NRIAG Journal of Astronomy and Geophysics (2017) 6, 19–29

National Research Institute of Astronomy and Geophysics

NRIAG Journal of Astronomy and Geophysics

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# Regional travel-time residual studies and station correction from 1-D velocity models for some stations around Peninsular Malaysia and Singapore

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Received 31 August 2016; revised 14 November 2016; accepted 14 November 2016
Available online 5 December 2016

**KEYWORDS**

Malay Peninsula;
1-D velocity models;
P arrivals;
Station correction

**Abstract** We have investigated the average P-wave travel-time residuals for some stations around Southern Thailand, Peninsular Malaysia and Singapore at regional distances. Six years (January, 2010–December, 2015) record of events from central and northern Sumatra was obtained from the digital seismic archives of Integrated Research Institute for Seismology (IRIS). The criteria used for the data selection are designed to be above the magnitude of mb 4.5, depth less than 200 km and an epicentral distance shorter than 1000 km. Within this window a total number of 152 earthquakes were obtained. Furthermore, data were filtered based on the clarity of the seismic phases that are manually picked. A total of 1088 P-wave arrivals and 962 S-wave arrivals were hand-picked from 10 seismic stations around the Peninsula. Three stations IPM, KUM, and KOM from Peninsular Malaysia, four stations BTDF, NTU, BESC and KAPK from Singapore and three stations SURA, SRIT and SKLT located in the southern part of Thailand are used. Station NTU was chosen as the Ref. station because it recorded the large number of events. Travel-times were calculated using three 1-D models (Preliminary Ref. Earth Model PREM (Dziewonski and Anderson, 1981, IASP91, and Lienert et al., 1986) and an adopted two-point ray tracing algorithm. For the three models, we corroborate our calculated travel-times with the results from the use of TAUP travel-time calculation software. Relative to station NTU, our results show that the average P wave travel-time residual for PREM model ranges from −0.16 to 0.45 s for BESC and IPM respectively. For IASP91 model, the average residual ranges from −0.25 to 0.24 s for SRIT and SKLT respectively, and ranges from −0.22 to 0.30 s for KAPK and IPM respectively for Lienert et al. (1986) model. Generally, most stations have slightly positive residuals relative to station NTU. These corrections reflect the differ-

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Peer review under responsibility of National Research Institute of Astronomy and Geophysics.

ELSEVIER Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.nrjag.2016.11.002
2090-9977 

ence between actual and estimated model velocities along ray paths to stations and can compensate for heterogeneous velocity structure near individual stations. The computed average travel-time residuals can reduce errors attributable to station correction in the inversion of hypocentral parameters around the Peninsula. Due to the heterogeneity occasioned by the numerous fault systems, a better 1-D velocity model for the Peninsula is desired for more reliable hypocentral inversion and other seismic investigations.



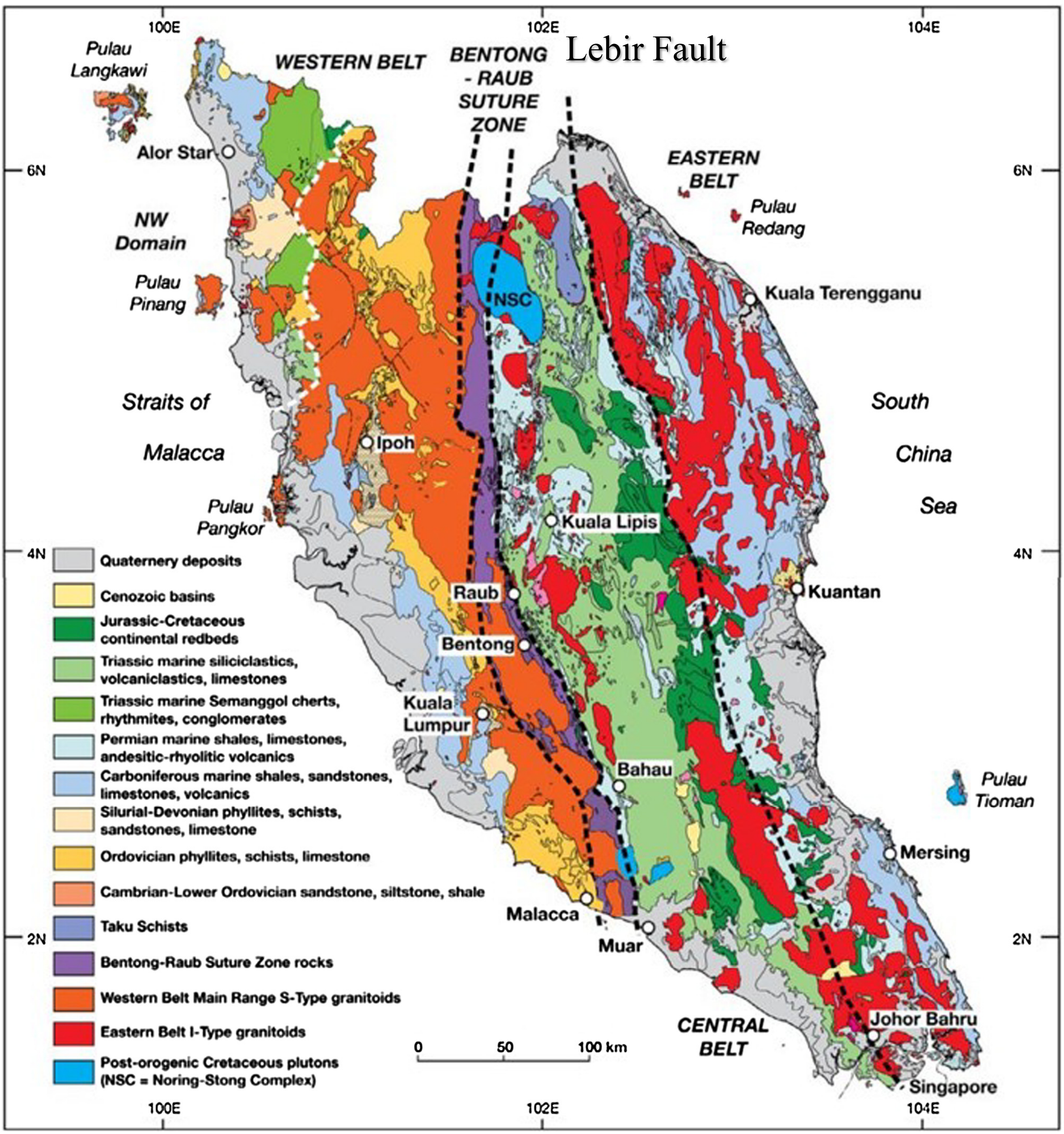


**Figure 1** Seismotectonic map of Malay Peninsula with major structure trends identified (after JMG (2006)).

## 1. Introduction

Precise earthquake location is determined by many factors, which among others include data quality, station distribution, prior information of the velocity structure of the area and appropriate station corrections. Even with accurate phase picks, and reliable model, station correction plays a significant role in the hypocentral parameters inversion process.

Peninsular Malaysia is situated close where the Indo-Australian Plate is actively subducting southwestward underneath the Eurasian Plate. The major structural elements in the Peninsular Malaysia are the Bentong-Raub shear zone and the Lebir fault trending in almost N-S direction (Fig. 1). Both Structures subdivide the peninsular Malaysia into three parts. Unfortunately, the stations used in the present work are situated in the Eastern part (i.e. Sibumasu terrane).

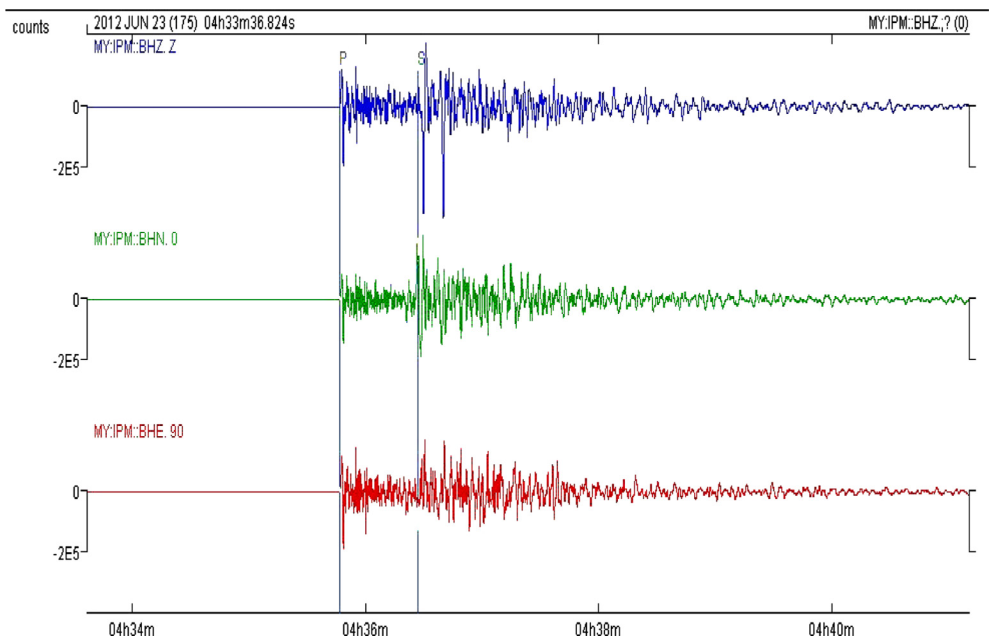


**Figure 2** Hand-picked $P_n$- and $S_n$-arrival times using SeisGram2K (Lomax et al., 2012) for station IPM at an epicentral distance of about 385 km with an S-P time of 79.92 s.

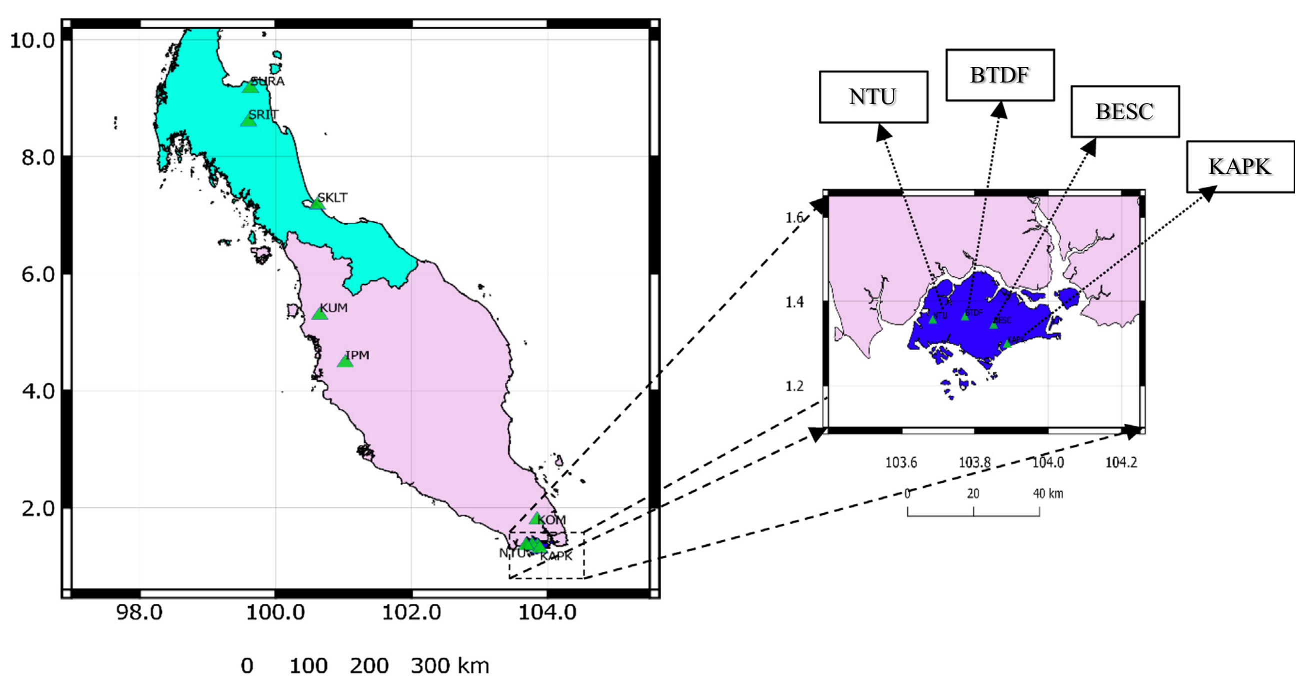


**Figure 3** Station distribution of the 10 stations (to the right are the four stations distributed around Singapore).

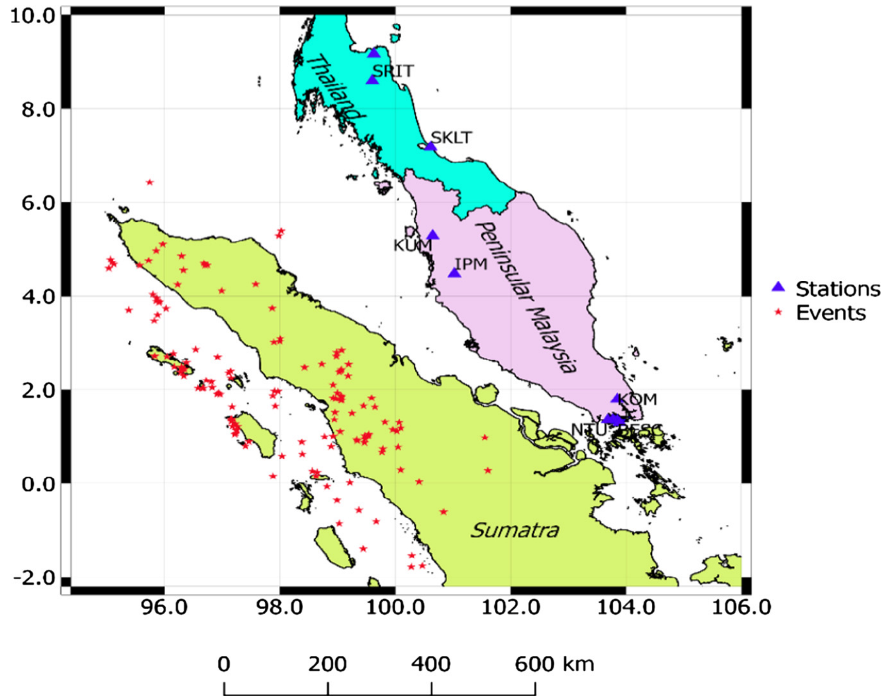


**Figure 4** Earthquake epicenter and station distribution.

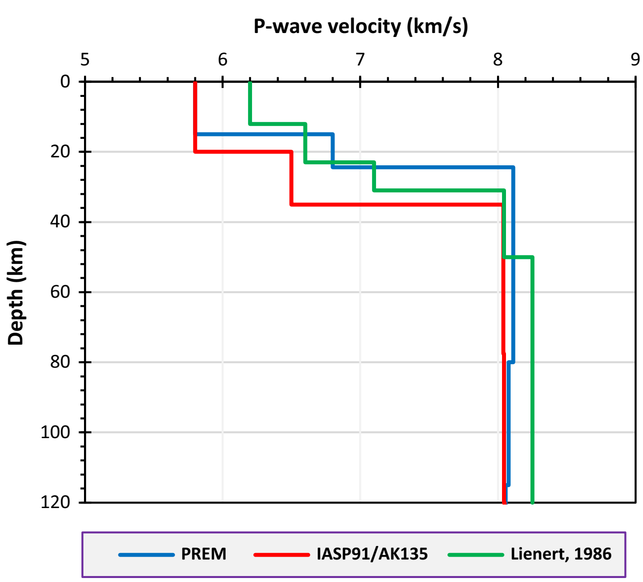


**Figure 5** Three Velocity model (PREM, IASP91 and Lienert et al., 1986) used for the analysis.

Fault lines in Peninsular Malaysia appeared to be infrequent and inactive. However, a series of large earthquakes in recent years had changed the tectonic setting in the Southeast Asian region, including Peninsular Malaysia (Bendick et al., 2001). Earthquake locations and other seismogenic investigations around Peninsular Malaysia will benefit from the determination of station corrections for some velocity models. The likelihood of laterally varying heterogeneities makes a single travel-time residual value for a station unsuitable to every hypocentral parameters inversions. However, from record of many events, an average value of travel-time residual obtained from generating synthetic travel-times for a seismic station using a known velocity model can reduce the effect of shifting the computed hypocentral parameters far from the real locations. The effects of lateral heterogeneity at a given station can be accounted for by constructing a source-specific station correction. This is achieved by ray tracing through the models from the events to each station.

**Table 1** Upper mantle 1-D velocity model for PREM, IASP91 and Lienert et al., 1986.

| PREM | | IASP91 | | Lienert et al. (1986) | |
|---|---|---|---|---|---|
| Depth (km) | Vel. (km/s) | Depth (km) | Vel. (km/s) | Depth (km) | Vel. (km/s) |
| 0.0 | 5.80 | 0.0 | 5.80 | 0.0 | 6.20 |
| 15.0 | 6.80 | 20.0 | 6.50 | 12.0 | 6.60 |
| 24.4 | 8.11 | 35.0 | 8.04 | 23.0 | 7.10 |
| 80.0 | 8.08 | 77.5 | 8.045 | 31.0 | 8.05 |
| 115.0 | 8.06 | 120.0 | 8.05 | 50.0 | 8.25 |
| 150.0 | 8.03 | 171.0 | 8.19 | 120.0 | 8.30 |
| 220.0 | 8.56 | 210.0 | 8.30 | – | – |

**Table 2** Selected events (152) from IRIS catalog.

| | yyyy/mm/dd | hh:mi:ss.00 | Lat (°) | Long (°) | Depth (km) | Mag | Id |
|---|---|---|---|---|---|---|---|
| 1 | 2010/01/26 | 06:53:25.85 | −0.3618 | 98.9902 | 61.50 | 5.0 | 1153 |
| 2 | 2010/02/28 | 12:13:27.48 | 2.0961 | 98.9219 | 53.40 | 5.1 | 1152 |
| 3 | 2010/03/13 | 14:59:03.73 | 1.3749 | 97.1691 | 34.50 | 5.8 | 1151 |
| 4 | 2010/03/14 | 08:21:50.59 | 0.9496 | 99.4759 | 25.00 | 4.8 | 1150 |
| 5 | 2010/04/03 | 14:50:02.58 | 1.8224 | 98.9253 | 134.90 | 4.8 | 1149 |
| 6 | 2010/04/06 | 22:15:02.13 | 2.3601 | 97.1113 | 33.40 | 7.8 | 1148 |
| 7 | 2010/04/06 | 22:54:05.28 | 2.2486 | 97.1554 | 33.00 | 5.3 | 1147 |
| 8 | 2010/04/07 | 04:22:15.99 | 2.6964 | 96.9212 | 33.80 | 5.1 | 1146 |
| 9 | 2010/04/08 | 22:21:32.20 | 3.6000 | 95.8800 | 33.00 | 5.0 | 1145 |
| 10 | 2010/04/09 | 06:29:37.61 | 1.8549 | 99.0668 | 32.90 | 4.9 | 1144 |
| 11 | 2010/04/12 | 20:33:28.02 | 2.3933 | 97.1469 | 41.40 | 5.0 | 1143 |
| 12 | 2010/04/21 | 18:03:35.16 | −0.6063 | 100.8380 | 169.80 | 4.9 | 1142 |
| 13 | 2010/05/09 | 05:59:42.34 | 3.7328 | 96.0278 | 42.30 | 7.3 | 1141 |
| 14 | 2010/05/11 | 12:17:46.81 | 3.4738 | 95.8228 | 40.80 | 5.4 | 1140 |
| 15 | 2010/06/03 | 09:24:15.87 | 4.7581 | 95.7256 | 80.50 | 5.4 | 1139 |
| 16 | 2010/06/30 | 10:54:51.81 | −0.8169 | 99.6697 | 85.90 | 5.0 | 1138 |
| 17 | 2010/07/01 | 15:21:48.78 | 1.2175 | 97.1780 | 29.50 | 5.1 | 1137 |
| 18 | 2010/07/13 | 04:26:24.82 | 1.3823 | 97.1485 | 28.00 | 5.1 | 1136 |
| 19 | 2010/07/13 | 22:21:03.40 | 1.3337 | 97.1615 | 27.30 | 5.0 | 1135 |
| 20 | 2010/07/24 | 02:11:26.02 | 1.0188 | 99.5342 | 39.70 | 5.3 | 1130 |
| 21 | 2010/07/24 | 02:48:20.10 | 1.0200 | 99.4700 | 10.00 | 4.8 | 1134 |
| 22 | 2010/07/24 | 03:40:53.40 | 1.0200 | 99.5300 | 10.00 | 4.9 | 1133 |
| 23 | 2010/07/24 | 08:56:01.30 | 1.0500 | 99.5400 | 10.00 | 4.5 | 1132 |
| 24 | 2010/07/24 | 14:59:21.96 | 0.8656 | 99.4678 | 33.20 | 4.7 | 1131 |
| 25 | 2010/07/24 | 15:17:48.84 | −1.3961 | 99.4454 | 21.50 | 5.0 | 1129 |
| 26 | 2010/08/21 | 05:42:54.13 | 2.1984 | 96.7234 | 33.20 | 6.0 | 1128 |
| 27 | 2010/09/28 | 23:44:37.20 | 1.9069 | 96.9135 | 23.50 | 5.3 | 1127 |
| 28 | 2010/10/14 | 09:14:27.98 | 1.3050 | 99.8224 | 197.30 | 4.7 | 1126 |
| 29 | 2010/10/15 | 12:43:54.27 | 3.7001 | 95.3813 | 43.00 | 5.0 | 1125 |
| 30 | 2010/10/22 | 04:45:59.70 | 0.6700 | 99.7700 | 10.00 | 4.9 | 1124 |
| 31 | 2010/11/19 | 21:55:15.67 | 1.1808 | 100.0952 | 215.80 | 5.7 | 1123 |
| 32 | 2010/11/21 | 22:51:40.96 | 6.4261 | 95.7452 | 261.00 | 5.0 | 1122 |
| 33 | 2010/11/25 | 07:00:49.19 | 0.9381 | 99.3306 | 20.40 | 4.5 | 1121 |
| 34 | 2010/12/01 | 00:50:21.72 | 2.7142 | 98.9789 | 163.40 | 5.6 | 1120 |
| 35 | 2010/12/05 | 15:45:22.70 | −0.5700 | 99.3700 | 51.00 | 5.0 | 1119 |
| 36 | 2010/12/21 | 14:07:49.05 | 2.7174 | 95.8302 | 26.90 | 5.8 | 1118 |
| 37 | 2010/12/23 | 00:01:37.62 | 3.9093 | 95.8845 | 43.90 | 5.5 | 1117 |
| 38 | 2011/01/15 | 11:23:54.31 | 2.4756 | 96.2914 | 28.10 | 5.8 | 1116 |
| 39 | 2011/01/15 | 11:45:19.71 | 2.3681 | 96.2809 | 23.90 | 5.0 | 1115 |
| 40 | 2011/01/15 | 16:26:08.56 | 2.4350 | 96.3458 | 28.50 | 5.5 | 1114 |
| 41 | 2011/01/18 | 11:33:44.98 | 2.5751 | 96.3816 | 23.70 | 6.0 | 1113 |
| 42 | 2011/01/26 | 15:42:29.72 | 2.1650 | 96.8128 | 23.80 | 6.0 | 1112 |
| 43 | 2011/02/ 7 | 08:08:36.59 | 0.8471 | 98.7980 | 80.70 | 5.1 | 1111 |
| 44 | 2011/02/18 | 23:12:05.44 | 1.9673 | 97.9071 | 49.70 | 5.2 | 1110 |
| 45 | 2011/02/20 | 14:32:23.33 | 1.3196 | 97.1661 | 28.80 | 5.3 | 1109 |
| 46 | 2011/02/28 | 23:10:25.25 | 3.8927 | 95.8541 | 54.90 | 5.0 | 1108 |
| 47 | 2011/03/04 | 08:07:34.36 | 1.6298 | 99.6471 | 166.40 | 4.5 | 1107 |
| 48 | 2011/03/19 | 02:33:46.25 | 0.7924 | 97.4034 | 27.40 | 5.1 | 1106 |
| 49 | 2011/03/25 | 09:14:29.60 | 1.1071 | 99.0453 | 109.60 | 5.2 | 1105 |
| 50 | 2011/04/06 | 14:01:44.65 | 1.6311 | 97.1723 | 31.30 | 5.9 | 1104 |
| 51 | 2011/04/29 | 08:56:48.97 | 4.0373 | 95.8005 | 58.20 | 5.4 | 1103 |
| 52 | 2011/05/06 | 18:56:44.14 | 0.7354 | 99.7858 | 150.00 | 5.1 | 1102 |
| 53 | 2011/05/18 | 03:21:16.17 | 4.2524 | 97.5817 | 169.60 | 4.6 | 1101 |
| 54 | 2011/05/18 | 12:50:45.30 | 1.5000 | 99.2500 | 107.00 | 4.6 | 1100 |
| 55 | 2011/06/14 | 00:08:34.39 | 1.7751 | 99.0744 | 29.30 | 5.5 | 1099 |
| 56 | 2011/06/14 | 03:01:30.65 | 1.8511 | 99.0753 | 28.80 | 5.7 | 1098 |
| 57 | 2011/06/18 | 11:57:59.60 | 1.7702 | 99.0581 | 16.90 | 5.2 | 1097 |
| 58 | 2011/07/31 | 23:17:55.08 | 2.5361 | 99.1916 | 168.40 | 4.5 | 1096 |
| 59 | 2011/07/31 | 23:56:37.32 | 0.0146 | 99.2137 | 87.20 | 5.1 | 1095 |
| 60 | 2011/08/03 | 20:02:18.65 | 0.9962 | 98.7747 | 81.10 | 5.2 | 1094 |
| 61 | 2011/08/31 | 03:08:28.53 | 2.4772 | 96.2990 | 32.20 | 5.0 | 1093 |
| 62 | 2011/09/05 | 17:55:12.93 | 3.0253 | 97.9991 | 106.60 | 6.7 | 1092 |
| 63 | 2011/09/14 | 10:37:02.82 | 0.7741 | 100.0502 | 191.50 | 4.7 | 1091 |

(*continued on next page*)

**Table 2** (*continued*)

| | yyyy/mm/dd | hh:mi:ss.00 | Lat (°) | Long (°) | Depth (km) | Mag | Id |
|---|---|---|---|---|---|---|---|
| 64 | 2011/10/ 6 | 01:33:35.50 | 0.6209 | 100.1590 | 202.00 | 4.5 | 1090 |
| 65 | 2011/10/16 | 17:16:20.44 | 2.4827 | 96.1701 | 39.00 | 5.4 | 1089 |
| 66 | 2011/11/18 | 05:40:36.70 | 0.2756 | 101.6059 | 35.00 | 4.5 | 1088 |
| 67 | 2011/11/27 | 11:01:06.99 | 0.1537 | 97.8800 | 28.60 | 5.4 | 1087 |
| 68 | 2012/01/01 | 18:09:02.81 | 4.5521 | 96.3288 | 8.50 | 5.4 | 1086 |
| 69 | 2012/01/05 | 23:14:50.12 | −0.8578 | 99.0303 | 45.70 | 5.0 | 1085 |
| 70 | 2012/01/13 | 20:03:47.07 | 2.4445 | 96.2964 | 41.10 | 5.2 | 1084 |
| 71 | 2012/01/28 | 14:47:17.94 | 2.0256 | 96.6594 | 28.30 | 5.3 | 1083 |
| 72 | 2012/01/30 | 13:20:34.42 | 2.0319 | 96.5820 | 29.90 | 5.2 | 1082 |
| 73 | 2012/02/20 | 02:28:17.61 | 1.8213 | 99.5901 | 191.60 | 5.2 | 1081 |
| 74 | 2012/03/05 | 06:55:28.92 | 4.1142 | 96.9922 | 27.20 | 5.1 | 1080 |
| 75 | 2012/03/30 | 22:02:10.88 | 4.5936 | 95.0360 | 51.10 | 5.0 | 1079 |
| 76 | 2012/03/31 | 03:58:19.34 | 0.9777 | 101.5528 | 10.00 | 4.6 | 1078 |
| 77 | 2012/05/08 | 22:23:50.48 | 1.9290 | 98.9980 | 133.00 | 4.6 | 1077 |
| 78 | 2012/06/23 | 04:34:53.18 | 3.0090 | 97.8960 | 95.00 | 6.1 | 1076 |
| 79 | 2012/07/25 | 00:27:45.26 | 2.7070 | 96.0450 | 22.00 | 6.4 | 1075 |
| 80 | 2012/08/04 | 02:00:30.07 | −1.7580 | 100.4710 | 72.20 | 5.1 | 1074 |
| 81 | 2012/08/04 | 11:24:15.01 | 4.8570 | 96.2960 | 36.50 | 5.3 | 1073 |
| 82 | 2012/08/10 | 04:41:40.25 | 1.9010 | 96.9650 | 8.00 | 5.2 | 1072 |
| 83 | 2012/08/27 | 09:01:23.13 | 2.3760 | 99.0310 | 149.50 | 5.2 | 1071 |
| 84 | 2012/09/20 | 20:47:46.61 | −0.0650 | 98.8170 | 72.10 | 5.3 | 1070 |
| 85 | 2012/09/29 | 20:19:09.18 | 2.4720 | 98.4290 | 104.20 | 4.8 | 1069 |
| 86 | 2012/10/17 | 19:38:55.81 | 1.2650 | 97.2290 | 32.60 | 5.0 | 1068 |
| 87 | 2012/10/29 | 02:22:44.50 | 0.8800 | 98.3810 | 58.90 | 5.4 | 1067 |
| 88 | 2012/11/09 | 19:59:45.99 | 0.8860 | 97.4640 | 22.10 | 5.2 | 1066 |
| 89 | 2013/01/10 | 13:47:03.78 | 4.7200 | 95.0950 | 38.00 | 5.7 | 1065 |
| 90 | 2013/01/21 | 22:22:52.90 | 4.9660 | 95.8560 | 11.60 | 6.1 | 1064 |
| 91 | 2013/02/06 | 22:12:17.60 | −1.5380 | 100.2860 | 10.00 | 5.3 | 1063 |
| 92 | 2013/02/07 | 00:41:32.60 | 1.3610 | 98.9450 | 96.30 | 5.0 | 1062 |
| 93 | 2013/02/09 | 02:50:38.60 | 2.2950 | 99.1830 | 163.20 | 4.6 | 1061 |
| 94 | 2013/02/18 | 12:01:48.00 | 1.8130 | 99.0500 | 129.70 | 4.8 | 1060 |
| 95 | 2013/04/04 | 19:34:31.01 | 1.2970 | 100.0690 | 201.70 | 4.5 | 1058 |
| 96 | 2013/04/05 | 17:35:29.90 | 0.2320 | 98.6470 | 40.00 | 5.1 | 1057 |
| 97 | 2013/04/29 | 13:42:59.60 | 3.8860 | 95.9180 | 61.10 | 5.0 | 1056 |
| 98 | 2013/05/16 | 01:11:28.90 | 0.0310 | 100.4140 | 164.80 | 4.7 | 1055 |
| 99 | 2013/06/11 | 02:30:36.40 | −1.7800 | 100.2780 | 35.20 | 5.1 | 1054 |
| 100 | 2013/07/02 | 07:37:02.90 | 4.6980 | 96.6870 | 10.00 | 6.1 | 1053 |
| 101 | 2013/07/02 | 13:55:41.00 | 4.6540 | 96.7060 | 31.80 | 5.5 | 1052 |
| 102 | 2013/07/02 | 15:36:46.80 | 4.6600 | 96.7440 | 32.00 | 5.3 | 1051 |
| 103 | 2013/07/05 | 16:54:39.82 | 2.5405 | 98.7282 | 15.90 | 4.7 | 1050 |
| 104 | 2013/07/11 | 07:16:25.42 | 1.8035 | 98.9646 | 10.00 | 4.8 | 1049 |
| 105 | 2013/07/16 | 23:41:14.76 | 5.3895 | 98.0248 | 29.20 | 5.3 | 1048 |
| 106 | 2013/08/30 | 04:40:48.57 | 1.1459 | 99.9575 | 207.60 | 4.5 | 1047 |
| 107 | 2013/09/04 | 09:11:57.58 | 2.7935 | 98.9843 | 161.40 | 4.8 | 1046 |
| 108 | 2013/10/13 | 17:32:45.61 | 3.9633 | 95.8634 | 46.00 | 5.6 | 1045 |
| 109 | 2013/10/22 | 05:40:39.10 | 5.1033 | 95.9709 | 9.80 | 5.4 | 1044 |
| 110 | 2013/11/28 | 16:02:54.06 | 0.2604 | 98.5620 | 51.40 | 5.1 | 1043 |
| 111 | 2013/12/01 | 06:29:57.80 | 2.0440 | 96.8261 | 20.00 | 6.0 | 1042 |
| 112 | 2013/12/02 | 07:34:55.93 | 2.0338 | 96.6783 | 18.10 | 5.4 | 1041 |
| 113 | 2013/12/20 | 21:10:47.35 | 4.2420 | 96.2285 | 90.20 | 5.1 | 1040 |
| 114 | 2014/02/22 | 17:27:59.30 | 1.0765 | 97.2362 | 28.00 | 5.1 | 1039 |
| 115 | 2014/02/22 | 17:29:48.74 | 1.2069 | 97.2622 | 12.50 | 5.3 | 1038 |
| 116 | 2014/03/15 | 10:58:46.16 | 2.8381 | 99.0717 | 171.60 | 5.4 | 1037 |
| 117 | 2014/04/20 | 08:43:51.93 | 0.6258 | 98.3891 | 43.10 | 5.4 | 1036 |
| 118 | 2014/05/01 | 14:35:37.06 | 1.9623 | 97.9671 | 37.00 | 5.9 | 1035 |
| 119 | 2014/05/03 | 14:47:04.76 | 1.8734 | 97.8773 | 43.40 | 5.4 | 1034 |
| 120 | 2014/07/05 | 09:39:27.79 | 1.9335 | 96.9388 | 20.00 | 6.0 | 1033 |
| 121 | 2014/08/04 | 12:09:47.51 | 0.1560 | 98.6285 | 56.00 | 5.0 | 1032 |
| 122 | 2014/08/08 | 16:57:01.04 | 2.4268 | 99.0692 | 151.70 | 4.5 | 1031 |
| 123 | 2014/08/18 | 00:56:52.01 | 0.2882 | 100.0955 | 166.30 | 4.6 | 1030 |
| 124 | 2014/09/04 | 07:28:46.39 | 1.8714 | 99.0596 | 132.40 | 4.5 | 1029 |
| 125 | 2014/09/08 | 19:07:00.59 | 1.1163 | 100.0274 | 1.90 | 4.9 | 1028 |
| 126 | 2014/09/14 | 04:52:26.94 | 1.1462 | 97.2556 | 36.60 | 5.3 | 1027 |

**Table 2** (*continued*)

| | yyyy/mm/dd | hh:mi:ss.00 | Lat (°) | Long (°) | Depth (km) | Mag | Id |
|---|---|---|---|---|---|---|---|
| 127 | 2014/09/14 | 16:34:22.65 | 1.1309 | 97.2441 | 38.60 | 5.1 | 1026 |
| 128 | 2014/09/25 | 08:29 58.39 | 6.0011 | 95.5588 | 194.70 | 5.0 | 1025 |
| 129 | 2014/10/16 | 00:56:30.69 | 1.0484 | 97.2210 | 26.80 | 5.1 | 1024 |
| 130 | 2014/10/27 | 00:02:49.63 | 5.2888 | 97.9817 | 59.70 | 4.7 | 1023 |
| 131 | 2014/11/07 | 00:20:47.17 | 4.7800 | 95.0654 | 39.00 | 5.5 | 1022 |
| 132 | 2014/11/16 | 11:06:08.98 | 1.6469 | 97.9208 | 36.00 | 5.4 | 1021 |
| 133 | 2014/11/24 | 15:30:08.67 | 2.7693 | 96.1550 | 46.00 | 5.3 | 1020 |
| 134 | 2014/12/15 | 12:37:30.96 | 3.7405 | 97.8673 | 137.90 | 4.9 | 1019 |
| 135 | 2015/01/09 | 22:59 11.90 | 2.5913 | 96.0946 | 49.90 | 5.1 | 1018 |
| 136 | 2015/01/27 | 00:53 19.12 | 1.3368 | 97.2402 | 12.60 | 5.7 | 1017 |
| 137 | 2015/03/03 | 10:37 30.05 | −0.7789 | 98.7161 | 28.00 | 6.1 | 1016 |
| 138 | 2015/04/19 | 18 40 24.95 | 1.8950 | 98.9580 | 122.70 | 5.3 | 1015 |
| 139 | 2015/05/08 | 03:12 21.52 | 1.5404 | 97.9026 | 36.00 | 5.7 | 1014 |
| 140 | 2015/05/21 | 02:42:06.75 | 3.8584 | 95.9029 | 48.40 | 5.1 | 1013 |
| 141 | 2015/06/01 | 14:07:50.20 | 4.6521 | 95.5695 | 73.50 | 5.0 | 1012 |
| 142 | 2015/06/17 | 07:42:57.27 | 1.5166 | 98.9553 | 105.70 | 4.5 | 1011 |
| 143 | 2015/08/03 | 19:55:39.92 | 4.6798 | 95.1216 | 47.00 | 5.0 | 1010 |
| 144 | 2015/08/04 | 13:51:49.30 | 1.6518 | 99.4507 | 164.80 | 4.5 | 1009 |
| 145 | 2015/08/06 | 10:08:54.80 | 1.0048 | 98.9226 | 77.90 | 5.1 | 1008 |
| 146 | 2015/09/09 | 12:41:46.14 | 2.2936 | 96.3370 | 24.50 | 5.1 | 1007 |
| 147 | 2015/10/21 | 21:04:31.37 | 2.4029 | 99.0526 | 149.30 | 4.8 | 1006 |
| 148 | 2015/11/04 | 08:12:13.89 | 0.5827 | 98.0365 | 28.90 | 5.3 | 1005 |
| 149 | 2015/11/08 | 09:34:57.31 | 0.7863 | 98.8905 | 69.00 | 5.7 | 1004 |
| 150 | 2015/11/25 | 13:05:23.96 | 0.9064 | 99.3425 | 111.70 | 4.6 | 1003 |
| 151 | 2015/11/27 | 15:46:42.84 | 2.8539 | 96.5417 | 45.00 | 5.0 | 1002 |
| 152 | 2015/12/01 | 14:46:42.71 | 3.0954 | 98.0064 | 80.80 | 4.5 | 1001 |

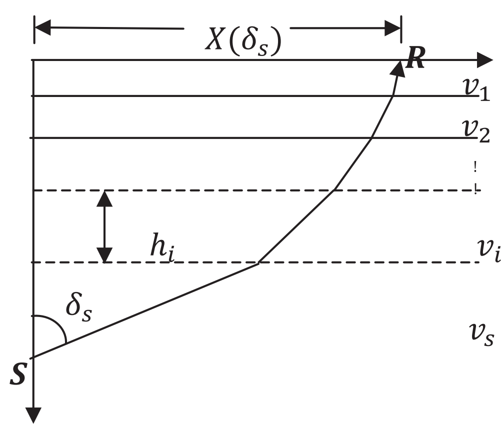


**Figure 6** Raypath segment from source **S** to receiver **R** in a layered medium with homogeneous velocity layers.

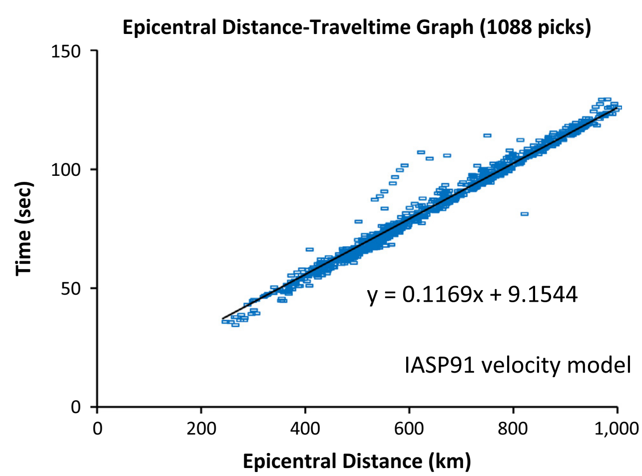


**Figure 7** Plot of travel-time against epicentral distances for Pn phases.

## 2. Data and velocity model

In this work, six years' seismic archive of Integrated Research Institute for Seismology (IRIS) was used to obtain source-specific station correction from three 1-D velocity models. We focus on earthquakes (delta < 1000 km) due to the limitations of a flat-earth layered velocity model. The epicentral distance ranges from 240.93 km to 996.32 km. JWEED software was used to retrieve the seismograms from IRIS database. SeisGram2K (Lomax et al., 2012) was used to identify the first arrival phases. Fig. 2 shows a sample of the identified arrival time pick for $P_n$ and $S_n$ phases for station IPM at an epicentral distance of about 385 km with an S-P time of 79.92 s.

During this period, 152 events (Table 2) with magnitude of 4.5 and above were selected and a total of 1088 P-wave arrivals and 962 S-wave arrivals where hand-picked from 10 broadband seismic stations distributed around the Peninsular. The stations include three situated in West Malaysia (IPM, KUM and KOM). The three stations are among the 17 weak motion stations distributed around Malaysia with 10 broadband seismometers and 7 short period seismometers (Chai et al., 2011). Four stations were situated in Singapore (BTDF, NTU, BESC and KAPK) and three in the southern part of

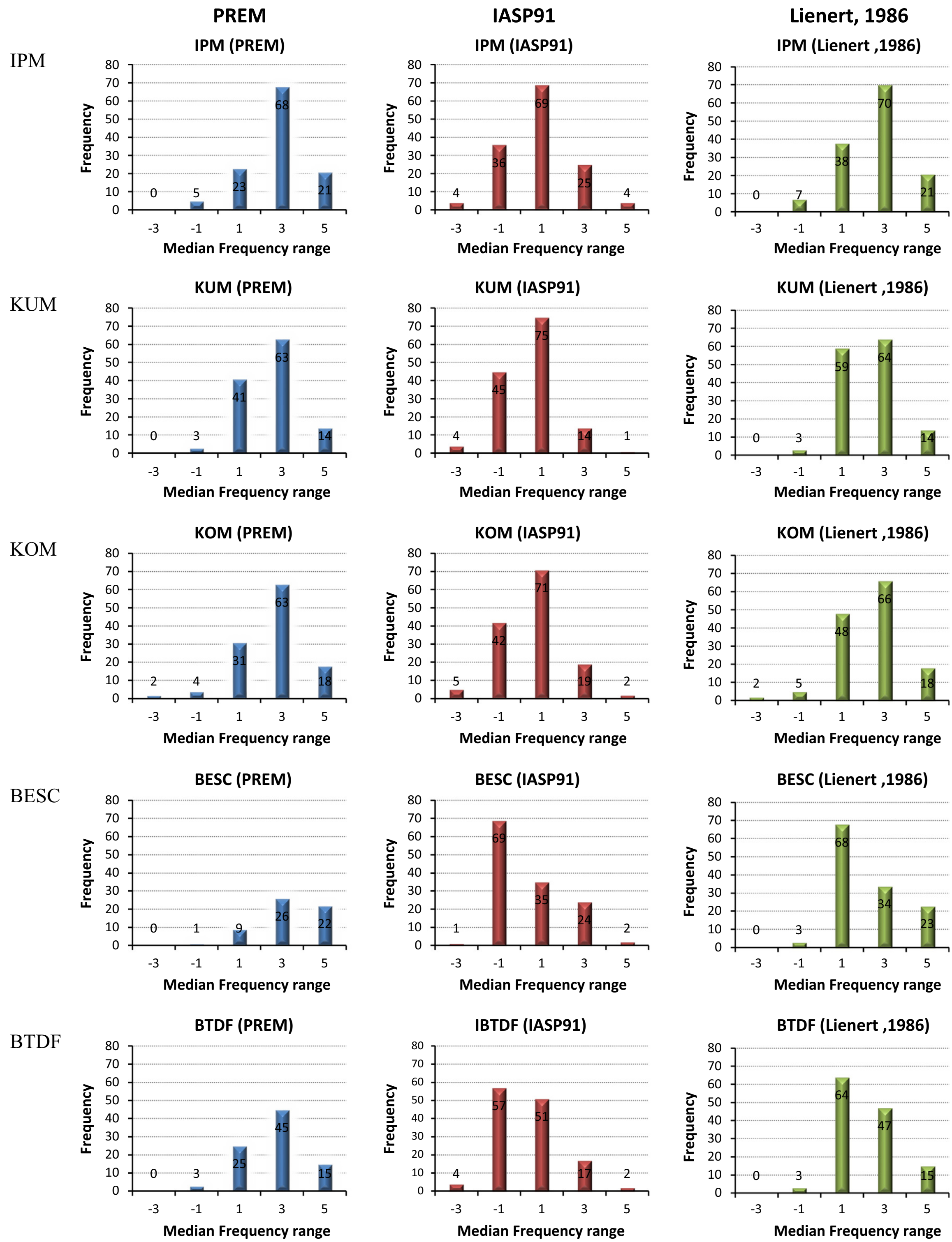


**Figure 8** Frequency of a range of residual values against the median range of values for stations IPM, KUM, KOM, BESC and BTDF.

Thailand (SURA, SRIT and SKLT). The location map of the 10 stations used in the analysis is shown in Fig. 3, whereas, the epicenter locations of earthquakes are presented in Fig. 4.

The three 1-D models selected (Fig. 5, Table 1) include Preliminary Reference Earth Model (PREM), IASP91 and Lienert et al., 1986. PREM according to Dziewonski and Anderson (1981) is an average Earth model that incorporates anelastic dispersion and anisotropy and therefore it is frequency-dependent and transversely isotropic for the upper mantle. In PREM, the crust consists of two uniform layers with dis-

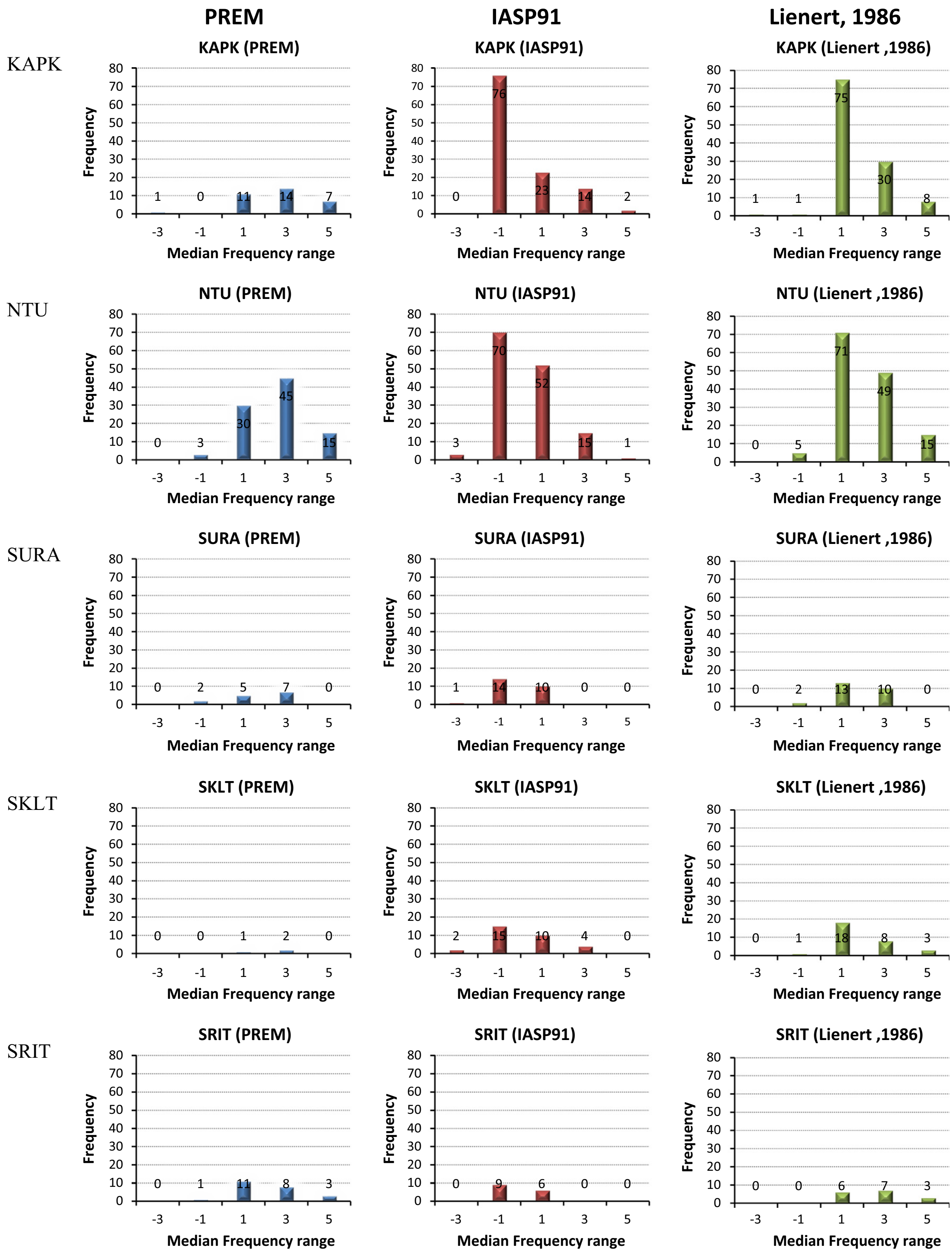


**Figure 9** Frequency of a range of residual values against the median range of values for stations KAPK, NTU, SURA, SKLT and SRIT.

continuities at 15 and 24.4 km. The IASP91 reference model (Kennett and Engdahl, 1991) is a parameterized velocity model that has been constructed to be a summary of the travel time characteristics of the main seismic phases. The crust consists of two uniform layers with discontinuities at 20 and 35 km. IASP91 model is similar to AK135 model for depths above the upper mantle, which is the region of focus of this work. The velocity model (Lienert et al., 1986) was chosen because

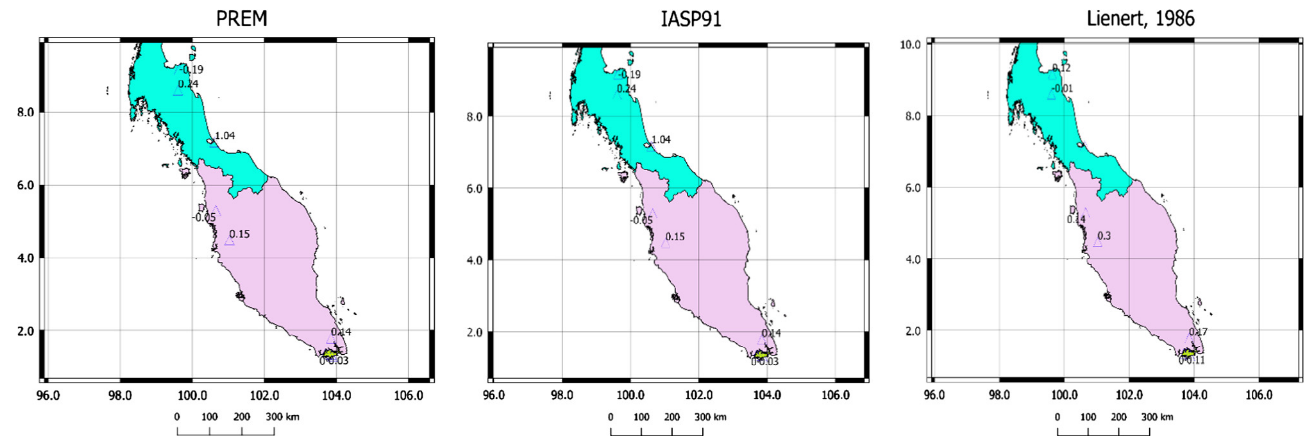


**Figure 10** Residual values for the stations with respect to station NTU for the three models.

it is adopted by METMalaysia department of earthquakes (Chai et al., 2011). The three models are widely accepted and used to represent the velocity structures within the earth.

## 3. Methodology

From the hypocentral parameters report of Integrated Research Institute for Seismology (IRIS), we use the two-point ray tracing technique for a horizontally layered media with constant velocity distribution in each layer (Kim and Baag, 2002), to compute travel-times for each station. In the technique, the horizontal distance $X(\delta_s)$ as a function of the takeoff angle at the source is given in Eq. (1) and illustrated in Fig. 6. A quadratic equation with respect to the difference between the true and calculated takeoff angles at the source is obtained in a Taylor series expansion. The takeoff angle is iteratively deduced with a high convergence rate. We compute ray paths for both Pg and Pn phases.

$$X(\delta_s) = \sum_{i=1}^{n} h_i \frac{\alpha_i \sin \delta_s}{\sqrt{1 - \alpha_i^2 \sin^2 \delta_s}} \tag{1}$$

where $\delta_s$ is the takeoff angle at source and $h_i$ is the layer thickness of the $i$-th segment. The velocity ratio is $\alpha_i = \frac{v_i}{v_s}$, where $v_s$ and $v_i$ are respectively the wave velocities of source layer and the layer corresponding to the $i$-th segment.

Using the respective values of their Moho depths for the three models, we separated IRIS reported focal depths into crustal and upper mantle events and computed travel-times. We corroborated our calculated travel time values with the results obtained with the use of TAUP travel-time calculation software for the three models. As expected, the computed values indicate that $P_n$ phases are first arrivals for the crustal events for the epicentral distance range of this study. We calculated travel-time residual for each station according to the number of record available.

## 4. Result and discussion

Travel-times of crustal events using IASP91 velocity model are computed for $P_n$ phase picks (Fig. 7). An average upper mantle velocity of approximately 8.55 km/s is deduced from the travel-time curve (the reciprocal of the line equation). We separated the residual values into a range from −4.0 to +6.0 s at an interval of 2 s, i.e., from −4.0 to −2.0 s on the left end and +4.0 to +6.0 on the other end. Frequency of a range of residual values against the median range of values for the three models is shown (Figs. 8 and 9) for the 10 stations.

Station NTU recorded the most number of events and was selected as the reference station. We subtracted the residual value of station NTU from the other stations. Our result is shown in Fig. 10 and Table 3. The number of record obtained for each station is shown in column 5 where seven stations recorded over 120 earthquakes. Relative to station NTU, we observe that stations BESC and KAPK have negative residual values. The number of picks is relatively small for stations SURA, SRIT and SKLT. For crustal events the average P-wave travel-time residuals are represented in columns 6, 9 and 12 for PREM, IASP91 and Lienert et al. (1986) model respectively. Columns 7, 10 and 13 indicate the corresponding values for events with focal depths below the Moho boundary depth of the respective models. Columns 8, 11 and 14 show average P-wave travel-time residual at all focal depths. The three stations in the southern part of Thailand (SURA, SRIT and SKLT) recorded the least number of earthquakes as most of their waveforms were difficult to pick. The three models generally show positive residual for all stations when all events are considered, indicative of a low velocity structure beneath the peninsula. Apart from stations SURA, SKLT and SRIT with very few picks compared to the other stations, the residuals appear to increase among the three models: IASP91, PREM, Lienert et al. (1986), in that order. The observed inconsistency in the stations may be due to their relatively few number of picks.

These corrections reflect the difference between actual and model velocities along ray paths to stations and can compensate for heterogeneous velocity structure near individual stations. The accuracy of earthquake location using any of the three models will benefit from their corresponding average residuals determined in this work. The computed average travel-time residuals can reduce errors attributable to station correction in the inversion of hypocentral parameters around the Peninsula.

**Table 3** The 10 selected station coordinates and their calculated average residual values.

| No | STN | Latitude (°) | Longitude (°) | Elev (km) | No. Used | PREM Crustal Res (s) | PREM Upper Mantle Res (s) | PREM Comb. Res (s) | IASP91 Crustal Res (s) | IASP91 Upper Mantle Res (s) | IASP91 Comb. Res (s) | Lienert et al. (1986) Crustal Res (s) | Lienert et al. (1986) Upper Mantle Res (s) | Lienert et al. (1986) Comb. Res (s) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | IPM | 4.4795 | 101.0255 | 0.2470 | 139 | 0.08 | 0.54 | **0.45** | −0.16 | 0.37 | **0.15** | 0.67 | 0.18 | **0.30** |
| 2 | KUM | 5.2902 | 100.6492 | 0.0740 | 140 | 0.11 | 0.28 | **0.24** | −0.21 | 0.08 | **−0.05** | 0.24 | 0.12 | **0.14** |
| 3 | KOM | 1.7922 | 103.8467 | 0.0490 | 141 | 0.19 | 0.47 | **0.42** | 0.09 | 0.18 | **0.14** | 0.55 | 0.05 | **0.17** |
| 4 | BESC | 1.3421 | 103.8513 | 0.0030 | 138 | −0.40 | −0.09 | **−0.16** | 0.24 | 0.07 | **0.16** | −0.21 | −0.16 | **−0.17** |
| 5 | BTDF | 1.3608 | 103.7729 | 0.0644 | 136 | 0.00 | 0.24 | **0.18** | 0.03 | 0.04 | **0.03** | 0.39 | 0.03 | **0.11** |
| 6 | KAPK | 1.2967 | 103.8883 | −0.0290 | 122 | −0.29 | −0.08 | **−0.12** | −0.13 | 0.00 | **−0.06** | −0.13 | −0.24 | **−0.22** |
| 7 | NTU | 1.3537 | 103.6851 | 0.0050 | 147 | 0.00 | 0.00 | **0.00** | 0.00 | 0.00 | **0.00** | 0.00 | 0.00 | **0.00** |
| 8 | SURA | 9.1663 | 99.6295 | 0.0010 | 27 | −0.39 | 0.20 | **0.09** | −0.53 | −0.02 | **−0.19** | −0.07 | 0.14 | **0.12** |
| 9 | SKLT | 7.1758 | 100.6156 | 0.0000 | 33 | 0.06 | 0.19 | **0.01** | 0.42 | 0.21 | **0.24** | −0.65 | 0.07 | **−0.01** |
| 10 | SRIT | 8.5955 | 99.6020 | 0.0990 | 20 | 0.25 | 0.19 | **0.19** | −0.26 | −0.17 | **−0.25** | 1.04 | −0.43 | **−0.08** |
| Col | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |

Bold values indicate the main result of the combination of the crustal and upper mantle phases.

## 5. Conclusion

The choice of the reference model for any hypocentral parameter inversion affects the computational result. In this paper, station correction has been deduced for 10 weak motion seismic stations distributed across Peninsular Malaysia and Singapore. The corrections determined at regional distances for three 1-D velocity models (PREM, IASP91 and Lienert et al., 1986) will benefit the accuracy of earthquake location using any of the three models. The three models generally show positive residual for all stations, indicative of a low velocity structure beneath the peninsula. The computed average travel-time residuals can reduce errors attributable to station correction in the inversion of hypocentral parameters around the Peninsula.

## Acknowledgments

We thank IRIS for access to their database.

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