Advancing End-to-End Earthquake Monitoring with Deep Learning

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The rapidly growing seismic archive poses challenges for conventional data analysis but provides opportunities to develop advanced seismic data mining techniques to discover hidden seismic signals, such as small earthquakes, often neglected in routine catalogs. Conventional methods for earthquake monitoring tasks, such as earthquake detection and phase picking, are being significantly enhanced by deep learning models, such as PhaseNet and EQTransformer. These models enable the rapid detection of a greater number of earthquakes and more precise earthquake source characterization, and have been applied to various earthquake sequences, including tectonic, induced, and volcanic earthquakes globally. Building on these successful applications of deep learning, we are further exploring ways to enhance the end-to-end earthquake monitoring workflow. We have developed a deep learning model, PhaseNet-DAS, for detecting and picking seismic phases on distributed acoustic sensing (DAS) data, enabling the integration of telecommunication fiber networks for earthquake monitoring. We have extended the PhaseNet model to introduce a multitask framework. This enhanced model, PhaseNet+, not only performs phase arrival time picking, but also determines first motion polarity for focal mechanism inversion, and estimates earthquake origin time for phase association. These advancements aim to improve seismic monitoring and enhance earthquake catalogs by adopting a more unified and efficient framework, thereby providing insights into underlying earthquake physics and diverse driving mechanisms.

The NEAM Tsunami Warning System and the INGV Italian Tsunami Alert Center.

Amato, A., F. Bernardi, L. Graziani, S. Lorito, L. Margheriti, A. Piatanesi, F. Romano, L. Scognamiglio and CAT Team

The INGV Tsunami Alert Center (Centro Allerta Tsunami, CAT) started its activities in 2013, after being designated as National Tsunami Warning Center for Italy and as candidate Tsunami Service Provider for the ICG/NEAMTWS (Intergovernmental Coordination Group of the North East Atlantic, the Mediterranean and connected seas Tsunami Warning and Mitigation System), one of the four ICGs coordinated by IOC-UNESCO. The CAT became operational TSP in 2016, covering the whole Mediterranean basin for earthquake-generated tsunamis.
Since then, several thousand events have been processed worldwide, although only for the Mediterranean region the alert messages were sent to the subscribers of UNESCO Member States and to the national civil protection department. For the Mediterranean a total of 42 events from 2017 to 2023 did activate the CAT procedures, for earthquakes with magnitude ranging from 5.5 to 7.9. The information or initial alert messages were sent between 5 to 10 minutes after the earthquake origin time.
CAT activities include tsunami hazard assessment at various scales (from global to local), monitoring and warning, risk mitigation activities (including education and outreach, information, and specifically the UNESCO Tsunami Ready recognition program for local communities).
In this contribution we will describe the monitoring and warning activities and the most recent advancements, such as the ongoing transition from the Decision Matrix currently in use to the Probabilistic Tsunami Forecast (PTF), the development of new instruments offshore to measure the sea level anomalies in real time, and the recent activity for extending the monitoring to non-seismic tsunamis, with a special focus on Stromboli island volcano, where a local TWS is operating. Moreover, we will describe a feasibility study under testing in cooperation with the University of Naples Federico II, to use Earthquake Early Warning Systems to feed Tsunami Warning systems, with promising results.

Seismologically Oriented Machine Learning - project results

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The SOME project aimed to explore the use of Machine Learning (ML) and Deep Learning (DL) techniques for seismic data analysis. The primary goals were to improve the ability to: i) detect earthquakes with greater accuracy; ii) study the propagation of seismic waves; iii) estimate ground shaking very rapidly with higher accuracy. The first step of the project was to acquire a dedicated computing infrastructure, consisting of a high-performance computing server with GPUs and storage unit. This infrastructure allows the installation of ML/DL software for seismic data analysis, with the possibility of creating a customized development environment. A major focus of the project has been the compilation of high-quality datasets for benchmarking whose availability is crucial for the implementation of ML/DL frameworks. To this end, we have assembled the INSTANCE dataset including over 1.3 million 3C waveforms and associated metadata for the Italian region. SOME also focused on the development of open source ML and DL algorithms and also general tools for seismic data analysis. This included the development of a new algorithm for seismic phase picking (DKPN) that uses seismological domain knowledge to accelerate the training when compared to the existing methodologies that adopt raw waveforms and it appears to be useful especially when analyzing datasets that contain a small amount of data as it occurs in the initial hours/days of an earthquake sequence. Another development included a general framework for the classification of seismic waveforms based on wavelet representation (ScatCluster). For the rapid characterization of strong ground motion for earthquake early warning (EEW), a ML technique has been developed using graph convolutional networks and applied at different source-receiver scale-lengths (local and nearly regional). The technique can provide estimates of peak ground motion at more distant recording stations within a few seconds (5s) from the origin time and it appears particularly suited for EEW purposes. Finally SOME is also providing new applications in different fields to exploit the capabilities of ML and DL approach, compare with the results of classic methods to analyze seismic data and possibly to provide new insights on the seismic processes inside the Earth. SOME studies relevant seismic sequences (e.g. Mugello 2019, Sannio Matese 2013-2014), volcanic tremors and LP signals at Mount Etna and develops and tests DL methodological advancements in early-warning seismic systems. Overall, the SOME project has demonstrated the effectiveness of ML/DL techniques for seismic data anal

ARISTOTLE: a multi-hazard scientific expert assessment service for the EC Emergency Response Coordination Centre

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The ARISTOTLE (All Risk Integrated System TOwards Transboundary hoListic Early warning) consortium delivers a flexible and scalable 24/7 multi-hazard impact oriented advice service at global level to the Emergency Response Coordination Centre (ERCC) of the European Civil Protection and Humanitarian Aid Operations Directorate (DG ECHO).
This presentation describes the service offered within the framework of the European Natural Hazards Scientific Partnership (ENHSP).

This service responds to the needs of the ERCC to coordinate very rapidly the delivery of assistance to disaster-stricken countries within EU Civil Protection Mechanism both within and outside the European Union.
It features a 24/7 operational system capable of assembling within a few hours (three from the activation) relevant information on natural events that have just occurred (e.g., geological unforecastable hazards), are ongoing or are developing (e.g., hydro-meteorological forecastable hazards).

ARISTOTLE harnesses operational expertise from nationally mandated scientific institutions and international agencies across Europe to provide multi-hazard, rapid assessment on natural disasters related to volcanoes, earthquakes, tsunami, severe weather, flooding and forest fires. Each hazard brings together experts to deliver a “collective analysis”' which is then fed into the partnership multi-hazard discussions to provide the sought assessment.

ARISTOTLE includes partner institutions from EU and non-EU Countries and from European international organizations operating in the Meteorological and Geophysical domains.
They constitute the European Natural Hazards Scientific Partnership, ENHSP.
This article presents the organization and the implementation of the project, its achievements and the interaction with the ERCC ---*ARISTOTLE model*.

Yuancong Gou, Richard Allen, Weiqiang Zhu and Taka'aki Taria, Application of submarine fiber optic cables for earthquake detection and warning

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Detecting offshore earthquakes in real-time is challenging for traditional land-based seismic networks due to insufficient station coverage. Application of DAS to submarine cables has the potential to extend the reach of seismic networks and thereby improve real-time earthquake detection and Earthquake Early Warning (EEW). We present results testing modified point-source EEW algorithms (EPIC) with data from SeaFOAM DAS deployment (52 km-long submarine cable) in Monterey Bay, CA. The region is seismically active with the nearby San Andreas Fault system, and the offshore San Gregorio Fault system (SGFs) which the cable crosses.

Around 2 year's data has been collected by the permanent SeaFOAM project, including more than 10 offshore events on the SGFs. We developed a workflow that can be migrated to other DAS cables to detect earthquakes in real-time. We took a transfer learning approach with recorded local earthquakes to get a locally optimized PhaseNet-DAS machine learning model for P and S arrivals picking. We used a grid search method with available picks from the whole DAS array and a local 1D velocity model to locate the earthquakes. A calibrated empirical strain rate-to-magnitude equation is used to perform a real-time estimation of the magnitude. We extended our analysis to more recorded earthquakes and demonstrated the independent earthquake detection ability of an offshore DAS array. In the future, this DAS-specific EEW algorithm will be integrated into the existing EPIC algorithm for testing. This approach has the potential to extend earthquake detection for EEW offshore, thereby increasing warning times significantly.

A ground motion model for MyShake smartphone records and its potential seismic hazard applications

Savvas Marcou, Richard Allen

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In the field of ground motion prediction, non-ergodic ground motion models (GMMs) that model ground motion for specific event clusters, event-to-site paths, and sites, are quickly becoming the norm. However, these models rely heavily on simulation ground motion datasets to achieve the desired level of spatial specificity in ground motion predictions. Densely-sampled crowdsourced ground motion intensity datasets, such as felt reports or smartphone accelerometer data, could provide a useful validation dataset for these simulations. MyShake is a free, globally available smartphone application that serves as the official delivery platform for earthquake early warning (EEW) messages from the USGS ShakeAlert system on the US West Coast. However, MyShake also collects triggered three-component acceleration waveforms (using the onboard smartphone accelerometer) and felt reports, as part of its citizen science functionality for crowdsourcing earthquake data. We present a crowdsourced smartphone waveform database with over 1500 records compiled using MyShake that heavily samples the near-field (epicentral distances <30 km) for M3-6 events. Using MyShake data in California from 2019 to early 2023, we derive a predictive model for smartphone-recorded peak accelerations. Using this model, we calculate MyShake within-event residuals, and compare these to free-field residuals for PGA and 0.3 s PSA. We illustrate how these residuals illuminate small-scale structure in ground motion spatial trends in these, while also correlating well independent empirical constraints of free-field ground motion spatial variability. Finally, we discuss how MyShake residual correlation with free-field residuals could be used to reduce modeling uncertainties in schemes that model the spatial distribution of ground shaking, such as ShakeMap.

Earthquake early warning and smartphone seismology: Successes, challenges and outlook

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Earthquake early warning (EEW) provides seconds to tens of seconds warning ahead of ground shaking. EEW has been rapidly expanding around the globe over the last few years using both traditional regional seismic networks, and also using smartphones to both detect earthquakes and issue the warnings. We will ask, what are the outcomes of this rapid expansion?

Firstly, the growth of EEW has resulted in the most rapid period of expansion for seismic observation networks collecting data for EEW and also for research. For example, networks in California have expanded by a factor of three. In addition, smartphones seismic networks are now collecting waveform data, and we are just beginning to understand how to harness this data for research. Second, how accurate are the warnings? In California, there have been 115 true alerts, 3 false alerts, and 8 missed alerts to date. That represents a precision of 97% and a recall of 93%. Third, how are users responding to the alerts? The first user surveys are now becoming available. They consistently show that the most common response to receiving an alert is to "mentally prepare", or to "brace for shaking". While many earthquake education advocates are disappointed there is not more actions such as drop, cover and hold on, these passive aware responses mean that people are more ready for the quake and feel more in control. This is likely the reason that the vast majority of respondents rate EEW very positively.

Non-Volcanic Tremor at Parkfield: A Non-Stationary Process

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Abstract

Deep (Moho) seismic sources underly the seismogenic zone in non-volcanic regions. They have low amplitudes and long durations and are referred to as Non-Volcanic Tremor (NVT). In proximity to Parkfield, CA, these phenomena occur frequently. However, they do not occur under steady-state conditions. Rather, they are non-stationary in their behavior and respond or correlate with nearby and distant earthquakes, noise correlated velocity changes, and deformation (GPS) decay rates. The tremor episodes are also anti-correlated with local earthquakes, and the most dense cluster of tremor occupy a critical location adjacent (from below) to the Parkfield segment at the intersection of the San Juan and SA Faults and below the NW end of the great Ft. Tejon earthquake of 1857. We explore these non-stationary processes, their systematic behavior, and there possible relationships to very low Vs, deep high pore-pressure fluid environment and the possible role they may play in the next Parkfield and Ft. Tejon earthquakes.

Machine Learning-based Approach for Discriminating Local and Off-Network Earthquakes

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Earthquake monitoring and accurate estimation of location and magnitude play pivotal roles in both seismic surveillance and emergency response. Despite advancements, the precise determination of location and magnitude for off-network earthquakes remains a persistent challenge. Seismic stations constantly receive signals from diverse sources, necessitating the prompt identification of events originating within the area of interest. The location accuracy hinges on acquiring sufficient P-wave and S-wave readings to ensure reliable results. Furthermore, seismic networks are subject to variations over time due to station changes or breakage, presenting a hurdle for conventional Machine Learning (ML) models that rely on fixed data structures.

We introduce an innovative approach to differentiate between local and off-network earthquakes, and to identify their back-azimuth by using the initial 3 P-picks. To address the challenges posed by variable network geometry, a grid is applied over the seismic area, where each station activation triggers the corresponding grid square. Rigorous validation of our methodology utilized data from the Italian National Seismic Network, specifically focusing on Central Italy and Messina Strait subnetworks, as well as a subnetwork of the Southern California Seismic Network.

Our approach demonstrated high effectiveness, achieving inside-outside accuracy rates of 95%, 93%, and 96%, and back-azimuth accuracy rates of 93%, 82%, and 97%, for Central Italy, Messina Strait, and Southern California subnetworks, respectively. Comparative analysis with the initial localization performed by PRESTo, which is a software specifically designed for earthquake early warning applications, revealed significant improvements in inside/outside classification accuracy, with an increase of 16% for Central Italy and 35% for Messina Strait. Notably, during the 2023/02/6 Kahramanmaras-Gaziantep, M 7.9, earthquake our tool accurately classified it outside the Central Italy subnetwork, providing the back-azimuth within 0.03 seconds in the east-southeast direction.

The tool developed in the present study, validated through extensive testing, offers advanced seismic monitoring capabilities suitable for integration into earthquake early warning systems. Beyond seismic surveillance, its potential extends to enhancing emergency response by promptly and accurately classifying earthquakes, thereby minimizing the risk of false alarms.

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INGV Projects "Rete multiparametrica" and "DL50" :
Feasibility, social impact, responsibility and implementation of EEWS

Simone Marzorati

The INGV Projects "Rete Multiparametrica" and "DL50" focus on the development of monitoring systems. In Italy, currently, there isn’t an operational Earthquake Early Warning System (EEWS) and the seismic networks were installed with the aim of monitoring the seismicity of the territory, ensuring the civil protection surveillance in a rapid response sense.
The main Italian seismic sources are located near urban areas so a greater comprehension of warning systems and their performance is crucial to understanding the main areas suited to effective EEWS.
In order to understand the feasibility of EEWS implementation, an event declaration simulation method was developed to assess the values of the time first alert (TFA), blind zone radius (BZ) and lead time (LT). The performance of existing seismic networks, the improvement with new stations and the design of new networks with dedicated instrumentation are the purposes of this task.
The rapid evolution of the instrumental technologies useful to implement EEWS overcomes the capability of government authority and civil population to understand costs and benefits of the implementation. The application of an EEWS causes a social impact which can be a benefit if people are ready to react to a seismic alert. The project aims to improve people’s awareness of the EEWS, through the development, creation and test of crowdsourcing products.
The implementation and management of an EEWS generates the responsibilities of the authorities, the institutions, the researchers and the operators. A careful investigation of the legal systems of other countries is also useful to understanding the potential gaps in the European/Italian system.
A successful EEWS can depend on diffusion of dense seismic networks equipped with dedicated instrumentation. The use and the performance of low-cost accelerometric mems stations is debated. The data collection and the analysis of earthquake signals recorded by mems sensors and the development of low-cost stations is the technological task of the project that set the goal of preliminary field tests of the products.

Effects on a Deep-Learning, Seismic Arrival-Time Picker of Domain-Knowledge Based Preprocessing of Input Seismograms

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Automated seismic arrival picking on large and real-time seismological waveform datasets is fundamental for monitoring and research. Recent, high-performance arrival pickers apply deep-neural-networks to nearly raw seismogram inputs. However, there is a long history of rule-based, automated arrival detection and picking methods that efficiently exploit variations in amplitude, frequency and polarization of seismograms. Here we use this seismological domain-knowledge to transform raw seismograms as input to a deep-learning picker. We preprocess 3-component seismograms into 3-component characteristic functions of a multi-band picker, plus modulus and inclination. We use these five time-series as input instead of raw seismograms to extend the deep-neural-network picker PhaseNet. We compare the original, data-driven PhaseNet and our domain-knowledge PhaseNet (DKPN) after identical training on datasets of different sizes and application to in- and cross-domain test datasets. We find DKPN and PhaseNet show near identical picking performance for in-domain picking, while DKPN outperforms PhaseNet for some cases of cross-domain picking, particularly with smaller training datasets; additionally, DKPN trains faster than PhaseNet. These results show that while the neural-network architecture underlying PhaseNet is remarkably robust with respect to transformations of the input data (e.g. DKPN preprocessing), use of domain-knowledge input can improve picker performance.

Caravel: A New Earthworm‑Based Open‑Source Development for the Italian Seismic Monitoring System

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Abstract

The Istituto Nazionale di Geofisica e Vulcanologia (INGV) is in charge of earthquake monitoring and surveillance in the Italian territory as a part of the civil protection system. Technological improvements in the last years were taken into account for developing new protocols and software to upgrade all the procedures in the monitoring centers. Real‑time earthquake evaluation consists of phase picks, preliminary and automatic hypocenters, local magnitudes and ground‑motion parameters. The real‑time analysis system presently in use at INGV is the starting point for a new multitier compound system that relies on four main components: an automatic earthquake detection and location system based on Earthworm; a new seismological relational database for parametric data; a full set of new webservices application programming interface specifications to share information and provide data at the application level and; finally, a set of multiplatform interactive revision tools developed to analyze, store, use, and distribute the seismic parameters in real time. These last three components are being completely developed ex‑novo at INGV in Rome. Such a system has been engineered to communicate with the International Federation of Digital Seismic Networks standard webservices as well as custom home‑made INGV services.

Through its custom embedded features Caravel will allow the INGV personnel on duty for seismic surveillance to evaluate and review all automatic estimations before they are communicated to the Italian civil protection agency and then published by external tools through e‑mail, SMS, Twitter, and webpages.

The social impact of Earthquake Early Warning systems. Testing the survey questionnaire

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Earthquakes pose a particular risk to human lives. They are in fact unpredictable, temporally and spatially variable as well as occurring sequentially or in series. Depending on the territorial context, even small magnitude earthquakes can cause damage. Most of the Italian peninsula has a high seismic hazard. Earthquake Early Warning (EEW) is one of the most effective tools to protect human lives. The EEW allows the public to be alerted or to activate automatic protection mechanisms from a few seconds to a to a few tens of seconds (depending on the distance of the hypocentre from the person receiving the alert) before the earthquake-induced vibration is felt. In some regions, EEW systems have been operational for several years. In New Zealand, the system has not yet been implemented, so a team of sociologists surveyed the opinions of a sample of citizens on the degree of acceptance and what they thought of such a system [Becker et al., 2020]. In Italy, an operational earthquake early warning system does not yet exist [Satriano et al., 2011]. Based on New Zealand's experience, we translated the questionnaire they implemented and then administered it to a sample of Italian students visiting the INGV headquarters in Grottaminarda (Fig.1) to assess the acceptability and social impact of an EEW system in Italy. This administration is also essential to pre-test the survey instrument and to understand whether it works. To date, 212 questionnaires have been collected. This initiative is part of the: "Ricostruzione Centro Italia DL50 - Monitoraggio e analisi fenomeni sismici / WP Earthquake Early Warning (coord. Simone Marzorati and Claudio Martino)" project.

Keywords:
Risk Perception; Earthquake Early Warning System

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Insights into potential earthquake early warning performance in Turkiye and California from replays of the February 2023 Kahramanmaras earthquakes

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Large onshore earthquakes are rare, but can be particularly devastating, as demonstrated by the February 6, 2023 M7.8 and M7.5 Kahramanmaraş, Türkiye events. It is thus vital to evaluate potential earthquake early warning system (EEWS) performance in such events. Here, we simulate what would be expected had the current US EEWS alert delivery pipeline been operational in Türkiye. We use local waveform data to obtain an alert progression through the rapid point-source algorithm EPIC for both the
Kahramanmaraş mainshocks. We then obtain warning time distributions by combining this alert progression with realistic alert delivery latencies informed by real-world data from MyShake, a smartphone app that delivers ShakeAlert messages to US West Coast users. In the M7.8 event, EPIC's rapid reporting (first alert at 5 s from origin time) combined with MyShake's parallelized processing of alert delivery would result in actionable warning times, despite a peak magnitude estimate of only M6.4. We show median warning times of up to 35 s in zones of MMI VIII shaking and ~20 s in the areas of most intense shaking (MMI IX) near Antakya. In the M7.5 event, the lower station density means a first alert is issued 24 s from origin time (at M6.7), but areas of MMI V shaking would still get up to 80 s of warning. Finally, we use the M7.8 event replay results as a reasonable proxy for a major San Andreas-Hayward Fault rupture to set realistic expectations for EEW in California.