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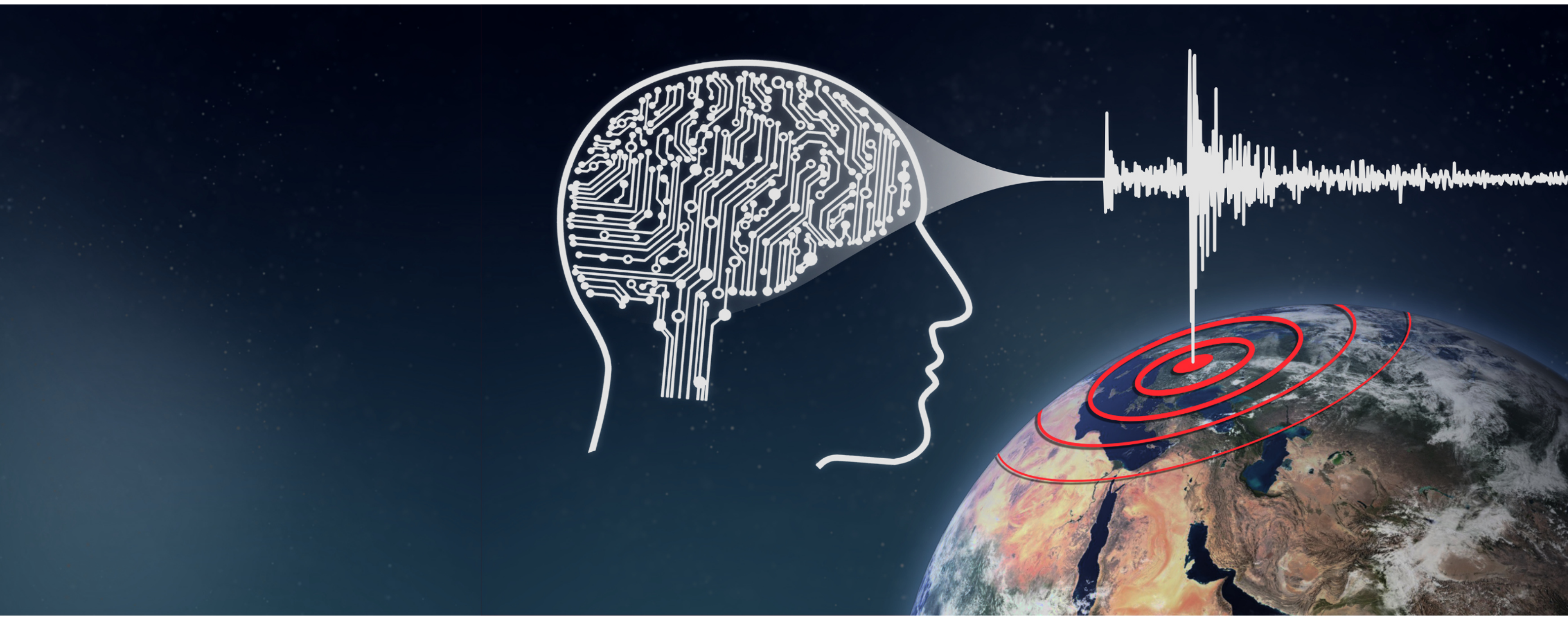

Seismology & Artificial Intelligence

Workshop 13. - 15. 09. 2023

Wednesday, 13 September 2023

08:00 - 08:30 **Registration**

08:30 - 09:00 **Welcome Talk by Prof. Dr. Eckhard Elsen and Prof. Dr. Horst Stöcker**

09:00 - 09:40

15 Years of Rigorous Testing of Scientific Models from Earthquake Forecasting to Risk - Lessons Learned

Danijel Schorlemmer
GFZ Potsdam

The Collaboratory for the Study of Earthquake Predictability (CSEP) is a global collaboration to improve our understanding of earthquake predictability, advance forecasting model development, test key scientific hypotheses and their predictive power, and improve seismic hazard/risk assessments. Since its inception 2007 in southern California, the collaboration has expanded to New Zealand, Japan, and Europe and has been conducting forecast experiments in a variety of tectonic settings to automatically and objectively evaluate models against prospective data, providing a multitude of results that are informing operational earthquake forecasting systems and seismic hazard models. Here, we report on the fundamental principles in testing models, the associated problems, the testing framework and its technicalities, and the lessons learned.

09:40 - 10:20

Earthquake Forecasting using Deep Learning

Jonas Köhler
SAI Group FIAS

Reliable earthquake forecasting methods have long been sought after, and so the rise of modern data science techniques raises a new question: does deep learning have the potential to learn this pattern? In this study, we leverage the large amount of earthquakes reported via good seismic station coverage in the subduction zone of Japan. We pose earthquake forecasting as a classification problem and train a Deep Learning Network to decide whether a timeseries of length > 2 years will end in an earthquake on the following day with magnitude ≥ or not.

Our method is based on spatiotemporal b value data, on which we train an autoencoder to learn the normal seismic behavior. We then take the pixel by pixel reconstruction error as input for a Convolutional Dilated Network classifier, whose model output could serve for earthquake forecasting. We develop a special progressive training method for this model to mimic continuous real life use. The trained network is then evaluated over the actual dataseries of Japan from 2002 to 2020 to simulate a real life application scenario. The overall accuracy of the model is 72.3 %. The accuracy of this classification is significantly above the baseline and can likely be improved with more data in the future

10:20 - 10:50 Coffee Break

10:50 - 11:30

Copahue volcano seismic event detection based on digital signal processing and machine learning techniques: towards an on-the-edge implementation

Romina Molina
ICTP, Italy

Copahue volcano is an active stratovolcano located on the border between Argentina and Chile, is part of the volcanic belt of the Andes, and is one of the most active volcanoes for both Chilean and Argentinian government institutions. Owing to the complexity of seismic events, the latest advancements in Machine Learning (ML) offer powerful solutions for handling large datasets and effectively extracting desired features.

Furthermore, in situations where the number of seismic stations is sparse, either because of low financial resources or difficult access, an on-the-edge detector can improve the monitoring because it does not depend on the records of the other stations.

In this presentation, Copahue volcano-seismic event detection based on digital signal processing techniques and ML is presented, which can be considered as an event-triggering system based on ML to operate on the edge.

11:30 - 12:10

Amplitude and Inter-Event Time Statistics for the Island Volcanoes Stromboli, Mount Etna, Yasur, and Whakaari

Darius Fenner
SAI Group FIAS

We analyze seismo-volcanic events to better understand the eruptive behaviour of the volcanoes Stromboli, Mount Etna, Yasur, and Whakaari. Using the automated method AWESAM, catalogs spanning multiple years are created. By examining event timing and event amplitudes, we find consistent patterns among the volcanoes, despite their different type. We also establish a new amplitude-frequency relationship and identify changing behavior in large events at Stromboli. Additionally, low-period and high-frequency events at Stromboli are classified, revealing alternating patterns around the double 2019 paroxysm.

12:10 - 13:00

Breakout Session 1

13:00 - 14:30 Lunch Break

14:30 - 15:10

Exploring the potential of Machine Learning to estimate building characteristics on a global scale

Kasra Rafiezadeh Shahi
GFZ Potsdam

Over the past decade, there has been impressive progress in the field of Machine Learning (ML). The increasing maturity of ML techniques has led to their widespread adoption in various domains. In this presentation, we demonstrate an ongoing project focused on investigating the potential of advanced ML techniques to predict building characteristics globally. Our project leverages an in-house developed global exposure database that is based solely on open data (e.g., OpenStreetMap, Global Human Settlement Layer) and attempts to describe every building on Earth separately. This exposure database is designed to estimate building characteristics and their vulnerability for each building to allow for high-resolution damage and loss assessments in case of natural catastrophes (e.g., earthquakes, floods) and to offer support for disaster response and resilience measures. However, theopen data we rely on suffer from the so-called "completeness" issue, wherein some areas have comprehensive mapping while others are hampered by insufficient information. Therefore, our objective is to bridge the gap between ML techniques and this open exposure database. Through this effort, we aim to enhance the accuracy and coverage of building characteristic estimations, which can contribute to more effective disaster response and other global-scale applications.

15:10 - 15:50

Blending physics-based numerical simulations and seismic databases using generative AI for earthquake engineering and structural health monitoring

Filippo Gatti
Université Paris-Saclay

This talk present a novel strategy to blend the outcome of physics-based numerical simulations with massive seismic databases is proposed, in order to improve earthquake ground motion prediction and and seismic structural health monitoring. The approach relies on generative AI techniques with the threefold purpose: (1) encoding both synthetic and experimental data into a non-linear manifold; (2) training a stochastic generator of synthetic seismic responses conditioned by the physics-based simulation results; (3) classifying the damage class based on the structural response and predict the post-earthquake damaged response. Regional three-dimensional high-fidelity numerical models accounting for both extended sources and complex geology are still limited to a low-frequency range. Moreover, they are prone to significant uncertainties induced by a lack of data on small scale geological structures and rupture processes. Databases of broadband seismic signals recorded worldwide at seismological networks are used to retrieve some pieces of information on these small-scale data to generate realistic broadband signals from synthetic ones. On the other hand, given the structural response of an undamaged structure, engineers need to predict the eventual damage beforehand, based on a monitoring network. The proposed tool demonstrates good performances in encoding seismic signals, together with efficient generation capabilities and clustering capabilities, provided that the physics-based results carry enough information to properly condition the stochastic generator and classify the damage state. In addition, the proposed method, fed only with raw data from both databases and numerical models, outperforms other random signal generators based on pre-existing expertise such as prescribed spectra and more or less complex phenomenological models.

15:50 - 16:20 Coffee Break

16:20 - 17:00

Neural-network optimization for travel-time tomography of a volcanic edifice under sparse ray coverage

Abolfazl Komeazi
Goethe University

In this study, we present an artificial neural network (ANN)-based approach for travel-time tomography of a volcanic edifice. We employ simple forward modeling to simulate the propagation of seismic waves through the heterogeneous medium of a volcanic edifice, and an inverse modeling algorithm that uses an ANN to estimate the velocity structure from the observed travel-time data. The performance of the approach is evaluated through 2-dimensional numerical study that I) simulates an active source seismic experiment with few (explosive) sources placed on one side of the edifice and a dense line of receivers placed on the other side, and II) simulates volcanic earthquakes with sources located inside the edifice and receivers placed on both sides of the edifice. The results are compared with those obtained from conventional linear inversion schemes, demonstrating that the ANN-based approach outperforms the classical methods, particularly in situations with sparse ray coverage. Our approach emphasizes the advantages of employing a simple ANN architecture in conjunction with second order optimizers to minimize the loss function. The ANN-based approach is computationally efficient and capable of providing high-resolution velocity images of anomalous structures within the edifice, making it a potentially valuable tool for the detection of low velocity anomalies related to magmatic intrusions or mush.

17:00 -18:00

Breakout Session 2

Thursday, 14 September 2023

09:00 - 9:40

Surface wave dispersion curve inversion using mixture density networks

Sabrina Kiel
LMU Munich

In many seismological, environmental and engineering applications a detailed S-wave velocity model of the shallow subsurface is required. This is generally achieved by the inversion of surface wave dispersion curves using various inversion methods. The classical inversion approaches suffer from several shortcomings, such as inaccurate solutions due to local minima or large computation times in case of a wide parameter space. A number of machine learning (ML) approaches have been suggested to tackle these problems, which however do not provide probabilistic solutions and/or constrain layer number and layer thickness to a fixed value. In this study, we develop a novel neural network (NN) approach in order to characterize the shallow velocity structure from Love and Rayleigh wave dispersion curves. The novelty of our method lies in the simultaneous estimation of layer numbers, layer depth and a complete probability distribution of the S-wave velocity structure. This is achieved by a two-step ML approach, where (1) a regular NN classifies the number of layers within the upper 100 m of the subsurface and (2) a mixture density network outputs the depth estimates together with a fully probabilistic solution of the S-wave velocity structure. We show the advantages of our ML approach compared to a conventional neighbourhood inversion and a Markov chain Monte Carlo algorithm. Our ML approach is then applied to dispersion curves extracted from recorded noise data in Munich, Germany. The resulting velocity profile is in accordance with lithologic information at the site, which highlights the potential of our approach.

09:40 - 10:20

Accurate and transferable predictions of 3D seismic wave propagation with Fourier Neural Operators

Fanny Lehmann
Université Paris-Saclay

Predicting ground motion via machine learning is a widely studied topic that still poses great challenges. The recent development of scientific machine learning is offering new perspectives to tackle them. From ground motion models to earthquake early warning systems, several models can predict ground motion features given a few earthquake parameters. However, they ignore path- and site-effects that are known to greatly impact ground motion. One way to include those effects is to use physics-based simulations that compute the propagation of seismic waves in three-dimensional (3D) domains. Their ability to reproduce observed ground motion is nevertheless limited by our limited knowledge of the geological domains. Therefore, they need to be complemented with machine learning to study a wide variety of geologies while avoiding the unbearable computational costs of high-fidelity 3D simulations.

To this end, we trained a Fourier Neural Operator (FNO) to predict the relationship between a geological domain and the corresponding ground motion. Once duly trained, the FNO provides accurate ground motion over the whole spatial domain and time window.

This presentation will describe the training database made of heterogeneous 3D geologies with S-wave velocities ranging from 1071 m/s to 4500 m/s. Each geology is associated with a 3-component velocity timeseries synthetized for 20 s and accurate up to a 5 Hz frequency. We will present the neural operator architecture allowing us to reach a 22% relative error and the implications in terms of ground motion features.

Since our geological database is not specific to a given region, machine learning models trained with it can serve as efficient pre-trained models for transfer learning tasks. This will be exemplified by specializing the FNO to a given class of geologies, with limited additional training.

Our findings suggest that the FNO is a well-suited machine learning method to build a surrogate of 3D seismic wave propagation. Training the model on a generic database paves the way for future tailored applications with affordable computational costs.

10:20 - 10:50 Coffee Break

10:50 - 11:30

Interpretation of geophysical data with the aid of machine learning algorithms

Olaf Cortes Arroyo
BGR Hannover

Acquisition, processing, and interpretation of geophysical data is a complex task influenced by, among other things, the type of physical phenomena registered, intrinsic noise, and computational complexity in processing the data. Even in the best scenario, the geophysicist´s goals of obtaining meaningful information about the underground remains a challenge.

In recent years, the quality and quantity of geophysical data that new equipment is able to acquire has increased by several orders of magnitude, while the expected time to provide meaningful results is substantially shorter. Luckily, modern technologies may not be just the cause but also provide possible solutions to these complex challenges and questions.

The Federal Office of Geosciences and Natural Resources (BGR) acknowledges the challenges of modern data analysis. The Environmental monitoring and Data Science working group of the Centre for research and development of post-mining areas (FEZB), as well as other departments inside the BGR, are exploring the benefits and limitations of including machine learning algorithms in their data analysis.

In this work, I describe our experiences involving machine learning algorithms in two BGR´s projects: DESMEX-II and FINA. The results encourage us not only to further explore new and advanced applications of such methodologies in early stages of our workflow, but also to strengthen communication with other departments and institutions regarding this topic.

11:30-12:10

The use of seismic microzonation and recurrence analyses for seismic hazard mitigation - the case of Caracas, Venezuela

Michael Schmitz
UCV-USB-FUNVISIS

Seismic microzonation is one of the fundamental procedures for seismic hazard mitigation, as it addresses variations of ground shaking due to local geological conditions. It includes the detailed identification, in a city or a region, of soil zones with similar vibratory behavior and secondary effects (landslides, soil liquefaction, or others) during an earthquake. It allows defining approximate parameters for the design and construction of seismic resistant buildings. The associated study integrates the evaluation of the seismic hazard at rock surface, the topographic characteristics, and the analysis of geophysical, geological, and geotechnical information of the subsoil. A fundamental tool to know the configuration of the subsoil and its influence on the seismic response are geophysical measurements, aimed at evaluating the arrangement of the strata, especially the thickness of the Quaternary sediments and their parameters (shear wave velocities - Vs), as well as the quality of the shallow soil that significantly affects the seismic response (Vs in the first 30 m - Vs30). This information is the basis for evaluation of the surface seismic responses and the construction of design spectra, by means of site analyses, adjusted to the different seismic microzones in the city. In the scope of the Caracas seismic microzonation project, a comparison between the seismic hazard in Caracas, considering site effects, and the recurrence of macroseismic intensities in downtown Caracas was evaluated. The seismic hazard was studied at rock sites with updates of the seismogenic model, and for the seismic code. Averages of the evaluations for several return periods, plus their uncertainties, are handled for the computation of the spectral responses at the city center, characterized by three microzones with site effects. The history of intensities was compiled, and those of the largest earthquakes that have affected Caracas were revised, leading to a recurrence analysis that estimates return periods for each intensity. The correlation between the intensities and the peak ground accelerations and velocities was studied, based on world data, obtaining functions that link them, including their uncertainties. Thus, spectral responses were associated to the intensities of several code return periods to compare with those from the hazard assessment, finding a good agreement between both studies. Probable seismic intensities in representative sites of the city (hills, center, and deep basin) were assessed. An intensity of 7.5 or 8 is expected in the center between the years 2024 and 2060, due to any earthquake in the region, which affects the constructions of the city, showing the need for a seismic risk mitigation plan. Moreover, it is essential to consider the nearby probable earthquakes and their recurrences, recently studied.

12:10 - 13:00 **Breakout Session 3**

13:00 - 14:30 Lunch Break

14:30 - 15:10

Evaluating the potential of cicese seismological network for its application in an earthquake early warning system for the northern region of Baja California

Sergio Arregui
CICESE, Mexico

In order to implement an Earthquake Early Warning System in northern Baja California, which allows issuing notifications to warn the people about the occurrence of a seismic event in the region, an evaluation of the response capacity of the CICESE Seismological Network, through the SeisComP detection and acquisition system, using the Virtual Seismologist method. This evaluation began in April 2017 and we have more 5000 events processed with this system, from which it could be noted that with the current network coverage and depending on the region where it occurs the earthquake, people can be notified up to 20 seconds in advance in some cases. We identify that for the earthquakes occurred in the Mexicali Valley, Baja California, there is good geographic coverage, while in the region of the Peninsular Mountain Range, Baja California, data collected indicates that coverage should be improved. Seismic signals are sent to the processing center at CICESE using different transmission methods, the transmission methods via commercial internet modem and cellular modem stand out due to low latency times (<2 s). Based on the obtained results, we consider that the implementation of an Earthquake Early Warning system in the CICESE Seismological Network is feasible, with the suggested recommendations.

15:10 - 15:50

SAIPy: A Python Package for Single-Station Earthquake Monitoring using Deep Learning

Megha Chakraborty
SAI Group FIAS

Seismology has witnessed significant advancements in recent years with the application of deep learning methods to address a broad range of problems. These techniques have demonstrated their remarkable ability to effectively extract statistical properties from extensive datasets, surpassing the capabilities of traditional approaches to an extent. In this study, we present SAIPy, an open-source Python package specifically developed for fast data processing by implementing deep learning. SAIPy offers solutions for multiple seismological tasks, including earthquake detection, magnitude estimation, seismic phase picking, and polarity identification. We introduce upgraded versions of previously published models such as CREIME_RT capable of identifying earthquakes with an accuracy above 99.8% and a root mean squared error of 0.38 unit in magnitude estimation. These upgraded models outperform state-of-the-art approaches like the Vision Transformer network. SAIPy provides an API that simplifies the integration of these advanced models, including CREIME_RT, DynaPicker_v2, and PolarCAP, along with benchmark datasets. The package has the potential to be used for real-time earthquake monitoring to enable timely actions to mitigate the impact of seismic events. Ongoing development efforts aim to enhance SAIPy's performance and incorporate additional features that enhance exploration efforts, and it also would be interesting to approach the retraining of the whole package as a multi-task learning problem.

15:50 - 16:20 Coffee Break

16:20 - 17:00

ML Emulation of High-Resolution Tsunami Inundation Maps

Steven Gibbons
Norwegian Geotechnical Institute

Modelling coastal tsunami impact demands the computation of inundation metrics such as maximum inundation height or momentum flux at all locations at which hazard assessment is required. By far the most expensive part of a tsunami simulation is the inundation modelling which demands solving the nonlinear shallow water equations on very high-resolution grids. Uncertainty quantification is an essential aspect of tsunami hazard assessment with up to tens of thousands of simulations often needed to adequately cover the source variability. This applies both to long term hazard assessment (Probabilistic Tsunami Hazard Assessment) and urgent tsunami computing (Probabilistic Tsunami Forecast). Calculation of the offshore tsunami wave heights is far less computationally expensive than the full inundation calculation. This makes a Machine Learning-based Site-Specific Tsunami Run-Up Emulator a very appealing goal. If we can train a model to predict a high-resolution inundation map based only on the offshore time-series, using a training set of a very limited number of full inundation calculations, we would be able to significantly reduce the time-to-solution for inundation predictions. We developed a convolutional encoder-decoder based neural network and applied it to a dataset of over 32000 high-resolution inundation simulations for the Bay of Catania in Sicily, calculated for different earthquake scenarios in the Mediterranean Sea. We demonstrate encouragingly accurate inundation

17:00 -18:00

Breakout Session 4

Friday, 15 September 2023

09:00 - 9:40

Machine Learning based Estimator for Ground Shaking maps

Marisol Monterrubio
Barcelona Supercomputing Center

Earthquakes constitute a major threat to human lives and infrastructure, hence it is crucial to quickly assess the intensity of ground motions after a major seismic event. Rapid estimation of the intensity of ground vibrations is essential to assess the impact after a major earthquake occurs.

The Machine Learning Estimator for Ground Shaking Maps (MLESmap) introduces an innovative approach that harnesses the predictive capabilities of Machine Learning (ML) algorithms, utilizing high-quality physics-based seismic scenarios. MLESmap aims to provide ground intensity measures within seconds following an earthquake. The inferred information can produce shaking maps of the ground providing quasi-real-time affectation information to help us explore uncertainties quickly and reliably.

To develop the MLESmap technology, we used ground-motion simulations generated by the CyberShake platform. Originally designed for Southern California, this physics-based Probabilistic Seismic Hazard Methodology was migrated to the South Iceland Seismic Zone recently.

Our methodology follows a three-step process: simulation, training, and deployment. By employing this approach, we can generate the next generation of ground shake maps, incorporating essential physical information derived from wave propagation, such as directivity, topography, and site effects. Remarkably, the evaluation times for MLESmap are comparable to empirical Ground Motion Models, whereas the predictive capacity of the former is superior for the $M_w > 5$ earthquakes.

In this work, we present the application of the MLESmap methodology in two different tectonic regions: the Los Angeles area and South West Iceland. In addition, we validate the technology using information from actual event records within these regions of interest.

09:40 - 10:20

Applications of AI/ML in seismology – challenges and opportunities in Gujarat Intraplate region

Sumer Chopra
ISR, India

In recent years, a lot of advancement in computing power and availability of advanced AI/ML tools created newer opportunities in seismology. Large amounts of datasets are available now from decades of investigations and monitoring of active areas. The same datasets can be used along with advanced algorithms to derive meaningful outputs that further can be used to prepare better models and answer some science questions. Institute of Seismological Research (ISR) is operating a dense network of seismic stations since 2006. Around 200 stations comprising of broadband seismographs and strong motion accelerographs are in operation. Around 30,000 local earthquakes have been recorded in this network since its inception. Few regions in Gujarat are prone to rainfall-induced seismicity in the form of swarms. Hundreds of them are recorded in past decade or so. The network is also recording quarry blasting along with earthquakes. Presently, it is challenging to separate manually the blasting and identify very small earthquakes in swarms which are embedded in background noise. In addition, ISR has large geophysical and geotechnical data obtained from all over Gujarat. The geophysical data sets comprise of shallow seismic, electrical, magnetotelluric, electromagnetic, gravity and magnetic. The AI/ML can be applied on this large dataset to detect small earthquakes, differentiate between earthquakes and blasts, characterise rainfall-induced earthquakes, characterise various earthquake sources, infer sub-surface geological information, predict ground motions for early warning, model cyclones using microtremors and prepare earthquake induced soil liquefaction hazard index maps for Gujarat. ISR has started the work of discriminating quarry blasts and earthquakes and identify more earthquakes in swarm data using AI/ML algorithms and achieved some degree of success.

10:20 - 10:50 Coffee Break

10:50 - 11:30

To be announced soon!

11:30-12:10

A deep learning approach for large earthquakes monitoring using High-rate Global Navigation Satellite System data

Claudia Quinteros Cartaya
SAI Group FIAS

The High-rate Global Navigation Satellite System (HR-GNSS) instruments provide a direct measurement of ground displacement with high-precision, detect P-waves, and aid in post-earthquake deformation monitoring. Integrating HR-GNSS data with other sensor data and models enhances the accuracy of earthquake assessments and provides valuable information for early warning and disaster preparedness. We have been working on deep-learning-based models for large earthquake detection and magnitude estimation using displacement waveforms from HR-GNSS recordings, to significantly enhance our ability to detect, assess, and respond to seismic events. However, algorithms based on deep learning for fast analyses of HR-GNSS data have been a recent challenge. To harness the full potential of deep learning, it is crucial to have access to large and high-quality datasets, but unfortunately, GNSS stations are not distributed enough in all regions, which can lead to data gaps. Also, in most cases, only earthquakes $Mw > 6$ are well-recorded for several GNSS stations. Hence, we have faced the lack of data, using both synthetic and real HR-GNSS data for model training, validation and testing. The influence of attributes such as noise, magnitude, number of stations, epicentral distance, and length of input time series on the model performance is evaluated. We aim to generalize this approach to real-time monitoring of large earthquakes from different tectonic regions.

12:10 - 13:00

Breakout Session 5

13:00 - 14:30 Lunch Break

14:30 - 15:10

Feasibility of Deep Learning in Shear Wave Splitting analysis: Synthetic-Data Training and Waveform Deconvolution

Megha Chakraborty
SAI Group FIAS

Teleseismic shear-wave splitting analyses are typically performed by reversing the splitting process through the application of frequency- or time-domain operations aimed at minimizing the transverse-component energy of waveforms. These operations yield two splitting parameters, ϕ (fast-axis orientation) and δt (delay time). In this study, we investigate the applicability of a recurrent neural network, SWSNet, for determining the splitting parameters from pre-selected waveform windows. Due to the scarcity of sufficiently labelled real waveform data, we generate our own synthetic dataset to train the model. SWSNet is capable of reliably determining ϕ and δt for for noisy synthetic test data. The application to real data involves a deconvolution step to homogenize the waveforms. When applied to data from the USArray dataset, the results exhibit similar patterns to those found in previous studies.

15:10 - 15:50

Benchmarking and evaluation in applications in machine learning for seismicity analysis

Frederik Tilmann
GFZ Potsdam

The use of machine learning has exploded in seismology in recent years, with applications in assembling catalogues through automatic processings and deep neural networks having become routine. Further data-driven neural network models for standard tasks of earthquake analysis such as estimation of magnitudes from waveforms, or other waveform-based estimators such as for focal mechanisms are still mostly experimental but show great promise.

Particularly, where algorithms are to be applied in operational contexts and the quality of results have civil protection implications, it is important to gain a very good understanding of the typical performance of the algorithm in different scenarios, but also at its robustness. In this review presentation, I will look at the related aspects of benchmarking and model comparisons, the choice of good strategies for defining test datasets and finally evaluation measures from the perspective of a seismologist in the context of earthquake monitoring and seismicity studies.

15:50 - 16:20 Coffee Break

16:20 - 17:00

Breakout Session 6 & Networking

17:30 onwards

Dinner @ Zum Lahmen Esel

Organizers:

Dr. Nishtha Srivastava (Chair)

Dr. Claudia Quinteros Cartaya

Johannes Faber

Co-organizers:

Jonas Köhler

Megha Chakraborty

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