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ORIGINAL ARTICLE

Determining hypocentral parameters for local earthquakes under ill conditions using genetic algorithm

Woohan Kim · In-Kyeong Hahm · Won-Young Kim · Jung Mo Lee

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Abstract We demonstrate that GA-MHYPO determines accurate hypocentral parameters for local earthquakes under ill conditions, such as limited number of stations (phase data), large azimuthal gap, and noisy data. The genetic algorithm (GA) in GA-MHYPO searches for the optimal 1-D velocity structure which provides the minimum traveltime differences between observed (true) and calculated P and S arrivals within prescribed ranges. GA-MHYPO is able to determine hypocentral parameters more accurately in many circumstances than conventional methods which rely on an a priori (and possibly incorrect) 1-D velocity model. In our synthetic tests, the accuracy of hypocentral parameters obtained by GA-MHYPO given ill conditions is improved by more than a factor of 20 for error-free data, and by a factor of five for data with errors, compared to that obtained by conventional methods such as HYPOINVERSE. In the case of error-free data, GA-MHYPO yields less than 0.1 km errors in focal depths and hypocenters without strong dependence on azimuthal coverage up to 45°. Errors are less than 1 km for data with errors of a 0.1-s standard deviation. To test the performance using real data, a well-recorded earthquake in the New Madrid seismic zone and earthquakes recorded under ill conditions in the High Himalaya are relocated by GA-MHYPO. The hypocentral parameters determined by GA-MHYPO under both good and ill conditions show similar computational results, which suggest that GA-MHYPO is robust and yields more reliable hypocentral parameters than standard methods under ill conditions for natural earthquakes.

Keywords Hypocentral parameter · Genetic algorithm · GA-MHYPO · Ill condition

Abbreviation

GA Genetic algorithm

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1 Introduction

Determining accurate hypocentral parameters (epicenter, focal depth, and origin time) is fundamental in earthquake seismology. Lomnitz (2006) pointed out clearly the problems in conventional methods for determining hypocentral parameters, which depend strongly upon an a priori velocity model and whose accuracy depends on the degree of discrepancy between the true velocity structure and the velocity model used for location. Even when using error-free arrival time information, the model will introduce location errors if it does not reflect the true velocity structure.

Many methods have been developed to determine hypocentral parameters of local earthquakes. Typical conventional methods include HYPO-71 (Lee and Lahr 1975), HYPOINVERSE (Klein 1978), HYPOELLIPSE (Lahr 1980), and HYPOSAT (Schweitzer 1997, 2001). These conventional methods use an initial model which may differ from the true velocity structure. VELEST (Kissling et al. 1994) determines hypocentral parameters and the velocity structure simultaneously, which are also affected by an initial velocity model.

Conventional methods are thus dependent upon the a priori models used and will yield different hypocentral parameters when provided with different models. GA-MHYPO (Kim et al. 2006) was developed to reduce the problems encountered in conventional methods by searching numerous velocity models that are generated randomly within a prescribed range for the optimal 1-D velocity structure and hypocentral parameters. The a priori model is not needed. Computational tests using synthetic data show that the weighted average velocity of the GA-optimized velocity structure between a source and receivers converges to that of the true one if it is within the prescribed range and if the phase data used have no picking error (Kim et al. 2009). The tradeoff between hypocentral parameters and the velocity model is almost negligible since GA-MHYPO uses the GA-optimized velocity structure.

By adaptively optimizing the 1-D velocity model between the source and receivers, GA-MHYPO can reduce the contributions of poor ray path estimation and focal depth dependence in the earthquake location problem. We test the robustness of the method using synthetic data in a variety of unfavorable circumstances such as poor azimuthal coverage and small number of stations. We also consider data with phase-arrival errors. We first generated synthetic phase data using the two-point ray tracing method (Kim and Baag 2002), assuming that the velocity structure and hypocentral parameters of an earthquake are known. The errors of our synthetic data are negligibly small (less than 10^{-10} s). We apply GA-MHYPO and HYPOINVERSE to determine the hypocentral parameters with a varying number of stations (phases), azimuthal gaps, and focal depths for the data, both without errors (noise) and with errors. HYPOINVERSE is chosen to represent the conventional methods which determine hypocentral parameters using an initial velocity model.

To demonstrate the robustness of GA-MHYPO for natural earthquakes recorded under a variety of conditions, we select a well-recorded earthquake that occurred on July 30, 2003 ($m_b = 2.8$) in the New Madrid Seismic Zone, Central USA. Using all available data, this event provides good conditions for determining its hypocentral parameters. The earthquake was recorded by more than 50 stations, the azimuthal gap was less than 50°, seven stations lie within an epicentral distance of 15 km, and the nearest one is about 2.5 km. Conventional algorithms can determine reliable hypocentral parameters under such excellent conditions even when the a priori velocity model differs from the true velocity. We explore the performance of GA-MHYPO by systematically reducing the number of phases and reducing the azimuthal coverage to test our results under increasingly ill conditions.

We then employ GA-MHYPO to relocate 68 earthquakes obtained from the Himalaya Nepal–Tibet Seismic Experiment (HIMNT), an IRIS/PASSCAL deployment of 27 broadband seismometers that recorded in the area between 2001 and 2003 (Monsalve et al. 2006). As discussed in the later section, the earthquakes occurring in the High Himalaya pose an ill-conditioned location problem, since few stations are available for each event, the data are noisy, the azimuthal coverage is poor (azimuthal gap > 180°), and the closest station from an epicenter (minimum epicentral distance: dmin) is greater than 70 km in most cases. Our results are compared with those of Monsalve et al. (2006) determined by VELEST (Kissling et al. 1994) using 1-D velocity model with three layers.

2 GA-MHYPO

GA-MHYPO (Kim et al. 2006) was developed by extending the HYPO-71 algorithm (Lee and Lahr 1975) through application of GA, a two-point ray tracing method, and a weighting factor. The GA is a stochastic global search method and is capable of near-optimal solutions for a multivariable function (Goldberg 1989). In this study, 50 data generations with 100 initial models were performed by the GA. The GA in GA-MHYPO searches for the optimal 1-D P-wave velocity structure (GA-optimized velocity structure) and for the optimal average v_p/v_s to estimate the S-wave velocity. The GA-optimized velocity structure is not the velocity structure from inversion but the one found by stochastic forward search. The number of layers in the model usually makes the problem underdetermined and the GA-optimized velocity structure is a possible solution which gives minimal errors in traveltimes. The GA-optimized velocity structure itself is not physically meaningful, but the weighted average velocity is physically meaningful. The two-point ray tracing algorithm (Kim and Baag 2002) in GA-MHYPO reduces raypath error between a source and a receiver. The weighting factor related to the take-off angle at the source in GA-MHYPO enhances the degree of the focal depth information, which depends on the focal depth to epicentral distance ratio (Hahm et al. 2007). The fitness function used in this study is

$$F_i = \sqrt{A\sum_{j=1}^{kp} Wp(j)\left(t_j^{\mathrm{tp}} - t_j^{\mathrm{cp}}\right)^2 + B\sum_{j=1}^{ks} Ws(j)\left(t_j^{\mathrm{ts}} - t_j^{\mathrm{cs}}\right)^2} \tag{1}$$

where F_i is the fitness function of the ith velocity model of P- and S-waves. t_j^{tp}, t_j^{ts}, t_j^{cp}, and t_j^{cs} are the values of true and calculated traveltimes of P- and S-waves for the jth station, respectively. A and B are constants, and Wp and Ws are the weighting factors, the values of data quality multiplied by focal depth information, for P- and S-waves, respectively. kp and ks represent the total number of arrivals for P and S, respectively. In this study, A and B are consistently assumed to be 3 and 1, respectively, reflecting higher weighting of P than S picks in inversion.

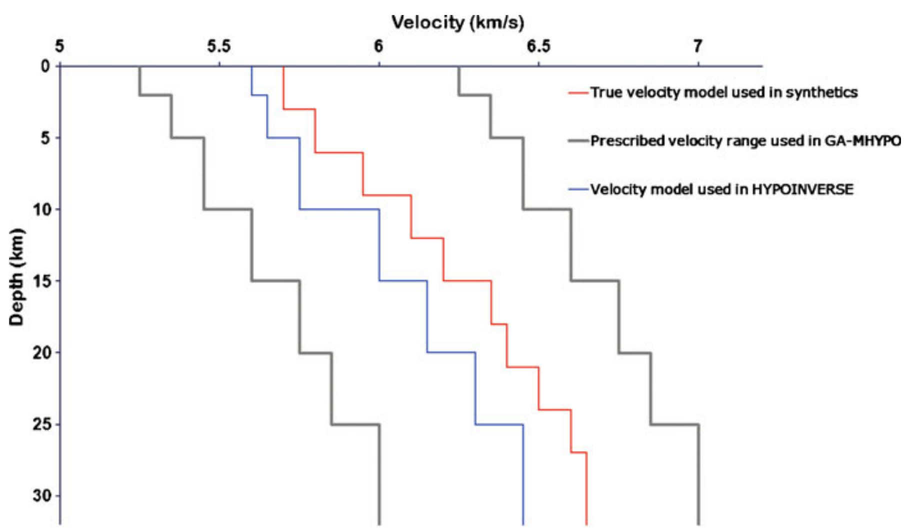


Fig. 1 The true velocity model used to synthesize the phase time data (*solid red line*), the prescribed velocity range used in GA-MHYPO (*hatched black lines*), and the velocity model used in HYPOINVERSE (*solid blue line*). It is worthwhile to note that the true velocity model has 10 layers but others have only 7 layers

3 Test with synthetic data

The synthetic data are obtained from the true model toward which we will test convergence (Fig. 1). The true model has 10 layers whose thicknesses are 3 km each from the top to the 9th layer and 4 km for the bottom (10th) layer. The synthetic data are generated by applying the two-point ray tracing method (Kim and Baag 2002). The numerical errors in the synthetic data are expected to be only machine errors and will term these error-free data. The epicentral distances of all arrivals are in the range from 10 to 100 km. Both focal depths and azimuthal gaps vary. To mimic phase picking errors, noisy data are obtained from error-free synthetic data by adding random noise having 0.1-s standard deviation which is equivalent to a maximum of about ±0.29-s phase timing error. The errors in phase time are constrained to increase as the epicentral distance increases to mimic the amplitude decay and resulting relative noise contamination increasing the errors in phase picks for real data.

The velocity model to test the performance of both GA-MHYPO and HYPOINVERSE has seven layers whose thicknesses are 2, 3, 5, 5, 5, 5, and 7 km from top to bottom as presented in Fig. 1. The prescribed velocity range for GA-MHYPO is given about ±0.4 km/s from the true value (green lines in Fig. 1) and ν_p/ν_s ranges between 1.66 and 1.78 whereas the true value is $\sqrt{3}$. The velocity model used in HYPOINVERSE has about 5–10% lower velocities than those in the true one as an example (blue line in Fig. 1) with the true ν_p/ν_s ratio, $\sqrt{3}$.

Hypocentral parameters under ill conditions are estimated using both GA-MHYPO and HYPOINVERSE, and the accuracies of results are compared. We estimate hypocentral parameters with varying numbers of arrivals, azimuthal gaps, and focal depths. We examine two cases: error-free data and noisy data. The tests using error-free data employ between four and 12 P and S phases, incremented by one, and the noisy data are incremented from 6 to 16 arrivals by steps of two. We vary the azimuthal gaps 315°, 270°, and 180°. Focal depths of 5, 17, and 29 km were tested. Station distribution for our synthetic test is presented in Fig. 2.

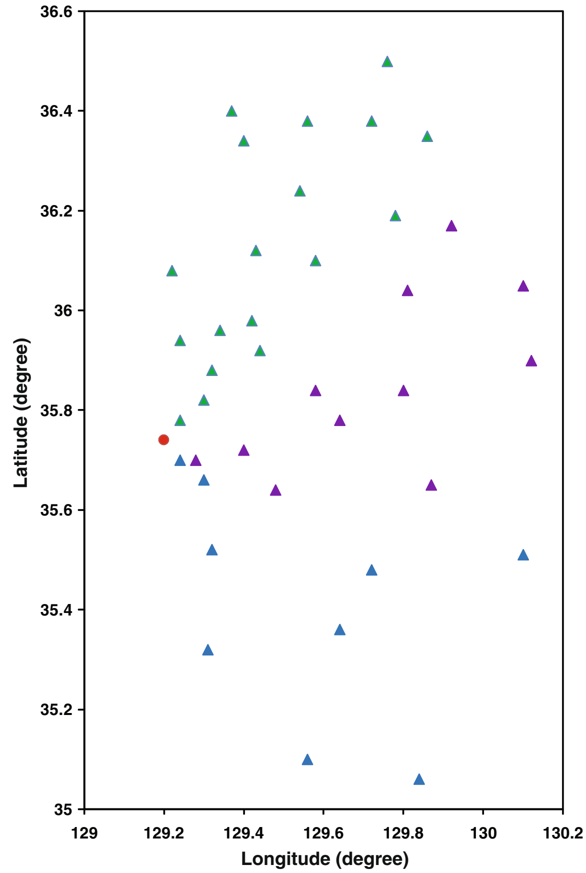


Fig. 2 The distribution of stations in the test with synthetic data. The epicenter location is marked by a *red dot* and the station locations are marked by *triangles*. The *green-colored stations* are used for the tests with 315° azimuthal gap. The *green* and *violet-colored stations* are used for those with 270° azimuthal gap. All stations are used for those with 180° azimuthal gap

3.1 Error-free data

The errors in focal depths estimated by GA-MHYPO and HYPOINVERSE using error-free synthetic data are presented in Fig. 3. As shown in Fig. 3a, GA-MHYPO yields reliable focal depths although the problem is poorly constrained. The errors are relatively large when P and S phases for only four stations are used. The azimuthal gap, focal depth, and number of stations do not significantly affect the accuracy of the depth determined by GA-MHYPO with error-free phase data when P and S phases for more than four stations are used.

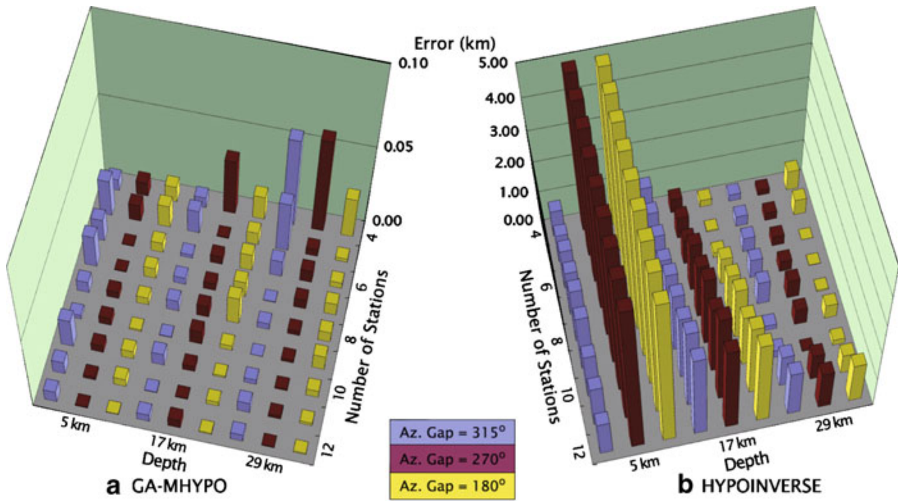


Fig. 3 Errors in focal depth determinations with error-free synthetic data by GA-MHYPO (**a**) and those by HYPOINVERSE (**b**). Focal depths of 5, 17, and 29 km are considered with four to 12 stations and 180°, 270°, and 315° azimuthal gaps

Generally, the focal depth errors are less than 0.1 km. The general trend of errors in focal depths determined by GA-MHYPO is stable and small under ill conditions compared with those by HYPOINVERSE (Fig. 3b). Errors in focal depths estimated by GA-MHYPO are less than those of HYPOINVERSE by more than a factor of fifty except for the cases of four or five stations, in which the inversion is likely unstable due to the limited number of arrivals.

HYPOINVERSE cannot resolve some focal depths such as the cases of a 5-km depth with azimuthal gaps of 270° and 180°, whereas the 5-km depth with an azimuthal gap of 315° is resolved (Fig. 3b). This is because the epicentral distance of the closest station (dmin) is 12 km for the case of the 315° azimuthal gap, whereas dmin is 18 km for the cases of azimuthal gaps of 270° and 180°. This exercise reinforces the generally well-known tenet that geometry of the station distribution is important in earthquake location using conventional location methods (Lomnitz 2006; Hahm et al. 2007). It appears that dmin is more critical than the number of arrivals, or the azimuthal gap, for constraining the focal depth using HYPOINVERSE.

Errors in epicenters determined by GA-MHYPO and HYPOINVERSE are presented in Fig. 4. The epicentral errors from GA-MHYPO are less than 0.1 km under ill conditions as shown

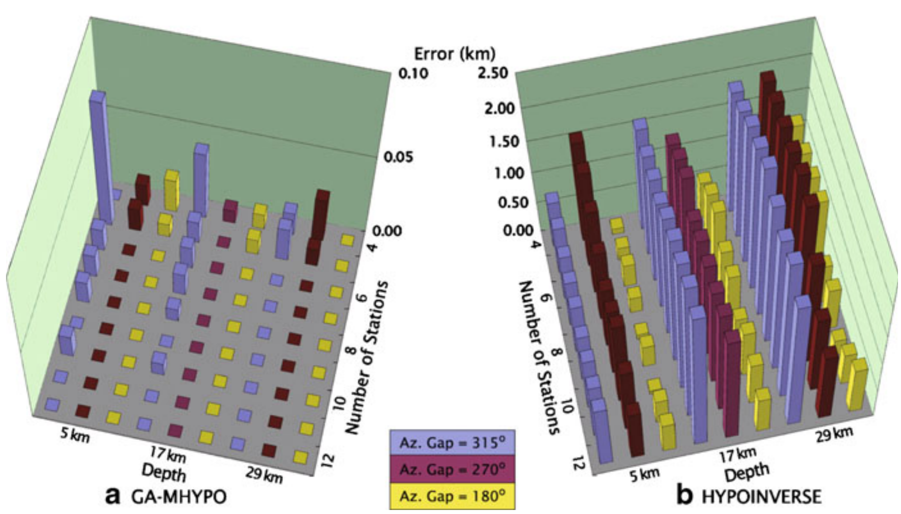


Fig. 4 Errors in epicenter determinations with error-free synthetic data by GA-MHYPO (**a**) and those by HYPOINVERSE (**b**). The considered cases are the same as those in Fig. 3

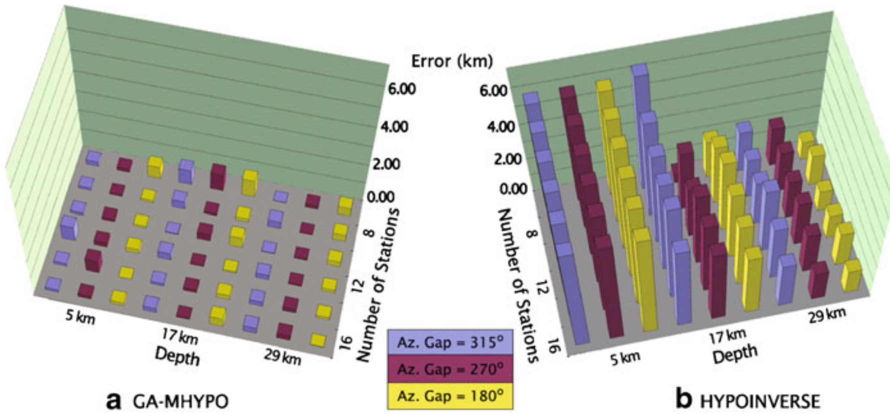


Fig. 5 Errors in focal depth determinations with noisy synthetic data by GA-MHYPO (**a**) and those by HYPOINVERSE (**b**). The noisy data are generated by adding the random noise of the 0.1-s standard distribution to the error-free synthetic data. Focal depths of 5, 17, and 29 km are considered with six to 16 stations and 180°, 270°, and 315° azimuthal gaps

in Fig. 4a. GA-MHYPO also yields a stable and small variation of errors in epicenters when the number of stations is greater than 5 and the azimuthal gap is less than or equal to 270°. The general trend of horizontal error decreases as the azimuthal coverage increases and/or the number of stations increases; however, its variation is small. Although the velocity model used in HYPOINVERSE is about 5–10% different from the true one in this specific exercise, the epicentral errors from HYPOINVERSE (Fig. 4b) are larger than those of GA-MHYPO by a factor of more than 20, except for the cases of four or five stations. As expected, the epicentral errors of HYPOINVERSE decrease as the azimuthal coverage increases. The errors, however, become larger as the focal depth increases. This is because the angle between the vertical and the path to the nearest station decreases as the focal depth grows larger; thus, the horizontal uncertainty increases.

3.2 Noisy data

The errors in focal depths determined by GA-MHYPO and HYPOINVERSE using noisy data are presented in Fig. 5. The errors in focal depths estimated by GA-MHYPO (Fig. 5a) are less than 0.5 km. The errors decrease as the focal depth increases from 5 to 29 km, and when the number of phase arrival data increases, similar to the case using error-free data (Fig. 3a). The errors using noisy data are, however, about five times greater

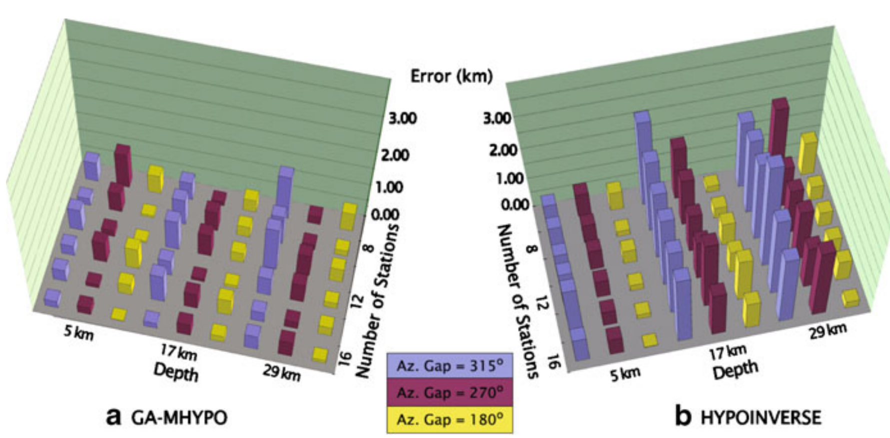


Fig. 6 Errors in epicenter determinations with noisy synthetic data by GA-MHYPO (**a**) and those by HYPOINVERSE (**b**). The used data and considered cases are the same as those in Fig. 5

Table 1 Hypocentral parameters of an earthquake (m_b (L_g) = 2.8, July 30, 2003) occurred in the New Madrid Seismic Zone determined by GA-MHYPO and HYPOINVERSE

Method	Az. Gap (deg)	No. of stations	Origin time (hh:mm:ss.ss)	Latitude (deg)	Longitude (deg)	Depth (km)	rms Error (s)
GA-MHYPO	80	33	02:50:18.40	36.5147	−89.5260	5.54	0.043
	180	25	02:50:18.19	36.5158	−89.5258	5.60	0.035
	270	11	02:50:18.21	36.5133	−89.5221	5.58	0.020
HYPOINVERSE	50	43	02:50:18.49	36.5195	−89.5267	5.83	0.197

The reliable phase time data are collected from records of 46 stations. Intentional ill conditions are generated by limiting the azimuthal coverage—reducing the number of stations

than those using error-free data. The errors are still much smaller than those determined by HYPOINVERSE (Fig. 5b).

In general, the magnitudes of the errors in focal depths by HYPOINVERSE using noisy data (Fig. 5b) are similar to those arising from error-free data (Fig. 3b). The focal depths of 5-km-deep events are again not resolved regardless of azimuthal coverage since the epicentral distances of the closest stations are between 12 and 14 km. Focal depths of 17- and 29-km-deep sources are resolved by HYPOINVERSE because dmin ranges from 18 to 21 km. These indicate the importance of the nearest stations for the focal depth determination in a conventional earthquake location process.

The errors in epicenters determined by GA-MHYPO and HYPOINVERSE using noisy data are presented in Fig. 6. Errors from GA-MHYPO are less than about 0.5 km, although the

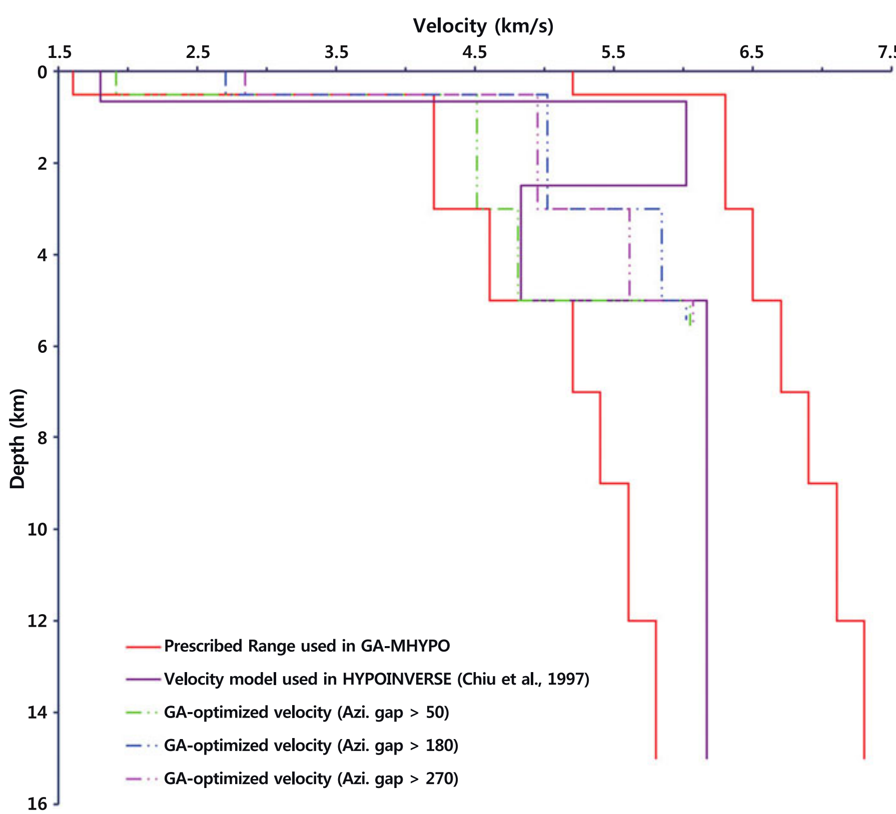


Fig. 7 The prescribed velocity range used by GA-MHYPO (*red*) and the velocity model used by HYPOINVERSE (*violet*) in the determination of hypocentral parameters of an earthquake (m_b (L_g) = 2.8, July 30, 2003) occurred in the New Madrid Seismic Zone. The GA-optimized velocity structures of the cases of 80°, 180°, and 270° azimuthal gaps by GA-MHYPO are presented by *different colored dotted lines*

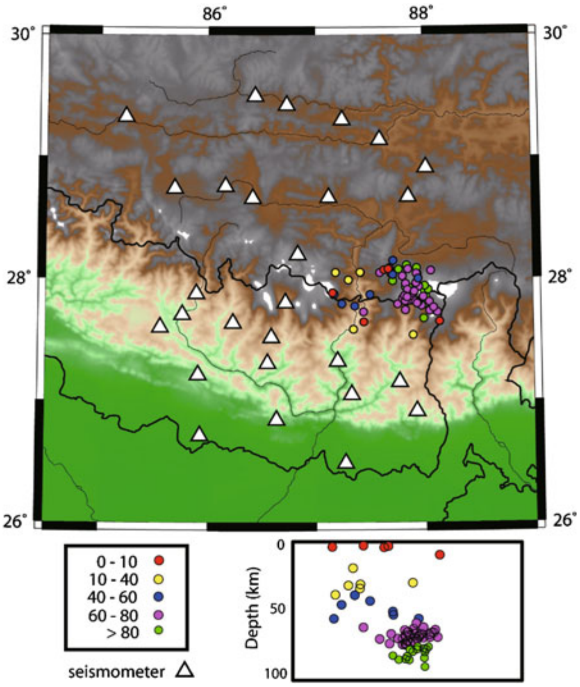
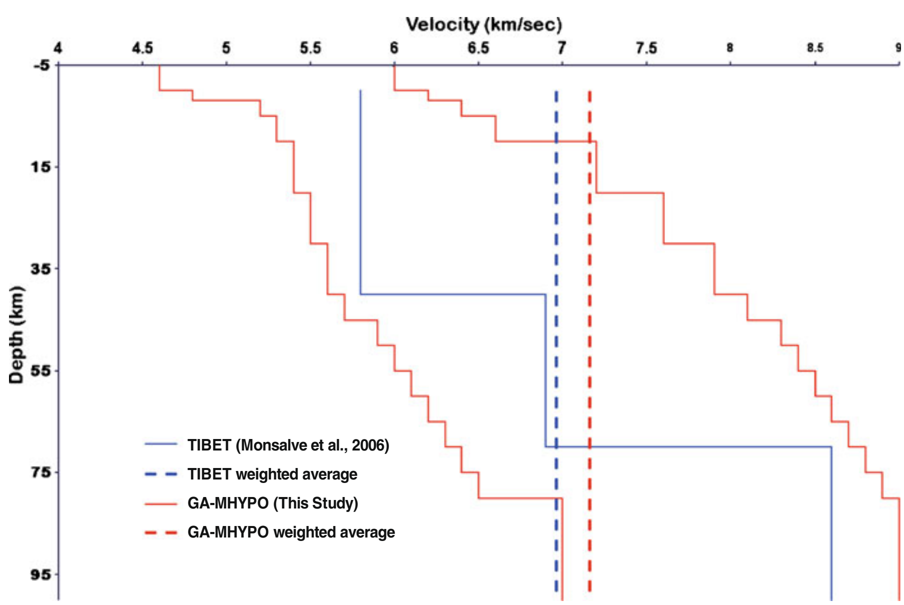


Fig. 8 The epicentral distribution of 68 earthquakes in the High Himalaya relocated by GA-MHYPO. *Colors* denote different focal depths as indicated in the legend. Seismic stations are presented by *white triangles*

errors increase up to 1 km for some events whose number of stations is less than 8 and a 315° azimuthal gap (Fig. 6a). The errors decrease as the azimuthal coverage improves for the same focal depth. Errors from GA-MHYPO using noisy data are about 10 times greater than those using error-free data (Fig. 4a). The trend of errors for HYPOINVERSE is similar to that using error-free data (Fig. 4b), and the errors are about twice as large as those from error-free data. The errors that arise for HYPOINVERSE using noisy data are, again, more than five times those of GA-MHYPO.

The various tests with the synthetic data indicate that GA-MHYPO is robust and yields more accurate hypocentral parameters under ill conditions than those determined by a conventional algorithm. Conventional algorithms generally show that the error in the focal depth decreases, but the error in the epicenter increases, with greater hypocentral depth. The errors in hypocentral parameters by GA-MHYPO are independent of the focal depth. This phenomenon appears to be partly because GA-MHYPO uses a weighting factor to enhance the degree of focal depth information contained in the traveltime data and partly because it uses the GA-optimized velocity model close to the true one. In contrast, conventional algorithms use an a priori velocity model, which, if incorrect, cannot achieve the true location except in cases of very well-recorded events with optimum station distribution. Since the

Fig. 9 The prescribed velocity ranges used in GA-MHYPO (*solid red lines*). The velocity structures of Tibet (*solid blue line*) estimated by Monsalve et al. (2006) are within the prescribed ranges. The weighted average velocities of the GA-optimized velocity structure (*dotted red line*) and Monsalve et al. (*dotted blue line*) are also presented



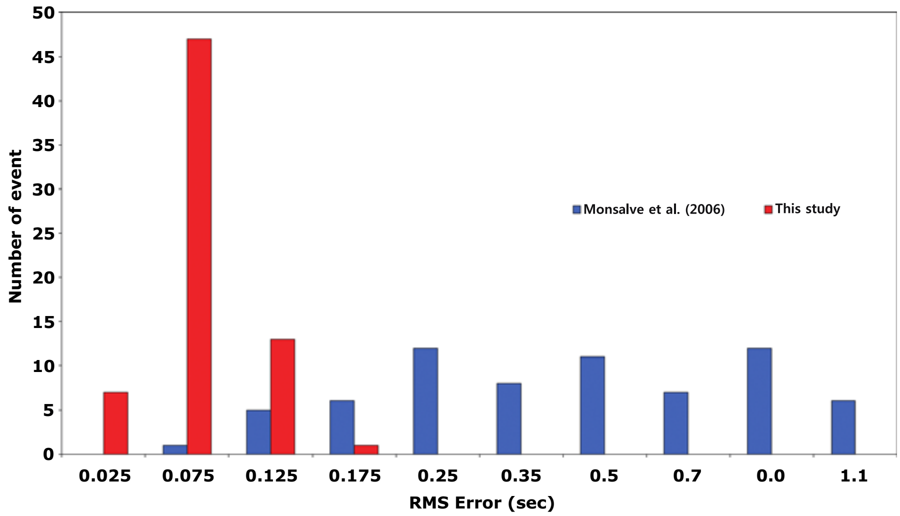


Fig. 10 Histogram of P phase time rms errors of 68 events relocated by GA-MHYPO of this work (*red*) compared with those by Monsalve et al. (2006) using VELEST (*blue*)

GA in GA-MHYPO converges to a 1-D velocity structure that includes noise effects in the data, GA-MHYPO is more sensitive to the noise (error in phase time) in data than the conventional algorithm, which does not map data error into its fixed velocity model. The location errors for

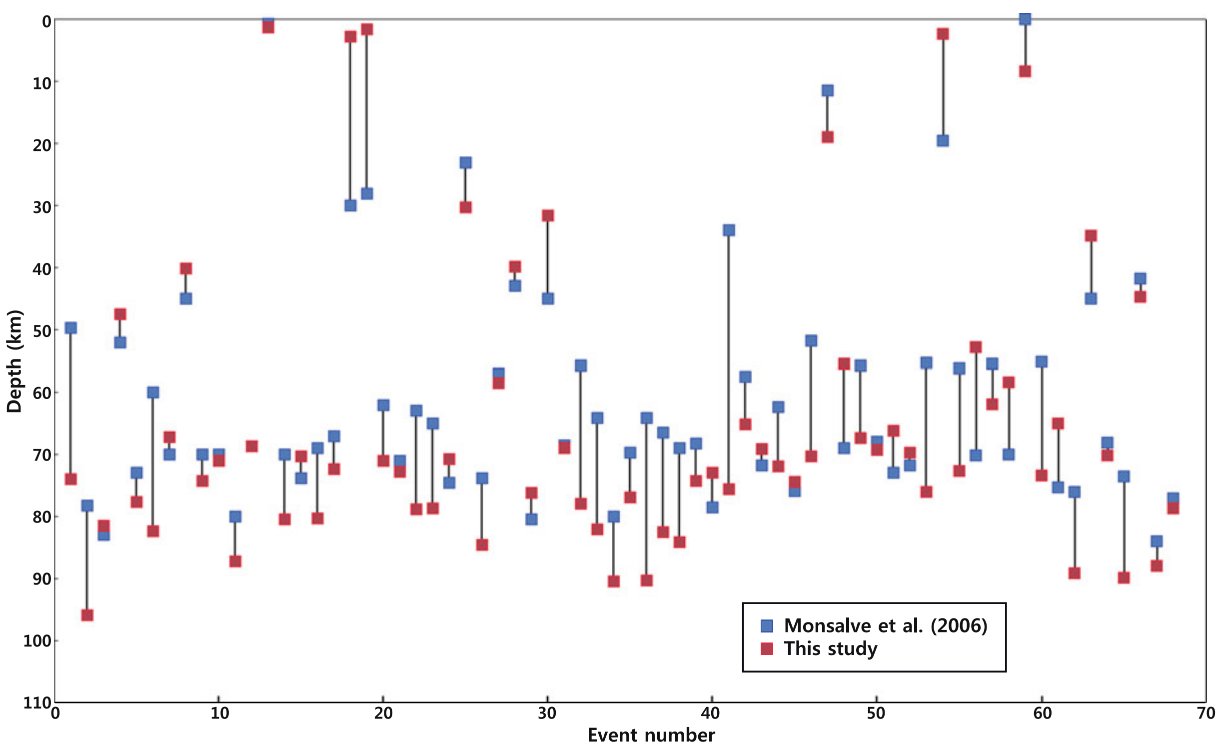


Fig. 11 Comparison of focal depths by GA-MHYPO of this work (*red*) with those by Monsalve et al. (2006) using VELEST (*blue*)

GA-MHYPO using noisy data are, however, much smaller than those produced with a conventional algorithm in this numerical test.

4 Application to earthquake data

4.1 New Madrid seismic zone

GA-MHYPO is used to relocate an earthquake (m_b (L_g) = 2.8, July 30, 2003) that occurred in the New Madrid Seismic Zone, Central USA, to demonstrate its success with real earthquake data under ill conditions. The event was recorded by more than 50 stations, and the azimuthal gap is less than 50°; seven stations are located within a 15-km epicentral distance, and the nearest one is about 2.5 km. The velocity structure of the New Madrid Seismic Zone has been studied in detail (e.g., Chiu et al. 1997). Thus, we can provide the conventional algorithm with a reasonably accurate a priori model and good arrival distribution for hypocentral parameter determination, and we test GA-MHYPO by modifying the input data to intentionally mimic an ill-conditioned situation. We select 43 records in which both P and S phase arrivals have been well picked, providing a 50° azimuthal gap. Ill conditions of 80°, 180°, and 270° azimuthal gaps are generated by reducing the number of stations to 33, 25, and 11, respectively. More than three stations are located within a 15-km epicentral distance for each case. Hypocenter and origin time are determined by GA-MHYPO for these three cases, and the results are presented in Table 1. For comparison, the hypocentral parameters are also determined with HYPOINVERSE using the whole dataset and the velocity model of Chiu et al. (1997); the result is likewise listed in Table 1.

The differences in the hypocentral parameters for the three cases using GA-MHYPO are less than about 0.2 s in the origin time, 0.34 km east–west and 0.29 km north–south, and 0.05 km in depth. The hypocentral parameters determined by HYPOINVERSE are similar to those of GA-MHYPO. This appears to be because the average velocity of the velocity structure used in HYPOINVERSE (5.06 km/s) is similar to those of

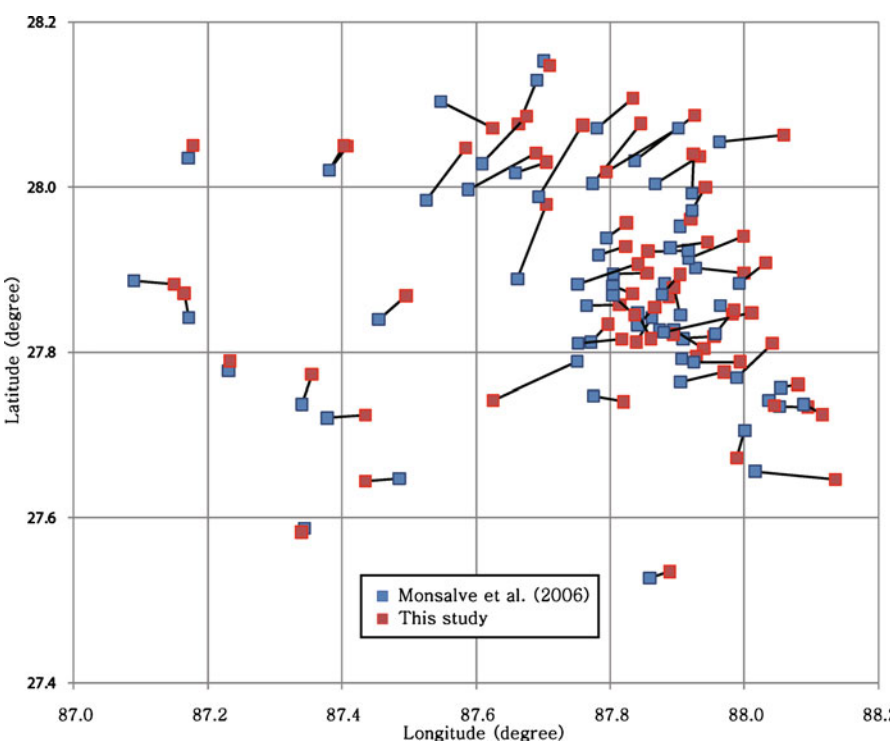


Fig. 12 Comparison of epicenters by GA-MHYPO of this work (*red*) with those by Monsalve et al. (2006) using VELEST (*blue*)

the GA-optimized velocity structures (4.53, 5.19, and 5.11 km/s for 50°, 180°, and 270° azimuthal gaps, respectively) for over around 6-km depth range from the surface (Fig. 7). The prescribed velocity range used in GA-MHYPO, the GA-optimized velocity structures of the cases of 80°, 180°, and 270° azimuthal gaps by GA-MHYPO, and the velocity model used in HYPOINVERSE are presented in Fig. 7. The GA-optimized velocity structures are significantly different from one another, suggesting the presence of a strong lateral velocity inhomogeneity in the region. The larger rms error associated with the case of a smaller azimuthal gap (best azimuthal coverage) may likewise support the presence of a lateral inhomogeneity, as the broader raypath coverage is more likely to encounter this unmodelled 3-D feature. The lateral heterogeneity may come from varying thickness of the sedimentary layer and/or the existence of a fault zone. We note that the rms error of the HYPOINVERSE result is four times larger than that of any GA-MHYPO solutions. The larger rms error of HYPOINVERSE is, however, not comparable to those of GA-MHYPO since GA-MHYPO has more free parameters.

4.2 High Himalaya

We relocated 68 earthquakes ($2.2 \leq m_b \leq 4.2$) in the High Himalaya using GA-MHYPO independently. The epicenters and seismic stations are presented in Fig. 8. As shown in Fig. 8, the distribution of the 27-broadband-station seismic network is not dense enough and suited for event location. Only a few stations are available for each event due to station spacing, and the closest station is more than 70 km from an epicenter in general. Records from 20 stations are used. The azimuthal coverage is poor and data are noisy. The relocation problem appears to be ill-conditioned. In the application of GA-MHYPO, the widths of the prescribed velocity range are from about 1.2 to 2 km/s, and the allowable range fully includes the velocity structure estimated by Monsalve et al. (2006) (Fig. 9). The range of the v_p/v_s ratio is given as 1.66–1.80. The model used in this study has 16 layers, whose upper bounds comprise the surface: 0 (sea level), 2, 5, 10, 20, 30, 40, 45, 50, 55, 60, 65, 70, 75, 80, and 100 km. The elevation of each station is included in the model thickness of the first layer to reduce errors from the extreme topography. This is crucial, since the station elevations vary from 0.077 to 5.1 km in the region of the HIMNT experiment. We selected only the events, which have at least six P arrivals and three S arrivals. The phase arrivals were re-picked for improved accuracy, and the average differences of P and S phase arrival times are about 0.08 and 0.14 s from those of Monsalve et al. (2006), respectively.

P arrival rms errors of events relocated by GA-MHYPO of this work are presented in Fig. 10, and they are compared with those from Monsalve et al. (2006) using VELEST. As shown in Fig. 10, GA-MHYPO yields 0.08 s of the average rms error for P while VELEST yields 0.50 s. Although an additional velocity parameter is introduced, the value of rms error likely indicates accuracy and reliability of hypocentral parameters for a specified method if the same data are used. The rms error from GA-MHYPO is about six times smaller than that from VELEST. Focal depths and epicenters calculated by both methods are shown in Figs. 11 and 12. The average differences of the focal depths and the epicenters determined by GA-MHYPO and VELEST are 10.0 and 5.5 km, while their maximum differences are 41.7 and 13.4 km, respectively.

5 Conclusion

When the velocity model is not well-known, GA-MHYPO determines more accurate hypocentral parameters under poorly constrained conditions than the conventional methods. In the tests with synthetic data, the errors in the focal depth and epicenter obtained by GA-MHYPO under ill conditions are about 0.1 km for error-free P and S phase time data and are about 0.5 km for the noisy data composed of the error-free data and random noise of the 0.1-s standard deviation. GA-MHYPO determines hypocentral parameters stably and accurately with error-free phase time data from five stations, whereas in case of noisy data, it requires at least six stations. GA-MHYPO yielded more accurate hypocentral parameters under ill conditions than those of HYPOINVERSE by a factor of 20 for error-free data and by a factor of five for noisy data. GA-MHYPO is, however, more sensitive to data with errors in phase time than the conventional method. GA-MHYPO shows relatively smaller variation in hypocentral parameter errors depending on azimuthal gap and focal depth than HYPOINVERSE does because GA-MHYPO first identifies GA-optimized velocity structure based on the input data, while HYPOINVERSE uses an initial model that is generally incorrect.

GA-MHYPO still yields accurate hypocentral parameters under ill as well as good conditions for an earthquake that occurred in the New Madrid Seismic Zone on July 30, 2003. Considering the rms errors in the relocation of earthquakes in the High Himalaya by GA-MHYPO and VELEST, GA-MHYPO allows us to improve the accuracy of hypocentral parameters significantly under ill conditions. As shown by the relocation of earthquakes in the New Madrid Seismic zone and in the High Himalaya, GA-MHYPO is robust and determines accurate and reliable hypocentral parameters under both ill and good conditions.

Although it is not fully resolved, the GA-optimized velocity structure partly releases the tradeoff problem between the hypocentral parameters and the velocity structure in hypocentral parameter determination. GA-MHYPO determines hypocentral parameters more accurately than the conventional methods, and the relative accuracy becomes better under ill conditions. The two-point ray tracing, the degree of focal depth information, and the GA-optimized velocity structure the weighted average of which converges to that of the true velocity structure appear to make GA-MHYPO robust and more accurate than the conventional methods. The code is available on request.

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