Deliverable

Deliverable D2.14: Assessment of the technology readiness and operational capability

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Contents

1. Summary

This report provides an assessment of the technology readiness of the new prototypes, products, services and capabilities delivered in Work Package 2 – 'Innovation' - in support of the aims of the RISE project. Section 2 introduces the Technology Readiness Level (TRL) scale, a means to indicate the maturity of a technology. The TRL for each technology in WP2 is assessed in section 3, in each case with a short narrative introducing the technology, listed by work package and referring to earlier deliverables and publications where appropriate, and a Table summarising the challenges addressed, the new technologies, an assessment of the technology readiness level according to the EU scale (Mihaly 2017), and a brief justification of the TRL. Section 4 outlines the current operational capability and the outlook for future application or further developments of the innovation delivered in Work Package 2.

2. Technology Readiness Levels

Technology Readiness Levels (TRL) are used to assess the maturity level of a technology. The TRL scale was originally defined by NASA (https://www.nasa.gov/directorates/heo/scan/engineering/technology/technology_readiness_level) to measure the maturity of space technology. In time the scale evolved through various mutations to become more general applicable to other technologies. The TRL scale became a tool for EC H2020 (and EC Europe) funded projects to better position the requested projects in the program, and to evaluate the output (Mihaly, 2017).

In this deliverable the technologies for new prototypes, products, services and capabilities are evaluated following the definitions used by the EC H2020 TRL scale (https://ec.europa.eu/research/participants/data/ref/h2020/other/wp/2016_2017/annexes/h2020-wp1617-annex-g-trl_en.pdf). Nine different levels of Technology Readiness are distinguished according to the level of maturity of the technology. TRL1 is the lowest level, starting with scientific research, while TRL 9 being the highest level of maturity which is proven in an operational environment. Usually these 9 levels are grouped into 4 phases: discovery (1, 2, 3), development (4, 5, 6), demonstration (7, 8) and deployment (9).

TRL level	Description
9	Actual system proven in operational environment
8	System complete and qualified
7	System prototype demonstration in operational environment
6	Technology demonstrated in relevant environment
5	Technology validated in relevant environment
4	Technology validated in laboratory
3	Experimental proof of concept
2	Technology concept formulated
1	Basic principles observed

Fig. 1: Technology Readiness Levels (EC H2020; see text).

3. New prototypes, technologies, and services

This section summarizes the innovative outcomes of the RISE project for WP2 and the TRLs for each outcome.

3.1 Utility and value of high-density DAS

Task 2.1 concentrated on applying existing state of the art techniques of DAS cable technology to the task testing its observational capabilities in various settings, including within Cities, and near seismic sources such as active faults and volcanoes. As such no new technologies were developed. Improvements to observational capabilities are reported in section 4.1.

3.2 Next generation sensors and hyper-dense networks for use in EEW, OEF and RLA

In the RISE project, QUAKE has developed both hardware and software components for smart seismic sensors. The hardware development involved creating two different cost-effective sensor types, QuakeSaver MEMS and QuakeSaver HiDRA (Short-Period), which were shipped to RISE partners for preliminary deployment. QUAKE has also tackled challenges in sensor designs. On the software side, QUAKE has developed an open-source software (firmware) stack for the sensors, including on-device algorithms for real-time data analysis and signal processing delivering meaningful data products for earthquake preparedness and structural analysis. They have also focused on developing data pipelines for exchanging seismic data products in real-time and contributing to the development of on-device analysis of seismic data.

1) Sensor Firmware Development

QUAKE has developed open-source firmware for its smart seismic sensors as part of the RISE project. This firmware allows for easy customization and modification of the sensors to meet the specific needs of different users and applications. By making the firmware open-source, QUAKE is fostering collaboration and knowledge-sharing within the seismological community. The open-source nature of the firmware also allows for continuous improvement and innovation, ensuring that the sensors remain up-to-date and relevant in the rapidly evolving field of earthquake monitoring and preparedness.

2) Sensor Fleet Management

QUAKE has developed a scalable network fleet management system to manage the growing number of smart seismic sensors deployed in the RISE project. The system allows for real-time monitoring of the sensors, remote configuration of sensor settings, and automatic firmware updates. It also enables data acquisition and processing from multiple sensors simultaneously, facilitating a scalable and efficient approach to data collection and analysis. The network fleet management system provides enhanced data quality control and assurance, allowing for reliable and accurate seismic data to be delivered to stakeholders and the scientific community.

3) Hardware Sensor Development

QUAKE has developed advanced hardware for its smart seismic sensors in the RISE project. The company has integrated modern cost-effective MEMS sensor technology with state-of-the-art data analysis to create new ways to prepare for ground shaking and monitor earthquake activity. QUAKE has designed two different sensor types: QuakeSaver HiDRA and QuakeSaver MEMS, both of which have been shipped to RISE partners. The sensors have undergone rigorous evaluation and testing, resulting in several updates to their printed circuit board (PCB) design. The latest prototype iteration incorporates an industrial compute platform that is ideal for large-scale deployments. The company has also been working to find alternatives for unavailable electrical components due to the global chip crisis, redesigning PCBs and taking other measures to mitigate the effects of the crisis on the RISE project.

The report containing detailed information on the deliverable can be found in D2.4. The TRLs and justification are given in the Table below.

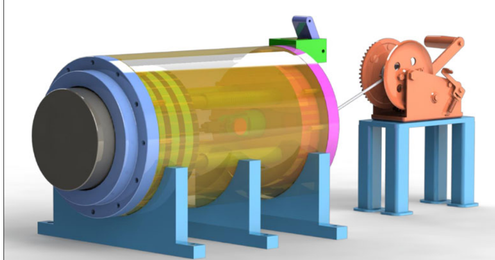
Challenge / infrastructure	**Technology, (bold if developed in RISE)**	**Description & justification of TRL**	**Technical readiness level**
Development of sensor firmware	• **Development of embedded real-time Linux firmware agnostic for both sensor platforms** • **Firmware remote updates** • **Continuous Integration and Continuous Deployment (CI/CD) for the firmware** • **Unittest coverage of 80%** • **Sensor fusion algorithms** • **Digital signal processing** • **Low-latency data pipelines for real-time exchange of seismic data** • **On-device algorithms for real-time signal analysis and processing** • **Framwork for efficient and flexible data handling** • **Open-source standard and code-standards for customization and community-driven development** • **On-device analysis of seismic data single-station methods. Including continuous ground motion analysis (PGA/PGV or instrument intensities), H/V spectra, single-**	MEMS sensors are deployed in Europe at partner institutions. Streaming wave forms and high-level data products to the back-end infrastructure.	**TRL8**

	station auto-correlation for site monitoring • **Advanced data products for risk modeling and rapid earthquake response** • **Web frontend development**		
Development of sensor fleet management and web APIs	• **Real-time data transmission** • **Scalable infrastructure for global application** • **Continuous Integration and Continuous Deployment (CI/CD) for the firmware** • **Redundant and robust infrastructure for high availability and scalability** • **Remote management and updates of sensors** • **Web frontend development**	Ingesting data from the sensors. Web front-ends and APIs are in production managing a fleet of 40+ sensors.	**TRL8**
Development of cost-effective MEMS sensors	• **Printed circuit board (PCB) design** • **Power management** • **TCP/IP communication protocols** • **Industrial compute platforms** • **Enclosure design**	Sensor platform online and reliable uptimes of many months	**TRL8**
Development of cost-effective short-period sensor (high-sensitivity)	• **Analog front-end design** • **Printed circuit board (PCB) design** • **Power management** • **TCP/IP communication protocols** • **Industrial compute platforms** • **Enclosure design (IP67 proof)**	Sensor platform tested and recording teleseismic earthquake events. Same firmware as the battle-proven MEMS.	**TRL6**

3.3 Innovative portable excitation sources for field testing of existing and densely instrumented structures

With the rapid developments in instrumentation and communication technologies, field-testing is now increasingly replacing analytical modelling and laboratory testing to assess the dynamic response of structures in the built environment. Today, a large number of structures are being monitored, either continuously with permanent monitoring systems, or temporarily with portable monitoring systems. Since natural excitation sources like earthquakes are not frequent, there is a need for man-made excitation sources to test such structures.

As part of BOUN-KOERI’s responsibility in WP2.3 of RISE, we have designed and have manufactured two complementary types of equipment to test structures: an Impact Hammer (IH) and an Eccentric Mass Shaker (EMS). The IH and EMS are illustrated in the 3D coloured technical drawings given below. Both are small and portable enough to be disassembled and moved to any floor of a multi-story building via elevators.



Momentum Capacity (kgxm/s)	100
Impact mass (kg)	80
Maximum contraction (mm)	54
Impact area (mm²)	31400
Maximum Velocity (mm/s)	1250 mm/s
Number of springs	4
Maximum force need for setting the springs (N)	~2000 N = 200 kg
Maximum height (mm)	430
Maximum width (mm)	466
Maximum length (mm)	~1000

Impact Hammer - IH

ECCENTRIC MASS SHAKER TECHNICAL SPECIFICATIONS

ACTUATOR TYPE:
Schneider Servo Motor
BMH100 Series
Maximum Revolution: 3000 rpm

TECHNICAL PROPERTIES	
Eccentricity Per Disc	0,181 kgm
Number of Discs	4 on each shaft, 8 in total
Mass Per Disc	4,2 kg
Maximum Force	1575 kgf
Axis of Force	Horizontal: X or Y (Depending on initial disc position)
Maximum Frequency	25 Hz
General Dimensions	Height: 440 mm Lenght: 250 mm Width: 470 mm
Total Weight	105 kg
Power Requirements	6 kW Single Phase 220 V AC

Eccentric Mass Shaker - EMS

The objective in developing an impact hammer is to give an impulsive force to a multi-story building and measure the propagation velocity and the reflections of the impulse along the height of the building. The impulsive forces can be given from any floor by moving the Impact Hammer. The data are used to identify the dynamic characteristics of each storey in the building, including the natural frequency and damping ratio of each storey, as well as the wave travel times in the building, wave reflection and transmission coefficients at floor levels, and story damping. Such information provides a better insight into the dynamic characteristics of the building than the modal properties.

The objective in developing an EMS (Eccentric Mass Shaker) is to identify the resonant frequencies of buildings and surrounding soil, as well as to identify the presence of soil-structure interaction. The EMS designed to have two sets of four discs each rotating in opposite directions and generating a uni-directional sinusoidal horizontal force acting on the structure or soil surface at selected frequencies between 1 to 25 Hz. The amplitude of the sinusoidal force can be adjusted by adding or removing the masses in the shaker.

More detail on IH and EMS can be found in RISE Deliverable D2.7. The following Table provides a technology assessment and justification, with work carried out in RISE highlighted in bold.

Challenge / infrastructure	Technology, (bold if developed in RISE)	Description & justification of TRL	Technical readiness level
Portable excitation sources for dynamic testing of structures.	**Designed and have built an Impact Hammer (IH) and Eccentric Mass Shaker (EMS) for structural testing**	**Since natural excitation sources like earthquakes are not frequent, there is a need for man-made excitation sources to test and identify the dynamic properties of structures. The excitation sources have been built, deployed and tested successfully on buildings in Istanbul, and are ready for mission testing.**	**TRL8**

3.4 Advancing observational capabilities for earthquake detection, location and magnitude

Task 2.4 concentrated on applying existing state of the art techniques of whole waveform analysis to the task of updating and customizing observational capabilities in producing earthquake catalogues. As such no new technologies were developed. Improvements to observational capabilities are reported in section 4.4.

3.5 Application of ambient noise correlations to systematically monitor the temporal evolution of active faults at National scale

The possibility to use noise correlations to monitor the crust has been originally demonstrated by Sens-Schönfelder et al., 2006 and Brenguier et al., 2008 using small dataset. The challenge of this work package was to upscale these algorithms so that they may be used at the scale of a nation or even at the scale of a continent. Report D2.10 presented the result obtained in Greece and Italy. Being able to monitor the crust using noise correlations at the scale of a nation/continent has required to design a specific workflow to download, process on the fly and manage large dataset of noise record (> 100Tb), to compute noise correlations, and to them to measure seismic velocity variations.

Therefore we designed *pycorr*, a new set of python codes, available for academic use at*:* *https://gricad-gitlab.univ-grenoble-alpes.fr/stehlyl/pycorr_dev/-/tree/master/v2.1_beta*

Pycorr can presently be used to download continuous noise records, compute noise correlations and dv/v over several years/decades at the scale of a nation (i.e. hundreds of sensors), and can be considered fully operational in this sense. This new software product has the following capabilities.

1) Mass Downloader and on the fly preprocessing of noise records

Challenge: 15 years of data on the whole IV Italian network (2006-2021) represent more than 80 Tb of data before decimation. Building our database of 10 years of noise records for the whole Europe has required downloading more than 200 Tb of data.

Solution: we designed a mass downloader that makes it possible to:
- download continuous noise records from EIDA day per day in parallel on multiple cores.
- process downloaded data on the fly before writing them to disk to 1) correct them for the instrumental response 2) decimate the data 3) synchronize them so that all records start and end at midnight 4) handle gaps in the data. Data is stored in a flexible way using the hdf5 file format.

<u>2) Computation of noise correlation for large datasets</u>

Challenge: Currently more than 1500 stations are available in Europe including both permanent and temporary networks. This corresponds to more than 1 million pairs of stations. Computing correlations for 10 years of data with a sliding window of 4 hours for all European stations separated by less than 500 km, requires to compute more than 1 billion of correlations, and to read more than 10 Tb of data (assuming that data are decimated to 5.0hz). This represents a challenge both in terms of computational time and on the number of I/O required.

Solution: We designed an algorithm that works on multiple cores which allows us to efficiently compute noise correlations. It is designed to reduce I/O and concurrent access to the database of noise records as much as possible. The resulting noise correlations are distributed in hdf5 files of a few Gb. A python and matlab API allows access to this dataset of noise correlations transparently.

<u>3) Efficient analysis of noise correlations and computation of relative changes in seismic velocity (dv/v)</u>

Challenge: analyze efficiently large dataset of noise correlations.

Solution: we designed the following.
- an algorithm to read noise correlations and save the result of the analysis (i.e dv/v) in parallel on multiple cores while reducing I/O and concurrent access to the data as much as possible. It can be used to make different type of analysis (dv/v for monitoring, and for extracting dispersion curves for tomographic application).
- A matlab API allows to visualize the results interactively and to access the dv/v measurements transparently.

4) Towards a real time usage of the *pycorr* package:
At the moment we do not think that it would be relevant to run this algorithm in real time for instance to update the dv/v measurements on a daily basis, since no change in the medium preceding earthquakes have been identified yet. However, monitoring the crust (even with a time delay) is still crucial to 1) better understand the seismic cycle and add constraint on the rheology of the crust and 2) to monitor the long-term evolution of aquifers. These types of applications do not require real-time measurements of the dv/v.

However, the code has been designed in a modular way, so that in future capabilities could be developed to modify the workflow to make it work in real time (specifically computing on the fly noise correlations and dv/v without saving the correlations.

Challenge / infrastructure	Technology, (bold if developed in RISE)	Description & justification of TRL	Technical readiness level
Upscaling of analysis of relative seismic velocity change dv/v, extracted from noise correlations to a National scale	***Pycorr* - a new set of python codes, available for academic use**	**Pycorr can download continuous noise records, compute noise correlations and dv/v over several years/decades at National scale (i.e hundreds of sensors). Prototype demonstrated in Greece and Italy.**	**TRL7-8** (System prototype demonstration in operational environment)
Real-time monitoring of dv/v on a National Scale	Parallelization of existing *Pycorr* code to speed up analysis and visualization	**The concept and pathway to development has been formulated within RISE**	**TRL2** (Technology concept formulated)

3.6 Novel strategies for scalability, high-volume data access and archival beyond existing waveform services, exploiting cloud-based services

This task explored and prototyped technical solutions to openly access, disseminate and interact with massive data volumes. Table 1 lists the challenges and infrastructures discussed in Deliverable D2.11, D2.12 and the associated technologies, along with a brief description of the technology to be used to justify the level of technical readiness. Some of the technologies were developed within the context of project RISE: they are highlighted using bold text in the table. The selected strategies for big-data management for seismological data in Europe are a) data management at large data centers, b) EIDA, c) Cloud infrastructure integration and d) SeiSpark.

Challenge / infrastructure	Technology, (bold if developed in RISE)	Description & justification of TRL	Technical readiness level
Big-data management at large data-centers in Europe and worldwide	• Data acquisition: seedlink (https://www.seiscomp.de/doc/apps/seedlink.html), possibly previous decimation in space and time • Data storage: SEED (https://www.fdsn.org/pdf/SEEDManual_V2.4.pdf), HDF5 (https://www.hdfgroup.org/solutions/hdf5/), THREDDS (https://www.unidata.ucar.edu/software/tds/), HDHS, Zarr, AWS • Metadata; StationXML (https://www.fdsn.org/xml/station/) • Data distribution: FDSN webservices (https://www.fdsn.org/we	Internationally adopted standards and data formats. **Dastool developed in the context of RISE to read, manipulate and convert seismic waveforms generated by DAS systems, in particular, the ones saved in TDMs format (https://git.gfz-potsdam.de/javier/dastools). Available via GitLab and already used to integrate datasets (https://geofon.gfz-potsdam.de/doi/net-**	**All TRL9** but Zarr at **TRL7-8** because it is not widely tested by the community yet.

	bservices/), IRIS ROVER (https://ds.iris.edu/ds/nodes/dmc/software/downloads/ROVER/current/) • **Data management / usage: dastool**	**work/9N/2018). Described in D2.11 and D2.12.**	
The European Integrated Data Archive (EIDA) http://www.orfeus-eu.org/data/eida/	• FDSN web services • EIDA web services • EIDA web interfaces • EIDA authorization and authentication system	The EIDA infrastructure is the result of more than a decade of joint developments by European datacenters; EIDA today provides federated, open or authenticated access to seismological waveform data & metadata of about 17,500 stations in Pan-Europe.	**All TRL 9**
Cloud-based strategy at the ORFEUS Data Centre ODC	• Cloud Amazon Web Services AWS (https://aws.amazon.com/?nc2=h_lg) • SURF Research Cloud (https://portal.live.surfresearchcloud.nl/) • Equinix facility for Governmental Infrastructure	Described in D2.11. The large scale of operations by AWS & SURF allows to operate more efficiently when outsourcing IT services than maintaining an in-house infrastructure. **All waveform data available in/from AWS S3 (cloud object storage) using the EIDA web services. Services to access (waveform) data are being migrated to AWS or being developed within AWS from the start (e.g. http://www.orfeus-eu.org/data/odc/quality/ppsd).**	**All TRL 9**
SeiSpark	**Project at INGV with the goals to add a) significant computational resources and b) an adequate framework to the seismological data archive, creating a "computational archive" where storage resources and computational resources converge. It follows the paradigm of data locality, avoiding unnecessary data transfers on every level as much as possible. It implements the following software stack:**	Described in D2.11 and D2.12. **Available internally at INGV.**	SeiSpark **TRL 6**. Software stack **all TRL9**.

	• Apache Hadoop (https://hadoop.apache.org/) • Apache HDFS (https://hadoop.apache.org/docs/current/hadoop-project-dist/hadoop-hdfs/HdfsDesign.html), a persistent distributed location-aware file system • Kubernetes (K8s), https://kubernetes.io/ for resource management, scheduling and scaling of containerized applications. • Apache Spark (https://spark.apache.org/), the principal analytics engine based on the Resilient Distributed Datasets (RDD) abstraction • Jupyter (https://jupyter.org/), the interactive notebook environment • JupyterHub (https://jupyter.org/hub) web-based access to multi-user environment • JupyterLab, https://jupyter.org/ new web-based GUI interface to Jupyter notebooks • a complete customized Python 3 (https://www.python.org/downloads/) kernel environment configured in JupyterLab • ObsPy (https://github.com/obspy/obspy/wiki), the seismological Python processing and analysis framework • various plotting and visualization tools for interactive plots		

2.7 An open, dynamic and high-resolution exposure model for EEW, OEF and RLA based on crowd-sourced big data

The main technological challenge in WP2.7 was to implement an exposure model describing every building and being updated on a minutely basis with crowd-sourced data. This is required as a critical step in the concept of dynamic risk, so that estimates of hazard can be propagated to calculate the risk in an operational environment.

Challenge / infrastructure	Technology, (bold if developed in RISE)	Description & justification of TRL	Technical readiness level
Data storage/handling	**We implemented several PostGIS databases (all dockerized for easy deployment)**	The databases, their migration and all implemented views are optimized and operational.	TRL9
Data processing	**We implemented an asynchronous processing engine (Rabotnik)**	The engine is operational, however, we still see limitations, e.g. only one instance per server and no concatenation of engines possible	TRL8
Data updating	**The current implementation of Rabotnik and the OpenStreetMap replication operates on a minutely basis**	The system works and is able to process every change within approx. 2 minutes.	TRL8
Data access	**We developed a tool to extract country or bounding-box data from the PostGIS into local SpatiaLite databases**	The tool works and can be used easily. Also, an API for this is available.	TRL9
Data visualization	**Website for visualizing building and tile exposure data**	The website is in prototype stage	TRL6

4. Operational Capability and Outlook

This section describes the current operational capability, including work package elements which did not produce new technology as such.

4.1 Utility and value of high-density DAS

The RISE project has established a utility and value of DAS that went considerably beyond the a priori expectations.

Utility mostly derives from the logistic feasibility of large-scale DAS experiments under a broad range of conditions. In volcanic and glacial environments, we demonstrated that fibre-optic cables of up to 12.5 km length could be deployed and coupled to the ground with reasonable effort and at very low cost per channel (below 10 Euro). Using Diesel generators for electrical power supply, we continuously operated DAS interrogators under harsh conditions for several weeks, without technical issues. In urban environments, we were able to co-use existing telecommunication infrastructure.

With little to no bureaucratic complications, municipalities and telecommunication companies provided access to their fibre-optic cables, e.g., in Bern, Athens, Santorini and Istanbul. We managed to interrogate cables of up to 40 km length.

Value is largely related to the high quality of the data in terms of spatio-temporal sampling and signal-to-noise ratio. Especially on glaciers, we were able to record signals with amplitudes as low as few tens of nanostrain per second. This enabled the detection of a broad spectrum of seismic events, including previously unknown forms of tremor and resonance, as well as unexpectedly high levels of seismicity. For example, in the case of Grimsvötn volcano, we detected nearly two orders of magnitude more eartquakes than the regional seismometer network, thereby opening completely new opportunities for high-resolution volcano monitoring.

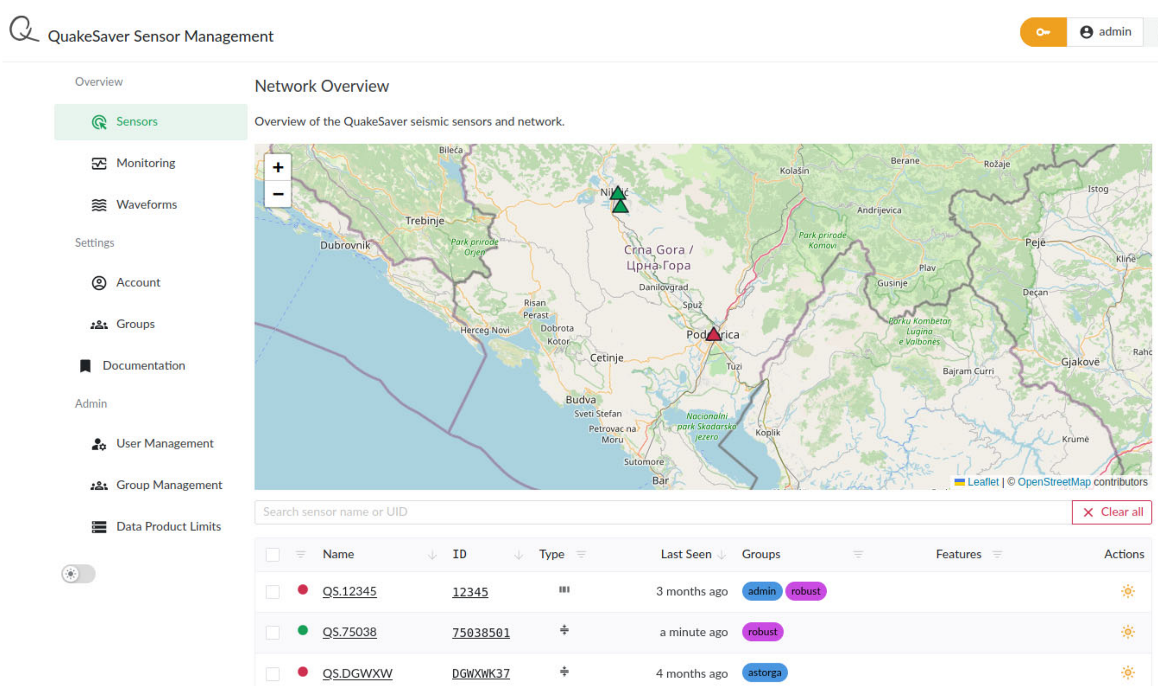
Also related to data quality is the tomographic resolving power of the DAS data. The pilot experiment in Bern demonstrates that metre-scale resolution of shallow subsurface structure is achievable.

The technology, as it currently stands and in conjunction with data processing and analysis tools has a TRL of 8 - 9.

The combination of seismicity detection and tomographic imaging based on DAS deployments are in the process of significantly advancing our capabilities in seismic risk assessment and mitigation, in line with the overall objectives of the RISE project.

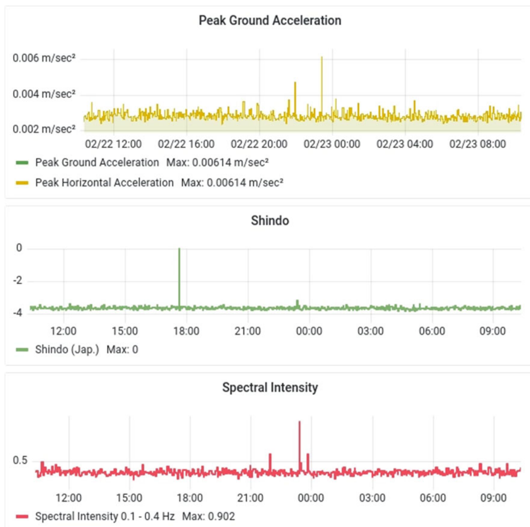
4.2 Next generation sensors and hyper-dense networks for use in EEW, OEF and RLA

The scalable sensor fleet solution developed by QUAKE is operation-ready for science and industry. The sensor solution is capable of continuous real-time monitoring of seismic activity, and can detect even small ground motions that could indicate structural changes of building and lays the foundation for deployment of on-device neural networks for EEW earthquake detection and characterization (i.e. P wave identification or single-station magnitude estimation). The developed solution includes on-device algorithms for real-time signal analysis and data processing, which allows it to deliver meaningful data products to the exposure and hazard modelling communities through web APIs. The scalability of the solution means that it can be easily deployed in large distributed networks for continuous monitoring of medium-scale building structures, and even for



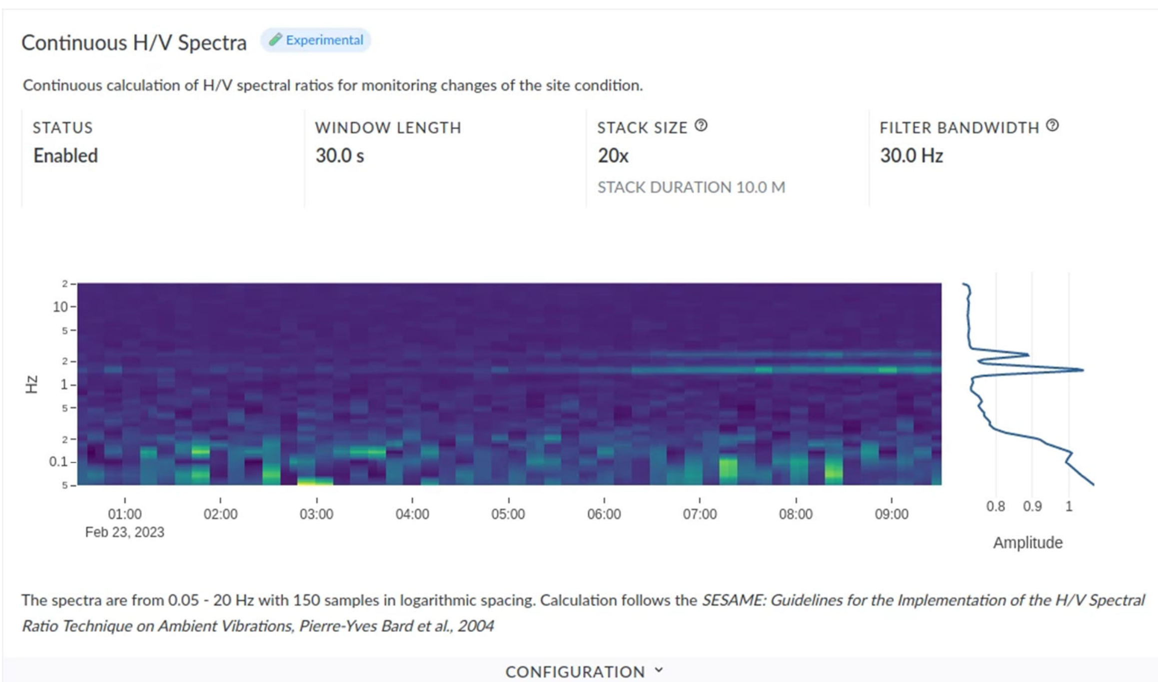
obtaining classical seismological data outdoors. Looking into the future, as the sensor technology and software continue to evolve, it is expected that the capabilities of the scalable sensor solution will expand to include even more advanced seismic data analysis and predictive modelling, which will greatly enhance our ability to prepare for and respond to earthquakes.

Screenshot of the fleet management console showing MEMS sensors deployed in Montenegro.



The development of open source firmware and network fleet management technologies demonstrate the commitment to continuous improvement and scalability. The use of edge computing allows for efficient data processing, reducing the need for large-scale data transmission and enabling the system to function in remote and resource-constrained areas.

Continuous real-time data of PGA/PGV and instrument intensities (Shindo) delivered by QuakeSaver sensor.



Continuous record of H/V spectra from a QuakeSaver MEMS installed in a 13 story building in Montenegro. Visible are clear resonance peaks for the building at ~1.5 Hz and ~2.1 Hz. Screenshot from intuitive web-frontend.

Overall, QUAKE's system is a capable and adaptable solution for earthquake preparedness, with the potential for growth and expansion in the future. As seismic monitoring technology continues to improve, QUAKE's open framework can evolve and integrate with future analysis methods.

QUAKE hopes to integrate Proof of concept neural network P- and S-phase detector into the sensor's firmware before the end of the RISE project.

4.3 Innovative portable excitation sources for field testing of existing and densely instrumented structures

The Impact Hammer (IH) and Eccentric Mass Shaker (EMS) are two tools to test structures dynamically in the field without waiting for a natural excitation, such as an earthquake. Both types of equipment are small and portable enough to be disassembled and moved to any floor of a multi-story building via elevators.

The IH can be used to identify the dynamic properties of each story of a multi-story building by moving it from floor-to-floor. By recording the response with portable sensors, we can identify the dynamic characteristics of each storey individually from the top-over-bottom spectral ratios of records. The approach is based on the transfer-matrix formulation of the dynamic response and shows that wave propagation properties provide a better insight into the dynamic characteristics of the building.

The EMS can give a sinusoidal excitation to buildings in a selected direction and frequency. It is a very useful tool to identify the natural frequencies of short and stocky buildings, as well as the dominant frequencies of the soil surrounding the foundation. For buildings 7-10 stories and higher, ambient vibration data taken from the top are normally sufficient to identify dominant frequencies. However, ambient vibrations taken from short buildings, ground levels or basements do not show the dominant frequencies because of very low signal-to-noise ratios in the records. For such cases, EMS provide a useful tool to identify their dynamic behaviour.

More detail and a list of related publications prepared within the RISE project are given in RISE Deliverable D2.7.

4.4 Advancing observational capabilities for earthquake detection, location and magnitude

Task 2.4 produced higher-resolution earthquake catalogues for the Italian peninsula, including both homogeneous locations and homogeneous related Wood-Anderson's amplitudes and local magnitudes (ML), in order to advance observational capabilities and for public dissemination, as described in deliverable D2.8, and summarised in the table below.

The following table lists the data, products, tools and software's used, disseminated, and/or under implementation at INGV monitoring/research infrastructure. In bold we indicate those developed within the context of the Task 2.4 (see also D2.8) of the RISE project.

id	Name	Description	Technical Relevance in RISE	Dissemination Status	In use at INGV
1	CLASS 1.0	Earthquakes Catalogue of Absolute Location of the Italian seismicity for the 1981–2018-time window. Grounded on material generated during 2012-2021 B2	Reference locations dataset for tests and for generating updated and/or refined catalogues e.g., CARS1.0)	https://doi.org/10.13127/class.1.0 https://doi.org/10.1016/j.tecto.2022.229664	CLASS locations setup has been implemented as standard for 3D NLL locations c to be computed in quasi-real time as one of the cascade moduli of INGV monitoring system [testing

		projects regulated by DPC-INGV Agreements. **Final and updated release (2015-2018) during RISE.**			phase running internally to INGV in a virtual machine]
2	CSI 2.0	Integrated catalog of P and S readings 1981-2008	Catalog of arrival times integrating bulletins from different permanent regional seismic networks in Italy, used joined with INGV BSI 2009-2018 for CLASS 1.0 and CARS 1.0	https://doi.org/10.13127/csi.2.0/phs	Used in off-line analysis.
3	Regionalization	Regional Polygons (selected based on homogeneous geological, geodynamical, and structural characteristics) including specific 1D velocity model derived from 3D model. Created during 2019-2021 - B2 DPC-INGV Agreement.	Reference for CARS 1.0 1D velocity models.		Regionalization was implemented as standard for 1D NLL locations (with specific stations corrections) in quasi-real time cascade of the INGV monitoring system [testing phase running internally to INGV in a virtual machine]
4	**PyAmp**	Python code, for the automatic advanced and configurable estimation of the maximum amplitude of the seismic signal (as defined by Richter) on a Wood-Anderson seismogram. Developed during EPOS-IP for the NFO-TABOO, **upgraded and extended during RISE.**	Used to estimate the amplitudes contained in WAC 1.0		
5	**PyML**	Python code for the automatic	Used to estimate M_L for CLASS 1.0 and	Open **github/INGV** dissemination in preparation	Under testing internally to

		calculation of the Ml of an event. Based on a minimal input json file of location and amplitudes, or on the full PyAmp output file, it applies several different methods to calculate Local Magnitudes from Wood-Anderson amplitudes.	CARS 1.0, contained in LMC 1.0		INGV monitoring system.
6	**WAC 1.0**	**Set of about 9 million Wood-Anderson maximum Wood-Anderson Amplitude Catalogue for Italy, 2009-2018**	**Basic information to compute ML of 2009-2018 events in CLASS and CARS.**		
7	**LMC 1.0**	**Catalog of the Local Magnitudes for Italy 2009-2018 based on the CLASS 1.0 location and CARS 1.0 locations**	**New homogeneous catalogue of ML.**		
8	**CARS 1.0**	**Earthquakes Catalogue of 1981-2018 Italian seismicity (based on double difference location algorithm running on absolute and relative travel times).**	**Base Catalog for Real Time Relative Locations for Italy**	**Official repository with associated doi (in preparation).**	**Double difference real time location (DDRT) of the Italian seismicity. Modulus currently under development as implementation of INGV Monitoring System.**

4.5 Application of ambient noise correlations to systematically monitor the temporal evolution of active faults at National scale

It is now technically possible to monitor the evolution of seismic faults at National scale by measuring the spatiotemporal evolution of the seismic wave velocity (dv/v) using seismic noise correlations. The seismic wave velocity variations reflect the evolution of the mechanical properties of the medium and can thus provide meaningful information on fault systems.

Operational application of this method requires that continuous seismic records are distributed through EIDA. The temporal and spatial resolution that one can obtain depends on the density of seismic stations and on the amplitude of the signal to be detected. Ideally to achieve the best resolution one would deploy dense arrays of sensors in target fault areas specifically for the purpose of monitoring them.

The computational cost scales with the number of station pairs to be analyzed. For typical application (one hundred sensors, data decimated to 5 Hz with a few years of data) a moderate cluster is sufficient (~16 cores) to compute the correlations and analyze them. One of the main difficulties is that downloading large amounts of data (> 10 Tb) through EIDA to get all data available at the scale of a country for more than one decade is quite slow and can take several weeks/months.

At short periods (<3s) where seismic waves are sensitive to the upper crust, the temporal resolution can be less than one week depending on the density of the network of stations used. Interpreting the results requires distinguishing the seismic velocity variations associated with the hydrological cycle from those related with tectonic processes.

At longer periods (>10s) where seismic waves are sensitive to the mid/lower crust, the convergence of the correlations toward the Green function of the medium is slower, so that the temporal resolution of the observation usually does not exceed two/three months.

4.6 Novel strategies for scalability, high-volume data access and archival beyond existing waveform services, exploiting cloud-based services

Assessment of the operational capability of the complex system to access large amounts of data in the distributed environment of EIDA is performed on a daily basis through a) auto-mated tests of the waveform availability of European EIDA stations and b) monitoring the responsiveness of the EIDA servers to metadata requests. (Reporting is currently available internal only).

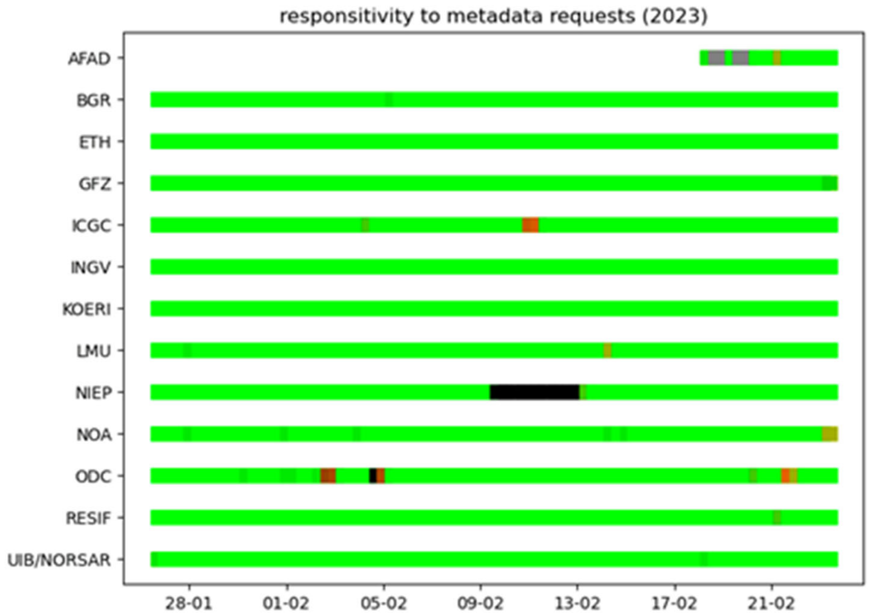
The availability test of EIDA stations uses Python and ObsPy and is carried out by the EIDA node BGR. The procedure comprises the following steps:

- Conduct random waveform requests to single channels of EIDA stations.
- One request per minute.
- Requested time span is randomly selected from last year with lengths between 60 and 600 seconds.
- Stations are randomly selected from the subset of unrestricted European EIDA stations offering at least one out of channels HHZ, BHZ, EHZ or SHZ.
- Request full station metadata from selected stations and choose channels random-ly, restricted to channels HH?, BH?, EH? and SH?.
- On successful request apply a instrumental deconvolution to the waveform data.
- Evaluate and store results of the request in a file database.
- Plot and statistically analyze content of file database.

Output is in terms of statistics for a) no data delivery, b) no data available, c) non-contiguous data, d) incomplete data and e) metadata failure. Output of this tool is being used by EIDA data-centers to monitor the overall performance of the system and the quality of services and data availability (http://www.orfeus-eu.org/data/eida/guidelines/).

net	OK	NODATA	FRAGMENT	INCOMPL	METAFAIL	NOSERV	RESTFAIL
1I	148	5	0	0	0	2	0
1J	471	27	2	0	0	4	0
3D	196	37	2	2	0	4	0
4P	7	2	0	0	0	47	0
7B	0	38	0	0	0	62	0
7C	98	20	2	0	0	1	0
7F	119	5	0	0	0	3	0
8D	2	0	0	0	0	0	0
8N	171	10	0	3	0	1	0
9S	43	33	0	0	0	0	0
AB	0	139	0	0	0	7	0
AC	286	35	3	0	0	3	1
AM	325	200	25	4	0	37	0

Snapshot of various statistics.



Example of responsiveness in 2023 of all servers plotted with a granularity of 8 hours; green =100% (no errors), orange = 90%, brown=50%, black =0%.

Cloud services at ODC: Recent (~1 week) data is stored and served from the Equinix infrastructure. All other data is stored in S3 buckets at AWS. Intelligent Tiering is used to move files that are not frequently accessed to slower, but cheaper storage while files being used frequently are moved to faster, but more expensive storage. AWS S3 is a bit slower compared to Equinix as files in S3 first need to be downloaded before sending it to the user, while Equinix serves files from local disk, so the response is instant.

5. References

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