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# An efficient GPU implementation for locating micro-seismic sources using 3D elastic wave time-reversal imaging

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ABSTRACT

Locating micro-seismic events is of utmost importance in seismic exploration, especially when searching for unconventional oil and gas resources. The arrival-time-difference approach is the dominant source location method currently used in the field of micro-seismic source location. However, micro-seismic events can be generated by any arbitrary rock movement and are often accompanied by interference noise. Recordings show characteristics of complicated wavelets and low signal-to-noise ratios. Under such conditions, conventional triangulation methods may have difficulty producing reliable locations; time-reversal imaging micro-seismic event location techniques are more promising. Locating micro-seismic events must be performed on-site for real-time monitoring of hydraulic fracturing. Introducing wave equation imaging techniques when locating micro-seismic events will increase the computation time, thus complicating real-time site monitoring. Therefore, the use of graphics processing unit (GPU) devices to accelerate time-reversal imaging micro-seismic event location technology becomes imperative. Three-dimensional synthetic data examples have demonstrated that the GPU-based time-reversal imaging micro-seismic event location method is typically 18 times faster than the central processing unit (CPU)-based implementation. The performance boost afforded by the GPU architecture allows us to locate micro-seismic events in 3D at a lower hardware cost and in less time than has been previously possible.



## 1. Introduction

Locating subsurface seismic sources is one of the most basic problems in geophysics. Earthquake location problems are especially widely discussed and studied in seismology. With industry's recent focus on unconventional resources such as tight gas reservoirs, shale gas, coal-bed methane, etc., locating micro-seismic events has become a technological focus in the geophysical community. By locating the micro-seismic events induced by hydraulic fracture, a reservoir engineer can depict the underground crack properties, including fracture orientation, density and dimension (Eisner et al., 2010; Maxwell and Urbancic, 2002); analyze the fracture pattern and its effect on the surrounding rock (Baig and Urbancic, 2010b; Phillips et al., 2002); identify the source mechanism (Baig and Urbancic, 2010a; Nolen-Hoeksema and Ruff, 2001); and monitor the reservoir exploitation process (Shan et al., 2002). Therefore, it is important to solve the micro-seismic location problem to facilitate unconventional oil and gas exploration and development.

The traditional earthquake location problem can be traced back to the works of Geiger in 1910 (Bratt and Bache, 1988; Geiger, 1912). Later geophysicists improved upon this work to form the Geiger method, now the most commonly used method of earthquake location. The core of the Geiger method has two parts: linearization of the nonlinear relationship between the earthquake source location and the seismic wave travel time and the use of the least squares method to solve this linear system. Due to the completeness of the evaluation system, these types of methods have been widely used in earthquake location (Flinn, 1965). These methods also have their limits, however; clear P and S wave travel times must be acquired from seismic records, which consequently must have a high signal-to-noise ratio (SNR). However, micro-seismic monitoring data are often very large datasets with a low signal-to-noise ratio. These characteristics limit traditional Geiger-type methods.

In recent years, geophysicists have applied the migration imaging principle of seismic exploration and developed migration-like locating methods that do not require seismic phase information and are suitable for low-SNR data. These methods treat micro- seismic sources in a manner analogous to diffraction within migration imaging: imaging methods from reflection seismology for processing

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diffraction are used to locate the source position. The corresponding locating process flow can be divided into two steps: continuation of the observation data to an underground wave field and application of the appropriate imaging conditions to obtain the source location and excitation time (Wang et al., 2013).

Time-reversal imaging micro-seismic event location technology has the advantages of being able to process low-SNR data without needing to extract seismic phase information. This approach has high locating accuracy and reliability, but because it uses wave equation time-reversal imaging technology, the number of calculations is very large. This is problematic because many applications of micro-seismic event locating occur in the real-time field monitoring of hydraulic cracks. For this reason, the location method must be computationally efficient, and therefore, these methods have not been widely used.

However, in recent years, with the heterogeneous accelerating platform developing rapidly and the coming of NVidia Compute Unified Device Architecture (CUDA), high-performance graphics processing unit (GPU) architecture has been widely applied in various intensive computing fields (Bader et al., 2011). Using GPU, many algorithms and applications in geophysics, which is traditionally among the most computationally intensive scientific research fields, have been able to run considerably more quickly. However, there has been very little work on the implementation of GPU in time-reversal imaging micro-seismic event location technology. In this paper, we focus on the implementation of high-performance 3D elastic wave seismic event location on GPU devices. After validating the high-efficiency performance in a single GPU device, we study the implementation of our method multi-GPU devices. With the acceleration brought by the use of GPU devices, which have excellent scalability, the computation time required for the 3D elastic wave time-reversal imaging micro-seismic event location method can be significantly reduced. In conclusion, by using GPU devices to run time-reversal imaging micro-seismic event location algorithms, we can achieve fast calculation speeds and high locating accuracy simultaneously.

This paper first presents the theory behind the time-reversal imaging micro-seismic event location method. It then outlines the details of the GPU implementation scheme and discusses the extensibility of the multi-GPU setup. Finally, through numerical examples, we show the validity of the principle and quantify the speedup brought by GPU devices.

## 2. Theory

According to the displacement representation theorem (Aki and Richards, 2002), the displacement generated by an earthquake fault can be expressed as follows:

$$U_n(x,t)=\int_{-\infty}^{+\infty}\mathrm{d}\,\tau\iint_{\Sigma}\left[\Delta\,u_i(\xi,\tau)\right]c_{ijpq}(\xi)\nu_j(\xi)\times G_{np,q}(x,t;\xi,\tau)\mathrm{d}\,\Sigma \tag{1}$$

here, $\Sigma$ represents the fault plane, $\xi$represents any point on the surface of the fault, $U_n(x, t)$is the $n$th component of displacement of observation points in the $x$direction, $c_{ijpq}(\xi)$is the elastic modulus of the medium in the $\xi$ location, $\nu_j(\xi)$ is the direction cosine of the fault plane in the $\xi$ location, and $G_{np,q}(x, t; \xi, \tau)$ is the spatial partial derivative with respect to $\xi_q$ to the Green's function $G_{np}(x, t; \xi, \tau)$. Finally, $G_{np}(x, t; \xi, \tau)$is the $n$th component of displacement in the $x$ direction at time $t$created by the unit concentration force in the $p$ direction over time $\tau$, acting on the fault plane at the point $\xi$.

Considering only the hypocenter, the overall effect of the earthquake fault is equal to the source effect of the fault on the $\xi_0$ location at time $t_0$. Then, Eq. (1) can be rewritten as follows (Aki and Richards, 2002):

$$U_n(x,t)=G_{nk}(x,t;\xi_0,\tau_0)M_k(\xi_0,\tau_0) \tag{2}$$

where $M_k(\xi_0, \tau_0)$ represents the source effect of the $k$-type earthquake source mechanism and $G_{nk}(x, t; \xi_0, \tau_0)$represents the medium effect between the source and the receiver of the $k$-type focal mechanism. If the source is located at the origin, then Eq. (2) can be rewritten as follows:

$$U_n(x-\xi_0,t-\tau_0)=G_{nk}(x-\xi_0,t-\tau_0;0,0)M_k(0,0) \tag{3}$$

where $x-\xi_0$is the hypocentral distance and $t-\tau_0$is the travel time. It is evident that if the seismic record of $U_n(0, 0)$ can be obtained, the source center location can be determined. Using this framework,

$$\begin{cases} x-\xi_0=0 \\ t-\tau_0=0 \end{cases} \tag{4}$$

where $x$ and $t$ are the observation point position and the time of the seismic signals arriving at the observation point, respectively, and $\xi_0$, $\tau_0$are the epicenter and the time of origin of the earthquake. Thus, if we propagate the signal obtained from each receiver to return to the source, we can solve the above problem.

To make every receiver record return to the source point, we can use the elastic wave equation to rebuild the subsurface wave fields from the record data and then apply a proper 'image condition' to extract the source parameters (i.e., position, time of excitation). A fundamental principle of the time-reversal imaging micro-seismic event location technique is that the data generated by the same source recorded by different receivers must have a unique time of excitation. Unlike the Reverse Time Migraiton, the excitation time is unknown; furthermore, we also lack information about the wave fields from the source. Thus, a simple zero-lag cross-correlating image condition is not suitable for seismic event location. We can detect the point with maximum energy by summing the wave field energy at every time step. The location of the maximum corresponds to the source position, and its time is the excitation time of the source. The basic principle is shown in Fig. 1, where the red star denotes the source position and excitation time and colors indicate the amount of energy. It is worth noting that the focused energy is not equal to the energy released from the source: the amplitude fails to define the magnitude.

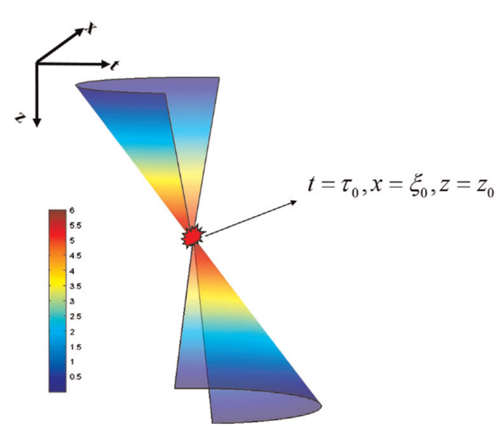


**Fig. 1.** The principle of 2D time-reversal imaging micro-seismic event location method, the red star shows the source location and the excitation time, and colors illustrate incremental concentrated energy, from low (blue) to high (red). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)