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1. Technical references

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2. Abstract

WP 4 is dedicated to the integration of existing and new knowledge on earthquake monitoring, Earthquake Early Warning (EEW) and Rapid Response (RR). Within this context, Task 4.1 is dedicated to the development, implementation, and testing of innovative methodologies for real-time seismic signal monitoring and for EEW estimates. In this task, algorithms, and methods for estimating EEW parameters and their uncertainties will be developed, both using physics-based approaches, and ground motion driven (data-driven) approaches. To a limited extent, the use of AI for real-time estimates and EEW applications will also be explored. All the proposed approaches will integrate local (at the target) and regional multiparametric observations. Specific research activities of this task include:

- Development, implementation, and testing of Impact-Based and Time-Evolutive Earthquake Early Warning Methods.
- Inclusion of Seismo and geodetic estimates for real time monitoring and deep learning data analysis.
- Testing of AI-assisted multimodal inspection tools using deep learning models for non-contact sensing.
- Contribution to monitoring network design and optimization.
- Investigation on the contribution of GNSS observations for EEW.

A more detailed description of the progress of specific research activity is provided below, followed by a synthetic paragraph illustrating the main outcomes of the project.

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4. Introduction

Earthquake Early Warning (EEW) systems and rapid monitoring infrastructures represent key technological components for reducing the impact of seismic events on society and critical infrastructures. By providing alerts seconds to tens of seconds before the arrival of destructive ground shaking, these systems can enable automated safety actions, support emergency management decisions, and improve situational awareness during the earliest stages of a seismic crisis. In recent years, significant advances have been achieved in the fields of real-time seismic monitoring, geodetic observation, and data-driven analysis, enabling the development of increasingly sophisticated early warning and rapid response frameworks.

Within this context, Work Package 4 (WP4) of the RETURN project focuses on the development of advanced monitoring systems, modelling approaches, and operational tools aimed at strengthening the capacity for real-time hazard assessment and emergency response in multi-risk environments. Task 4.1 specifically addresses the integration of innovative methodologies for earthquake monitoring, early warning, and rapid characterization of seismic events. The activities carried out in this task combine seismological research, geodetic monitoring, synthetic modelling, and algorithm development in order to improve the reliability, speed, and operational applicability of early warning systems.

The research presented in this report contributes to this objective through several complementary lines of investigation. First, the development and validation of the QuakeUp shaking-forecast earthquake early warning system explore a hybrid methodology capable of predicting ground shaking directly from early P-wave observations and continuously updating impact maps during rupture propagation. Second, the creation of a physics-based synthetic testing framework using the SPEED simulation platform provides a controlled environment for evaluating early warning performance under realistic seismic scenarios representative of Southern Italy. Third, the study of the deterministic behaviour of earthquake rupture initiation investigates whether the earliest seconds of seismic signals contain predictive information about the final magnitude, proposing a novel parameter for rapid magnitude estimation. Finally, the deployment of multiparametric monitoring infrastructures, including GNSS RTX geodetic networks and seismo-electromagnetic stations, contributes to enhancing real-time observation capabilities and expanding the available datasets for multi-disciplinary seismic research.

Together, these activities aim to strengthen the integration between seismic monitoring, physical modelling, and operational early warning applications. By combining methodological innovation with technological deployment and open data infrastructures, the work carried out in Task 4.1 contributes to the broader RETURN objective of developing integrated systems for multi-hazard monitoring and rapid response. The results presented in this document therefore represent an important step toward more reliable and scalable earthquake early warning solutions capable of supporting civil protection authorities, infrastructure operators, and communities exposed to seismic risk.

5. Novel methods and technologies for real-time monitoring

5.1. A Shaking-Forecast Based Earthquake Early Warning System: Development and Applications

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

Earthquake Early Warning Systems (EEWS) have been developed worldwide to mitigate seismic risk by issuing alerts seconds to tens of seconds before the arrival of destructive ground shaking. Operational systems are active in Japan, Mexico, Taiwan, South Korea, and along the U.S. West Coast, while research and pilot implementations exist in Europe and South America (Allen & Melgar, 2019; Clinton et al., 2016). These systems generally adopt either:

- Network-based approaches (Zollo et al., 2023), which estimate hypocenter and magnitude from early P-wave recordings and predict ground motion using Ground Motion Prediction Equations (GMPEs);
- Onsite approaches (Caruso et al., 2017), which estimate expected shaking at a site directly from early P-wave amplitudes recorded locally, without explicit source characterization.

Recent developments have progressively integrated both philosophies. Network-based earthquake early warning systems are generally classified as either source-based or wavefield-based regional approaches. Source-based systems estimate earthquake location and magnitude from early seismic recordings and use regional ground motion prediction equations to forecast expected shaking at target sites. In contrast, wavefield-based systems (Hoshiba, 2021) directly track the spatial and temporal evolution of observed ground motion using dense acceleration networks and physics-based interpolation, issuing alerts when predefined shaking thresholds are exceeded without explicit source characterization.

To bridge these two paradigms, a P-wave shaking-forecast methodology poroposed by Zollo et al. (2023) has been proposed that integrates real-time source parameter estimation with continuously updated ground motion mapping. This hybrid approach enables evolutionary tracking of the Potential Damage Zone, defined as the area where predicted intensity measures exceed user-defined thresholds during the ongoing rupture. It combines real-time source parameter estimation with P-wave-derived ground motion predictions and GMPE-based spatial interpolation. This approach enables the generation of time-evolving ShakeMaps within seconds from origin time.

Applications to large-magnitude events (e.g., Türkiye sequence) and moderate offshore earthquakes have demonstrated the feasibility of predicting peak ground velocity (PGV) and instrumental intensity from early P-wave amplitudes, achieving promising lead times and high percentages of successful alerts. Comparative analyses against other impact-based EEWS confirmed the robustness of this methodology in both densely and moderately instrumented regions.

5.1.2. Research objectives

The research activities carried out within RETURN WP4 were aimed at developing, validating, and operationally testing a shaking-forecast-based earthquake early warning system (acronym QUAKEUP) adaptable to different tectonic contexts and seismic network configurations. The primary objective was to design an impact-oriented early warning framework capable of predicting ground shaking directly from early P-wave observations and real-time source characterization, ensuring applicability in both densely instrumented and moderately instrumented regions. Particular attention was devoted to testing the system in distinct geodynamic environments, including Mediterranean tectonic settings characterized by offshore seismicity and moderate to large magnitude, complex rupture processes.

A second major objective concerned the quantitative evaluation of system performance. The assessment framework was based on internationally recognized early warning performance metrics, including the classification of successful alerts, successful no-alerts, missed alerts, and false alerts. The analysis also focused on warning lead time, defined as the time difference between predicted threshold exceedance and observed strong ground motion at a target site. Evaluating the rapidity of magnitude stabilization and the temporal evolution of predicted shaking fields was considered essential to understand the operational reliability of the system in real-time conditions.

Another key objective was to compare the shaking-forecast methodology with other impact-based earthquake early warning approaches. This comparison aimed to assess robustness under different magnitude ranges, rupture complexities, and network densities. A special emphasis was placed on moderate-to-large offshore earthquakes, which often challenge classical magnitude-based early warning systems. The broader goal of the research was to demonstrate that a P-wave-based shaking-forecast methodology could serve as a scalable and transferable solution for regional and national real-time seismic networks, contributing directly to the integrated monitoring and rapid response vision of RETURN WP4.

5.1.3. Methods, Algorithms, and Data Analysis

The implemented methodology follows an evolutionary shaking-forecast framework in which earthquake detection, source parameter estimation, and ground motion prediction are continuously updated in real time. The first step consists of automatic P-wave picking performed on vertical-component velocity records using a robust trigger algorithm. Once a minimum number of stations detect the P-wave arrival, the system computes a preliminary hypocenter location and origin time through a real-time location algorithm. These parameters are progressively refined as additional stations are triggered, allowing the first operational solution to be issued within a user-set window after the earthquake origin time.

The moment magnitude is estimated from empirical relationships linking P-wave peak amplitudes measured in acceleration, velocity, and displacement to hypocentral distance and magnitude. Peak amplitudes are measured within progressively expanding time windows ensuring that rupture evolution is captured while avoiding contamination from later seismic phases. The moment magnitude is calculated independently at each station and then averaged across the network at each time step. The magnitude evolution typically shows a stabilization phase, referred to as the magnitude plateau time, which marks the convergence to the final source parameter estimation.

Ground motion prediction is based on two complementary approaches. First, empirical regressions directly relate P-wave peak amplitudes to predicted peak ground velocity, allowing onsite estimation of expected shaking before the arrival of destructive S waves. Second, a region-specific ground motion prediction equation uses the evolving magnitude and source-to-site distance to estimate shaking at both instrumented and non-instrumented locations. The system continuously selects the maximum value between P-wave-based and GMPE-based predictions, ensuring conservative and robust impact estimation. A physics-based interpolation algorithm is then applied to generate a time-evolving ShakeMap, which provides spatially continuous predictions of peak ground velocity and instrumental intensity. Alert logic is threshold-based, meaning that warnings are issued when predicted instrumental intensity exceeds predefined operational thresholds corresponding to damage-related intensity levels. Performance evaluation is conducted by comparing predicted and observed intensity values at recording stations, computing lead times, and classifying alerts according to decision matrices based on threshold exceedance levels. Figure 1 shows the scheme of the methodology, from the 3-component input data to the computation of the real-time shake map.

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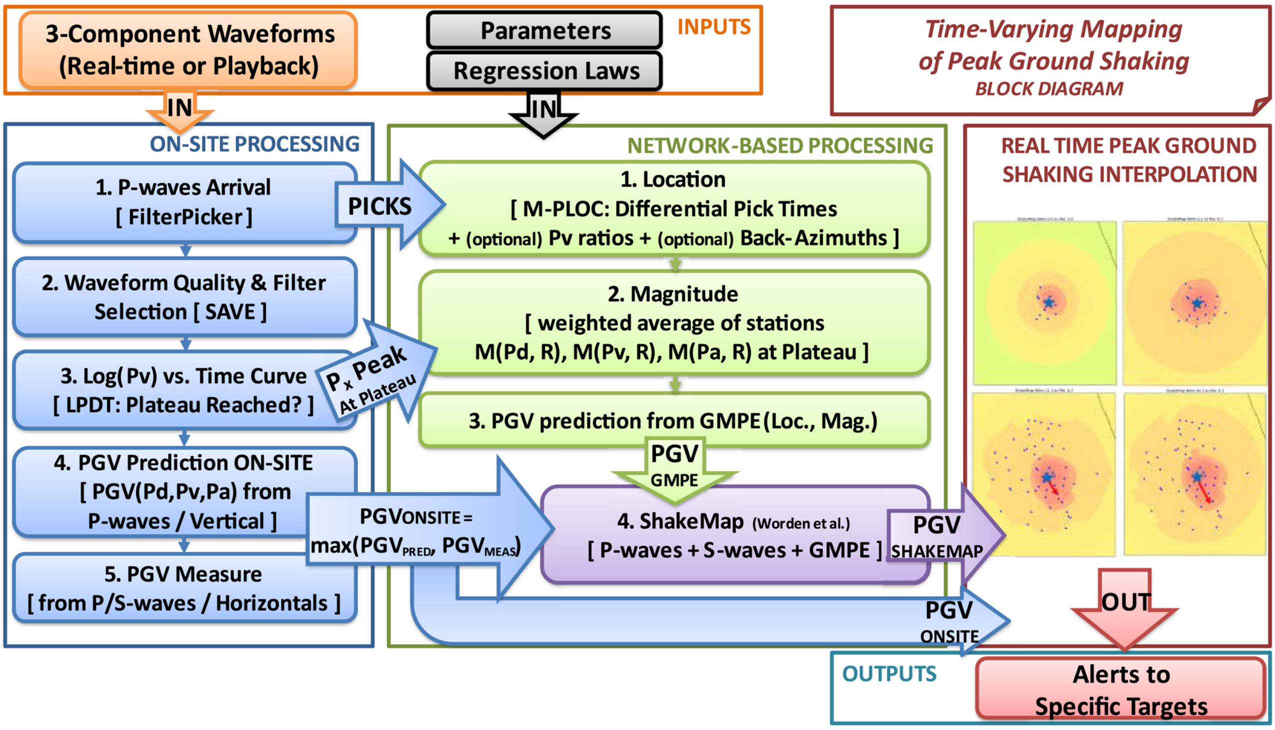

Figure 1: Block Diagram of the method. The figure shows the block diagram of the methodology, in which on-site PGV predictions (left) are combined with network-based PGV predictions (center), for a refined, real-time shake map construction and dissemination of alerts at target sites (right). (from Zollo et al., 2023).

5.1.4. Results, Validation, and Applications

The shaking-forecast-based early warning methodology was validated across multiple tectonic contexts and magnitude ranges, including moderate offshore events, large continental strike-slip earthquakes, and comparative benchmarking against a pure impact-based operational system.

The first validation concerned the retrospective real-time playback of the 6 February 2023 Mw 7.8 Turkey–Syria earthquake using the dense AFAD strong motion network. This event, characterized by a complex, multi-segment rupture extending over approximately 350 km along the Eastern Anatolian Fault, provided an exceptional test for evaluating the performance of a P-wave-based shaking-forecast system under extreme rupture complexity. Simulated real-time analysis showed that with an instrumental intensity threshold IMM = IV, alerts could be issued within 10–20 seconds after origin time, achieving approximately 95% successful warnings (including both successful alerts and successful no-alerts) and lead times between 10 and 60 seconds within the potential damage zone. When a higher threshold (IMM = VI) was adopted, larger alert times of approximately 50–60 seconds were required to achieve about 90% successful warning, with correspondingly shorter lead times. The analysis revealed that the predicted strong-shaking zone exceeding IMM VIII was detected and tracked approximately 20 seconds after nucleation and subsequently expanded coherently along the northeast–southwest rupture propagation path, closely matching independent kinematic rupture models. The time evolution of magnitude showed a progressive increase, stabilizing around 60 seconds after origin time, reflecting the evolving moment rate function of the large bilateral rupture. Although early magnitude underestimation initially limited GMPE-based predictions at distant sites, the integration of onsite P-wave amplitude measurements allowed progressive refinement of shaking forecasts, and by approximately 70 seconds after origin time, predictions were successful at essentially all strong-motion stations. Importantly, the spatial expansion of the predicted high-intensity zone mirrored the rupture directivity and segmentation, demonstrating that near-fault P-wave amplitudes are sensitive to rupture kinematics and can effectively track complex source evolution in real time. Figure 2 shows the snapshots of the P-wave based instrumental intensity shake-map at different times after the origin time.

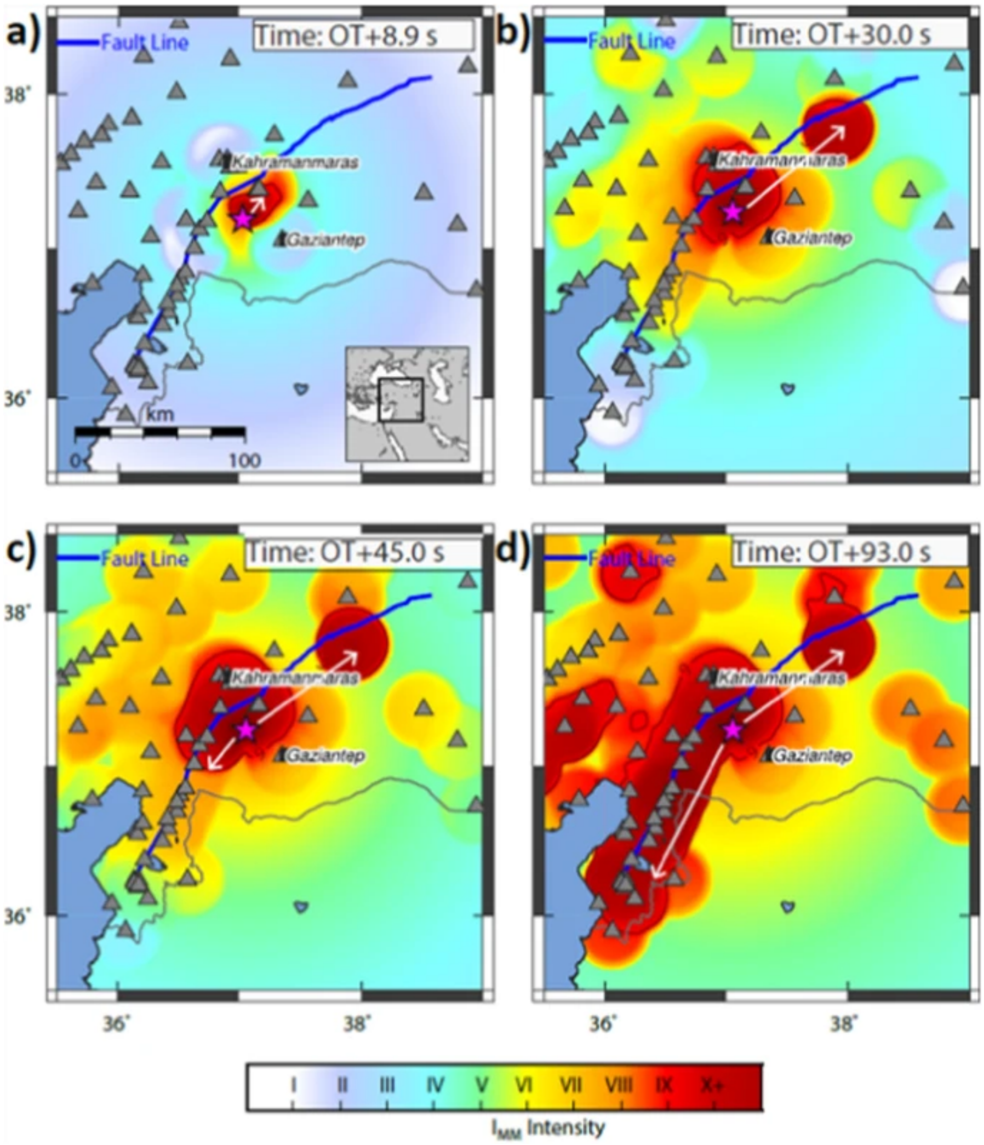

Figure 2: Snapshot of the P-wave based shake-map of the Mw 7.8, February 6, 2023, Turkey–Syria earthquake. After 8.9 s from the event origin time (OT) the system detects the event occurrence and, using the near-epicenter P-signal records, starts the calculation of the location, magnitude and predicted. b) 30 s after the origin time, the intensity IX+ (dark red color) zone extends in the northern direction along the EAF, pointing out the initial rupture direction. c) 45 s after the origin time, the IX+ zone begins to expand bi-laterally along the southern segment of the EAF. d) At the end of the event (about 90 s after OT) the intensity IX+ zone well delineates the entire rupture zone along the EAF. (From Rea et al., 2024).

The second validation framework concerned the 2016 Alboran Sea seismic sequence (Mw 5.0–6.4), where the system demonstrated its capability to issue the first operational solution approximately twenty-three seconds after origin time, with magnitude stabilization typically achieved within forty to seventy-five seconds. Lead times ranged between fourteen and sixty-two seconds for moderate instrumental intensity thresholds and approximately twenty seconds for higher thresholds, depending on epicentral distance and station geometry. The blind zone was estimated at roughly eighty kilometers, mainly controlled by network density. The percentage of successful alerts progressively increased with time, reaching values close to ninety percent as magnitude and shaking predictions stabilized, while false alerts remained limited due to the threshold-based decision logic. For moderate magnitude events within the same sequence, magnitude discrepancies after stabilization were generally below 0.3 units, and predicted instrumental intensity differed from observations by no more than one intensity unit at the majority of stations, confirming the reliability of the shaking-forecast approach in moderately instrumented regions.

A third validation framework consisted of a direct comparative performance analysis between the hybrid shaking-forecast system (QuakeUp) and the pure impact-based PLUM (Propagation of a Local Undamped Motion) method for the 2016 Mjma 6.6 Central Tottori earthquake in Japan. PLUM relies exclusively on the spatial propagation of observed instrumental intensities without real-time source parameter estimation. Retrospective simulations using 32 stations in Tottori Prefecture allowed quantitative comparison in terms of alert timing, blind zone extent, and prediction accuracy. For a JMA intensity threshold corresponding to PGV = 0.78 cm/s, PLUM exhibited a blind zone of approximately 28 km, within which predicted threshold exceedance occurred after observed shaking, while beyond this radius lead times were generally limited to about 5 seconds. In contrast, QuakeUp reduced the blind zone to roughly 12 km and provided substantially larger lead times, reaching approximately 12 seconds at 40 km epicentral distance. For higher intensity thresholds, PLUM yielded blind zones of about 19 km and lead times between 1 and 8 seconds, whereas QuakeUp maintained blind zones near 15 km and achieved lead times up to 16 seconds. ShakeMap comparisons further highlighted methodological differences: PLUM forecasts were confined within prefectural administrative boundaries and displayed localized high-intensity "hot spots" around stations due to limited propagation radii, whereas QuakeUp produced smoother and more spatially coherent intensity fields by combining onsite measurements with GMPE-based regional forecasting. Overall, the comparative analysis demonstrated that the hybrid shaking-forecast approach provides earlier and spatially broader alerts, particularly in regions with uneven station distribution, while maintaining comparable or superior alert reliability relative to the pure impact-based PLUM method.

Collectively, these multi-scale validations—from moderate offshore Mediterranean earthquakes to a Mw 7.8 continental megathrust-like strike-slip rupture and a controlled comparison against an operational Japanese system—demonstrate that the shaking-forecast methodology is robust across different tectonic regimes, rupture complexities, and network geometries. The results confirm its capability to provide rapid, dynamically evolving impact forecasts, reduce blind zones, and extend warnings to non-instrumented areas through integration of real-time source characterization and empirical ground motion prediction.

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

The research conducted within RETURN WP4 significantly advances the realization of an integrated end-to-end earthquake monitoring, early warning, and rapid response system. By demonstrating the feasibility of a P-wave-based, impact-oriented early warning methodology, the project bridges the gap between rapid seismic monitoring and actionable emergency response. The developed system operates in real time on regional seismic networks, automatically generating shaking forecasts and impact maps within tens of seconds after earthquake initiation. This capability directly supports the rapid risk reduction objectives of WP4.

The threshold-based alert logic enables direct connection with automated actuators and safety devices, such as infrastructure control systems, transportation shutdown procedures, and industrial safety mechanisms. In this way, the methodology supports the full operational chain from earthquake detection to emergency action. The adaptability of the system to different tectonic contexts and network densities confirms its scalability at regional and national levels, aligning with the strategic objectives of RETURN to enhance resilience of critical infrastructures.

Furthermore, the research contributes to improved situational awareness during the first minute of an earthquake, a critical time window for civil protection authorities and infrastructure operators. The dynamic tracking of the potential damage zone and the continuous updating of impact maps provide valuable decision-support information for emergency management. By integrating physics-based approaches, empirical regressions, and real-time data assimilation, the shaking-forecast system strengthens the technological foundation of WP4 and represents a key component of the broader RETURN strategy for seismic risk mitigation and operational resilience.

5.2. A Shaking-Forecast Based Earthquake Early Warning System: Development and Applications

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

The activities carried out in the RETURN Project introduce several innovative elements aimed at improving both the reliability and applicability of impact-based earthquake early warning. The project focuses on the implementation and validation of advanced methodologies capable of combining rapid source characterization with predictive ground-motion modelling in realistic monitoring conditions. An important innovative element of this work is the integration of the QuakeUp methodology with physics-based synthetic datasets generated by SPEED, allowing systematic and controlled testing of the early warning performance under a wide range of earthquake scenarios. The use of realistic broadband synthetic seismograms provides a robust basis for quantitative validation and sensitivity analyses.

5.2.2. Research objectives

The study focuses on evaluating the applicability of the methodology in regions characterized by heterogeneous seismic network coverage. Another important objective is the assessment of the system performance under realistic monitoring conditions using synthetic earthquake scenarios representative of the seismic hazard of Southern Italy. Particular attention is devoted to evaluating the accuracy of predicted ground shaking and the capability of the methodology to identify areas potentially affected by damaging ground motion. A further objective is the quantitative evaluation of alert reliability and warning times, including the analysis of successful and unsuccessful alerts and the estimation of achievable lead times at different distances from the seismic source.

5.2.3. Methods, Algorithms, and Data Analysis

5.2.3.1. Synthetic Data Generation (SPEED Platform)

Synthetic seismograms used in this study were generated using the SPEED platform (https://speed.mox.polimi.it/) to reproduce realistic earthquake ground-motion scenarios consistent with the seismotectonic characteristics of Southern Italy. The synthetic dataset was designed to provide broadband ground-motion time series.

Earthquake rupture processes were modelled using the kinematic rupture generator developed by Herrero and Bernard (1994), which produces heterogeneous slip distributions consistent with the adopted fault geometry, focal mechanism, and target magnitudes. The method assumes a k^{-2} spectral decay in the wavenumber domain, corresponding to the classical ω^{-2} spectral decay in the frequency domain described by Brune (1970), ensuring physically consistent source spectra.

The broadband ground-motion dataset combines complementary modelling approaches. The low-frequency wavefield (up to approximately 1.5–2 Hz) was computed using 3D physics-based numerical simulations that account for realistic velocity structures and wave propagation effects. The high-frequency portion of the signals was generated using the Artificial Neural Network broadband simulation technique (ANN2BB) (Paolucci, et al., 2021). The resulting dataset consists of broadband synthetic acceleration and velocity time series at virtual station locations corresponding to the considered seismic networks. These data provide a consistent framework for evaluating the performance of the early warning methodology across multiple network configurations.

5.2.3.2. QuakeUp

The early warning methodology adopted in this study is based on the QuakeUp approach, which integrates automatic P-wave detection, real-time earthquake location, magnitude estimation, and ground-motion prediction using continuously recorded seismic waveforms.

Depending on network configuration, either velocity or acceleration recordings can be used as input. Once one ground-motion component is available, the remaining components (acceleration, velocity, and displacement) are obtained through numerical differentiation or integration, allowing consistent amplitude measurements across different data types. When a predefined minimum number of stations detect the P-wave arrival, an initial estimate of hypocentral location and origin time is computed. Source parameters are progressively refined as additional P-wave picks become available.

Earthquake magnitude is estimated using empirical relationships between peak P-wave amplitudes and hypocentral distance. Peak amplitudes are measured within expanding P-wave time windows on acceleration, velocity, and displacement records. Station-based magnitude estimates are combined to obtain a network-averaged magnitude that evolves as additional waveform data are incorporated.

Ground-motion prediction is performed using empirical relationships. Predicted PGV values are continuously updated as the P-wave time window expands, and new observations become available. The spatial distribution of ground shaking is obtained by combining observed and predicted PGV values with regional ground-motion prediction equations through interpolation techniques. This approach allows estimation of shaking levels both at recording stations and at locations without instrumentation. Predicted PGV values are converted into macroseismic intensity using empirical relationships, allowing the generation of time-evolving shaking maps and the identification of potential damage zones.

System performance is evaluated through retrospective simulations of the synthetic earthquake scenarios. Predicted and observed shaking parameters are compared to assess the accuracy and timeliness of the early warning estimates. Alert performance is analyzed using standard metrics including successful alerts, missed alerts, false alerts, and successful no-alert cases. Lead times are calculated as the time difference between predicted and observed exceedance of selected shaking thresholds. The analysis focuses on evaluating the robustness of the methodology under realistic monitoring conditions, including spatially variable station distributions

5.2.4. Results, Validation, and Applications

Validation results show that the methodology provides reliable estimates of peak ground velocity and macroseismic intensity at recording stations, with prediction errors generally consistent with the expected uncertainty of empirical relationships. The comparison between predicted and reference shaking values indicates that the system can identify areas affected by moderate to strong shaking with satisfactory accuracy.

System performance evaluation shows a high proportion of successful alerts and successful no-alert cases, with limited numbers of missed and false alerts. The simulations indicate that useful warning times can be achieved at regional distances, while expected limitations remain in near-source areas where warning times are intrinsically short.

The developed approach has potential applications in real-time seismic risk mitigation, including rapid situational awareness, automatic alarm generation, and support for emergency response activities. The capability to generate time-evolving shaking forecasts and potential damage zones represents a valuable tool for civil protection authorities and infrastructure operators.

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

Within the RETURN Project framework, this research demonstrates the feasibility of implementing advanced impact-based earthquake early warning methodologies characterized by complex tectonic settings and heterogeneous seismic network coverage.

The integration of physics-based synthetic simulations with advanced early warning algorithms provides a robust framework for performance evaluation and methodological improvement. The results support the development of next-generation early warning capabilities and provide a basis for future operational implementation and integration with multi-risk monitoring platforms.

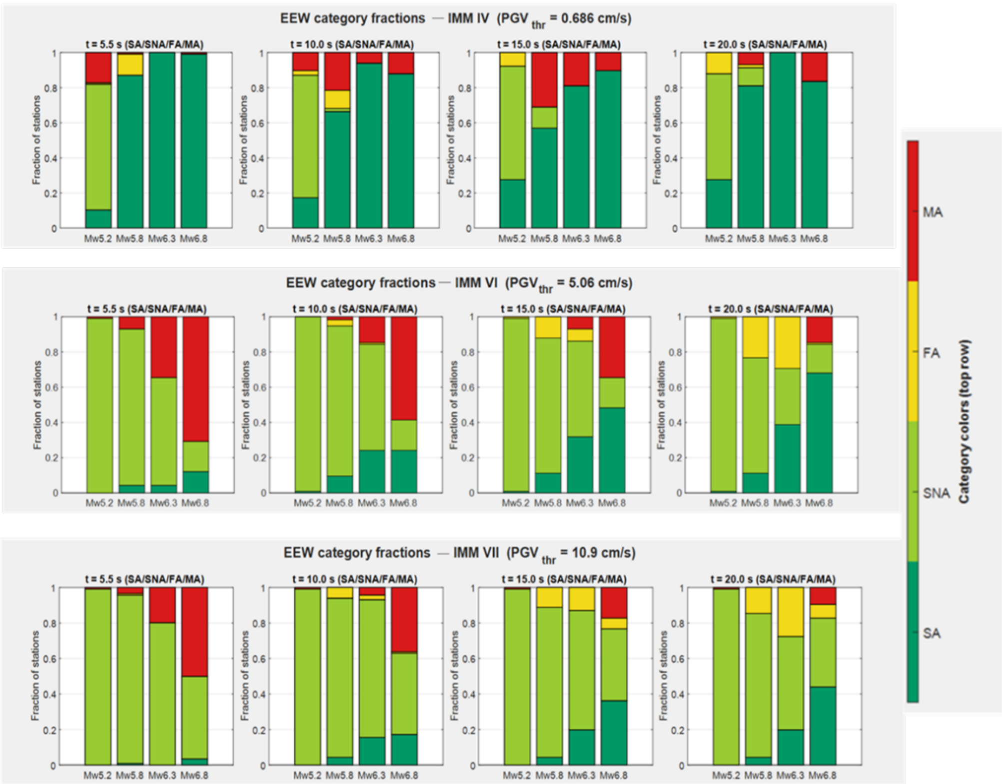

Figure 3: Following the classification of Zollo et al. (2023), the time evolution of the percentage of stations classified as successful alerts (SA, dark green), missed alerts (MA, red), false alerts (FA, yellow), and successful no-alerts (SNA, light green) is shown as a function of time (from left to right; 5, 10, 15, and 20 s) after the earthquake origin time (OT). This is done for 3 different threshold values for the intensity).

5.3. The Deterministic Behaviour of Earthquake Rupture Beginning

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

For decades, the seismological community has debated whether earthquakes begin in a universal way—independent of their final magnitude—or whether large and small earthquakes exhibit distinct characteristics from the very onset of rupture. Previous investigations based on early P-wave characteristics have produced contrasting results, largely due to limited datasets, regional constraints, or methodological heterogeneity [1–3] . The present study [4] introduces significant innovation through the analysis of an extensive global dataset comprising more than 200 earthquakes (Mw 4–9) and approximately 7000 waveforms recorded within 500 km of the epicenter. The authors propose a parameter for fast magnitude estimation: the initial slope of the Logarithm of P-Peak Displacement vs Time (LPDT) curve. This metric provides robust statistical evidence that earthquakes of different magnitudes already diverge during the first second of radiated P-wave signal. Within the broader framework of RETURN (Multi-Risk Science for Resilient Communities under a Changing Climate), this innovation directly contributes to advancing scientific understanding of natural hazards and to strengthening monitoring and forecasting tools. In particular, the deterministic interpretation of rupture initiation aligns with RETURN's objectives of enhancing risk prediction capabilities and improving operational response strategies.

5.3.2. Research objectives

The primary objective of the research is to determine whether the earliest phase of earthquake rupture contains predictive information about the final magnitude. A further goal is to evaluate whether the LPDT slope can serve as a reliable proxy for rapid magnitude estimation in real-time applications.

5.3.3. Methods, algorithms, data analysis

The methodology is grounded in large-scale waveform analysis. The authors selected 200 global earthquakes with moment magnitudes between 4 and 9, covering diverse tectonic settings. For each event, seismic records from stations located within 500 km were analyzed to ensure high signal quality and minimize attenuation effects. Velocity and acceleration records were integrated to obtain displacement waveforms. From these, the authors built the LPDT curves by calculating the Logarithm of P-peak displacement versus time. Two key time markers were identified: a minimum reliable time (t_MIN) and an intermediate time related to half-peak displacement (t_HALF). The initial slope between these time points was computed and statistically analyzed. Regression analyses were performed to investigate the relationship between LPDT slope and final magnitude. Correlation coefficients and statistical significance tests were used to validate the robustness of the observed trends. The analysis demonstrates a consistent linear relationship between the early displacement growth rate and earthquake magnitude across the global dataset.

5.3.4. Results, validation, and/or applications

The results provide strong empirical support for deterministic rupture behavior. Specifically, the study finds that the initial LPDT slope decreases with increasing magnitude. Smaller earthquakes exhibit steeper early displacement growth rate, while larger events show slower initial growth rates. The overall behavior is observed within less than 1 second of P-wave signal (Figure 1). These findings have direct applications for Earthquake Early Warning Systems, where rapid magnitude estimation is critical for issuing alerts and initiating automated protective measures. The LPDT-based approach offers a physically grounded and statistically validated parameter that could be integrated into real-time processing algorithms.

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

The objectives of RETURN include improving multi-risk understanding, enhancing monitoring capabilities, and strengthening mitigation strategies for natural hazards under changing environmental conditions. The results of this study contribute significantly to these goals. First, by demonstrating that rupture initiation contains predictive information about final magnitude, the research advances fundamental knowledge of seismic source physics. Second, it provides a measurable and operational parameter that can enhance real-time risk assessment systems. Third, it supports the development of more reliable early warning tools, which are essential for reducing societal vulnerability. In relation to WP4, which focuses on monitoring, modeling, and operational tools for risk management, the LPDT method bridges research and operational implementation, reinforcing RETURN's mission to translate advanced scientific insights into tangible risk mitigation solutions. By improving rapid earthquake characterization, the study ultimately contributes to increasing the resilience of communities exposed to seismic hazards.

5.3.5.1. List of outputs

- Peer-reviewed scientific article.
- Global curated seismic waveform dataset (200 events).
- LPDT methodological framework.
- Conceptual basis for implementation in EEW algorithms.

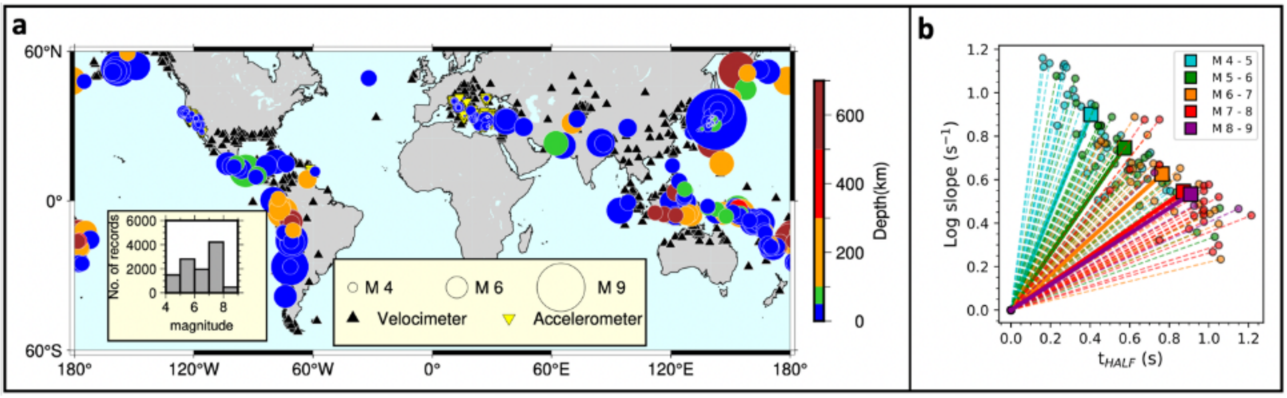

Figure 4: (a) Map of the earthquakes analyzed in our study, colored by depth and sized by magnitude. histogram shows the total number of seismic records. (b) The initial amplitude growth rate versus its characteristic time, colored by magnitude scale. Circles are single earthquakes measures. Squares are averaged measures in magnitude bins indicated by the legend in the upper right corner.

5.4. Seismo and geodetic real time monitoring and deep learning data analysis. Seismo-electromagnetic real time monitoring

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

The research done follows two distinct lines focussed on: a) geodetic and b) electromagnetic (*em*) data.

a) The OTRIONS Interreg project made important contribution to the National Seismic Network (RSN, INGV) and allowed a good definition of the seismogenic structures of the Garganic crust. The deformation field in Gargano area can be detected by geodetic investigation by increasing the spatial resolution of the geodetic network installed on the territory (GNSS network of the Puglia region and the Smart Net network).
b) The seismic-electromagnetic (SEM) phenomenon entails the generation of transient electromagnetic signals, which can be observed both simultaneously (co-seismic) and prior to (pre-seismic) a seismic wave arrival. Despite the growing interest in this phenomenon, there is a lack of freely available observational database of earthquake-related electromagnetic signals recorded at co-located seismic and magnetotelluric stations. To fill this gap, we set up two multicomponent monitoring stations in two seismically active areas of Southern Italy: the Gargano Promontory (GARG) and the High Agri Valley (HAVO).

5.4.2. Research objectives

a) The purpose of the research is to implement a new CORS (Continuously Operating Reference Station) geodetic network in the Gargano region capable of real-time monitoring of the displacement field using new RTX technology and a DISCRETE geodetic network to densify the geodetic data by programmed data acquisition survey.
b) The objectives are dual: 1) to extend the observation of multiparametric station to several sites and populate a database of SEM transients and 2) to model coupling of elastic and electromagnetic field in porous suitable to detect IR signals and to make tests about the support of the SES pre-seismic detection in the early warning scheme.

5.4.3. Methods, algorithms, data analysis

a) RTX represents an evolution of the RTK service. RTK technology presents several problems due to the quality of measurements, highly dependent on the quality of the closest station position used as reference. RTX techniques allow corrections to be decoupled from a single reference station through a network of stations placed regionally, with a great error reduction. The RTX techniques improve performance also when the azimuth gap of the sending correction stations is high and/or when the closest station is noisy.

b) Data from the two multiparametric (seismic and *em* data) monitoring and remote-controlled stations were analysed both in time domain and with the continuous wavelet transform (CWT). The seismo-electric transfer function on earthquake related data was estimated, whose value is due to the combination of fluid and medium properties of the layer/zone where the coupling arises. Furthermore, a synthetic modeling of pre-seismic *em* signals detected during the 2012-2014 Pollino swarm (thanks to a cooperation with ISterre in Grenoble) was performed.

5.4.4. Results, validation, and/or applications

a) As concerns CORS network, the 6 planned instruments were purchased and installed and now the CORS network is operative. The server for receiving and processing data was purchased, delivered and placed at DiSTeGeo of UniBa; the required software for collecting data and managing RTK and RTX positioning services has been installed. The signal quality tests are successful. As concerns the Discrete network, the antenna prototype has been designed, built, produced and delivered. The patenting process is pending. The first 5 instruments and 5 geodetic markers have been delivered. The survey has being scheduled to identify the locations for installing the geodetic markers.

b) The dataset of the experimental seismic-electromagnetic waveforms recorded by HAVO station during 2021-2023 has been released [1], filling the gap in literature of freely available observational database of earthquake-related electromagnetic signals from co-located seismic and magnetotelluric station. As concern the multiparametric GARG station, *em* transients were recorded during the seismic swarm that follow the earthquake (Mw 4.8) offshore Gargano on 14.03.2024 (see an example in Fig. 1). As concern the modelling, simulation has suggested the influence of the azimuth between station and earthquake hypocentre on the em pre-seismic signal amplitude.
Furthermore, the electromagnetic signal recorded during the May 2024 geomagnetic storm (Gannon storm) was analysed together with the geomagnetic observatories to assess its impact on the Italian region.

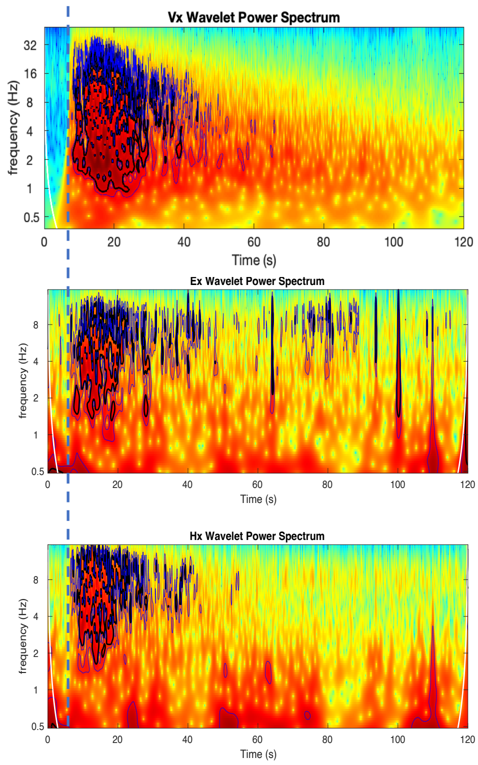

Figure 5: CWT of NS components of seismo-electromagnetic transients during the earthquake (Mw 4.8) offshore Gargano on 14.03.2024: Vx (top), Ex (middle) and Hx (bottom). The vertical dashed line indicates the P-wave arrival time at the seismic station; note the weak electrical signals above 1 Hz before the arrival of seismic one.

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

a) The impact is multiple as the new geodetic network of Gargano completes the integration between seismic and geodetical data to provide a seismotectonic framework of the area thanks to a multidisciplinary approach.

b) The seismo-electromagnetic released database permits to the scientific community to make independently analyses; it was downloaded by several external people (>1000). The synthetic modelling has confirmed that the weak electrical signal recorded can be reproduced, thus stimulating further research on them for early warning. The continuous monitoring of *em* signals has permitted to study the Gannon storm and their impact on Italy [2]. Geomagnetic induced currents (GICs) can potentially cause extensive damage to grounded infrastructure (link with the objectives of Spoke 7).

6. Conclusions

Across Task 4.1, the project achieved substantial progress in both methodological innovation and technological deployment. The state of advancement of research activities carried on within Task 4.1 has been extensively reported in the present document, while the main outcomes are summarized below:

Development and multi-scenario validation of the QuakeUp shaking forecast EEW system
The QuakeUp evolutionary shaking-forecast methodology has been successfully implemented and validated it across multiple tectonic settings and network configurations. Retrospective and synthetic tests demonstrate its scalability and adaptability to both dense and moderately instrumented regions.

Real-time playback experiments on significant events, including the 2023 Mw 7.8 Turkey–Syria earthquake, confirmed high percentages of successful warnings and demonstrated that the system is capable of dynamically tracking the rupture evolution and the expanding damage zone.

Creation of a physics-based synthetic testing framework
A comprehensive validation environment was built using broadband synthetic seismograms generated with the SPEED platform. This framework enables controlled sensitivity analyses and realistic performance testing under Southern Italy seismic scenarios.

Evidence for deterministic rupture behavior enabling faster magnitude estimation
Large-scale analysis of global datasets showed that earthquakes of different magnitudes are different within the first second of P-wave signal. The proposed LPDT slope provides a physically grounded proxy for rapid magnitude estimation in EEW applications.

Deployment of new GNSS RTX and multiparametric monitoring infrastructure

A new CORS RTX geodetic network was installed in the Gargano area, alongside two multiparametric seismic–electromagnetic stations. These infrastructures enhance real-time deformation monitoring and multiparametric observation capabilities in Southern Italy. The seismic–electromagnetic waveform datasets has been made available to the community, for reproducibility and further research.

Initial testing of VarioPy GNSS variometric package

Preliminary real-data tests of the VarioPy software confirmed its potential for real-time GNSS variometric applications. The tool represents a promising component for integrating high-rate geodetic information into rapid monitoring workflows.

Overall, the results significantly advance the integrated end-to-end earthquake monitoring, early warning, and rapid response vision of RETURN WP4.

The research activities developed within Task 4.1 also generate significant scientific, technological and socio-economic impacts, fully aligned with the objectives of the RETURN project and with the strategic goals of WP4. From a scientific perspective, the work advances the understanding of earthquake rupture processes and their early observable characteristics, providing new insights into the deterministic behavior of seismic sources and introducing novel parameters for rapid magnitude estimation. At the same time, the integration of physics-based synthetic simulations with real-time early warning methodologies contributes to strengthening the methodological foundations of impact-oriented earthquake monitoring systems. From a technological standpoint, the project delivers important advances in real-time seismic monitoring and early warning capabilities. The development and validation of the QuakeUp shaking-forecast system demonstrates the feasibility of scalable early warning methodologies capable of dynamically tracking rupture evolution and forecasting ground shaking in near real time. In addition, the deployment of new GNSS RTX geodetic infrastructure and multiparametric seismic–electromagnetic monitoring stations enhances the observational capacity of Southern Italy and provides valuable datasets for multidisciplinary hazard analysis. The release of open databases and software tools further promotes reproducibility and future innovation within the scientific community. The socio-economic relevance of these results lies in their potential to improve preparedness, situational awareness and rapid decision-making during seismic crises. By enabling faster characterization of earthquakes and more reliable forecasts of potential damage zones, the proposed approaches support the operational needs of civil protection authorities and infrastructure operators. Ultimately, the outcomes of Task 4.1 contribute to strengthening the resilience of territories exposed to seismic hazards by advancing integrated end-to-end monitoring, early warning, and rapid response systems within the broader RETURN framework.

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