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# Parametrization of electromagnetic radiation pulses obtained by triaxial fracture of granite samples

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ABSTRACT

We have accurately measured and parametrized individual pulses of electromagnetic radiation (EMR) obtained during a fracture experiment. Analysis of the parameters shows that they follow a log-normal distribution. Results indicate no dependence between fracture lengths and widths.

## § 1. INTRODUCTION

Material fracture induces emissions of electrons and positive ions, neutral atoms and molecules, visible photons and long-wave radiation (radio emission) (for example Langford and Dickinson (1989), Panov and Streletskii (1991) and Enomoto and Chaudhri (1993)). In this paper, only long-wave radiation (electromagnetic radiation (EMR)) is considered.

EMR from materials fractured under compression was observed by Stepanov (see Urosovskaja (1969)) on samples of rock salt (KCl). This investigation was followed by numerous studies aimed at investigating EMR excitation under different loadings and understanding the EMR mechanism (for example Gol'd *et al.* (1975), Nitsan (1977), Warwick *et al.* (1982), Ogawa *et al.* (1985) and Cress *et al.* (1987)). During the 1970s and 1980s, interest in the EMR increased in connection with the problem of earthquake prognosis (Yamada *et al.* 1989, Fujinawa *et al.* 1992, Yoshino *et al.* 1993). It was found that the EMR amplitude sharply increased hours or even days before an earthquake (Gokhberg *et al.* 1979). However, all efforts to use EMR for earthquake forecasting have encountered very small success. This failure is partly due to the lack of a detailed quantitative understanding of the EMR mechanism. Several attempts have appeared in the past to explain the origin of EMR. These include the acceleration and deceleration of dislocations (Perelman and Khatiashvilli 1981, Golovin and Shibkov 1986a, b), rupture of bonds (Khatiashvilli 1984, Gershenzon *et al.* 1985), the movement of charged crack sides (Miroshnishenko and Kuksenko 1980) and electrical breakdown (discharge between charged crack sides) (for example Gol'd *et al.* (1975) and Enomoto and Chaudhri

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(1993)). Unfortunately, none of these was able to explain the properties of the detected EMR (King 1983, Rabinovitch *et al.* 1995, 1996).

EMR appears as individual pulses or as pulse clusters caused by the different fracture mechanisms involved (Rabinovitch *et al.* 1995, 1996). The first step towards achieving the desired quantitative information is to measure individual EMR pulses and to parametrize them as accurately as possible.

## § 2. Experimental method

Our experience shows that to register accurate EMR pulses the measuring system must have the following features: a frequency band from 10 kHz up to 20 MHz with a sensitivity of 1 μV throughout the whole band. These stringent demands surpass hitherto achieved sensitivities of experimental systems. Our experimental system (figure 1) consisted of a TerraTeck stiff press, a magnetic loop antenna of 3 cm diameter (EHFP-30 set, Electro-Metrics Penril Corporation), a 60 dB low-noise microsignal amplifier (Mitek Corporation Ltd) and a Tectronix TDS 420 digital storage oscilloscope connected by way of general-purpose inferface parallel ports to an IBM PC with special software. We measured EMR in a thick-wall steel load cell of the stiff press. Granite samples were loaded by an axial strain rate of $1 \times 10^{-5}\,s^{-1}$ and laterally by hydrostatic oil pressure (the axial compressive load was changed from 0 to 285 MPa and the lateral compressive load was varied from 0 to 14 MPa). The antenna was situated 2 cm away from the centre of the loaded samples with its normal pointing perpendicular to the cylinder axis. All samples were standard cylinders of 100 mm length and 52 mm diameter, cut from an Eilat granite block with unified co-orientation. Measurements were carried out in the so-called

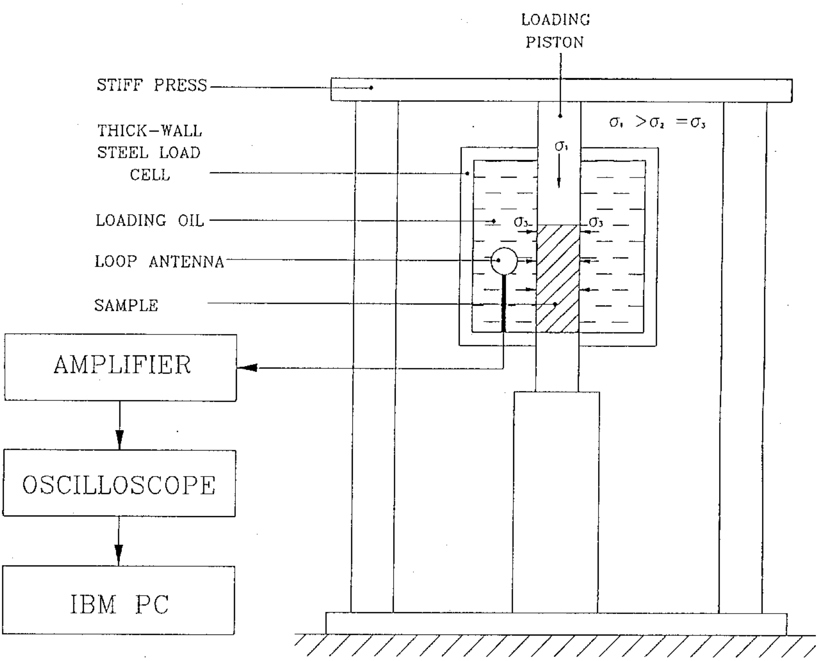


Figure 1. Schematic diagram of the experimental arrangement.

'near zone'. Our measuring device fulfilled the above-mentioned requirement of 1 μV sensitivity over the whole frequency band. Individual EMR pulses induced by triaxial compression were monitored during all periods of sample loading and were observed, digitized and memorized by a storage oscilloscope and an IBM PC in real time at the moment of pulse excitation.

## § 3. Parametrization of electromagnetic pulses

Results show that an EMR pulse (voltage A against time t) can be characterized by the following general relationship (figure 2):

$$A = \begin{cases} A_0 \sin\left[\omega(t - t_0)\right]\left[1 - \exp\left(\dfrac{-(t - t_0)}{\tau}\right)\right], & t < T, \\ A_0 \sin\left[\omega(t - t_0)\right]\exp\left(\dfrac{-(t - T)}{\tau}\right)\left[1 - \exp\left(\dfrac{-(T - t_0)}{\tau}\right)\right], & t \geq T, \end{cases} \tag{1}$$

where t is the time, $t_0$ is the time from the origin up to the pulse beginning and T is the time from the origin up to the EMR pulse envelope maximum. Thus, $T' = T - t_0$ is the time interval to reach pulse maximum, $\tau$ is the rise-and-fall time (RFT), which turn out to be the same, $A_0$ is the pulse amplitude and $\omega$ is the frequency. All these parameters except t (experimental variable) were calculated by a least-squares fit from the experimental results.

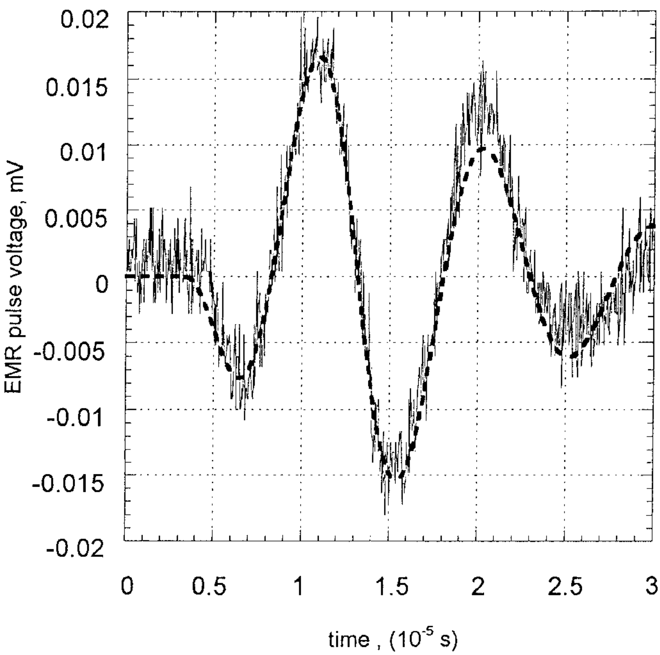


Figure 2. An experimental pulse shape (output voltage against time) and a numerical fit according to equation (1) (- - - - -).

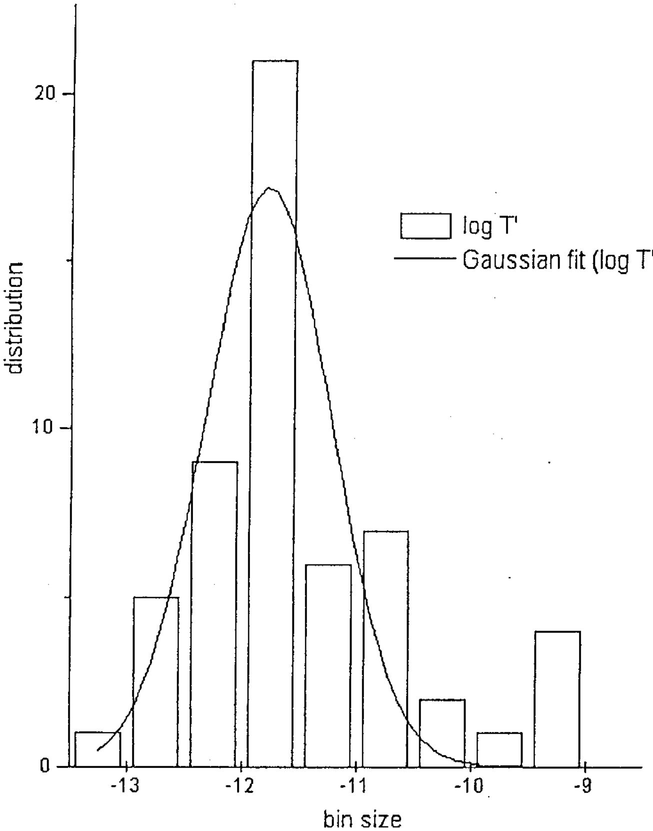


Figure 3. Histogram of log $T'$ (where $T'$ is the time interval to reach the pulse maximum) and its Gaussian fit.

In the granite experiment treated here, 60 EMR pulses were registered during all ranges of compressive loads up to the peak stress and 55 were analysed. Five were discarded, being too complex to analyse. An example of an EMR pulse with its least-squares fit is shown in figure 2. As can be seen, both the accuracy of the measurement and that of the parametrization procedure are adequate.

The results show that $T'$ obeys a log-normal distribution (figure 3). A possible explanation for this distribution could be as follows. $T'$ is proportional to crack length (see below). If we assume that the fracture process develops incrementally and that each new increment is proportional to the existing crack length (as previously observed by Gillespie *et al.* (1992), and by Cowie and Scholtz (1992a, b)), then a log-normal distribution should be expected (Aitchison and Brown 1976).

Another problem is the possibility of a scaling relation between crack length and width. We maintain that the pulse amplitude increases as long as the crack continues to grow, when new atomic bonds are severed and their contribution is added to the EMR. When the crack halts, the pulse amplitude starts to decay. The time from the start of the pulse up to its maximum ($T' = T - t_0$) should be proportional to the number of severed atomic bonds and thus to the crack length (the crack velocity is almost constant). The frequency of the EMR pulse probably relates to the crack width b by the following argument. We assume that the wavelength of the atomic perturbation creating the EMR is limited by the crack width (since, on both sides of the crack, atomic movements are restricted to about zero). Its frequency $\omega$ can be calculated through $\omega = \pi v/b$, where v is the wave velocity and 2b is the minimal wavelength (by the above restriction). Note that in most experiments (for example Walmann *et al.* (1996)), it is the aperture u (and not the width of the crack) that is measured with respect to crack length l and results show a fractal relation, $u \propto l^{\beta}$, where $\beta$ ranges between 0.5 and 1.

We therefore tried to find a fractal correlation between T′ and $\omega$: $\omega \propto (T')^{-\upsilon}$, which would have implied a similar scaling between crack length and width. Results, however, show that the obtained $\upsilon$ is of the order of zero. This result suggests that the crack length is independent of its width or alternatively that the width is constrained by some other mechanism, such as grain boundaries or intergranular spacing. A similar constraint has already been noted (Bahat 1988) in geological fractures in chalks where, in a given layer of a constant width, there is a wide range of fracture lengths.

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