Extracting Microseismic Ground Motion From Legacy Seismograms

De Plaen Raphael - Seismology-Gravimetry, Royal Observatory of Belgium, Brussels, Belgium, raphael.deplaen@gmail.com

Lecocq Thomas - Seismology-Gravimetry, Royal Observatory of Belgium, Brussels, Belgium, thomas.lecocq@seismology.be

Polina Lemenkova - Université Libre de Bruxelles, Brussels Faculty of Engineering, Laboratory of Image Synthesis and Analysis, Brussels, Belgium, polina.lemenkova@ulb.be

Olivier Debeir - Université Libre de Bruxelles, Brussels Faculty of Engineering, Laboratory of Image Synthesis and Analysis, Brussels, Belgium, olivier.debeir@ulb.be

Fabrice Ardhuin - Laboratoire d'Océanographie Spatiale, Institut Francais de Recherche pour l'Exploitation de la Mer, Plouzané, France, fabrice.ardhuin@ifremer.fr

Marine De Carlo - Laboratoire d'Océanographie Spatiale, Institut Francais de Recherche pour l'Exploitation de la Mer, Plouzané, France, marine.de.carlo@ifremer.fr

Abstract

Before digital recordings became available in the 1970s, the ground motion was recorded using ink on white paper, scratching black-smoked paper, or light on photographic paper. While those analog seismic records offer unique continuous observations from the last century, most of them are now stacked and archived in boxes and potentially exposed to physical decay and permanent loss. To preserve those records and ultimately subject them to modern methods of analysis, it is time-sensitive to scan and digitize them. Here, we worked on a method for automatic digitization of paper seismograms using image processing and machine learning to extract microseismic ground-motion periods and amplitudes. We implemented the method on legacy data recorded at the Royal Observatory of Belgium to extract power spectral densities for major storms during the last century, which are compared with modeled microseisms levels computed using a numerical ocean wave model. This further shows how digitizing analog seismograms does not only preserve the scientific legacy but also makes new research possible by bringing analog data to the digital age.

Keywords: analog seismograms; seismic noise; oceanic storms; digitalization; machine learning; oceanic climate

1. Introduction

The Royal Observatory of Belgium (ROB) has been operating seismic stations since the late 19th century with the first instrument, a von Rebeur-Ehlert triple horizontal pendulum built by Bosch, installed in Uccle at the end of 1898. Throughout the 20th century, other analog instruments were installed at the observatory and recorded ground motion on smoke paper, photographic paper, and magnetic tapes. The ROB eventually transitioned towards the digital age following the MS4,7 Liège earthquake of 1983 (Van Camp and Camelbeeck, 2004). Since then, the legacy seismograms that resulted from a century of investment in seismology at the ROB were stacked and stored to be preserved from physical decay (Figure 1), awaiting future use. Those historical instruments were designed to specifically record ground motion caused by earthquakes, but they recorded a broad range of other signals. The unwanted signals then labeled "seismic noise", are dominated by faint long-continuing background oscillation of the ground caused by water waves in the oceans, the microseisms.

While the oceans were passively recorded by seismometers on the land throughout the last century, global measurements of oceanic storms did not become were lacking until satellites measurements became ubiquitous in 1993. This creates a remarkable opportunity to digitize valorize the corpus of legacy seismograms at and beyond the ROB, not only for the purpose of preservation but also to improve our general knowledge of the ocean wave climate during the last century using quantitative observation extracted from seismic data (Lecocq et al., 2020).

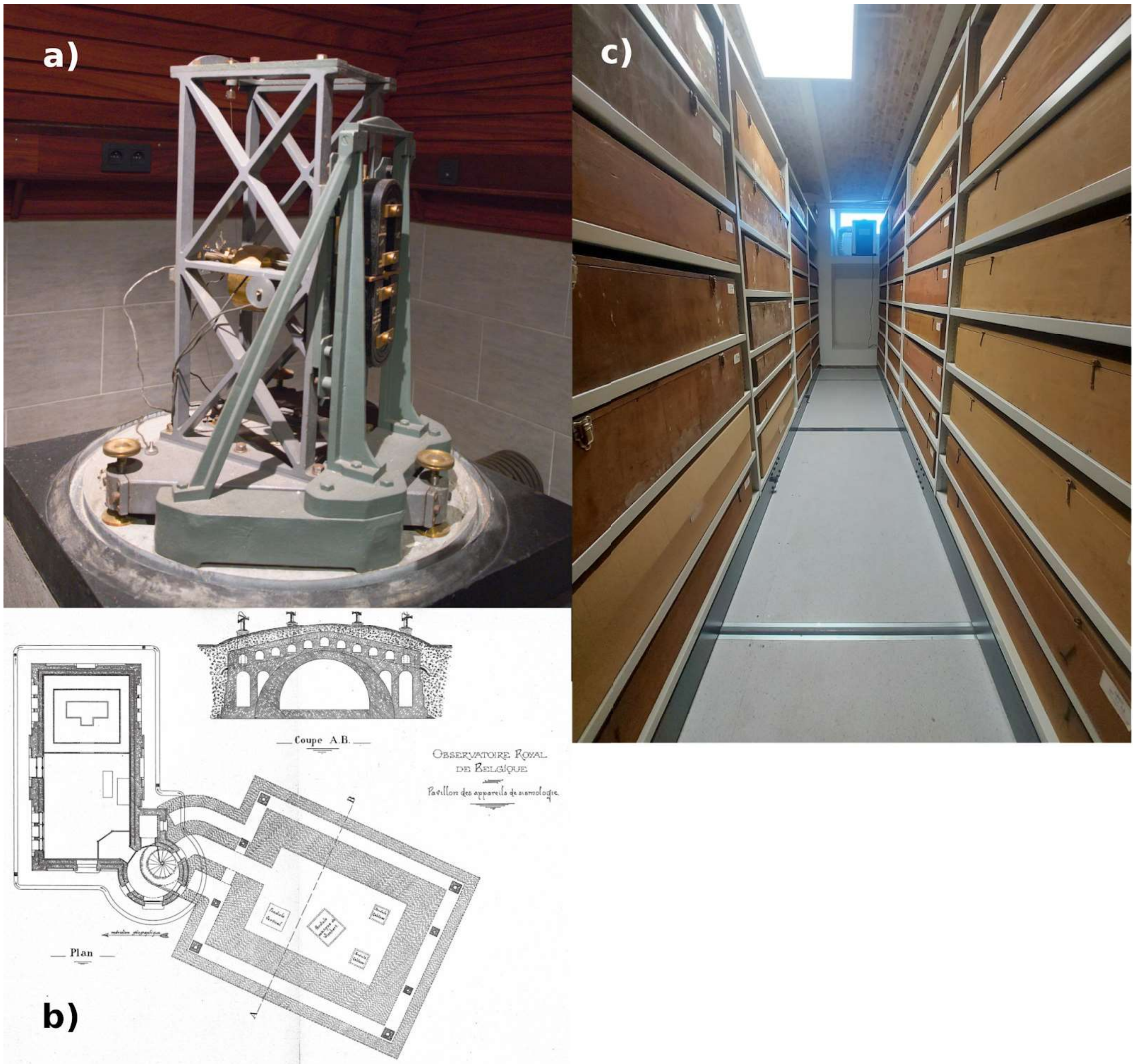

Figure 1. a) The horizontal component Galitzin seismometer. b) Plan of the UCC seismic station "le Pavillon" that was built in 1908 on the site of the ROB. c) Archive storage of the legacy seismograms of the ROB.

2. Digitization of analog seismograms

The ROB operated several instruments in the last century, recording on different analog support. The Galitzin (horizontal) and Galitzin-Wilip-Somville (vertical) seismometers of the station UCC (Figure 1) provided the best starting point for this project as their recordings on photographic paper were the cleanest (Figure 2), and the horizontal and vertical components had their maximum sensitivity in the primary and secondary microseisms, respectively. Indeed, Galitzin seismometers used a galvanometric system to direct a beam of light onto photographic paper which generally offered greater contrast between the trace and the background than the scratches on smoked paper. The scanned seismograms are digitized using Cytomine, an open-source image processing tool originally developed for the biomedical field (Figure 3). The cleanest wiggles can be vectorized and time-coded using computer vision processing. More complex cases such as intercrossing lines or heavily stained paper are addressed using machine learning techniques to optimize the vectorized waveforms. The resulting time series are coveted to ground motion using the amplitude-frequency instrument responses determined from the metadata compiled in the official monthly bulletins of the ROB. The final times series are then validated by comparing their amplitude spectra with that of models of the microseism.

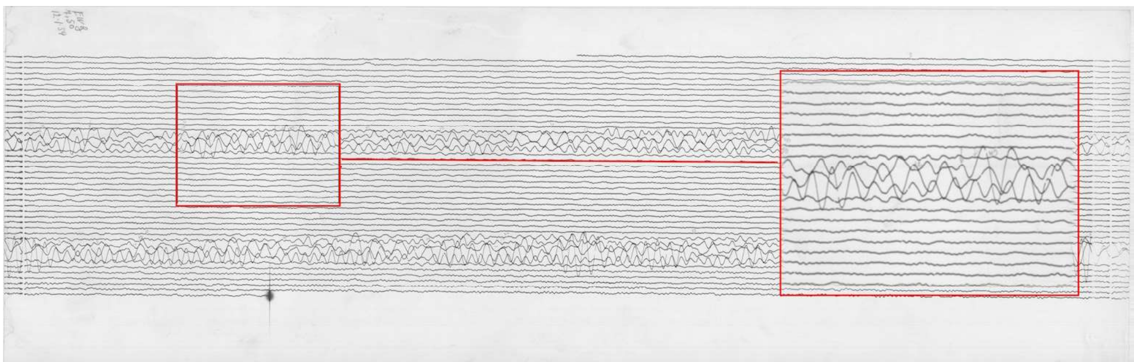

Figure 2. Recording on photographic paper by the horizontal N-S component Galitzin seismometer of the UCC station for 9 February 1954. The relatively clean line justified using those seismograms as a starting point, especially when developing an approach to deal with intercrossing lines.

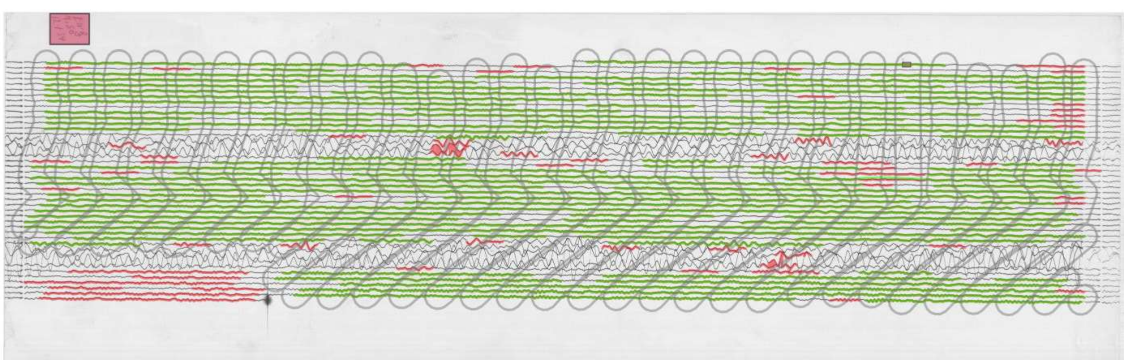

Figure 3. Visualization and initial annotation (the position of the first-hour segment) are achieved using Cytomine (Marée et al. 2016), a web-based interface for big images originally developed for the biomedical field. The classical computer vision (coded in python) approach manages to accurately retrieve and time-code the cleanest traces (in green), the most complex traces, such as the intercrossing lines, will require an improved machine learning-based approach. A change in speed of the acquisition can be clearly observed, following a first high amplitude event.

3. Microseism modeling

The microseism models used are a combination of numerical wave models processed using WAVEWATCH III (Tolman, 2009) and a transformation of wave spectra into microseisms

(Ardhuin et al., 2011; Rascle and Ardhuin, 2013). The wave models are forced by winds from the European Centre for Medium-Range Weather Forecasts' twentieth-century reanalysis (Poli et al., 2016), and previous work established that the Uccle station is sensitive to oceanic storms in the deep waters off the British Isles, the Norwegian coast, south of Iceland along the mid-Atlantic ridge, and the northwestern Mediterranean Sea (Lecocq et al., 2020).

4. Validation of the digitized waveforms

The validation of the time series is achieved by using the modeled microseisms associated with strong oceanic storms that occurred in the operating period of the instrument (Figure 4). The selection of storms used for this step is based on attenuation and ocean-solid earth coupling, which defines the largest sensitivity of the UCC station in the first 1000 km around it and is sensitive to strong sources up to 2000 km. The comparison of the spectra of the digitized waveforms with the modeled ground motion is expected to be similar, with differences that could likely be associated with uncertainties in the calibration parameters of the instruments. In the case of an error in the amplification factor, we expect to observe a scalar multiplication factor between observed and modeled time series.

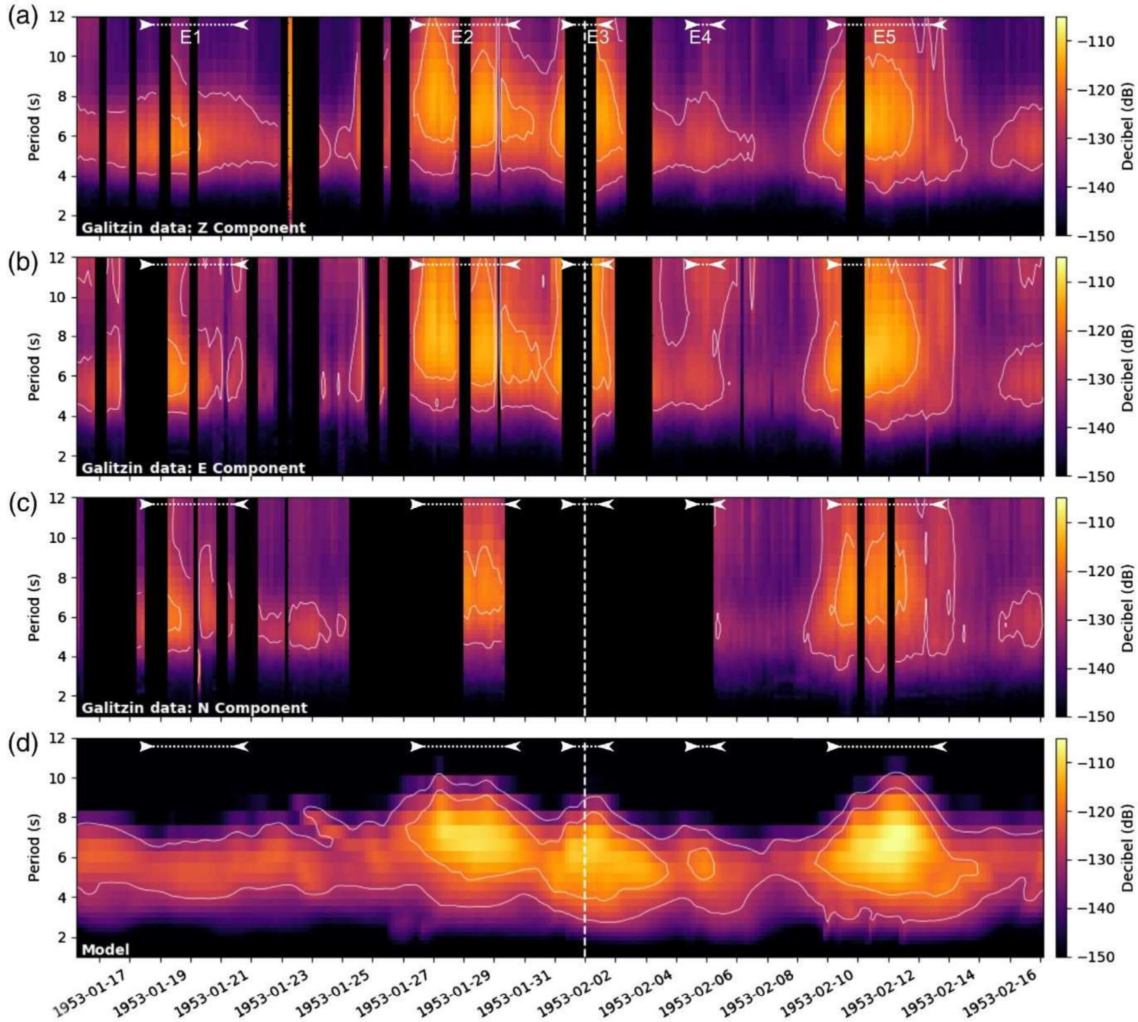

Figure 4. Displacement power spectral density spectrograms of the microseismic activity between 15 January–15 February 1953 for the (a) vertical, (b) east-west, (c) north-south components, and (d) the corresponding modeled microseism at station UCC. The thick dashed white line indicates "Big Flood". From Lecocq et al. (2020).

6. Future perspectives

This project builds upon pilot research that demonstrated its feasibility by focussing on the period around the February 1953 "Big Flood", a storm surge that affected the region and was recorded by Galitzin seismometers. The digitization tools developed within this project should later be applied to other analog seismograms such as the Weichert that were recorded on smoked paper, although they expect to suffer from less contrast between the trace and the background. The tools developed in this work should also be implemented at other locations with significant archives of legacy seismic data.

7. Conclusions

Legacy seismic data are in a time-critical need of being digitized for preservation before they are permanently lost, but our work also shows their scientific potential goes beyond their historical value. Our new methods for digitizing the analog paper seismogram collection will impact the scientific exploitation of the rich information that is stored in the untapped continuous data.

Bringing these datasets to the digital age opens the door to modern seismic applications for the entire 20th century and specifically the extraction of quantitative observational data on oceanic storms that are only contained in seismograms.

Acknowledgments

This research is part of the SEISMOSTORM project funded by the BELSPO program BRAIN-be 2.0. We are grateful to Thierry Camelbeek and Fabienne Collin who played a key role in maintaining and organizing the ROB archive of legacy seismic data. We also acknowledge useful discussions with Céline Hadziioannou and Josep Batlló.

References

- Ardhuin, F., Stutzmann, E., Schimmel, M., and Mangeney, A.: Ocean wave sources of seismic noise, J. Geophys. Res. Oceans, 116, https://doi.org/10.1029/2011JC006952, 2011.
- Lecocq, T., Ardhuin, F., Collin, F., and Camelbeeck, T.: On the extraction of microseismic ground motion from analog seismograms for the validation of ocean-climate models, Seismol. Res. Lett., 91, 1518–1530, https://doi.org/10.1785/0220190276, 2020.
- Raphaël Marée, Loïc Rollus, Benjamin Stévens, Renaud Hoyoux, Gilles Louppe, Rémy Vandaele, Jean-Michel Begon, Philipp Kainz, Pierre Geurts and Louis Wehenkel. Collaborative analysis of multi-gigapixel imaging data using Cytomine, Bioinformatics, DOI: 10.1093/bioinformatics/btw013, 2016. http://dx.doi.org/10.1093/bioinformatics/btw013
- Poli, P., Hersbach, H., Dee, D. P., Berrisford, P., Simmons, A. J., Vitart, F., Laloyaux, P., Tan, D. G. H., Peubey, C., Thépaut, J. N., Trémolet, Y., Hólm, E. V., Bonavita, M., Isaksen, L., and Fisher, M.: ERA-20C: An atmospheric reanalysis of the twentieth century, J. Clim., 29, 4083–4097, https://doi.org/10.1175/JCLI-D-15-0556.1, 2016.
- Rascle, N. and Ardhuin, F.: A global wave parameter database for geophysical applications. Part 2: Model validation with improved source term parameterization, Ocean Model., 70, 174–188, https://doi.org/10.1016/j.ocemod.2012.12.001, 2013.
- Tolman, H. L.: User manual and system documentation of WAVEWATCH III TM version 3.14, Tech. Note MMAB Contrib., 276, 2009.
- Van Camp, M. and Camelbeeck, T.: Histoire des stations sismiques belges: de la station «Solvay» au réseau national de surveillance sismique, Ciel Terre, 120, 162--176, 2004.