Deliverable

D2.4 : Field ready internal next generation sensors

Deliverable information	
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2. Summary

QuakeSaver developed two kinds of connected smart seismic sensors for monitoring within the RISE project: (1) A cost-effective and highly sensitive seismometer for monitoring buildings and seismicity at local, regional and global scale. (2) An affordable, integrated MEMS accelerometer for monitoring strong motion and the structural health of high-rise buildings.

The sensor software platform is connected to retrieve information in real-time and configure the sensors remotely. Furthermore, the developed sensor software serves as a foundation for RISE partners to access the computing capabilities of embedded devices to extract meaningful hig(h-level data products from the sensor time series, through an extensible software plugin mechanism.

3. Smart Seismic Sensor Development

Within the RISE project, QuakeSaver developed two affordable smart seismic sensors: (1) a highly sensitive short-period sensor real-time building monitoring for seismic monitoring of seismicity at local, regional and tele-seismic distances. These sensors are designed to be deployed indoors and in harsh outdoor environments. (2) A compact sensor for indoor installation equipped with a low noise MEMS accelerometer for building monitoring.

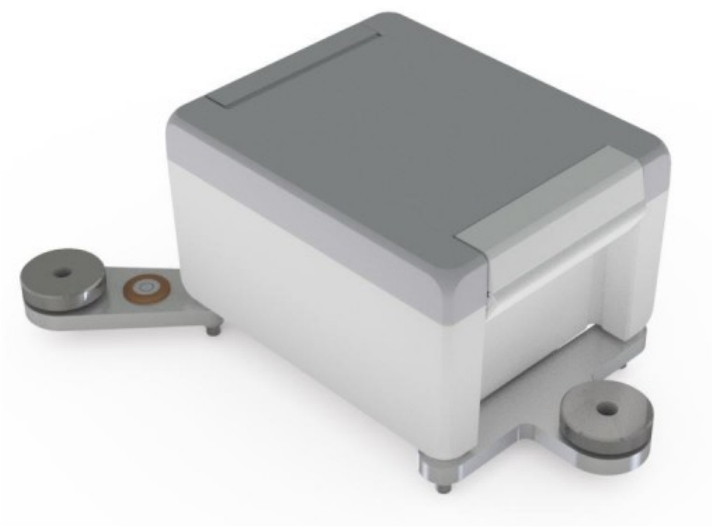

Figure 1: QuakeSaver highly-sensitive 24 bit short-period and combined accelerometer HiDRA smart seismic sensor for use in harsh outdoor environments, following IP67 standard.

Key features of the short-period QuakeSaver HiDRA sensor (Fig. 1) are:

- 3-component short-period seismometer with a cut-off frequency f_c of 0.5 Hz.
- Ultra-low noise 24-bit ADC (RMS[1] ~2 counts; 139 dB) with variable sampling rate of 50 Hz, 100 Hz and 200 Hz and analog pre-amplification 1x, 2x and 4x.
- Low noise 3-component 20-bit MEMS accelerometer with variable sampling rate from 50 Hz, 100 Hz and 200 Hz and configurable acceleration range of 2 g and 4 g (optional).
- Flexible power supply from 9 to 18 V.
- Hygrometer, barometer (atmospheric pressure) and temperature sensor for continuous system and instrument health monitoring.

[1]Root mean square

- Time synchronisation via NTP and/or external GNSS antenna[2].

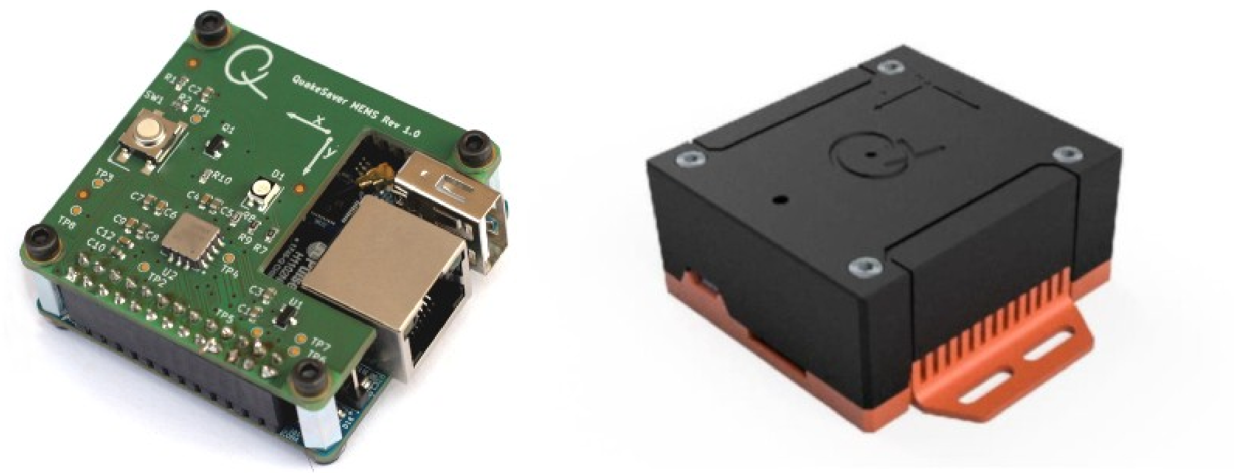

Figure 2: QuakeSaver low-noise 20 bit MEMS accelerometer for strong-motion monitoring. (left) The bare-bones compute unit with Ethernet port for scale. (right) The sensor unit enclosure for indoor deployment in buildings.

Key Features of the QuakeSaver MEMS (Fig. 2) sensor developed in the RISE project:

- Low noise 3-component 20-bit MEMS accelerometer with variable sampling rate from 50 Hz, 100 Hz and 200 Hz and configurable range of 2 g and 4 g.
- 5 V Power supply over USB. Power consumption ~1 Watt.
- Connected via Wi-Fi and Ethernet.

Advances in sensor, communication and embedded computation technology allowed the development of low-cost 20 bit strong-motion sensors. The evaluation and testing of QuakeSaver MEMS sensors was undertaken with RISE partners at ETH Zürich (MS10). The feedback from the conducted sensor tests was important and taken into account during development iterations which led to the development of highly sensitive dampened velocity-proportional coil transducers. The development led to a hight sensitive (24 Bit) sensor with adaptable dynamic range and analog gain which is suited for a variety of operations from monitoring noise in ambient conditions and structures to local and teleseismic events.

4. Network and System Architecture

Within the RISE project, we developed a flexible software architecture that empowers the sensor instrument to process the data “on-the-edge”. This innovative approach opens new ways for data handling and real-time processing of the data for swift integration into exposure maps and rapid loss assessment (RLA) models. Already implemented data products for example are Peak-Ground-Acceleration and Velocity (PGA/PGV) and instrument intensities (e.g. spectral intensity of JMA Shindo). Additional data products are on the roadmap for this year such as PPSDs and neural networks for event onset detection.

The sensor firmware is written in the programming languages C and Python. C programming language is used for all time-critical tasks, thus ensuring a steady and reliable data acquisition. High-level functions are written in modern-style Python programming language. The code and software API is described in online documentation, to ease the integration of signal processing plugins by stakeholders, e,g, for structural health monitoring (SHM) applications (WP4), global dynamic exposure (WP6) or rapid loss assessment (T4.1 and 7.1).

[2] GNSS time synchronization is currently a prototype feature

The web management consoles of the sensor and central fleet management are written in modern TypeScript using the Vue3 framework. These interfaces are being used for visualising seismic data and data products for easy communication with the stake holder and network operator (RISE). The architecture and frameworks allow easy maintenance and easy extension of features, such as integration of sophisticated processing schemes and visualisations.

We rely on cooperative development and research with RISE partners to fill this ecosystem and exchange endpoints with meaningful data processing modules e.g. analysis of dominant frequency of a building, tailored to the demands of stakeholders.

5. System Design

Central in the system design is a reliable autonomous sensor firmware that can communicate in an secure manner with a central message broker (RabbitMQ). This communication is two-way and handled in almost real-time. This means that datagrams can be received (e.g. configuration) by the broker and sent to the broker (e.g. waveform or data products). This design also enables inter-sensor communication, which can be used to calculate inter-sensor data products such as inter-story drift.

The leveraged open-source software libraries (e.g. for signal processing and real-time data communication) as well as services (e.g. database and message broker) were chosen to be compatible with an open-source licensing scheme that will allow us to publish the sensor software stack as open-source.

For an overview of the technical architecture see Figure 3.

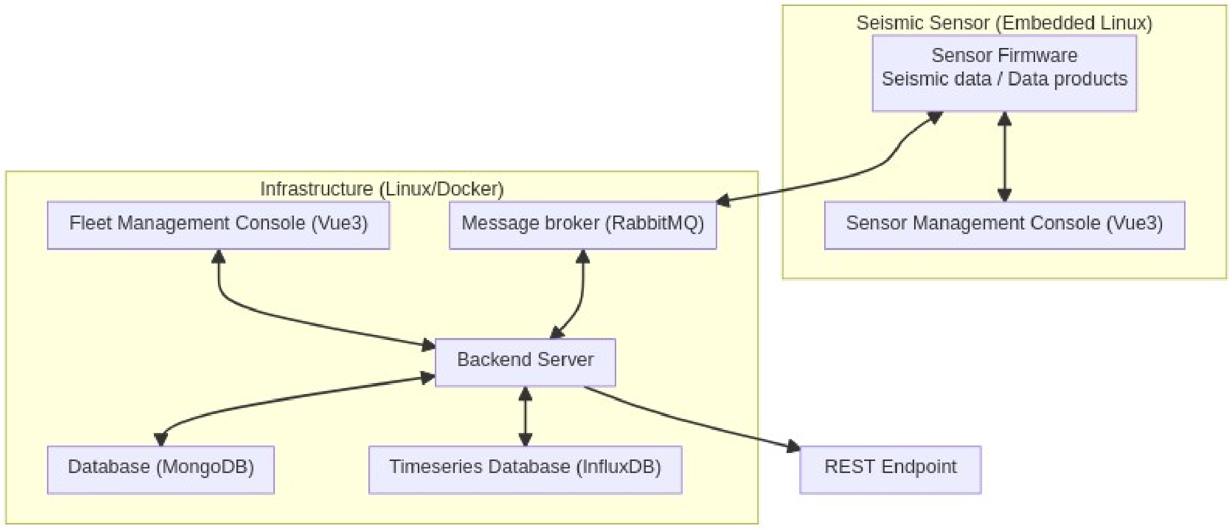

Figure 3: Flowchart showing the architecture and design of the smart seismic network solution.

6. System Operation Reliability and Maintainability

The firmware shipped to the sensors is tailored to the hardware and leverages the Yocto[3] Embedded Linux stack. The operation of sensors connected to the internet implies a high responsibility to secure the system against intrusion from third parties (hackers). Software patches must be deployable at any time to the entire fleet to quickly fix security issues including the underlying embedded linux stack. To our surprise we found this to be a neglected aspect in others vendors sensor products.

The sensor system developed in RISE relies on Mender[4], an industry proven update mechanism for remote over-the-air (OTA) updates. The industry-grade update mechanism uses an A/B strategy to reliably test entire new firmware images on the sensor on a previously inactive partition. If the update is accepted by the sensor, the updated partition becomes the active partition while the previously active partition is ready to receive the next update. If the update gets rejected (e.g. due to a network outage) the device continues operation in the previous state. This ensures reliable system and firmware upgrades to roll out security patches and new features for the seismic sensors remotely.

This minimizes the on-site maintenance overhead and crucial reliability of large fleets of earthquake and ground-motion sensors. This technology is open-source and development driven by the Linux foundation.

To ensure data and system integrity we follow best security practices also on the server side. All traffic is encrypted and only required ports opened following the principle of least privilege. Sensitive components are protected within a virtual private network using wireguard[5] to minimize potential attack vectors. All server components are managed in using ansible[6] to ensure reproducibility, scalability and resilience of the infrastructure.

7. Data Exchange and Metadata

QuakeSaver sensors implement well-established data exchange protocols for streaming the seismic data in real-time to central data centres, such as SeedLink (SeisComp3; T2.4) which is the de-facto international standard. Our custom implementation reduces the latency of seismic data streams to a minimum (at the cost of data traffic).

Other means of data distribution are FDSN[7] dataselect, which is implemented on the sensor itself and in the management console for central data aggregation.

The metadata management is carried out on the sensor itself, which keeps a complete history of the metadata and changing responses (e.g. gain and range) - thus serving a consistent repository of metadata. This automated and complete metadata handling by the sensor is a novelty. It reduces the probability of incorrect metadata - a common and costly (time) issue when working with sensor metadata. The metadata are distributed via FDSN station queries in the StationXML data format.

As an outlook we are investigating the implementation of SensorML data format for circulating the metadata.

[3] https://www.yoctoproject.org/

[4] https://mender.io/

[5] https://www.wireguard.com/

[6] https://www.ansible.com/

[7] https://www.fdsn.org/

The high-level data products are distributed in JSON format through the message broker and a documented REST API which is served on the sensor as well as the central server infrastructure. To facilitate real-time communication we leverage communication over a documented WebSocket interface, thus messages and data can be pushed to the client side.

8.Sensor Fleet Management

The increased numbers of sensors and ever-increasing amount of sensor data demand sophisticated software solutions and intuitive communication design to manage the growing fleet of seismic sensors. The developed management backend allows to manage a fleet of QuakeSaver sensors in a modern and reliable fashion. An intuitive and powerful user interface can be accessed from any device and in any web browser. Sensors can be configured remotely in bulk or individually.

The digital twin of each sensor provides a detailed reflection of all state parameters and continuous data analysis. Data products are graphically presented as maps, graphs and searchable lists. accessible as descriptive GeoJSON for seamless integration in any GIS software. This enables a continuous overview and health monitoring of the entire seismic network.

We are working on a real-time alerting system to send out messages via E-Mail and other mobile clients (e.g. push notifications). These alerts can be raised when sensors go offline or critical thresholds (e.g. PGA, H/V ratios) are exceeded. This infrastructure development can integrate in T2.4 and the developed semantics leads to MS21.

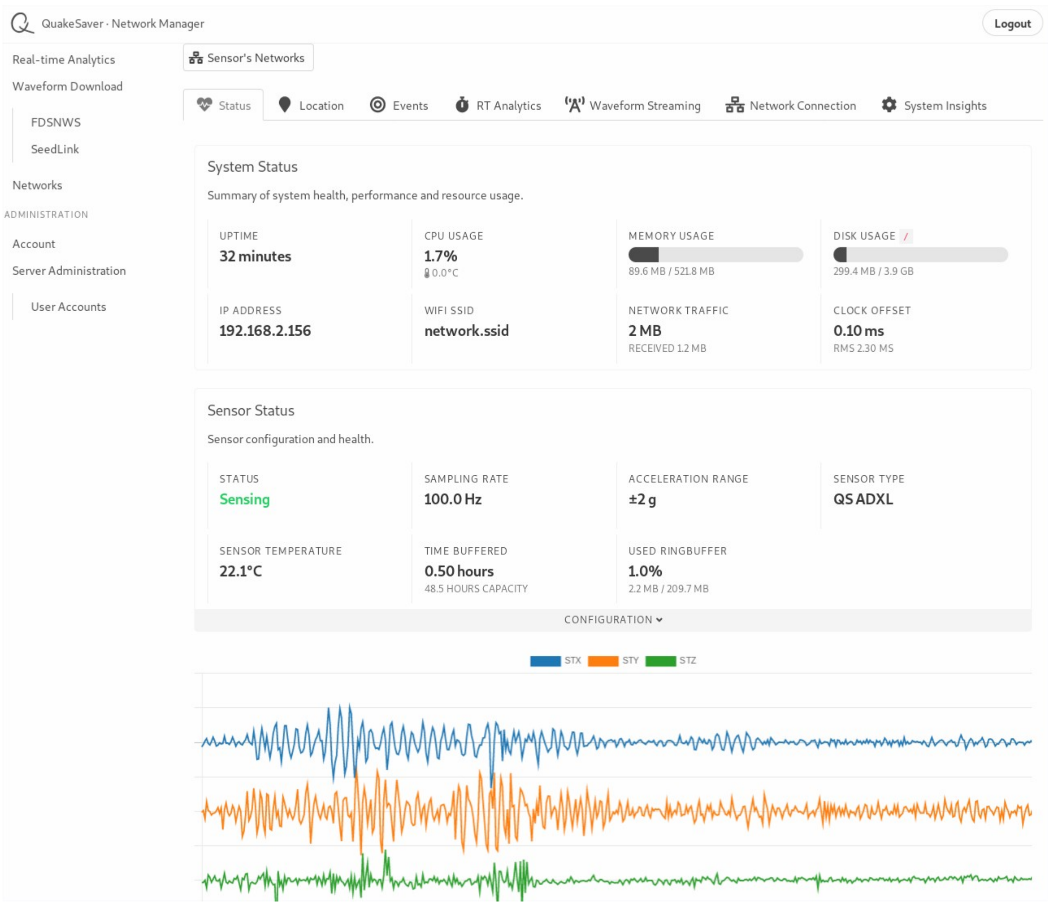

Figure 4: Sensor user interface to configure and monitor a single sensor in the field.

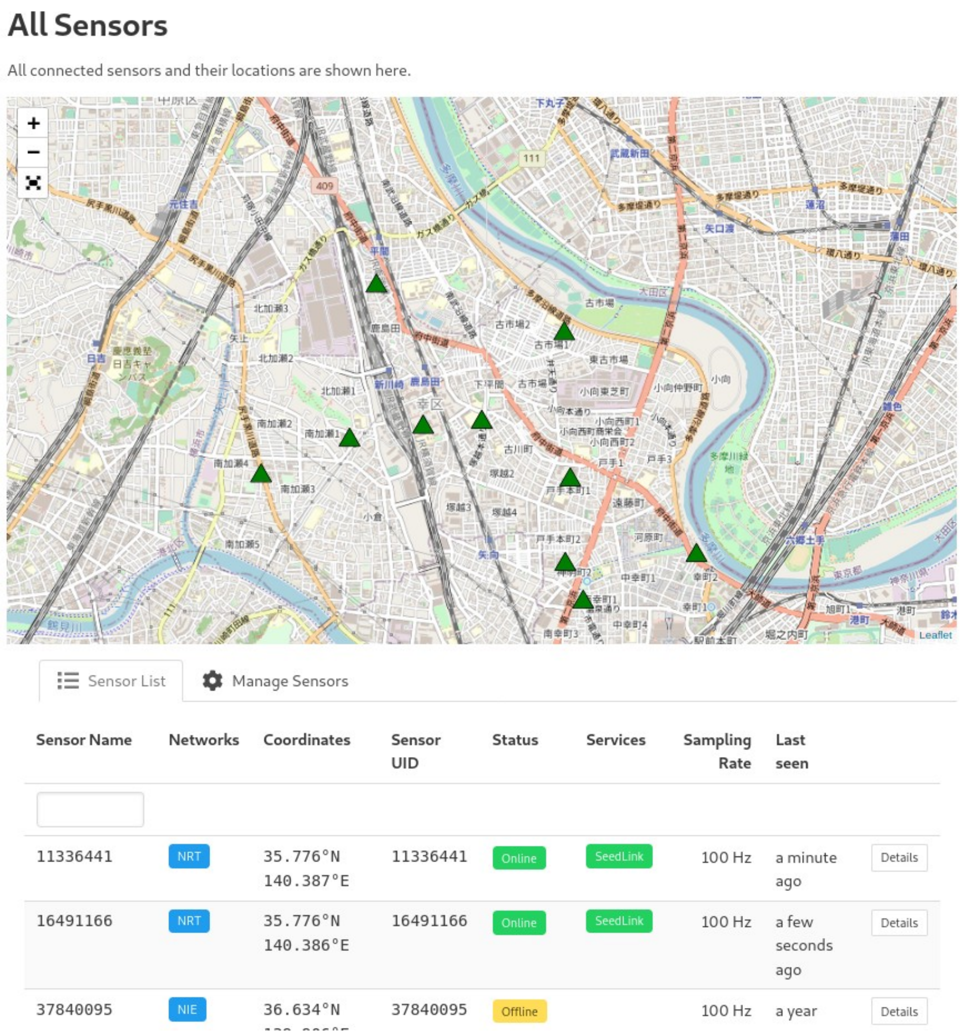

Figure 5: Network management of sensor fleets through an intuitive browser interface. Sensors' digital twins can be managed and monitored remotely (MS37).

9. Preliminary Network Deployment

As of Q2 2021 first batches of QuakeSaver MEMS were shipped to RISE partners in ETH Zürich, ISTerre Grenoble, University of Montenegro and University of Istanbul. The deployment of more QuakeSaver HiDRA and MEMS sensor nodes will follow in 2022.

The RISE project will now see a growing number of smart and cheap seismic sensors which can be exploited for real-time risk assessment.

10. Challenges and Further Work

The two different sensor types are currently under evaluation by QUAKE as well as project partners. A recently conducted study showed that the more sensitive integrated sensor has a low amplitude noise signal at 1 Hz that becomes apparent only in extremely quiet environments. This issue has been resolved in an updated PCB design by decoupling the power supply from the analog sensor front-end. This work was carried out by a QUAKE contracted electro-technical engineer. Further modifications of the PCB allow us to integrate an industrial compute platform designed for large scale embedded applications.

Unfortunately, the manufacturing of the latest prototype iteration and the MEMS sensors came to a halt following the unforeseeable global chip crisis, which is a direct result of the corona virus pandemic. This crisis has led to significant shortages of electrical parts. Across many industries including the semi-conductor industry the demand and supply chain has collapsed.

Due to unavailability of critical electrical components (e.g. MEMS accelerometer, analog-digital-converter, industrial SD cards and more) the production of more seismic sensors will be delayed until the market has recovered. Some experts estimate that the crisis will be overcome in mid-2023[8]. We are eagerly working to find alternatives for unavailable components, redesigning PCBs and taking other measures to mitigate the effect of the ongoing crisis in the best interest of the RISE project.

Our further work will engage cooperation with RISE partners to research and develop on-device algorithms to deliver meaningful real-time data products into the exposure and hazard modeling communities.

Further development of the software stack will be needed to guarantee a redundant, high availability and robust infrastructure that will scale for global application of the developed system. Funds allocated in the amendment will be dedicated to employ a professional full-stack software developer.

We will open-source the developed sensor software under free licenses (i.e. GPL) to empower and drive the sensors capabilities further together with the seismological community.

11. Impact of the global chip crisis on smart seismic sensor development

As a beneficiary of RISE QuakeSaver [QUAKE] develops seismic sensors and software for smart real-time analysis of seismic data on the device (edge-computing), as well as a unified management console and web based user interface for orchestration of large fleets of smart seismic sensors.

The instruments and software are developed, with the aim to deliver a modern monitoring solution to RISE partners in Europe (ETH Zurich, Swiss; ISTERRE, Grenoble, France; BOUN, Istanbul, Turkey; Univ. of Montenegro, Montenegro; ERI, Tokyo, Japan).

To achieve this, QUAKE has successfully developed a low-cost MEMS sensor for recording strong ground motions and ambient vibration in high rise buildings. A first batch of these low-cost MEMS sensors was shipped to partners in late 2020/early 2021, where they are tested in low- and high-rise buildings.

In discussion with RISE partners, the demand for a highly sensitive seismometer was raised. The requirement was for a low-cost instrument capable of monitoring ambient vibrations and microseismicity, important for earthquake forecasting, risk analysis and structural health monitoring. In response, QUAKE developed a short-period seismic instrument based on cost-effective modern electrical components. This was done by efficiently leveraging the developed firm- and software.

The development of the hard- and software is following the milestones (MS10, MS11). The production of the hardware is still impacted heavily by the global chip crisis since late 2020. The

[8] https://www.techtimes.com/articles/260243/20210514/global-chip-shortage-persist-until-2023-demands-pc-slightly-soften.htm

collapse of the global semi-conductor market and supply chains has led to scarcity of critical components, needed for manufacturing the instruments. The most critical being the SoC (System on a chip), high-resolution MEMS and the high-sensitivity ADC (Analog-to-Digital Converter). The components are highly integrated into the design of hard- and software and cannot be exchanged easily.

An excerpt of required parts which have been unavailable for several months to a year are the following.

The projected delivery time for the System on a Chip (SoC; Part Number: CM4104000) is June 2022.
The projected delivery time for the ADC (Part Number: AD7779ACPZ) is May 2022.

Other periphery IC components (e.g. power monitor, optocopler) are out of stock and have long lead times from the manufacturer. Only some of these ICs can be replaced by other components. That, however, requires a time and labour intensive re-design and following that a re-evaluation of the sensor PCB with regard to noise characteristics, power consumption, heat build-up and other mission critical parameters. The global chip shortage has also led to significant price increase of ICs as a whole.

Due to these unforeseen market circumstances, QUAKE cannot deliver the seismic sensors in the projected quantities. From experience, the stated IC delivery times are influenced by market dynamics and may change.

12. Focusing on RISE

Looking forward, QUAKE proposes to shift efforts and more resources to the research and development of the smart seismic sensor software and on-device real-time signal analysis. This will compensate for having fewer sensors by increasing their performance by more efficient and more flexible data handling. The real-time software and infrastructure management are key for integrating seismic data and data-products into risk models or rapid earthquake response. To support this, QUAKE hired a full-time software developer through RISE in mid 2021.

Together with RISE partners (WP2, WP6), QUAKE wants to define modern data pipelines for exchanging meaningful seismic data products in real-time. This requires a discussion on protocols and leveraged online technologies. Further QUAKE wants to engage the discussion of on-device analysis of seismic data (e.g. spectral ratios, EEW P-wave detection using neural network and other single-station methods) through the organization of a project workshop in 2022.

This more software-focused strategy will contribute to the legacy of RISE: The developed software components, firmware and software, as well as real-time plugins for seismic analysis will be published as open-source. All of these deliverables will follow the European Open Source Software Strategy. Regardless, QUAKE will pursue the delivery of seismic sensors to RISE partners following the availability of semiconductor on the market.