

ISRM Suggested Method

for Laboratory Acoustic Emission Monitoring

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1. Introduction

Acoustic emission (AE) is defined as high frequency elastic waves emitted from defects
such as small cracks (microcracks) within a material when stressed, typically in the
laboratory. AE is a similar phenomenon to microseismicity (MS), as MS is induced by
fracture of rock at an engineering scale (*e.g.* rockbursts in mines), that is, in the field. Thus,
seismic monitoring can be applied to a wide variety of rock engineering problems, and AE is
a powerful method to investigate processes of rock fracture by detecting microcracks prior

36 to macroscopic failure and by tracking crack propagation.

37 A basic approach involves the use of a single channel of data acquisition, such as with a
38 digital oscilloscope, and analyzing the number and rate of AE events. Perhaps the most
39 valuable information from AE is the source location, which requires recording the waveform
40 at several sensors and determining arrival times at each. Thus, investing in a multichannel
41 data acquisition system provides the means to monitor dynamics of the fracturing process.

42 The purpose of this suggested method is to describe the experimental setup and devices
43 used to monitor AE in laboratory testing of rock. The instrumentation includes the AE
44 sensor, pre-amplifier, frequency (noise) filter, main amplifier, AE rate counter, and A/D
45 (analog-to-digital) recorder, to provide fundamental knowledge on material and specimen
46 behavior in laboratory experiments. When considering in-situ seismic monitoring, the reader
47 is referred to the relevant ISRM Suggested Method specifically addressing that topic (Xiao
48 et al., 2016).

50 2. Brief Historical Review

51 2.1 Early Studies of AE Monitoring for Laboratory Testing

52 AE / MS monitoring of rock is generally credited to Obert and Duval (1945) in their seminal
53 work related to predicting rock failure in underground mines. Laboratory testing was later
54 used to understand better the failure process of rock (Mogi 1962a). For example, the nature
55 of crustal-scale earthquakes from observations of micro-scale fracture phenomena was a
56 popular topic. Mogi (1968) discussed the process of foreshocks, main shocks, and
57 aftershocks from AE activity monitored through failure of rock specimens. Scholz (1968b,
58 1968c) studied the fracturing process of rock and discussed the relation between
59 microcracking and inelastic deformation. Nishizawa et al. (1984) examined focal
60 mechanisms of microseismicity, and Kusunose and Nishizawa (1986) discussed the concept
61 of the seismic gap from AE data obtained in their laboratory experiments. Spetzler et al.
62 (1991) discussed stick slip events in pre-fractured rock with various surface roughness by
63 combining acoustic emission with holographic interferometry measurements. Compiling
64 years of study, Scholz (2002) and Mogi (2006) published books on rock failure processes
65 from a geophysics perspective. Hardy (1994, 2003) focused on geoenvironmental applications
66 of AE, while Grosse and Ohtsu (2008) edited topics on the use of AE as a health monitoring
67 method for civil engineering structures.

69 2.2 AE Monitoring in Novel Application

70 Many researchers have used AE in novel ways. Yanagidani et al. (1985) performed creep
71 experiments under constant uniaxial stress and used AE location data to elucidate a cluster
72 of microcracks prior to macro-scale faulting. His research group also developed the concept

1 73 of using AE rate to control compression experiments (Terada et al. 1984). Using this
2 method, Lockner et al. (1991) conducted laboratory experiments under controlled loading by
3 74 keeping the AE rate constant and discussed the relation between fault growth and shear
4 75 fracture by imaging AE nucleation and propagation.
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6 77 Besides the research on rock fracturing, AE monitoring has been applied to stress
7 measurement using the Kaiser effect (Kaiser, 1953), that is the stress memory effect with
8 78 respect to AE occurrence in rock. This application was started by Kanagawa et al. (1976)
9 79 and patented by Kanagawa and Nakasa (1978). Lavrov (2003) presented a historical review
10 80 of the approach.
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13 83 2.3 AE Monitoring with Development of Digital Technology

14 84 With development of digital technology, AE instrumentation advanced through the use of
15 85 high speed and large capacity data acquisition systems. For example, using non-standard
16 86 asymmetric compression specimens, Zang et al. (1998, 2000) located AE sources, analyzed
17 87 the fracturing mechanism, and compared the results with images of X-ray CT scans. Studies
18 88 of the fracture process zone include Zietlow and Labuz (1998), Zang et al. (2000), and
19 89 Nasser et al. (2006), among others. Benson et al. (2008) conducted a laboratory experiment
20 90 to simulate volcano seismicity and observed low frequency AE events exhibiting a weak
21 91 component of shear (double-couple) slip, consistent with fluid-driven events occurring
22 92 beneath active volcanoes. Heap et al. (2009) conducted stress-stepping creep tests under
23 93 pore fluid pressure and discussed effects of stress corrosion using located AE data. Chen and
24 94 Labuz (2006) performed indentation tests of rock using wedge-shaped tools and compared
25 95 the damage zone shown with located AE sources to theoretical predictions.

26 96 Ishida et al. (2004, 2012) conducted hydraulic fracturing laboratory experiments using
27 97 various fluids, including supercritical carbon dioxide, and discussed differences in induced
28 98 cracks due to fluid viscosity using distributions of AE sources and fault plane solutions.
29 99 Using AE data from triaxial experiments, Goebel et al. (2012) studied stick-slip sequences to
30 100 get insight into fault processes, and Yoshimitsu et al. (2014) suggested that both millimeter
31 101 scale fractures and natural earthquakes of kilometer scale are highly similar as physical
32 102 processes. The similarity is also supported by Kwiatek et al. (2011) and Goodfellow and
33 103 Young (2014).

34 104 Moment tensor analysis of AE events has been applied to laboratory experiments. Shah
35 105 and Labuz (1995) and Sellers et al. (2003) analyzed source mechanisms of AE events under
36 106 uniaxial loading, while Graham et al. (2010) and Manthei (2005) analyzed them under
37 107 triaxial loading. Kao et al. (2011) explained the predominance of shear microcracking in
38 108 mode I fracture tests through a moment tensor representation of AE as displacement
39 109 discontinuities.

3. Devices for AE Monitoring

One of the simplest loading arrangements for AE monitoring in the laboratory is that for uniaxial compression of a rock specimen; Figure 1 shows a typical arrangement. Since an AE signal detected at a sensor is of very low amplitude, the signal is amplified through a pre-amplifier and possibly a main amplifier. Typically the signal travels through a coaxial cable (a conductor with a wire-mesh to shield the signal from electromagnetically induced noise) with a BNC (Bayonet Neill Conelman) connector. It is usually necessary to further eliminate noise, so a band pass filter, a device that passes frequencies within a certain range, is used. In the most basic setup using one sensor only, the rate of AE events is counted by processing the detected signals. In more advanced monitoring, for example, for source location of AE events, more sensors are used and AE waveforms detected at the respective sensors are recorded through an A/D converter. Figure 2a shows a twelve sensor array for a core 50 mm in diameter and 100 mm in length (Zang et al. 2000); an AE-rate controlled experiment was performed to map a fracture tip by AE locations, as shown in Figure 2b. To locate AE, it is advantageous for the sensors to be mounted so as to surround the source, as shown in Figure 2. The three lines indicate paths to monitor P-waves transmitted from sensor No. 12 by using it as an emitter.

3.1 AE Sensor

AE sensors are typically ceramic piezoelectric elements. The absolute sensitivity is defined as the ratio of an output electric voltage to velocity or pressure applied to a sensitive surface of a sensor in units, V/(m/s) or V/kPa, and its order is 0.1 mV/kPa. However, the absolute sensitivity often depends on the calibration method (McLaskey and Glaser 2012). From this reason, a sensitivity of an AE sensor is usually stated as relative sensitivity in units of dB.

Figure 3 shows a typical sensor with a pre-amplifier. AE sensors can be classified into two types, depending on frequency characteristics: resonance and broadband. Figure 4a illustrates the frequency response of a resonance type sensor, while Figure 4b shows the characteristics of a broadband type sensor. Both sensors have a cylindrical shape with the same size of 18 mm in diameter and 17 mm in height. However, it can be seen that the resonance type sensor (Figure 4 (a)) has a clear peak around 150 kHz while the broadband type (Figure 4(b)) has a response without any clear peak from 200 to 800 kHz. Since the resonance type detects an AE event at the most sensitive frequency, it tends to produce a signal having large amplitude in a frequency band close to its resonance frequency, independent of a dominant frequency of the actual AE waveform. As a result, the resonance type sensor conceals the characteristic frequency of the “actual” AE signal and it may lose

1 147 important information about the source.

2 148 On the other hand, it is often claimed that the broadband type records a signal
3 149 corresponding to the original waveform. However, comparing Figure 4a and 4b illustrates
4 150 that the sensitivity of the broadband type is on average 10 dB less than that of the resonance
5 151 type. For this reason, the resonance type sensor is often employed for AE monitoring. In an
6 152 early study on rock fracturing (Zang et al. 1996), both sensor types, resonance and
7 153 broadband, were used to investigate fracture mechanisms in dry and wet sandstone. Further,
8 154 broadband sensors have been developed to provide high fidelity signals for source
9 155 characterization (Proctor 1982; Boler et al. 1984; Glaser et al. 1998; McLaskey and Glaser
10 156 2012; McLaskey et al. 2014). One additional item that should be noted is that sensor
11 157 selection should be dependent on rock type. For weak rock like mudstone having low
12 158 stiffness and high attenuation, an AE sensor having a lower resonance frequency is
13 159 recommended because it is difficult to monitor high frequency signals in a weak rock.

14 160 For counting AE events, two or more sensors should be used to check the effect of
15 161 sensor position and distinguish AE signals from noise. For 3D source locations of AE
16 162 events, at least five sensors (or four sensors and one other piece of information) are
17 163 necessary, because of the four unknowns (source coordinates x , y , z , and an occurrence time
18 164 t) and the quadratic nature of the distance equation. More than eight sensors are usually used
19 165 to improve the locations of the AE events through an optimization scheme (Salamon and
20 166 Wiebols 1974).

21 167 For setting an AE sensor on a cylindrical specimen, it is recommended to machine a
22 168 small area of the curved surface to match the planar end of the sensor. To adhere the sensor
23 169 on the specimen, various kinds of adhesives can be used, such as a cyanoacrylate-based glue
24 170 or even wax, which allows easy removal. It is recommended to use a consistent but small
25 171 amount of adhesive so as to reduce the coupling effect (Shah and Labuz 1995). Many AE
26 172 sensors are designed to operate within a pressure vessel, so from the perspective of the AE
27 173 technique, the issues are the same for uniaxial and triaxial testing.

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29 175 3.2 Amplifiers and Filters

30 176 When AE events generated in a specimen are detected by an AE sensor, the motion induces
31 177 an electric charge on the piezoelectric element. A pre-amplifier connected to the AE sensor
32 178 transfers the accumulated electric charge as a voltage signal with a gain setting from 10 to
33 179 1000 times. Thus, a pre-amplifier should be located within close proximity (less than one
34 180 meter) from an AE sensor, and some commercial AE sensors are equipped with integrated
35 181 pre-amplifiers. Since a pre-amplifier needs a power supply to amplify a signal, it should
36 182 be connected to a “clean” power unit so that the signal is not buried in noise.

37 183 A signal amplified by a pre-amplifier is often connected to another amplifier, and a

1 184 frequency filter is inserted to reduce noise. A high pass filter passes only a signal having
2 185 frequencies higher than a set frequency to eliminate the lower frequency noises; a low pass
3 186 filter eliminates the higher frequency noise. A filter that combines the two is called a band
4 187 pass filter and is often used as well. When the AE sensor shown in Figure 3, having a
5 188 resonance frequency of 150 kHz is employed, a band pass filter from 20 to 2000 kHz is
6 189 common. A band frequency of the filter should be selected depending on frequency of the
7 190 anticipated waves and on the frequency of the noise.
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10 191 11 192 3.3 AE Count and Rate

12 193 The AE count means a number of AE occurrence, whereas the AE count rate means the AE
13 194 count per a certain time interval. Figure 5 shows a typical example of AE count rates
14 195 monitored in a uniaxial compression test on a rock core. It is possible to show a relation
15 196 between impending failure and AE occurrence, when AE count rates are shown with a load-
16 197 displacement curve. Noting that the AE count rate on the y-axis is plotted on a logarithmic
17 198 scale, a burst of AE is observed just before failure (peak axial stress) of the specimen. This
18 199 suggests that AE count rate is a sensitive parameter for observing failure.

19 200 Methods to determine AE counts are classified into ring-down count and event count. In
20 201 both cases, a certain voltage level called the threshold or discriminate level is set for AE
21 202 recording (Figure 6). The level is set slightly higher than the background noise level
22 203 regardless of rock properties and test conditions, and consequently the AE count and rate
23 204 depend on the threshold level. In a ring-down counting method, a TTL (Transistor-
24 205 Transistor-Logic) signal is produced every time a signal exceeds a threshold level. In the
25 206 case shown in Figure 6b, five TTL signals are produced for one AE event, and they are sent
26 207 to a counter as five counts. On the other hand, an event count records one count for each AE
27 208 event; a typical method generates a low frequency signal that envelopes the original signal
28 209 (Figure 6c). After that, when the low frequency signal exceeds a threshold level, one TTL
29 210 signal is produced and sent to a counter. The function to generate the TTL signals should be
30 211 mounted in a main amplifier or a rate counter as shown in Figure 1.

31 212 Whichever method is selected, AE counts and rates depend on the gain of the amplifiers
32 213 and the threshold level. Thus, the threshold level should be reported together with the
33 214 respective gains of the pre-amplifier and amplifier, along with the method selected for
34 215 counting. Nonetheless, comparison of AE counts and rates between two experiments should
35 216 be done cautiously, as the failure mechanism, or more importantly, coupling may differ.
36 217 Sensitivity of an AE sensor is strongly affected by the coupling condition between the
37 218 sensor and specimen. For example, the area and shape of the couplant (adhesive) can be
38 219 different, even if the couplant is applied in the same manner (Shah and Labuz 1995). For
39 220 these reasons, comparison of exact numbers of AE counts and rates between two
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221 experiments is not recommended, although their changes within an experiment become very
222 good indices for identifying the accumulation of damage and extension of fracture.

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224 3.4 Recording AE Waveforms

225 AE waveforms contain valuable information on the fracture process, including location of
226 the AE source. AE waveforms can be recorded by an A/D converter and stored in memory.

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228 (1) Principle of A/D conversion

229 To record an AE waveform, as shown in Figure 7, an electric signal from an AE sensor
230 flows through an A/D converter. When the amplitude of the signal exceeds a threshold level,
231 which is set in advance, a certain “length” of the signal before and after the threshold is
232 stored in memory. While the voltage level set in advance is called the threshold level or
233 discriminate level, the time when a signal voltage exceeds the level is called the trigger time
234 or trigger point. Note that “trigger” can mean either to start a circuit or to change the state of
235 a circuit by a pulse, while, in some cases, “trigger” means the pulse itself. In actual
236 monitoring, the TTL signal for the AE rate counter is usually branched and connected into
237 an A/D converter as the trigger signal. Sometimes, to avoid recording waveforms that
238 cannot provide sufficient information to determine a source location, a logic of AND/OR for
239 triggering is used; e.g. triggering occurs only when signals of two sensors set in the opposite
240 position on the specimen exceed a threshold level at the same time. Indeed, it is possible to
241 use much more complex logic. Using an arrival time picking algorithm, automatic source
242 location of AE events can be realized.

243 When recording an AE waveform, a time period before the trigger time needs to be
244 specified and this time period is called the pre-trigger or delay time. In A/D conversion,
245 voltages of an analog signal are read with a certain time interval and the voltages are stored
246 in memory as digital numbers. The principle is illustrated in an enlarged view of an initial
247 motion of the waveform in the lower part of Figure 7. The time interval, Δt , is called the
248 sampling time. On the other hand, the recording time of a waveform is sometimes
249 designated as a memory length of an A/D converter.

250 For example, in an hydraulic fracturing experiment on a 190 mm cubic granite specimen
251 (Ishida et al. 2004) and a uniaxial loading experiment on a 300 x 200 x 60 mm rectangular
252 tuff specimen (Nakayama et al. 1993), the researchers used a sensor having a resonance
253 frequency of 150 kHz, which is shown in Figure 3, and monitored AE signals by using a
254 sampling time of 0.2 μ s and a memory length of 2 k (2,048 words). In this case, the
255 recording time period was around 0.4 ms (0.2 μ s x 2,048). The pre-trigger was set at 1 k,
256 one-half of the recording time; the pre-trigger is often reported as memory length rather than
257 in real time.

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(2) Sampling Time

To explain selection of a proper sampling time, consider the case where a sine curve is converted at only four points from analog data to digital. If the sampling points meet the maximum and the minimum points of the curve, as shown in Figure 8a, a signal reproduced by linear interpolation from the converted digital data is similar to the original signal. However, if the sampling points are moved 1/8 cycle along the time axis, as shown in Figure 8b, the reproduced signal is much distorted from the original one. These two examples suggest that four sampling points for a cycle are not sufficient and at least ten points for a cycle are needed to reproduce the waveform correctly from the converted digital data.

A specification of an A/D converter usually shows a reciprocal number of the minimum sampling time. For example, if the minimum sampling time is 1 μ s, the specification shows the reciprocal number, 1 MHz, as the maximum monitoring frequency. However, this does not mean the frequency of a waveform that can be correctly reproduced. In this case, around one-tenth of the frequency, or 100 kHz, can be recorded.

(3) Resolution of Amplitude

Whereas the sampling time corresponds to the resolution along the x-axis of an A/D converter, the resolution capability along the y-axis (amplitude), usually called dynamic range, is the range from the discriminable or the resolvable minimum voltage difference to the recordable maximum voltage, and it depends on the bit length. When the length is 8 bits, its full scale, for example, from -1 to +1 volt, is divided into $2^8 = 256$. Thus, in this case, any differences smaller than $2/256$ volts in the amplitude are automatically ignored. If the bit length is 16 bits, the full scale from -1 to +1 volt is divided into $2^{16} = 65,536$ and much smaller differences can be discriminated. The dynamic range is from $7.8 \times 10^{-3} (= 2/256)$ to 2 V for 8 bits, whereas it is from $3.1 \times 10^{-5} (= 2/65,536)$ to 2 V for 16 bits.

When using amplitude data of the waveform in analysis, for example, to calculate the b-value using Gutenberg-Richter relation (Gutenberg and Richter 1942), a large dynamic range is essential. The unit “word” of a recording length is sometimes used, noting that one word corresponds to 8 bits (1 byte) where the bit length is 8 bits, whereas it corresponds to 16 bits (2 bytes) for a case of 16 bits.

(4) Continuous AE acquisition

A conventional transient recording system has a certain dead-time, where AE data are not recorded during this interval; this could result in loss of valuable information, especially in the case of a high level of AE activity. Continuous AE acquisition systems record without AE data loss, but the disadvantage of such systems is the huge dataset, requiring additional

1 295 software for processing. With the increase of installed memory, systems that can record all AE
2 296 events continuously through an experiment have become commercially available. Since some
3 297 researchers have already started to use this type of system, continuous monitoring (without
4 298 trigger) may become increasingly popular in the near future.

5 299 The following examples show the capability of continuous AE acquisition. A continuous
6 300 recorder was used to record 0.8 seconds at 10 MHz and 16 bits (Lei et al. 2003). A
7 301 continuous AE recorder was used to store 268 seconds of continuous AE data on 16 channels
8 302 at a sampling rate of 5 MHz and at 14-bit resolution (Thompson et al. 2005, 2006; Nasser et
9 303 al. 2006). A more advanced continuous AE acquisition system, which can record
10 304 continuously for hours at 10 MHz and 12 or 16 bits, was used within conventional triaxial
11 305 and true-triaxial geophysical imaging cells (Benson et al. 2008; Nasser et al. 2014). In
12 306 addition, there exists a combined system with the capability for conventional transient
13 307 recording where there is a low AE activity and for recording AE continuously in the case of
14 308 a high level of AE activity; this provides zero dead-time and avoids the loss of AE signals
15 309 (Stanchits et al. 2011). A disadvantages of such a system is that it costs more than a
16 310 conventional transient or a continuously recording system.

17 311 18 312 19 313 4. Analysis

20 314 AE data analysis could be classified into the four categories; (1) event rate analysis to
21 315 evaluate the damage accumulation and fracture extension, (2) source location, (3) energy
22 316 release and the Gutenberg-Richter relation, and (4) source mechanism. In this section, AE
23 317 data analysis is explained in this order.

24 318 25 319 4.1 Event counting

26 320 The most basic type of AE data analysis involves counting events as a function of time. As
27 321 shown in Figure 5, by comparing AE rates with change of stress, strain, or other measured
28 322 quantity characterizing the response, valuable insight on the accumulation of damage and
29 323 extension of fracture can be obtained. Various statistical modeling methods can be used to
30 324 extract additional information, including the Kaiser effect (Lockner 1993; Lavrov 2003).

31 325 32 326 4.2 Source location

33 327 If waveforms of an AE event are recorded at a number of sensors, the source can be located,
34 328 providing perhaps the most valuable information from AE. Different approaches can be
35 329 taken to determine source locations of AE events, but a common approach is to use a non-
36 330 linear least squares method to seek four unknowns, the source coordinates x , y , z , and an
37 331 occurrence time t , knowing the P-wave arrival time at each sensor and the P-wave velocity

1 332 measured before the experiment under the assumption that it does not change through the
2 333 experiment. A seminal contribution to the source location problem is the paper by Salamon
3 334 and Weibols (1974). Other valuable references include Section 7.2 of Stein and Wysession
4 335 (2003) and Section 5.7 of Shearer (2009). Source locations of AE events in laboratory
5 336 experiments are reported in many papers (Lei et al. 1992; Zang et al. 1998, 2000; Fakhimi et
6 337 al. 2002; Benson et al. 2008; Graham et al. 2010; Stanchits et al. 2011, 2014; Ishida et al.
7 338 2004, 2012; Yoshimitsu et al. 2014). In addition, the calculation of fractal dimension using
8 339 spatial distributions of AE sources can be quite valuable in identifying localization (Lockner
9 340 et al. 1991; Lei et al. 1992; Shah and Labuz 1995; Zang et al. 1998; Lei et al. 2003;
10 341 Stanchits et al. 2011).

11 342 12 343 4.3 Energy release and the Gutenberg-Richter relation

13 344 A signal recorded at only one sensor should not be used to estimate energy released due to
14 345 geometric attenuation of the signal. However, for a large number of sensors with sufficient
15 346 coverage, an average root-mean-square (RMS) value from all the sensors will be
16 347 representative of the AE energy. The RMS value is obtained by taking the actual voltage $g(t)$
17 348 at each point along the AE waveform and averaging the square of $g(t)$ over the time period
18 349 T ; the square root of the average value gives the RMS value.

19 350 The Gutenberg-Richter relationship, originally proposed as a relation between
20 351 magnitudes of earthquakes and their numbers, can also be applied to AE data. Mogi (1962a
21 352 and 1962b) indicated through his laboratory experiments that the relation depends on the
22 353 degree of heterogeneity of the material. Scholz (1968a) found in uniaxial and triaxial
23 354 compression tests that the state of stress, rather than the heterogeneity of the material, plays
24 355 the most important role in determining the relation. These findings have been applied in
25 356 order to understand the phenomena of real earthquakes and the Gutenberg-Richter
26 357 relationship is often used as an index value for fracturing in rock specimens (e.g. Lei et al.
27 358 1992, 2003; Lockner 1993; Zang et al. 1998; Stanchits et al. 2011).

28 359 29 360 4.4 Source mechanism

30 361 If the polarity of the initial P-wave motion at several sensors is identified, the source
31 362 mechanism can be analyzed using a fault plane solution. The polarity of a waveform is
32 363 defined as positive if the first motion is compressive or outward and negative if it is tensile
33 364 or inward. Microcrack opening and volumetric expansion mechanisms cause positive first
34 365 motions in all the directions around the source, whereas microcrack closing and pore
35 366 collapse mechanisms cause all negative first motions. A pure sliding mechanism causes
36 367 equal distributions of positive and negative polarities. The distribution of polarities for a
37 368 mixed-mode mechanism (e.g. sliding with dilation) is more complex. Since the theory

1 369 applied to seismology can be directly applied to AE owing to the same physical mechanism
2 370 of fracturing, the approach is described in several seismology texts, including Chapter 3 of
3 371 Kasahara (1981), Section 4.2 of Stein and Wysession (2003), and Chapter 9 of Shearer
4 372 (2009). The fault plane solutions of AE events in laboratory experiments are reported in Lei
5 373 et al. (1992), Zang et al. (1998), and Benson et al. (2008).

6 374 With proper sensor calibration and simplifying assumptions (Davi et al. 2013; Kwiatek
7 375 et al. 2014; Stierle et al. 2016), a detailed analysis of the source mechanism using the
8 376 concept of the moment tensor can be performed. The AE source is characterized as a
9 377 discontinuity in displacement, a microcrack, and represented by force dipoles that form the
10 378 moment tensor. An inverse problem is solved for the six components of the moment tensor,
11 379 which are then related to the physical quantities of microcrack displacement and orientation.
12 380 In general, the directions of the displacement vector and the normal vector of the microcrack
13 381 can be interchanged, but an angle 2α between the two vectors indicate opening when $\alpha = 0^\circ$,
14 382 sliding when $\alpha = 45^\circ$, and anything in between is mixed-mode. The theory is reviewed in
15 383 seismology texts e.g. Section 4.4 of Stein and Wysession (2003) and Chapter 9 of Shearer
16 384 (2009), as well as in papers by Ohtsu and Ono (1986), Shah and Labuz (1995), and Manthei
17 385 (2005). Applications of the moment tensor analysis to model AE events as microcracks are
18 386 found in Kao et al. (2011), Davi et al. (2013), Kwiatek et al. (2014) and Stierle et al. (2016).

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32 389 5. Reporting of Results

33 390 A report on AE laboratory monitoring should include the following:

- 34 391 (1) Size, shape, and rock type of the specimen.
- 35 392 (2) Size and frequency of the sensor and type (resonance or broadband).
- 36 393 (3) Number of AE sensors used and sensor arrangement.
- 37 394 (4) Block diagram of AE monitoring system or explanation of its outline.
- 38 395 (5) Gain of pre- and main-amplifier of each channel.
- 39 396 (6) Setting frequencies of high pass and low pass filter of each channel.
- 40 397 (7) Threshold level of each channel for count rate and/or trigger for waveform recording.
- 41 398 (8) If a triggering system is used, how to select AE sensors and how to use logical AND/OR
- 42 399 for triggering. Dead time or continuous AE acquisition should be stated as well.
- 43 400 (9) Sampling time, memory length (recording time period of each waveform), pre-trigger
- 44 401 time and resolution of amplitude, if waveform is recorded.
- 45 402 (10) Analysis of results, for example, AE count rate as a function of time, location of AE
- 46 403 events, mechanisms of AE events including fault plane, moment tensor, or other solutions.
- 47 404 (11) Other measured quantities related to the purpose of the experiment, for example, stress,
- 48 405 strain, pressure and temperature, should be reported in comparison with the AE data.

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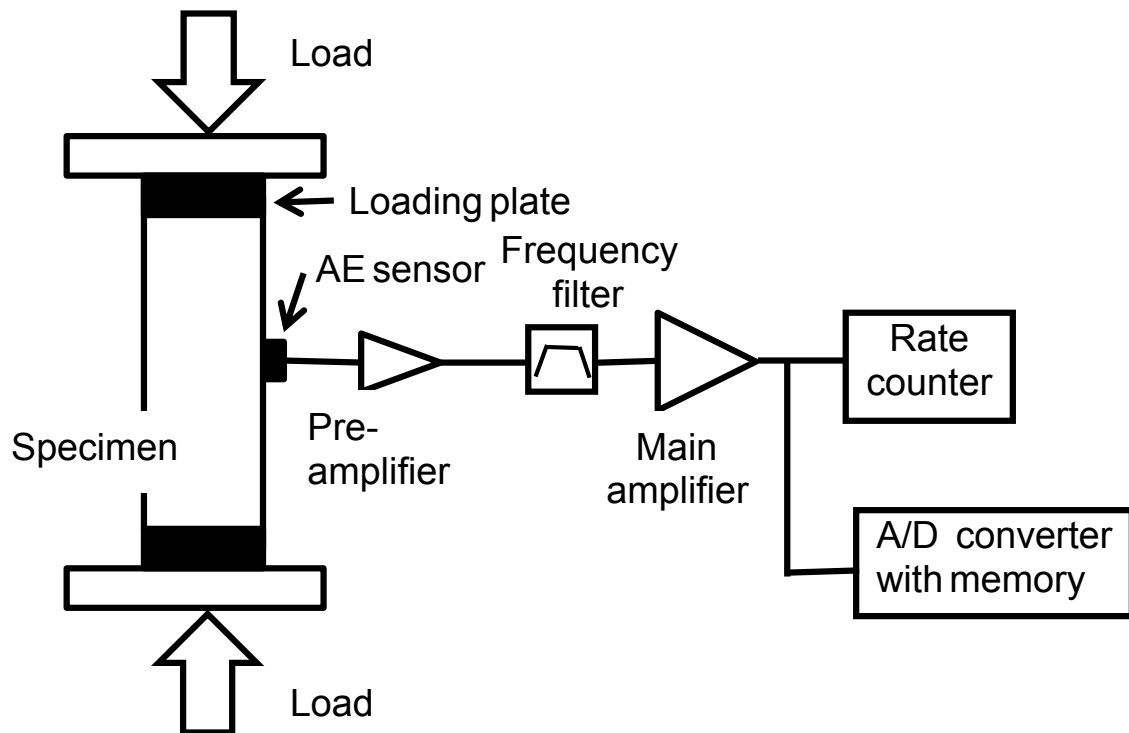
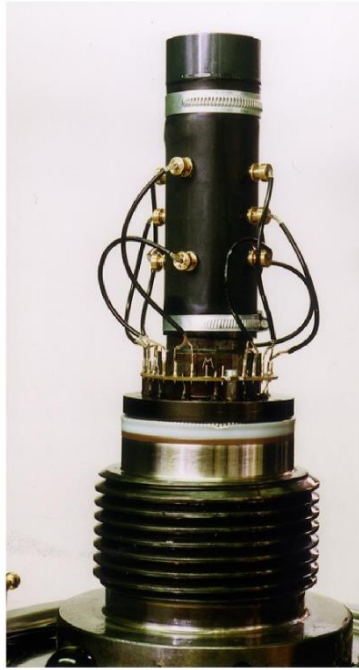
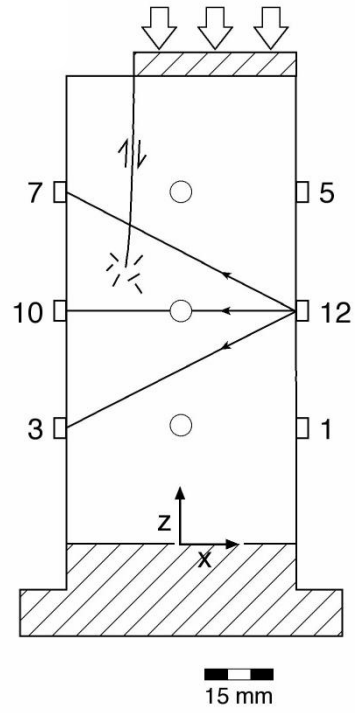


Figure 1. Typical AE monitoring system for a laboratory uniaxial compression test.



(a) Photograph



(b) Illustration

Figure 2. Example of the twelve sensor array for a core measuring 5 cm in diameter and 10 cm in length after Zang et al. (2000).



Figure 3. Typical AE sensor and pre-amplifier for a laboratory experiment. Coin is 24.26 mm in diameter (a quarter of US dollar) for scale.

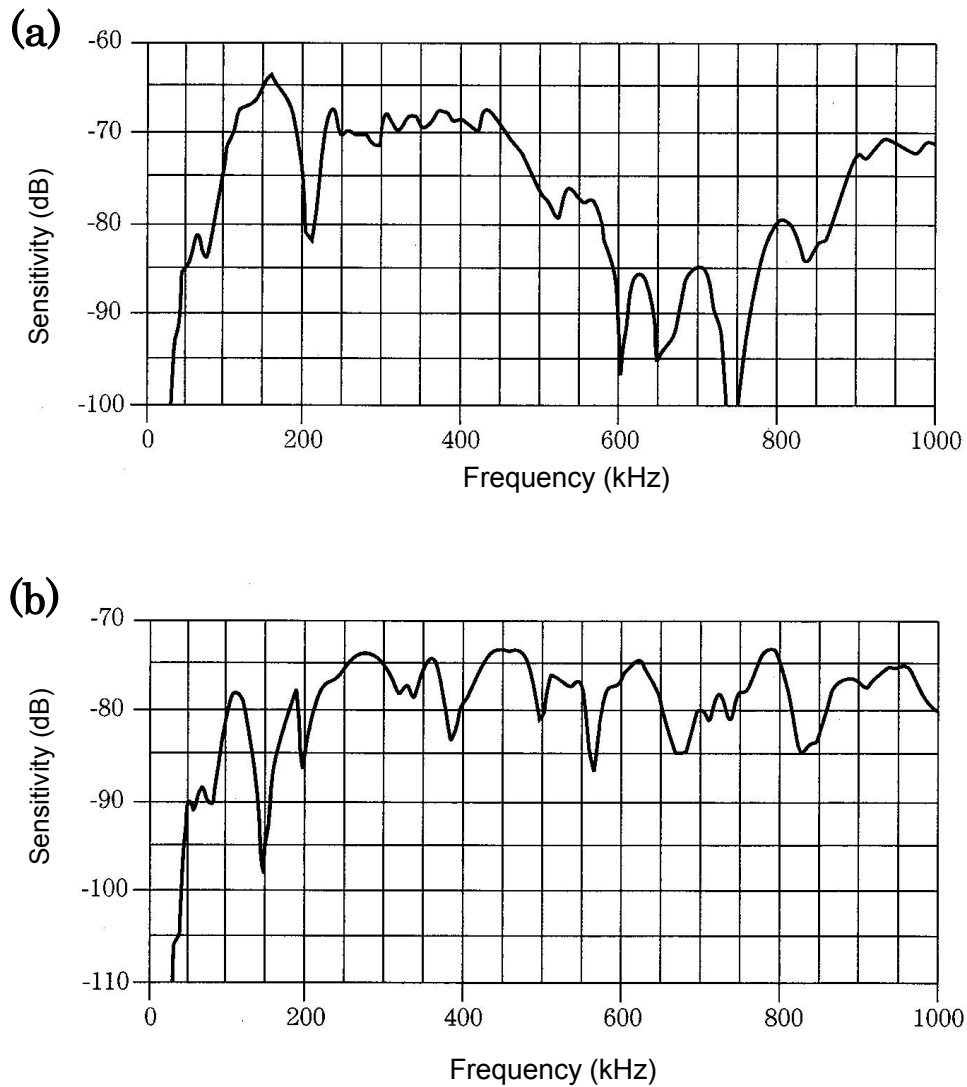


Figure 4. Examples of frequency response characteristics of AE sensors. (a) Resonance type sensor, PAC Type R15 with a resonance frequency 150 kHz. (b) Broadband type sensor, PAC Type UT1000. Both sensor models from Physical Acoustics Corporation, Princeton, NJ, USA.

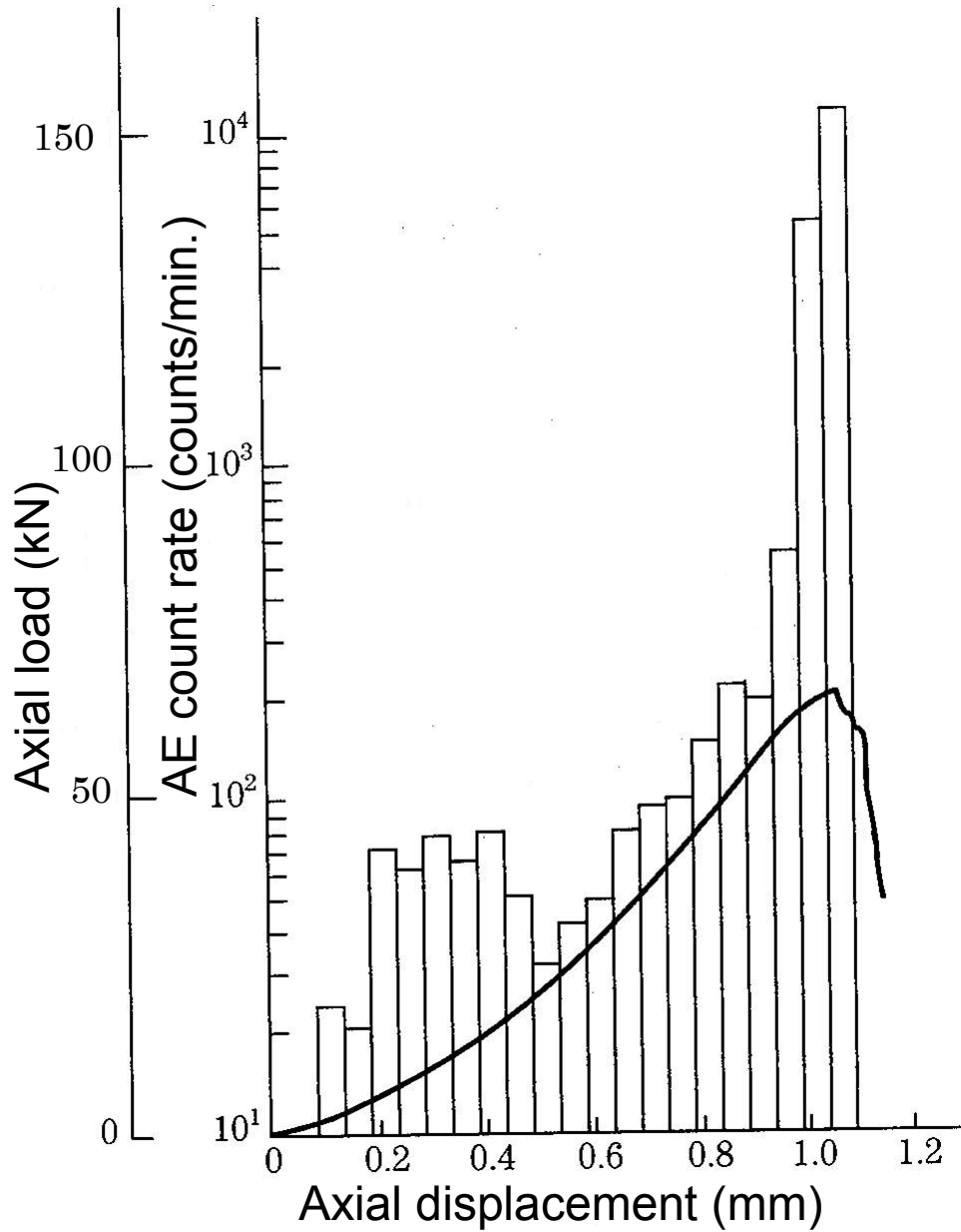


Figure 5. Typical AE count rate monitored in a uniaxial compression test under a constant axial displacement rate. The bar graph and the bold line indicate AE count rates and the load-displacement curve, respectively.

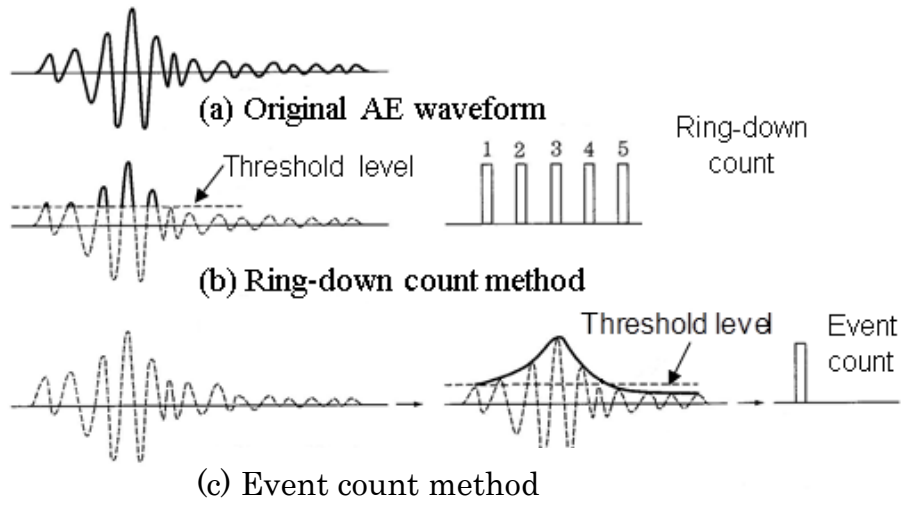


Figure 6. Two methods to count AE events. (a) The original AE waveform. (b) The ring-down count. (c) The event count.

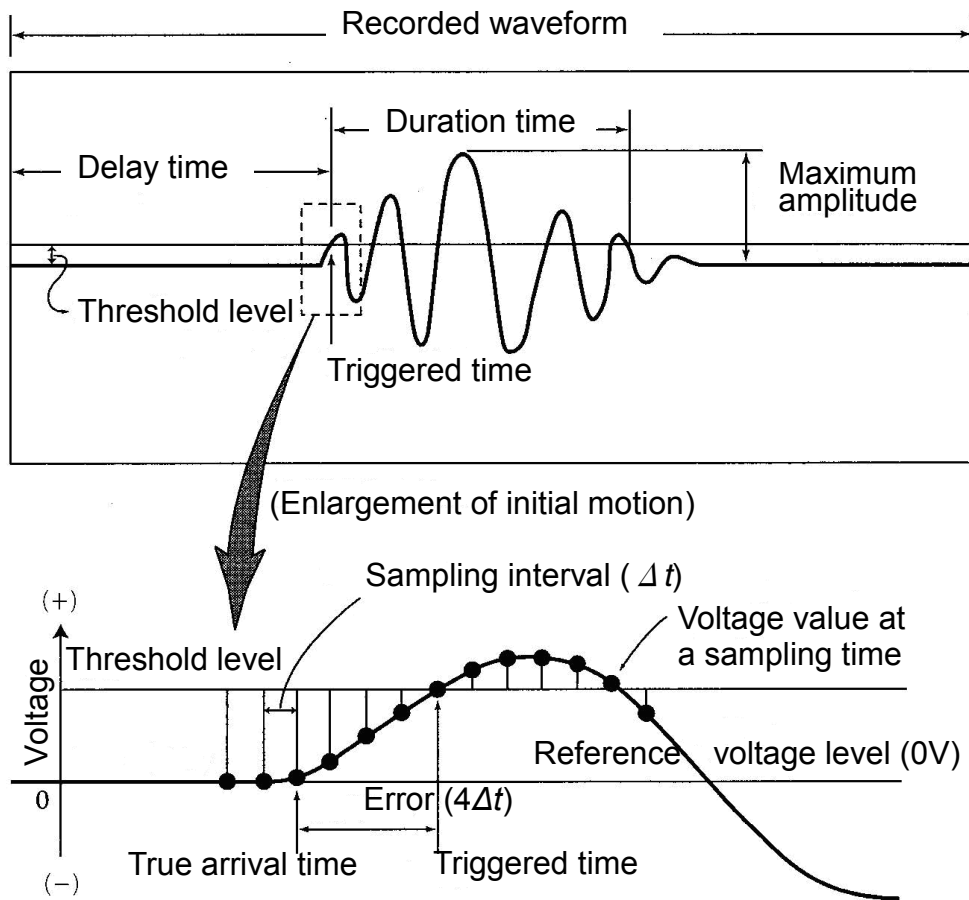


Figure 7. Example of recorded AE waveform and illustration of its Analog/Digital conversion.

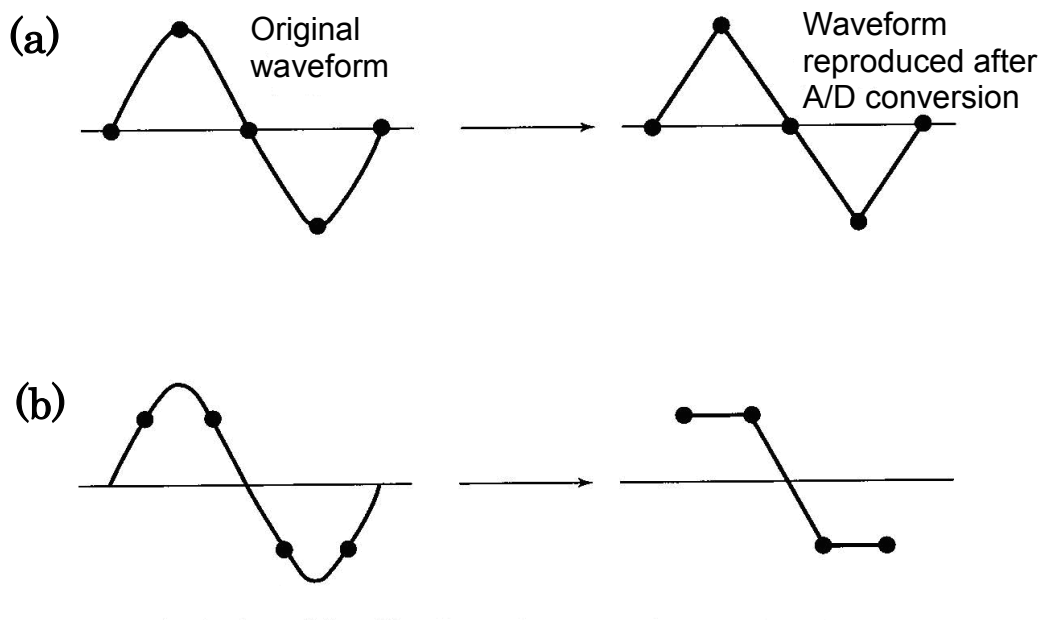


Figure 8. Relationship between an original waveform and a waveform reproduced after A/D conversion. (a) Ideal case where sampling points meet the maximum and the minimum points of the original waveform. (b) Actual case where the sampling points are displaced $1/8$ cycle along the time axis.