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Determination of hypocentral parameters of local earthquakes using weighting factor based on take-off angle

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ABSTRACT: This paper introduces an improved method of determining hypocentral parameters of local earthquakes by applying a weighting factor based on take-off angle at a source. The hypocentral parameters determined by the existing methods contain errors if the true velocity structure is not used, and they are not identical depending on the velocity models used. Variation in the traveltime caused by a focal depth may indicate the degree of focal depth information contained in the data. The degree of information will decrease rapidly as the epicentral distance increases. The take-off angle at the source is related to the epicentral distance. Therefore, a weighting factor representing the degree of focal depth information could be described in terms of the take-off angle at the source. The accuracy of hypocentral parameters, especially the focal depth and the origin time, is improved by applying the take-off angle as the weighting factor and two-point ray tracing to the existing methods. Synthetic traveltime data both with noise and without noise are generated using the two-point ray tracing technique with a model in which velocity structure and hypocentral parameters are known. The effect of the weighting factor is examined by comparing the estimated hypocentral parameters with the true, known values. The computational results show that the focal depth and the origin time estimated by the improved method (MHYPO) in this work are more accurate than those estimated by other existing methods.

Key words: hypocentral parameters, weighting factor, epicentral distance, take-off angle

1. INTRODUCTION

Determination of accurate hypocentral parameters – the epicenter, the focal depth, and the origin time – is one of the most important problems in earthquake seismology. Hypocentral parameters can be determined almost exactly if the true velocity structure is known. The hypocentral parameters determined by the existing packages such as HYPO-71 (Lee and Lahr, 1975), HYPOELLIPSE (Lahr, 1980), VELEST (Kissling, 1995), and HYPOSAT (Schweitzer, 1997 and 2002) differ from one another according to the velocity models used. Since the true velocity structures are unknown in most regions, it is difficult to obtain reliably accurate hypocentral parameters for local earthquakes using the existing packages. Lomnitz (2006) pointed out the problems in the existing methods clearly.

Generally, the error in the focal depth is much lager than that in the epicenter in hypocenter determination since the seismometers are usually located on or near the Earth's surface. Another possible cause of the lager errors in the focal depth might be the traveltime sensitivity to the focal depth. If traveltimes do not vary with the focal depth changes, the focal depth can not be determined from the observed traveltimes. The traveltime sensitivity to the focal depth cannot be, however, presented analytically since it depends on the velocity structure, the focal depth, and the epicentral distance. The traveltime variations as functions of focal depths with various velocity structures will be systematically analyzed, and a new weighting factor to improve the accuracy in determining hypocentral parameters, especially, the focal depth will be introduced in this work. The weighting factor will be employed in the determination of focal parameters and the improvement will be investigated quantitatively with synthetic traveltime data by comparing the results of some existing packages. Throughout numerical tests, five velocity structure models presented in Figure 1 will be consistently used.

2. WEIGHTING FACTOR

When a source is located at the bottom of the n-th layer, the traveltime T for a direct wave (P_g) in a horizontally layered velocity model is given by, as presented in Figure 2.

$$T = \sum_{i=1}^{n} \frac{h_i}{v_i \cos\theta_i} = \sum_{i=1}^{n} \frac{\sqrt{h_i^2 + h_i^2 \tan^2\theta_i}}{v_i} \tag{1}$$

where h_i, v_i, and θ_i are the thickness and the velocity of the i-th layer, and the take-off angle in it, respectively. The terms h_i^2 and $h_i^2 \tan^2 \theta_i$ in the square root on the right-hand side of equation (1) represent the vertical and horizontal components of a ray segment in the i-th layer, respectively. Based on Figure 2, the contribution of the vertical component to

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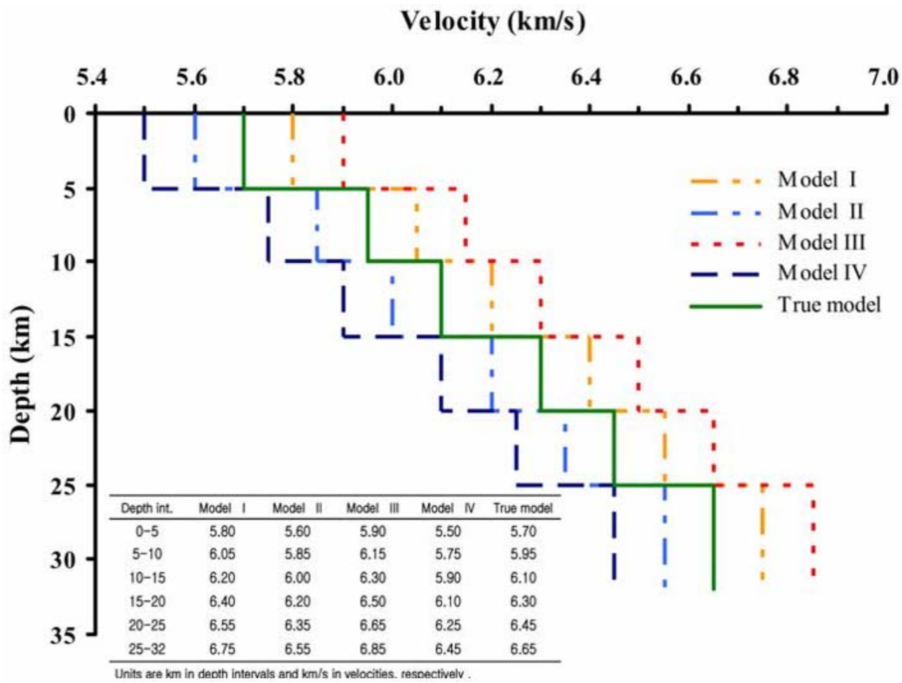

Depth int.	Model I	Model II	Model III	Model IV	True model
0–5	5.80	5.60	5.90	5.50	5.70
5–10	6.05	5.85	6.15	5.75	5.95
10–15	6.20	6.00	6.30	5.90	6.10
15–20	6.40	6.20	6.50	6.10	6.30
20–25	6.55	6.35	6.65	6.25	6.45
25–32	6.75	6.55	6.85	6.45	6.65

Fig. 1. True and four velocity models used in this work: The velocity deviations from the true velocities in each layer are ±0.1 km/s in models I and II and ±0.2 km/s in models III and IV, respectively. The true velocities of each layer are 5.7, 5.95, 6.1, 6.3, 6.45, and 6.65 km/s from top to bottom, respectively. The layers are 5-km thick from the top to the fifth layer and the bottom (sixth) layer is 7-km thick.

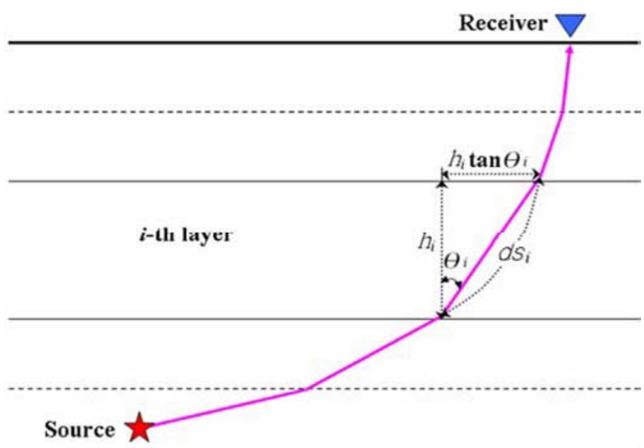

Fig. 2. The diagram of the ray path and its horizontal ($X_i = h_i \tan\theta_i$) and vertical ($Z_i = h_i$) components: The parameters, h_i and θ_i, denote thickness of the i-th layer and take-off angle in the i-th layer, respectively.

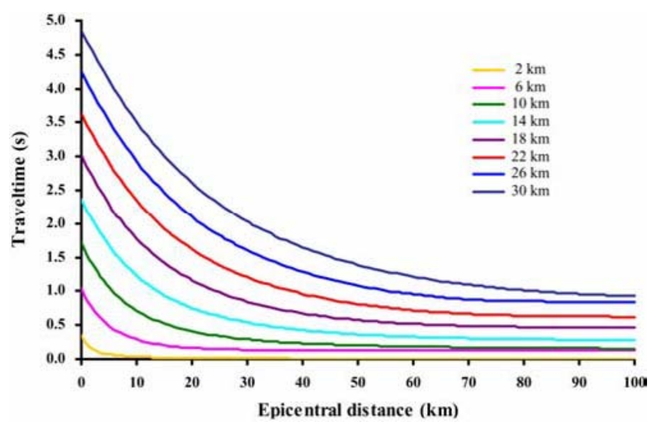

Fig. 3. Traveltimes contributed by the focal depths as a function of the epicentral distance for events with focal depths of 2, 6, 10, 14, 18, 22, 26, and 30 km. Values were computed by equation (2) with the true velocity model presented in Figure 1.

the traveltime (T_z) can be defined as,

$$T_z = T - \sum_{i=1}^{n} \frac{h_i \tan\theta_i}{v_i}. \quad (2)$$

The main contribution of T_z in equation (2) results from the focal depth, the cross terms among layers generated in equation (1) are, however, neglected here. The traveltime curves with respect to the epicentral distance based on equation (2) are presented in Figure 3. Colors used in Figure 3 denote the focal depths which vary from 2 to 30 km with a 4-km interval. It is observed that the variation of traveltime, T_z, with respect to the focal depth decreases rapidly as the epicentral distance increases. This variation indicates the sensitivity of traveltime to the focal depth. Therefore, the focal depth information in data decreases as the epicentral distance increases. Lack of variation in T_z means that T_z contains almost no focal depth information. Figure 3 also shows that the amount of variation in T_z for a shallow focal depth decrease more rapidly compared to that for a deep focal depth.

It can be one of ways to use the weighting factor based on the traveltime sensitivity to the focal depth to improve the accuracy of the focal depth in the determination of hypocentral parameters. The existing methods used only a weighting factor reflecting the data quality and types of waves such as P- and S-wave. Since the epicentral distance can be represented in terms of the take-off angle at the source, the new weighting factor W is defined as the variation, dT_z/dX. It is described by the take-off angle at the source, θ_s, and the incidence angle in the i-th layer, θ_i, using equations (1) and (2), and equation (5) of Kim and Baag (2002).

$$W = \frac{dT_z}{dX} = \sum_{i=1}^{n}\frac{dT_z}{d\theta_i}\frac{d\theta_i}{dX_i} = \sum_{i=1}^{n}\left(\frac{1}{v_i} - \frac{\sin\theta_s}{v_s}\right) \qquad (3)$$

where $\frac{dT_z}{d\theta_i} = \sum_{i=1}^{n}\frac{h_i}{v_i} - \frac{1}{\cos^2\theta_i}(1-\sin\theta_i)$ and $\frac{d\theta_i}{dX_i} = \sum_{i=1}^{n}\frac{\cos^2\theta_i}{h_i}$.
The parameters, v_i and h_i denote velocity and thickness of the i-th layer. The take-off angle θ_i and θ_s have been accurately determined by the two-point ray tracing technique (Kim and Baag, 2002). Note that the value of W_j decreases as the epicentral distance (θ_s) increases.

The weighting factor in equation (3) reflects the sensitivity of the traveltime to the focal depth, and is expected to improve the accuracy of focal depth estimation. The origin time accuracy is also expected to be improved. This weighting factor is included to HYPO-71. The existing ray tracing algorithm in HYPO-71 is also replaced by the two-point ray tracing. The improved package is named MHYPO.

3. NUMERICAL TESTS

The traveltime data used in this study are synthesized using the two-point ray tracing method (Kim and Baag, 2002). All velocity models used in this work have six layers; the layers are 5-km thick from the top to the fifth layer and the bottom (sixth) layer is 7-km thick. The true velocities of each layer are 5.7, 5.95, 6.1, 6.3, 6.45, and 6.65 km/s from the top to the bottom, respectively. The velocity differences between the true and other models are ±0.1 km/s in models I and II and ±0.2 km/s in models III and IV. The velocity structures of the five models including the true velocity model are presented in Figure 1. In each test, the five velocity models including the true velocity model are used. The hypocentral parameters for six events (events 1 through 6) with the focal depths ranging from 2.5 to 27 km are estimated. Each event is assumed to have 10 to 20 traveltime data. Errors in the results can be directly measured from the true velocity structure and the known hypocentral parameters.

First, tests with noiseless data are carried out, and the results are presented in Table 1. Table 1 shows the estimated hypocentral parameters determined by MHYPO and by the conventional packages such as HYPO-71 and HYPOSAT for the six events. For the comparison purpose, errors in the estimation of the focal depths, the origin times, and the epicenters tabulated in Table 1 are plotted in Figures 4, 5, and 6, respectively. Clearly, MHYPO improves the accuracy in the estimation of hypocentral parameters compared to those

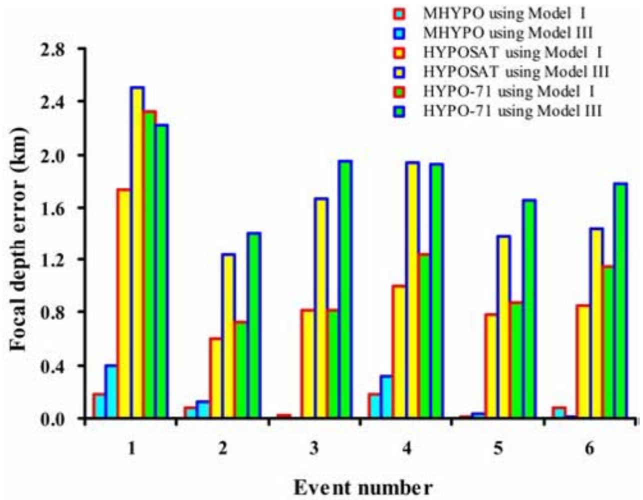

Fig. 4. Comparison of errors in the focal depth estimation by MHYPO, HYPO-71 and HYPOSAT using velocity models I and III. The errors by MHYPO are much smaller than those by HYPO-71 and HYPOSAT regardless of models used. Numerical values are tabulated in Table 1.

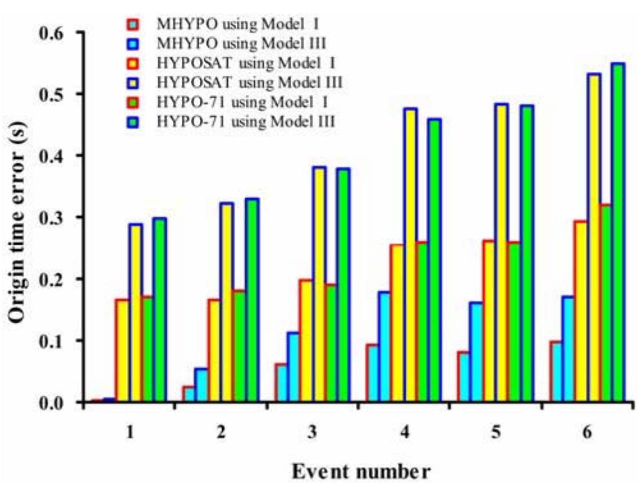

Fig. 5. Comparison of errors in the origin time estimation by MHYPO, HYPO-71 and HYPOSAT using velocity models I and III. The errors by MHYPO are much smaller than those by HYPO-71 and HYPOSAT regardless of models used. Numerical values are tabulated in Table 1.

by HYPO-71 and HYPOSAT which do not use the weighting factor (Figs. 4 and 5). MHYPO slightly improves the accuracy in epicenter estimation (Fig. 6). Cyan, yellow, and green, colors represent the results of MHYPO, HYPOSAT, and, HYPO-71 packages, respectively. In Figures 4 to 6, the outline color denotes the model used; the red means velocity model I while the blue means velocity model III.

Errors in focal depth estimation with different velocity models, velocity models I and III, are presented in Figure 4. The errors in focal depth estimation by MHYPO are much smaller than those by HYPO-71 and HYPOSAT. The focal

Table 1. Errors in hypocentral parameter estimation by MHYPO, HYPO-71, and HYPOSAT: Six hypocenters of different focal depths, 2.5, 7.5, 11, 16.5, 21.5, and 27 km, are tested with synthetic traveltime data excluding noise using five different velocity models.

Event	Method	Model	Latitude (ºN)	Longitude (ºE)	Depth (km)	Origin time error (sec)	RMS error (sec)
1	True value		35.8600	129.0800	2.50	0.00	
	HYPO-71	True	35.8600	129.0800	2.46	0.01	0.01
		I	35.8603	129.0797	0.18	0.17	0.07
		II	35.8600	129.0808	3.70	-0.14	0.03
		III	35.8607	129.0793	0.28	0.30	0.12
		IV	35.8597	129.0803	4.55	-0.28	0.07
	HYPOSAT	True	35.8600	129.0800	2.45	0.003	0.003
		I	35.8600	129.0800	0.76	0.166	0.063
		II	35.8600	129.0810	3.71	-0.141	0.040
		III	35.8610	129.0800	0.00	0.288	0.128
		IV	35.8590	129.0810	4.51	-0.270	0.071
	MHYPO	True	35.8600	129.0799	2.5195	-0.0008	0.0011
		I	35.8606	129.0805	3.3727	-0.0202	0.1075
		II	35.8630	129.0804	1.1376	0.0165	0.1231
		III	35.8621	129.0815	3.3118	0.0145	0.1751
		IV	35.8624	129.0798	1.1041	-0.0142	0.2002
2	True value		35.7400	129.2000	7.50	0.00	
	HYPO-71	True	35.7400	129.2000	7.51	0.00	0.0010
		I	35.7400	129.2007	6.77	0.18	0.06
		II	35.7407	129.1988	8.29	-0.19	0.07
		III	35.7402	129.2018	6.09	0.33	0.11
		IV	35.7402	129.1985	9.34	-0.40	0.12
	HYPOSAT	True	35.7400	129.2000	7.47	0.007	0.003
		I	35.7400	129.2010	6.90	0.165	0.058
		II	35.7400	129.1990	8.07	-0.169	0.064
		III	35.7390	129.2020	6.27	0.324	0.121
		IV	35.7400	129.1980	8.80	-0.356	0.123
	MHYPO	True	35.7400	129.2000	7.4985	0.0004	0.0004
		I	35.7393	129.2002	7.5798	0.0251	0.0854
		II	35.7404	129.1998	7.4699	-0.0302	0.0854
		III	35.7386	129.2000	7.6257	0.0529	0.1660
		IV	35.7402	129.1988	7.4727	-0.0636	0.1717
3	True value		35.8200	128.9400	11.00	0.00	
	HYPO-71	True	35.8200	128.9400	10.98	0.00	0.01
		I	35.8200	128.9408	10.18	0.19	0.07
		II	35.8200	128.9392	11.89	-0.20	0.07
		III	35.8203	128.9407	9.05	0.38	0.13
		IV	35.8202	128.9382	12.91	-0.44	0.14
	HYPOSAT	True	35.8200	128.9400	10.94	0.012	0.004
		I	35.8200	128.9410	10.18	0.196	0.063
		II	35.8200	128.9390	11.50	-0.179	0.066
		III	35.8200	128.9420	9.33	0.381	0.116
		IV	35.8190	128.9380	12.04	-0.367	0.126
	MHYPO	True	35.8200	128.9400	11.0011	0.0001	0.0002
		I	35.8210	128.9397	10.9807	0.0611	0.0671
		II	35.8189	128.9400	11.1318	-0.0766	0.0605
		III	35.8221	128.9393	10.9965	0.1117	0.1338
		IV	35.8183	128.9403	11.1467	-0.1386	0.1345

Table 1. (Continue) Errors in hypocentral parameter estimation by MHYPO, HYPO-71, and HYPOSAT: Six hypocenters of different focal depths, 2.5, 7.5, 11, 16.5, 21.5, and 27 km, are tested with synthetic traveltime data excluding noise using five different velocity models.

Event	Method	Model	Latitude (°N)	Longitude (°E)	Depth (km)	Origin time error (sec)	RMS error (sec)
4	True value		35.7200	129.0600	16.50	0.00	
	HYPO-71	True	35.7200	129.0600	16.50	0.00	0.01
		I	35.7205	129.0600	15.27	0.26	0.09
		II	35.7202	129.0600	17.43	-0.25	0.08
		III	35.7202	129.0590	14.57	0.46	0.15
		IV	35.7210	129.0592	18.37	-0.51	0.16
	HYPOSAT	True	35.7200	129.0600	16.39	0.023	0.008
		I	35.7200	129.0610	15.50	0.254	0.081
		II	35.7200	129.0600	17.06	-0.214	0.075
		III	35.7190	129.0610	14.56	0.475	0.142
		IV	35.7210	129.0590	17.67	-0.447	0.152
	MHYPO	True	35.7200	129.0600	16.5034	-0.0002	0.0004
		I	35.7196	129.0607	16.3156	0.0926	0.0698
		II	35.7203	129.0593	16.7858	-0.1057	0.0660
		III	35.7192	129.0614	16.1837	0.1770	0.1407
		IV	35.7206	129.0587	17.0912	-0.2178	0.1327
5	True value		35.9400	129.0800	21.50	0.00	
	HYPO-71	True	35.9400	129.0800	21.50	0.01	0.01
		I	35.9403	129.0803	20.63	0.26	0.08
		II	35.9392	129.0792	22.27	-0.25	0.07
		III	35.9398	129.0805	19.84	0.48	0.15
		IV	35.9388	129.0765	22.82	-0.47	0.13
	HYPOSAT	True	35.9400	129.0800	21.37	0.029	0.011
		I	35.9420	129.0800	20.72	0.263	0.092
		II	35.9390	129.0800	21.91	-0.205	0.073
		III	35.9430	129.0810	20.12	0.484	0.168
		IV	35.9370	129.0790	22.44	-0.444	0.158
	MHYPO	True	35.9400	129.0799	21.5004	0.0002	0.0007
		I	35.9404	129.0796	21.4870	0.0807	0.0827
		II	35.9396	129.0805	21.6054	-0.0936	0.0794
		III	35.9408	129.0789	21.4607	0.1609	0.1618
		IV	35.9387	129.0809	21.7109	-0.1889	0.1611
6	True value		35.9200	129.2400	27.00	0.00	
	HYPO-71	True	35.9207	129.2437	26.21	0.10	0.08
		I	35.9203	129.2402	25.85	0.32	0.10
		II	35.9198	129.2462	26.30	-0.09	0.13
		III	35.9242	129.2422	25.22	0.55	0.17
		IV	35.9205	129.2500	26.65	-0.30	0.18
	HYPOSAT	True	35.9200	129.2400	26.78	0.042	0.015
		I	35.9220	129.2420	26.15	0.294	0.102
		II	35.9180	129.2390	27.34	-0.215	0.078
		III	35.9240	129.2440	25.56	0.532	0.182
		IV	35.9160	129.2370	27.89	-0.478	0.171
	MHYPO	True	35.9200	129.2400	26.9962	0.0003	0.0004
		I	35.9216	129.2421	26.9189	0.0966	0.0832
		II	35.9183	129.2380	27.2426	-0.1188	0.0743
		III	35.9212	129.2415	27.0094	0.1701	0.1836
		IV	35.9168	129.2364	27.3390	-0.2232	0.1628

Table 2. Errors in hypocentral parameter estimation by MHYPO: A 2.5-km deep event is tested with different number of data having focal depth information using five different velocity models.

Model	No. of data	Latitude (°N)	Longitude (°E)	Depth (km)	Origin time error (sec)	RMS error (sec)
True value		35.8600	129.0800	2.50	0.00	
True	1	35.8602	129.0801	2.6482	-0.0077	0.0053
	2	35.8601	129.0799	2.5130	-0.0011	0.0018
	3	35.8600	129.0799	2.5195	-0.0008	0.0011
	4	35.8600	129.0799	2.5144	-0.0001	0.0011
	5	35.8600	129.0799	2.5124	-0.0001	0.0010
I	1	35.8606	129.0805	3.3727	-0.0202	0.1075
	2	35.8574	129.0791	2.8898	-0.0020	0.1047
	3	35.8595	129.0793	2.6808	0.0027	0.0902
	4	35.8594	129.0792	2.6899	0.0025	0.0869
	5	35.8594	129.0793	2.6873	0.0024	0.0837
II	1	35.8630	129.0804	1.1376	0.0165	0.1231
	2	35.8655	129.0812	1.4755	0.0025	0.1264
	3	35.8607	129.0808	2.3206	-0.0054	0.0920
	4	35.8608	129.0808	2.3145	-0.0049	0.0888
	5	35.8607	129.0807	2.3245	-0.0050	0.0855
III	1	35.8621	129.0815	3.3118	0.0145	0.1751
	2	35.8544	129.0780	3.2049	0.0013	0.2041
	3	35.8583	129.0782	2.8994	0.0043	0.1794
	4	35.8582	129.0782	2.9162	0.0027	0.1736
	5	35.8583	129.0784	2.9038	0.0022	0.1676
IV	1	35.8624	129.0798	1.1041	-0.0142	0.2002
	2	35.8658	129.0818	1.2096	-0.0015	0.2191
	3	35.8616	129.0822	2.1923	-0.0254	0.1771
	4	35.8616	129.0823	2.1942	-0.0250	0.1705
	5	35.8615	129.0819	2.2805	-0.0289	0.1618

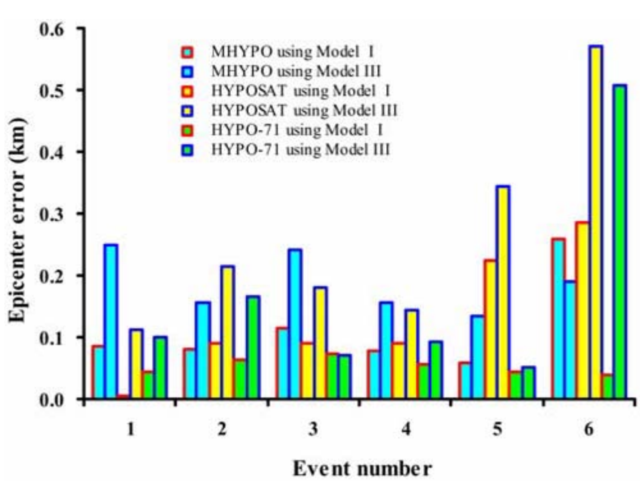

Fig. 6. Comparison of errors in the epicenter estimation by MHYPO, HYPO-71 and HYPOSAT using velocity models I and III. The errors by MHYPO are slightly smaller than those by HYPO-71 and HYPOSAT regardless of models used. Numerical values are tabulated in Table 1.

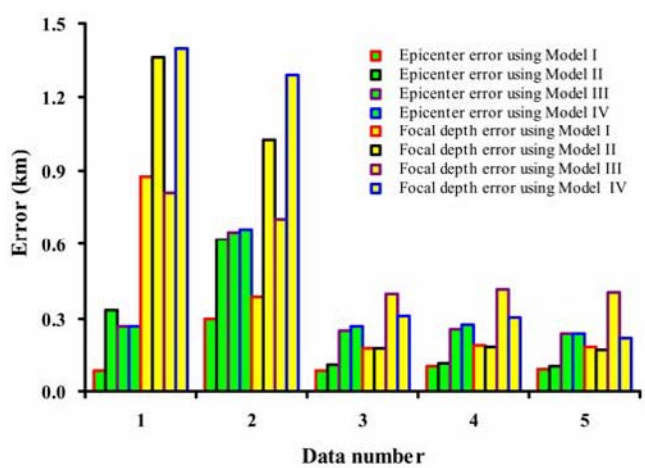

Fig. 7. Errors in the epicenter (green) and focal depth (yellow) estimation with varying numbers of data having focal depth information for Event 1. Red, black, purple, and blue outline colors denote the velocity models I, II, III, and IV, respectively. Numerical values are tabulated in Table 2. Errors of hypocentral parameters decreased if the number of data is greater than three, in general. Errors in focal depth estimation are, however, exceptionally large if number of data was two or less.

Table 3a. Errors in hypocentral parameter estimation by MHYPO, HYPO-71, and HYPOSAT: Six hypocenters of different focal depths, 2.5, 7.5, 11, 16.5, 21.5, and 27 km, are tested with noisy synthetic traveltime data using three different velocity models. Zero mean and standard deviation of 0.05 random noise is added to the synthetic traveltime data.

Event	Method	Model	Latitude (°N)	Longitude (°E)	Depth (km)	Origin time error (sec)	RMS error (sec)
1	True value		35.8600	129.0800	2.50	0.00	
	HYPO-71	True	35.8615	129.0815	2.19	0.01	0.04
		I	35.8618	129.0808	0.91	0.17	0.09
		III	35.8622	129.0797	0.07	0.28	0.13
	HYPOSAT	True	35.8610	129.0820	2.09	0.010	0.036
		I	35.8620	129.0820	1.00	0.155	0.085
		III	35.8620	129.0810	0.00	0.270	0.147
	MHYPO	True	35.8614	129.0813	2.3752	-0.0038	0.0384
		I	35.8605	129.0800	2.5864	0.0047	0.1097
		III	35.8599	129.0790	2.7955	0.0052	0.1953
2	True value		35.7400	129.2000	7.50	0.00	
	HYPO-71	True	35.7405	129.1997	7.68	-0.02	0.05
		I	35.7403	129.2005	6.90	0.16	0.06
		III	35.7408	129.2015	6.15	0.32	0.11
	HYPOSAT	True	35.7410	129.2000	7.48	0.016	0.043
		I	35.7400	129.2010	7.03	0.155	0.063
		III	35.7400	129.2010	6.54	0.295	0.105
	MHYPO	True	35.7400	129.2000	7.4946	0.0079	0.0514
		I	35.7391	129.2001	7.6359	0.0249	0.0897
		III	35.7382	129.2000	7.7666	0.0423	0.1704
3	True value		35.8200	128.9400	11.00	0.00	
	HYPO-71	True	35.8212	128.9395	11.23	-0.01	0.06
		I	35.8210	128.9405	10.40	0.18	0.08
		III	35.8215	128.9398	9.54	0.36	0.13
	HYPOSAT	True	35.8210	128.9390	11.16	-0.001	0.050
		I	35.8210	128.9400	10.46	0.181	0.072
		III	35.8210	128.9410	9.65	0.367	0.120
	MHYPO	True	35.8198	128.9401	10.9641	0.0109	0.0571
		I	35.8205	128.9399	11.0883	0.0528	0.0788
		III	35.8216	128.9396	11.2607	0.0912	0.1456
4	True value		35.7200	129.0600	16.50	0.00	
	HYPO-71	True	35.7205	129.0583	16.39	0.01	0.04
		I	35.7213	129.0575	14.97	0.27	0.10
		III	35.7210	129.0580	14.21	0.48	0.16
	HYPOSAT	True	35.7210	129.0590	16.26	0.035	0.044
		I	35.7200	129.0590	15.33	0.267	0.099
		III	35.7200	129.0600	14.41	0.484	0.155
	MHYPO	True	35.7202	129.0583	16.4832	-0.0023	0.0424
		I	35.7195	129.0602	16.6467	0.0517	0.1163
		III	35.7190	129.0614	16.8017	0.1058	0.2036
5	True value		35.9400	129.0800	21.50	0.00	
	HYPO-71	True	35.9393	129.0810	21.43	0.01	0.03
		I	35.9395	129.0812	20.58	0.26	0.09
		III	35.9406	129.0815	19.63	0.50	0.15
	HYPOSAT	True	35.9390	129.0800	21.50	0.001	0.014
		I	35.9380	129.0800	21.72	0.081	0.028
		III	35.9370	129.0790	21.94	0.157	0.050
	MHYPO	True	35.9401	129.0805	21.4951	-0.0025	0.0323
		I	35.9393	129.0791	21.7661	0.0464	0.1134
		III	35.9391	129.0777	21.9632	0.1021	0.2077

Table 3a. (Continued) Errors in hypocentral parameter estimation by MHYPO, HYPO-71, and HYPOSAT: Six hypocenters of different focal depths, 2.5, 7.5, 11, 16.5, 21.5, and 27 km, are tested with noisy synthetic traveltime data using three different velocity models. Zero mean and standard deviation of 0.05 random noise is added to the synthetic traveltime data.

Event	Method	Model	Latitude (°N)	Longitude (°E)	Depth (km)	Origin time error (sec)	RMS error (sec)
6	True value		35.9200	129.2400	27.00	0.00	
	HYPO-71	True	35.9218	129.2427	26.40	0.08	0.09
		I	35.9238	129.2423	26.01	0.29	0.11
		III	35.9237	129.2427	25.38	0.53	0.17
	HYPOSAT	True	35.9220	129.2400	26.84	0.032	0.068
		I	35.9240	129.2420	26.22	0.284	0.118
		III	35.9260	129.2430	25.64	0.522	0.189
	MHYPO	True	35.9186	129.2402	27.0213	-0.0158	0.0792
		I	35.9205	129.2400	27.3629	0.0193	0.1556
		III	35.9208	129.2369	27.8874	0.0272	0.2954

Table 3b. Errors in hypocentral parameter estimation by MHYPO, HYPO-71, and HYPOSAT: Six hypocenters of different focal depths, 2.5, 7.5, 11, 16.5, 21.5, and 27 km, are tested with noisy synthetic traveltime data using three different velocity models. Zero mean and standard deviation of 0.1 random noise is added to the synthetic traveltime data.

Event	Method	Model	Latitude (°N)	Longitude (°E)	Depth (km)	Origin time error (sec)	RMS error (sec)
1	True value		35.8600	129.0800	2.50	0.00	
	HYPO-71	True	35.8598	129.0813	2.52	-0.01	0.07
		I	35.8595	129.0818	1.44	0.15	0.10
		III	35.8602	129.0792	0.47	0.26	0.12
	HYPOSAT	True	35.8600	129.0810	2.43	0.000	0.060
		I	35.8600	129.0810	1.80	0.111	0.071
		III	35.8610	129.0810	0.79	0.217	0.095
	MHYPO	True	35.8603	129.0796	2.5077	0.0005	0.0783
		I	35.8598	129.0789	2.6820	0.0025	0.1241
		III	35.8589	129.0777	2.8959	0.0046	0.2003
2	True value		35.7400	129.2000	7.50	0.00	
	HYPO-71	True	35.7382	129.2067	7.68	-0.01	0.07
		I	35.7380	129.2078	7.06	0.15	0.10
		III	35.7377	129.2092	6.36	0.31	0.14
	HYPOSAT	True	35.7390	129.2050	7.68	-0.011	0.067
		I	35.7390	129.2040	7.41	0.098	0.073
		III	35.7390	129.2040	7.15	0.204	0.089
	MHYPO	True	35.7413	129.2022	7.4502	0.0121	0.0985
		I	35.7399	129.2015	7.7181	0.0126	0.1371
		III	35.7385	129.2007	7.9793	0.0124	0.2213
3	True value		35.8200	128.9400	11.00	0.00	
	HYPO-71	True	35.8198	128.9388	10.63	0.02	0.14
		I	35.8210	128.9382	10.65	0.15	0.15
		III	35.8203	128.9397	8.95	0.38	0.18
	HYPOSAT	True	35.8200	128.9390	11.00	-0.002	0.072
		I	35.8200	128.9380	10.92	0.101	0.080
		III	35.8200	128.9370	10.91	0.199	0.098
	MHYPO	True	35.8194	128.9399	10.9213	0.0077	0.1270
		I	35.8205	128.9395	11.0970	0.0455	0.1546
		III	35.8219	128.9388	11.2991	0.0828	0.2099

Table 3b. (Continue) Errors in hypocentral parameter estimation by MHYPO, HYPO-71, and HYPOSAT: Six hypocenters of different focal depths, 2.5, 7.5, 11, 16.5, 21.5, and 27 km, are tested with noisy synthetic traveltime data using three different velocity models. Zero mean and standard deviation of 0.1 random noise is added to the synthetic traveltime data.

Event	Method	Model	Latitude (°N)	Longitude (°E)	Depth (km)	Origin time error (sec)	RMS error (sec)
4	True value		35.7200	129.0600	16.50	0.00	
	HYPO-71	True	35.7200	129.0627	16.40	0.02	0.12
		I	35.7198	129.0612	15.91	0.23	0.12
		III	35.7195	129.0613	14.67	0.46	0.16
	HYPOSAT	True	35.7200	129.0600	16.30	0.040	0.072
		I	35.7190	129.0600	16.26	0.151	0.077
		III	35.7180	129.0600	16.27	0.256	0.093
	MHYPO	True	35.7211	129.0635	16.4383	0.0119	0.1165
		I	35.7211	129.0619	16.4396	0.0854	0.1185
		III	35.7206	129.0628	16.5881	0.1400	0.1764
5	True value		35.9400	129.0800	21.50	0.00	
	HYPO-71	True	35.9402	129.0752	21.66	0.00	0.05
		I	35.9405	129.0753	20.66	0.26	0.10
		III	35.9400	129.0755	20.00	0.47	0.15
	HYPOSAT	True	35.9390	129.0760	21.66	-0.004	0.032
		I	35.9380	129.0760	21.87	0.075	0.034
		III	35.9370	129.0750	22.10	0.152	0.049
	MHYPO	True	35.9396	129.0794	21.5302	0.0052	0.0840
		I	35.9382	129.0784	22.0015	0.0268	0.1386
		III	35.9367	129.0774	22.4666	0.0480	0.2453
6	True value		35.9200	129.2400	27.00	0.00	
	HYPO-71	True	35.9220	129.2452	26.18	0.08	0.13
		I	35.9242	129.2442	25.86	0.29	0.15
		III	35.9227	129.2415	25.39	0.52	0.18
	HYPOSAT	True	35.9180	129.2400	27.09	-0.005	0.015
		I	35.9200	129.2420	27.33	0.070	0.026
		III	35.9220	129.2430	27.56	0.143	0.045
	MHYPO	True	35.9193	129.2411	27.0023	0.0021	0.1010
		I	35.9210	129.2406	27.4553	0.0200	0.1778
		III	35.9212	129.2383	27.9750	0.0298	0.3104

depth errors determined by HYPO-71 are similar to those by HYPOSAT. As shown in Table 1, the errors in the focal depth of event 1 estimated by MHYPO are much larger than those of the other events because of the lack of data having focal depth information. The errors in the focal depth of event 1 , however, decrease rapidly when the number of data having focal depth information increases from one to three (Table 2).

Figure 5 presents that errors in the origin time by MHYPO become much smaller than those by HYPO-71 and HYPOSAT. The errors in the origin time by HYPO-71 have a trend similar to those by HYPOSAT. Furthermore, the errors in the origin time estimation by both HYPO-71 and HYPOSAT increase as the focal depth increases in general, while the errors by MHYPO show a stable variation regardless of the focal depth. As shown in Figure 6, the errors in the epicenter estimation by MHYPO decreases slightly compared to those by HYPOSAT and HYPO-71. All of them show a similar trend. As shown in Table 1 and Figures 4 to 6, the RMS traveltime errors generated by MHYPO are mainly caused by the velocity differences between the true and models used. The hypocentral parameters estimated by MHYPO are more accurate than those by HYPO-71 and HYPOSAT. MHYPO reduces the errors in the estimation of hypocentral parameters as well as the dependence on the velocity model used.

Figure 7 presents errors in the epicenter (green) and focal depth (yellow) estimation with varying numbers of data having focal depth information for event 1. Red, black, purple, and blue outline colors denote the velocity models I, II, III, and IV, respectively. The errors in epicentral distances and focal depths decrease rapidly as number of data having focal depth information increases from one to three. If the number of data is greater than three, the errors do not decrease so rapidly as the previous case. It is worthwhile to note that more than three data having focal depth information are required to estimate reliable focal depth.

Second, tests with noisy data are carried out. Errors in

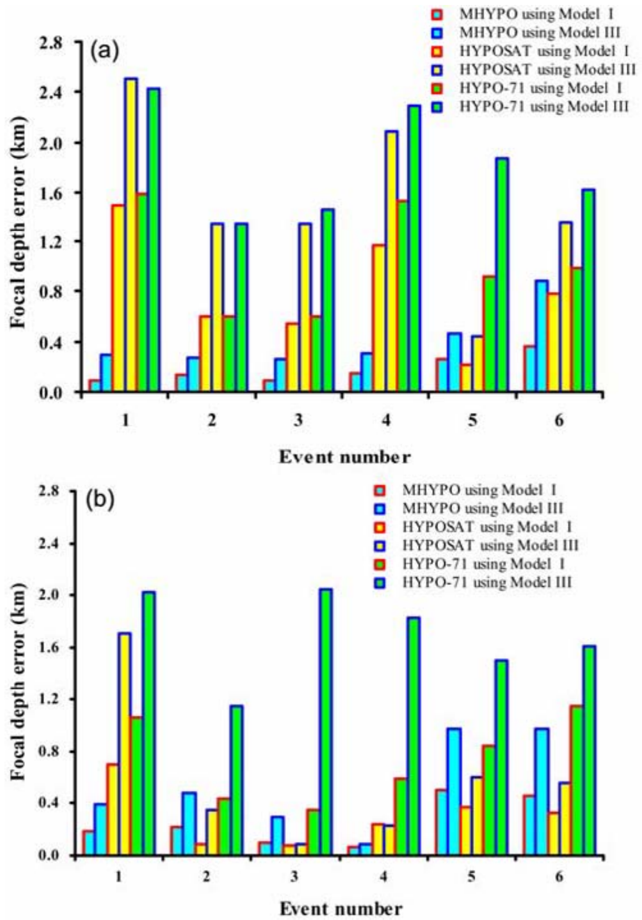

Fig. 8. (a) Comparison of errors in the focal depth estimation by MHYPO, HYPO-71 and HYPOSAT using velocity models I and III. The errors by MHYPO are much smaller than those by HYPO-71 and HYPOSAT regardless of models used. Numerical values are tabulated in Table 3a. Zero mean and standard deviation of 0.05 random noise is added to the synthetic traveltime data, **(b)** Comparison of errors in the focal depth estimation by MHYPO, HYPO-71 and HYPOSAT using velocity models I and III. The errors by MHYPO are much smaller than those by HYPO-71 and HYPOSAT regardless of models used. Numerical values are tabulated in Table 3b. Zero mean and standard deviation of 0.1 random noise is added to the synthetic traveltime data.

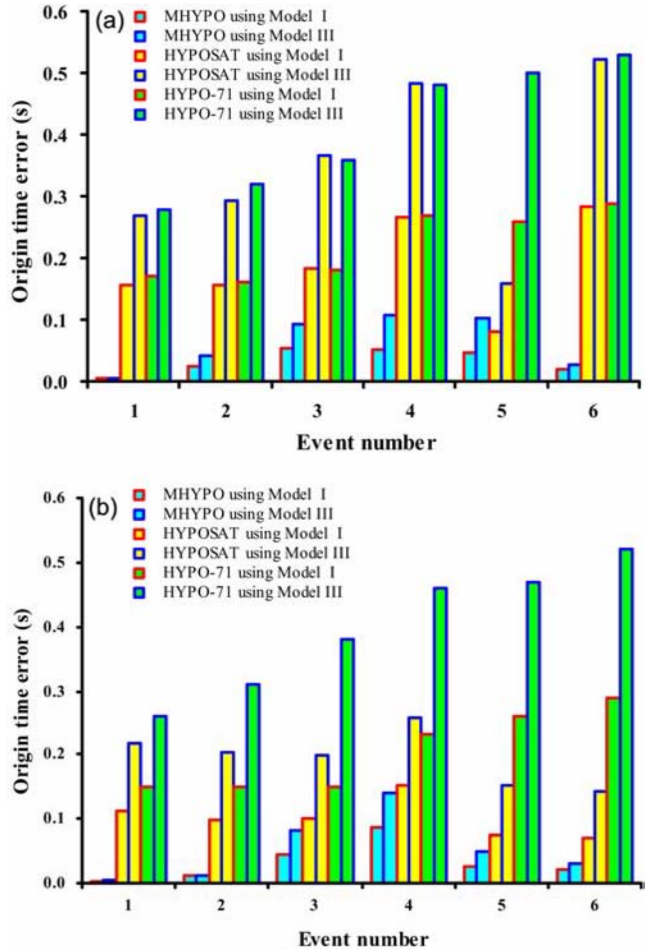

Fig. 9. (a) Comparison of errors in the origin time estimation by MHYPO, HYPO-71 and HYPOSAT using velocity models I and III. The errors by MHYPO are slightly smaller than those by HYPO-71 and HYPOSAT regardless of models used. Numerical values are tabulated in Table 3a. Zero mean and standard deviation of 0.05 random noise is added to the synthetic traveltime data, **(b)** Comparison of errors in the origin time estimation by MHYPO, HYPO-71 and HYPOSAT using velocity models I and III. The errors by MHYPO are slightly smaller than those by HYPO-71 and HYPOSAT regardless of models used. Numerical values are tabulated in Table 3b. Zero mean and standard deviation of 0.1 random noise is added to the synthetic traveltime data.

hypocentral parameters estimated by the HYPO-71, HYPOSAT, and MHYPO are listed in Tables 3a and 3b for the same events presented in Table 1. In comparison to Table 1, random noise is added to the synthetic traveltime data. The noise is simulated by random numbers of a standard normal distribution with zero mean and the standard deviation of 0.05 and 0.1 seconds. The test results of the one are presented in Table 3a, and those of the other are presented in Table 3b. The maximum errors in traveltime data are 0.13 and 0.25 seconds, respectively. The RMS traveltime error of data attributed to noise is about 0.054 and 0.1 seconds, respectively. Figures 8 to 10 present errors in the estimation of focal depths, origin times, and epicenters by event numbers tabulated in Tables 3a and 3b with velocity models I and III. As shown in Tables 3a and 3b and Figures 8 to 10, the errors by MHYPO much smaller than those by HYPO-71 and HYPOSAT. Some exceptions are observed. The errors in the focal depth estimation by MHYPO for events 5 and 6 in Figure 8b are slightly larger than those by HYPOSAT. The errors in origin time and epicenter estimation by MHYPO are, however, much or slightly smaller than those by HYPOSAT (Figs. 9b and 10b). These features may result from compensation between velocity error and data error in the algorithms.

Compared with the existing packages, MHYPO estimates

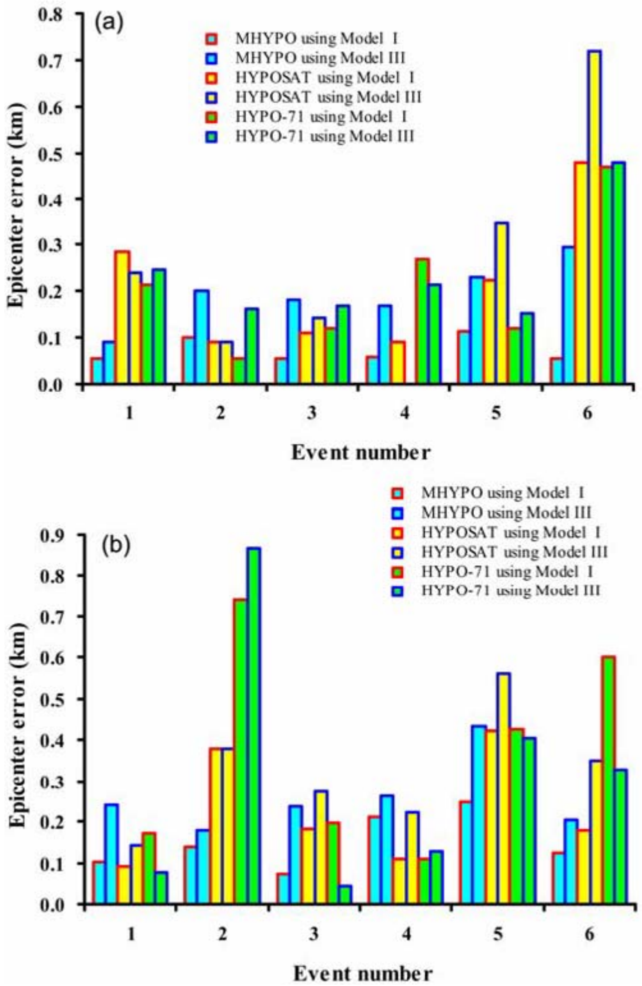

Fig. 10. (a) Comparison of errors in the epicenter estimation by MHYPO, HYPO-71 and HYPOSAT using velocity models I and III. The errors by MHYPO are slightly smaller than those by HYPO-71 and HYPOSAT regardless of models used. Numerical values are tabulated in Table 3a. Zero mean and standard deviation of 0.05 random noise is added to the synthetic traveltime data, **(b)** Comparison of errors in the epicenter estimation by MHYPO, HYPO-71 and HYPOSAT using velocity models I and III. The errors by MHYPO are slightly smaller than those by HYPO-71 and HYPOSAT regardless of models used. Numerical values are tabulated in Table 3b. Zero mean and standard deviation of 0.1 random noise is added to the synthetic traveltime data.

more accurate focal depths and origin times. MHYPO also slightly improves the accuracy in epicenter estimation. MHYPO reduced the dependence on velocity models used.

4. CONCLUSIONS

A weighting factor related to the sensitivity of traveltime to the focal depths and the two-point ray tracing technique are applied to an existing hypocentral parameter estimation method to reduce the dependence on velocity models used and to improve their accuracies. The variation in traveltimes caused by the focal depth changes indicate the degree of focal depth information contained in the traveltime data. The degree of focal depth information decreases as the epicentral distance increases. The variation is nearly zero when the epicentral distance exceeds a certain limit. The traveltime data obtained beyond this limit contain almost no information about the focal depth. The weighting factor is described by the variation of the vertical component traveltime (T_z) as a function of take-off angles at the hypocenter (source) since the take-off angle depends on the epicentral distance. The new packages called MHYPO is developed applying the weighting factor and the two-point ray tracing technique to HYPO-71. MHYPO appears to be robust, improves the accuracy in hypocentral parameter estimation, and reduces dependence on velocity models used. Various numerical tests show that MHYPO yields more accurate hypocentral parameters, especially the focal depth and origin time, than HYPO-71 or HYPOSAT. To obtain the reliable hypocentral parameters, MHYPO requires at least three data whose epicentral distances are less than three times of the focal depth.

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REFERENCES

Kim, W., and Baag, C.-E., 2002, Rapid and accurate two-point ray tracing based on a quadratic equation of takeoff angle in layer media with constant or linearly varying velocity functions. Bull. Seis. Soc. Am., 92, 2251–2263.

Kissling, E., Ellsworth, W.L., Eberhart-Phillips, D., and Kradolfer, U., 1994, Initial reference models in local earthquake tomography. J. Geophys. Res, 99, 19635–19646.

Lahr, J.C., 1980, HYPOELLIPSE/MULTICS: a computer program for determining local earthquake hypocentral parameters, magnitude, and first motion pattern. U.S. Geol. Surv. Open File Rep., 59–80.

Lee, W.H.K., and Lahr, J.C., 1975, A computer program for determining local earthquake hypocenter, magnitude, and first motion pattern of local earthquakes. U.S. Geol. Surv. Open File Rep., 75–311.

Lomnitz, C., 2006, Three theorems of earthquake location. Bull. Seis. Soc. Am., 96, 306-312.

Schweitzer, J., 1997, HYPOSAT-a new routine to locate seismic events. NORSAR Scientic Report, 1-97/98, 94-102.

Schweitzer, J., 2002, HYPOSAT-an enhanced routine to locate seismic events. Pure and Applied Geophysics, 158, 277-289.

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