Lopez Comino, J., Heimann, S., Cesca, S., Milkereit, C., Dahm, T., Zang, A. (2017): Automated Full Waveform Detection and Location Algorithm of Acoustic Emissions from Hydraulic Fracturing Experiment. - *Procedia Engineering*, *191*, pp. 697—702.

DOI: http://doi.org/10.1016/j.proeng.2017.05.234

Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 191 (2017) 697 – 702

Procedia Engineering

www.elsevier.com/locate/procedia

Symposium of the International Society for Rock Mechanics

Automated Full Waveform Detection and Location Algorithm of Acoustic Emissions from Hydraulic Fracturing Experiment

José Ángel López Comino*, Sebastian Heimann, Simone Cesca, Claus Milkereit,
Torsten Dahm, Arno Zang

GFZ German Research Centre for Geosciences, Telegrafenberg, D-14473 Potsdam, Germany

---

Abstract

A near field network with 11 acoustic emission (AE) sensors was installed for the in situ underground experiment (Nova project 54-14-1) that took place 410 m below surface in the Äspö Hard Rock Laboratory, Sweden. The acquisition system for the piezo-electrical sensors has been improved to record signals with 1 MHz sampling rate, to detect signals produced by weaker sources and enhance the microseismic catalogue. The acquisition system was capable to operate in trigger and continuous mode. The basic idea of the experiment was to compare hydraulic fracturing growth and induced seismicity under controlled conditions for different loading scenarios as conventional versus progressive, and pulse-like water injections. In this work, we consider continuous recordings and apply recently developed automated full waveform detection and location algorithms which are based on the stacking of characteristic functions calculated from squared amplitudes. Waveform stacking and coherence techniques are adapted to detect and locate AE signals for massive datasets with extremely high sampling. We significantly increase the detection rate in comparison to trigger mode routines. Most detection concentrated during the fluid injection occurred around the fracking stages. Frequency-magnitude distribution characteristics are investigated using a relative magnitude scale estimated from the amplitude recorded at AE sensors. We demonstrate that the stacking of characteristic functions yields to a significant improvement of the detection and location also in presence of noisy records, supporting the adoption of similar techniques for other induced and natural seismic activity monitoring systems.

Peer-review under responsibility of the organizing committee of EUROCK 2017

Keywords: Hydraulic fracturing, induced seismicity, acoustic emission, full waveform detection, detection performance

---

* Corresponding author. Tel.: +49-331-288-1325; fax: +49-331-288-1127.
E-mail address: jalopez@gfz-potsdam.de

Peer-review under responsibility of the organizing committee of EUROCK 2017
doi:10.1016/j.proeng.2017.05.234

1. Introduction

An in situ hydraulic fracturing experiment was performed at Äspö Hard Rock Laboratory (Sweden) aiming at optimizing geothermal heat exchange in crystalline rock mass [1]. A near field network with 11 acoustic emission (AE) sensors was installed 410 m below surface to map the seismic response of hydraulic fractures for different fluid injection scenarios (Figure 1). The location of the experimental tunnel TASN is seen from which four long boreholes were drilled sub-parallel to orientation of minimum horizontal compressive stress. The middle borehole (Figure 1, blue line) serves as hydraulic testing borehole and was drilled to a total length of 28.40 meter, down dipping -4°. The rest of monitoring boreholes were drilled with inclination upwards to allow water outflow from AE sensor chains. This geometry in the predetermined stress state allows propagating hydraulic fractures perpendicular to the hydraulic testing borehole, in the direction of maximum horizontal compressive stress, and in a direction towards the monitoring boreholes.

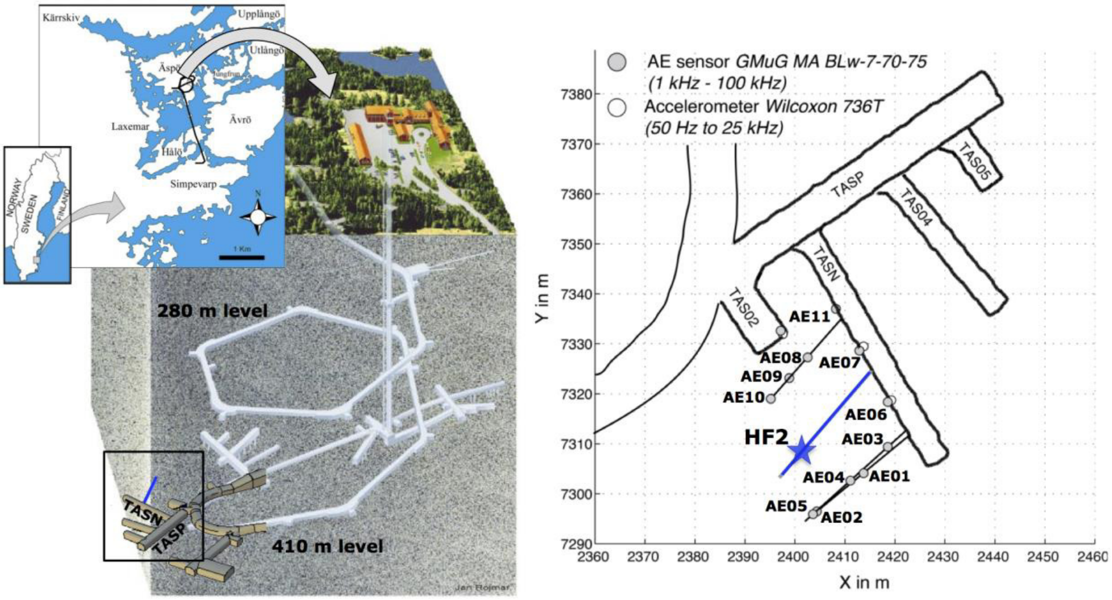

Fig. 1. Test site for hydraulic fracturing in an experimental tunnel of Äspö Hard Rock Laboratory, Sweden (left). [elaborated after http://www.skb.se/upload/publications/pdf/Aspo_Laboratory.pdf]. Sensors are employed in the near-field (right): a blue line indicates the hydraulic testing borehole, the blue star identifies the fluid injection segment corresponding to the HF2 experiment.

The basic idea of the experiment was to compare hydraulic fracturing growth and induced seismicity under controlled conditions in a horizontal borehole 30 meter long for continuous fluid injection versus progressive fluid injection, and dynamic pulse hydraulic fracturing [1]. The in-situ AE monitoring network consists of eleven AE sensors (GMuG MA BLw-7-70-75) and four accelerometers (Wilcoxon 736T). AE sensors employed are uniaxial side-view sensors for borehole installation, developed by GMuG for sensitive recording in the frequency range 1 kHz to 100 kHz and capable to monitor fractures from centimeter to meter scale. Sampling rates were extended to 1 MHz and all sensors are installed inside boreholes. Eight AE sensors are installed in long monitoring boreholes, surrounding the fracturing borehole. The remaining sensors are installed in short boreholes near the tunnel roof. Data was recorded using the measuring system GMuG AE-System that is suitable both for continuous recording of data and recording in trigger mode. In this work, we present the results obtained during the conventional, continuous water-injection experiment HF2 (Hydraulic Fracture 2) in Ävrö granodiorite, and discuss the detection performance using a recently developed automated full waveform detection algorithm.

2. Automated full waveform detection

We consider continuous recordings and apply a recently developed automated full waveform detection and location algorithms (Lassie [2]). Lassie has been extended for this specific dataset to analyze extremely high sampled data (1 MHz). Lassie is a python-based earthquake detector, which relies on the stacking of characteristic functions. It follows a delay-and-stack approach, where the likelihood of the hypocentral location in a chosen seismogenic volume is mapped by assessing the coherence of arrival times at different stations (see [3] for an overview). However, in the Lassie implementation, the adoption of smooth characteristic function calculated from normalized amplitude envelopes allows to reduce the spatial and temporal sampling. This improves the computational performance of the algorithm and allows its application to high-sampling data as a detector. The outstanding computational performance and smooth imaging of the coherence function are achieved at the cost of a larger location uncertainties which accuracy can still be improved upon each event detection by applying different characteristic functions [4, 5].

Preliminary locations are found for each detected event according the maximum value of coherence and the travel-time stacking corrected with P and S-wave velocities. We have considered a homogeneous full space model where the velocities for both P- and S-waves were obtained from active ultrasonic transmission tests (v_p= 5810 ± 120 m/s and v_s = 3400 ± 200 m/s). The waveform signature of most noise events differ clearly from seismic events, however, a visual inspection of seismic waveforms reveals different kinds of detected signals that we have classified as: acoustic emission (AE) detections (Figure 2), false detections, electronic noise, anthropogenic noise, long period noise and other signals (Table 1 and Figure 3).

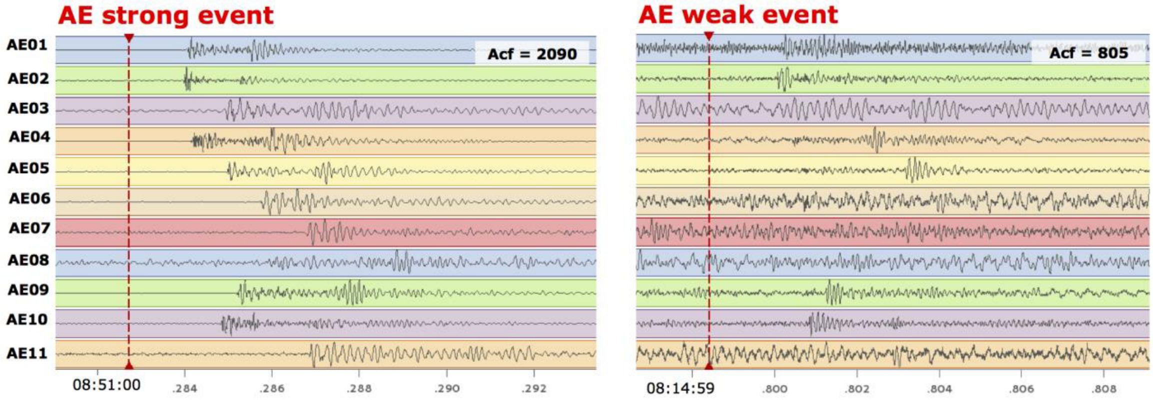

Fig. 2. Typical waveform of seismic Acoustic Emission (AE) events detected by the Lassie algorithm [2] during HF2, showing timing and amplitude of the characteristic function (Acf). Waveforms are band-pass filtered in the frequency range 3 – 70 kHz. The time (ms) is shown on the x-axis and the reference time is displayed in the lower left corner of each box.

Table 1. Class and number of detected events in the Hydraulic Fracture 2 (HF2) experiment.

Class of detected events	Number of detections
Acoustic emissions detections	4179
False detections	4158
Electronic noise	18894
Long period noise	361
Anthropogenic noise	58
Other signals	215

3. Detection performance

The detection rate results highly discontinuous, with the highest AE detection rates well corresponding to all fluid injection stages (Figure 3). Three AE events are detected during the packer inflation before the initiation of HF2. A rapid microseismicity increase is experimented when the constant injection rate is applied, afterwards, a rapid decrease is observed corresponding with few and isolated events. The number of AE events is accounted for the different stages of HF2 (table 2), being the Refrac 1 and 5 where the microseismicity is larger. Note that the continuous AE recording was not in operation during the whole experiment Refrac 2 and finished prematurely. This explains the detection of only 4 events during this stage.

Table 2. Number of acoustic emissions events during the different stages for the Hydraulic Fracture 2 (HF2) experiment.

Experiment - HF2	Number of AE events
Pulse Test	3
Frac	690
Refrac 1	1325
Refrac 2	4
Refrac 3	551
Refrac 4	595
Refrac 5	990

A low detector threshold is chosen, in order not to loose weaker events and reach a complete catalogue. However, the small threshold also increases the number of false detections requiring an accurate classification. The dataset has been revised manually, and detected events classified in terms of real AE events, electronic noise, anthropogenic noise, long period noise and other signals. The waveform signatures of most noise events differ clearly from seismic events and were identified using recording in trigger mode for (near) real time assessment (see noise examples in [6]). Electronic noise is found temporally associated with the fluid injection stages. Its occurrence hinders the search of real events. These signals share the same arrivals in all traces and similar frequency content and duration. Classification algorithms matching waveform or spectral patterns may be used for future analysis, but are not considered here. However, noise events generated by people working near the network are difficult to identify because they display a transient character like seismic events, especially when they were generated by (hammer) blows to the rock wall or dropping tools. A careful visual inspection is required to consider these aspects. Long period noise corresponds with harmonic signals originates inside the monitoring borehole and is presumably due to the irregular water inflow. We found other signals that can not fit in the previous families and do not share similar characteristics to establish other possible families. Most of them are detected after the well is shut-in and could also be caused by human factors. However, some of them are observed during the constant injection rate is applied, in that case, they may indicate overlap of electronic noise and possible real events, which hinders a safe classification. Excluding the AE signals and electronic noise, for the remaining types of signals the amplitude of the characteristic function are usually low, so that these events can be easily removed by increasing the detection threshold (e.g. to an amplitude of characteristic function value of 750, as shown in Figure 3).

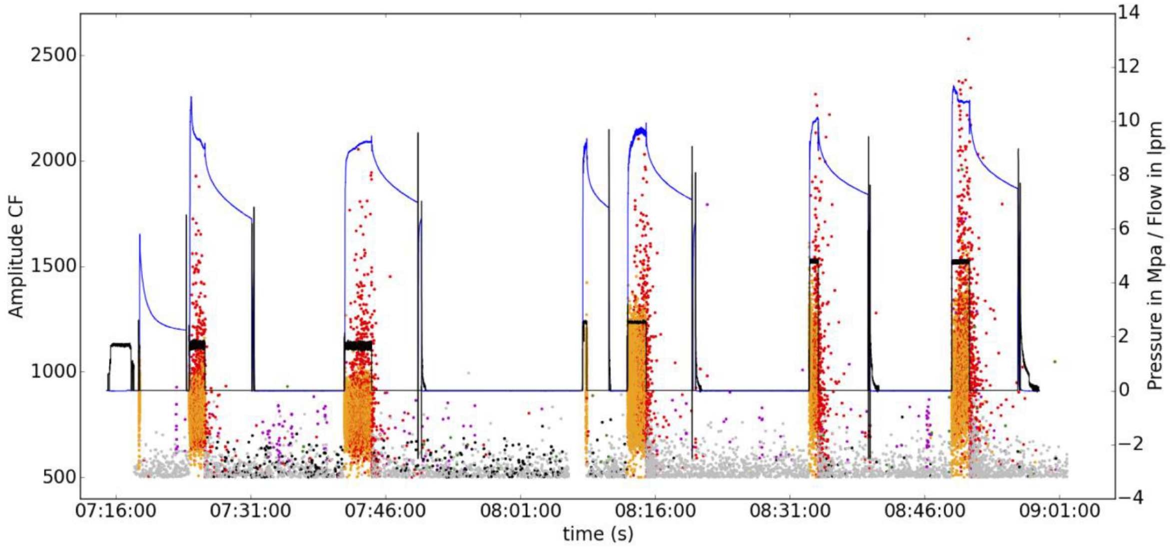

Fig. 3. Acoustic emission detections (red dots) using continuous recordings and other kinds of detected signals from a visual inspection that do not correspond with seismic events: false detections (gray dots), electronic noise (orange dots), anthropogenic noise (green dots), long period noise (black dots) and other signals (magenta dots). Amplitude of the characteristic function (left ordinate) calculated from Lassie detector, injection pressure (black line) and flow rate (blue line) for hydraulic fractures (right ordinate) in the experiment HF2 are shown. Different stages for HF2 are indicated using gray background (PT: Pulse test; F: Frac; RF1 - RF5: Refrac 1 - Refrac 5).

4. Conclusions

Based on the analysis of acoustic emission events from continuous recording in an underground experiment with hydraulic fracture growth in naturally fractured crystalline rock, we draw the following conclusions:

- We adapted and successfully used for the first time a full-waveform based detector, which relies on the location-based stacking of smooth characteristic functions to detect AE signals for massive datasets with large number of sensors and/or extremely high sampling (here 1 MHz). Using continuous waveforms we are able to identify a large number of events, even in presence of microseismicity bursts, when multiple events occur close in space and time. Moreover, our approach is based on the detection of coherent increased in waveform amplitude at multiple sensors, being able to detect events even in presence of noisy data. At this respect it should be noted that a triggered based approach [1] was able to detect 102 events in the same dataset, whereas our catalogue is finally composed of 4158 events. The better detection performance leads to a relevant increment of the catalogue size, implying a decrease of the magnitude of completeness, Our results extend the adoption of similar detection techniques, successfully applied for monitoring induced and natural seismic activity at local and regional distances [7,8], also to small-scale applications and for hydraulic fracturing.
- The detection threshold is the most relevant parameter which influences the detection performance of the used algorithm. A low threshold allows the detection of weak events at the cost of a higher number of false detection and noise signals of different types. In this sense, it is desirable that the detection setup can be combined with a classification algorithm (here we showed results of a visual classification) to distinguish true and false events, and classify different signals in an automatic manner. The inspection of the temporal evolution of signal detection reveals that 85% of AEs take place during the phases of increased flow rate and increasing pressure, dropping very quickly in time as soon as the pressure decrease and the flow stopped. In the time periods between each fracture and refrature operations, very few and weak events are detected.

Acknowledgements

This work is funded by the EU H2020 SHEER project (www.sheerproject.eu). Nova project 54-14-1 was financially supported by the GFZ German Research Center for Geosciences (75%), the KIT Karlsruhe Institute of Technology (15%) and the Nova Center for University Studies, Research and Development (10%). An additional in-kind contribution of SKB for using Äspö Hard Rock Laboratory as test site for geothermal research is greatly acknowledged.

References

[1] A. Zang, O. Stephansson, L. Stenberg, K. Plenkers, C. Milkereit, G. Kwiatek, G. Dresen, E. Schill, G. Zimmermann, T. Dahm, M. Weber, Hydraulic fracture monitoring in crystalline rock mass at 410 m depth using an advanced fluid-injection protocol and extensive sensor array, Geophys. J. Int. 208(2) (2017) 790–813.

[2] S. Heimann, C. Matos, S. Cesca, I. Rio, S. Custodio, Lassie: A versatile tool to detect and locate seismic activity, Seismological Research Letters, in preparation. Note: interested users to preview Lassie can write to: sebastian.heimann@gfz-potsdam.de, 2016.

[3] Cesca, S. and F. Grigoli (2015). Chapter Two – Full Waveform Seismological Advances for Microseismic Monitoring. - Advances in Geophysics, 56, p. 169–228.

[4] F. Grigoli, S. Cesca, M. Vassallo, T. Dahm, Automated seismic event location by traveltime stacking: An application to mining induced seismicity, Seismol. Res. Lett. 84 (4) (2013) 666–677.

[5] F. Grigoli, S. Cesca, O. Amoroso, A. Emolo, A. Zollo, T. Dahm, Automated seismic event location by waveform coherence analysis, Geophys. J. Int. 196 (3) (2014) 1742–1753.

[6] Plenkers, K. and T. Fischer, Field report: GMuG Acoustic emissions monitoring in FHF experiment, Äspö underground laboratory, Oscarshamn, Sweden, 29 May to 22 June, 2015.

[7] Matos, C., S.,Heimann, F. Grigoli, S. Cesca and S. Custódio, Seismicity of a slow deforming environment: Alentejo, south Portugal, EGU General Assembly 2016, EGU2016-278.

[8] López Comino, J. A., S. Cesca, M. Kriegerowski, S. Heimann, T. Dahm, J. Mirek and S. Lasocki, Monitoring performance using synthetic data for induced microseismicity by hydrofracking at the Wysin site (Poland), Geophys. J. Int. (2017), under review.