bridge, where Channel indicates the Sensors Number

A short-term operational pattern observed between 29 July and 29 August 2025 shows that on 29 July only Sensors 4 and 5 indicated leakage, corresponding to the pattern 0,0,0,1,1,0,0. From 1 August onward, the pattern changed to 0,1,1,1,1,0,0, meaning that Sensors 2, 3, 4, and 5 indicated leakage, while Sensors 1, 6, and 7 remained inactive in



this period. This shift suggests that the leakage indication expanded from a localized response in Sensors 4 and 5 to a broader cluster involving Sensors 2 and 3 after a delay of approximately three days.

Over the full monitoring period, the leakage classification frequency differed noticeably between the channels. Channel 3 showed 14,937 leaking events and a leakage share of 15.28%, while Channel 4 showed 14,244 leaking events and 14.57%, making these the most responsive channels in the monitored setup. Channel 5 also showed elevated activity with 13,856 leaking events and a leakage share of 14.17%, and Channel 6 showed a nearly identical level with 13,863 leaking events and 14.18%. Channel 1 recorded 10,041 leaking events corresponding to 10.27%, while Channel 2 recorded 7,429 leaking events corresponding to 7.60%. Channel 7 showed the lowest activity, with 4,524 leaking events and a leakage share of 4.63%, and therefore served as the most stable reference channel during the observation period as shown in Figure 58.

Analysis_Type	Finding
Overall System Status	System operational with intermittent leakage detection
Leakage-Free Periods	84.41% of monitoring time - normal dry conditions
Minor Leakage Events	1.42% of time - isolated single/dual channel events
Moderate Leakage Events	12.28% of time - multi-channel simultaneous leakage
Severe Leakage Events	1.05% of time - all channels affected (widespread issue)
Channel 1 Status	10.27% leakage rate - moderate sensitivity
Channel 2 Status	7.60% leakage rate - low false positive rate
Channel 3 Status (CRITICAL)	15.28% leakage rate - highest detection rate (primary monitor)
Channel 4 Status	14.57% leakage rate - high detection rate
Channel 5 Status	14.18% leakage rate - high detection rate
Channel 6 Status	14.18% leakage rate - high detection rate
Channel 7 Status (RELIABLE)	4.63% leakage rate - minimal false positives
Recommendation	Investigate causes of 15.59% leakage event frequency; cross-validate with physical inspection

Figure 58. Cross selection analysis of detection rate



The raw signal statistics also show clear differences in baseline response and variability among the sensors. Sensor 1 had a mean raw value of 104,307.50 with a standard deviation of 34,671.11, while Sensor 6 had a mean of 105,080.92 with a standard deviation of 30,528.22. Sensor 7 showed the highest average raw value at 116,517.49 and the lowest variability among the high-baseline sensors, with a standard deviation of 23,282.15. In contrast, Sensors 2, 3, 4, and 5 had substantially lower mean values, ranging from 48,831.61 to 50,303.88, and relatively high standard deviations between 47,938.83 and 56,302.07, which is consistent with stronger fluctuation and more frequent switching behavior in the channels most associated with leakage indications.

The operational data further indicate that the system was able to distinguish between channels with consistently low activity and channels with repeated wet-state responses. In particular, Channels 3 and 4 can be considered the principal monitoring channels within this pilot setup because they combined the highest number of leakage events with sustained activity over the total monitoring window. Channels 1, 2, 5, and 6 provided supporting information on the spatial distribution and temporal progression of moisture influence, whereas Channel 7 functioned as a low-activity reference with clearly reduced leakage indication frequency as shown in Figure 60.

Category	Value	Assessment
System Status	INTERMITTENT LEAKAGE	Pattern indicates environmental triggers
Overall Leakage	11.53% (78,900 events)	Below catastrophic threshold
Normal Operation	88.47% (605,364 events)	Good baseline dry periods
Event Frequency	0.96 events/min	Environmental cycling likely
Most Critical Channel	Channel 3 (15.28%)	Primary detection sensor
Most Reliable Channel	Channel 7 (4.63%)	Validated control reference
Peak Severity	All channels (1.05%)	Severe moisture event detected

Figure 59. Sensor's results comparison, indicating the primary detection

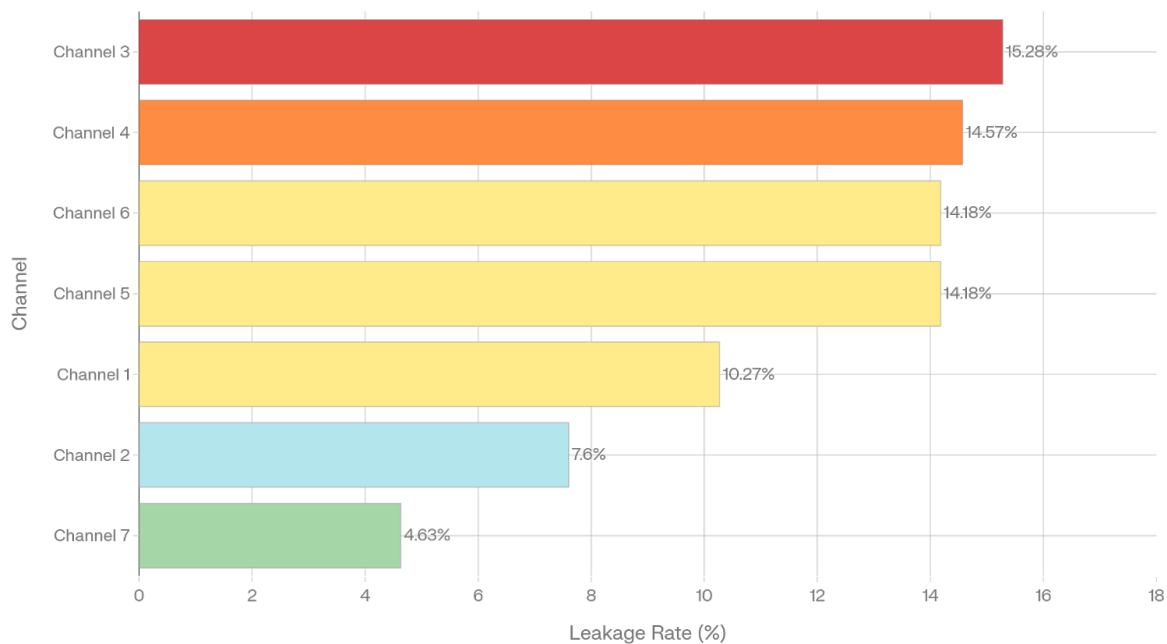


Figure 60. Sensor's leakage rate depending on the sensor position

An abnormal sensor behavior was observed in August, when several sensors indicated continuous leakage for an extended period. Based on site observation and interpretation of the measurement behavior, this continuous indication was likely not caused solely by actual water ingress but by water condensation trapped beneath the adhesive tape used in the sensor installation. This explanation is consistent with the sudden persistence of leakage signals across multiple adjacent sensors and should therefore be considered when interpreting the August data. The abnormal behavior does not invalidate the monitoring campaign as a whole, but it indicates that the August interval should be treated with caution because environmental and installation-related effects likely influenced the measured response.

Overall, the pilot installation at the openLAB bridge demonstrated that the leakage sensing concept can provide continuous channel-based information on wetting behavior, identify differences between more active and less active sensor positions, and detect temporal changes in the moisture pattern across the monitored area. At the same time, the observed August anomaly shows that field installation details, especially sealing of contacts and protection against condensation, are critical for reliable long-term interpretation of leakage events. The pilot results therefore provide both operational evidence for the usability of the monitoring system and practical guidance for improving sensor mounting and environmental robustness in future bridge deployments.



5.2.3. Traffic data

openLAB bridge is a laboratory structure, so no traffic passes over it. The exception is a railway bogie used in structural test, shown in Figure 61.



Figure 61. Railway bogie at openLAB bridge

The bridge WIM system was not designed to weigh railway vehicles, but it performed well at openLAB. The GVW of the bogie and its axles were detected consistently (Figure 62). The measurement remained consistent after the structural tests with the hydraulic press.

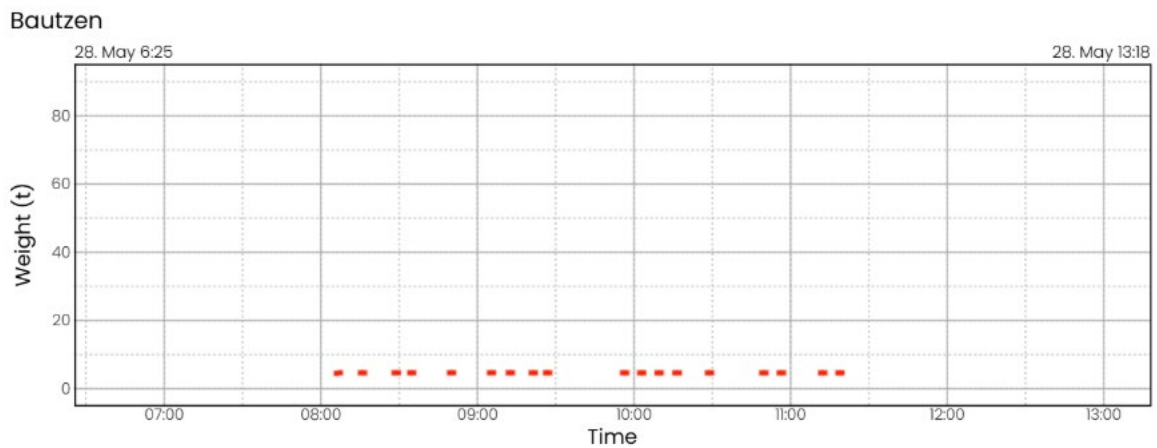


Figure 62. GVW measurements of a railway bogie at openLAB

5.3 Sant'Ambrogio Bridge

5.3.1. Existing monitoring system

The data collected by the pre-existing monitoring system was analysed over the time window in which the research monitoring system was operational, namely from early November 2025 to the end of March 2026.



The first graph illustrates the trend of the air temperature measured during the period of interest. Temperature data were recorded at 15-minute intervals. The curve shown has been averaged daily to reduce noise associated with hourly fluctuations and to better highlight seasonal trends. Throughout the monitoring period, air temperature ranged between -1°C and 15°C .

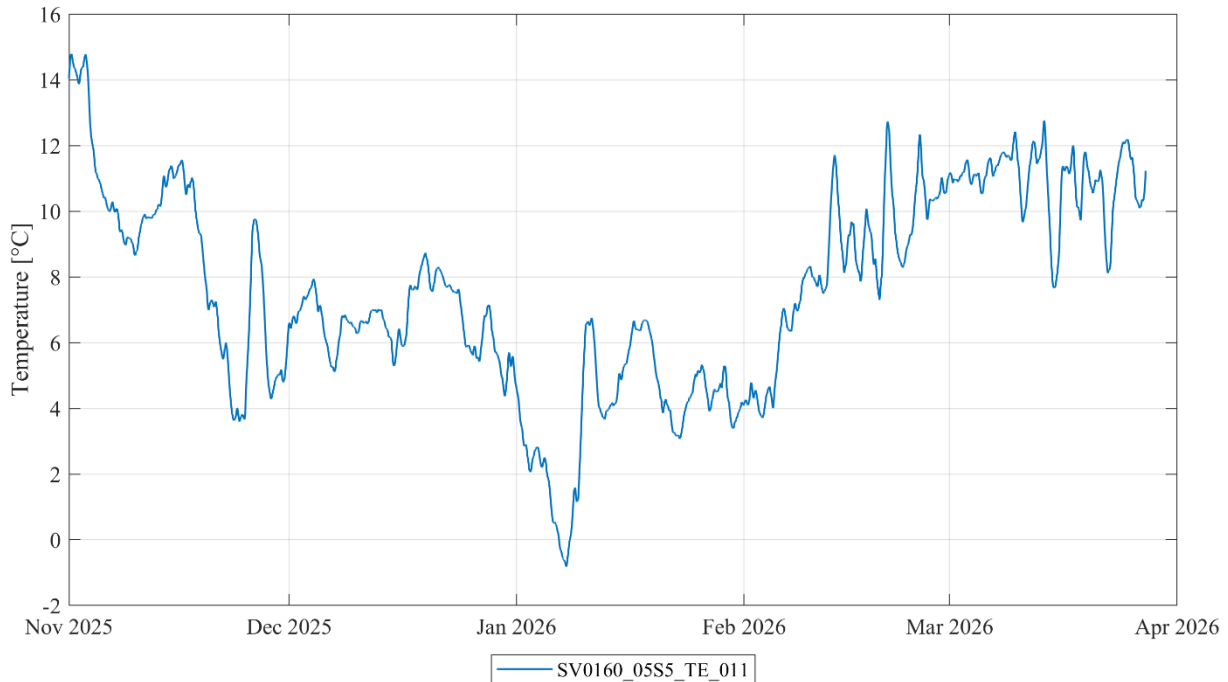


Figure 63. Air temperature trend

The second graph presents the longitudinal (L) and transverse (T) relative displacements between the deck and the substructure, measured at the bearings on the monitored abutment and pier. Displacements were recorded at 15-minute intervals. The data were first normalised with respect to the mean value of the first day (zeroed) and subsequently averaged daily to reduce noise from short-term oscillations and to better observe seasonal behaviour. Longitudinal and transverse displacements at the abutment are essentially null, as expected for a fixed bearing. At the pier, longitudinal displacements exhibit variations of approximately 4.5 mm correlated with the temperature variations, whereas transverse displacements remain negligible.

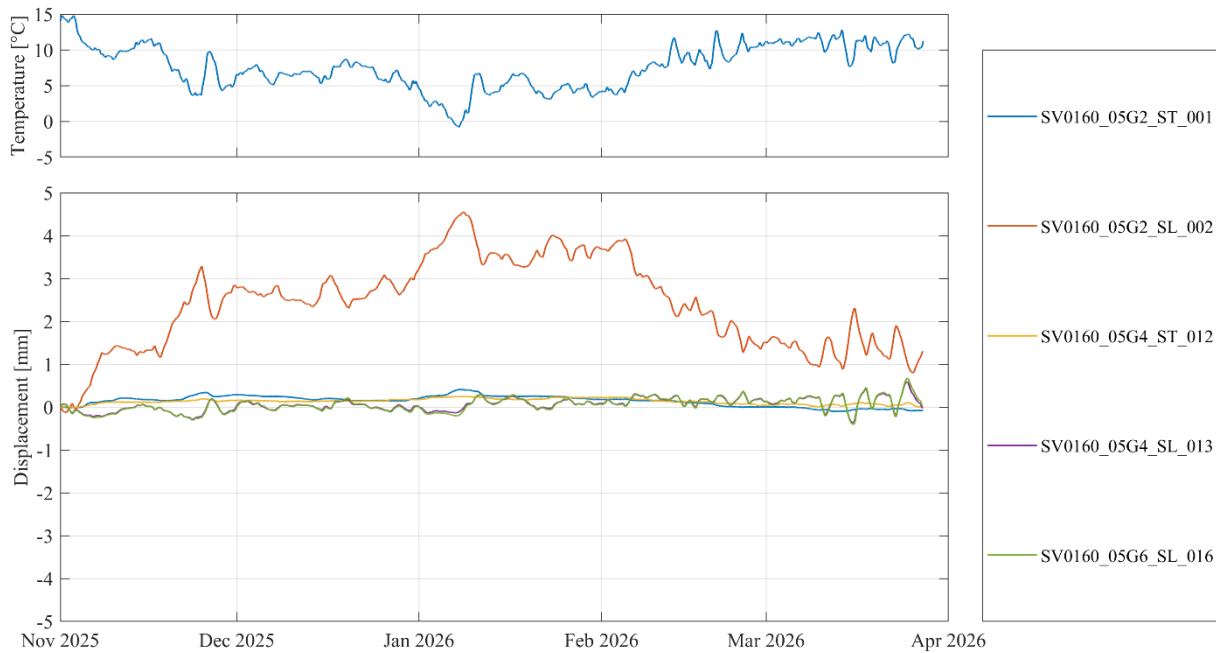


Figure 64. Trend of relative transverse (T) and longitudinal (L) displacements

The third graph shows the rotations measured in the longitudinal (X) and transverse (Y) planes at the abutment, pier, and deck. Rotations were acquired at 15-minute intervals. As for displacements, the data were normalised with respect to the mean value of the first day (zeroed) and then averaged daily to reduce noise and highlight seasonal patterns. The rotations exhibit a clear correlation with temperature variations and remain within the range of -0.03° to $+0.03^\circ$.

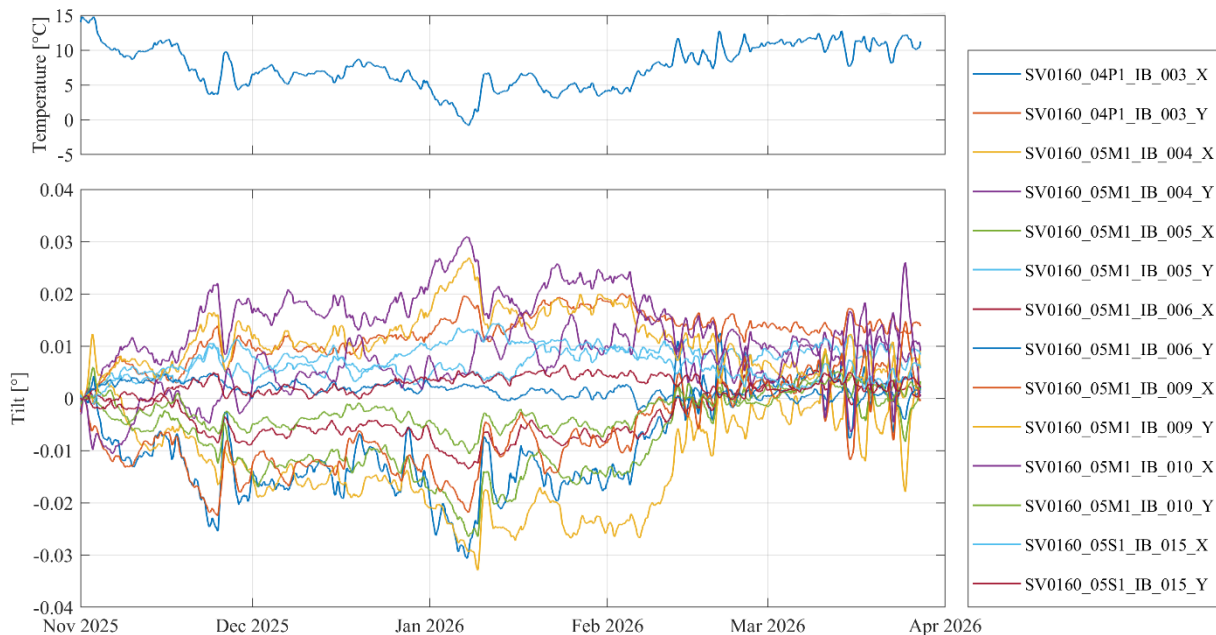


Figure 65. Trend of tilt in the transverse (Y) and longitudinal (X) vertical planes

Regarding the accelerations acquired at 200 Hz over four daily 30-minute windows (2:00, 8:00, 14:00, and 20:00), the vertical accelerations measured on the deck for a selection



of representative sample windows within the observation period are provided in the Annex A.

Although dynamic data acquisition was carried out four times per day, only one frequency identification per week is performed and displayed in the figure.

The annex also includes the FFTs computed from the acceleration data, which illustrate the frequency content. Analysis of the FFTs enabled the identification of the vibration frequencies associated with the first vertical mode shapes of the deck. The table and figure below report the trend of the mean air temperature and the corresponding identified frequencies.

Day	Temperature [°C]	Mode 1 [Hz]	Mode 2 [Hz]	Mode 3 [Hz]
02/11/2025	14,2	4,63	5,50	8,40
09/11/2025	9,0	4,70	5,20	8,13
16/11/2025	11,2	5,00	5,45	8,38
23/11/2025	3,8	4,78	5,23	8,38
02/12/2025	7,0	4,90	5,35	8,30
09/12/2025	6,5	4,65	5,13	8,38
16/12/2025	5,9	4,75	5,18	8,48
23/12/2025	7,5	4,90	-	8,25
02/01/2026	2,4	4,93	5,20	8,53
09/01/2026	2,2	4,73	5,13	8,50
16/01/2026	6,1	4,73	5,28	8,55
23/01/2026	3,4	5,08	5,63	-
02/02/2026	4,5	4,85	5,33	8,28
09/02/2026	8,2	5,03	5,88	8,33
16/02/2026	8,1	4,78	5,60	8,33
23/02/2026	9,2	4,88	5,63	8,18
02/03/2026	11,0	4,65	5,35	8,03
09/03/2026	11,9	4,53	5,08	8,10
16/03/2026	11,3	4,88	5,38	8,20
23/03/2026	10,7	4,63	5,15	8,20

Table 6. Trend of temperature and first three natural frequencies

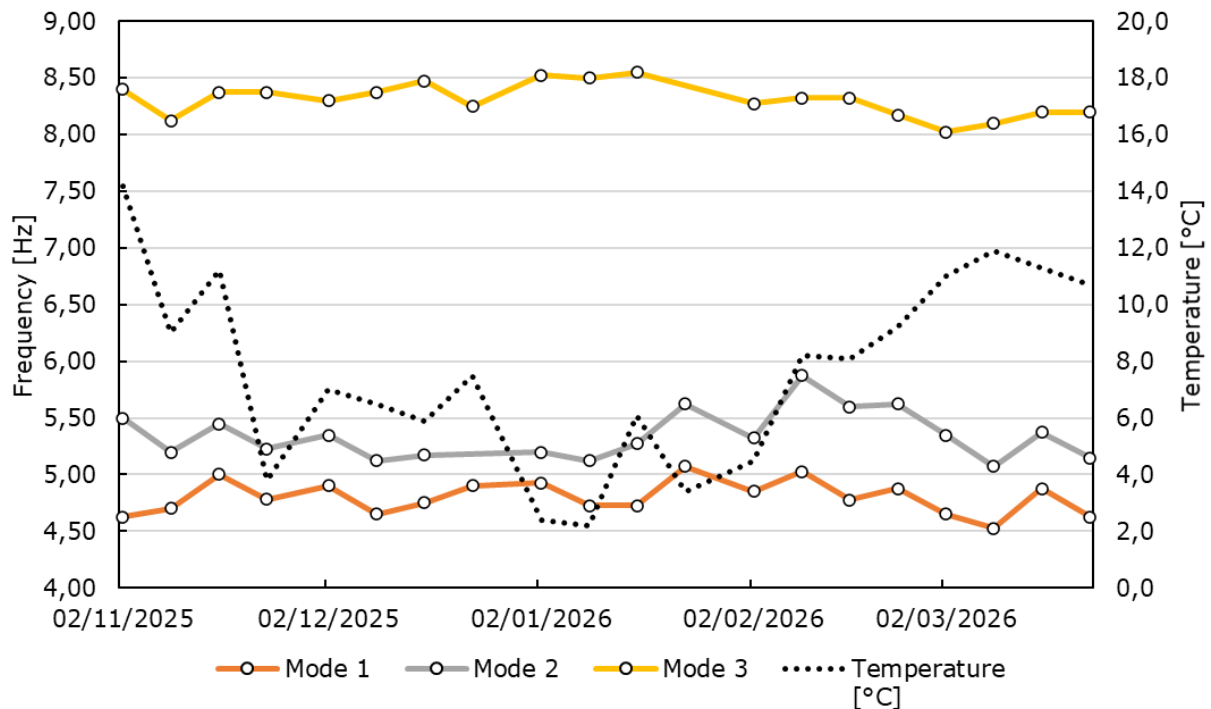


Figure 66. Trend of first three vertical natural frequencies and temperature

5.3.2. Traffic data

The structure of the Sant'Ambrogio viaduct is not suitable for a high-accuracy weigh-in-motion measurement due to it being a continuous deck bridge, which results in multi-span dynamical effects caused by the passing vehicles. Induced dynamics makes it difficult for the system to accurately detect axles, which is a prerequisite for vehicle classification. These effects were less pronounced on lane 1 (slow lane toward Torino), where a limited analysis was done.

5-axle articulated HGVs were the most common type of detected vehicles (Figure). Since the system was positioned on a motorway, we did not detect any significant overloading, as the weight control on motorways is stricter, plus these vehicles are mostly in transit (and thus submitted to multiple controls). We did not detect a significant number of 3- or 4-axle rigid HGVs, which are of interest in bridge analysis due to their short length and relatively high GVW.



Figure 67. A 5-axle HGV at Sant'Ambrogio bridge (GVW approx. 40 t)

Some exceptional transports were detected at night – their GVW ranged between 70 and 100 t (Figure 68).



Figure 68. An exceptional transport at Sant'Ambrogio bridge (GVW approx. 80 t)

From the point of view of traffic safety, a number of HGV with an improper safety distance was detected. The Figure 69 shows an extreme example, where the safety distance was less than half a second.



Figure 69. A 5-axle HGV with a safety distance of less than 0.5 seconds

6. Conclusion

This report presents the results obtained from the implementation and evaluation of bridge monitoring systems within the BIM4CE project across three pilot sites: the Tomačev Bridge (Slovenia), the IDA-KI openLAB research bridge (Germany), and the Sant'Ambrogio Bridge (Italy). The objective of BIM4CE was to develop a cost-effective, scalable, and digitally integrated monitoring solution that combines proven and innovative sensor technologies, data acquisition systems, and digital twin concepts.

The results demonstrate that the proposed monitoring approach is capable of reliably capturing key structural and environmental parameters under real operational conditions. In particular, the deployment of leakage sensors provided continuous and spatially distributed information on water ingress, enabling the identification of both localized and evolving leakage patterns over time. Across multiple pilot sites, the system proved effective in distinguishing between active and inactive zones, as well as in tracking temporal changes in environmental exposure.

At the same time, the pilot tests highlighted important practical considerations for real-world deployment of this novel concept. Observed anomalies, primarily related to condensation effects and installation details, underline the critical role of proper sensor mounting, sealing, and environmental protection in ensuring reliable long-term measurements. These findings provide valuable guidance for improving sensor robustness and data interpretation in future implementations.

The integration of multiple sensor types, including weigh-in-motion systems, accelerometers, and environmental sensors, further demonstrated the potential of combining structural response data with operational and environmental information. This integrated approach supports a more comprehensive understanding of bridge behaviour and lays the foundation for advanced data-driven analysis, including the identification of structural characteristics such as natural frequencies and their correlation with environmental conditions. This knowledge is crucial for detecting anomalies in bridge behaviour that cannot be explained by environmental conditions. Systematic deviations from the established bounds may indicate the onset of damage and thus warrant an extraordinary inspection.



From a system perspective, the use of standardised communication protocols (e.g., EtherCAT and Wi-Fi) and a centralised data management platform proved effective in enabling reliable data transmission, storage, and visualisation.

The ability to integrate monitoring data into a digital twin environment represents a significant step toward more efficient and informed bridge management.

Overall, the pilot implementations confirm that the BIM4CE monitoring concept is a viable solution for supporting bridge maintenance and asset management in Central Europe. The developed system achieves a balance between technical capability and cost-effectiveness, addressing a key barrier to the wider adoption of smart monitoring systems. The results obtained in this report provide a strong basis for future upscaling and deployment on a broader range of infrastructure assets.

Future work should focus on improving sensor installation techniques, enhancing environmental robustness, and developing robust monitoring algorithms for the reliable interpretation of measured data. In particular, the integration of monitoring data with predictive models and artificial intelligence tools offers significant potential for advancing toward fully automated, real-time bridge health assessment systems.

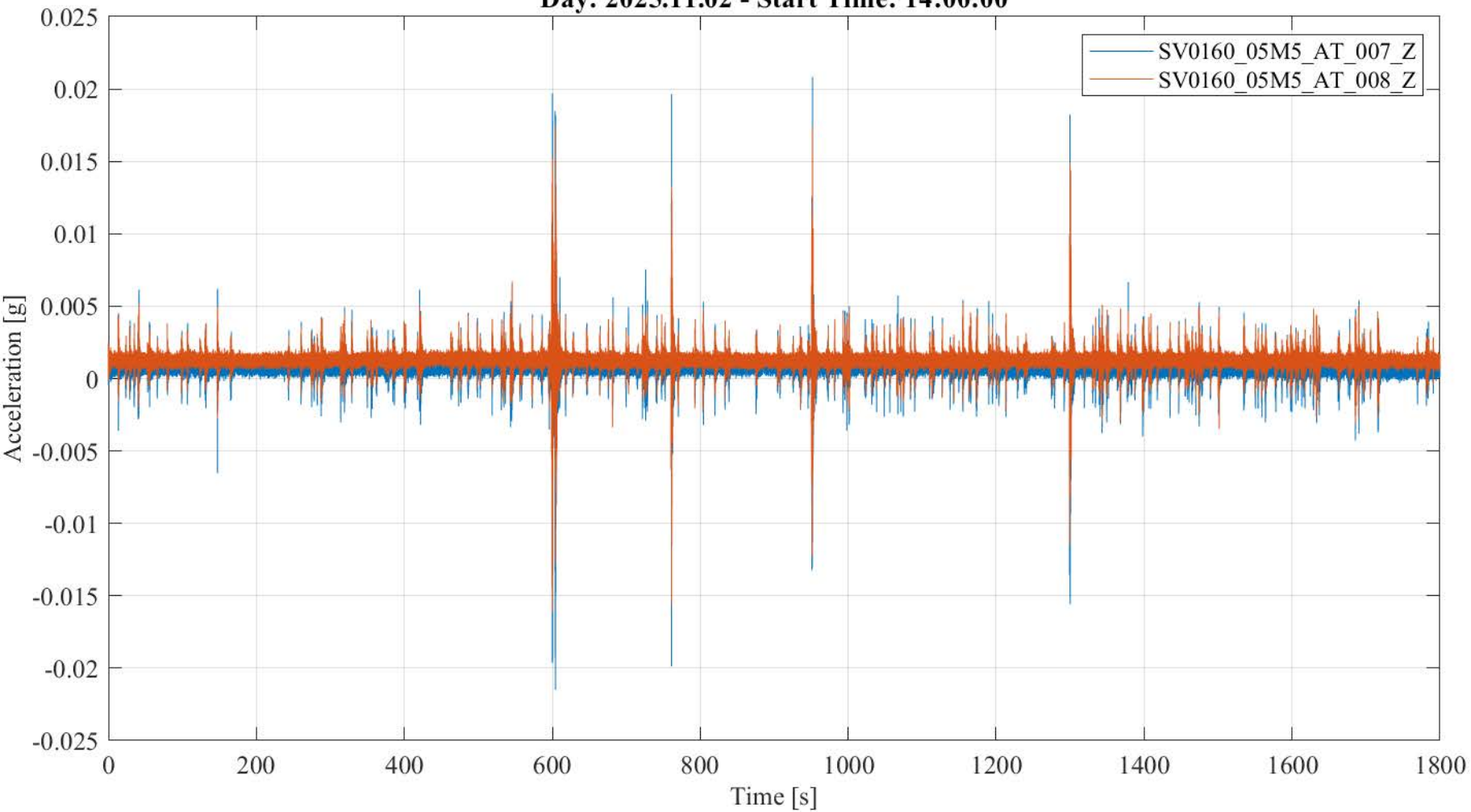


7. References

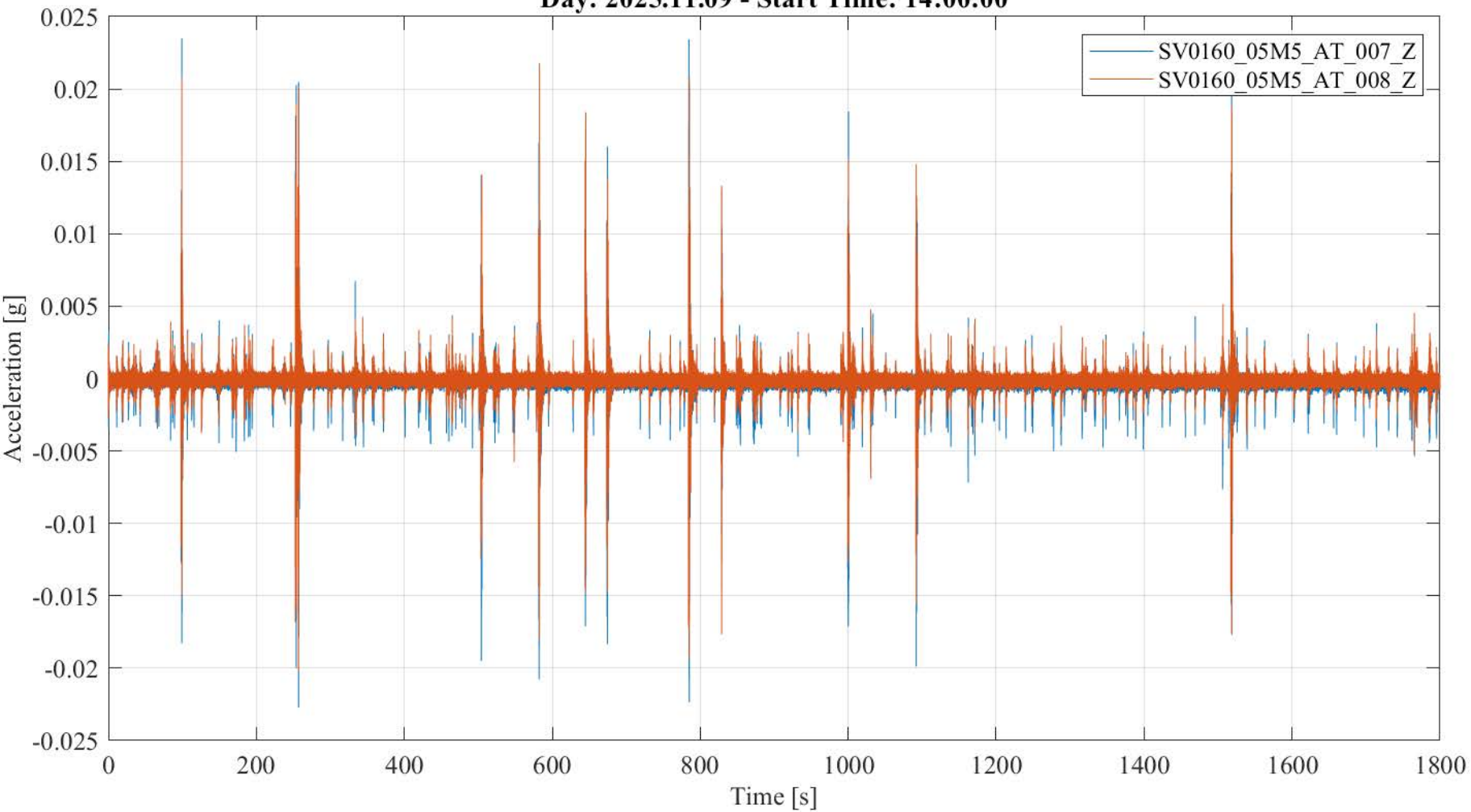
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Annex A

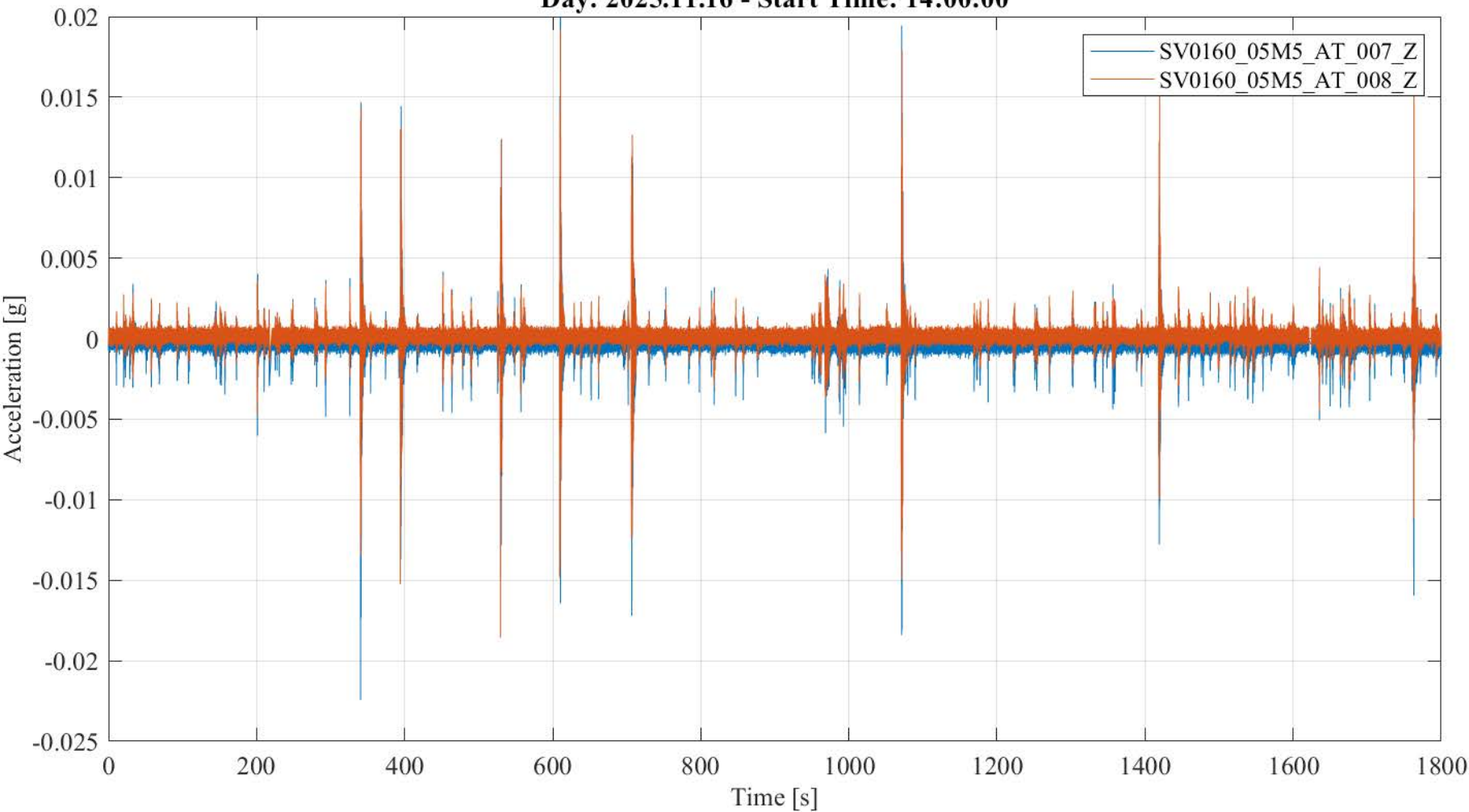
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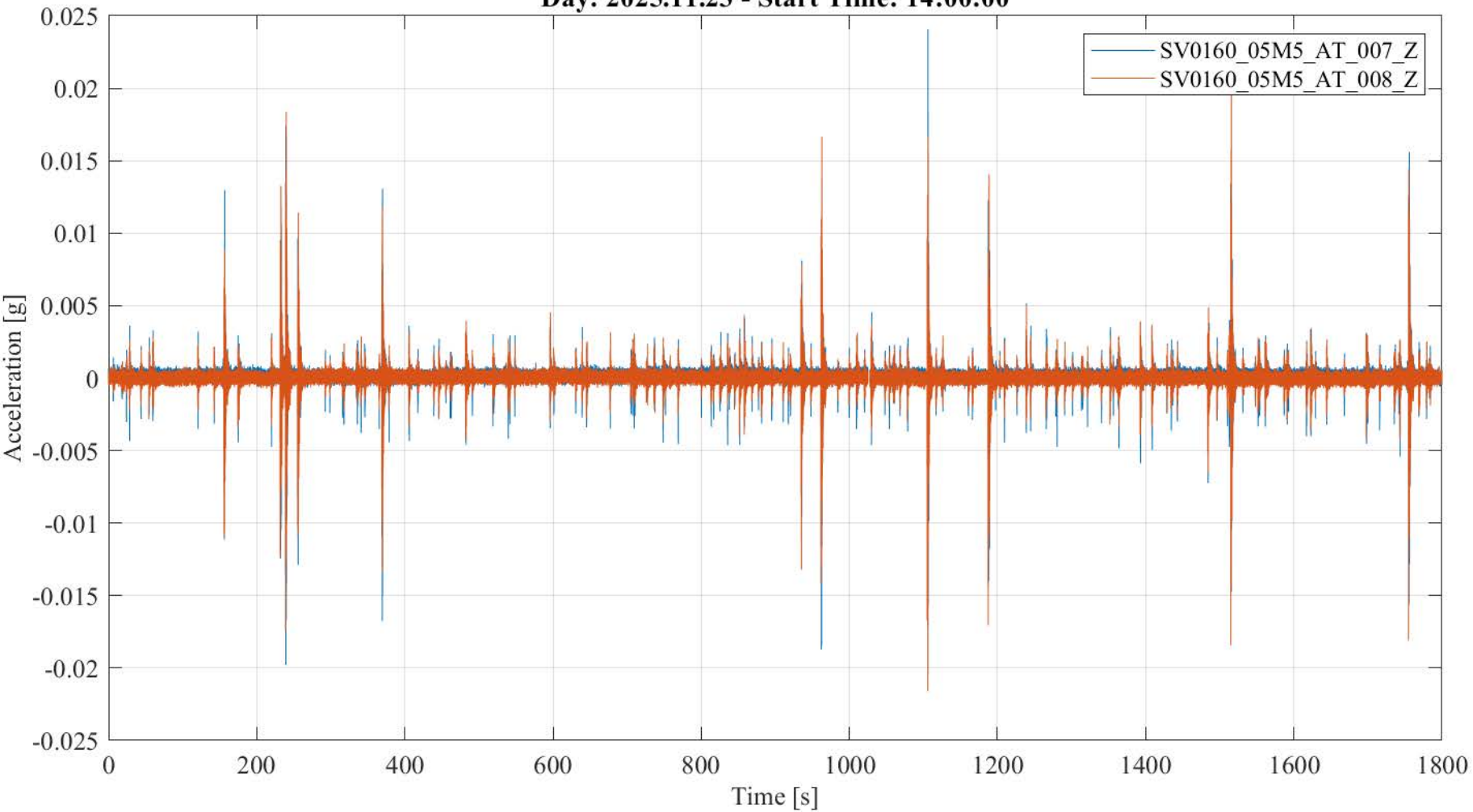
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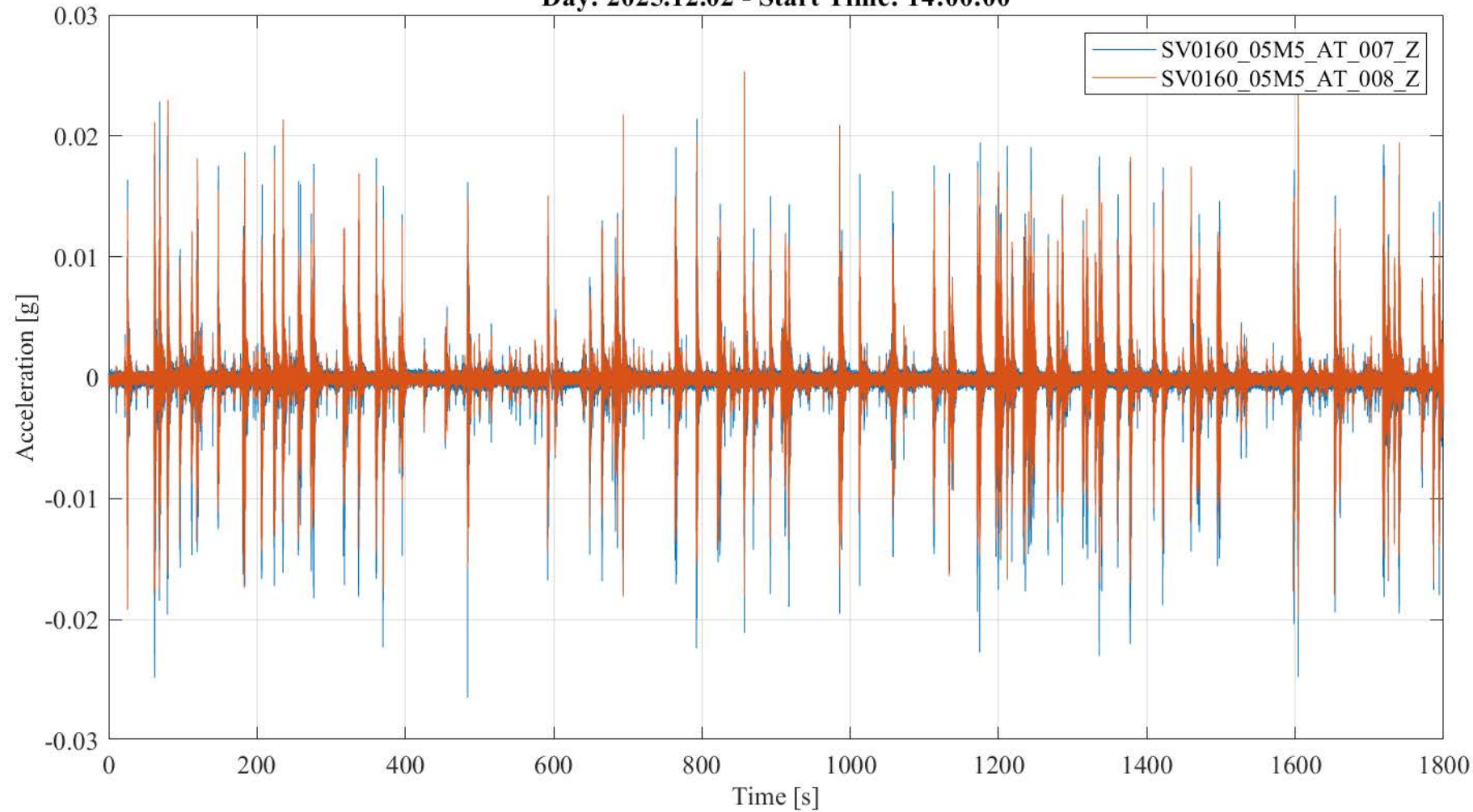
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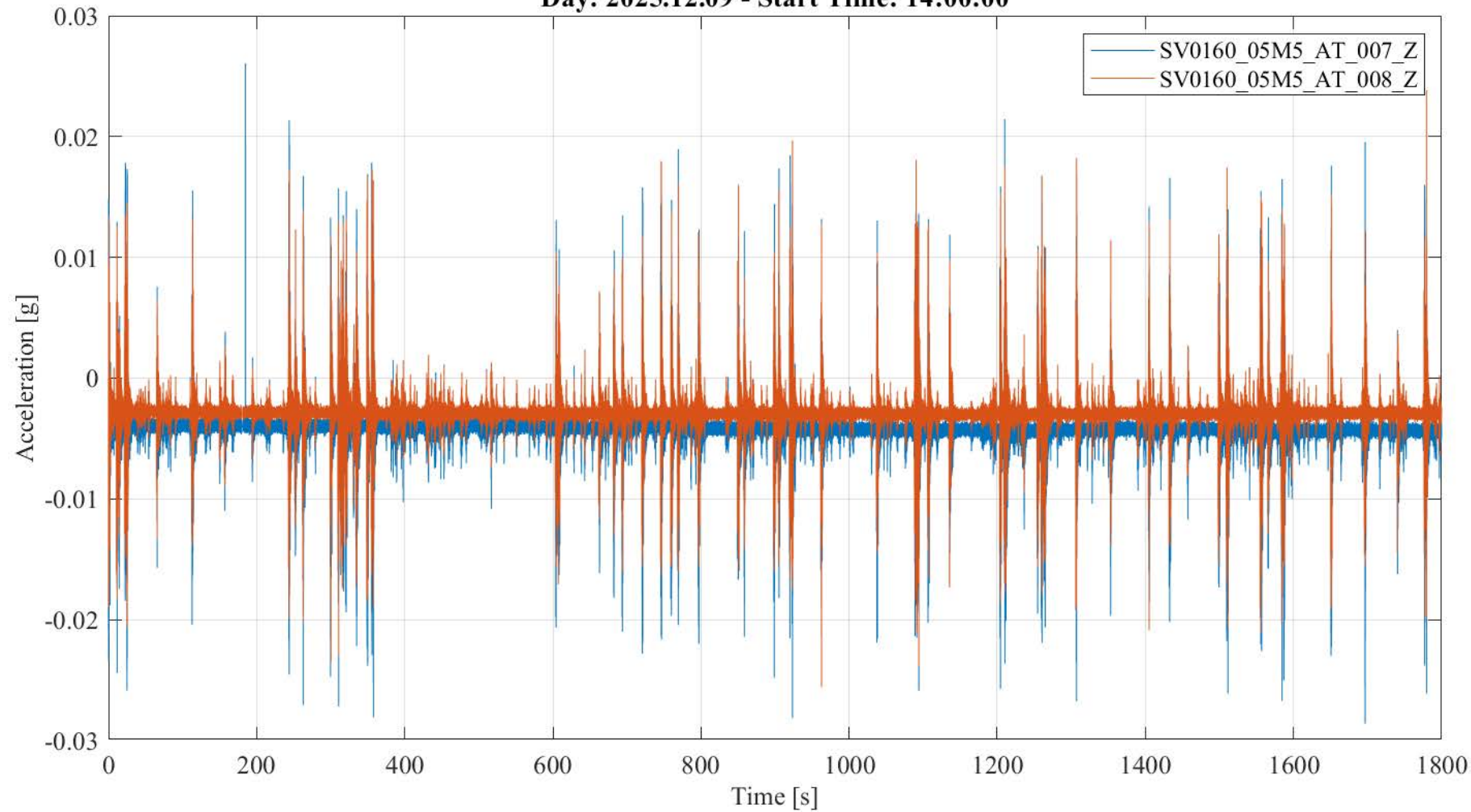
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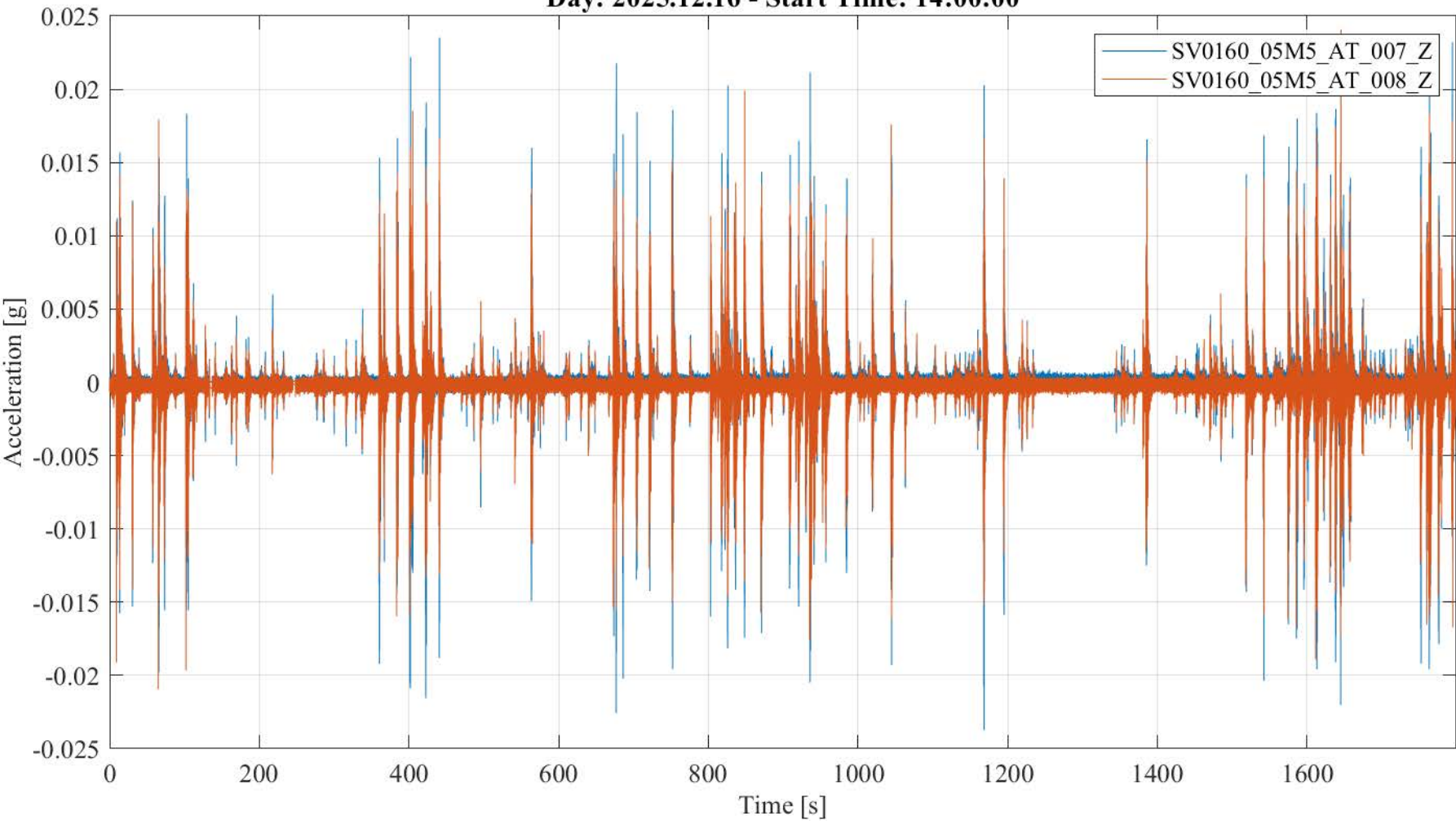
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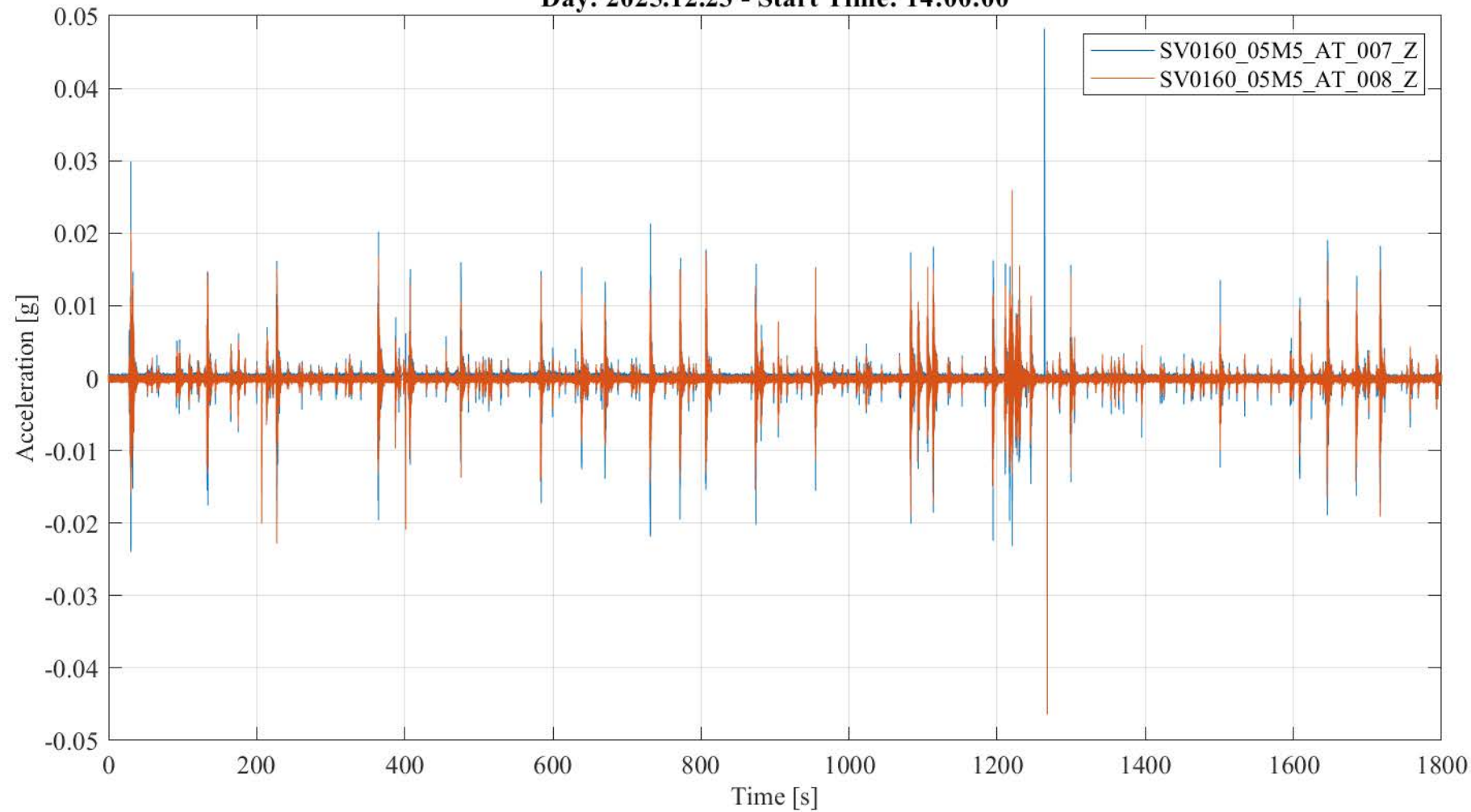
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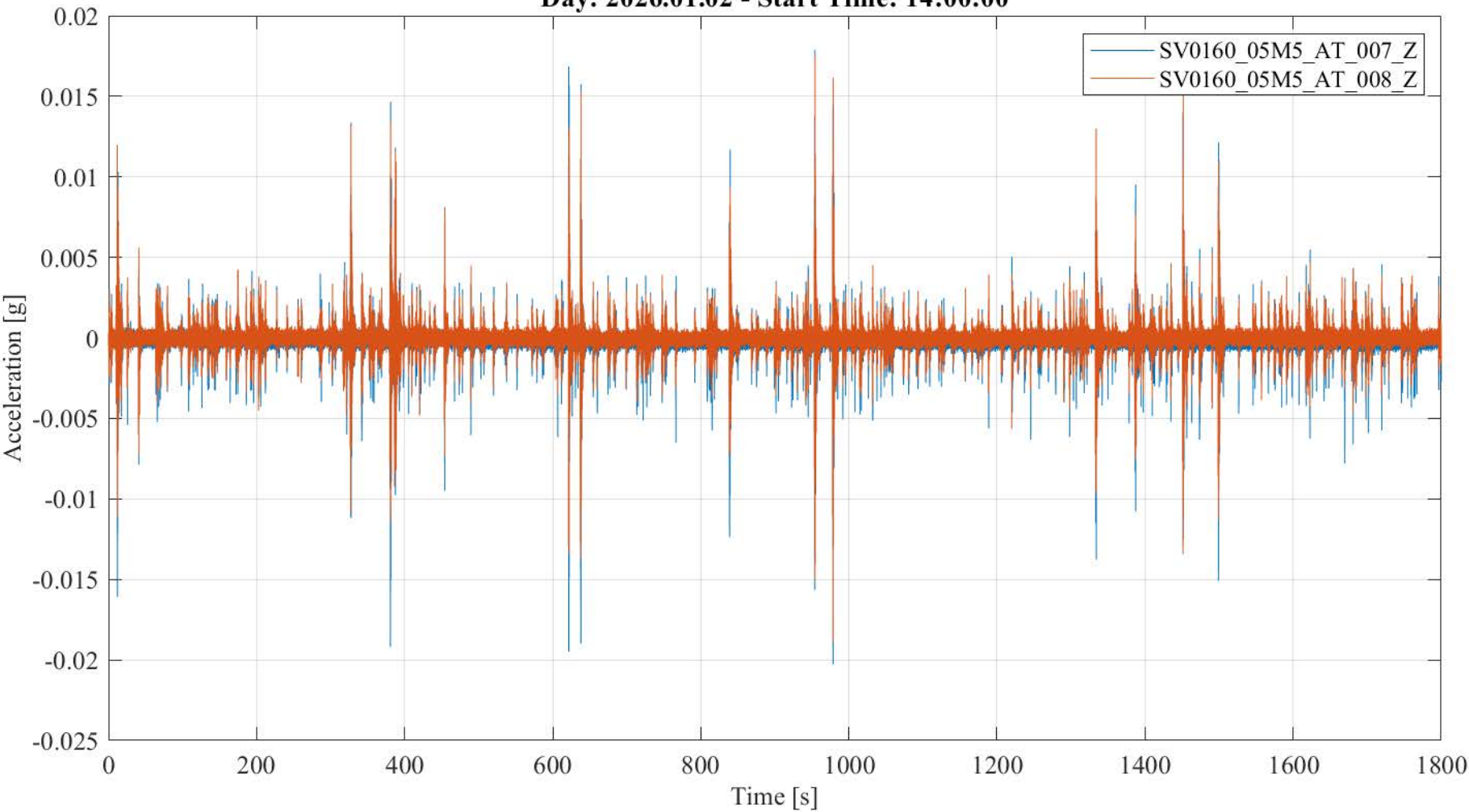
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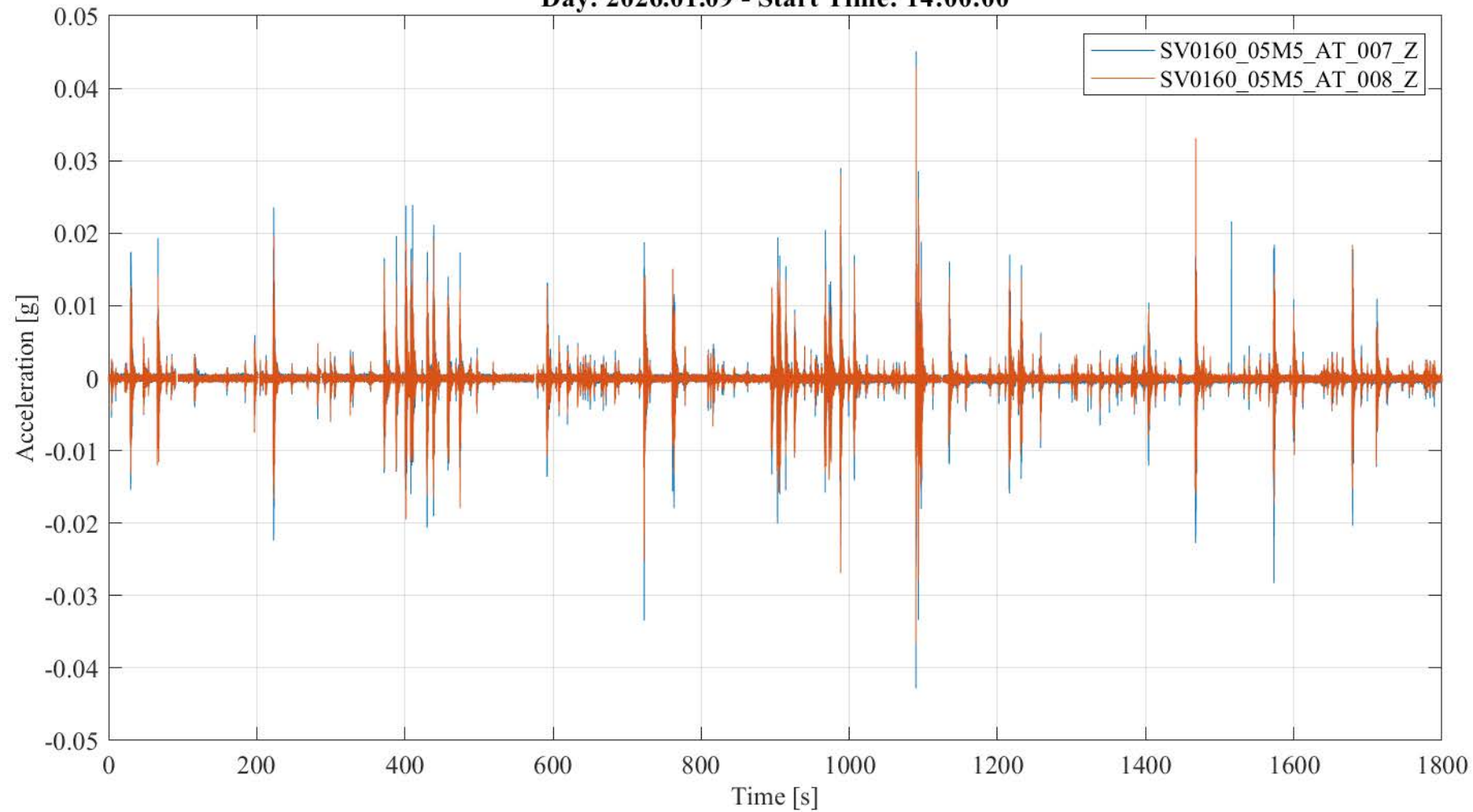
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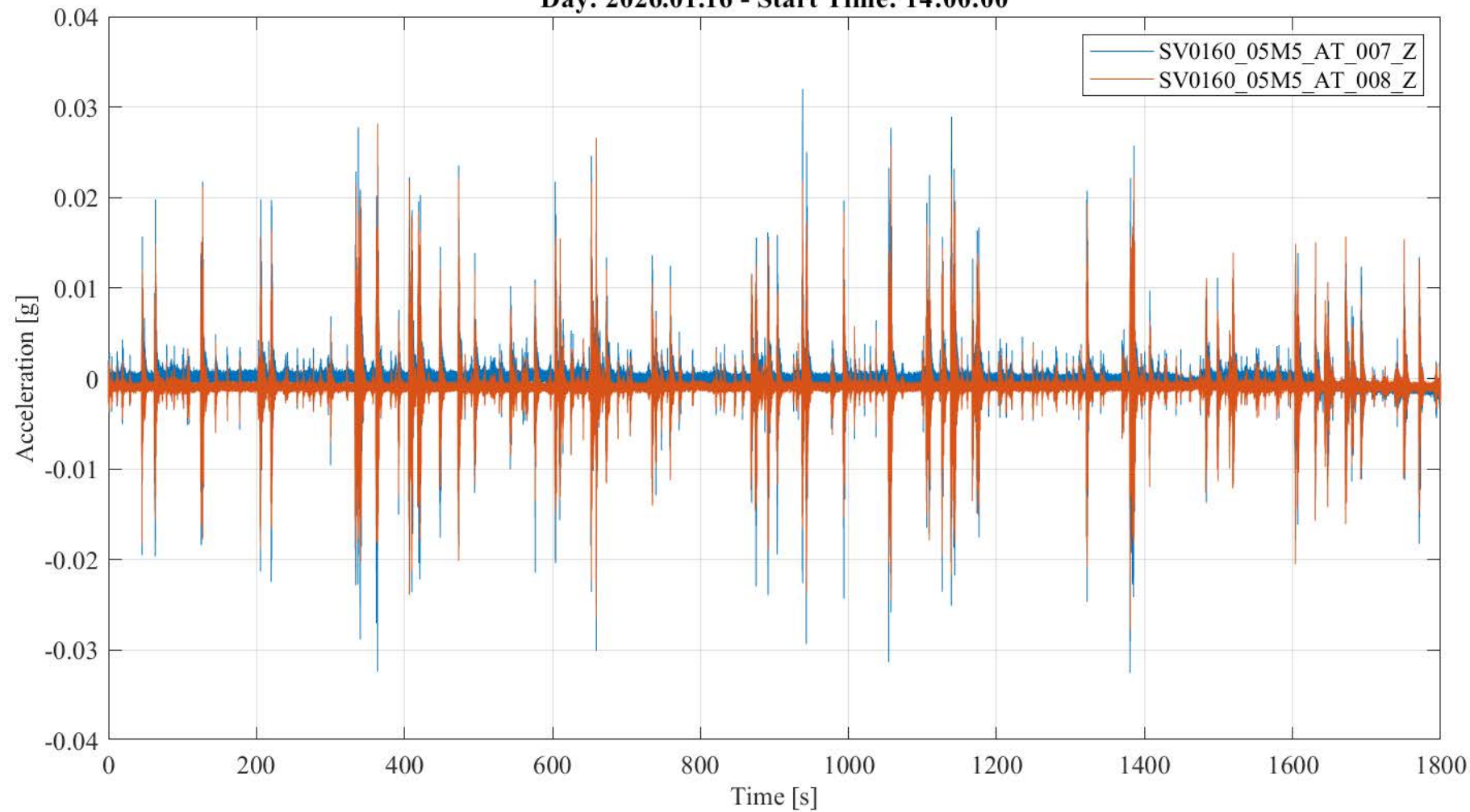
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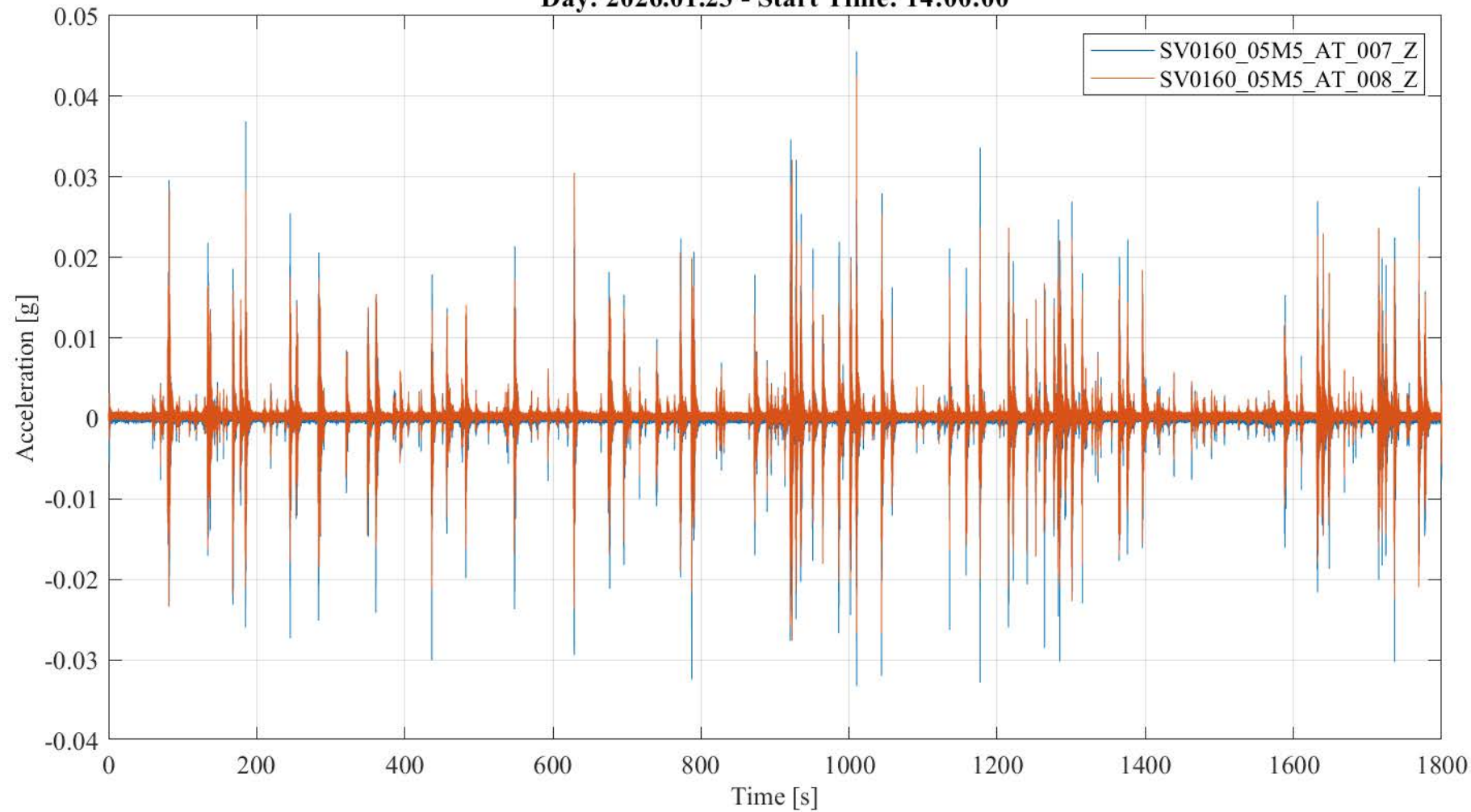
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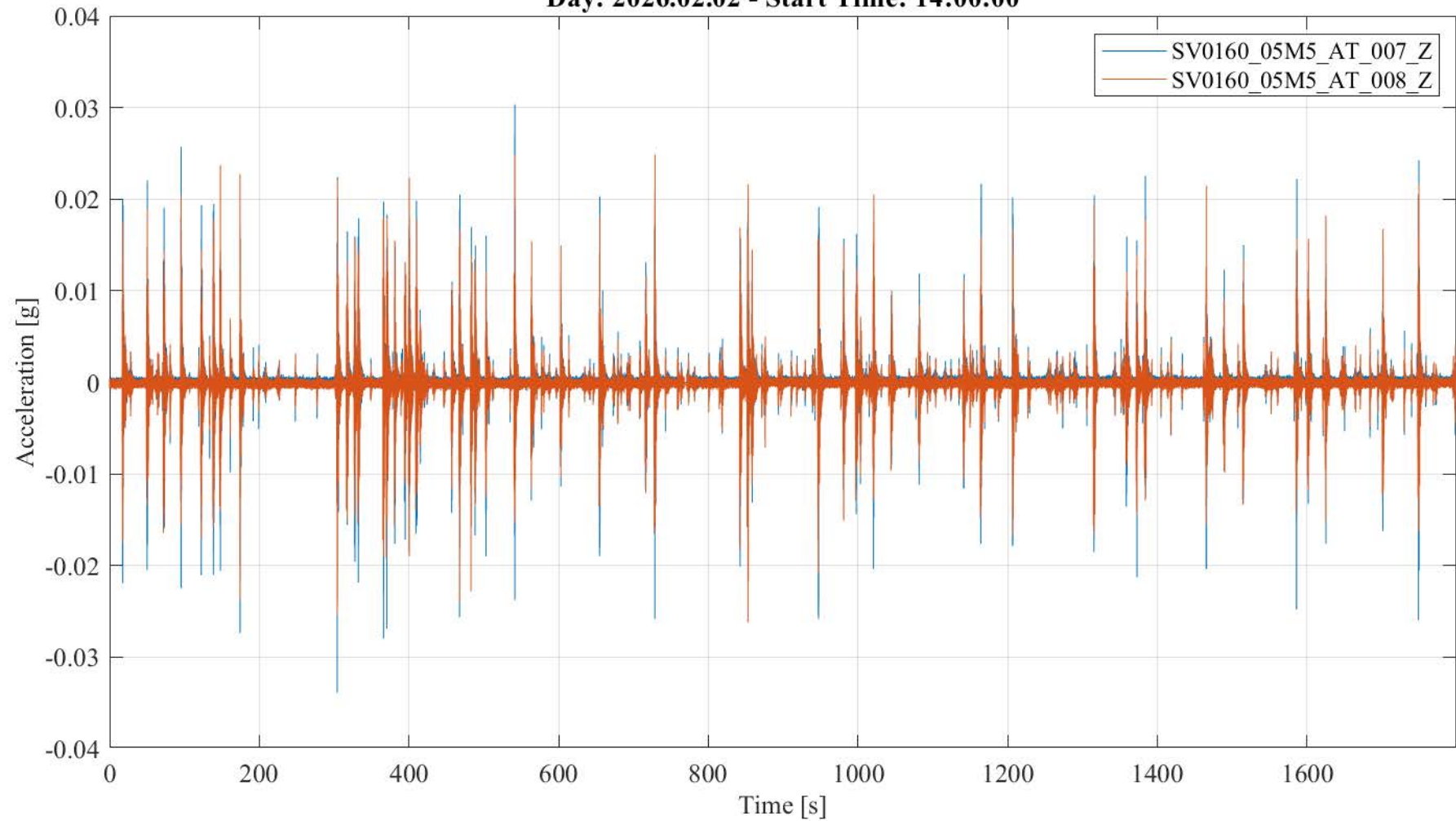
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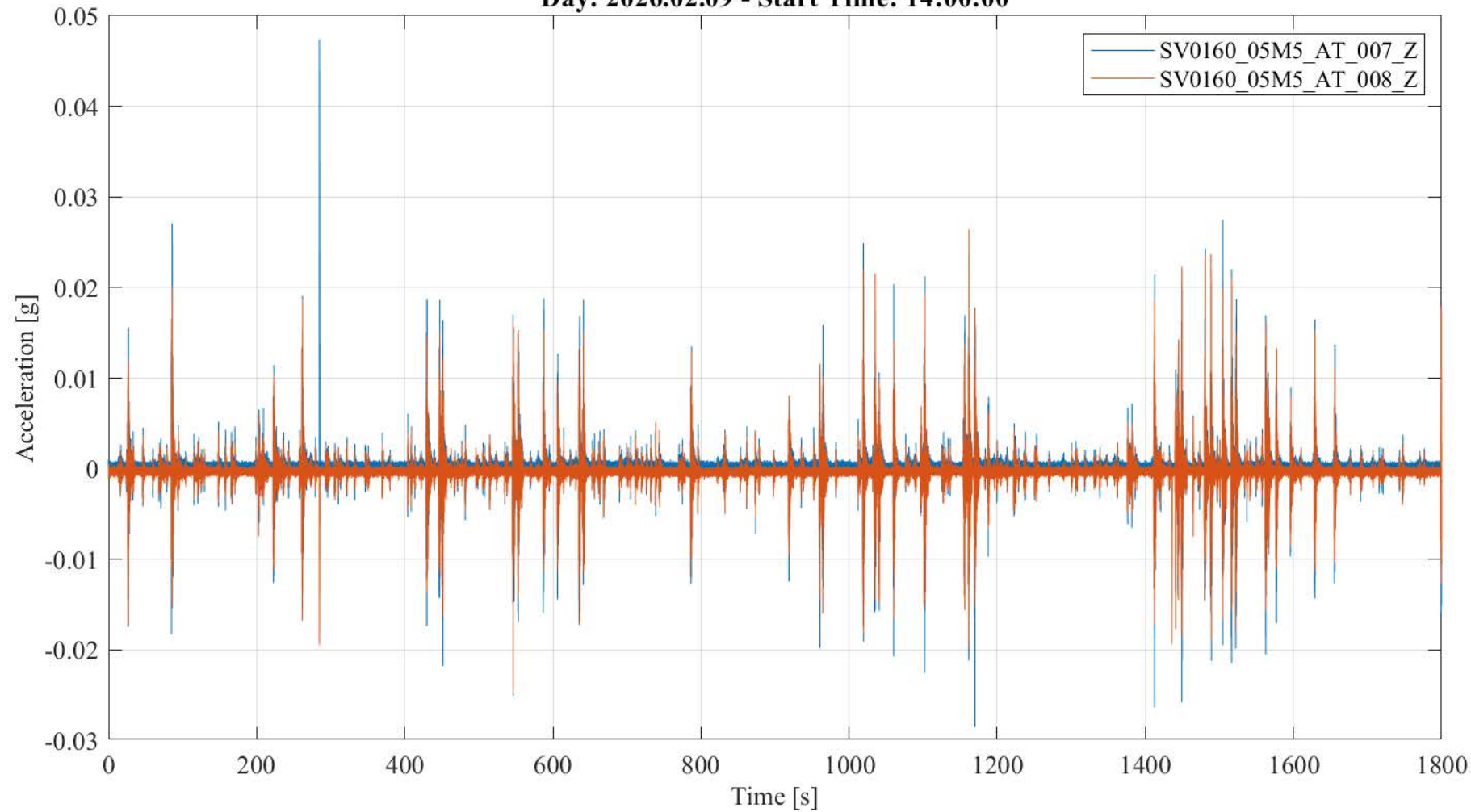
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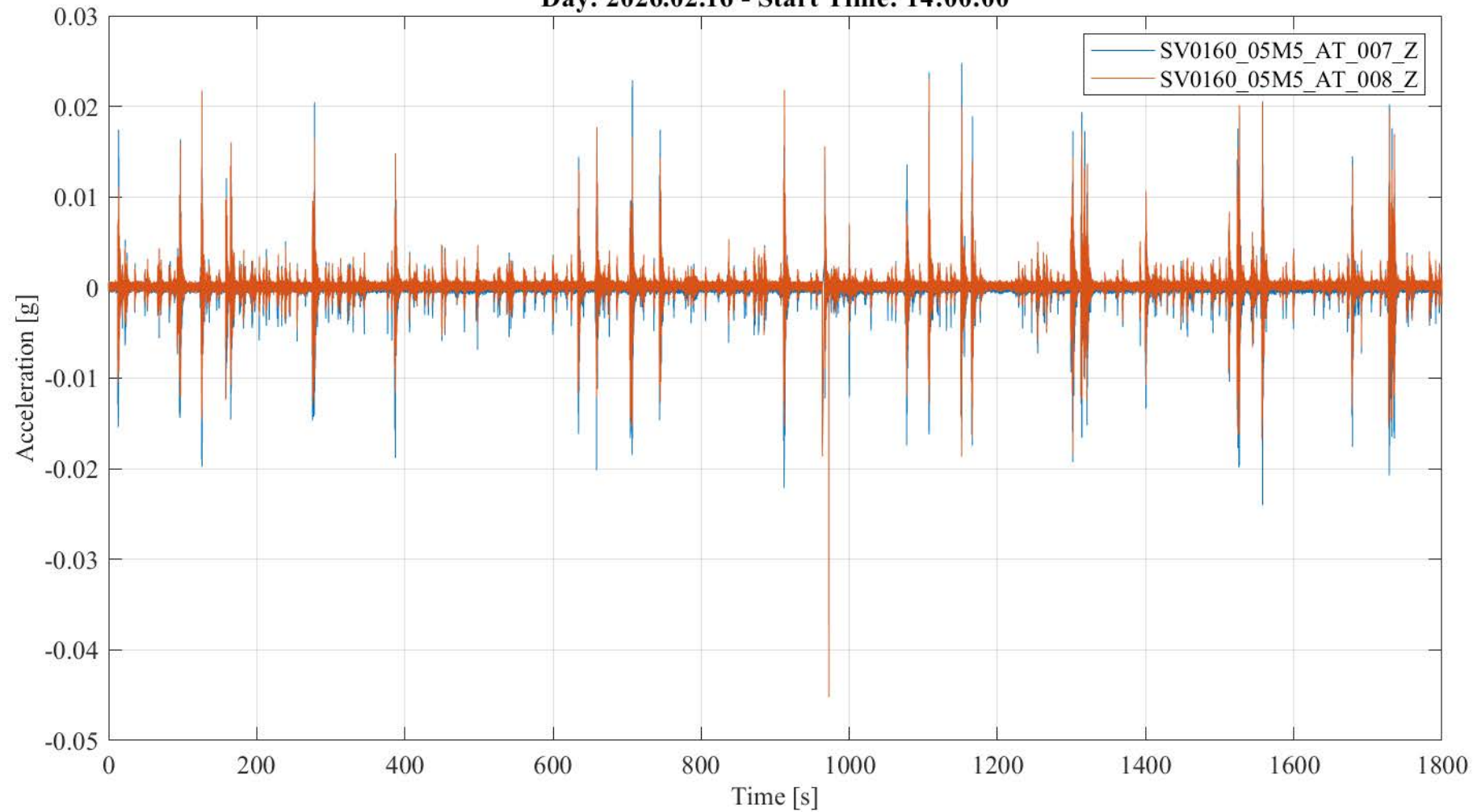
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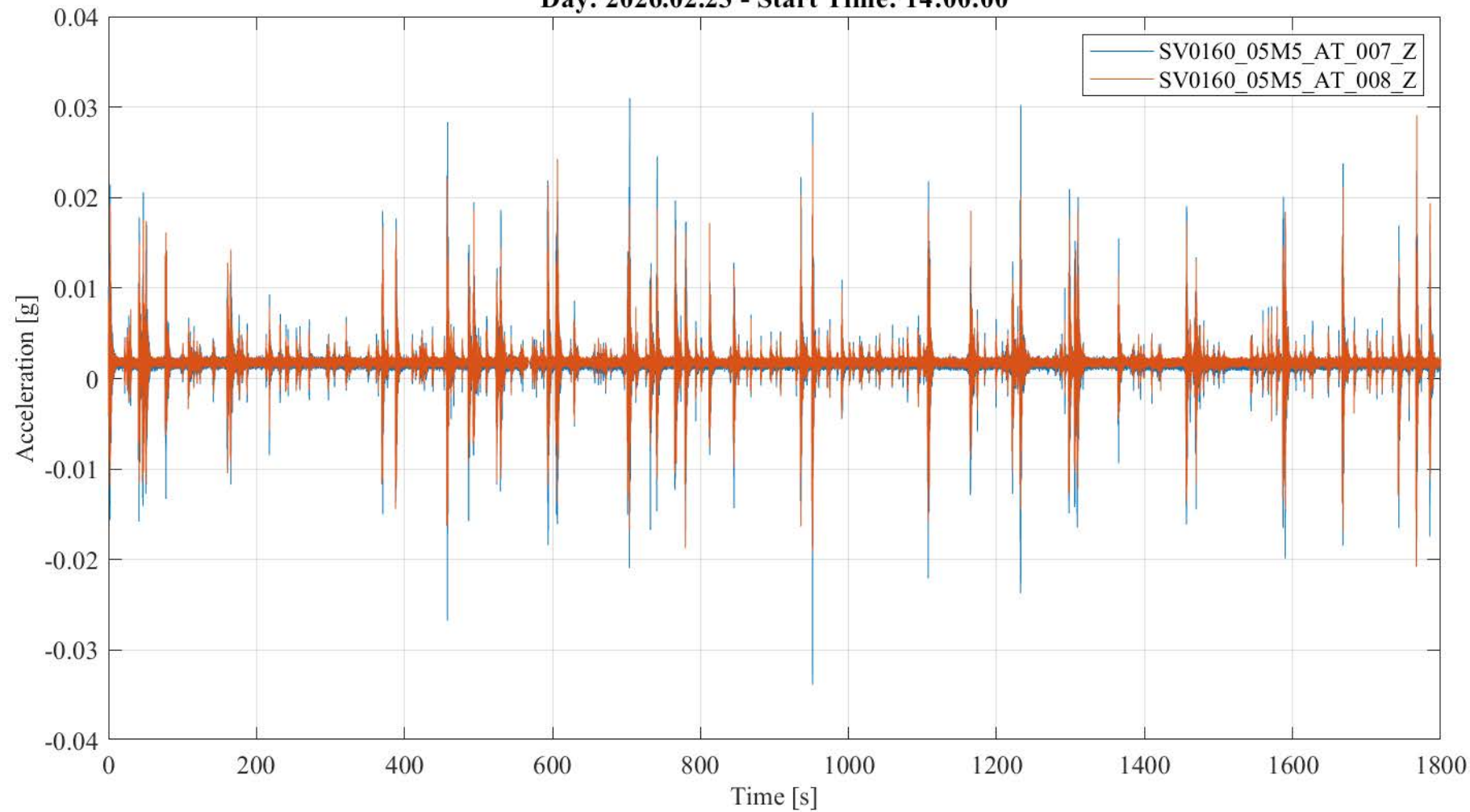
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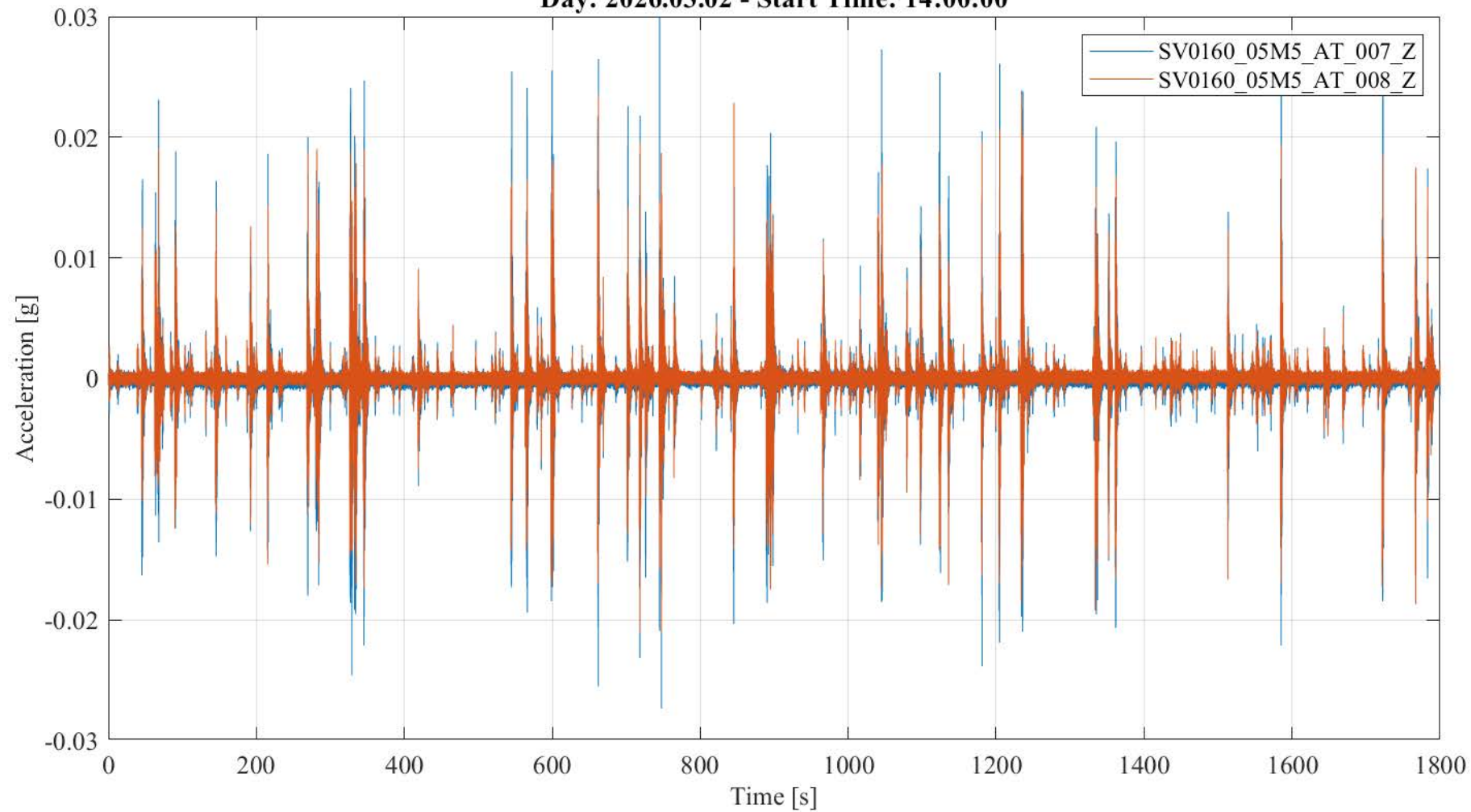
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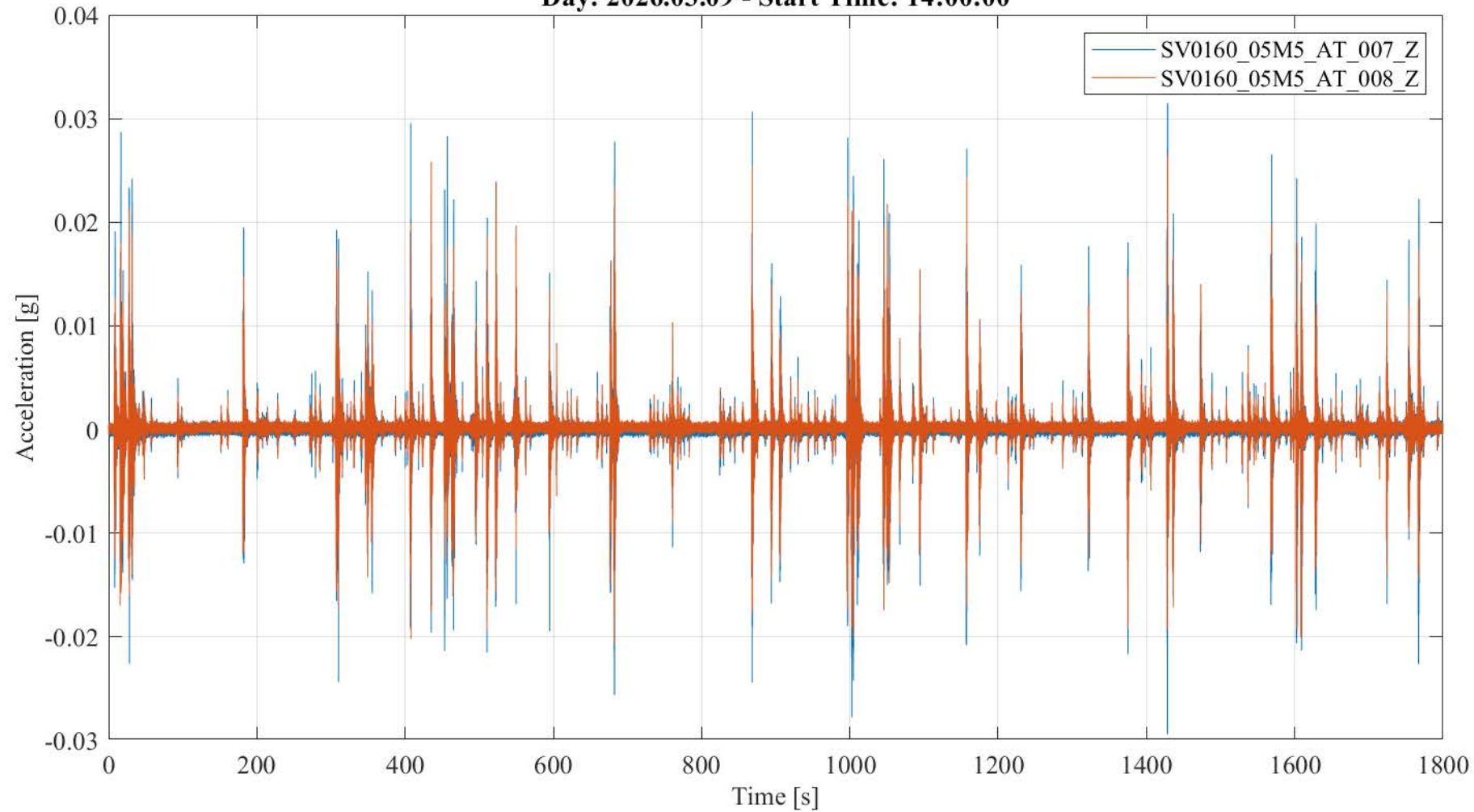
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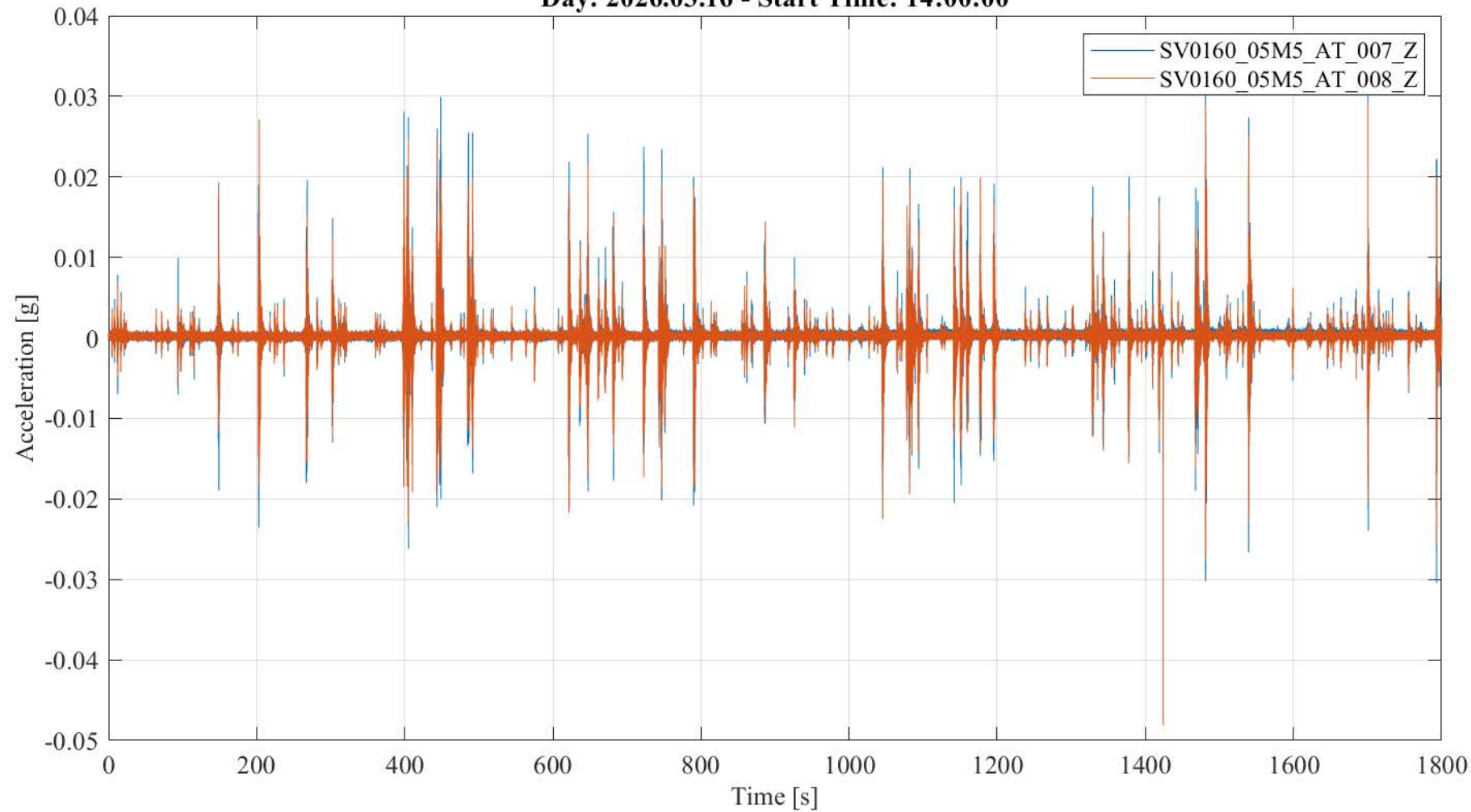
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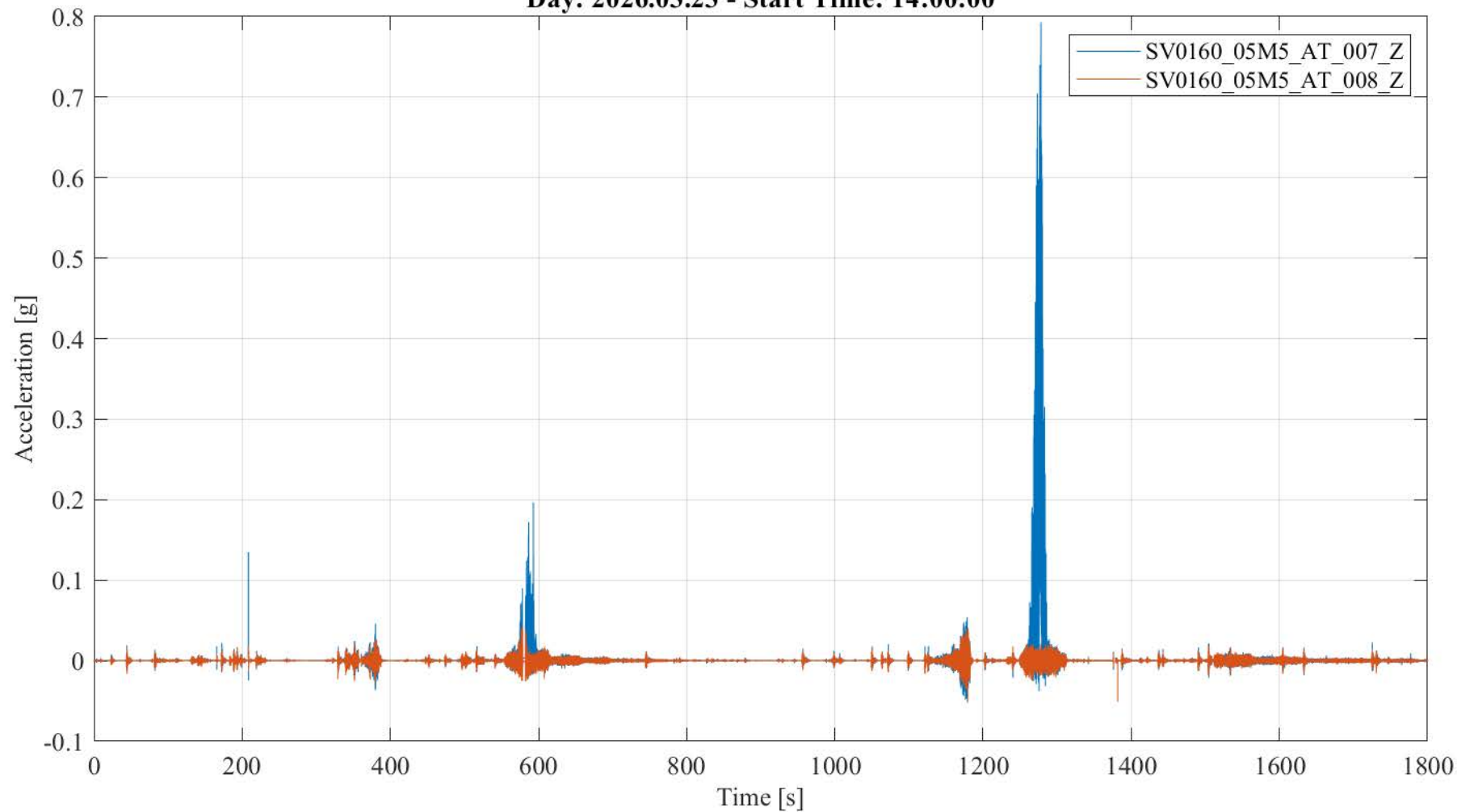
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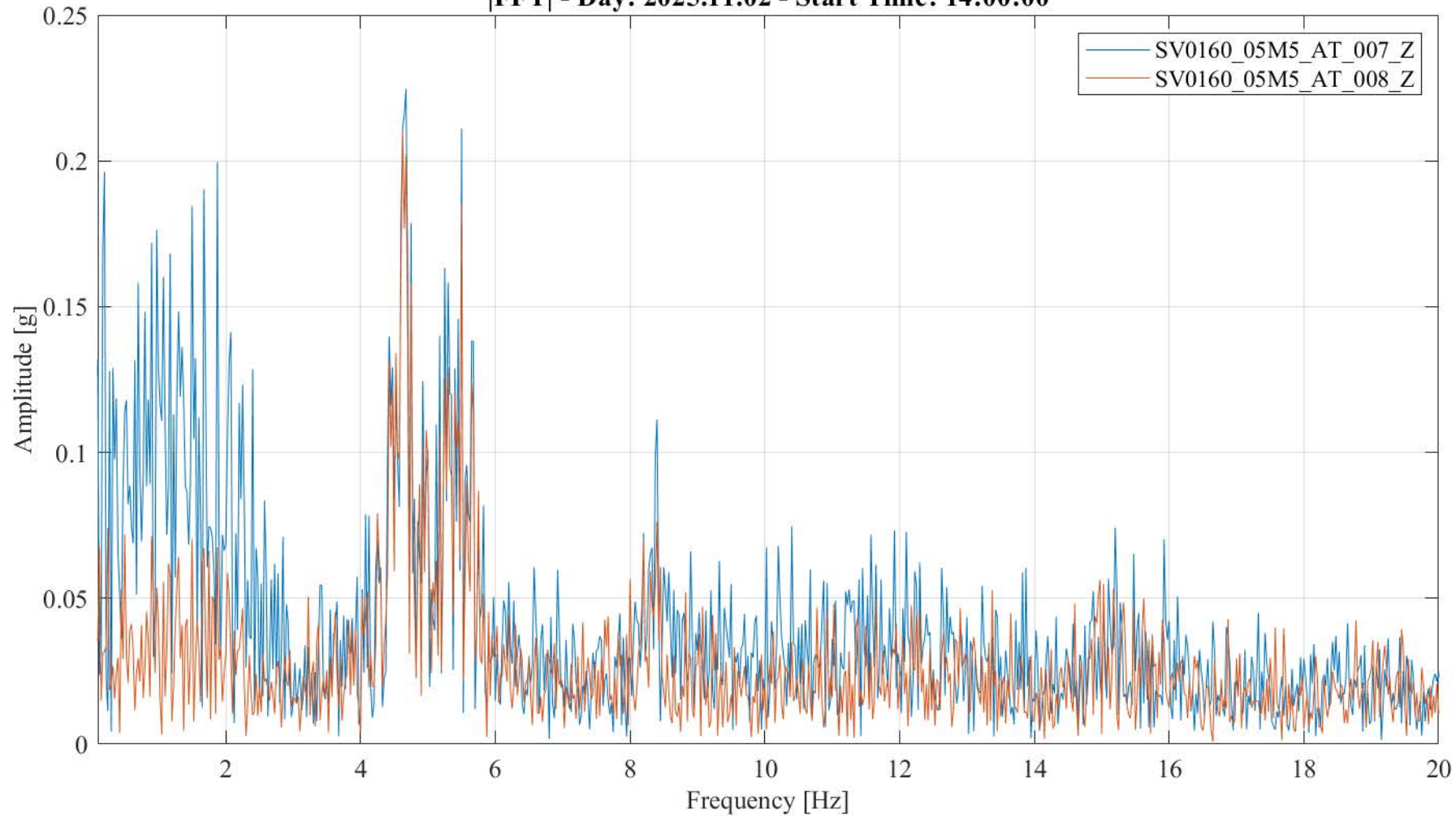
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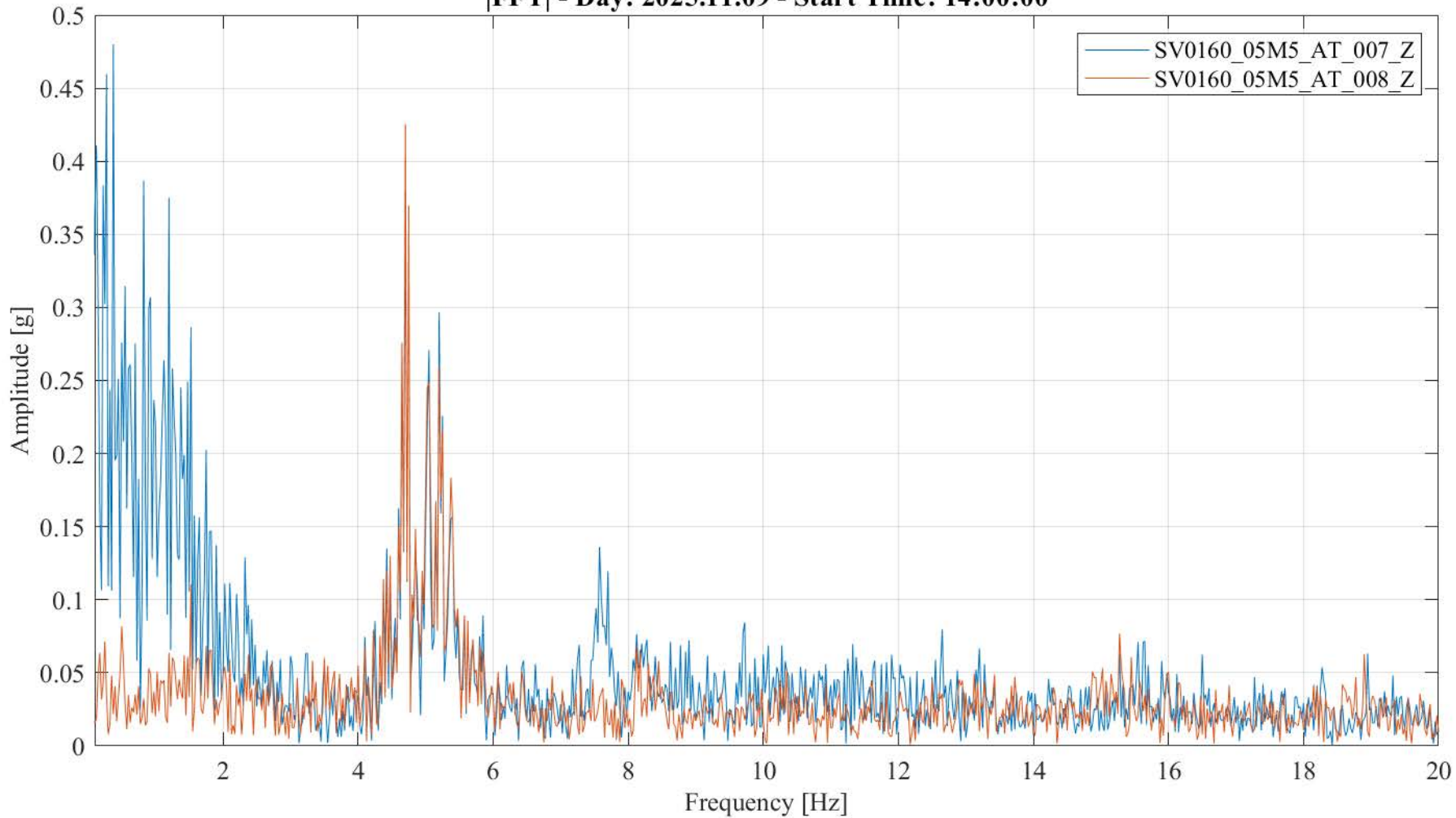
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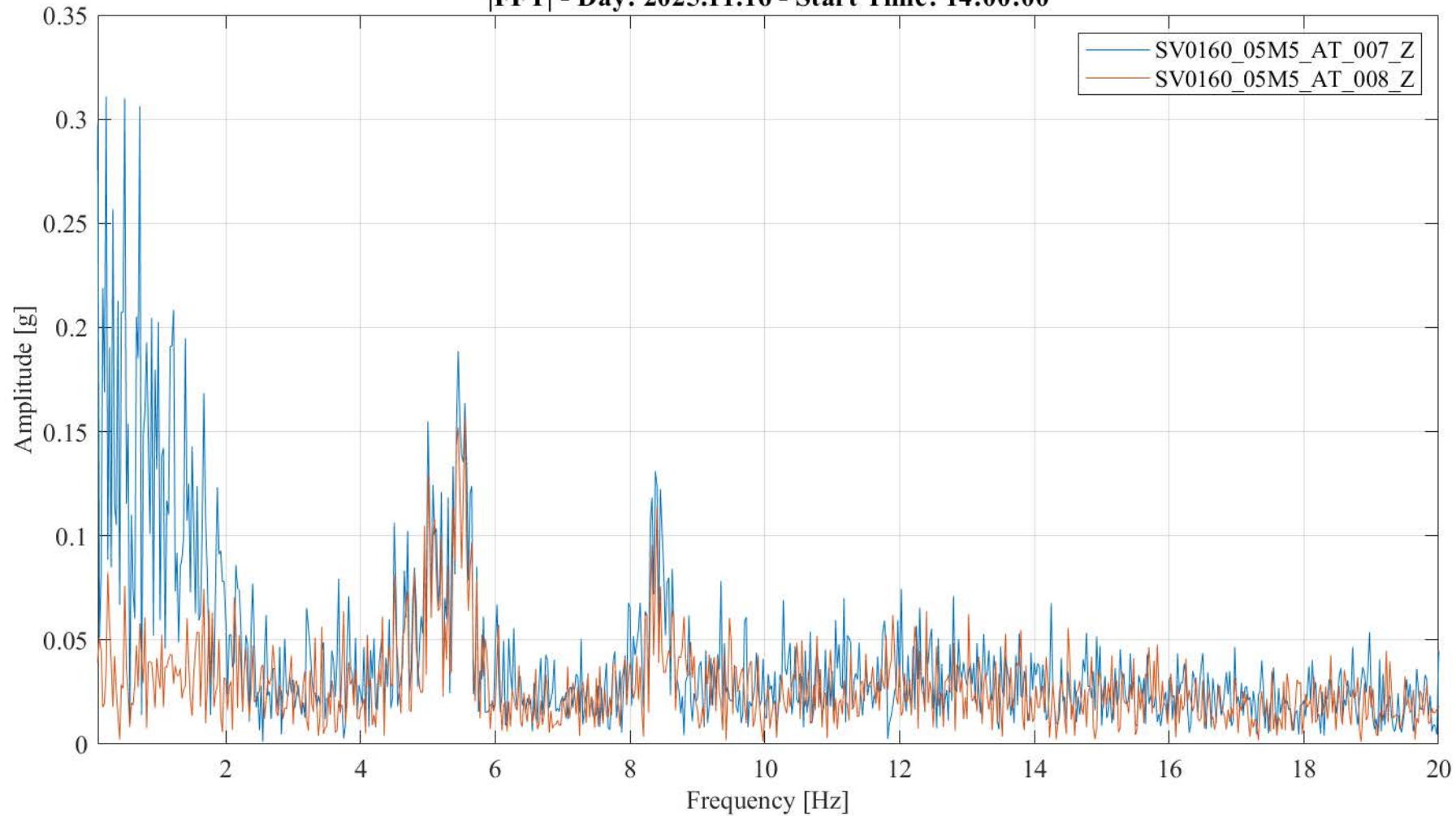
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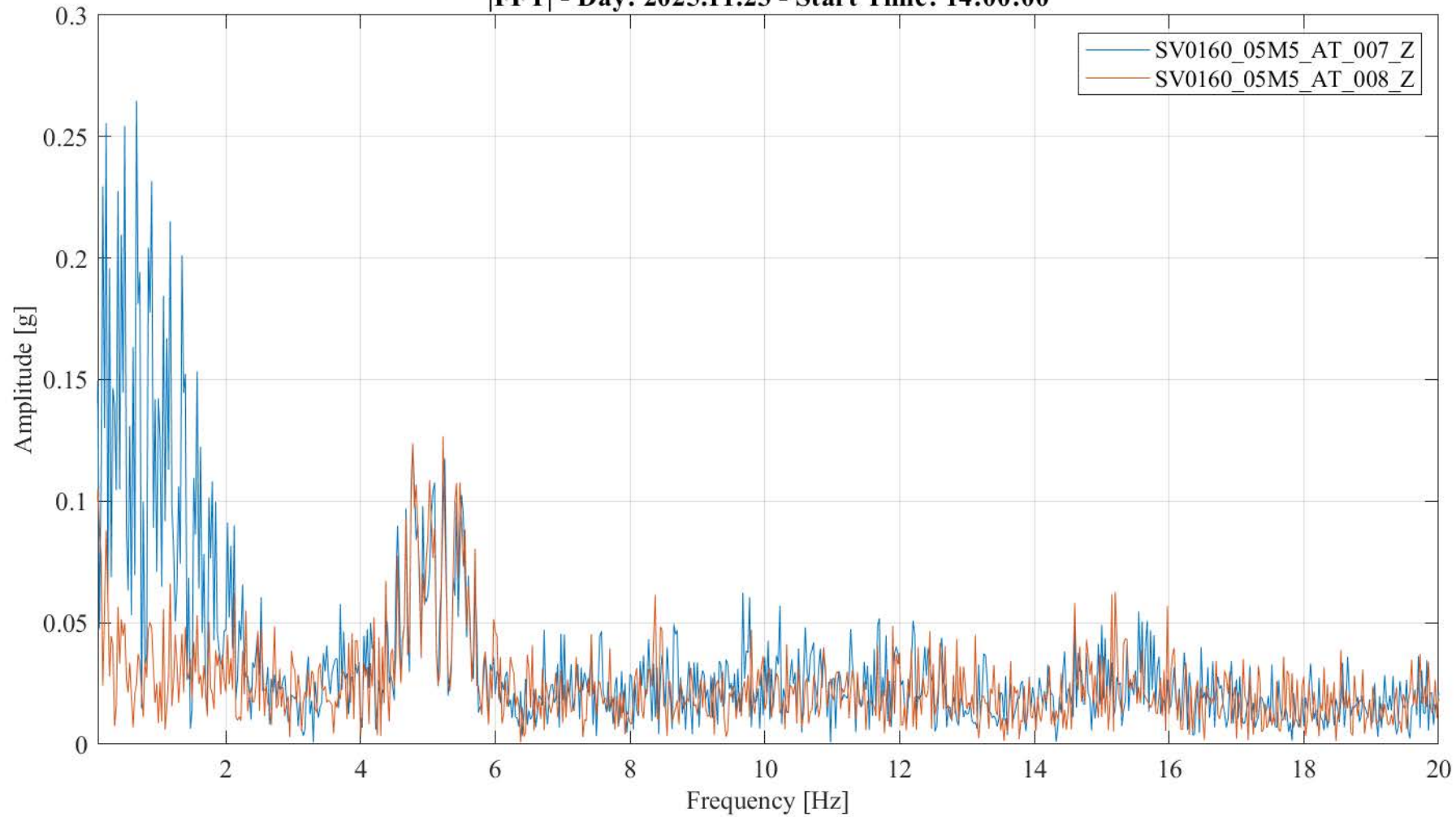
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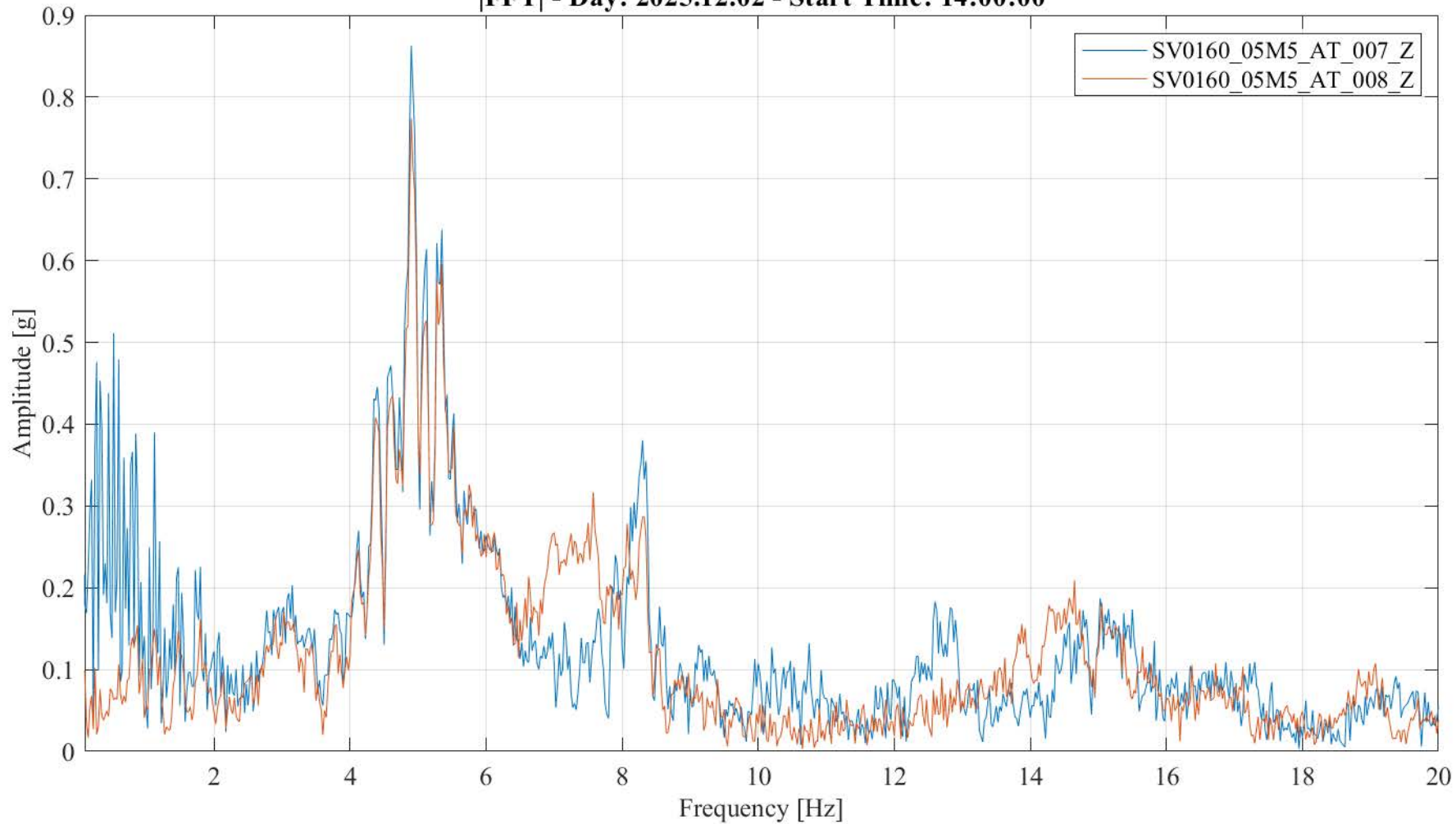
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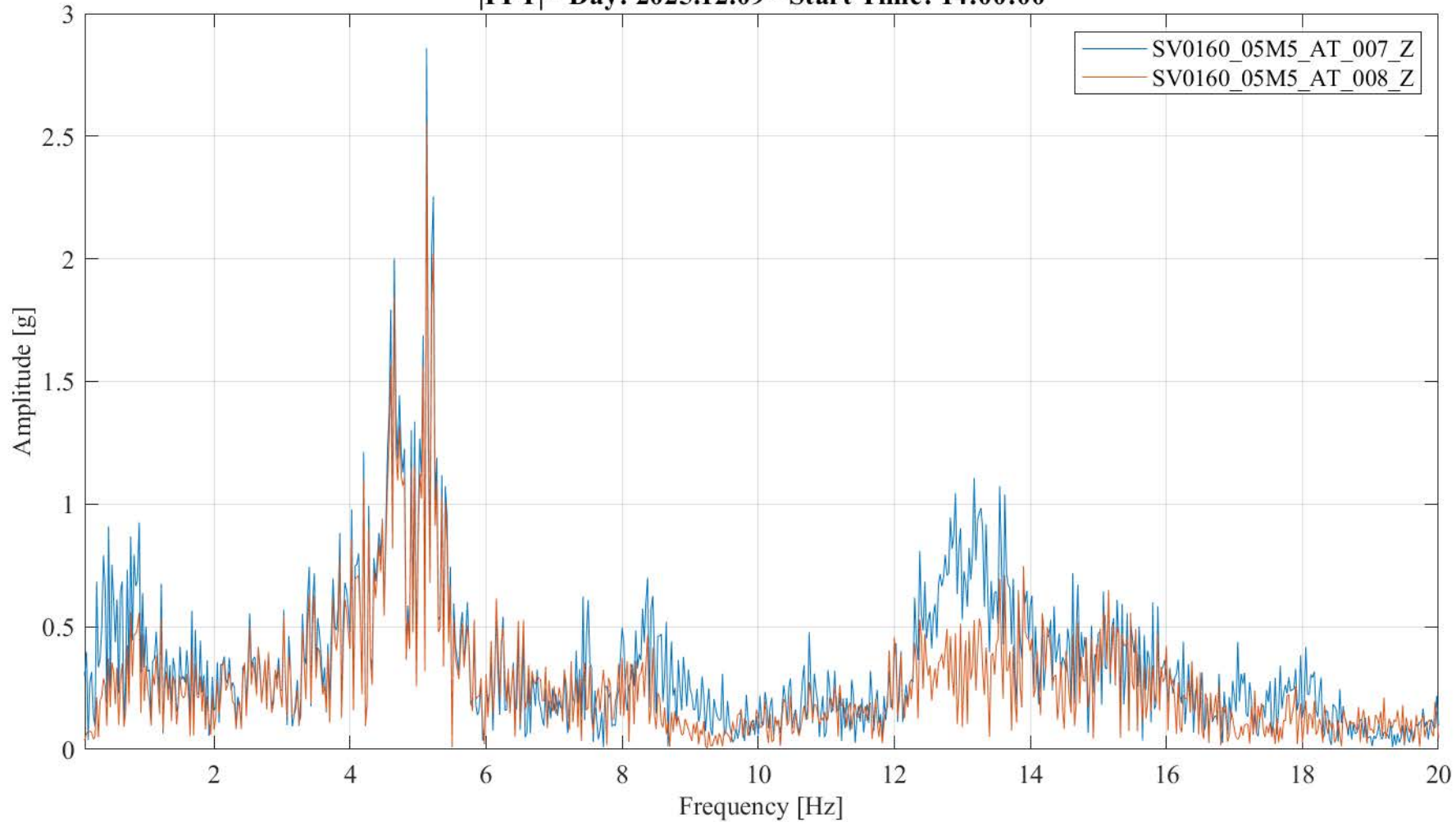
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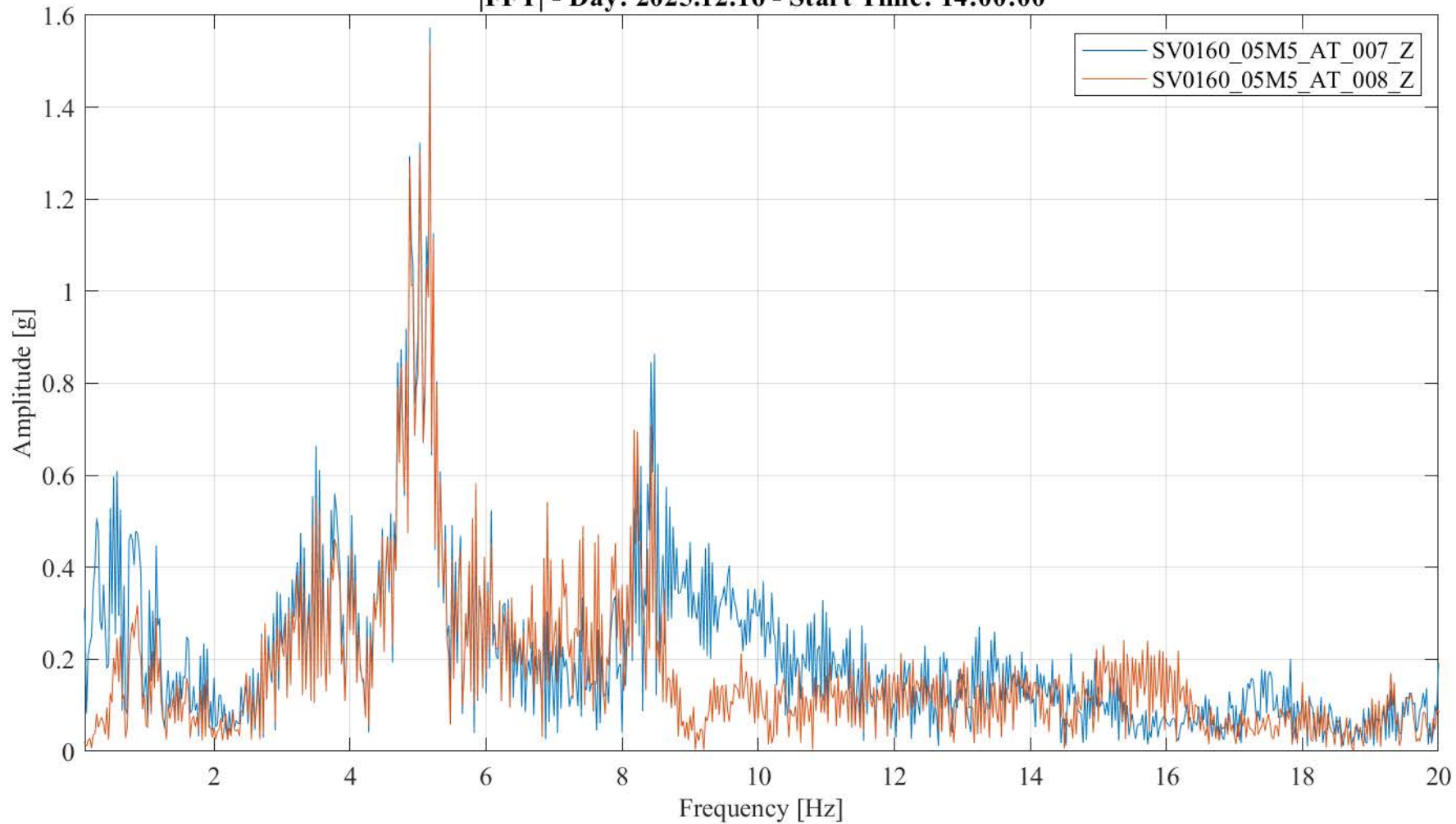
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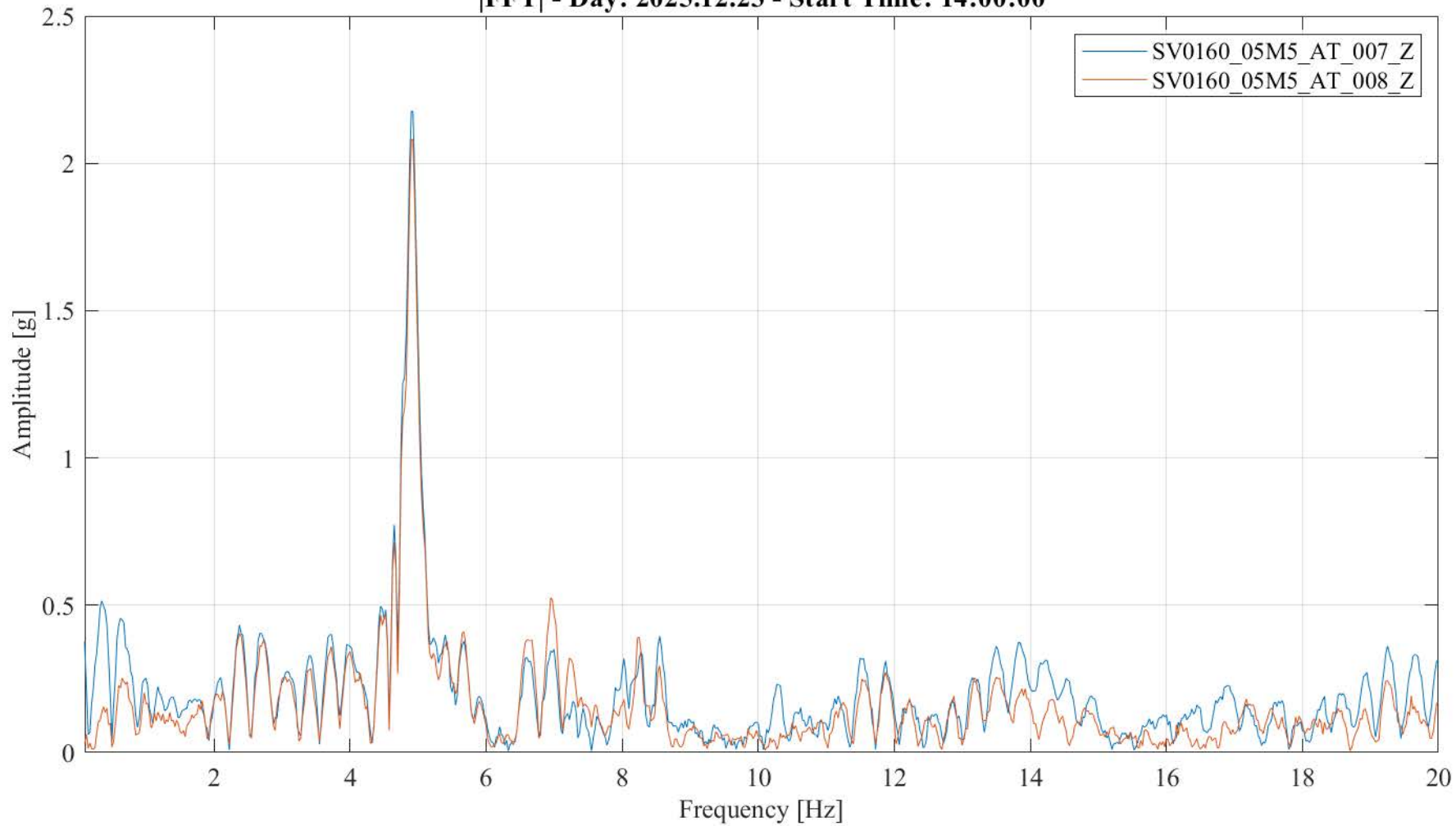
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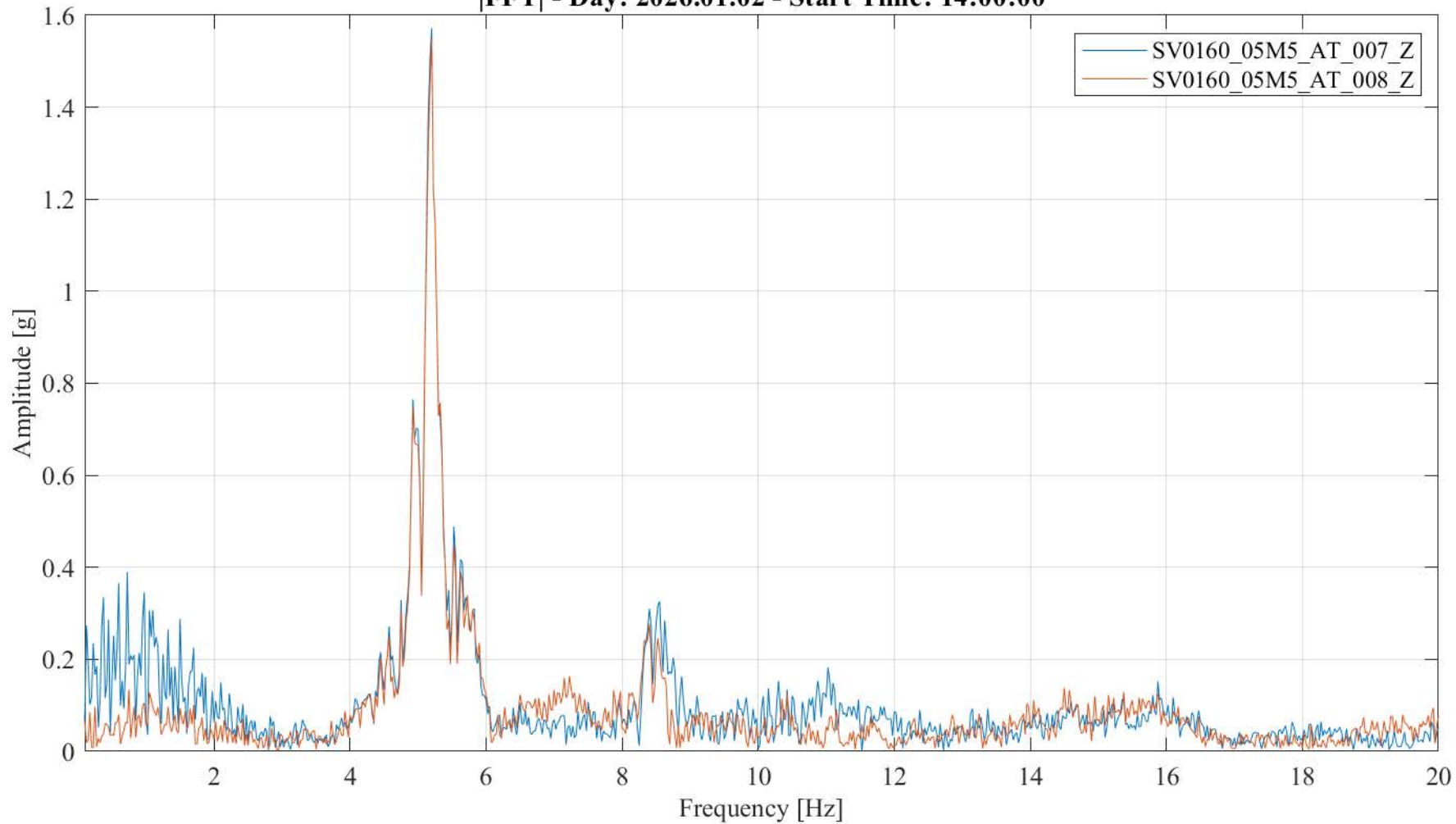
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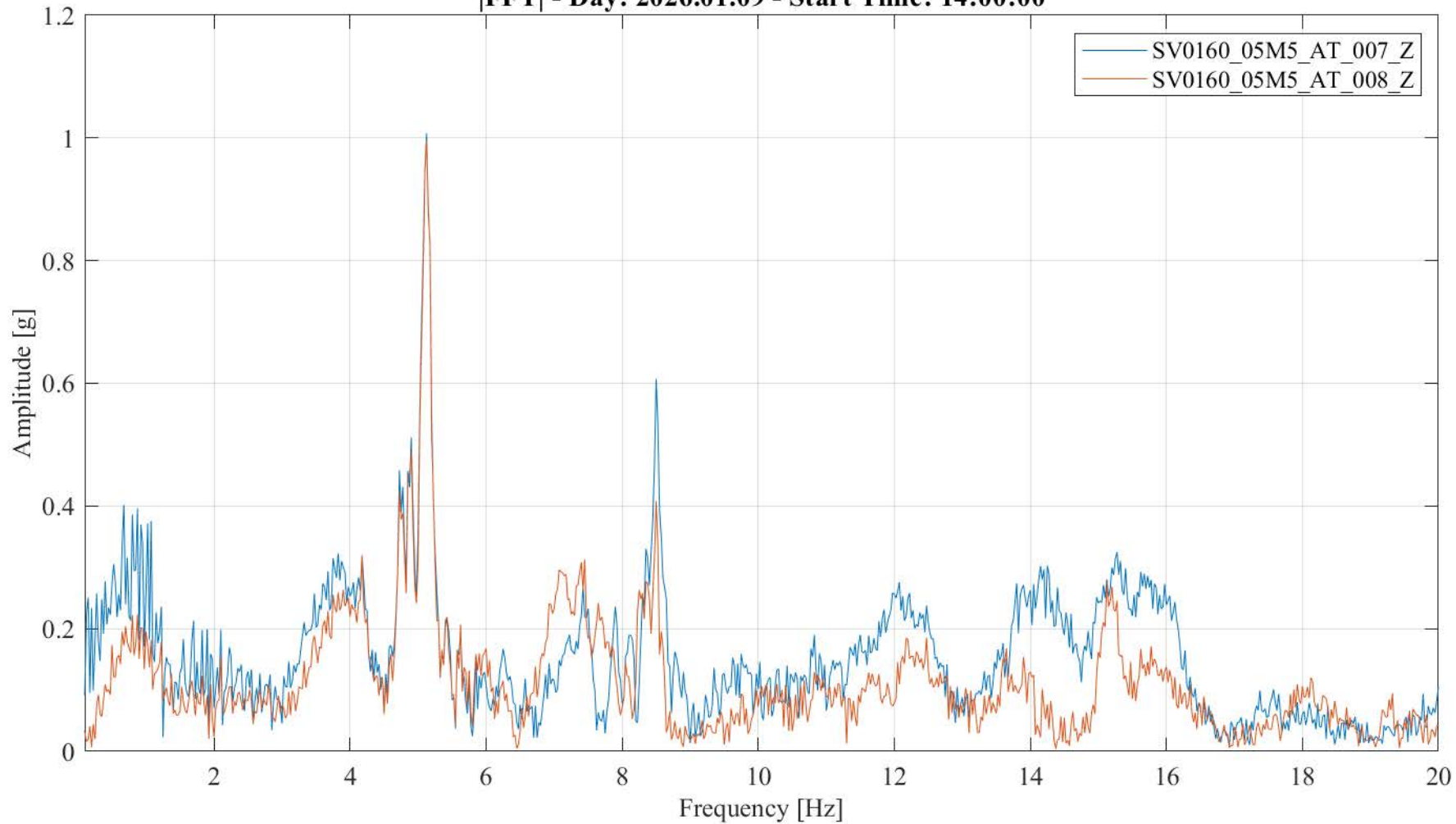
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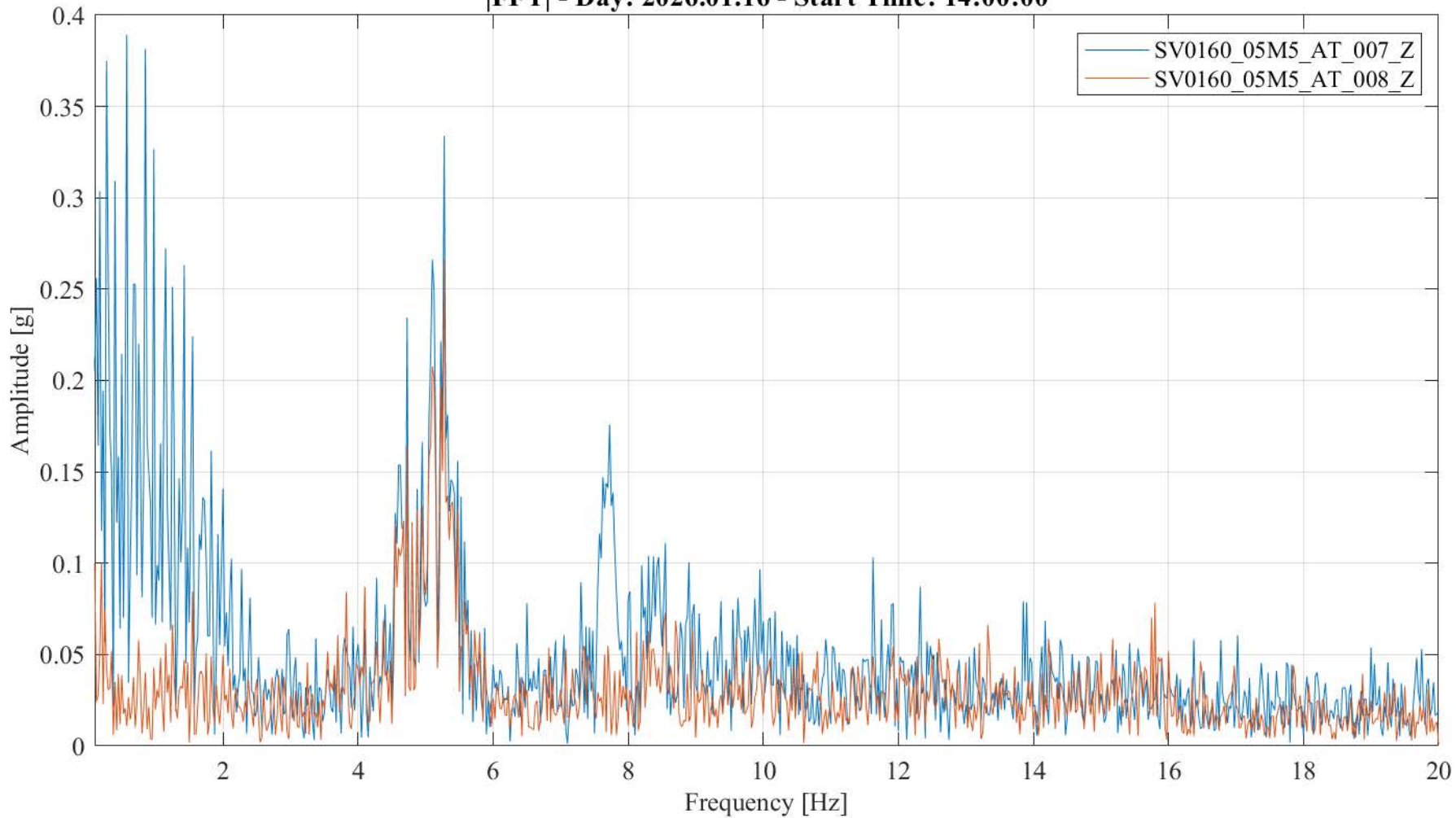
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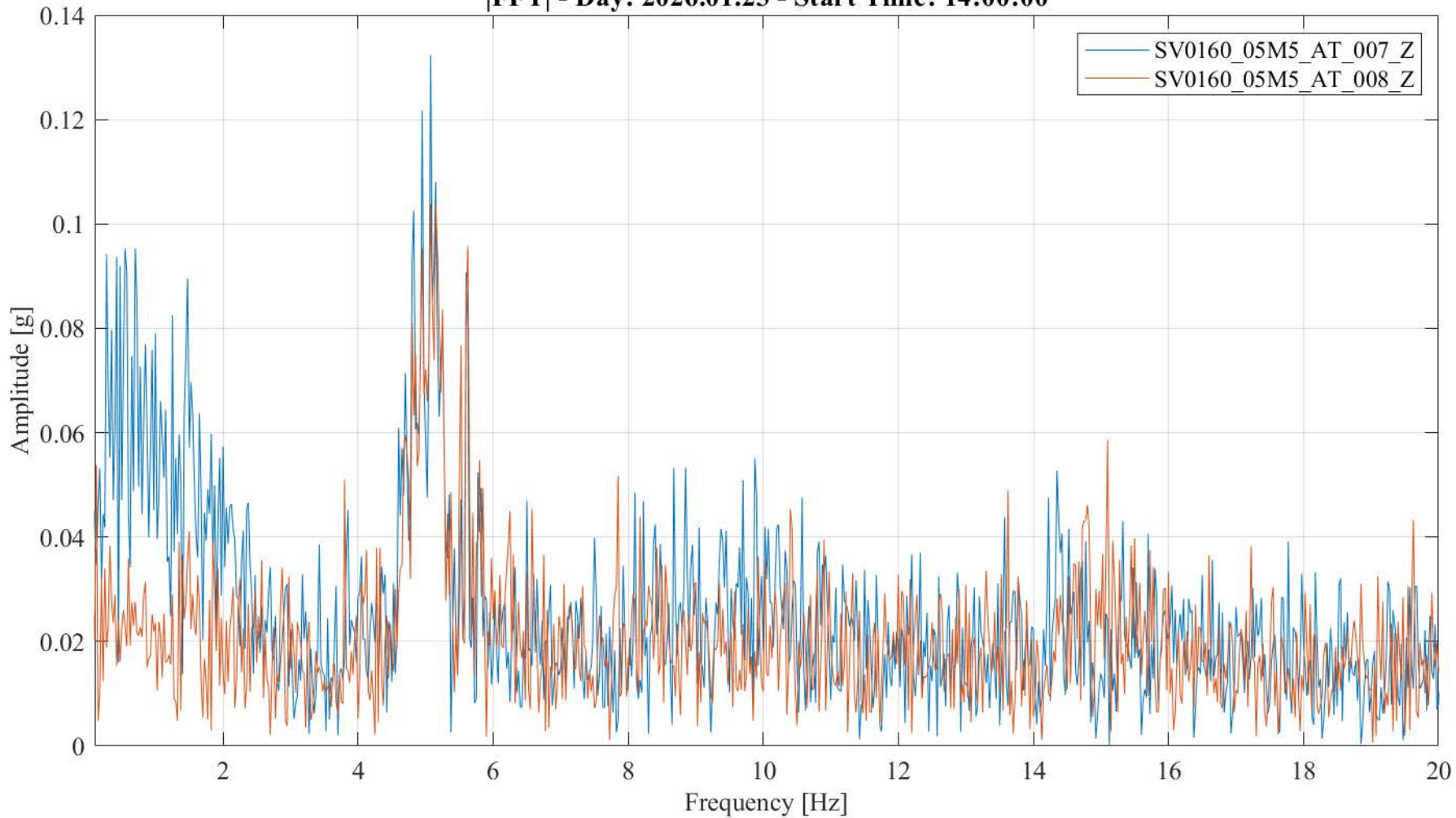
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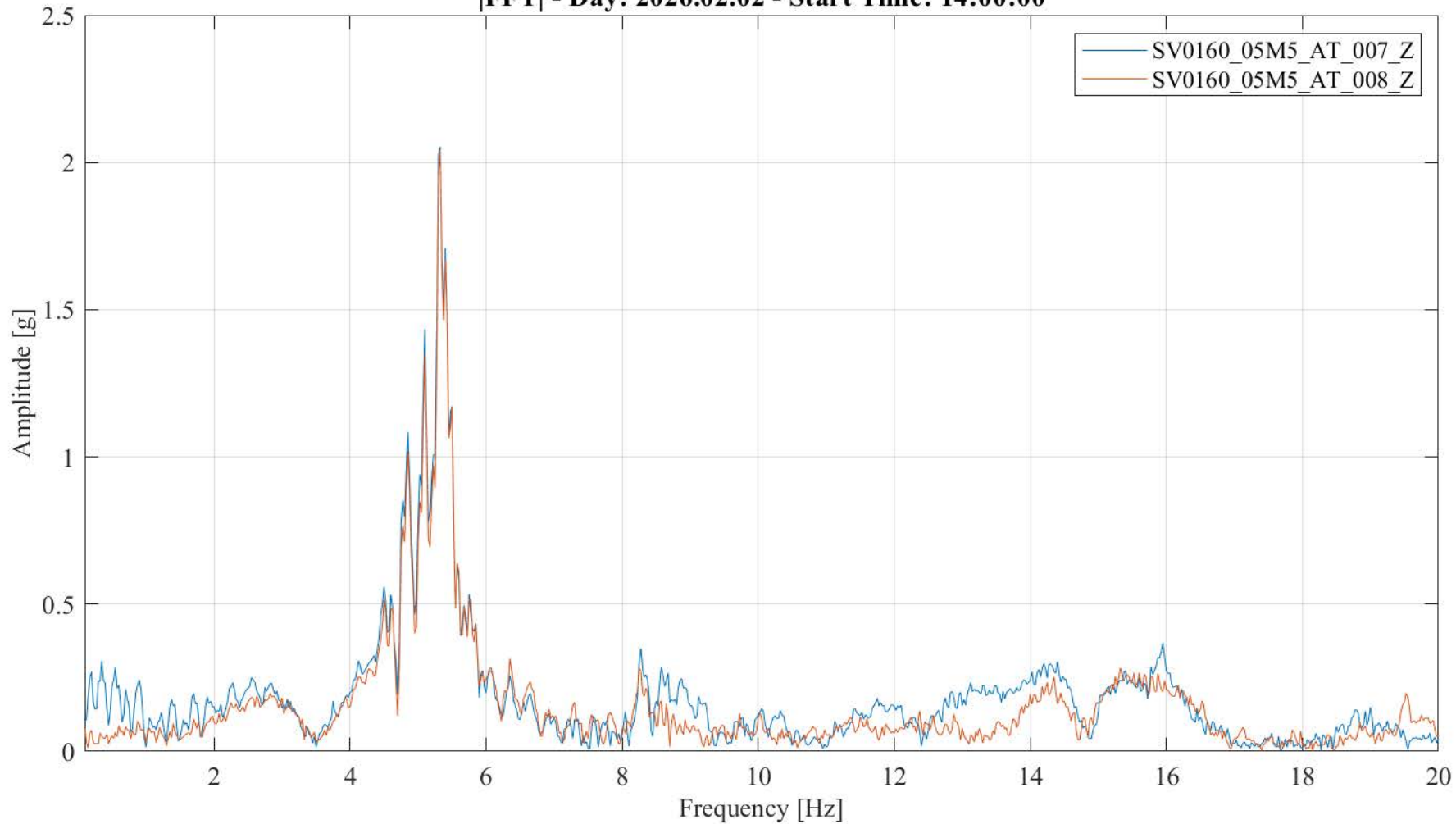
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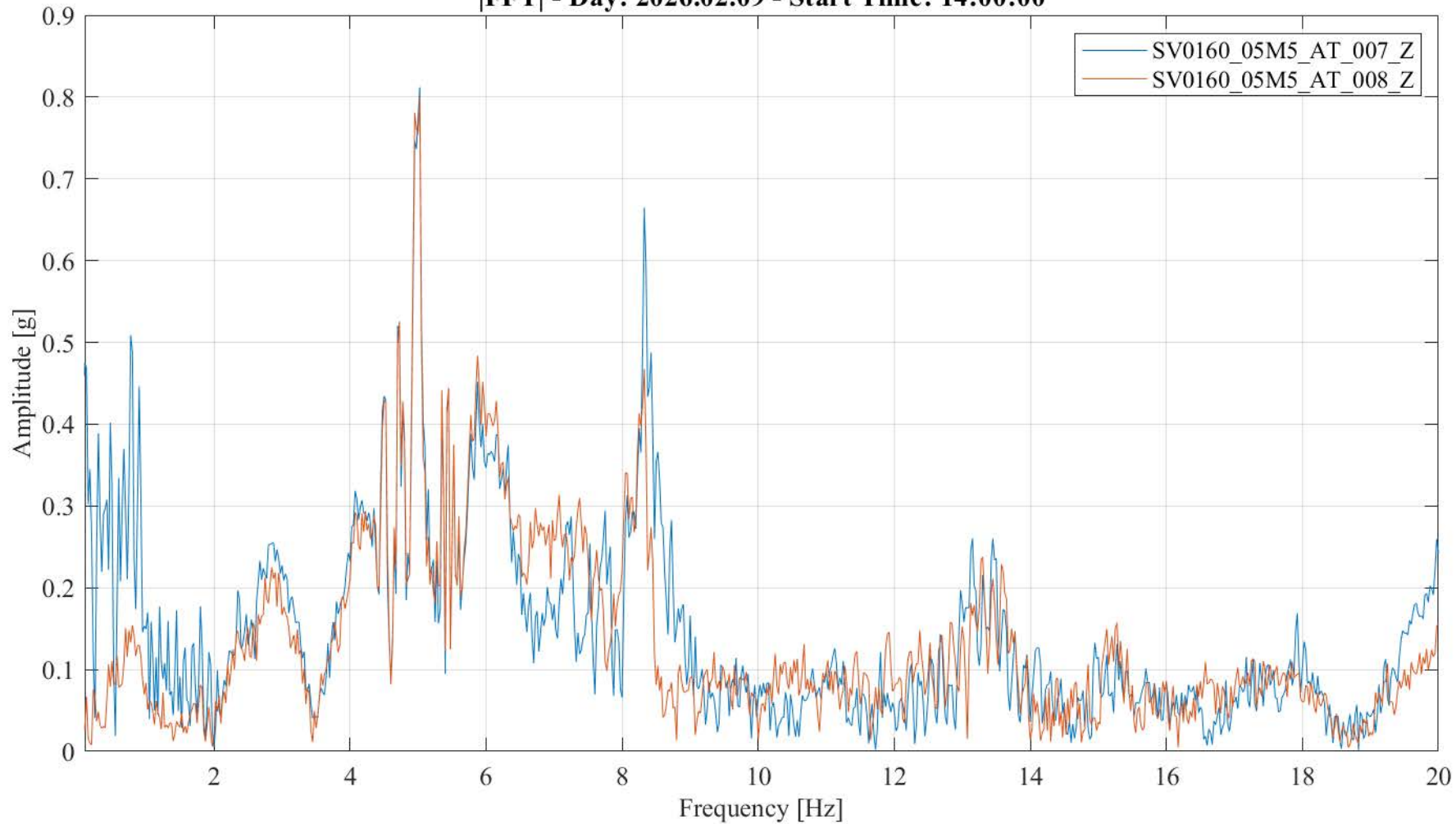
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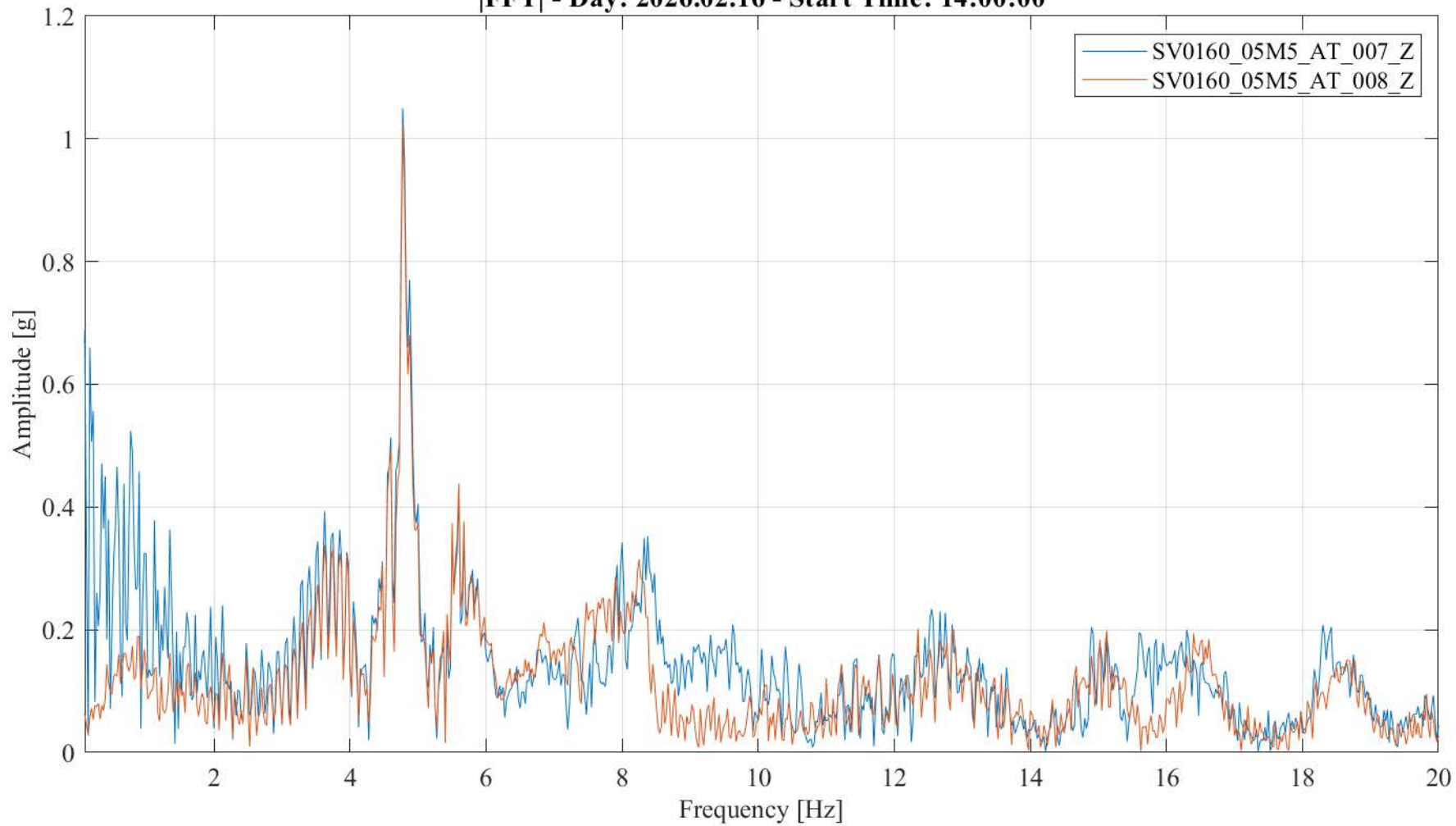
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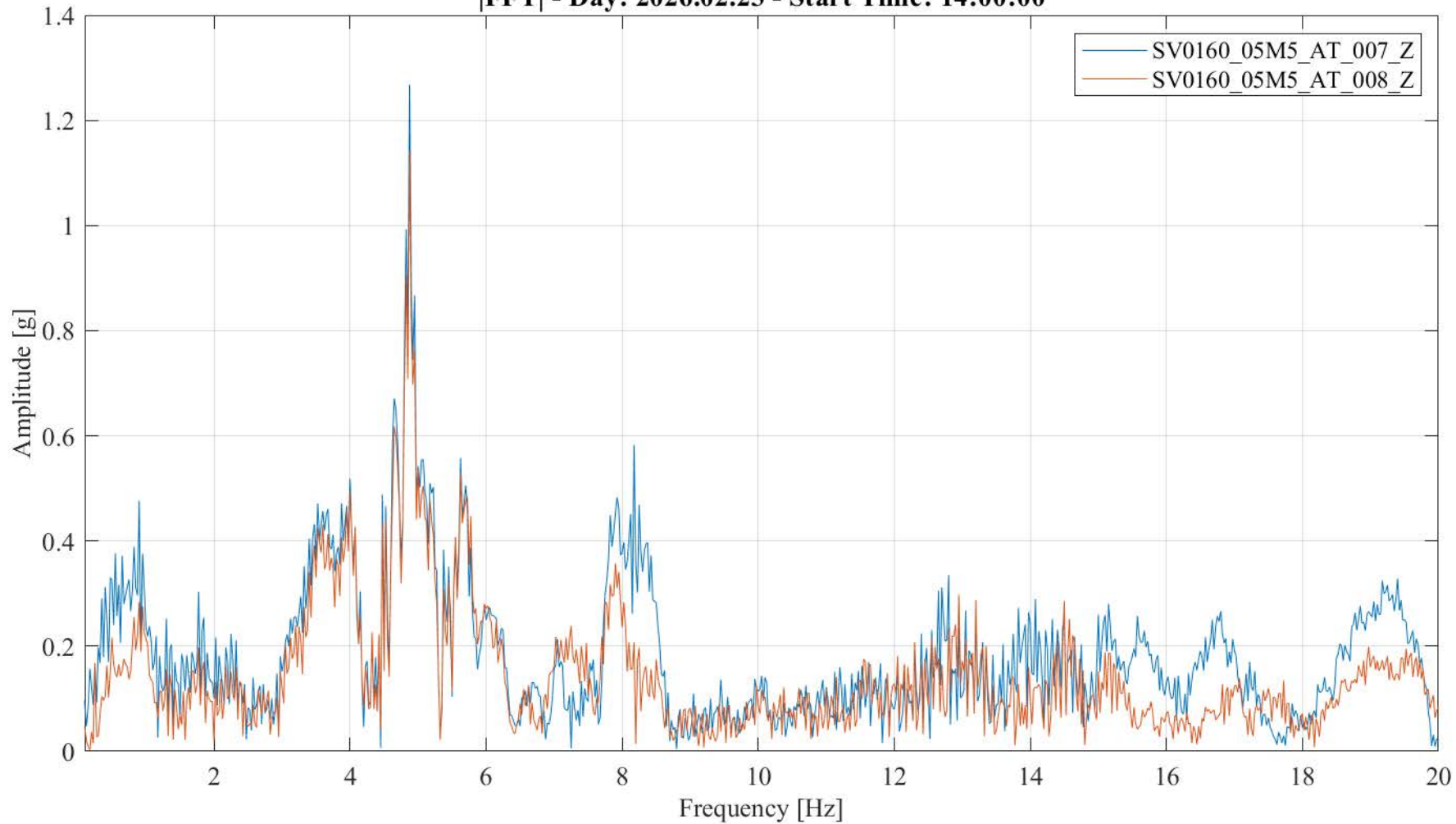
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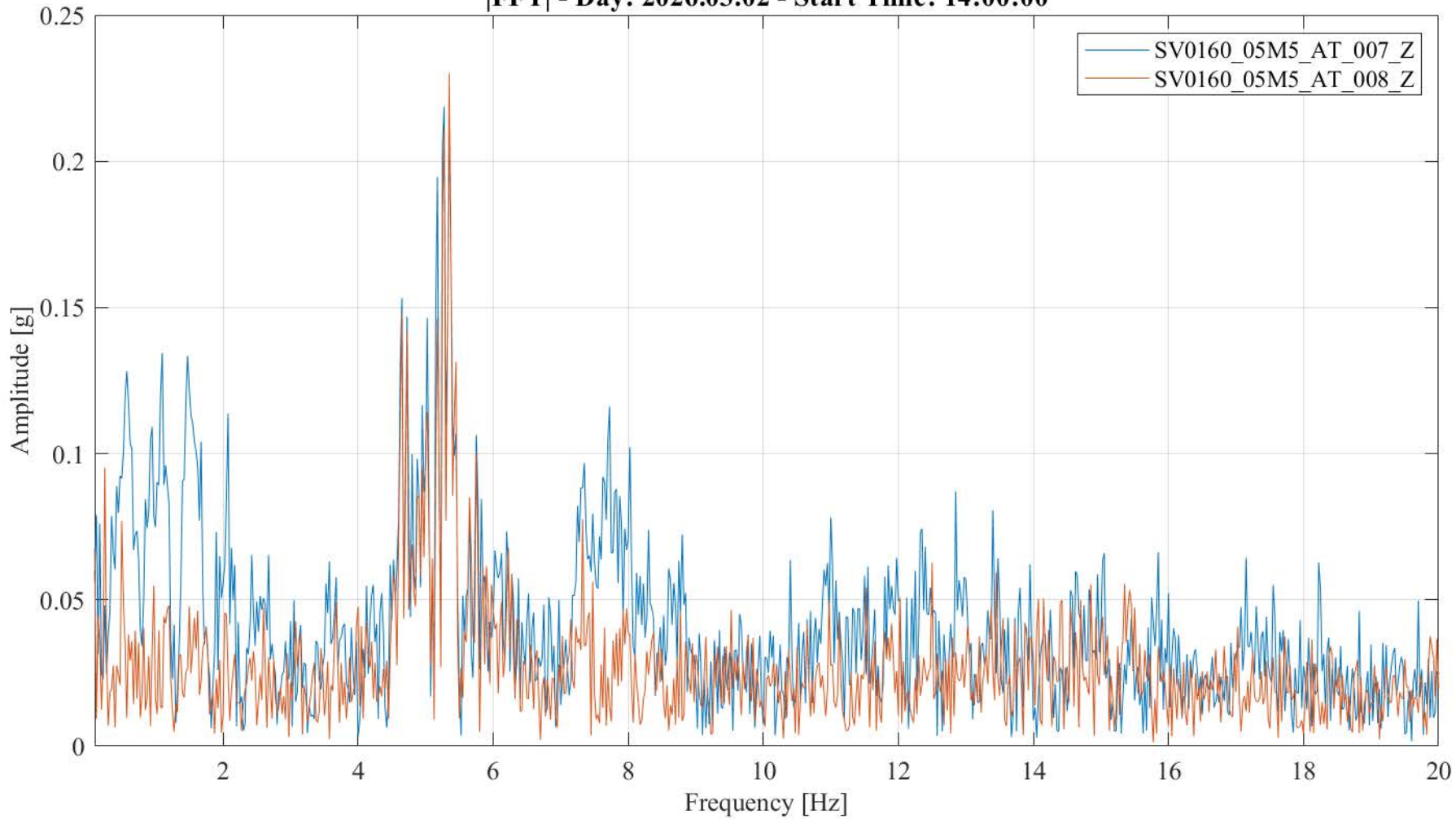
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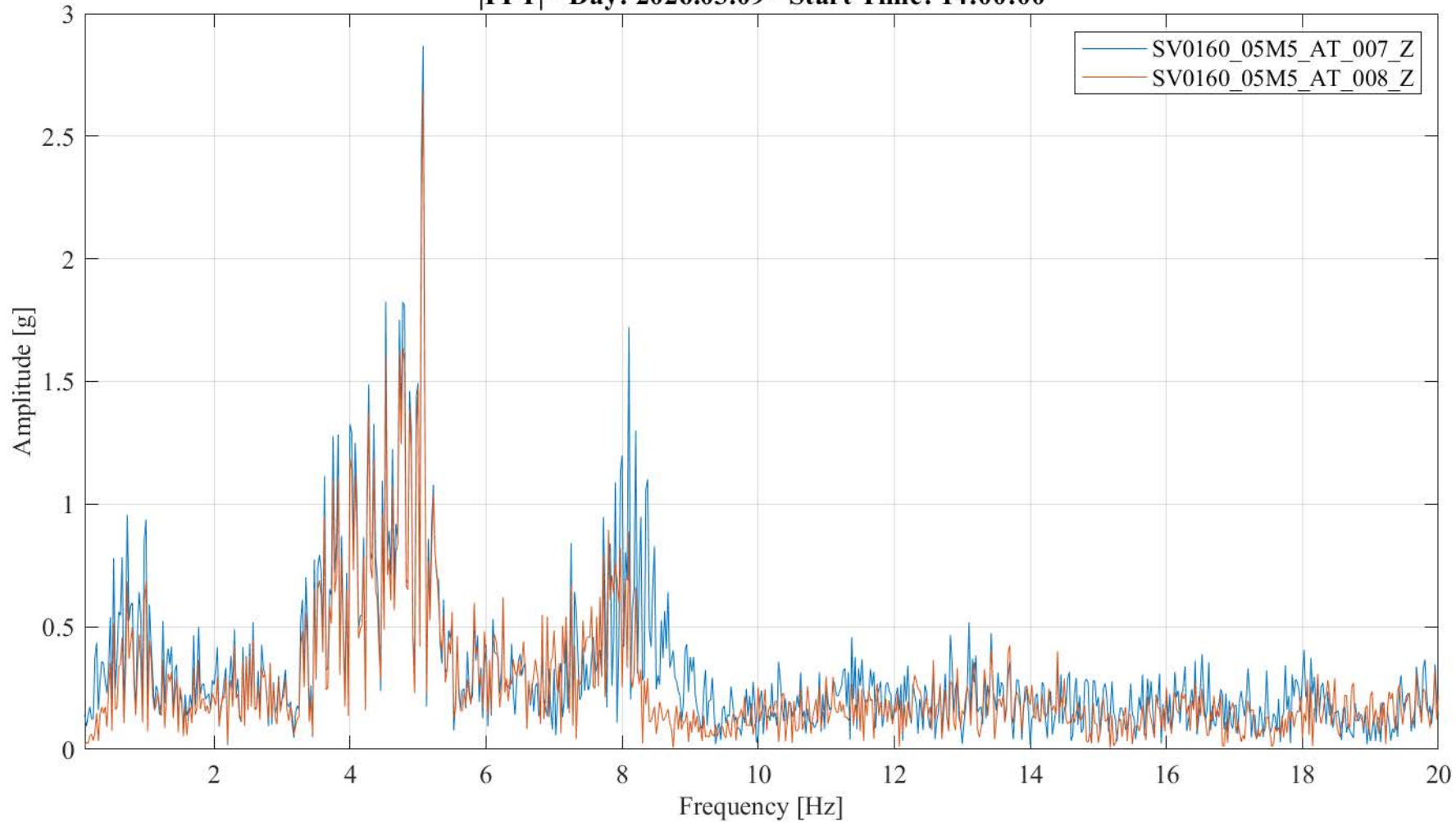
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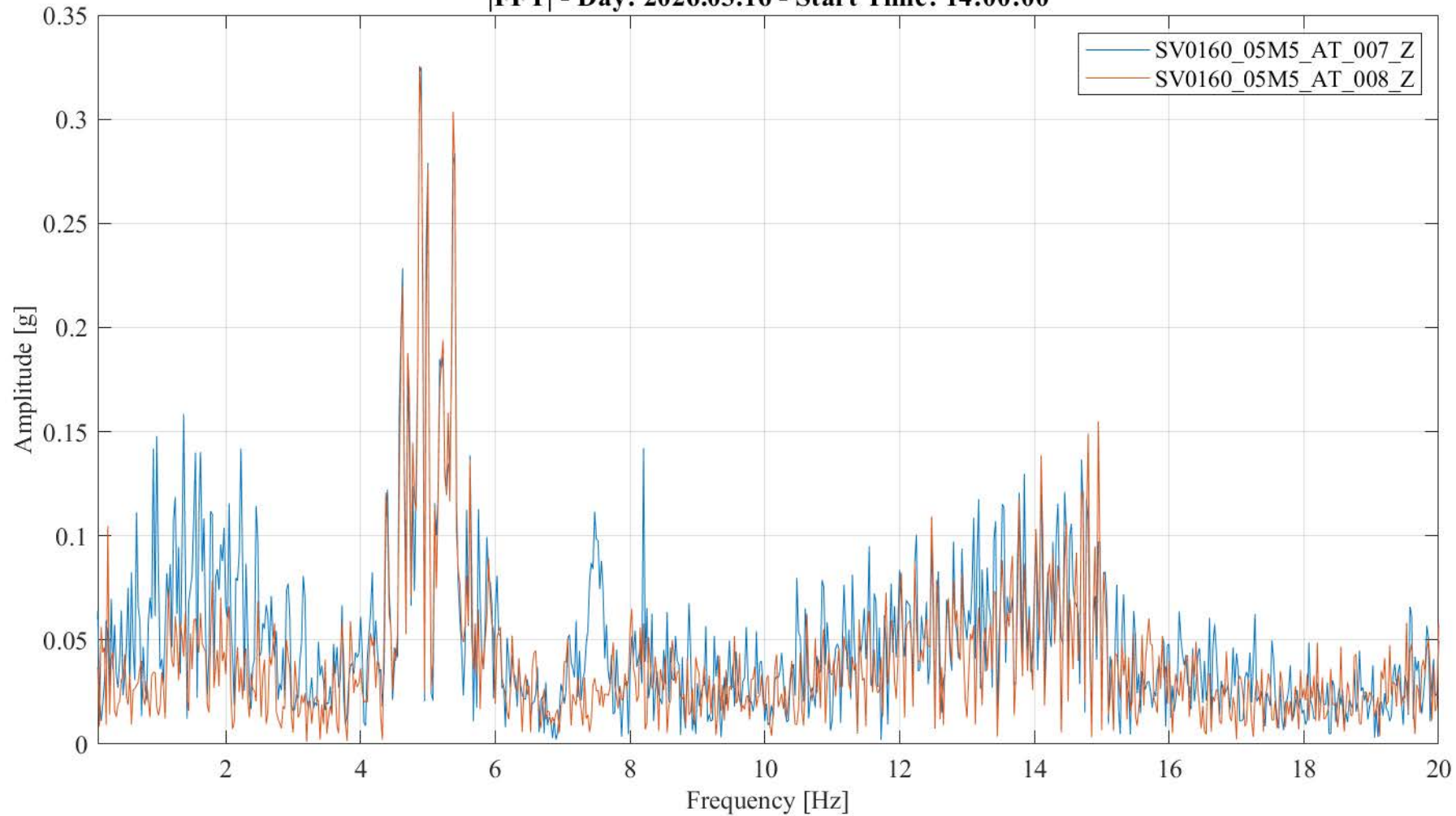
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