Deliverable

D2.5: Functional next generation sensors and hyper-dense networks

Deliverable information	
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1 Introduction

1.1 Purpose and Scope of the Deliverable

The developed next-generation sensors described in D2.4 were deployed and field-tested by RISE partners. This report presents the development of the sensors and management infrastructure, the challenges and seismic data analysis gathered in the (ongoing) field deployments.

1.2 Impact of the COVID crisis on D2.5

The COVID-19 pandemic, and the resulting global chip crisis has caused unforeseen market circumstances, which has strongly impacted the delivery of seismic sensors in the projected quantities to project partners. As a result, QUAKE was unable to manufacture and provide the projected sensor quantities to its partners as expected.

In addition, several project partners were unable to deploy the sensors in buildings and the field in the expected quantities. The pandemic-related restrictions and logistical challenges have caused delays in the procurement and installation of the sensors. This has not only impacted the data collection efforts but also the development and testing of the RLA and SHM algorithms.

Despite these challenges, the project team has been working tirelessly to mitigate the effects of the chip crisis and find alternative solutions to ensure the success of the project. This includes exploring new sensor technologies and collaborating with other partners to optimize the deployment strategies. While the situation remains challenging, the team is optimistic about the potential of the open-source QuakeSaver firmware and the impact the developed edge-computing technology can have on earthquake resilience and hazard mitigation efforts.

1.3 Acronyms

Acronym	Description
RLA	Rapid Loss Assessment
SHM	Structural Health Monitoring
SHA	Structural Health Assessment
MEMS	Micro Mechanical System
PoE	Power over Ethernet
USB	Universal Serial Bus
PGA	Peak Ground Acceleration
PHA	Peak Horizontal Acceleration
PGV	Peak Ground Velocity
RMS	Root Mean Square
EEW	Earthquake Early Warning
ANI	Ambient Noise Interferrometry
API	Application Programming Interface
V	Volts
Hz	Hertz
g	Earth’s Standard Acceleration

2 Next Generation Sensors

QuakeSaver has created two cost-effective smart seismic sensors as part of the RISE project. The first sensor is a short-period, highly sensitive device designed for real-time monitoring of buildings and seismic activity at local, regional, and tele-seismic distances. It is suitable for deployment both indoors and in harsh outdoor environments. The second sensor is a compact device equipped with a cost-effective low -noise MEMS accelerometer that is specifically designed for indoor installation and building monitoring purposes as well as strong-motion monitoring. This sensor is favourable for large-scale SHM and RLA applications.

2.1 QuakeSaver MEMS

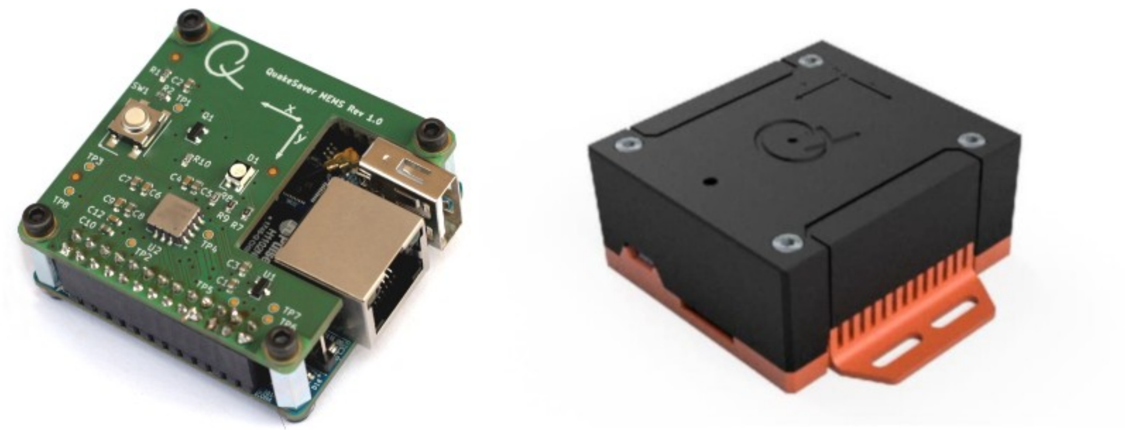

Figure 1: QuakeSaver low-noise 20 -bit MEMS accelerometer for strong-motion monitoring. (left) The bare-bones compute unit with Ethernet port for scale. (right) The sensor unit enclosure for indoor deployment in buildings.

The QuakeSaver MEMS sensor developed during the RISE project is characterized by the following features (as shown in Figure 1):

- It includes a low noise 3-component MEMS accelerometer with a resolution of 20 bits, which allows for a variable sampling rate of 50 Hz, 100 Hz, and 200 Hz, and a configurable range of 2 g and 4 g.
- The sensor requires a 5 V power supply, which can be provided through a USB connection or Power over Ethernet (PoE). Its power consumption is approximately 1 Watt.
- It can be connected to a network through Wi-Fi and Ethernet interfaces and remotely configured.

2.2 QuakeSaver HiDRA

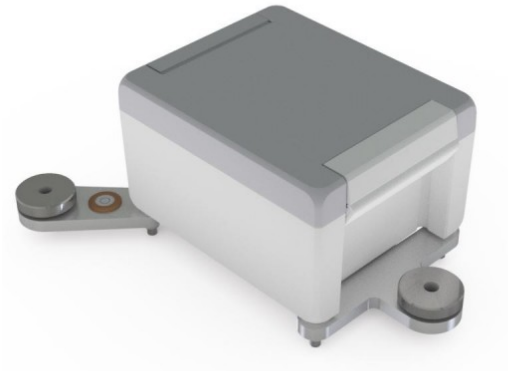

Figure 2: QuakeSaver highly-sensitive 24 bit short-period and combined accelerometer HiDRA smart seismic sensor for use in harsh outdoor environments, following IP67 standard.

The QuakeSaver HiDRA sensor (Fig. 2) has the following key features:

- A 3-component short-period seismometer with a 0.5 Hz cut-off frequency.
- An ultra-low noise 24-bit ADC (RMS1 ~2 counts; 139 dB) that offers a variable sampling rate of 50 Hz, 100 Hz, and 200 Hz and analog pre-amplification options of 1x, 2x, and 4x.
- A low noise 3-component 20-bit MEMS accelerometer that can be set to a variable sampling rate of 50 Hz, 100 Hz, and 200 Hz with the option to configure acceleration range between 2 g and 4 g (if desired).
- Gain factors and sampling rates are remotely configurable
- A power supply that can range from 9 to 18 V for flexibility.
- A hygrometer, barometer (measuring atmospheric pressure), and temperature sensor for continuous monitoring of system and instrument health.

3 Development

3.1 Real-Time System Architecture

Within the RISE project we developed a versatile software architecture for large and smart seismic monitoring networks that enables open-source signal-processing edge computing by the sensor instrument. This novel and innovative approach provides new avenues for data handling and real-time processing, facilitating swift integration into exposure maps and rapid loss assessment (RLA) models. Notably, the sensor firmware is coded in both C and Python programming languages, with the former ensuring steady and reliable data acquisition for time-critical tasks and the latter facilitating the development of high-level functions. To promote stakeholder involvement, the code and software API are described in online documentation, easing integration of signal processing plugins for applications like structural health monitoring (SHM) (WP4), global dynamic exposure (WP6), or rapid loss assessment (T4.1 and 7.1). Additionally, the web management consoles for the sensor and central fleet management are written in modern TypeScript using the Vue3 framework, enabling easy visualisation of seismic data and data products for effective communication with stakeholders and network operators via real-time web frontend as well as programmable web APIs.

To further facilitate the integration of developed services and data access to raw as well as higher level data products an open sources Python client is currently under development (https://github.com/QuakeSaver/quakesaver-client). This will allow interfacing sensor network data in few lines of code, despite the already implemented interfaces such as FDSNWS or seedlink.

The architecture and frameworks provide easy maintenance and feature extension, such as the integration of sophisticated processing schemes and visualisations. Collaborative development and research with RISE partners are pivotal for populating the ecosystem and exchanging endpoints with meaningful data processing modules tailored to stakeholder needs, such as building dominant frequency analysis.

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A detailed system architecture, data exchange formats and APIs is described in D2.4.

3.2 Edge Computing for Seismic Monitoring

The developed smart seismic sensors employ edge computing technology to provide scalability and large-data benefits. With edge computing, data processing and analysis occur on the device itself, reducing the amount of data that needs to be transferred to a centralized server. This not only reduces network congestion but also minimizes latency, allowing for real-time processing and analysis of data. In the context of seismic monitoring, this means that critical data can be rapidly processed and analyzed, allowing for faster detection of seismic events and more efficient implementation of safety protocols.

Furthermore, edge computing enables the developed QuakeSaver sensors to scale its sensor network easily. By processing data locally, the network can be expanded without requiring a significant increase in centralized processing power. This reduces costs and enhances the network's reliability by reducing its dependence on centralized processing resources. Moreover, by employing open-source signal processing software, QuakeSaver enables research institutions, national stakeholders and third-party developers to contribute to the development of the smart network's capabilities, resulting in a more robust and feature-rich sensor network. Overall, the use of edge computing technology in QuakeSaver's smart seismic sensors provides numerous benefits, including scalability, real-time processing, and cost-effectiveness, making it a compelling solution for real-time seismic monitoring.

3.3 Sensor Fleet Management

Fleet management is a critical aspect of earthquake and ground-motion sensors. With our comprehensive fleet management system, we empower network operators to manage and monitor their entire sensor network with ease. Our system provides real-time data visualization, fleet status monitoring, and sensor health diagnostics. As well as direct access to data through web APIs. At the same time QuakeSaver sensors can integrate into existing infrastructure (e.g. SeisComp3) via standard data exchange inferfaces.

Our fleet management system is designed to minimize on-site maintenance overhead and ensure crucial reliability of large fleets of earthquake and ground-motion sensors. It leverages cutting-edge technologies to enable remote firmware updates, automated meta data organization, and data processing on-the-edge. With this comprehensive suite of tools, seismic sensor network operators can monitor their sensor network's health and performance, quickly troubleshoot any issues that arise, and ultimately provide crucial input to hazard models, RLA and SHA to make informed decisions.

3.4 Metadata Management

Ensuring the accuracy and reliability of seismic data is of utmost importance in the field of earthquake and ground-motion monitoring. In this regard, the meta data of sensors, which includes operational information such as their location, sampling rate, and other relevant details, plays a vital role. Despite that, meta data handling can be cumbersome especially when sensor locations are changed, sampling rates modified or devices exchanged during a mission. To address this issue and to ensure consistency and integrity of this data, we have developed a system that enables sensors to record and maintain their own meta data.

This innovative approach eliminates the risk of errors and inconsistencies that may arise from manual data entry or reliance on external sources for meta data. With this system in place, the network operator can have access to the up-to-date information in StationXML format, which is crucial for effective data analysis and interpretation.

In addition, we recognize that a proper and automated meta data organization is particularly important for large-scale monitoring networks. As such, we have implemented a comprehensive system that ensures efficient management and organization of meta data across multiple sensors and network nodes. This system is designed to streamline the data collection and management process, while also minimizing the risk of errors or discrepancies.

3.5 Website and Documentation

To grow the seismic networks we extended the website and online documentation for the network operators. Both available at https://quakesaver.net. Our goal was to create a website that would not only showcase the features and capabilities of QuakeSaver, but also provide a user-friendly experience that would allow visitors to easily navigate and find the information they need.

4 Field Deployments

Figure 3: Test installation of colocated MEMS and HiDRA sensor.

We shipped dozens of QuakeSaver sensors to our RISE partners across Europe (WP4 and WP6), where they were strategically deployed in carefully chosen buildings and locations to monitor ground motion and gain valuable insights into building responses.

These institutions include the Swiss Seismological Service at ETH Zurich. In addition, the Montenegro Seismological Observatory deployed QuakeSaver sensors in a variety of low- to high-rise buildings to assess the seismic hazard and building vulnerability in this seismically active region. ISTERRE in Grenoble France received sensors for test installations in the well-monitored city hall.

These deployments, among others, have enabled us to collect data on ground motion and building response (WP4 and WP6), which has helped to improve our understanding of seismic hazards and advance earthquake engineering and resilience. It further enhanced the sensor eco-system in terms of its feature richness and applications.

4.1 UCG Montenegro

Our partners in Montenegro have successfully installed QuakeSaver sensors across four different buildings ranging from low to high-rise. The placement of these sensors has been carefully chosen to capture data on the structural response of buildings to seismic events. The data collected from these sensors is analyzed to gain insight into the structural health of the buildings.
We had several bilateral very fruitful discussions with the partners at UCG Montenegro from which numerous improvements arouse. Most notably the python client (https://github.com/QuakeSaver/quakesaver-client) was driven by their feedback as structural engineers who are less familiar with the protocols usually used commonly in the seismological domains. The result is a significantly simplified API for data integration of our sensor data across scientific domains.

4.2 ISTERRE Grenoble

The city hall in Grenoble has provided a unique opportunity for ISTERRE partners to investigate the structural health of a critical public building. The QuakeSaver MEMS sensors, along with the HiDRA sensor, are integrated into the building's structure and provide real-time data on ground motion and building responses. The building is being used as an experimental playground for structural health experts at ISTERRE and the University of Grenoble to test their latest methods and techniques for structural health monitoring.

The data collected by the QuakeSaver sensors in the city hall is being used to develop and validate new algorithms for structural health monitoring. The installation helped in the development of new techniques for real-time monitoring of building structures, which will improve the resilience of critical infrastructure in earthquake-prone regions.

4.3 ETH Zurich

A dozen sensors were shipped to partners at ETH Zürich in Switzerland. Their installation was delayed due to the COVID pandemic and delays in the instrumentation of the pilot site in Vallais. ETHZ tested the MEMS sensors with regard to their noise characteristics. They also provided significant feedback which drove the sensor development and their features as well as when designing the more sensitive HiDRA sensor.

4.4 NIED Japan

The MEMS network installed by colleagues from Japan is a crucial component in their ongoing efforts to improve seismic monitoring. The network is currently targeting a range of different structures, including single buildings as well as high-rise buildings such as the 43-story Tokyo Metropolitan Government Building. With the installation of QuakeSaver MEMS sensors, the

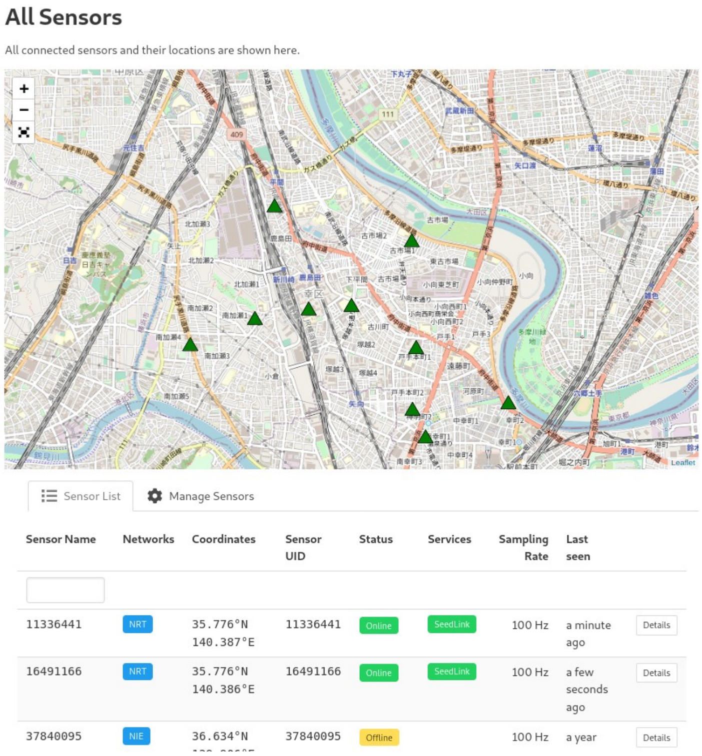

Figure 4: Network management of sensor fleets through an intuitive browser interface. Sensors' digital twins can be managed and monitored remotely (MS37). The map shows the distribution of sensors in Kawasaki during an earthquake drill experiment.

network is providing data that can be used to better understand the dynamics of these structures during seismic events. The data can be analyzed to identify the modes of vibration, natural frequencies, and other key parameters that are critical for assessing the seismic performance of the structures.

Moreover, the data from the MEMS network can be used to improve the accuracy of earthquake early warning systems. By detecting the arrival times of primary and secondary seismic waves, it is possible to estimate the location, magnitude, and expected ground motion of an earthquake. The use of QuakeSaver MEMS sensors in these systems is particularly important because of their low power consumption and small size, which makes them ideal for deployment in large numbers.

Figure 5: Twelve QuakeSaver sensors are installed in the Tokio Metropolitain Government Building by RISE partners at National Research Institute for Earth Science and Disaster Resilience (NIED).

Several deployments of QuakeSaver sensors were maintained by ERI and NIED to investigate how people can better use the sensors in buildings. The deployments took place in 2021 in the Zama region southwest of Tokyo and in 2022 in the greater Tokyo region, see Fig. 6. In both deployments the participants were split into two groups, one with sensors at home and a control group without sensors. After every event that potentially could have been felt, all participants were sent a questionnaire about how they felt the earthquake, how they interpret the sensor output and whether or not the reported intensities by the sensor and by the official network match the felt intensity. Results showed that the sensors located on various stories report the expected different intensities but no residual bias in the sensor reports were found beyond that expected for the floor in question due to the natural response of the building.

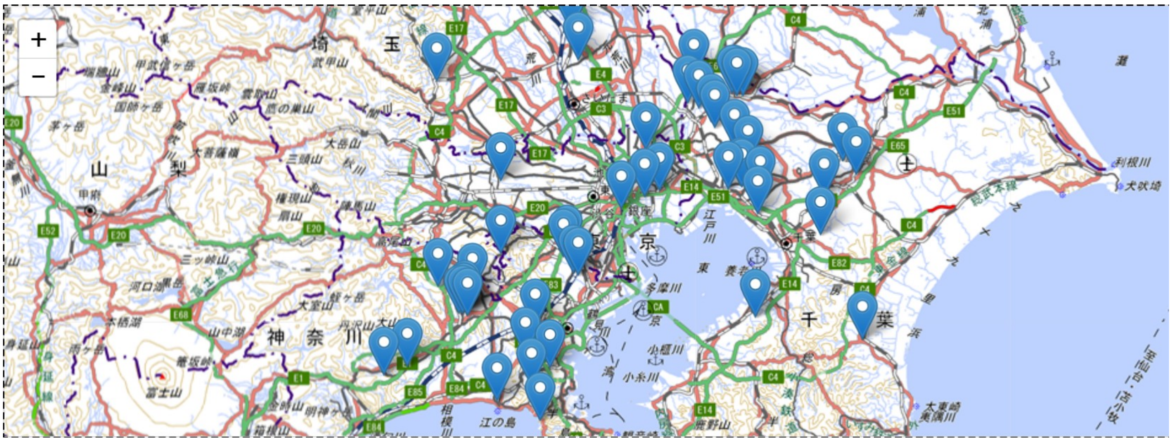

Figure 6: Distribution of Sensors in the greater Tokyo experiment 2022.

5 Real-Time Data Aggregation at RISE Pilot Locations

5.1 Ground Motion Analysis

The QuakeSaver smart seismic sensors are designed to continuously process basic ground-motion parameters, providing accurate and reliable measurements of seismic events and site conditions. The sensors are capable of detecting and recording peak ground accelerations (PGA), peak horizontal acceleration (PHA) and velocity (PGV), which are critical parameters used to assess the potential damage and hazards that can be caused by an earthquake. The real-time availability of these measurements allows for rapid assessment and response in the event of an earthquake, making the QuakeSaver sensors an essential tool for earthquake monitoring and early warning systems.

In addition to the aforementioned parameters, the QuakeSaver sensors also calculate real valued instrument intensity, such as Modified Mercalli Scale, Japanese intensity measures (Shindo) or spectral intensities. The real valued instrument intensities are based on ground motion measurments and provide a proxy for shaking intensities, thus providing critical insight into the local ground shaking and site conditions. These parameters are crucial for understanding the impact of an earthquake on the environment and infrastructure, as well as for assessing the risks associated with future seismic activity. The sensors also measure RMS as a means of determining the average signal amplitudes and site noise conditions. The availability of these parameters in real-time is a significant benefit for seismic monitoring, as it allows for efficient data analysis and decision-making, especially in situations where time is essential. This data is particularly valuable for both Rapid Loss Assessment (RLA) and Structural Health Monitoring (SHM) applications.

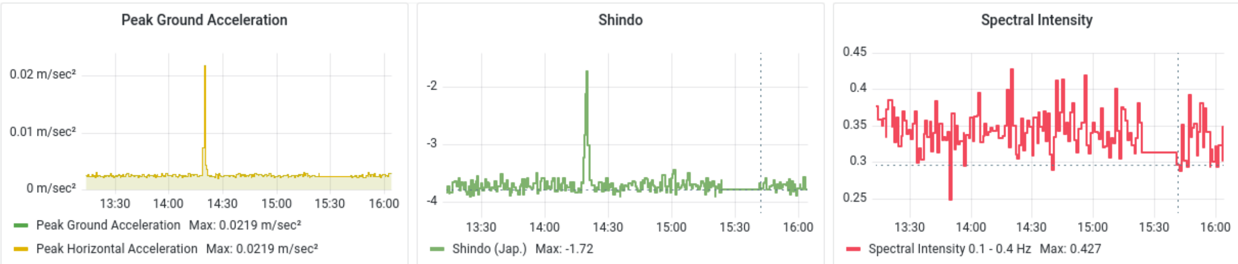

Figure 7: Real-time ground monitorings from the Montenegro network showing caluclated peak ground acceleration, Japanese intensity measure (Shino) and spectral acceleration.

5.2 Horizontal over Vertical Spectra

Horizontal over Vertical (H/V) spectra are important parameters for assessing the potential damage and hazards that can be caused by an earthquake. QuakeSaver smart seismic sensors continuously calculate H/V spectra, which provide critical information about the resonant frequencies of a building or structure. This data is valuable for both Rapid Loss Assessment (RLA) and Structural Health Monitoring (SHM) applications.

For RLA, H/V spectra can be used to estimate the peak ground acceleration and velocity, which are fundamental parameters for assessing the damage potential of an earthquake. For SHM, H/V spectra can provide insights into the dynamic behavior of a structure, including its natural frequencies and modes of vibration. This information can be used to identify potential structural weaknesses or damage, and to guide decisions about necessary repairs or retrofits.

With the ability to continuously measure and analyze H/V spectra on the edge, QuakeSaver sensors offer a powerful tool for both RLA and SHM applications. This real-time data can enable rapid decision-making and response in the event of an earthquake, and can help to improve the resilience of structures and communities in earthquake-prone regions.

Figure 8: Continuous H/V spectra delivered by a QuakeSaver MEMS sensors installed in a 13 storey building by RISE partners in Switzerland. Clear Eigenfrequency modes of the building are visible in the delivered data.

5.3 Single Station Ambient Noise Auto-Correlation

Single station auto correlations, also known as ambient noise interferometry (ANI), are a powerful tool for Structural Health Monitoring (SHM) and Rapid Loss Assessment (RLA) applications. By utilizing the continuous noise signal recorded by smart seismic sensors, the method calculates cross-correlations between pairs of signals from a single station, providing information about the subsurface velocity structure. This information can be used to identify changes in the structure of buildings and infrastructure, and can also be used to estimate soil properties, which are critical for assessing the potential damage and hazards caused by earthquakes.

In addition to providing valuable information for SHM and RLA, the noise interferometry technique is well-suited for deployment on the QuakeSaver sensors, complementing that done in Task 2.5 using national networks in Greece and Italy. The method can be computed directly on the sensor firmware, without requiring additional data transfer and processing on external servers. This allows for real-time monitoring and analysis of the seismic data, providing immediate feedback to stakeholders and decision-makers in the event of an earthquake or other seismic event. The implementation of noise interferometry on the QuakeSaver sensors enhances the overall functionality and utility of the smart seismic network for earthquake monitoring and risk assessment.

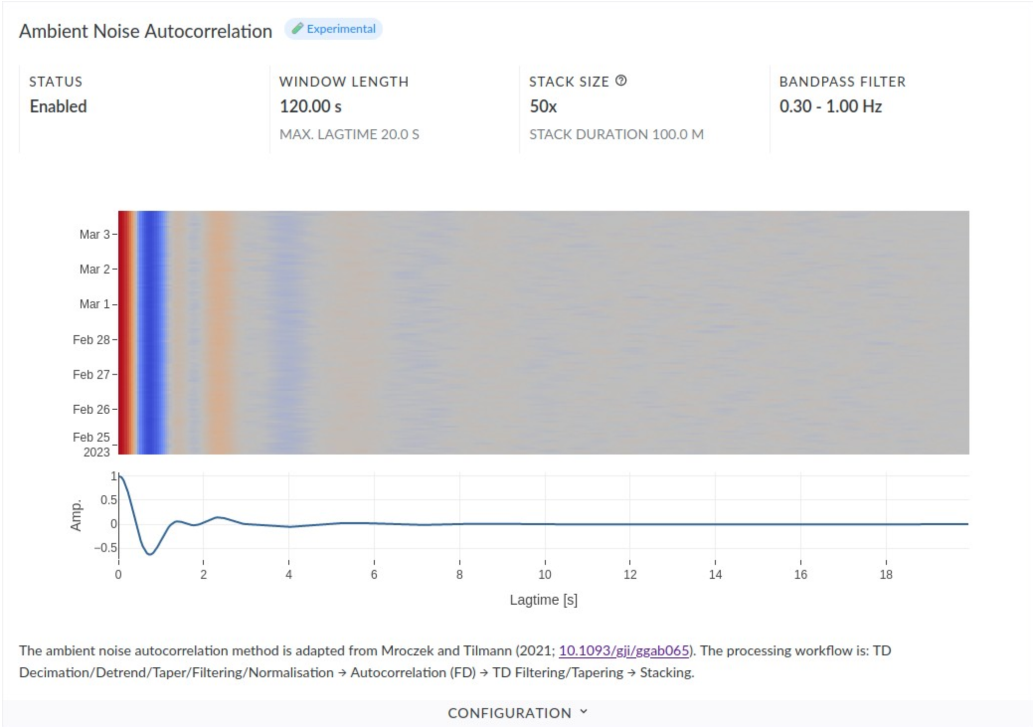

Figure 9: Noise autocorrelations calculated on the QuakeSaver sensor deployed by RISE partners in Montenegro.

5.4 Outlook: Neural Networks on the Edge

The implementation of a neural network phasepicker, specifically PhaseNet, onto the QuakeSaver sensor firmware represents a significant oportunity and advancement in the field of earthquake detection and monitoring. PhaseNet is a state-of-the-art deep learning model that is capable of accurately and efficiently detecting seismic wave arrivals in real-time. By integrating this model into the firmware of the QuakeSaver sensor, stakeholders can now benefit from the improved accuracy and speed of the neural network in detecting seismic events. This has important implications for earthquake early warning (EEW) systems and other applications that rely on accurate and timely detection of seismic activity.

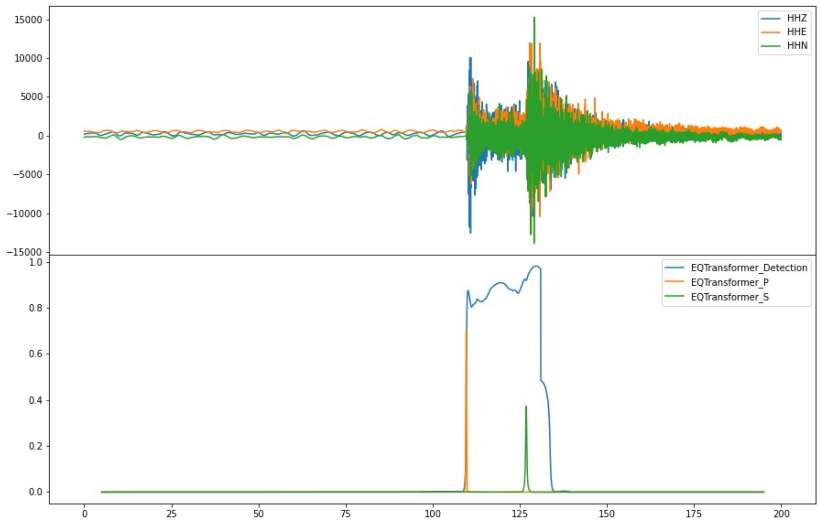

Figure 10: Example of neural network earthquake phase picks. Shown here are P and S wave phase picks dervied from PhaseNet using the SeisBench framework for neural networks in seismology.

The implementation of PhaseNet onto the QuakeSaver sensor firmware also represents a significant technological achievement in the field of edge computing made possible by RISE. By deploying the neural network onto the sensor itself, rather than relying on external processing resources, users can now benefit from the scalability and large-data benefits of edge computing. This means that the QuakeSaver sensors can operate autonomously, processing data locally and providing real-time alerts without the need for external computing resources. This not only improves the reliability and speed of earthquake detection and monitoring, but also makes it more accessible and cost-effective, particularly in areas where computing resources are limited or unreliable.

6 Growing Networks from QuakeSaver Open Sensor Platform

The COVID pandemic had a significant impact on global supply chains, including the chip industry. This led to a chip crisis, resulting in an unforeseen market circumstance that affected the delivery of QuakeSaver seismic sensors to project partners. The project partners were facing significant challenges in deploying the sensors in the expected quantities, and the delays were causing substantial setbacks in the research and development process.

To mitigate the effects of the COVID/chip crisis and build on the legacy of RISE the sensor firmware is released as open source. This provides a unique opportunity to grow seismology, particularly with regards to structural health assessment (SHA) and rapid loss assessment (RLA). The firmware, which is designed for smart seismic sensors, is based on the Yocto Embedded Linux stack and uses Mender as the industry-grade update mechanism for remote over-the-air updates of the sensor operating system underlingin our commitment to provide a system that can securely operated for long time periods. The firmware allows for reliable, continuous monitoring of seismic activity and records crucial meta-data such as location and sampling rate. With the implementation of neural network phase picker (PhaseNet), H/V spectra and single station auto-correlations, the firmware is able to provide accurate ground motion parameters that are essential for assessing the potential damage and hazards caused by an earthquake.

The open source nature of the firmware will enable the seismology community to build upon the existing code base and develop new applications that leverage the capabilities of smart seismic sensors. This can lead to the growth of large-n networks that provide more comprehensive coverage of seismic activity. Additionally, the ability to process data on the edge using advanced signal processing techniques provides significant benefits for SHA and RLA. Real-time processing of data from multiple sensors allows for early detection of structural damage and more accurate assessments of building safety. Overall, the release of QuakeSaver open source firmware is a significant step towards improving seismic monitoring and building safer and more resilient communities.