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1. Technical references

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2. ABSTRACT

This deliverable presents the activities carried out within Task 4.2 of WP4, aimed at developing, integrating, and validating automatic procedures that connect Earthquake Early Warning (EEW) and rapid impact assessment within a coherent multi-risk operational framework. The primary objective is to bridge ultra-rapid source characterization, ground-motion prediction, and near-real-time impact evaluation, ensuring methodological consistency and progressive refinement of information from the first seconds after P-wave detection to the generation of actionable hazard and impact scenarios within minutes.

To achieve this objective, complementary and mutually reinforcing methodological approaches were implemented. First, a hybrid EEW–Tsunami Early Warning workflow was developed and tested through retrospective case studies and a suite of synthetic scenario simulations. Results demonstrated that rapid empirical source estimates can be effectively combined with probabilistic tsunami forecasting, significantly improving lead-time exploitation and forecast robustness in near-field, time-critical environments. Second, locally calibrated Ground Motion Models (GMMs) were developed for the Campi Flegrei volcanic area and integrated into ShakeMap workflows. These models reduced systematic biases associated with generic GMPEs and enhanced the physical consistency of shaking estimates in complex volcanic settings. Third, the implications of time-dependent source properties for rapid-response ShakeMaps were investigated, showing that spatially persistent fault segmentation and variability in seismic energy radiation can introduce systematic, predictable deviations from standard magnitude-based ground-motion assumptions.

In parallel, a semi-analytical Fourier-domain ground-motion modeling framework was calibrated using a large regional dataset, providing computationally efficient spectral scenario generation and enabling near-real-time source parameter estimation. This approach supports progressive scenario refinement and offers a complementary pathway between purely empirical and fully physics-based simulations. Impact-oriented developments included the integration of the EASE seismic impact model into early warning architectures and the implementation of a decentralized, probabilistic on-site early warning methodology for structural damage assessment. The latter was further strengthened through multi-sensor fusion of strong-motion and GNSS observations using Kalman-based displacement reconstruction, improving the stability and reliability of displacement-based damage proxies. Finally, the deployment of the EEW@ALTA seismic array at Campi Flegrei provided high-resolution monitoring capabilities and served as an operational validation platform for the hybrid Early Response methodology under realistic volcanic-seismic conditions.

Overall, Task 4.2 demonstrates that integrating empirical calibration, semi-analytical modeling, real-time source physics, multi-sensor observations, and impact-based assessment significantly enhances the coherence, reliability, and operational value of early warning and rapid response systems. The results contribute to the development of a scalable, physically grounded, and impact-oriented framework aligned with the scientific and technological objectives of WP4 within the RETURN project.

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4. Introduction

Earthquake risk mitigation in densely populated and multi-hazard environments requires the ability to transform rapidly evolving geophysical observations into reliable and actionable information within very short time windows. Over the last decades, significant advances have been achieved in the fields of Earthquake Early Warning (EEW), probabilistic seismic hazard assessment, physics-based ground-motion modeling, and impact estimation. However, these components are often developed and operated as partially independent systems, characterized by different temporal scales, methodological assumptions, and levels of uncertainty. Bridging these domains into a coherent operational workflow remains one of the main scientific and technological challenges in contemporary seismic risk management.

Traditional regional EEW systems are primarily designed to estimate earthquake source parameters—location and magnitude—within seconds after the first P-wave detections, and to forecast expected ground shaking at target sites before the arrival of damaging S-waves. While highly effective in regions with sufficient source-to-site distances, their performance becomes intrinsically constrained in near-field environments, such as volcanic calderas or compact urban areas, where the so-called "blind zone" may overlap with the impact region. In parallel, rapid-response products such as ShakeMaps rely on Ground Motion Prediction Equations (GMPEs) and early instrumental data to generate spatial distributions of shaking intensity within minutes. Although operationally robust, these products often assume stationary source and path properties, and may not fully capture local attenuation characteristics, fault segmentation effects, or time-dependent source variability.

A further limitation of conventional workflows lies in the separation between hazard estimation and impact assessment. Early warning systems typically disseminate ground-motion metrics (e.g., PGA, PGV, intensity) without explicitly translating them into expected structural damage or socio-economic consequences. Conversely, impact assessment models are frequently implemented as post-event tools, activated once stable source parameters and shaking maps become available. This sequential architecture can delay actionable decision support during the most critical phase of an emergency.

Within this context, Task 4.2 of WP4 addresses a central objective of the RETURN project: the development of an integrated, impact-oriented framework that connects ultra-rapid source characterization, ground-motion modeling, and near-real-time consequence assessment into a unified operational strategy. The goal is not merely to improve individual components, but to ensure methodological consistency and progressive refinement of information across temporal stages—from the first second after P-wave detection to the generation of spatially explicit hazard and impact scenarios in the following minutes.

To achieve this objective, the activities of Task 4.2 are structured along three complementary axes.

First, the project investigates the integration of rapid empirical source estimates with scenario-based and probabilistic forecasting approaches. This includes hybrid EEW–Tsunami Early Warning workflows and the development of semi-analytical Fourier-domain ground-motion models capable of providing computationally efficient yet physically grounded spectral predictions. These approaches aim to bridge purely empirical regression-based models and computationally intensive full-waveform simulations, enabling scalable and progressively refined hazard estimates.

Second, the task focuses on improving the physical realism and regional consistency of rapid-response ground-motion products. This is pursued through the calibration of locally derived Ground Motion Models for complex environments such as the Campi Flegrei volcanic area, and through the investigation of time-dependent source properties and fault-segmentation effects that may systematically influence ground-motion residuals. By addressing ergodicity assumptions and regional attenuation characteristics, the work contributes to reducing epistemic uncertainty in operational ShakeMaps.

Third, Task 4.2 explicitly incorporates impact-based methodologies into early-warning architectures. This includes the integration of the EASE seismic impact assessment tool and the development of a decentralized, probabilistic on-site early response strategy for structural damage estimation. The latter is strengthened through multi-sensor fusion of strong-motion and GNSS observations, improving displacement stability and enhancing the robustness of drift-based damage proxies. The deployment of the EEW@ALTA small-aperture seismic array further provides high-resolution monitoring and an operational testbed for validating hybrid Early Response approaches in a short-latency volcanic environment.

Through this integrated strategy, Task 4.2 advances from a paradigm centered solely on rapid detection toward a comprehensive framework in which early warning, ground-motion prediction, and impact estimation are dynamically linked. In this perspective, the workflow is conceived as a temporally progressive system: ultra-rapid on-site or single-station estimates provide immediate, locally actionable information within one second; empirical and semi-analytical models enable spatial extrapolation and spectral scenario generation in the following tens of seconds; and impact-oriented modules translate ground-motion metrics into expected structural and societal consequences within minutes. Each stage is not isolated, but methodologically consistent with the others, ensuring that successive refinements are based on compatible physical and statistical assumptions.

A key element of this approach is the explicit reduction of fragmentation between empirical regression models, physics-inspired spectral modeling, and operational impact tools. Rather than replacing one methodology with another, the framework establishes interoperability among them. Rapid empirical estimates are used to trigger and constrain scenario-based forecasts; locally calibrated attenuation and site functions improve regional coherence of spatial predictions; energy-based source characterization informs uncertainty quantification; and displacement-based structural proxies allow early translation from shaking intensity to damage probability. This layered structure enables both robustness in the earliest seconds—when information is necessarily uncertain—and progressive accuracy as additional data and modeling components become available.

From a monitoring standpoint, the integration of multi-sensor observations and dense small-aperture arrays strengthens the reliability of the input data feeding the early response chain. From a modeling standpoint, the combination of locally calibrated GMMs and Fourier-domain inversion techniques reduces epistemic uncertainty associated with generic regional assumptions. From an operational standpoint, embedding impact estimation within the early warning architecture shifts the focus from hazard metrics to decision-support information. In this way, Task 4.2 does not only enhance individual tools, but contributes to defining a coherent methodological architecture for next-generation rapid response systems.

The following sections detail the specific methodological developments, validation analyses, and operational implementations that collectively realize this integrated vision within WP4 of the RETURN project.

5. Integrating automatic procedures for EEW and rapid response

5.1 Feasibility study of an integrated earthquake and tsunami early warning system

5.1.1. Scientific Context and Rationale

Traditional tsunami early warning systems (TEWS) rely on preliminary earthquake source estimates (magnitude, location) to trigger alerts. In near-coastal tsunamigenic settings, short tsunami travel times limit available lead time, making rapid and reliable estimation of source parameters critical. Conventionally implemented algorithms, such as *Early-Est*, can be too slow for near-field tsunami mitigation, particularly when source-to-coast distances are only a few kilometers. In this situation, rapid EEWS might benefit from a denser network installed along the coastlines. The study introduces an integrated workflow combining Earthquake Early Warning System (EEWS) outputs with probabilistic tsunami forecasting (PTF), explicitly designed for near-field tsunamigenic earthquakes. Within the RETURN project, this represents an innovative approach that merges kinematic source simulations with rapid empirical estimates to enhance multi-hazard ShakeMap development. Key innovations include: the use of source simulations to generate synthetic seismograms and tsunami scenarios, providing an extensive set of controlled tests for near-field early warning, the integration of real-time EEWS parameter updates with scenario-based forecasts, bridging empirical and physics-based modelling and the quantitative assessment of lead time versus forecast accuracy, supporting operational decision-making for WP4 multi-hazard workflows.

5.1.2. Objectives

Within the framework of WP4 of the RETURN project, this study had the general goals of evaluating the potential of integrating rapid EEWS source estimates into tsunami forecasting for near-field scenarios and studying the feasibility of a hybrid EEWS-TEWS system that can provide timely alerts for both ground shaking and tsunami hazards. Beyond that, the study aimed also to quantify how source parameter stability evolves in time and its impact on probabilistic hazard assessment and develop a simulation-based framework for generating multiple synthetic events in the Messina Strait, providing a robust testbed for integrated and evolutionary updated ShakeMap.

5.1.3. Methodological development

The study was based on two main analyses. The first one was a retrospective analysis of a real case, the 30 October 2020 Mw 7.0 Aegean Sea earthquake. This event was used to evaluate the real-time performance of EEWS algorithms (*QuakeUp* vs *Early-Est*), in particular to predict tsunami inundation scenarios. Source estimates from the first P-wave arrivals were compared with final catalog values to quantify earliness, accuracy, and alert performance.

The second analysis was based on a synthetic case scenario set in the context of a potential event in the Strait of Messina. In this test-case, a suite of 150 synthetic earthquake scenarios (Mw 6–7) was generated using kinematic source models, including realistic rupture geometries, slip distributions, and shallow source depths. For each scenario synthetic seismograms were computed enabling a systematic evaluation of the integrated EEWS-TEWS workflow. This latter test directly showed the importance of incorporating seismic source physics to risk mitigation actions, offering a controlled environment to validate real-time ShakeMap computation strategies under near-field, time-critical conditions.

5.1.4. Validation and Case Studies

Key findings highlight the critical role of source simulations. In particular we evidenced how: (i) EEWS (*QuakeUp*) provided stable and accurate hypocenter and magnitude estimates in ~40 s, even for offshore events, being substantially faster than conventional approaches (i.e. the ones based on Early-Est); (ii) for the

Messina Strait simulations, source modelling allowed detailed exploration of the effects of rupture geometry and slip heterogeneity on both ground shaking and tsunami hazard; (iii) Probabilistic forecasts derived from the simulation suite showed high consistency across scenarios, confirming that even early, slightly uncertain EEWS estimates can trigger useful hazard alerts; (iv) alert metrics demonstrated high Successful Alert rates (>90 %) with significant lead times, validating the feasibility of near-field multi-hazard early warning; (v) analysis of synthetic scenario results informed the optimal combination of early empirical estimates with physics based ShakeMap updates, improving the timing and spatial resolution of hazard maps.
These results emphasize the added value of source simulations for testing, calibrating, and operationalizing integrated EEWS-TEWS workflows within WP4. The main results, in terms of lead time and inundation forecasting capabilities, are summarized in Figure 1.

5.1.5. Operational implementation

This activity contributes directly to RETURN objectives by demonstrating how physics-based source simulations might be used to enhance rapid hazard estimation and ShakeMap computation workflows, quantifying the lead-time improvement achievable when combining EEWS with scenario-based tsunami forecasts, providing validated workflows for near-field multi-hazard ShakeMap products, bridging empirical and physics-based methods and supporting operational WP4 protocols for rapid situational awareness, even during tsunamigenic earthquakes, including both shaking and secondary hazards.
The study establishes a methodological benchmark for integrating source simulations into operational early warning systems, enhancing the accuracy, robustness, and timeliness of multi-hazard ShakeMap products.

5.1.6. Produced Outputs

- Database of 150 synthetic Messina Strait earthquake scenarios with corresponding synthetic seismograms and tsunami simulations.
- Hindcast analysis of the 2020 Aegean Sea earthquake comparing EEWS algorithms.
- Lead-time statistics and alert performance metrics for integrated EEWS-TEWS workflows.
- Description of the hybrid workflow methodology for inclusion of EEWS within TEWS.

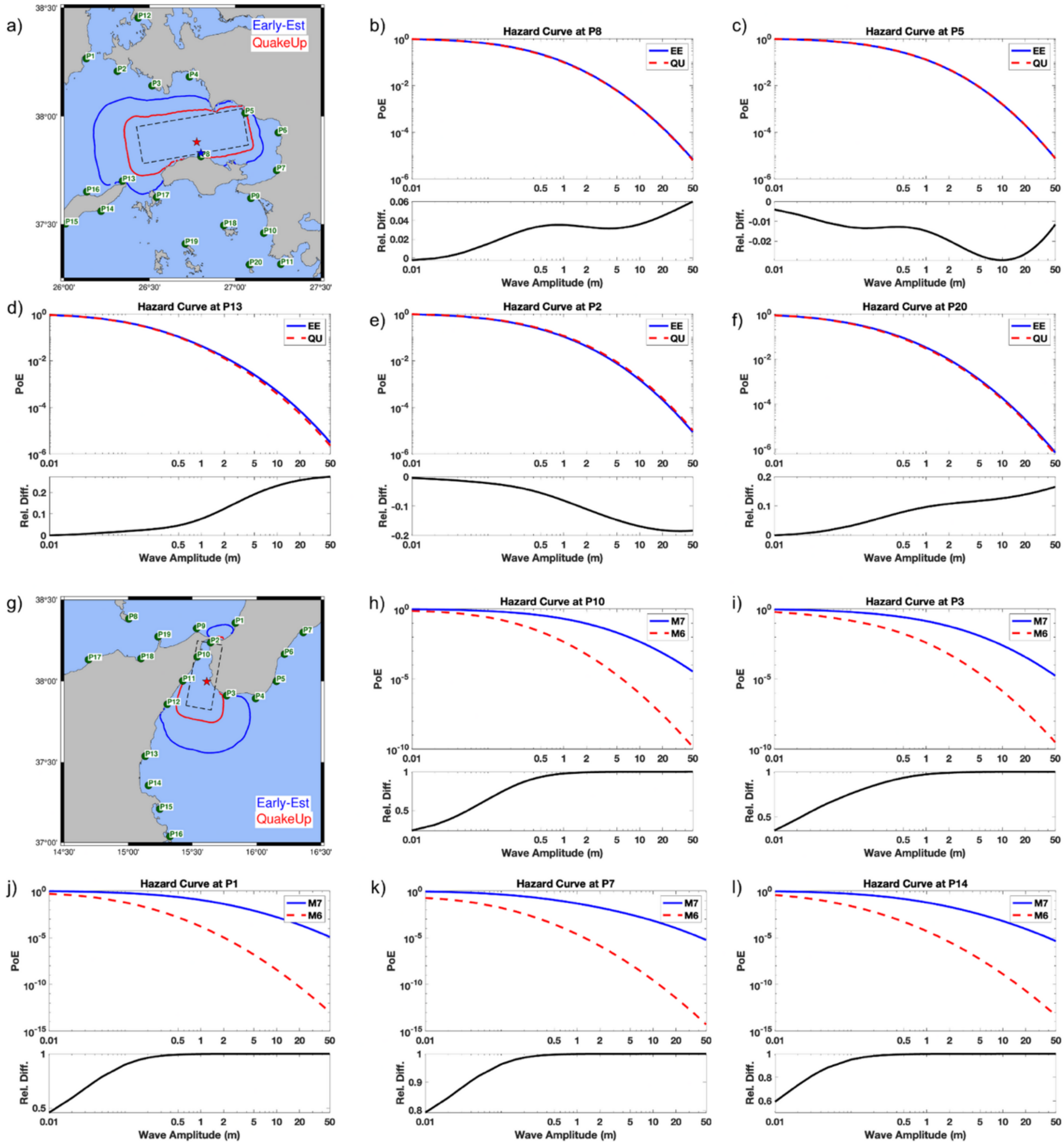

Figure 1: Maps of forecasted waves heights. Panels (**a**) and (**g**) show the regions around the epicenters of the 2020 Samos earthquake and the 1908 Messina earthquakes. The green points represent the points in the regions where the PTF performs its predictions (prediction points), while the faults are indicated as dashed black boxes. The red stars are the epicentral locations estimated by QuakeUp and the blue star in panel (**a**) is the location estimated by Early-Est. The red shapes around the faults are the blind zones associated with the tsunami alert produced by the combination of QuakeUp and PTF, while the blue shapes are the blind zones associated with the combination of Early-Est and PTF. Panels (**b**)–(**f**) show the hazard curves calculated in some prediction points (**b** and **c** are the nearest ones to the epicenter) using the QuakeUp estimation (red dashed curve) and the Early-Est estimation (blue solid curve); the set of hazard curves for the full set of points can be found in the Supplementary Material. The black curves in the lower parts of panels (**b**)–(**f**) are the relative difference between the two curves in the upper part. Panels (**h**)–(**l**) show the hazard curves calculated at some prediction points for an event of magnitude 7 (blue solid line) and an event of magnitude 6 (red dashed line) having the same epicenter. The black solid lines represent the relative difference between the two hazard curves.

5.2 Ground Motion Models for the Campi Flegrei Volcanic Area (Southern Italy)

5.2.1. Scientific Context and Rationale

Traditional operational ShakeMap implementations typically rely on generic Ground Motion Prediction Equations (GMPEs) calibrated at national or regional scales. However, these models may not adequately capture the attenuation properties and frequency content of ground motion associated in particular for peculiar conditions like volcanic seismicity. Campi Flegrei represents a particularly challenging context due to its shallow earthquake sources, heterogeneous crustal structure, and strong spatial variability of shaking. Within the RETURN project, the innovative element introduced by this work consists of integrating locally calibrated empirical GMMs into ShakeMap computation workflows. The main innovation lies in both introducing volcanic-area-specific empirical constraints into ShakeMap generation and improving the physical consistency of shaking estimates in areas affected by volcanic unrest.

5.2.2. Objectives

The research activity pursued the following objectives within the RETURN framework and WP4 tasks: evaluate the performance of newly developed Campi Flegrei GMMs in predicting local ground motion characteristics, assess differences between local GMM predictions and standard GMPE-based ShakeMap estimates, improve the accuracy and operational robustness of shaking estimates for volcanic seismic crises, investigate the potential damage from volcanic seismicity through a comprehensive analysis and forecast of both Peak Ground Velocity/Acceleration and spectral pseudo-acceleration over a broad range of periods.

5.2.3. Methodological Development

The study relied on a dataset composed of recent seismic events recorded within the Campi Flegrei caldera and surrounding areas. Ground motion intensity measures analysed included peak ground acceleration (PGA), peak ground velocity (PGV), and spectral pseudo-accelerations at multiple periods. The methodological workflow included: statistical regression analysis for deriving local GMMs, a systematic comparison between predicted and observed ground motion parameters, the analysis of magnitude and distance scaling and the evaluation of attenuation behaviour specific to shallow volcanic seismicity.

Within the RETURN WP4 activities, additional analyses were performed to integrate these empirical models into ShakeMap workflows. This included: both the comparison between GMM-based predictions and ShakeMap outputs derived from real events and the assessment of spatial residual patterns to identify systematic biases in standard GMPE-based approaches.

As a future step, an integration process focused on using empirical GMM outputs as reference constraints for validating simulated ground motion fields and for improving rapid initial estimates prior to full simulation availability will be performed.

5.2.4. Validation and Case Studies

The analysis confirmed that locally calibrated Campi Flegrei GMMs reproduce key features of local seismicity that are poorly represented by other GMPEs proposed for other Italian volcanic regions. In particular, the models indicate relatively high shaking levels at short spectral periods and rapid attenuation with distance, reflecting the shallow source depth and local geological complexity (see Figure 2a-d). Comparisons with operational ShakeMap estimates showed that region-specific GMMs reduce systematic biases in predicted peak ground motion values, especially in near-source regions. Validation against recorded ground motion demonstrated improved agreement between empirical predictions and observations (see Figure 2e-g).

Applications explored within RETURN WP4 might be used to support rapid preliminary shaking estimation during a seismic crisis and may allow, in the near future, the calibration of physics-based ground motion simulations, and hence the improvement of scenario-based ShakeMap generation integrating these laws with physics-based synthetic seismograms.

5.2.5. Operational Implementation

The work directly contributes to the objectives of RETURN and WP4 by potentially extending hybrid methodologies for ShakeMap computation to a complex volcanic environment like the Campi Flegrei caldera. The integration of local GMMs enhances both the physical realism and the operational applicability of shaking maps generated during volcanic unrest.

Specifically, the research supports the improvement of hazard assessment for volcanic seismic sequences, the reduction of uncertainty through empirical calibration and a future development of multi-stage workflows combining rapid empirical estimates with physics-based simulations and real observations.

The outcomes strengthen the capacity of operational monitoring systems to produce accurate and timely ground motion maps in complex tectonic–volcanic environments.

5.2.6. Produced Outputs

The activity produced the following outputs within the RETURN project framework:

- GMMs for Campi Flegrei seismicity for PGV, PGA and PSA at 18 periods between 0.02 and 5 seconds
- comparative ShakeMap using locally calibrated and already available GMMs.

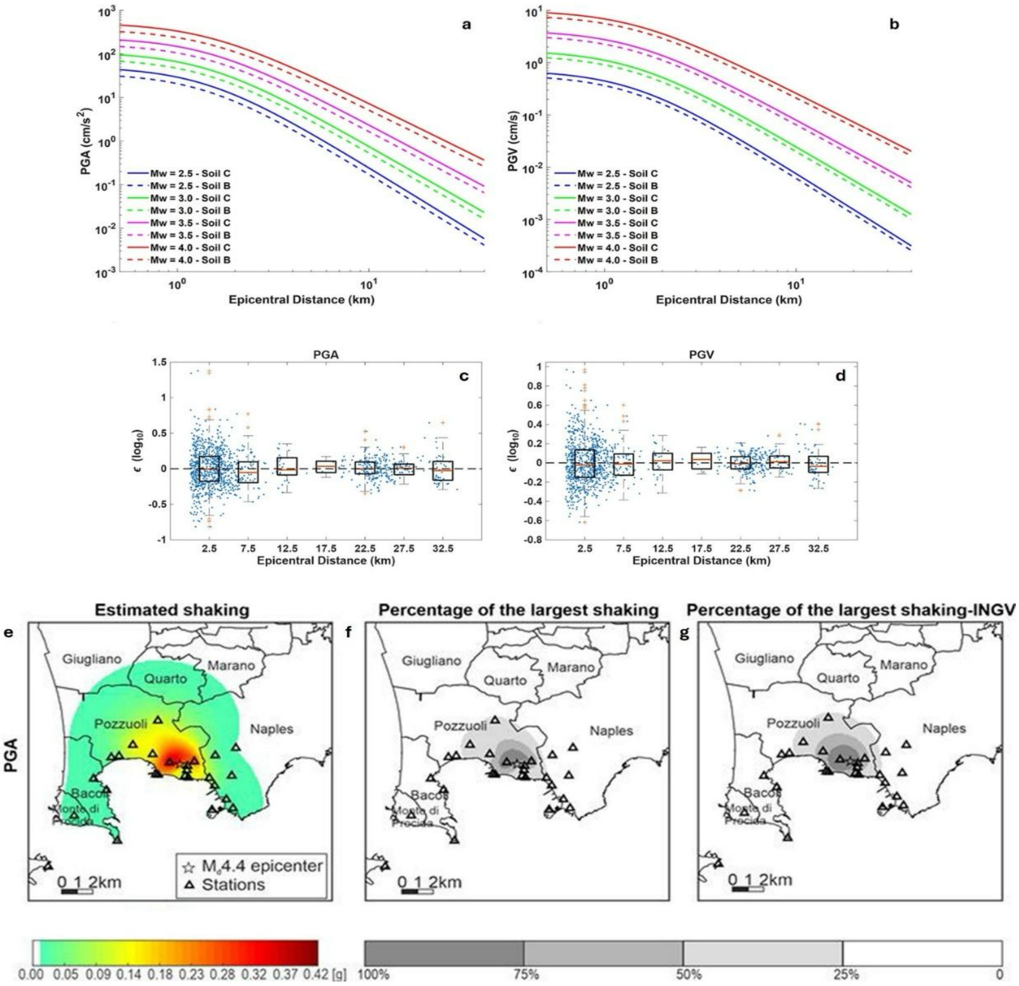

Figure 2: (a)-(b) GMMs for PGA and PGV for different magnitude bins and considering soils of type B and C according to the EC8 classification. (c)-(d) residuals of PGA and PGV as a function of epicentral distance. (e): Shaking prediction obtained interpolating the real PGA observation and the locally calibrated GMM through the ShakeMap interpolation scheme. (f)-(g): Level of attenuation depicted by means of the percentage of largest shaking. These percentages are obtained using the locally calibrated GMM (f) and one of the available models used for the ShakeMap released by INGV for volcanic seismicity (g)

5.3 Time-Dependency of Ground Motion Prediction Equations and Impacts on Rapid-Response ShakeMap

5.3.1. Introduction

Ground Motion Prediction Equations (GMPEs) are a cornerstone of seismic hazard assessment and real-time impact products, including ShakeMaps. They are typically calibrated assuming *stationary* source, path, and site properties. However, increasing evidence from dense seismic monitoring shows that earthquake source properties, and consequently ground motion characteristics, can vary in space and time, even when magnitudes and distances are comparable. This time-dependent behavior challenges the assumption of ergodicity embedded in standard GMPEs and may affect the reliability of rapid-response ShakeMaps during evolving seismic sequences. The paper by Picozzi et al. (2026) provides new insights into this problem by analyzing small-to-moderate earthquakes in the Southeastern Alps through source-related parameters derived directly from ground-motion measurements. Although the study is not a GMPE paper per se, its results have direct implications for time-dependent ground-motion modeling and near-real-time shaking scenarios.

5.3.2. Time-Dependent Source Properties and Ground Motion

The study exploits the Energy Index (EI), defined as the deviation of observed radiated seismic energy from a regional reference scaling with seismic moment. EI is derived from ground-motion proxies (S-wave peak displacement and integrated squared velocity) using the RAMONES framework (Spallarossa et al., 2021), which closely mirrors real-time magnitude and energy estimation procedures. A key result is that, while EI shows no clear *temporal trend* over the 2016–2025 observation window, it exhibits persistent spatial heterogeneity, reflecting long-lived mechanical differences among fault segments (Figure 1). These differences are interpreted primarily in terms of frictional stress and rupture efficiency, rather than changes in tectonic loading rate or network performance.

From a GMPE perspective, this implies that:

- Earthquakes occurring on mechanically weak fault segments systematically radiate more energy per unit seismic moment.
- Conversely, events on stronger or more segmented faults tend to be less efficient radiators.

Since radiated energy and rupture efficiency strongly influence high-frequency ground motion, these findings indicate that ground shaking is not purely magnitude-controlled but depends on the evolving mechanical state of the fault system.

5.3.3. Implications for Time-Dependent GMPEs

Standard GMPEs assume that the between-event residuals are random and stationary. The results of Picozzi et al. suggest instead that part of this variability is *systematic* and linked to fault-zone properties that persist over years to decades.

In particular:

- Spatially coherent EI anomalies correspond to domains with distinct seismic efficiency and stress-drop characteristics.
- These domains remain stable through time, implying that time-dependent effects are not necessarily transient, but may reflect quasi-permanent fault segmentation.

For GMPE development, this has two main consequences:

1. Violation of full ergodicity: Ground-motion variability cannot always be reduced by averaging over space and time, as assumed in conventional models.
2. Potential predictability of residuals: If fault-related energy radiation patterns are known a priori, part of the between-event variability could be anticipated.

This opens the door to *adaptive or domain specific GMPEs*, where source terms are conditioned on fault mechanical properties inferred from ongoing microseismicity analysis.

5.3.4. Impact on Rapid-Response ShakeMaps

Rapid-response ShakeMaps rely on a limited set of inputs immediately after an event: hypocenter, magnitude, and a predefined GMPE. During the first minutes, they cannot account for event-specific rupture efficiency or stress conditions.

The findings of Picozzi et al. have several implications for these products:

- Systematic under- or over-estimation of shaking may occur if an earthquake ruptures a fault segment with anomalously high or low seismic efficiency.
- These biases are expected to be spatially coherent and repeatable for earthquakes occurring on the same fault domain.
- ShakeMaps generated early in a sequence may not reflect the true shaking potential if the fault system is in a mechanically evolving state.

Importantly, the RAMONES-style estimation of seismic moment and radiated energy is designed for near-real-time application. This suggests a pathway toward progressive ShakeMap refinement, where early maps based on standard GMPEs are updated as soon as source-specific energy information becomes available.

5.3.5. Toward Time-Aware ShakeMap Workflows

The study supports a conceptual shift from static to *time-aware* ground-motion modeling. Rather than modifying GMPE coefficients on the fly, the authors' approach suggests integrating source-parameter anomalies as complementary information.

A possible operational strategy would involve:

- Routine monitoring of EI (or equivalent energy-based metrics) for small earthquakes.
- Identification of fault segments characterized by persistent high or low rupture efficiency.
- Conditioning ShakeMap source terms or uncertainty estimates on the known behavior of the activated fault domain.

Such an approach would not replace GMPEs but would reduce epistemic uncertainty in rapid-response products, especially during seismic sequences or in regions with strong mechanical segmentation.

5.3.6. Conclusions

Although the paper focuses on fault segmentation and seismic energy radiation, its implications for ground-motion prediction are substantial. The key message is that ground motion is time-dependent through the evolution and spatial organization of fault mechanical properties, even in the absence of obvious temporal trends in seismicity rate or magnitude.

For rapid-response ShakeMaps, this means that:

- Early shaking estimates may systematically miss source-related effects.
- Integrating real-time energy-based source parameters can improve both accuracy and interpretability.
- Long-term monitoring of microseismicity provides actionable information for time-dependent ground-motion assessment.

Overall, the study demonstrates that bridging advanced source physics with operational ground-motion products is both feasible and scientifically justified, representing a natural next step for next-generation ShakeMap systems.

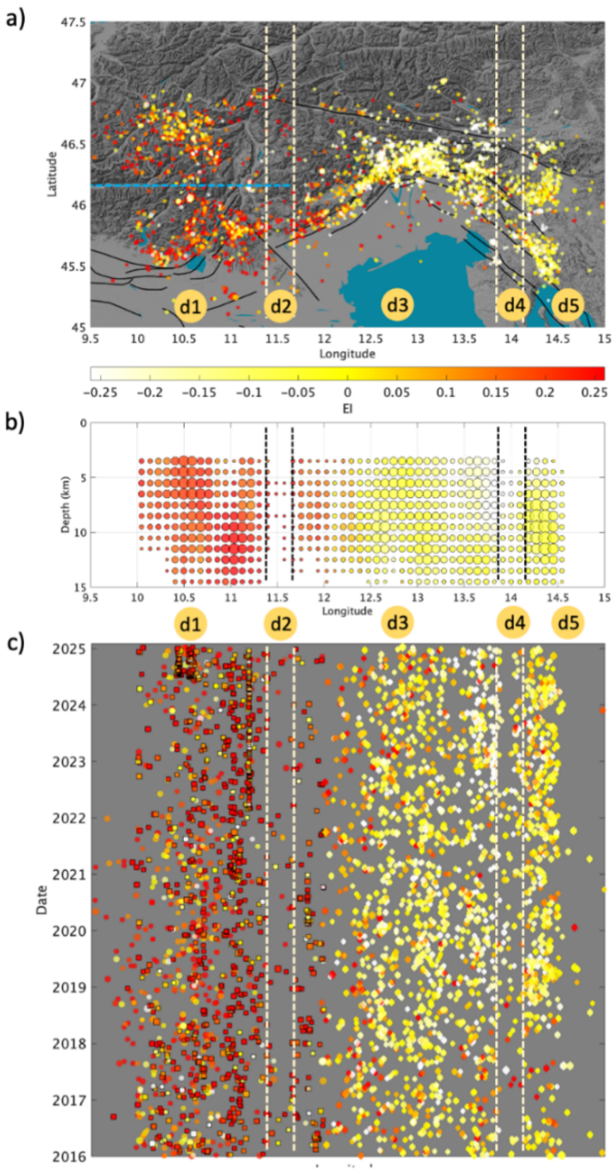

Figure 3: a) Distribution of earthquakes colored per EI. Seismogenic sources from DISS (https://diss.ingv.it; black lines). White dashed lines identify the five domains discussed within the text. The light blue dashed line separates EOA and CSA_MG faults (see text). b) Section showing the mean of EI, $\langle EI \rangle$, over a regular grid. The dimension of dots is related to the amount of data for grid node. c) Spatio-temporal distribution of EI.

5.4 Integration in the Rapid Response (ShakeMap) system of a model to assess the seismic impact.

5.4.1. Scientific Context and Rationale

The effectiveness of an Early Warning (EW) system does not depend solely on the timely detection of hazardous events, but increasingly on the capability to translate hazard information into actionable impact estimates. In the context of seismic events, this requires moving beyond the sole identification of earthquake parameters (e.g. magnitude, location and depth) towards the rapid assessment of the expected consequences on exposed and vulnerable elements.

The integration of seismic impact models within Rapid Response (ShakeMap) systems represents therefore a key step in bridging the gap between hazard detection and emergency response. Impact-based information allows emergency managers to better understand the potential severity of an event in terms of damage, casualties and disruption, enabling more informed and timely decision-making during the most critical phases following an earthquake.

Within this framework, the experience developed by PLINIVS at the University of Naples Federico II provides a consolidated example of how seismic impact assessment models can be integrated into operational systems supporting Civil Protection activities. The EASE (Earthquake AShfall Evaluation) tool constitutes a near real-time impact assessment model designed to estimate the effects of seismic events on the built environment and population and therefore represents a relevant reference for integration within Rapid Response (ShakeMap) system architectures.

5.4.2. Objectives

The integration of the seismic impact model within an Rapid Response (ShakeMap) framework pursues several complementary objectives. First, it aims to translate seismic hazard information provided by real-time monitoring networks into quantitative estimates of expected impacts on the territory. This enables a rapid assessment of potential consequences immediately after the occurrence of an earthquake.

A second objective is to support emergency management and Civil Protection activities by providing spatially explicit information on potential damage and losses. Such information can help authorities prioritize search and rescue operations, allocate resources and identify the most critical areas requiring immediate intervention.

Finally, the integration of impact modelling within Rapid Response (ShakeMap) systems contributes to the transition from hazard-based to impact-based early warning approaches, which represent an increasingly important paradigm in modern risk management frameworks.

5.4.3. Methodological Development

The seismic impact model implemented within the EASE tool follows a scenario-oriented approach. Unlike classical seismic risk analyses, which estimate the probability of damage over a given time span, the scenario-based approach focuses on the probabilistic distribution of damage generated by a specific reference event. This approach is particularly suitable for Rapid Response (ShakeMap) applications, where the objective is to support rapid response immediately after an event.

The methodology integrates three main components: seismic hazard, exposure and vulnerability.

Seismic hazard information is provided in near real-time by the national seismic monitoring system operated by INGV. Event parameters such as epicenter location, magnitude and depth are automatically acquired through standard FDSN Web Services and stored within the system database. These parameters trigger the execution of the impact assessment model whenever predefined thresholds in terms of magnitude and location are exceeded.

Exposure and vulnerability information are derived from a comprehensive GIS database developed by PLINIVS, which includes spatial data on population distribution, building typologies and structural characteristics at regional scale. Buildings are classified according to construction typology and structural features, allowing the application of vulnerability models calibrated on the Italian building stock.

The spatial resolution of the analysis is defined through a regular grid of 250 × 250 m cells, enabling a detailed spatial representation of the expected impacts across the territory.

5.4.4. Validation and Case Studies

The methodology has been implemented and tested through the EASE platform developed by PLINIVS. The system integrates seismic event data with exposure and vulnerability information to produce rapid estimates of expected damage and losses.

The outputs of the model include quantitative estimates of collapsed and uninhabitable buildings, as well as the expected number of fatalities, injured and homeless people for each spatial unit of analysis. The entire computational process, from hazard data acquisition to result generation, is performed automatically and requires only a few minutes, making the approach suitable for near real-time applications.

The platform also provides visualization tools that allow operators to explore impact scenarios through interactive maps and dashboards, supporting rapid situational awareness during emergency phases.

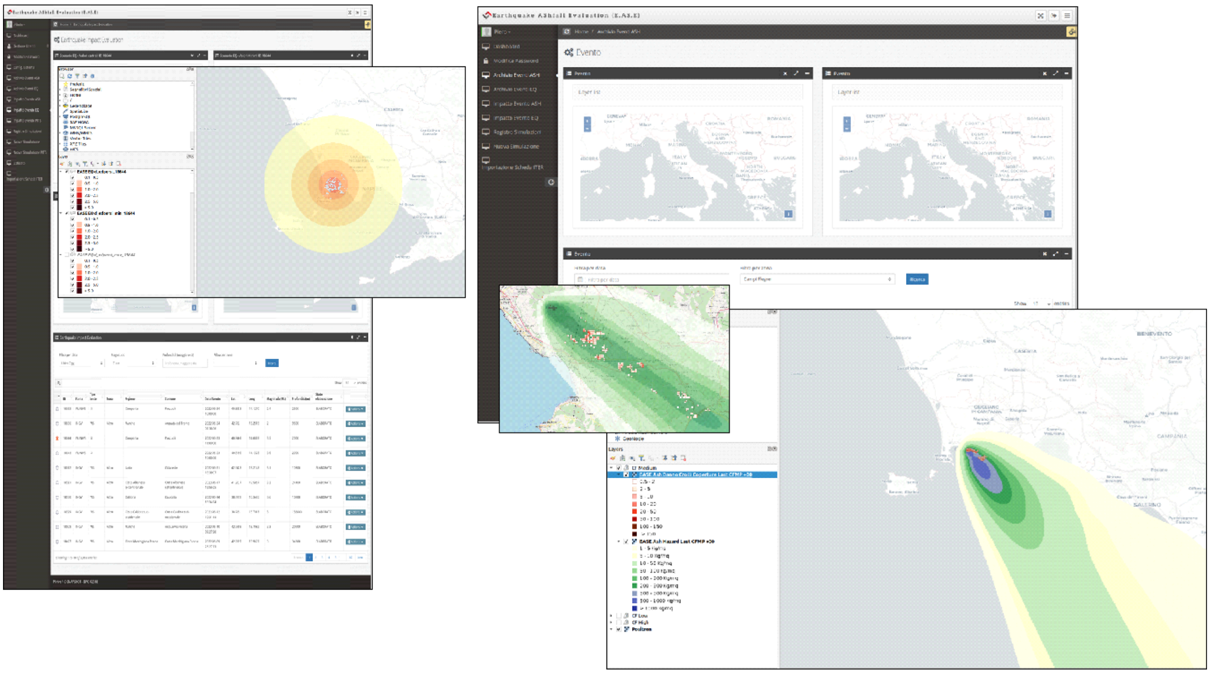

Figure 4. EASE tool: Impact scenario analyses consequent earthquakes and ash fall at the volcanoes of Campania Region (PLINIVS-UNINA).

The figure illustrates some examples of the graphical interface of the system, including the visualization of impact maps, seismic event information and the spatial distribution of expected damage.

5.4.5. Operational Implementation

From an operational perspective, the seismic impact model acts as a rapid response module that complements earthquake detection and alert components within an Rapid Response (ShakeMap) system. The integration is based on automated data flows and asynchronous processing, ensuring that impact information is generated without manual intervention.

The system periodically queries the seismic event services provided by INGV and acquires new events incrementally. Once a relevant event is detected, the impact assessment workflow is automatically executed and the results are stored within the platform database.

The adoption of standard geospatial services (OGC WMS and WFS) allows the seamless integration of impact maps into broader Rapid Response (ShakeMap) platforms, web-based dashboards and GIS clients used by emergency managers.

Although the EASE tool does not directly issue public alerts, its outputs are specifically designed to support decision-making processes within Civil Protection organizations by providing rapid estimates of the expected consequences of seismic events.

5.4.6. Produced Outputs

The integration of the seismic impact model within the Rapid Response (ShakeMap) framework produces several operational outputs that can support emergency management activities.

These include spatially distributed estimates of expected building damage, including the number of collapsed and uninhabitable structures, as well as estimates of human losses such as fatalities, injured and homeless people. All outputs are generated for each grid cell of the analysis domain, enabling detailed spatial analyses of the affected areas.

In addition to numerical estimates, the system provides interactive maps and dashboards that allow operators to visualize impact scenarios and explore the spatial distribution of expected consequences. These products contribute to improving situational awareness during the early stages following a seismic event.
The EASE tool is currently operational at the Volcanic Service of the Italian National Civil Protection Department and at the Civil Protection of the Municipality of Pozzuoli, where it supports the management of emergencies related to seismic and volcanic phenomena.
Overall, the integration of seismic impact assessment models within Rapid Response (ShakeMap) architecture represents a significant step towards impact-based early warning systems capable of supporting timely and informed decision-making during seismic crises.

5.5. Development of semi-analytical Fourier-domain ground motion prediction model for rapid earthquake hazard scenario calculation

5.5.1. Scientific Context and Rationale

The choice of ground motion estimates used for seismic hazard scenario calculation plays a key role in determining how well hazard estimates can be constrained. A common solution is to use one of the many available methodologies for physics-based ground-shaking simulations (Igel, 2016), which are analytically accurate but usually have the disadvantage of using limited frequencies below 1 or 2 Hz and are computationally time consuming. As a complementary approach, we aim to produce ground shaking estimates in the Fourier domain using a semi-analytical model of the Fourier Amplitude Spectra (FAS). The resulting FAS models obtained with this methodology contain information from a wide frequency range and require less computational time than fully analytical simulations (e.g., Bora et al., 2015). It is also possible to use the rapid estimates from semi-analytical models in synergy with more refined and time-consuming analytical estimates, for example to produce increasingly refined simulations with increasing time after an event. This activity is carried out in synergy with the RETURN Tasks 4.3 and 4.4 of VS3, which are dedicated to real-time hazard assessment and risk mitigation measures.

5.5.2. Objectives

The activity is aimed at producing ground shaking estimates in the Fourier domain using a semi-analytical modelling technique to describe the Fourier Amplitude Spectra in terms of their source, propagation and site components.
A careful calibration of the model is a central aspect to improve the accuracy of the estimates. The calibration process aims on the one hand, to validate the theoretical choices made for the analytical model components and, on the other hand, to estimate the empirical components to be included in the forward model, namely the regional attenuation function and the site response functions.

5.5.3. Methodological Development

A test area in north-eastern Italy was selected to test the calibration workflow (Fig. 1a), where many regional monitoring institutions provide good data coverage (e.g., Bragato et al., 2021). In collaboration with the UNIGE partners working on the same Task, a dataset of 1191 events occurred in the area between 2016 and 2024 was selected and carefully processed with strict quality criteria to create the spectral database used for the calibration.
The methodology selected for the calibration process is the Generalized Inversion Technique (Andrews, 1986; Castro et al., 1990), a robust method for jointly inverting Fourier amplitude spectra to separate source, path attenuation and site amplification effects. GIT has been widely used and refined since its introduction in the 1980s (e.g.: Oth et al., 2011; Bindi et al., 2025).
We first explored a parametric implementation of GIT (e.g.: Drouet et al., 2008; Cataldi et al., 2023) and developed a dedicated python algorithm, *spectral_modelling*, which is distributed as open-source code. Subsequently, as the dataset was perfectioned, we preferred a nonparametric GIT strategy (e.g.: Oth et al, 2011;

Bindi et al., 2020), which is more data-driven and allows for greater modeling flexibility. The nonparametric GIT calibration was performed using the *gitpy* algorithm (D'Amico et al., 2024, 2025) made available as open-source code by INGV and UNIGE.

5.5.4. Validation and Case Studies

The calibrated regional model obtained from GIT inversion consists of nonparametric source, attenuation and site functions; all results are available from Cataldi et al. (2025). The attenuation curves, calculated at discrete distance intervals, are characterized by a dependency on frequency and an overall monotonical decrease with distance at a rate that increases with frequency. Our site response functions are in very good agreement, within uncertainty, with independent estimates from literature (e.g., Klin et al., 2021). The goodness of fit was checked in terms of residual distributions, which did not show any trend with frequency or magnitude and are centered around zero.

The nonparametric source spectra were subsequently fitted to a point source Brune model (Brune 1970, 1971) over magnitude-wise selected frequency bandwidths, and the resulting source parameters (corner frequency and seismic moment) analyzed. The modelled and non-parametric spectral source curves show good overall consistency (Fig. 1b), as confirmed by their residual distributions. Possible improvements of the analytical model were analyzed (e.g., extended source modeling and directivity effects); however, the point source approximation was kept as more suitable to describe the regional seismicity up to moderate magnitude events.

5.5.5. Operational Implementation

The results of this activity can be used for the rapid production of spectral scenarios for the case study region (Fig. 1c); the same methodology can be extended to different case study areas. It is also possible to subsequently combine the Fourier-domain models with an additional model of the corresponding phase spectra, to obtain realistic time-domain ground motion estimates. This additional activity, initially planned, was subsequently left as a future development to dedicate more resources to the spectral model calibration, which is less trivial and has a bigger impact on the final results.

In addition, the resulting spectral site and attenuation functions can be used to correct the FAS spectra of new events, obtaining apparent source spectra which in turn can be fitted to produce source parameter estimates in near real time. These estimates can find an indirect application as input for the traditional analytic ground motion models, such as those based on synthetic waveforms generation.

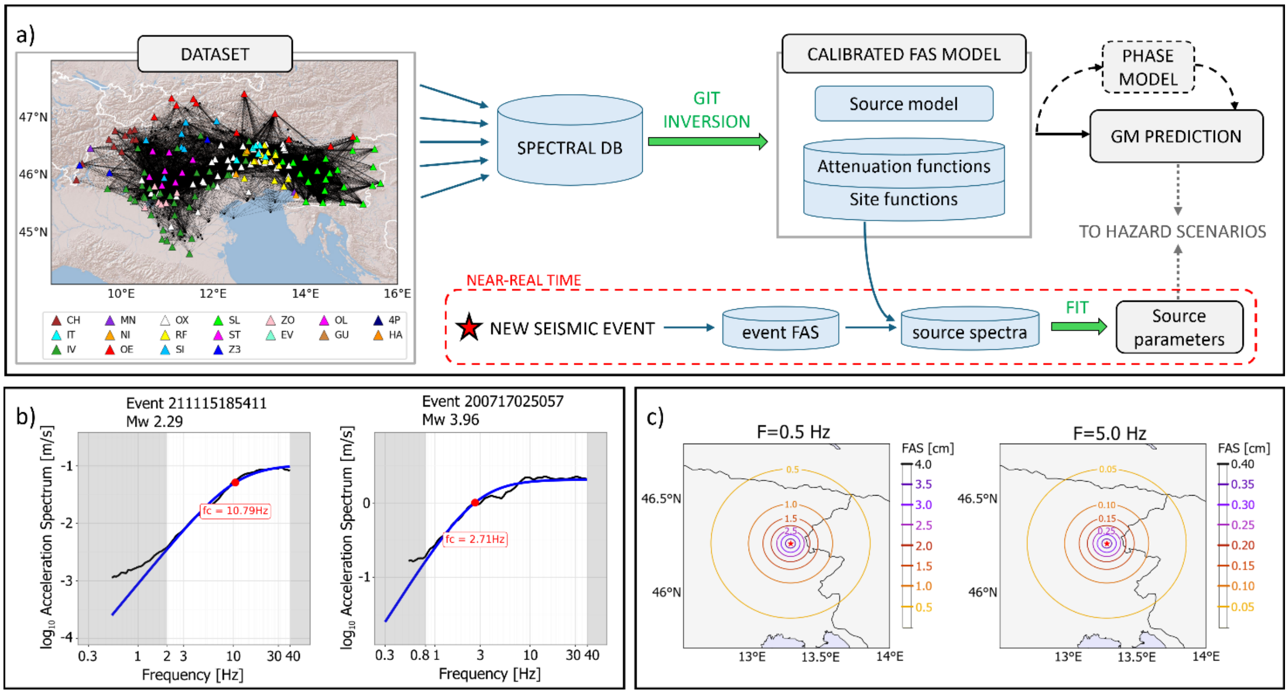

Figure 5. a) Workflow of the activity: model calibration (dataset selection, extraction of the spectral database, GIT inversion to obtain calibrated attenuation and site functions and the source model, production of spectral GM predictions) and additional applications (combination with phase model; near-real time extraction of source parameters). b) Examples of source spectra obtained from GIT inversion (black lines) and the corresponding modelled spectra obtained from their fit (blue lines). c) Examples of spectral ground motion prediction maps at 0.5 Hz and 1.0 Hz for a target earthquake in the case study area.

5.5.6. Produced Outputs

The activity produced multiple outputs within the RETURN project framework. The open source software for seismic spectra modeling and inversion is freely available on Github (https://github.com/sheyala/spectral_modelling_public/tree/main-obspy), and the database of calibrated source, attenuation and site functions for the test area and dataset of the corresponding fitted source parameters is published on Zenodo (Cataldi et al., 2025). A paper reporting on the calibration findings and beyond was submitted to Journal of Geophysical Research: Solid Earth on March 2025, currently under review ("*Stress drop and seismic efficiency distributions over the Adriatic indenter (European Southeastern Alps)*" by Cataldi, L., Picozzi, M., D'Amico, M., Morasca, P., Bindi, D., Poggi, V., Costa, G., Viganò, A., and Spallarossa, D.).

5.6. Multi-sensor onsite early-warning combining strong-motion and GNSS observations

5.6.1. Scientific Context and Rationale

In recent years, significant advances have been achieved worldwide in natural disaster management through the development of new tools capable of monitoring infrastructure and territory in real time. In this field, Earthquake Early Warning (EEW) systems represent a key instrument for mitigating seismic risk, since they are designed to provide sufficient time for the decision-making process and for taking actions before the arrival of strong shaking, thereby mitigating the impact on the population and infrastructure as much as possible. The aim of this activity is to implement a decentralized on-site earthquake early warning system for infrastructures, that combines strong-motion and GNSS observations.

5.6.2. Objectives

The objective of this activity is the development of a decentralized on-site early warning system integrating strong-motion and GNSS observations for rapid structural damage assessment. The proposed framework builds upon the on-site early warning methodology originally developed by Parolai et al. (2015, 2017), extending it toward a probabilistic formulation capable of estimating, in near real time, the probability of exceeding drift and inter-storey drift thresholds associated with structural damage. In contrast to traditional regional early warning systems, the approach is conceived for local deployment at instrumented buildings, where rapid measurements of ground motion and displacement proxies can be directly translated into engineering-relevant indicators. The integration of GNSS measurements within this framework aims at enhancing displacement stability and robustness, particularly for low-frequency components and evolving deformation conditions.

5.6.3. Methodological Development

Strong-motion records from Italian earthquakes with magnitude greater than 4.5 were retrieved from the *Osservatorio Sismico delle Strutture* (OSS) database, after authorized access to the platform. The selected dataset includes instrumented buildings for which base and upper-floor recordings are available, allowing direct estimation of structural response parameters. Acceleration time series were processed to obtain displacement histories through standard signal processing procedures, including baseline correction and numerical integration. For each recording, the peak ground displacement (PGD) at the building base was computed within a 3 s time window following the P-wave arrival, consistent with the rapid-response philosophy of decentralized early warning. In addition, total drift and inter-storey drift ratios were estimated from relative floor displacements. The resulting dataset was then partitioned into a training subset, used for model calibration, and an independent validation subset, used to assess predictive performance and generalization capability.

GNSS data recorded by the OGS-developed receiver installed at the Engineering building in Piazzale Tecchio were subsequently integrated into the multi-sensor early warning framework to evaluate their contribution to rapid displacement estimation and structural response assessment. The objective was to test whether co-located geodetic measurements could enhance the stability and robustness of displacement-based proxies derived from strong-motion recordings, particularly in the early stages of shaking.

The GNSS receiver operates in co-location with the seismic sensors within the multiparametric monitoring architecture established under WP2 (Figure 7). This configuration enables simultaneous observation of high-frequency dynamic ground motion and low-frequency ground deformation associated with bradyseismic processes, thus providing an independent estimate of absolute displacement. Integration of GNSS within the processing chain was facilitated by the development of Python-based APIs allowing uniform and programmatic access to both strong-motion waveforms and GNSS position time series, handled within a consistent MiniSEED-compatible framework. This unified data layer ensures coherent ingestion of heterogeneous sensor streams within the decentralized early-warning algorithms.

Figure 6. Installation of the multi-sensor monitoring system at the Piazzale Tecchio site (UNINA, Campi Flegrei area). Photographs document representative mounting configurations of the accelerometric (ADEL ASX2000), velocimetric (Lunitek Sentinel GEO) and GNSS (LZERO) sensors.

5.6.4. Validation and Case Studies

When total drift and inter-storey drift ratios were plotted as a function of the PGD measured at the building base within the first 3 s after P-wave arrival, an approximately linear trend emerged in logarithmic scale. The relationship between log(PGD) and log(drift) was therefore modeled using Bayesian linear regression, allowing explicit quantification of parameter uncertainty and predictive variance (Figure 6). The Bayesian formulation provides posterior distributions of regression coefficients rather than single deterministic estimates, enabling probabilistic assessment of damage-related thresholds.

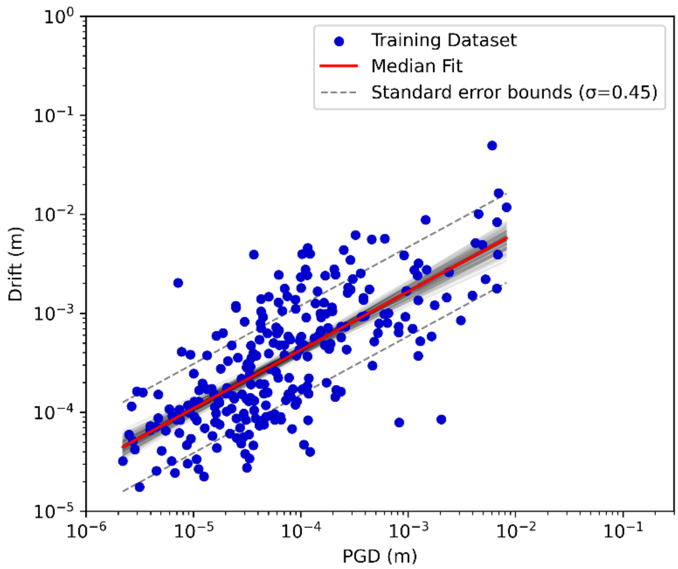

Figure 7. Results for Bayesian Linear Regression applied to the drift dataset.

Based on the posterior distributions obtained from the Bayesian regression, the probability of exceeding drift and inter-storey drift thresholds defined in the literature (Lagomarsino and Giovinazzi, 2006; Borzi et al., 2008; Mouroux and Brun, 2006) was computed for each record. These probabilities were used to define alarm criteria within the decentralized early-warning framework. Optimal probability thresholds were selected by maximizing classification performance metrics, namely precision, recall and overall accuracy (Table 1). Thresholds were determined separately for different building typologies (reinforced concrete frames, unreinforced masonry regular and simple stone), height classes (low-rise and mid-rise) and structural damage states (moderate, extensive and complete), ensuring consistency with engineering vulnerability classifications.

BUILDING TYPOLOGY	DAMAGE STATE	THRESHOLDS (%)	PRECISION (%)	RECALL (%)	ACCURACY (%)
RC frames, low-rise	moderate	13.26	67.00	100.00	97.00
RC frames, low-rise	extensive	12.37	33.00	100.00	94.00
RC frames, low-rise	complete	9.06	n.d.	100.00	97.00
RC frames, mid-rise	moderate	9.69	100.00	100.00	100.00
RC frames, mid-rise	extensive	9.13	100.00	100.00	100.00
RC frames, mid-rise	complete	4.23	n.d.	100.00	97.00
URM regular, low-rise	moderate	6.34	38.00	100.00	67.00
URM regular, low-rise	extensive	17.32	40.00	100.00	80.00
URM regular, low-rise	complete	10.33	50.00	100.00	93.00
URM regular, mid-rise	moderate	5.08	30.00	100.00	74.00
URM regular, mid-rise	extensive	8.27	100.00	100.00	100.00
URM regular, mid-rise	complete	5.02	100.00	100.00	100.00
URM simple stone, low-rise	moderate	11.66	56.00	100.00	73.00
URM simple stone, low-rise	extensive	12.66	50.00	100.00	87.00
URM simple stone, low-rise	complete	12.19	100.00	100.00	100.00
URM simple stone, mid-rise	moderate	32.19	75.00	75.00	95.00
URM simple stone, mid-rise	extensive	6.38	50.00	100.00	95.00
URM simple stone, mid-rise	**complete**	**10.71**	**100.00**	**100.00**	**100.00**

Table 1. Optimal Probability of exceeding Lagomarsino and Giovinazzi drift limits for Precision, Recall and Accuracy. Thresholds are defined for Moderate Damage State, Extensive Damage State and Complete Damage State and for different building typologies (Reinforced Concrete [RC] low-rise and mid-rise, Unreinforced Masonry [URM] Regular and Simple Stone, low-rise and mid-rise). For RC buildings, low-rise and mid-rise, Precision is not defined (n.d.) considering Complete Damage State.

The selected probability thresholds were further evaluated in terms of false alarm rate, missed alarm rate and achievable lead time relative to the onset of damaging ground motion. Performance metrics were computed on the independent validation dataset to assess the robustness of the classification scheme.

Building upon the strong-motion probabilistic framework described above, a sensor-fusion strategy was implemented to combine accelerometric and GNSS observations. A Kalman filter was adopted to reconstruct displacement time series by exploiting the complementary characteristics of the two sensors: the high-frequency sensitivity of accelerometers and the long-period stability of GNSS measurements. The approach

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was first validated using synthetic signals derived from real earthquake records (including the 2016 Norcia event) combined with realistic sensor noise, demonstrating stable displacement reconstruction and effective mitigation of long-period integration drift typically affecting double integration of acceleration records (Figure 8).
Following this methodological validation, the integrated framework was applied to real data from the Piazzale Tecchio installation. GNSS-derived displacement time series were processed and quantitatively compared with strong-motion-based estimates in terms of waveform consistency and spectral content within the engineering-relevant frequency band. At the current stage, the probabilistic drift estimation model remains primarily based on strong-motion PGD measured at the building base; however, the multisensor configuration provides an independent constraint on displacement amplitude and long-period behavior, increasing robustness in conditions characterized by complex shaking or potential accelerometer saturation.

5.6.5. Operational Implementation

The results indicate satisfactory predictive capability, with most lead times ranging between 1 and 5 seconds after P-wave detection. Such lead times confirm that the decentralized on-site approach is suitable primarily for fully automated, rapid-response actions (e.g., system shutdown or safety triggering).
Ongoing analyses are aimed at quantifying the contribution of GNSS measurements to early displacement estimation during local moderate events in Campi Flegrei, particularly within repeated seismic sequences associated with bradyseismic unrest. In this framework, GNSS integration does not substitute the strong-motion-based decentralized approach but complements it by improving stability and reliability of displacement-based damage proxies. The co-located multisensor installation at Piazzale Tecchio therefore serves as a real-world validation platform for decentralized on-site early warning strategies integrating seismic and geodetic observations.

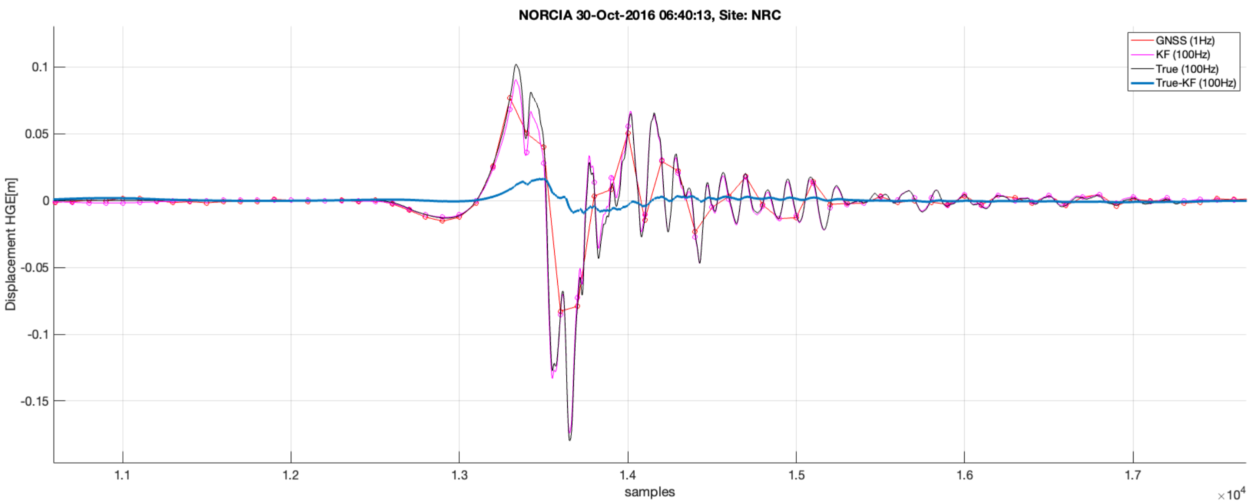

Figure 8: Example of sensor-fusion process combining accelerometric and GNSS signals through a Kalman filtering approach. The reconstructed displacement time series mitigates long-period drift while preserving high-frequency content.

5.6.6. Produced Outputs

A paper reporting the methodology described above was submitted to Soil Dynamics and Earthquake Engineering on November 2025, currently under review ("Improving Decentralized On-Site Earthquake Early Warning by rapid estimation of drift and inter-storey drift" by Morga, R., Parolai, S., Poggi, V., Romanelli, F.).

5.7. One-Second-Lead Earthquake Warning and Impact Assessment at Campi Flegrei

5.7.1. State of the art and innovative elements introduced within the RETURN project

Campi Flegrei is currently experiencing an intensifying bradyseismic crisis, characterized by accelerated ground uplifts and frequent shallow, moderate-magnitude earthquakes. These seismic events occur within a very limited spatial extent, where epicenters are often located only a few kilometers from exposed urban areas [1]. Under these conditions, conventional regional, source-based EEW approaches — which rely on rapid hypocenter and magnitude estimation before forecasting ground motion — are constrained by extremely short source-to-site distances. As a result, the so-called "blind zone," where strong shaking arrives before alert dissemination, overlaps with the actual impact area, significantly reducing the practical effectiveness of standard EEW systems. Within this state-of-the-art context, the present research introduces a conceptual and methodological innovation consistent with the objectives of RETURN [2]. Rather than focusing exclusively on pre-shaking alerts, the study advances an Earthquake Early Response (EER) paradigm, in which ultra-rapid estimation of expected ground motion becomes the central operational objective.

5.7.2. Research objectives

The main objective is to design and validate a hybrid, on-site, impact based EEW system capable of: delineating the spatial extent of the expected impact around the target site so that the information can be fast accessed by Civil Protection Authorities.

5.7.3. Methods, algorithms, data analysis

The system was calibrated using more than 500 earthquakes (Md 1–4) recorded between 2016 and 2024 by the INGV-Osservatorio Vesuviano seismic network [2]. After preprocessing and quality control, the dataset was divided into training and test subsets for empirical calibration and validation. The methodology consists of: (1) extracting the peak P-wave displacement (Pd) and the characteristic period (τc) within a 1-second P-wave time window; (2) calibrating an empirical scaling law linking log(PGV/PGA) to log(Pd); (3) estimating seismic moment and deriving a single-station magnitude (Mew) assuming a triangular source time function having Pd as peak and τc as duration; (4) combining predicted PGV and magnitude with local Ground Motion Prediction Equations (GMPEs) to compute the Area of Competence radius, defined as the area around the station where PGV remains stable within ±50% of the predicted site value. System performance is evaluated using intensity thresholds (IMCS) and standard metrics such as Precision and Recall.

5.7.4. Results, validation, and/or applications

The magnitude estimate (Mew) shows no systematic bias relative to moment magnitude, with a standard deviation of approximately 0.36 magnitude units. System performance depends on the selected intensity threshold. At IMCS ≥ IV (clearly felt shaking), the system achieves the best balance, with Precision of 84.2% and Recall of 80.0%. The methodology was tested on two significant independent scenarios (Md 4.4 in May 2024 and Md 4.6 in March 2025). In both cases, the system successfully predicted peak shaking and delineated realistic AoCs within one second, demonstrating its operational feasibility in a short-latency volcanic environment (Figure 1).

5.7.5. Impact of the research according to the objectives of RETURN and WP4 in particular

This research is strongly consistent with the objectives of RETURN, and with the strategic goals of WP4, which focuses on advanced monitoring systems, modeling approaches, and operational tools for multi-risk management. The study contributes to WP4 by developing a low-latency, impact-based monitoring.

methodology specifically designed for compact, hazard-prone regions such as volcanic calderas and densely urbanized seismic areas. By delivering reliable estimates of ground shaking and magnitude within one second of P-wave detection, the proposed system enhances real-time situational awareness in contexts where traditional early warning approaches are physically constrained. A central innovation of the work is the introduction of a spatially explicit impact quantification framework through the concept of the Area of Competence (AoC). Rather than limiting early warning information to the recording station itself, the AoC extends predictions to a defined surrounding area within which expected shaking remains stable within a certain threshold. This approach transforms point-based seismic measurements into actionable information, strengthening the operational value of monitoring outputs for civil protection and emergency management. Finally, although calibrated for the Campi Flegrei caldera, the methodological framework is inherently transferable. With appropriate local calibration of ground motion models and network geometry, the system can be adapted to other volcanic or densely urbanized seismic regions worldwide, thereby reinforcing RETURN's broader mission of developing scalable, impact-oriented solutions for resilient communities exposed to natural hazards.

List of outputs

- A validated hybrid on-site EEW system.
- A novel single-station magnitude estimation procedure;
- Definition and operational implementation of the Area of Competence (AoC)

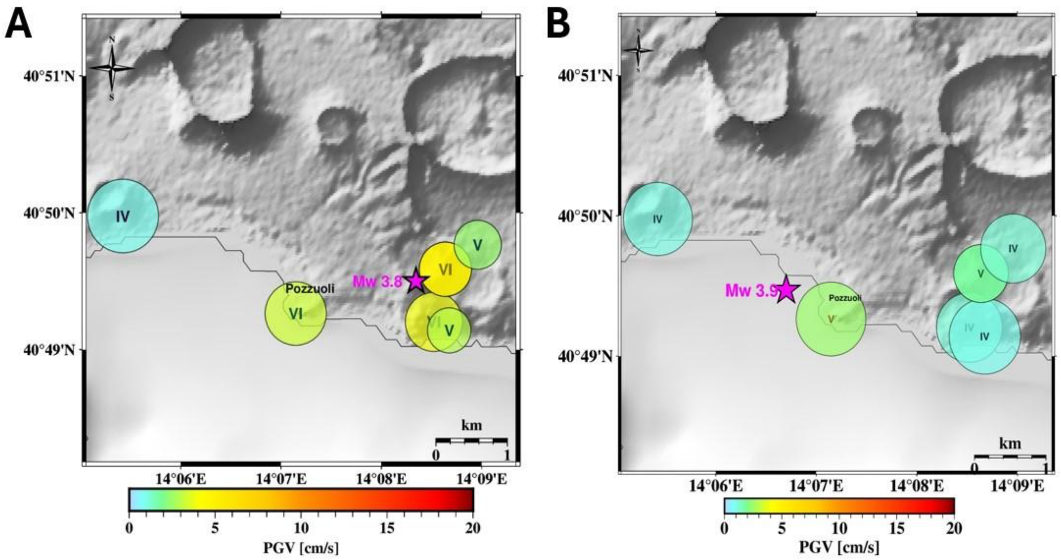

Figure 9: (A) Test on the Md 4.4 earthquake of May 20, 2024. (B) Test on the Md 4.6 of March 13, 2025. Magenta star represents the earthquake location. Each circle represents the area centered on the station within which the predicted PGV varies between +-50% of its value. Color follows PGV. In each circle, the estimated shaking intensity (IMCS) at the site is also reported.

5.8. Deployment and Operational Implementation of a Seismic Array for High-Resolution Monitoring at Campi Flegrei

5.8.1. State of the Art and Innovative Elements Introduced within the RETURN Project

The Campi Flegrei caldera is characterized by persistent volcanic unrest, shallow seismicity, and recurrent bradyseismic uplift episodes. Effective monitoring in this environment requires high spatial resolution and sensitivity to very low-magnitude events (often below Md 1–2), which are fundamental for tracking stress redistribution, fluid migration, and the temporal evolution of the volcanic system [1]. Although the regional seismic network provides reliable hypocentral determinations at the caldera scale, its resolving power decreases in highly localized and persistently active sectors such as Pisciarelli and Solfatara, where microseismicity plays a key role in interpreting ongoing unrest dynamics. Within the framework of RETURN, the EEW@ALTA seismic array experiment has been designed and implemented as an integrated monitoring and operational platform. The innovation lies in the combination of a dense small-aperture array geometry with real-time impact-oriented processing. The array enhances high-resolution characterization of microseismicity, while simultaneously serving as a testbed for the operational implementation of the hybrid Early Response (EER) system. This dual-purpose infrastructure represents a methodological advancement toward integrated, process-oriented and impact-based monitoring of bradyseismic dynamics.

5.8.2. Research Objectives

The EEW@ALTA experiment aims to strengthen monitoring and operational capabilities in the most active portion of the Campi Flegrei caldera. The objectives are twofold. From a scientific perspective, the array improves detection and precise localization of low-magnitude earthquakes, refines depth resolution and clustering patterns, and supports detailed analysis of source properties. From an operational perspective, the experiment integrates real-time Early Response processing within the array framework, enabling rapid magnitude and ground-motion estimation directly at selected stations.

5.8.3. Methods, Algorithms, and Data Analysis

The EEW@ALTA array is installed within the Altamira complex, a few kilometers from Pisciarelli and Solfatara, in one of the most active sectors of the caldera. It consists of five stations deployed with inter-station distances between 50 and 80 meters, forming a dense small-aperture configuration optimized for coherent wavefield analysis. Each station is equipped with a three-component short-period velocimeter, a high-resolution data logger, and a GPS receiver for precise timing synchronization. The array has been fully operational since June 2025 and continuously streams real-time data to the seismology laboratories of the University of Naples Federico II. Automated workflows perform detection, relocation, and spectral analysis. Importantly, two of the five stations are currently running the hybrid Early Response algorithm in real time [2], providing immediate local magnitude and peak ground-motion estimates.

5.8.4. Results, Validation, and Applications

Since deployment, the EEW@ALTA array has demonstrated enhanced sensitivity to microseismicity in the Pisciarelli–Solfatara sector. Preliminary results indicate improved localization accuracy compared to solutions derived from the broader regional network alone, particularly for shallow events clustered within a few hundred meters. Array-derived waveform and spectral analyses provide refined constraints on source duration and frequency content, supporting improved interpretation of seismic processes associated with bradyseismic uplift. The real-time Early Response implementation on two stations has proven capable of delivering rapid magnitude and shaking estimates, enhancing situational awareness during seismic swarms (Figure 1).

5.8.5. Impact of Research According to the Objectives of RETURN and WP4

The EEW@ALTA experiment directly supports the objectives of RETURN, particularly within WP4, which focuses on advanced monitoring systems, modeling approaches, and operational tools for risk management. By increasing spatial resolution and detection capability in a densely populated volcanic environment, the array provides higher-quality input data for modeling stress changes and fluid-driven processes. The integration of real-time Early Response processing strengthens the operational dimension of WP4 by linking detailed seismic observation with immediate impact estimation. This integrated scientific-operational infrastructure enhances situational awareness during unrest phases, supports hazard scenario evaluation, and feeds high-resolution real-time data into broader multi-risk platforms. The EEW@ALTA experiment thus represents both an infrastructural enhancement and a methodological step toward fully integrated, impact-oriented monitoring systems in compact multi-risk environments.

List of Outputs

- Design and deployment of the EEW@ALTA five-station small-aperture seismic array in Campi Flegrei;
- Refined high-resolution catalogs for low-magnitude seismicity in the Pisciarelli–Solfatara area;
- Implementation and operational testing of the hybrid Early Response system on two array stations

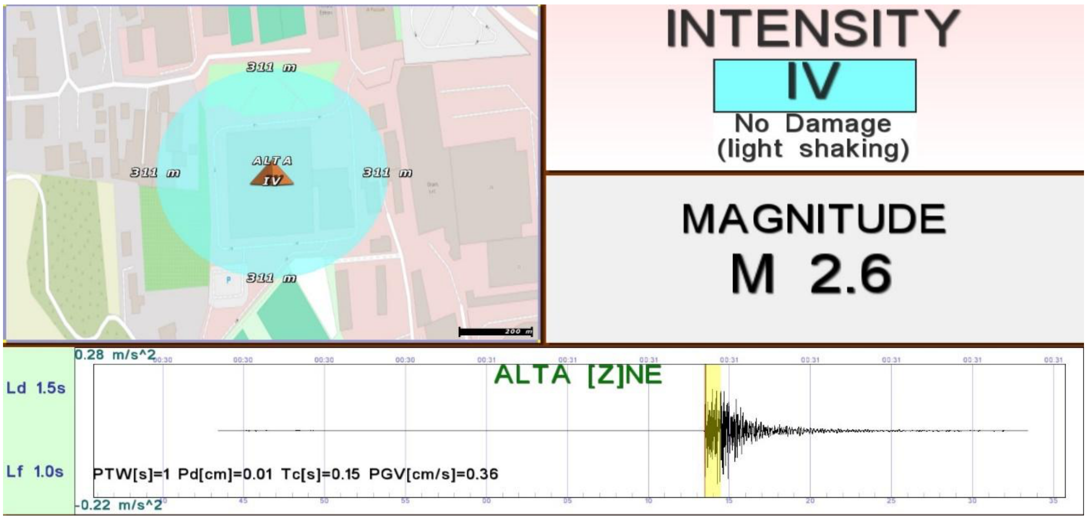

Figure 10: Example of real-time output from one station of the Altamira seismic array during a local event). The upper-left panel shows the station location and the corresponding Area of Competence (AoC), represented by the circular region within which the predicted ground motion is expected to remain stable within ±50% of the station estimate. The upper-right panel reports the automatically computed intensity level (IMCS IV – light shaking, no damage) and the estimated magnitude. The lower panel displays the vertical-component waveform (ZNE), with the 1-second P-wave time window highlighted. Real-time parameters extracted within the P-wave window (Pd, Tc, PGV) are shown, illustrating the operational implementation of the hybrid Early Response system running on the array station.

6. Conclusions

Task 4.2 of WP4 was conceived with the objective of developing and validating an integrated methodological framework capable of linking Earthquake Early Warning (EEW), rapid ground-motion modeling, and near-real-time impact assessment into a coherent operational chain. The activities presented in this deliverable collectively address this objective by acting on complementary components of the rapid-response workflow, spanning from ultra-rapid source characterization to impact-oriented decision support.

A first major outcome concerns the integration of rapid empirical source estimation with scenario-based hazard forecasting. The hybrid EEW–Tsunami Early Warning workflow demonstrated that early source parameters derived from P-wave observations can be effectively coupled with probabilistic tsunami forecasting, even in near-field and time-critical environments. Synthetic scenario testing and retrospective analyses confirmed that early, moderately uncertain source estimates can still provide operationally useful hazard information when embedded within a probabilistic framework. This result validates the feasibility of exploiting the earliest seconds of available data without compromising forecast robustness.

A second key contribution lies in improving the physical consistency and regional specificity of rapid ground-motion estimation. The development and calibration of local Ground Motion Models (GMMs) for the Campi Flegrei volcanic area showed that generic GMPEs may introduce systematic biases in complex volcanic settings characterized by shallow seismicity and heterogeneous attenuation properties. The integration of locally derived attenuation and site functions within ShakeMap workflows significantly enhances regional reliability. In parallel, the investigation of time-dependent source properties demonstrated that part of the between-event variability commonly treated as random residuals may instead reflect spatially persistent fault segmentation and energy radiation characteristics. This finding supports the need for adaptive or domain-aware approaches in rapid-response ground-motion prediction.

The semi-analytical Fourier-domain modeling framework represents an additional methodological advancement. By calibrating nonparametric source, path, and site functions through generalized inversion techniques, the activity provides a computationally efficient tool for spectral scenario generation. The approach bridges empirical regression-based models and full-waveform physics-based simulations, enabling rapid spectral ground-motion prediction and near-real-time extraction of source parameters. The validation of attenuation curves, site amplification functions, and residual behavior confirms the internal consistency of the calibrated model and its suitability for operational applications in the tested region.

A central innovation of Task 4.2 is the explicit integration of impact-oriented methodologies within the early warning architecture. The incorporation of the EASE seismic impact model demonstrates the operational feasibility of translating rapid hazard information into spatially explicit damage and loss estimates within minutes. Furthermore, the decentralized on-site probabilistic early response framework, based on Bayesian regression between early peak ground displacement and structural drift, provides a physically interpretable and statistically robust approach for building-specific damage assessment. Validation on independent datasets indicates that drift exceedance probabilities can be estimated with satisfactory classification performance and lead times compatible with automated protective actions.

The integration of strong-motion and GNSS observations through Kalman-based displacement reconstruction further strengthens the reliability of displacement-based damage proxies, particularly in low-frequency or long-duration shaking conditions. The deployment of the EEW@ALTA seismic array at Campi Flegrei complements these developments by enhancing detection capability, improving source characterization in a compact volcanic environment, and serving as an operational validation platform for hybrid Early Response algorithms.

Taken together, these results demonstrate that the objectives of Task 4.2 have been substantially achieved. The deliverable does not present isolated methodological advancements but rather defines an interoperable architecture in which ultra-rapid detection, empirical and semi-analytical modeling, multi-sensor monitoring, and impact estimation are methodologically aligned. The framework supports progressive refinement of information across temporal scales and reduces fragmentation between hazard and impact domains, in line with the strategic objectives of WP4.

Nevertheless, several limitations and open challenges remain. First, some components—particularly local GMM calibration and Fourier-domain inversion—have been validated primarily within specific regional case studies. Their transferability to other tectonic or volcanic contexts requires additional datasets and calibration efforts. Second, while time-dependent source effects have been characterized in terms of spatially persistent energy anomalies, their systematic integration into operational GMPE frameworks remains at a conceptual stage. Third, the decentralized on-site early response methodology, although statistically validated, depends on the availability of instrumented buildings and representative structural typologies, limiting immediate large-scale deployment. Moreover, GNSS integration, while promising for displacement stabilization, requires further quantification of performance during moderate-to-strong events with complex waveform characteristics.

The research conducted within this study contributes significantly to the scientific, technological, and socio-economic objectives of WP4 of the RETURN project, which aims to develop advanced monitoring systems, modelling approaches, and operational tools for multi-risk management and rapid response.

From a **scientific perspective**, the work advances the understanding and modelling of seismic and tsunami hazards through several innovative approaches. These include the integration of earthquake early warning (EEW) outputs with probabilistic tsunami forecasting for near-field scenarios, the development of locally calibrated ground motion models for complex environments such as the Campi Flegrei volcanic area, and the investigation of time-dependent ground-motion variability related to fault mechanical properties. Additional contributions include the development of semi-analytical Fourier-domain ground-motion models and hybrid early-response methodologies capable of estimating shaking and impact within seconds of P-wave detection. Together, these studies improve the physical consistency, reliability, and adaptability of rapid response hazard assessment.

From a **technological and operational standpoint**, the research delivers several tools and datasets that directly support WP4 activities. These include synthetic scenario databases for the Messina Strait, locally calibrated ground-motion models, open-source spectral modelling software, and the integration of impact assessment tools within ShakeMap rapid-response systems. The development of decentralized early warning approaches combining strong-motion and GNSS observations, as well as the deployment of a high-resolution seismic array at Campi Flegrei, further strengthens real-time monitoring and early response capabilities.

The **socio-economic impact** lies primarily in the improved capacity for rapid hazard and impact assessment supporting civil protection authorities. By moving from purely hazard-based products to **impact-oriented early response systems**, the research enables faster identification of affected areas, improved situational awareness during crises, and more effective allocation of emergency resources. These advancements contribute to reducing potential losses, enhancing community resilience, and supporting evidence-based risk management in densely populated and multi-hazard environments.

Future developments should therefore focus on (i) extending calibration and validation of spectral and attenuation models to additional regions, (ii) formalizing adaptive or domain-conditioned ground-motion prediction strategies informed by real-time source parameters, (iii) strengthening interoperability between regional EEW systems and decentralized on-site modules, and (iv) systematically integrating uncertainty propagation from source estimation to impact metrics. The operational implementation of hybrid Early Response algorithms on dense arrays and multi-sensor platforms also offers opportunities for testing robustness during prolonged seismic sequences and unrest phases.

In conclusion, Task 4.2 advances the state of the art by moving from a detection-centered paradigm toward a physically consistent, impact-oriented, and scalable rapid-response framework. By integrating empirical calibration, semi-analytical modeling, multi-sensor monitoring, and probabilistic impact assessment within a unified architecture, the activities contribute substantively to the scientific, technological, and operational goals of WP4 and to the broader objectives of the RETURN project.

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