The Preliminary Results of GMSTech: A Software Development for Microseismic Characterization

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Abstract. The processing of microseismic data requires reliable software for imaging the condition of subsurface related to occurring microseismicity. In general, the currently available software is only specific for certain processing module and developed by the different developer. However, the software with integrated processing modules will give a better value because the users can use it easier and faster. We developed GMSTech (Ganesha Microseismic Technology), a C\# language-based standing-alone software consisting several modules for processing of microseismic data. Its function is to solve a non-linear inverse problem and imaging the subsurface. C\# library is supported by ILNumerics to reduce time consumption and give good visualization. In this preliminary result, we will present four developed modules: (1) hypocenter determination, (2) moment magnitude calculation, and (3) 3-D seismic tomography. In the first module, we provide four methods for locating the microseismic events that can be chosen by a user independently: simulated annealing method, guided grid-search method, Geiger’s method, and joint hypocenter determination (JHD). The second module can be used for calculating moment magnitude using Brune method and to estimate the released energy of the event. At last, we also provided the module of 3-D seismic tomography for imaging the velocity structures based on delay time tomography. We demonstrated the software using both a synthetic data and a real data from a certain geothermal field in Indonesia. The results for all modules are reliable and remarkable, reviewed statistically by RMS error. We will keep examining the software using another set of data and developing further modules of processing.
1. Introduction

Observation of micro-seismic events is very important to characterize geothermal field or volcanotectonic activity. Our previous works in geothermal characterization [1, 2, 3], the reservoir can be characterized for example for detecting fracture and permeability zone, Vp/Vs anomaly in water liquid replacement, attenuation structure, shear wave splitting to image anisotropy distribution, etc. In volcano-tectonic [4, 5, 6], its activity is imaged by a distribution of the event’s locations. By observing that distribution, we can map active fault on a shear zone, as well as fluid compression.

The processing of micro-seismic data requires reliable software for imaging the condition of subsurface related to occurring micro-seismicity. In general, the currently available software is only specific for certain processing module and developed by the different developer. Two examples of these softwares are VELEST, GAD (Geiger’s method with Adaptive Damping) and SIMULPS. In 1984 E. Kissling and W. L. Ellsworth modified VELEST, the program based on Fortran. They used it to calculate a Minimum 1-D model (i.e., a well-suited 1-D velocity model of earthquake location and 3-D seismic tomography) of Long Valley area, California [7]. In 2005, K. Nishi developed hypocenter calculation software GAD based on Fortran. This software uses least square optimization to determine hypocenter location [8]. Originally, in 1983 Thurber developed SIMULPS to calculate tomography inversion. It provides alternative forward solution methods (ray tracer), approximated ray tracing plus pseudo-bending (ART-PB) and 3D shooting method using paraxial rays and perturbation theory (RKP) [9].

The software with integrated processing modules will give a better value because the users can use it easier and faster. We developed GMSTech (Ganesha Micro-seismic Technology), a C# language-based standing-alone software consisting of several modules for micro-seismic data processing. Its main function is to solve the non-linear inverse problem and to image the subsurface. C# library is supported by ILNumerics to reduce time consumption and give better visualization. The compiled program is an executable file which is compatible with Windows Operating System.

2. Methods

2.1. Ray Tracing

2.1.1. Straight Method

This method uses straight line connecting the source to the receiver. It is so simple using the assumption that the medium is homogenous.

2.1.2. Shooting Method

In wave propagation, this method uses Snell’s Law to determine incident and transmission angles at the boundary layer. These angles affect total path length from the source to the receiver. This method will calculate root mean square of error then choose minimum error to determine the best location. The Snell’s Law used follows bellow equation:

$$\frac{V_1}{V_2} = \frac{\sin \theta_1}{\sin \theta_2}$$  \hspace{1cm} (1)

2.1.3. Pseudo-Bending Method

Pseudo-bending is an approach in minimization of travel time based on Fermat’s Principle by giving small perturbations gradually on ray paths. Equation bellow is used to calculate travel time (T).

$$T = \int_{source}^{station} \frac{1}{v} dl$$  \hspace{1cm} (2)

Where l is ray path and v is velocity. Travel time is calculated by sum all of Ray segment. The pseudo-bending method calculates it using perturbation scheme. Initial definition is defined by 3
points which are interpolated linearly. The middle point is an estimation of initial trajectory. Furthermore, it will be perturbed iteratively using wave equation to calculate optimum travel time (the wave propagates using the fastest travel time). The segments of initial trajectory are separated to calculate travel time which is more optimum. Zhao et al. modified the equation using Snell’s law to determine the middle point to calculate more optimum travel time [10].

2.2. Hypocenter Determination

2.2.1. Simulated Annealing Inversion

One method of guided random search is simulated annealing method (SA) [11, 12]. In the inversion process, SA is based on the thermodynamic formulation of substance’s crystal annealing. The important step is to define a prior model. The model is defined by choosing the interval of the minimum value and the maximum value of the model parameter (earthquake location). The model parameter will be determined randomly in that its value following equation:

\[ \text{Model}_t = \text{Model}_{t}^{\text{min}} + R (\text{Model}_{t}^{\text{max}} - \text{Model}_{t}^{\text{min}}) \]  

(3)

Where \( R \) is a uniform probability.

The annealing process in thermodynamic is adopted in the inversion problem solving. It uses the model parameter to define system configuration and uses the objective function as energy. Temperature factor is controller factor that has the same unit as the objective function. The model perturbation probability is following equation:

\[ P(\Delta E) = \exp\left(-\frac{\Delta E}{T}\right) \]  

(4)

Where \( \Delta E \) is the objective function change or the misfit change caused by the model perturbation.

2.2.2. Grid Search Inversion

The global approximation is an alternative to obtain a solution of non-linear inversion. This method evaluates value of the objective function for each model in space model. This systematic evaluation is the easiest way to obtain the solution of the non-linear solution. Basic calculation of the objective function is a forward modeling.

2.2.3. Geiger’s Method Inversion

Geiger’s method is one of single event determination (SED). It is an iterative processing using least square optimization to determine hypocenter. Its principle is solving the objective function that gives smaller residual square cumulative of all stations [8].

2.2.4. Joint Hypocenter Determination

This method adapts Geiger’s Method to relocate hypocenter. The difference is hypocenter determination calculated using all events in one matrix.

2.3. Moment Magnitude Calculation

In this calculation, we adapt Brune’s method. The classic Brune model of a shear source is used to fit the far-field displacement spectra, computed by integrating the series in time or frequency domain the velocity particle motion. That method is used to optimized the model, to obtain low-frequency level, and corner frequency that will be used to calculate seismic moment [13]. Seismic moment can be
estimated from low-frequency plateau. Seismic moment is converted to moment magnitude following the equation below [14]:

\[ M_w = \frac{2}{3} \log(M_0) - 6.07 \]  

(5)

2.4. Delay Time Tomography
Delay time tomography is the method that was developed in this research. The delay time is the difference of travel time observation and travel time calculation. Travel time observation is obtained in field observation. Another one is calculated using velocity model which is known [15]. For resolving tomography inversion, least square method was implemented iteratively to minimize the differences between observed and calculated travel times.

3. Results and Discussions
3.1. Graphical User Interface
Ganesha Micro-seismic Technology (GMSTech) is a software for micro-seismic processing to determine hypocenter location, magnitude, 1D and 3D seismic velocity structure in geothermal, oil, and gas exploration field. There are four modules in this software such as hypocenter determination, moment magnitude calculation, the 1D velocity model, and tomography. Each module has specific parameter and file required to be loaded. Graphical user interface of GMSTech is shown in Figure 1.

![Figure 1. Graphical user interface of GMSTech for micro-seismic processing](image)

3.2. Hypocenter Determination
In general, this module requires arrival time data, location of station data, and 1D velocity. Furthermore, this module requires ray tracing method to obtain ray path and calculated travel time. In the calculation, ray tracing of straight method or shooting method can be used. Straight method is used for contras medium which is not extreme or homogenous medium. For high contras medium, shooting method is available by calculating incident angle and transmission angle at each layer. Like the straight method, shooting method can be used in homogenous medium but requires more time due to angle calculation. Figure 2 shows the histogram of Simulated Annealing Inversion result applied for synthetic and real data. The number of event of synthetic data and real data respectively are ten events and 482 events, respectively. In this case, inversion results using ray tracing Shooting Method is better than inversion results using ray tracing Straight Method (Figure 2). These ray tracing will be applied for all method of hypocenter determination.
Figure 2. Histogram of Simulated Annealing Inversion results using (a) Shooting Method and (b) Straight Method applied for synthetic data; using (c) Shooting Method; and (d) Straight Method applied for real data.

Figure 3. Hypocenter determination results using (a) Grid Search Inversion, (b) Simulated Annealing, (c) Inversion Geiger’s Method Inversion, and (d) Joint Hypocenter Determination; and histogram of RMS error (e) Grid Search Inversion, (f) Simulated Annealing Inversion, (g) Geiger’s Method inversion, and (h) JHD.

Grid Search Inversion calculates the hypocenter by trying at every grid [16]. The calculation is processed for each event and each station. The optimization of this method uses error value and maximum iteration as iteration boundary. The optimum result will be defined as the final result. This
method has a limitation that the result may be trapped in minimum local. The calculation that process in every grid makes this method requires much time. Figure 3 (a) and (e) respectively show the result of hypocenter determination using Grid Search Inversion.

Simulated Annealing Inversion can solve Grid Search Inversion limitation by finding minimum global. The optimization using temperature function reduces time consumption. Figure 3 (b) shows the result of hypocenter determination using Simulated Annealing Inversion and (f) its histogram of error rms.

Geiger’s Method Inversion is single event determination like Grid Search Inversion and Simulated Annealing Inversion, but it doesn’t process for each station. An event recorded in several stations is calculated in a matrix. The inversion uses Least Square Inversion guided by error value and maximum iteration. Actually, this method requires initial hypocenter. In this software, there are two choices to use initial hypocenter or not. The choice without initial hypocenter uses the station that has the fastest velocity as initial hypocenter. The result using initial hypocenter is better than the result without initial hypocenter.

Joint Hypocenter Determination adapts Geiger’s Method Inversion. The difference is the calculation for all events and all stations. It requires initial hypocenter like Geiger’s Method Inversion.

3.3. Moment Magnitude Calculation
The required data for moment magnitude calculation are the location of the station, arrival time data, hypocenter data, velocity model and waveform list. We use the same format for the location of the station, arrival time data, and hypocenter data as we used in hypocenter determination process. The waveform list is list of events, the station recording related events, and the waveform file for each direction.

Waveform loaded is processed by converting from velocity domain to displacement domain, calculating signal to noise ratio, spectral fitting, calculating moment seismic and then converting it to moment magnitude. In spectral fitting, we optimize to fit the spectral and amplitude and to determine corner frequency and low-frequency level. Figure 4 (b) shows spectral fitting for P wave and S wave, event one recording by station bor3. Figure 4 (a) shows the magnitude of all events.

![Figure 4.](image)

**Figure 4.** (a) The result of magnitude calculation and (b) spectral fitting between observed and modeled spectrum for P wave and S wave

3.4. Tomography
The required data in this module are the event catalog, the location of the station and 1-D velocity model. Furthermore, the definition of space model and the grid size are important. The space model accommodates event location and the location of the station. The other important parameters are the
number of bending points, maximum perturbation number, normal and gradient damping value, the maximum number of iteration and RMS error. The results of this processing are checkerboard and velocity perturbation. The checkerboard images the resolution (shown in Figure 5). We can draw a line to establish a section. Figure 5.(a) and 5.(b) images the different line and its section.

Figure 5. Tomographic inversion display. (a) & (b) Vertical section of Vp structure and (c) checkerboard resolution test displays.

4. Conclusions

We present the data storage format in ASCI for all modules. Hypocenter Determination module is available to use four methods, Simulated Annealing, Grid Search, Geiger’s method, and JHD Inversion. The results are plotted in the 3D display that can be rotated in any direction. Magnitude calculation using Brune’s method shows spectral fitting and plotting data. Delay time tomography produces 3D seismic velocity structure and the model resolution is evaluated by checkerboard resolution test.

5. Reference

[1] Ry R V and Nugraha A D 2016 Reservoir characterization around Geothermal Field, West Java, Indonesia derived from 4-D seismic tomography IOP Conf. Series: Earth and Environmental Science 29 (1) doi: 10.1088/1755-1315/29/1/012001.

[2] Nugraha A D, Syahputra A, Fatkhan and Sule R 2013 Seismic velocity and attenuation structures in the geothermal field AIP. Conf. Proc. 1554 238-241 doi: 10.1063/1.4820329.

[3] Hasanah M U, Nugraha A D and Sule R 2013 Attenuation tomography using microearthquake (MEQ) data in the a geothermal field AIP. Conf. Proc. 1554 273-276 doi: 10.1063/1.4820338.

[4] Nugraha A D, Widiyantoro S, Gunawan A, Suantika G 2013 Journal of Mathematical and Fundamental Sciences 45 (1) 17-28 doi: 10.5614/j.math.fund.sci.2013.45.1.2.

[5] Ry R V, Priyono A, Nugraha A D, and Basuki A 2015 Seismicity study of volcano-tectonic in and around Tangkuban Parahu active volcano in West Java region, Indonesia AIP Conf. Proc. 1730 020004
[6] Firmansyah R, Nugraha A D and Kristianto 2015 The preliminary results: Internal seismic velocity structure imaging beneath Mount Lokon *AIP. Conf. Proc.* **1658** 050012 DOI: 10.1063/1.4915051.

[7] Kissling E, Ellsworth W L and Cockerham R S 1984 Three-dimensional structure of the long valley caldera, California region by geotomography. In Active Tectonic and Magmatic Processes beneath Long Valley Caldera, Eastern California, *Open-le Report 84-939. U. S. Geol. Survey*, Menlo Park.

[8] Nishi K 2005 Hypocenter calculation software GAD (Geiger’s method with Adaptive Damping) *Manual. JICA*

[9] Thurber C H 1983 *J. Geophys. Res.* **88** 8226-8236.

[10] Um J and Thurber C H 1987 *Bull. Seism. Soc. Am.* **77** 972–986.

[11] White S R 1984 Concepts of scale in simulated annealing *Proc. IEEE Int. Conference on Computer Design, Port Chester* pp.646–651.

[12] Weber Z 2000 *Elsevier Physics of Earth and Planetary Interiors* **199** pp.149-159.

[13] Brune J N 1970 *J. Geophys. Res.* **75** 4997–5009.

[14] Kanamori H and Hanks T C 1979 *J. Geophys. Res.* **84** (B5)

[15] Widiyantoro S, Gorbatoc A, Kennett B L N and Fukao Y 2000 *Geophys. J. Int.* **141** 747-758

[16] Ry R V and Nugraha A D 2015 Improve earthquake hypocenter using adaptive simulated annealing inversion in regional tectonic, volcano-tectonic, and geothermal observation *AIP. Proc. Conf.* **1658** 030004 DOI: 10.1063/1.4915012.