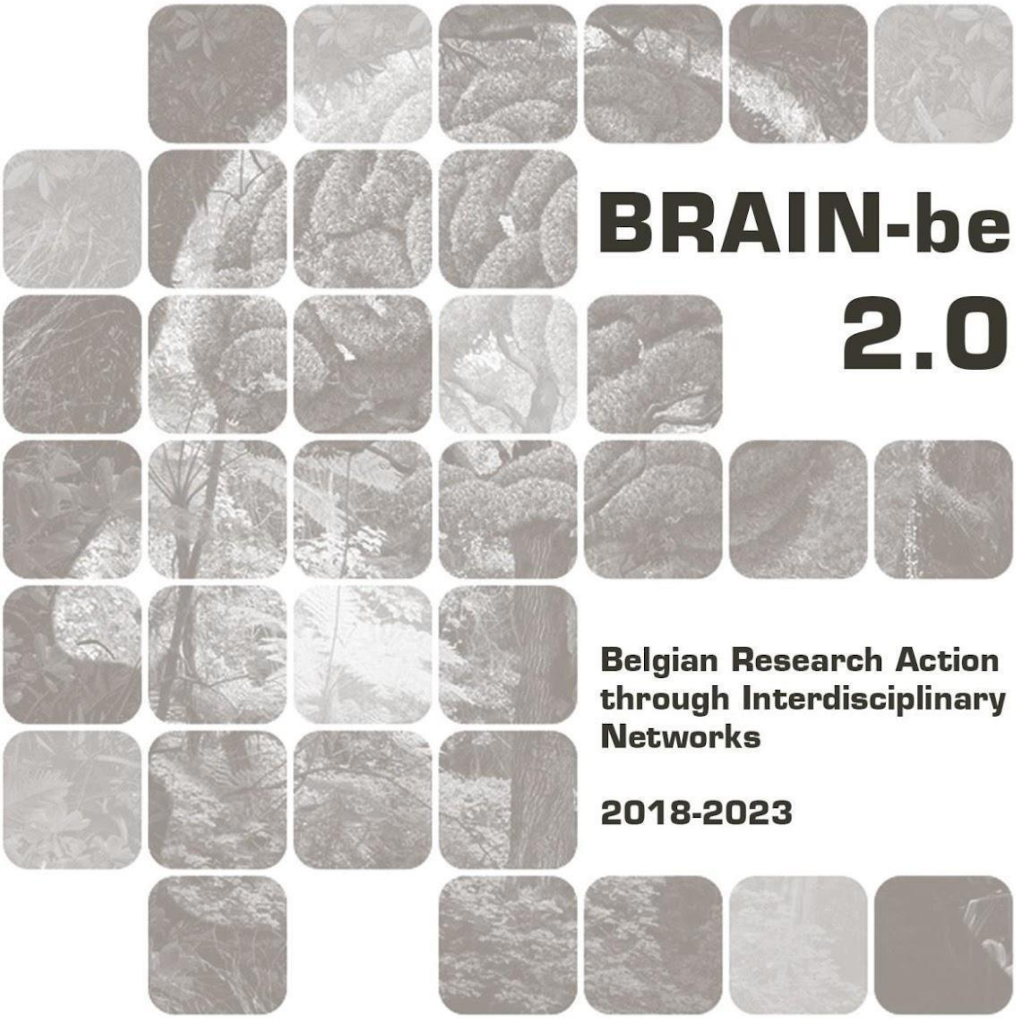

SEISMOSTORM

Making Analog Seismograms FAIR to Enable Research

Thomas Lecocq (Royal Observatory of Belgium) - Olivier Debeir (Université Libre de Bruxelles) - Raphael De Plaen (Royal Observatory of Belgium) - Polina Lemenkova (Université Libre de Bruxelles)

Pillar 2: Heritage science

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BRAIN-be 2.0

Belgian Research Action through Interdisciplinary Networks

2018-2023

NETWORK PROJECT

SEISMOSTORM

Making Analog Seismograms FAIR to Enable Research

Contract - B2/202/P2/SEISMOSTORM

FINAL REPORT

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ROYAL OBSERVATORY OF BELGIUM
SEISMOLOGY GRAVIMETRY

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Published in 2024 by the Belgian Science Policy Office
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Thomas Lecocq, Olivier Debeir, Raphael De Plaen, Polina Lemenkova. Making Analog Seismograms FAIR to Enable Research. Final Report. Brussels: Belgian Science Policy Office 2024 – 36 p. (BRAIN-be 2.0 - (Belgian Research Action through Interdisciplinary Networks))

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ABSTRACT

Context

Seismographs have recorded ground motion since the end of the 19th century until digital recordings became available in the 1970s (Okal, 2015). Pre-digital seismic records were typically created by using ink on white paper, scratching black-smoked paper, or by using light on photographic paper. With most of these legacy seismic data now stored in archives and exposed to physical decay, several projects in the last 20 years (i.e., Bent et al., 2020; Ferrari & Pino, 2003) started to dedicate resources to digitising them to preserve and exploit the unexplored scientific wealth they contain and, in turn, introduce them into the age of modern seismology. This effort has become increasingly important due to the increasing risk of permanently losing those ageing paper seismograms combined with their recently found exclusive potential in recovering the global oceanic climate for the last century (Lecocq et al., 2020).

Objectives

The Royal Observatory of Belgium (ROB) possesses a vast archive of legacy seismic data (Van Camp & Camelbeeck, 2004), some of which has recently been scanned. Our project used computer vision and recently developed machine learning approaches to digitise waveform data extracted from these scanned images. This process results in the creation of calibrated and time-coded seismic time series, which can subsequently be disseminated to the scientific community via international web services following seismic community-defined standards.

By providing access to continuous seismic data spanning the past century following the FAIR principles (findability, accessibility, interoperability, and reusability), the project aims to facilitate the investigation of historical oceanic climates using seismic data and to improve the accessibility to tools necessary for the digitization efforts across various institutes, observatories, and universities. Furthermore, the broad availability of quantitative observational data from around the world will significantly enhance existing oceanic wave models of the 20th century, contributing to climate research.

Conclusions

We meticulously compiled all the information on the seismic archive of the ROB, along with its metadata. Our decision to concentrate on Galitzin data was informed by the instruments' high response in the microseismic frequency band, rendering them ideal proxies for sea state analysis. We developed an algorithm to vectorize and extract digital seismic waveforms from scanned seismograms using traditional computer vision techniques, supplemented by a distinct module leveraging deep neural networks to address more complex scenarios, such as line inter-crossing induced by high-amplitude events like earthquakes. We also developed a tool to compare vectorized waveforms with theoretical microseismic ground motions derived from the WaveWatch III oceanic models, facilitating initial validation of the time series.

The work conducted within this project is continually evolving to ensure its enduring utility for the widest possible audience. Furthermore, the project has made significant contributions to the broader scientific community through the establishment of working groups, participation in international initiatives, provision of training courses, and ongoing contributions to a book chapter. Alongside

targeted outreach efforts within the scientific community, initiatives aimed at engaging the general public were also undertaken.

Moreover, the project has catalysed new avenues of research and collaboration, including a master's thesis in machine learning, and has provided beneficial synergies with other projects at the Royal Observatory of Belgium, such as Belshake.

Keywords

Legacy seismograms, microseisms, seismic noise, oceanic storms, computer vision, deep neural networks, analog data.

SAMENVATTING

Context

Seismografen registreren grondbewegingen sinds het einde van de 19e eeuw totdat in de jaren 1970 digitale opnames beschikbaar kwamen (Okal, 2015). Pre-digitale seismische opnames werden meestal gemaakt door inkt op wit papier te gebruiken, zwartgerookt papier te krassen of door licht op fotografisch papier te gebruiken. Nu de meeste van deze oude seismische gegevens zijn opgeslagen in archieven en zijn blootgesteld aan fysiek verval, zijn verschillende projecten in de afgelopen 20 jaar (e.i., Bent et al., 2020; Ferrari & Pino, 2003) begonnen met het digitaliseren van deze gegevens om de onontgonnen wetenschappelijke rijkdom die ze bevatten te behouden en te exploiteren en ze op hun beurt in het tijdperk van de moderne seismologie te introduceren. Deze inspanning is steeds belangrijker geworden vanwege het toenemende risico op permanent verlies van deze verouderende papieren seismogrammen in combinatie met hun recent gevonden exclusieve potentieel voor het herstellen van het wereldwijde oceaanklimaat van de afgelopen eeuw (Lecocq et al., 2020).

Doelstellingen

De Koninklijke Sterrenwacht van België (KSB) bezit een enorm archief van oude seismische gegevens (Van Camp & Camelbeeck, 2004), waarvan een deel recentelijk is gescand. Ons project gebruikte computer vision en recent ontwikkelde machine learning benaderingen om golfvormgegevens uit deze gescande beelden te digitaliseren. Dit proces resulteert in de creatie van gekalibreerde en tijdgecodeerde seismische tijdreeksen, die vervolgens verspreid kunnen worden naar de wetenschappelijke gemeenschap via internationale webdiensten volgens door de seismische gemeenschap gedefinieerde standaarden.

Door toegang te verschaffen tot continue seismische gegevens van de afgelopen eeuw, wil het project het onderzoek van historische oceaanklimaten met behulp van seismische gegevens vergemakkelijken en de toegankelijkheid verbeteren van instrumenten die nodig zijn voor digitalisering in verschillende instituten, observatoria en universiteiten. Bovendien zal de brede beschikbaarheid van kwantitatieve observatiegegevens van over de hele wereld de bestaande modellen van oceaangolven van de 20e eeuw aanzienlijk verbeteren, wat bijdraagt aan het klimaatonderzoek.

Besluiten

We verzamelden zorgvuldig alle informatie over het seismisch archief van de KSB, samen met de metadata. Onze beslissing om ons te concentreren op Galitzin-gegevens werd ingegeven door de hoge respons van de instrumenten in de microseismische frequentieband, waardoor ze ideale proxies zijn voor de analyse van de toestand van de zee. We ontwikkelden een algoritme om digitale seismische golfvormen te vectoriseren en te extraheren uit gescande seismogrammen met behulp van traditionele computervisietechnieken, aangevuld met een aparte module die gebruik maakt van diepe neurale netwerken om complexere scenario's aan te pakken, zoals het doorkruisen van lijnen door gebeurtenissen met een hoge amplitude, zoals aardbevingen. We hebben ook een hulpmiddel ontwikkeld om gevectoriseerde golfvormen te vergelijken met theoretische microseismische grondbewegingen afgeleid van de WaveWatch III oceanische modellen, wat een eerste validatie van de tijdreeksen mogelijk maakt.

Het werk dat binnen dit project is uitgevoerd, wordt voortdurend verder ontwikkeld om ervoor te zorgen dat het blijvend bruikbaar is voor een zo breed mogelijk publiek. Verder heeft het project belangrijke bijdragen geleverd aan de bredere wetenschappelijke gemeenschap door de oprichting van werkgroepen, deelname aan internationale initiatieven, het aanbieden van trainingen en doorlopende bijdragen aan een boekhoofdstuk. Naast gerichte outreach-inspanningen binnen de wetenschappelijke gemeenschap werden ook initiatieven ondernomen om het grote publiek erbij te betrekken.

Bovendien heeft het project nieuwe wegen van onderzoek en samenwerking gekatalyseerd, met inbegrip van een masterproef in machinaal leren, en heeft het gezorgd voor nuttige synergieën met andere projecten aan de Koninklijke Sterrenwacht van België, zoals Belshake.

Trefwoorden

Oude seismogrammen, microseismiek, seismische ruis, oceaanstormen, computervisie, diepe neurale netwerken, analoge gegevens.

RESUMÉ

Contexte

Les sismographes ont enregistré les mouvements du sol depuis la fin du XIXe siècle jusqu'à l'apparition des enregistrements numériques dans les années 1970 (Okal, 2015). Les enregistrements sismiques pré-numériques étaient généralement créés en utilisant de l'encre sur du papier blanc, en grattant du papier noir fumé ou en utilisant de la lumière sur du papier photographique. La plupart de ces anciennes données sismiques étant désormais stockées dans des archives et exposées à la dégradation physique, plusieurs projets au cours des 20 dernières années (e.i., Bent et al., 2020; Ferrari & Pino, 2003) ont commencé à consacrer des ressources à leur numérisation afin de préserver et d'exploiter la richesse scientifique inexplorée qu'elles contiennent et, en retour, de les faire entrer dans l'ère de la sismologie moderne. Cet effort est devenu de plus en plus important en raison du risque croissant de perdre définitivement ces sismogrammes papier vieillissants, combiné à leur

potentiel exclusif récemment découvert pour récupérer le climat océanique mondial du siècle dernier (Lecocq et al., 2020).

Objectifs

L'Observatoire royal de Belgique (ORB) possède de vastes archives de données sismiques anciennes (Van Camp & Camelbeeck, 2004), dont certaines ont été récemment numérisées. Notre projet a utilisé la vision par ordinateur et des approches d'apprentissage automatique récemment développées pour numériser les données de forme d'onde extraites de ces images numérisées. Ce processus aboutit à la création de séries temporelles sismiques calibrées et codées, qui peuvent ensuite être diffusées à la communauté scientifique par l'intermédiaire de services web internationaux suivant des normes définies par la communauté sismique.

En donnant accès à des données sismiques continues couvrant le siècle dernier, le projet vise à faciliter l'étude des climats océaniques historiques à l'aide de données sismiques et à améliorer l'accessibilité aux outils nécessaires aux efforts de numérisation dans divers instituts, observatoires et universités. En outre, la large disponibilité de données d'observation quantitatives provenant du monde entier permettra d'améliorer considérablement les modèles de vagues océaniques du 20e siècle, contribuant ainsi à la recherche sur le climat.

Conclusions

Nous avons méticuleusement compilé toutes les informations sur les archives sismiques de l'ORB, ainsi que leurs métadonnées. Notre décision de nous concentrer sur les données Galitzin a été motivée par la réponse élevée des instruments dans la bande de fréquence microsismique, ce qui les rend idéaux pour l'analyse de l'état de la mer. Nous avons développé un algorithme pour vectoriser et extraire des formes d'ondes sismiques numériques à partir de sismogrammes scannés en utilisant des techniques traditionnelles de vision par ordinateur, complétées par un module distinct utilisant des réseaux neuronaux profonds pour traiter des scénarios plus complexes, tels que l'entrecroisement de lignes induit par des événements de forte amplitude comme les tremblements de terre. Nous avons également mis au point un outil permettant de comparer les formes d'ondes vectorisées avec les mouvements du sol microsismiques théoriques dérivés des modèles océaniques WaveWatch III, ce qui facilite la validation initiale des séries temporelles.

Les travaux menés dans le cadre de ce projet sont en constante évolution afin de garantir leur utilité durable pour le plus grand nombre. En outre, le projet a apporté des contributions significatives à la communauté scientifique au sens large par la création de groupes de travail, la participation à des initiatives internationales, l'organisation de cours de formation et des contributions permanentes à un chapitre de livre. Parallèlement aux efforts de sensibilisation ciblés au sein de la communauté scientifique, des initiatives visant à impliquer le grand public ont également été entreprises.

En outre, le projet a catalysé de nouvelles pistes de recherche et de collaboration, notamment un mémoire de maîtrise en apprentissage automatique, et a créé des synergies bénéfiques avec d'autres projets de l'Observatoire royal de Belgique, tels que Belshake.

Mots-clés

Sismogrammes anciens, microséismes, bruit sismique, tempêtes océaniques, vision par ordinateur, réseaux neuronaux profonds, données analogiques.

1. INTRODUCTION

The ground vibration has been recorded continuously by seismic stations all around the world for over a century. Until the transition to digital data, most of these waveforms were recorded and stored on analog support such as photographic paper, smoked paper (Okal, 2015). Besides countless earthquake arrivals, seismometers record a wide range of continuous sources, natural and human made, typically referred as seismic ambient noise (Nakata et al., 2019). The analysis of this seismic noise has led in the last decades in the development of a numerous methods to study the upper crust (Campillo & Paul, 2003; Shapiro & Campillo, 2004). These methods have also increasingly highlighted the rich repository of information on past and current natural disasters withheld in seismic datasets worldwide. More specifically, the seismic signals generated by the ocean-solid earth interaction, known as microseisms, are the dominant source of seismic ambient noise, making seismograms a good source of information to study oceanic storms (Ebeling, 2012). This creates a potential to contribute to the study of the oceanic climate using seismic data, which is exacerbated by the reality that most of this quantitative data was recorded before global satellite data became available in the 1980s. However, while seismograms may be the only source of such environmental records, they require and advanced digitisation and vectorization process before they can be analysed using modern seismic methods.

While a global approach will be necessary to efficiently contribute to the analysis of the oceanic climate of the entire XXth century, a proof of concept highlighted the potential of the method bay focussing on the records of the Uccle seismic station, in Belgium, for the 1952 “big flood” (Lecocq et al., 2020). This triggered a project that aim to develop the open-sourced tools, from the vectorisation of seismic waveform to the validation of the microseisms amplitude spectra, so that they can be disseminated and made available to the rest of the community to bring a larger number of seismic archives at observatories worldwide to the digital age.

2. STATE OF THE ART AND OBJECTIVES

Seismic records and scanning

Ground motion has been recorded by seismographs since the end of the 19th century, with waveforms typically stored using ink on white paper, scratched black-smoked paper, or light on photographic paper until the advent of digital recordings in the 1970s (Okal, 2015). In Belgium, several instruments recorded from the seismic station of the Royal Observatory of Belgium in Uccle. The station remained the only one in the country until 1958, after which the Belgian network gradually started to grow (Van Camp & Camelbeeck, 2004). Each instrument had their specific properties and calibrations, but they were all engineered to ensure accuracy in both timing, crucial for earthquake location via travel time calculations, and amplitude, essential for measuring earthquake magnitude.

These legacy seismic records are typically stored in various conditions of preservation and are hard to use in their analog form to do modern research. As a result, when there is a digitization effort, it is often focused on significant earthquakes (e.g., Ferrari & Pino, 2003). The digitization of legacy seismic data has been a topic of increasing interest since the late 1990s, especially due to ageing analog support that risks seismic data being lost permanently. Nevertheless, to this date, very few labs and observatories have scanned their entire collection.

While there are increasing efforts toward the preservation and exploitation of legacy seismic data, a concurrent trend has evolved toward the use of the continuous seismic signal or “seismic noise” (Nakata et al., 2019). Continuous ground motion is generated by the interactions between the atmosphere, ocean, and solid earth, which produce low-frequency vibrations observed by all seismic stations on Earth (Hasselmann, 1963; Longuet-Higgins, 1950). This is compounded by local human activity, such as traffic, transportation, and industrial operations, near seismic stations contributing to higher frequency noise. This passive seismology has opened a lot of research opportunities for modern research and has become routinely used for geophysical imaging, volcano monitoring, fault and reservoir analysis, and climate research (Nakata et al., 2019). The exploration of the information contained in the continuous signal of legacy seismic data presents a significant research potential that further supports the need for its digitization.

It is in this framework that Lecocq et al. (2020) developed a proof of concept around the basic automated vectorization of scanned seismogram images, time-coding each waveform, and conducting spectral analysis for each minute of data. Their method incorporates real ground motion interpretations, using amplitude-frequency instrument responses derived from metadata compiled in the official monthly bulletins of the ROB. Comparing the measured amplitudes and dominant periods of the ocean generated seismic signal to microseism models proved the method to be promising. The general limitation is related to the digitization process, with high amplitude events such as earthquakes and strong storms causing unclear overlapping traces resulting in skipped data/time intervals.

Digitizing seismic archives

Various published studies on historical earthquake re-analyses have used manual or semi-automatic vectorization methods to convert analogue seismograms into digital time series (e.g., Başarır Baştürk et al., 2016; Ichinose et al., 2003, 2003).

Several GUI-based software tools have been developed to extract digital seismograms from raster images. For instance, SeisDig by Bromirski et al. (2003) and DigitSeis by Bogiatzis and Ishii (2016), both operating on the MATLAB platform and DigitSeis the only one actively maintained (i.e., Ishii & Ishii, 2022). Additionally, the TESEO program, part of the SISMOS project by Pintore et al. (2005), functions as a GIMP-GNU plugin. Other programs include those by Church et al. (2013) and Wang, Liu, et al. (2016). Despite advancements, these manual and semi-automatic tools often necessitate extensive human interaction, limiting their efficiency, particularly for digitising large seismogram collections.

SKATE (Bartlett et al., 2018) offers an open-source web-based alternative for digitising extensive volumes of seismogram images. It provides reusable code and has already digitised over 30,000 World-Wide Standard Seismographic Network (WWSSN) images, with the potential for further feature detection and enhancement.

Digitising old or damaged smoked seismograms, particularly those with thin and discontinuous traces, presents additional challenges. Even with semi-automatic functions, the process remains time-consuming. Tiitba (Corona-Fernandez & Santoyo, 2023) addresses this challenge by offering an interactive open-source GUI in Python specifically designed for vectorizing smoked paper seismograms, including those from Wiechert seismographs.

More advanced digitization tools are necessary to efficiently work on large collections of seismograms while maximising the extraction of continuous seismic data from scanned images, and preserving as much of the valuable information they contain. Improvements in vectorization processes can be achieved through the integrated application of image preprocessing and machine learning techniques.

Data validation

The digitization of legacy seismic data aims to enable their use along with data from other historical observatories. This requires precise time and amplitude information, which is critical to comparing synchronous records from different stations and using them for localization and characterization of seismic sources. This is particularly important for the analysis of microseismic noise as it will provide ocean modellers with the only quantitative information on the oceanic climate available for the pre-satellite era (Bromirski, 2023). This control is first established by carefully extracting the metadata from the analog seismograms and the seismic bulletins compiled throughout the last century. Another validation is then implemented through a first order comparison of the amplitude of the recorded and modelled microseism (Stopa et al., 2019).

Data preservation and sharing

Digitizing legacy seismic data serves to preserve them and enable their exploitation for further research. Ensuring the data's discoverability and reusability with modern tools is crucial to giving new life to the old waveforms. As mentioned above, some projects, such as SKATE (Bartlett et al., 2018) may have processed thousands of images. However, the resulting continuous data from these projects is still not readily available through simple web services as it is standard for modern seismic data, preventing open research in the process. Webservices, such as the FDSN webservice, provide researchers with access to openly available seismic data and metadata from many seismic stations around the world. Such tools are critical for modern seismology as they freely provide invaluable access to data from many seismic stations worldwide, which is necessary for even basic tasks such as earthquake localization. This explains why seismology has always been at the forefront of data and metadata sharing and the standardisation of data formats. Converting vectorized data to those standards is therefore important to ensure their exploitation with modern seismic methods, including when analysing the oceanic microseisms.

3. METHODOLOGY

This project aims to modernise century-old analog seismic data and metadata, aligning them with contemporary standards through the integration of seismology and machine learning expertise. Our objective is to develop methodologies that adhere to FAIR principles, enhancing data discoverability and usability for researchers. To achieve our goal, the project is divided into four primary work packages (WP), supported by two transversal data and valorization packages:

- WP1 focuses on gathering instrument characteristics and metadata from historical ROB Bulletins, transforming them into usable "instrument responses" compatible with current software workflows. This includes compiling information on all ROB seismic instruments and reconstructing instrument changes over time.
- WP2 aims to forward model analog seismograms using current-day seismic observations to generate realistic synthetic time series, accounting for variations in instrument types and recording media.
- WP3 is dedicated to transforming scanned seismogram images into digital seismic waveforms by automating the extraction of wiggles. This involves implementing image processing and machine learning techniques to detect and characterise seismic traces accurately.
- WP4 validates the digitised time series by comparing them with independent time series, computed from theoretical microseismic ground motions generated by atmosphere-ocean-solid earth coupling mechanisms. This includes testing various microseisms generation mechanisms and evaluating model-data agreements.
- Additionally, WP5 manages data formatting and standards for archiving, discovery, and sharing of scanned images and digitised time series, ensuring compliance with seismological standards.
- WP6 focuses on promoting project results through various outreach activities to the scientific community, stakeholders, and the general public.

Overall, the project aims to make data accessible and reusable, promoting transparency and collaboration within the scientific community. All codes and software developed will be released as open source.

4. SCIENTIFIC RESULTS AND RECOMMENDATIONS

WP1 - Frequency/amplitude instrument response functions for historical seismographs

While the ROB had several different instruments operating in the 20th century (Van Camp & Camelbeeck, 2004), a focus on the data from the Galitzin seismometer was decided early as its instrumental response had the highest amplitude in the microseismic frequency bands (Lecocq et al., 2020). The many official seismic bulletins of the ROB contained all the information on the calibration values of the ROB seismometers throughout their activity period. These bulletins were compiled in 1999 as part of the Italian SISMOS project to create a convenient resource for the future correction of digitized waveforms and remain available to this day through the ISC (Figure 1).

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	File	Size
1901	✗	✗	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	Seism_Bulletins_May_1901_1902_Uccle.pdf	348.43MB
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1902	✗	✗	✗	✗	✗	✗	✓	✓	✓	✓	✓	✓	Seism_Bulletins_May_1901_1902_Uccle.pdf	348.43MB
1903	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	Seism_Bulletins_1903_Uccle.pdf	217.88MB
1904	✓	✓	✓	✗	✗	✗	✓	✓	✓	✓	✓	✓	Seism_Bulletins_1904_1905_Uccle.pdf	57.92MB
1905	✓	✓	✓	✓	✓	✗	✗	✗	✗	✗	✗	✗	Seism_Bulletins_1904_1905_Uccle.pdf	57.92MB
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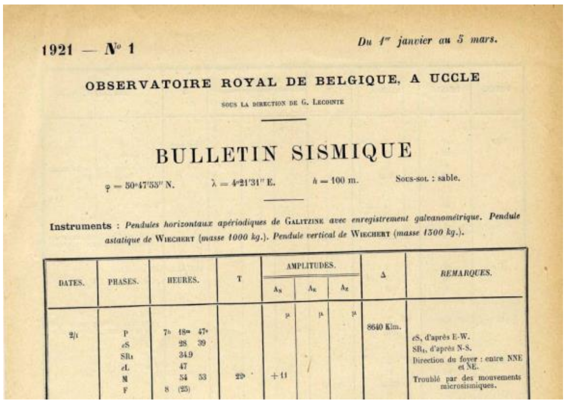
1921 — N° 1

Du 1er janvier au 5 mars.

OBSERVATOIRE ROYAL DE BELGIQUE, A UCCLE

SOUS LA DIRECTION DE G. LECOINTE

BULLETIN SISMIQUE

φ = 50°47'55'' N. λ = 4°21'31'' E. h = 100 m. Sous-sol : sable.

Instruments : *Pendules horizontaux apériodiques de* GALITZINE *avec enregistrement galvanométrique. Pendule astatique de* WIECHERT *(masse 1000 kg.). Pendule vertical de* WIECHERT *(masse 1300 kg.).*

DATES.	PHASES.	HEURES.	T	AMPLITUDES. A_N	A_E	A_Z	Δ	REMARQUES.
				μ	μ	μ		
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During various international meetings, Raphael De Plaen, Thomas Lee and Dan Burke shared and discussed their work dealing with legacy seismic data. This triggered a collaboration to develop a more comprehensive open-source tool specifically dedicated to generating instrumental response files based on the type of instrument and its calibration data. This output of this collaboration is expected soon.

The inventory work allowed us to highlight gaps in the scanned data of the ROB. This was in part solved thanks to several students who were hired over two summers to scan the missing seismograms and helped digitize seismograms associated with the Liège 1983 earthquake. Other gaps were also revealed to be related to thousands of paper seismograms that had been stored on microfilms while their paper format had been destroyed to save storage space. Another collaboration with the State Archives of Belgium helped evaluate the potential of scanned microfilms for vectorization. The collaboration proved promising but will likely require the purchase of a dedicated microfilm scanner in the frame of a future project.

WP2 and WP3 - algorithms for digitizing analog seismograms

The vectorization of seismic waveforms is first divided in two separate approaches: the traditional computer vision and the machine learning. The computer vision-based vectorisation alone has the potential to efficiently work on most of the continuous signals associated with the microseisms. With the focus of the project on the oceanic signal, a greater effort was dedicated to that approach. Stronger signals causing crossing of lines are ignored and expected to be tackled using the machine learning approach, or more specifically Deep Neural Networks.

Traditional computer vision

In this phase, the seismic waveform vectorization is achieved exclusively through image processing to convert them into digital waveforms in the MiniSEED format, which is the standard format in seismology. This vectorization method was developed by Olivier Debeir (LISA-ULB) with assistance from Polina Lemenkova, initially focusing on data from Galitzin seismometers due to their relatively easier digitization process and their natural period, which facilitates the analysis of microseisms in ocean wave modelling. The vectorization system was implemented in Python and uses various platforms depending on the specific application (Lemenkova et al., 2023). The Cytomine platform (Figure 2), originally designed for biomedical analysis, proves ideal for managing the extensive database of scanned images (Marée et al., 2016), handling metadata, and facilitating manual annotation.

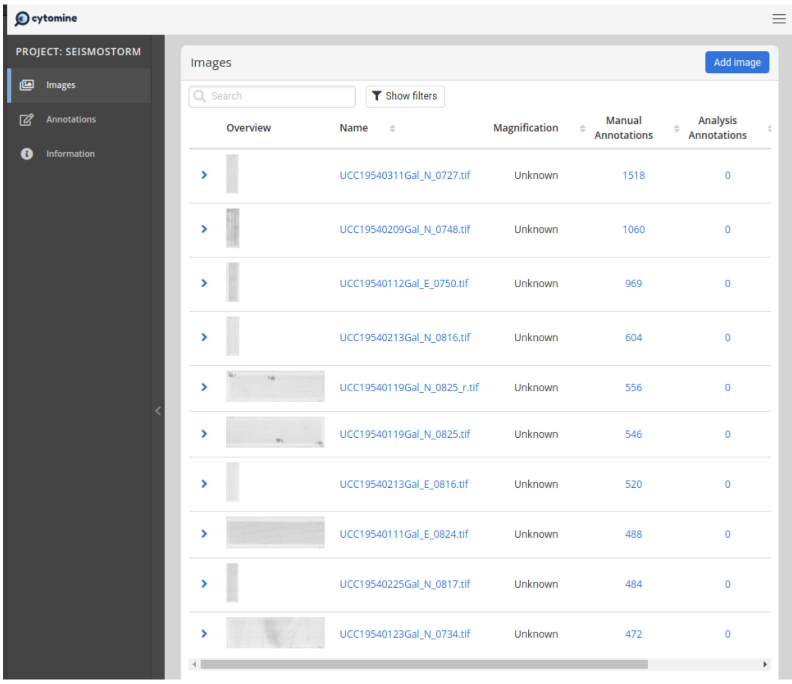

Figure 1. Management of the scanned seismograms inside the Cytomine platform.

The second step, which can be considered as a heavy python client, is developed based on an interactive framework Napari (Chiu et al., 2022, Figure 3). It allows the user to open a large scan image into memory and to display it in a reactive display. It employs traditional computer vision techniques to vectorize the waveforms and generate MiniSEED files.

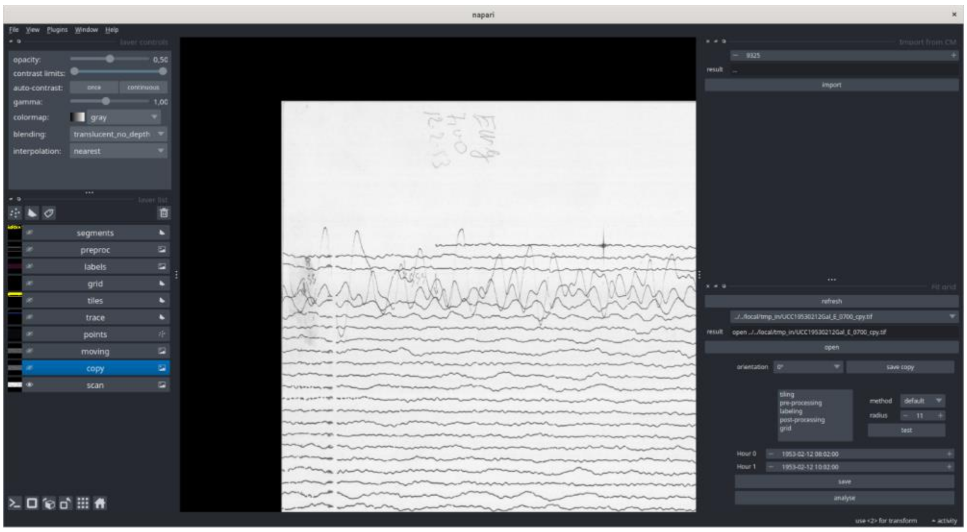

Figure 3. Napari interactive platform for the vectorisation of the seismic waveform using computer vision.

In addition to the image orientation, the designation of reference timestamp inside the scan is also done by the user as illustrated below (Figure 4), here two spots inside the image are identified as given time stamps.

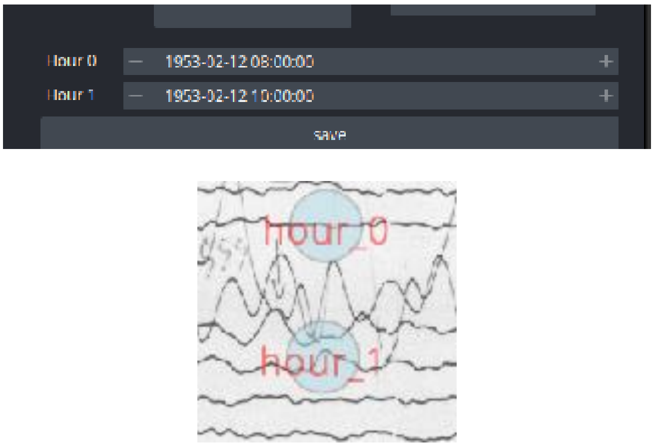

Figure 4. designation of the reference timestamps.

The automatic labelling can then be propagated throughout the complete image as illustrated in Figure 5.

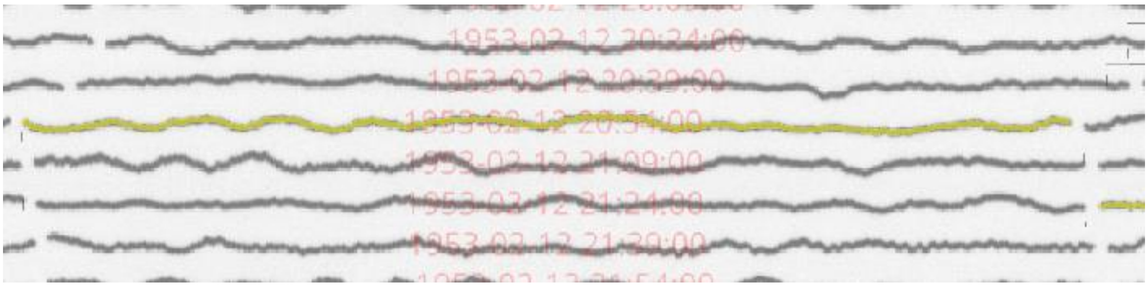

Figure 5. Automatic propagation of the timestamps.

The current software development offers an interactive approach that is still compatible with the high number of images to process since the user interaction remains minimal and can be separated from the heavy computing load (the user can annotate quickly a bunch of images without waiting for the result of the automatic processes. The heavy client approach is more robust in terms of timestamp automatic attribution. While this approach is efficient for most continuous traces dominated by low-amplitude seismic ambient noise, it encounters challenges with more complex cases (Figure 6), such as earthquakes with large amplitudes causing overlapping lines on the paper, which processed independently but constitute a limited number of occurrences.

This motivated the development of a third platform dedicated to more complex cases which relies on Deep Neural Networks with a transformer-based approach to tackle specific artefacts. These last two platforms are currently independent but should ultimately be integrated. As it stands, the computer vision approach can nevertheless produce batches of MSEED files from a large volume of scanned images with a relatively high completeness for passive seismology applications.

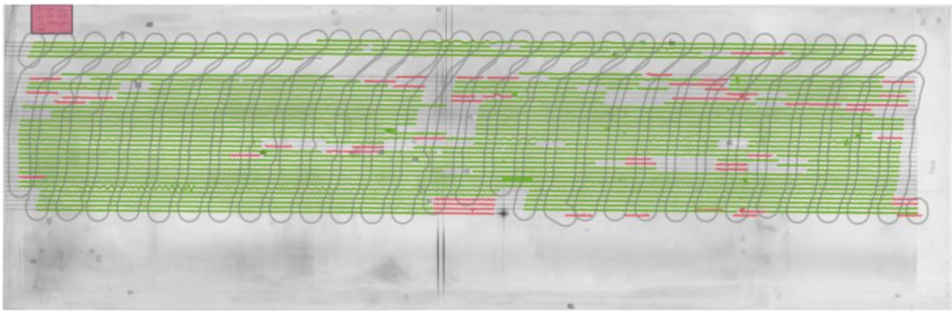

Figure 6. Vectorised waveform overlaid over the corresponding scanned seismogram in the Cytomine platform. Visual artefacts are causing gams in the vectorized waveform (green), but most of the image is properly processed.

Machine learning implementation

This part of the project became the MSc Thesis of Alexandre Missenard (2022, ULB-LISA):” Exploitation of EQTransformer and application to Belgian seismic data”. This work was based on the development of two models: one convolutional neural network (CNN) and a long-short term memory (LSTM), a type of recurrent neural network (RNN).

Unlike the RNN-based algorithm, the CNN-based algorithm proved to be subjected to high deviations when the number and complexity of the anomalies becomes too high. The final model is now able to take an image containing multiple segments and, by starting from a given coordinate, process the full image window by window to output an array of points forming a line that summarises the main trace (Figure 7). No integration between the Classical computer vision and the CCN yet. Because there is no clear benefit to processing the images using exclusively machine learning, a hybrid approach is favoured to exploit the benefit of both methods.

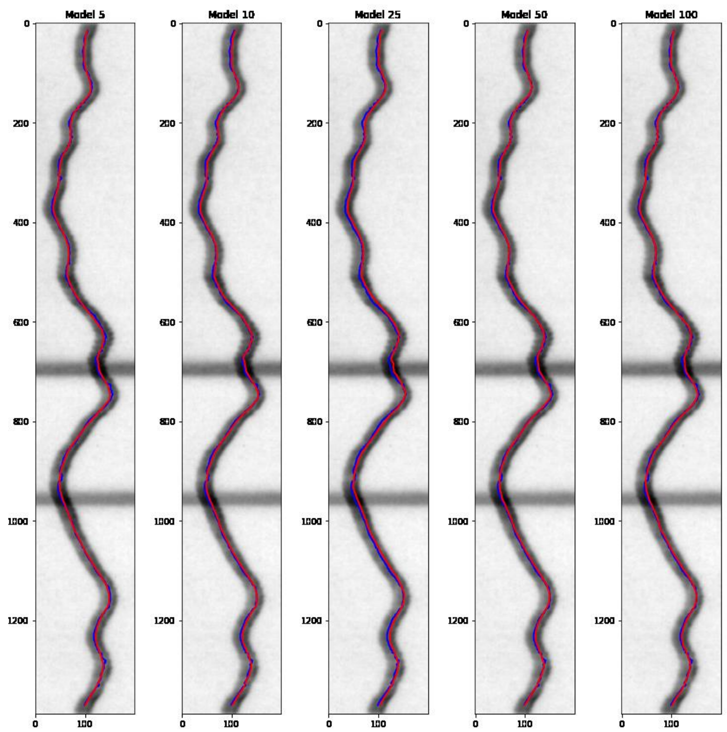

Figure 7. LSTM dense number comparison

WP4 - Validation of time series with modelled microseisms ground motions

The computation of the theoretical microseismic ground motions in Uccle was developed in partnership with IFREMER. The chosen strategy was developed around processing the theoretical ocean-generated second-order pressure (P2L), responsible for the microseisms recorded on land due to interaction with the ocean bottom using the WaveWatch III (WWIII) ocean model (Tolman, 2014) at the global scale and at high resolution of 0.5 degrees for the entire XXth century (Figure 8). The simulations of the microseism spectra are calculated following Ardhuin et al., (2011) and Stutzmann et al., (2012) with a parametrization designed by Fabrice Arduin in the frame of the SeismoStorm project. These products are currently available for any seismologist around the globe to guarantee that everyone benefits from the same state of the art parameterization when comparing theoretical microseismic ground motions to observed ground motion. They are currently accessible along with the other hindcast products of the ocean wave model on the IFREMER ftp (ftp.ifremer.fr/ifremer/ww3), but a more sustainable and practical repository will be organized soon to make the reanalysis of past oceanic storms and their corresponding seismic signatures widely and permanently accessible to the scientific community. Raphael De Plaen and Thomas Lecocq worked on the development of an open-source companion tool in Python (De Plaen et al., 2022) to simplifies the access to the microseism source models and streamline the calculation of theoretical microseismic ground motion from the modelled seismic sources for any seismic station in the world (Figure 9).

The validity of the vectorized traces is confirmed by comparing their amplitude and frequency characteristics with those of recorded secondary microseisms. This comparison is made against the corresponding generation model derived from the WWIII ocean model by transforming the wave spectra into theoretical microseisms on land and operating a first order comparison with observations obtained from the digitized waveforms (e.g., Lecocq et al., 2020). This python code was tested and taught during the 2023 edition of the Munich Earth Skience School for dedicated to environmental seismology.

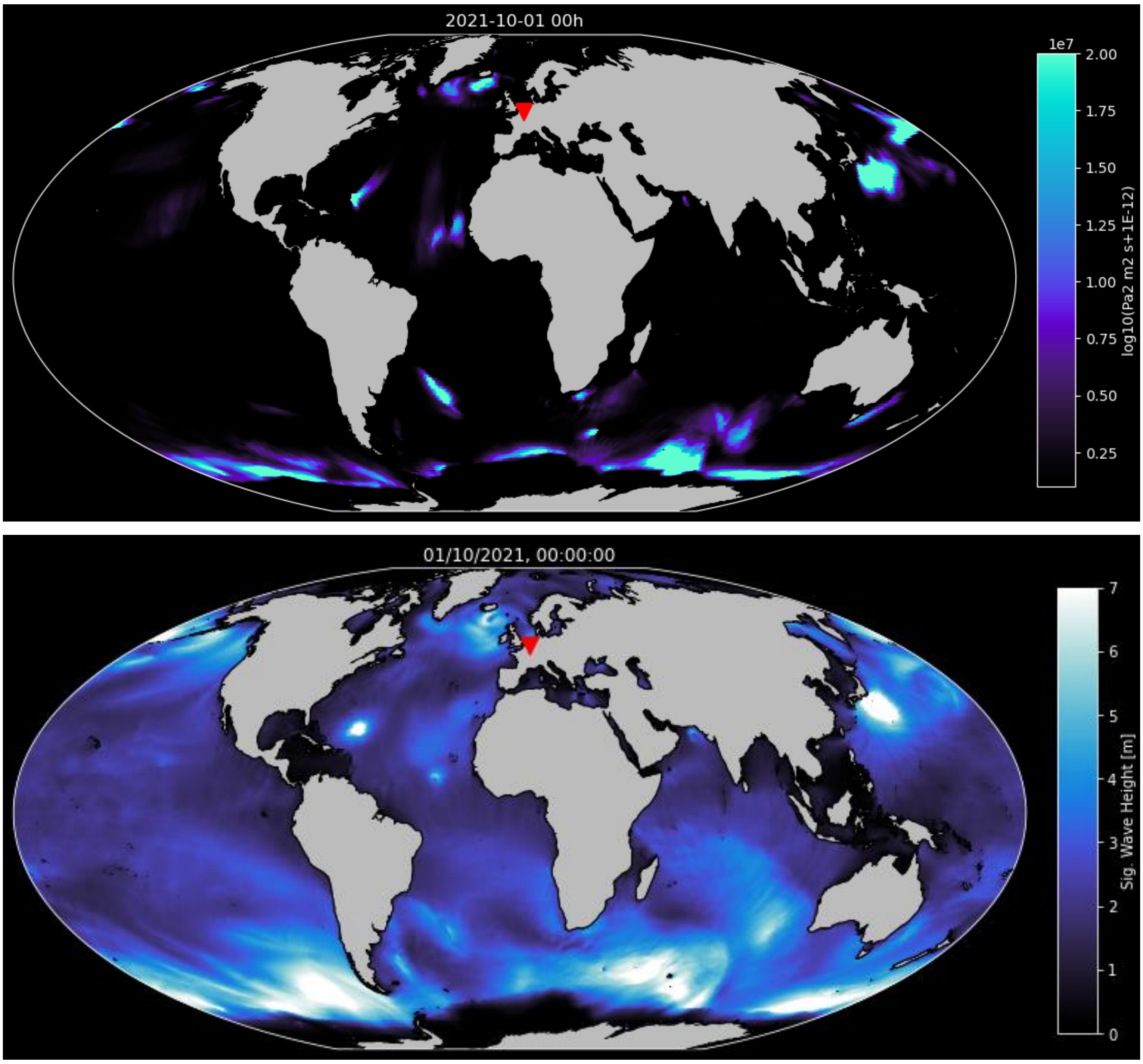

Figure 8. Microseismic noise sources (P2L) summed over all frequencies(top) and the significant wave height (bottom) of the ocean waves that generated them at the global scale, 0.5 degree resolution.

The applicability of the project’s output was successfully tested with observations from the Italian seismic network during periods of severe storms in the Mediterranean Sea, also known as Medicanes. This work was done during the 6-month long visit of the PhD student Marco Alfio Borzi and yielded several publications (Borzì et al., 2022; Borzì, Minio, De Plaen, Lecocq, Alparone, et al., 2024; Borzì, Minio, De Plaen, Lecocq, Cannavò, et al., 2024; Borzì, Minio, Plaen, et al., 2024). This validation also highlights the project's potential to extend beyond legacy seismic data and beyond the Royal Observatory of Belgium (ROB), encompassing a broader range of applications.

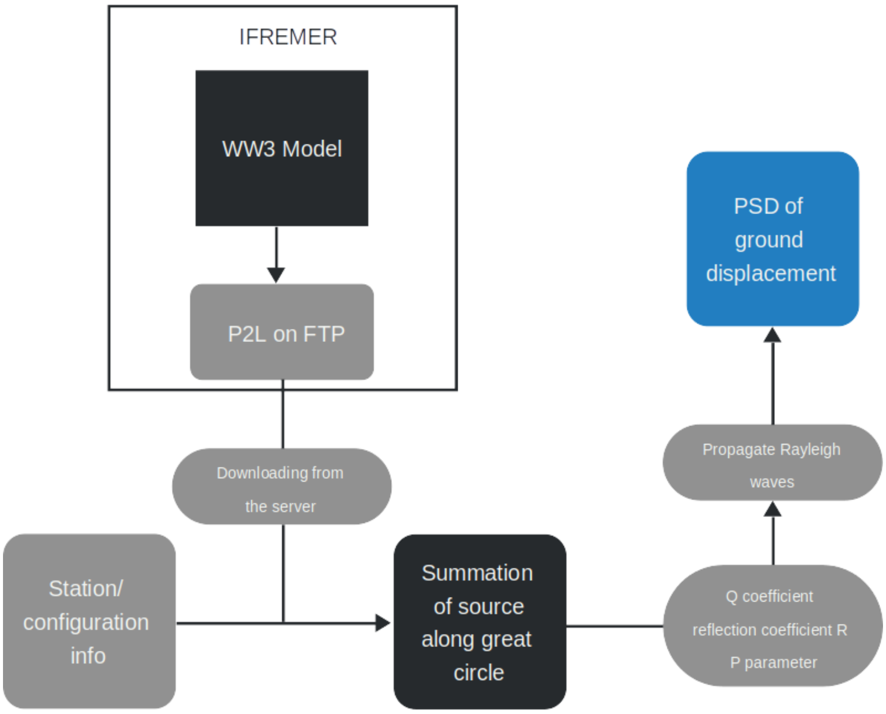

Figure 9. Workflow of the open-source companion tool to access microseism source models and calculate the theoretical microseismic ground motion for any seismic station in the world

WP5 - Time series availability through web services

The digitised time series were converted to MiniSEED using the Obspy (Krischer et al., 2015) python library and kept in their original sampling rate for archiving. Those raw files were also processed to create a coherent seismic archive at 20 Hz sampling rate, as this is necessary for serving them through web services. A development server was set up and configured to run JANE (https://github.com/krischer/jane), a python package designed to automatically index and serve MiniSEED data for configured stations. The server exposes standard FDSN web services (“station”, “dataselect”), allowing standard libraries to request and download the seismic data. This proof-of-concept server (currently available on http://jane.lisa.ulb.ovh/) shows that it is indeed to make the digitised time series FAIR.

WP6 - Outreach

The ROB worked on several outreach strategies, within the seismology community to the greater public. `A key outreach vector within the seismology community came through the integration of the ROB team within the European Seismological Commission’s Working Group (WG) on Legacy Seismograms (https://legacy-seismograms.eu/). Since the mission of the WG is directly in line with that of the SeismoStorm project, all the activities of the WG helped provide a greater visibility to the project. The Belgian leadership on legacy seismic data preservation and valorization has since been recognised by all members of the WG and beyond has it has helped update the inventory of legacy seismic data throughout Europe (Figure 9) with the opening of future international collaboration dedicated to the vectorisation of old seismograms. This leadership has triggered other collaboration initiatives, such as the creation of a Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) working group on legacy seismic data, further discussed below.

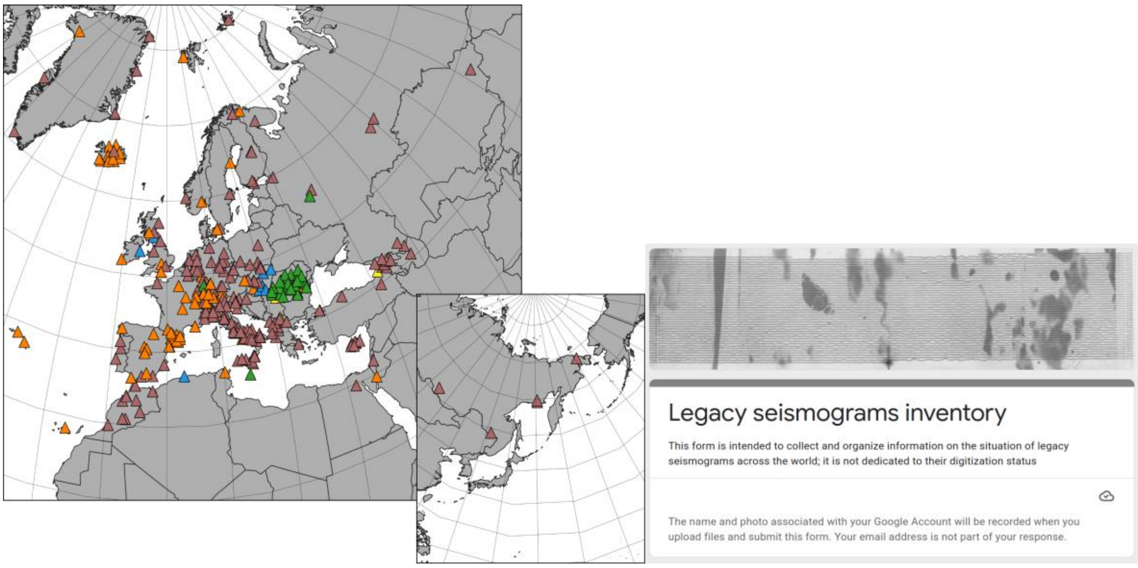

Figure 10. Maps of the compiled inventories of legacy seismic data compiled by the ESC WG on legacy seismic data (left), and welcome page of the ongoing census campaign (right).

Another outreach strategy within the seismology community was dedicated to training the new generation of researcher to analyse and compare the secondary microseism generated by oceanic storms in seismic measurement with WWIII simulations during the 2023 Skience winter school. Another training focussed on everything legacy seismic data has been plan for the IAGA-IASPEI joint meeting in Lisbon in 2025 (https://iaga-iaspei-lisboa-2025.isel.pt/).

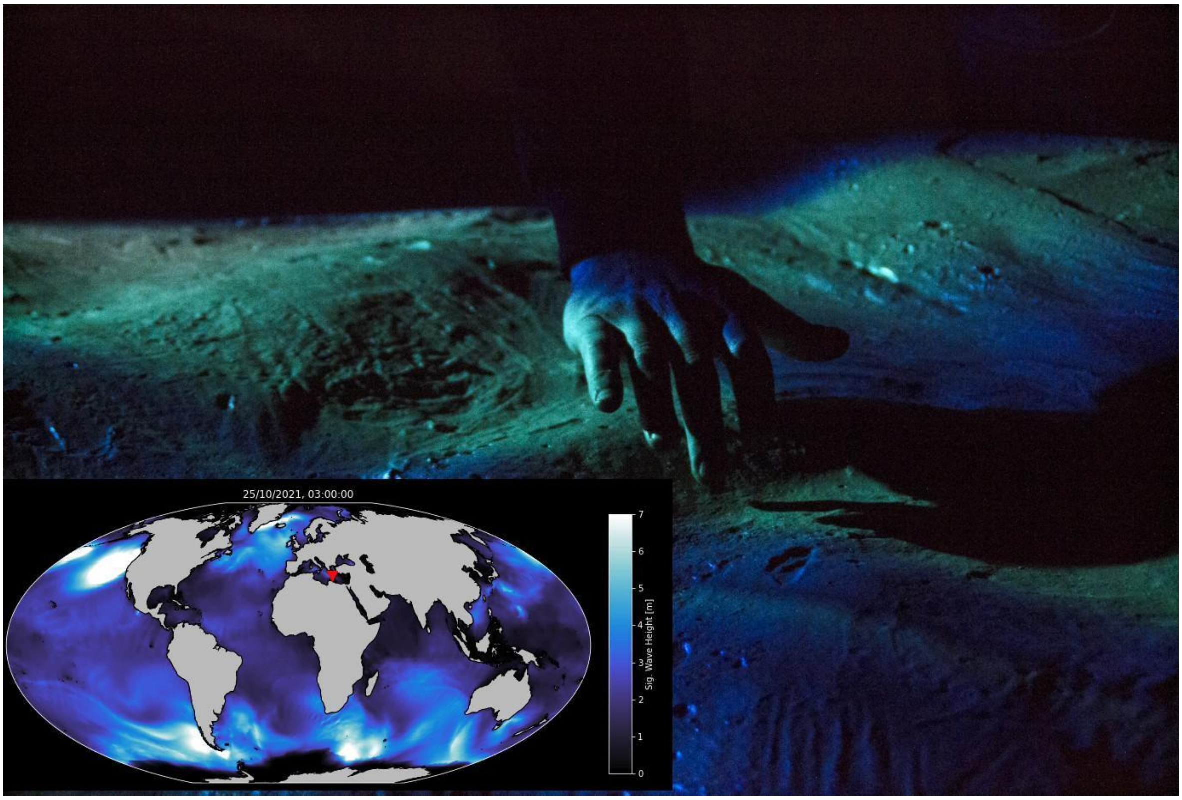

Figure 11. Art installation during the "Seas & Oceans" exhibition at Talc CEC, in Ixelles. The installation by Thiébaut Grivel illustrated the seismic energy generated by ocean waves over the sea floor.

Other public outreach initiatives included the participation to the exhibition "Seas & Oceans" at Talk CEC, Ixelles. The exhibition was dedicated to bringing together art and science on the theme of the ocean and nature. An art installation was created on the theme of the SeismoStorm project and Raphael De Plaen gave a presentation in the exhibition hall in May 2023.

Other outreach opportunities were also blended in more general outreach activities of the seismology – gravimetry service of the ROB, including in Schools, visits of observatory, planned or spontaneous, and TV interviews.

Recommendations and future prospects

The vectorisation algorithm is very advanced but is not yet ready to be disseminated externally as it requires further documentation and the further development of the integration of the traditional computer vision with the Deep Neural Networks module dedicated to inter-crossing lines. A master thesis in engineering in partnership with UCLouvain has been developed to that end with an official start in September 2024. The objective will be to have a version of the code ready to be distributed and tested by researchers outside of the ROB on their own data and documented in a way that facilitates the future maintenance and development of the code.

Modelling microseismic sources globally throughout the entire 20th century produces large P2L files, posing challenges for storage and access. As a short-term solution, these files are stored on the Hindcast ftp of IFREMER, alongside WaveWatch III products for the ocean and climate research community. However, given the size of these files and the potential traffic they may generate, an alternative storage solution tailored to the seismology community still needs to be developed for the future. The companion tool dedicated to the conversion and the comparison of those modelled microseismic sources to the observed ground motion for any station around the world has also been extensively developed and is openly accessible. However, recent collaborations of the ROB with Pierre Boué and Lisa Tomasetto for ISTerre, Grenoble, presented the opportunity to further consolidate the global impact of the SEISMOSTORM project on the seismology community. Because they work on Teleseismic P-wave sources in the secondary microseismic band using hindcasts from the same WaveWatch III oceanographic models (Tolman, 2014), the idea arose to combine the tools developed in both institutes into one that would reach and benefit a broader audience in the seismology community.

5. DISSEMINATION AND VALORISATION

Training

- 26 February - 3 March, 2023: Thomas Lecocq and Raphael De Plaen taught at the 13th Munich Earth **Skience** School focussed on Environmental seismology (https://www.skience.de/2023) in Sudelfeld, Germany, in February 2023 (Figure 12). A practical exercise related to the SeismoStorm project was taught and titled "From ocean noise to ground motion, and back!". The practical remains openly and freely available at https://github.com/heinerigel/skience2023/tree/main/04_Thursday/Afternoon.

Figure 12. Thomas Lecocq teaching at the 13th Munich Earth Skience School focussed on Environmental seismology in Sudelfeld, Germany.

Meetings, Commissions, working groups.

- 29 March 2022: Raphael De Plaen gave a presentation on « Monitoring oceanic storms using seismometers » at the **BELQUA** annual scientific workshop 2022, an annual workshop at the “Academy Palace” that aims to review ongoing Quaternary research in Belgium and abroad.
- 2022/03/14: The **SeismoStorm** project partners meeting gathered Thomas Lecocq, Raphael De Plaen, Olivier Debeir, Polina Lemenkova, Fabrice Ardhuin, and Céline Hadziioannou

- 2022/05/23–27: Raphael De Plaen attended the second SPIN Workshop (Monitoring a Restless Earth), in Carcans. He presented the SeismoStorm project and worked with Céline Hadziioannou
- 2022/06/13-16: Raphael De Plaen attended the 2022 Summer waves school **WAVEWATCHIII** organised by Fabrice Ardhuin in Brest, France (Figure 13). He presented the SeismoStorm project and worked with Fabrice Ardhuin and Mickael Accensi on the production microseismic ground motion models. Details on the summer school can be found here: https://gitlab.ifremer.fr/wave/Training/-/wikis/WW3-2022

Figure 13. Participants of the 2022 Summer waves school WAVEWATCHIII organised by IFREMER in Brest, France.

- 2022/09/06: Business meeting for the **ESC** working group 02-12 “Preservation, valorisation and analysis of seismological legacy data” at the Third European Conference on Earthquake Engineering and Seismology (**3ECEES**) in Bucharest, Romania. The meeting had 14 people in attendance and reviewed the activities of the working group since its creation: The creation of a website, the launch of a new census of legacy seismic data at a global scale and reaching a larger audience to increase its number of members in and outside of Europe. It was also decided to develop the draft of a manual of preservation for legacy seismic data.
- 2023/01/11: **SeismoStorm** project **follow-up meeting** in Uccle, Belgium. The Meeting had 9 people in attendance. The meeting reviewed the activities in SeismoStorm project over its first year, promoted scientific exchange between the participants and promoted constructive feedback on the project from the follow-up committee (Georges Jamart, Céline Hadziioannou, Josep Batlló, Frank Krueger, Eleonore Stutzmann, and Denis Haumont).
- 2023/06/8-9: **i-waveNET** workshop, Palermo, Sicily. Raphael gave a presentation online on the “Validation of microseisms from ocean models, and its implications for legacy seismic data valorisation”. i-waveNET is an Italian-Maltese Interreg project on the “Implementation of an innovative system for monitoring the state of the sea in climate change scenarios”. It used the

tools developed within the frame of the SeismoStorm to validate the seismic signal generated by medicanes, which are Mediterranean tropical-like cyclone.

- 2023/09/27-29: First Comprehensive Nuclear-Test-Ban Treaty Organization (**CTBTO**) Technical Meeting on Legacy Data from Nuclear Tests, Vienna, Austria (Figure 14). Raphael De Plaen Presented the missions of the ESC working group on the legacy seismic data and the contributions of the SeismoStorm project. The meeting was organised to bring together experts involved in recovering historical geophysics or radionuclide recordings and experts in the analysis of seismic data for nuclear explosion monitoring.

Figure 14. First Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) Technical Meeting on Legacy Data from Nuclear Tests, Vienna, Austria.

Assemblies, symposia, conferences and presentations

- 2022/04/20: Raphael De Plaen: “Preservation, valorisation and analysis of seismological legacy data” Invited talk presented at Seismological Society of America (**SSA)** Annual Meeting 2022 (online)
- 2022/05/23–27: Raphael De Plaen: “Monitoring oceanic storms using seismometers” presented at the second **SPIN** Workshop (Monitoring a Restless Earth), in Carcans.
- 2022/05/30: Raphael De Plaen: “Validation of Vectorized Analog Seismograms Using Microseismic Ground-Motion Models”. Invited talk presented at 28th **WISE** Meeting (online)

- 2022/06/13-16: Raphael De Plaen: "Validation of Vectorized Analog Seismograms Using Microseismic Ground-Motion Models". 2022 Summer waves school **WAVEWATCHIII**
- 2022/09/04-09: Raphael De Plaen: "Extracting Microseismic Ground Motion from Legacy Seismograms", and "A new census for legacy seismological data". Presented at **3ECEES**, Bucharest.
- 2023/04/17-20: Raphael De Plaen: "European Efforts for Legacy Seismograms Preservation and Use: The Esc WG on Seismological Legacy Data and the SeismoStorm Project". Presented at the **SSA** Annual Meeting 2023 in San Juan, Puerto Rico.
- 2023/12/11-15: Raphael De Plaen: "A peek into the past: Validation of oceanic models with legacy seismic data". Presented at the American Geophysical Union (**AGU**) annual Fall Meeting 2023 in San Francisco, United States of America.

Public outreach

- 2023/05/14 Raphael De Plaen gave a presentation on "Ocean waves and their relation to oceans dynamics", at **Talk CEC** (Figure 15). Talk CEC "**Seas & Oceans**": Raphael De Plaen collaborated with artist Thiébaut Grivel on an art installation about the seismic noise generated by Ocean waves. Exposed several months in 2023.

Figure 15. Presentation on the seismic signal of the oceans by Raphael De Plaen at the Talk CEC "Seas & Oceans" exhibition.

- 2023/11/08: A commemorative event was organised by the Royal Observatory of Belgium at the occasion of the 40 years of the 8 November **1983 Liège** earthquake. For this occasion, the seismograms from the earthquake were vectorised during the preceding summer and highlighted during the event. They will eventually also be used in the frame of the BELSHAKE project, which aims to build a solid base for earthquake ground-motion modelling in Belgium.

International collaborations

Organisations

- ESC Working Group 02-12 "Preservation, valorisation and analysis of seismological legacy data": The European Seismological Commission (ESC) is a regional branch of the International Association of Seismology and Physics of the Earth's Interior (IASPEI), dedicated to fostering seismological research and initiatives across Europe and Mediterranean nations. Within the Commission, Working Groups are established with specific objectives aimed at specific scientific challenges. The ESC Working Group 02-12 aims to promote collaboration and coordination in preserving, disseminating, and utilizing analog seismograms, as well as bulletins and associated documents (such as clock state books, station logs, and even instruments) produced during the analog era (from the inception of instrumental seismic recording until approximately the end of the 20th century). The working group is led by Josep Batlló and Thomas Lecocq, with Raphael De Plaen acting as its secretary. The organisers meet online one to two times a month and publish an activity report every year. Details about the working group's activities and its relationship with the SeismoStorm project can be found here: https://www.legacy-seismograms.eu/

- **IASPEI** WG on Legacy seismic data: In July 2023, during the Commission on Seismological Observation and Interpretation (CoSOI) meeting at the 28th IUGG General Assembly in Berlin, Germany. The decision to create a working group with a global scope beyond that of the ESC WG on legacy seismic data was taken. This WG is currently under the helm of Josep Batlló and Raphael De Plaen. The first key mission of the working group is the elaboration of a new chapter on the preservation and use of legacy seismic data for the next revision of the New Manual of Seismological Observatory Practice (**NMSOP**).

- **CTBTO** WG on Legacy Data from Nuclear Tests: during the technical meeting of September 2023, the creation of a working group dedicated to the legacy seismic data on nuclear test explosions was decided. Raphael De Plaen was voted as the point of contact for that community.

- Collaboration with the **State Archives of Belgium**: Through the inventory process of the SeismoStorm project, it was discovered that thousands of seismograms had been stored on microfilms while their paper version had been destroyed. Colleagues from the Belgian National Archives (Pierre-Alain Tallie, Annelies Coenen, Guillaume Lebbe) helped scanning a few of those 16mm microfilms to assess the resources required to scan the full inventory (Figure 16), and eventually the possibility to vectorize those scanned microfilms.

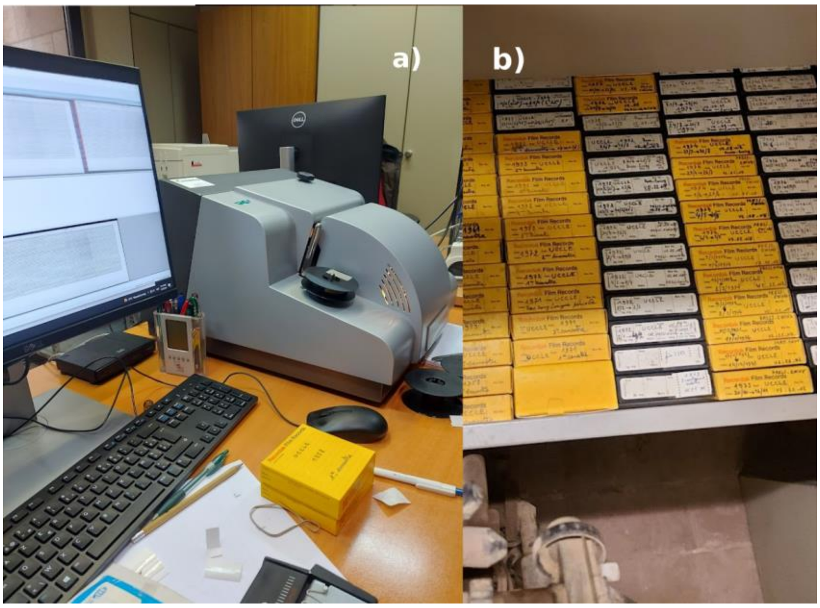

Figure 16. Digitization of the 16mm microfilms of seismograms from the ROB at the Belgian National Archive (a). A large portion of the analog seismic archive is currently preserved on that medium (b).

Individuals

- Thomas Lee: PhD student in seismology at Harvard University. He is part of the group working of the development of the DigitSeis software and is working on volcanic tremor and oceanic microseisms in the context of the digitization of analog records. Thomas Lee and Raphael De Plaen met at SSA 2023 and AGU 2023 to discuss common challenges and future collaborations. They also arranged the visit of Rick Aster at the Royal Observatory of Belgium in Fall 2024 work further work on the oceanic signal held in legacy seismic data.

- Taka'aki Taira: Research Seismologist at Berkeley University. Has been working to digitize the analog seismic data of the Berkeley Seismology Laboratory (BSL) and especially stations of interest for the analysis of the microseisms (BKS). Taka'aki Taira and Raphael De Plaen met at the CTBTO meeting in September 2023, and along with Thomas Lecocq at the AGU Fall meeting 2023 to plan future collaborations.

- Dan Burke: Research Engineer, Seismotectonics Laboratory, Department of Earth & Environmental Sciences of Michigan State University. He has been working on writing software for supporting legacy seismic data research, working on databases, and solving metadata issues, especially in challenging areas of the former USSR. Dan Burke and Raphael De Plaen met at the CTBTO meeting in September 2023 and discussed collaborating on the new NMSOP chapter on legacy seismic data, and the development of an open-source tool for instrumental correction of legacy seismograms.

- Marco Alfio Borzi: PhD student from the University of Catania. He visited the ROB for 6 months from January 2023 in the context of his PhD and the Italian i-waveNET project to train with tools developed within the SeismoStorm project. His visit resulted in several peer-review publications on the seismic signature of Medicanes.

- Yesim Cubuk; Postdoc in seismology at the Icelandic Meteorological Office. She visited the ROB on several occasions in the frame of the ISTREMOR project and benefited from the expertise and the tools developed within the frame of the SeismoStorm project. This resulted in several peer-reviewed publications.

- Pierre Boué and Lisa Tomasetto: Assistant professor and PhD student at the university of Grenoble, ISTerre. They work on the microseisms and the seismic signature of oceanic storms. They met with Raphael De Plaen during WaveWatch III summer school and AGU Fall meeting 2023 to discuss collaborating on the python package that brings together oceanic microseism models and observation for comparisons, validations and iterative simulations.

6. PUBLICATIONS

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Borzì, A. M., Minio, V., De Plaen, R., Lecocq, T., Cannavò, F., Ciraolo, G., D'Amico, S., Re, C. L., Monaco, C., Picone, M., Scardino, G., Scicchitano, G., & Cannata, A. (2024). Long-term analysis of microseism during extreme weather events: Medicanes and common storms in the Mediterranean Sea. *Science of The Total Environment*, *915*, 169989. https://doi.org/10.1016/j.scitotenv.2024.169989

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7. ACKNOWLEDGEMENTS

This project was made possible thanks to the support of the Brain-BE program of the Belgian Science Policy Office. We are grateful to all the ROB colleagues from the Seismology - Gravimetry service, especially Fabienne and all who assisted with moving and inventorying the archive, and Thierry Camelbeeck for its extensive knowledge of the history of seismic instruments in Belgium. We appreciate the numerous students who scanned paper seismograms across several summers, as well as the National Archives for their help in testing microfilm scanning. We are also grateful to the members of the ESC Working Group on Legacy Seismograms, especially Josep Batlló, and the SSA Legacy Data Working Group, particularly Lorraine Hwang and Allison Bent, for their collaboration and contributions to our shared objectives. Special thanks to the members of the follow-up committee for their support and recommendations.

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