

Direction-Based P wave Traveltime Residual Estimation for some Stations Around Southern Thailand, Peninsular Malaysia, Singapore and Sumatra Using a New Ray Tracing Algorithm

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November 21, 2022

Abstract

Path dependent corrections relative to traveltimes have been demonstrated to improve event locations. Using available global velocity models, direction-based station corrections can be estimated in a region without calibration data. In this study, traveltime corrections have been obtained for 117 broadband seismic stations around southern Thailand, Peninsular Malaysia, Singapore and Sumatra region of Indonesia. A total of 82,325 first-arrival waves are obtained from 15,212 earthquakes that have occurred around the Sumatra Subduction Zone over five decades (1964 – 2018). The dataset is a combination of arrival time data from the Bulletin of International Seismological Centre and waveforms from the Incorporated Research Institutions for Seismology. A newly developed algorithm for three-dimensional ray tracing is used to compute traveltimes and raypaths. The corrections are based on the IASP91/AK135 velocity models at four back-azimuthal directions. The estimated residuals in seconds (s) ranges from -2.15 to 2.25 s for stations distributed around southern Thailand and a range of -0.76 to 1.60 s for stations within Peninsular Malaysia. A range of 0.59 to 1.08 s for stations within Singapore and -1.52 to 2.46 s for stations distributed around Sumatra (in Indonesia). Station PSI in Sumatra Island recorded the highest number with 4877 arrivals. Stations LEM, KLM and KGM show consistent high residual values at all calculated angles and distances. The result of this study will support routine location of hypocentral parameters within the region. The scheme is being implemented for use in the forward computational process of seismic tomographic inversion in the study area.

1 **Direction-Based P wave Traveltime Residual Estimation for some Stations Around Southern**
2 **Thailand, Peninsular Malaysia, Singapore and Sumatra Using a New Ray Tracing Algorithm**
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7 **Key Points:**

- 8 • This study used 82,325 first-arrival p waves from 15,212 earthquakes spanning over five
9 decades from two data centers.
- 10 • A newly developed algorithm is used to compute traveltimes and raypaths. Residuals are
11 plotted on a back-azimuth versus epicentral distance.
- 12 • The residual values are separated into four back-azimuthal directions. The average values
13 are estimated for each station in the directions.

14
15

16 **Abstract**

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32 consistent high residual values at all calculated angles and distances. The result of this study will
33 support routine location of hypocentral parameters within the region. The scheme is being
34 implemented for use in the forward computational process of seismic tomographic inversion in
35 the study area.

36 **Plain Language Summary**

37 Earthquake locations is usually announced after occurrence. These earthquakes release seismic p
38 waves which are the first to arrive at seismic stations with known locations. Seismologists
39 determine the location of earthquakes by using an arbitrary velocity model of the earth's
40 subsurface. With many earthquakes, it is sometimes helpful to make create a table with specific
41 time associated with each station in order to improve earthquake locations. This adjustment is
42 called station correction. This paper attempts to determine corrections for 117 stations distributed
43 around southern Thailand, Peninsular Malaysia, Singapore and Sumatra region of Indonesia. To
44 do so, a total of 82,325 first-arrival P waves are obtained from 15,212 earthquakes that have
45 occurred around the Sumatra Subduction Zone over five decades (1964 – 2018). The idea is to
46 calculate traveltime residuals (in seconds) based on the bearing of the earthquake to the station
47 (divided into four quadrants). The average residual is estimated for each quadrant and for each
48 station. This is expected to improve the location of earthquakes around the stations.

49 **1 Introduction**

50 Precise location of earthquakes continues to be among the main objectives of seismology.
51 This helps to make good inferences about the subsurface structures responsible for the observed
52 seismicity. Knowledge of the subsurface brings many other benefits which may include
53 economic (in mineral exploration) and safety (in engineering designs). Unfortunately, events
54 with smaller magnitudes at regional distances are usually recorded by fewer stations around the
55 region. Besides, the precision of locations is affected by limitations imposed by other factors
56 like, data quality, the velocity model and the algorithm used for locating the events. There are
57 usually tradeoffs between earthquake locations and velocity model. Fortunately, technological
58 advances have improved the quality of seismic data and different algorithms have been
59 developed to increase the reliability of event locations. However, information about near-surface
60 velocity structures at local/regional distances is not common knowledge.

61 Global one-dimensional (1-D) reference velocity models like PREM (Dziewonski &
 62 Anderson, 1981), IASP91 (Kennett & Engdahl, 1991) and AK135 (Kennett et al., 1995) are good
 63 approximations for the purpose of locating hypocentral parameters. However, these
 64 approximations may not satisfy velocity variations at local and regional distances. This is due to
 65 lateral variations in the crustal and upper mantle which cause deviations in predicted raypaths.
 66 The raypath deviation can introduce errors in traveltime calculations. The Group of Scientific
 67 Experts' Third Technical Test (GSETT3) has adopted the IASPEI91 (Kennett and Engdahl,
 68 1991) model as the reference traveltime set since 1st January, 1995 (Yang et al., 2001). The
 69 IASPEI91 traveltimes can deviate considerably from true traveltimes at regional distances. The
 70 deviation in traveltime and raypath can be as much as 2 seconds and 100 km respectively
 71 (Bijwaard & Spakman 2000), and as much as 3.9 seconds and 77 km respectively (Zhao & Lei,
 72 2004).

73 The effect of lateral heterogeneity can be reduced, either by, (1) using regional velocity
 74 model or by, (2) applying traveltime corrections to known models for event locations (Yang, et
 75 al., 2001). The former requires the development of improved velocity models of the crust and
 76 mantle for better prediction of seismic traveltimes (e.g., Villaseñor et al., 2003) while the latter
 77 applies traveltime corrections based on the residuals observed for calibration events of known
 78 locations (Shearer, 2001). Station corrections e.g., the Source-Specific Station Correction
 79 (SSSC) may be required to account for the effects of lateral heterogeneity at a given seismic
 80 station. These model-predicted SSSC's may be obtained by ray tracing techniques through the
 81 model from each station to points on a specified latitude-longitude grid within specified
 82 distances from the station (Villaseñor et al., 2003). Station corrections can be constructed in
 83 regions (e.g., with frequent earthquakes and/or explosions) to obtain good calibration data.
 84 Regional SSSCs for International Monitoring System (IMS) stations have been developed. Path
 85 dependent corrections relative to the IASPEI91 traveltimes have been demonstrated to improve
 86 event locations (e.g., Yang et al., 2001). Unfortunately, many regions around the globe do not
 87 have calibration data. Hence, station correction may be estimated using available regional and/or
 88 global velocity models.

89 The objective of this research is to estimate the average traveltime residual values (\overline{AR})
 90 based on back-azimuth (θ) for regional first-arrival p phases up to 10 degrees ($^{\circ}$) epicentral
 91 distances (Δ) for some stations distributed around the southern part of Thailand, Peninsular
 92 Malaysia, Singapore and the Sumatra region of Indonesia. To achieve the objective, a new
 93 algorithm capable of ray tracing in 1-D/3-D models is developed to compute traveltimes and
 94 raypaths at local and regional distances. The algorithm can use any global 1-D velocity model as
 95 reference to create a 3-D model and calculate raypaths and traveltimes within the model.
 96 Perturbations can also be carried out within the scheme for tomographic purposes. Calculations
 97 of traveltime residual values (\mathcal{R}) for stations are based on θ in four quadrants: NE ($\theta \leq 90^{\circ}$), SE
 98 ($90^{\circ} < \theta \leq 180^{\circ}$), SW ($180^{\circ} < \theta \leq 270^{\circ}$) and NW ($270^{\circ} < \theta \leq 360^{\circ}$) directions. For validation, the
 99 overall calculated \overline{AR} are compared with the published results from the Bulletin of International
 100 Seismological Center (BISC). Traveltimes computed with the scheme for hand-picked
 101 waveforms from the Incorporated Research Institutions for Seismology (IRIS) are also validated
 102 by the results obtained from the TauP Toolkit software (Crotwell et al., 1999) for the same
 103 velocity model, hypocenters and station distribution. Station corrections determined in this work
 104 are based on the IASP91 model which can also be used for the AK135 model since both models
 105 are similar at the crust and upper mantle.

106 2 Materials and Methods

107 2.1 The Study Region

108 The study region encompasses the Sumatran Fault System (SFS) which runs parallel to
 109 the Sumatra Subduction Zone (SSZ) where the Indo-Australia plate subducts beneath the Burma
 110 microplate and Sunda Block (Amalfi et al., 2016). The predominant tectonic structures in the
 111 area are the SSZ and the SFS. Some authors (e.g., Irsyam et al., 2008; Lin et al., 2009) have
 112 reported that the SFS consist of 19 segments. The segments are separated by dilatational and
 113 contractional step-overs and abrupt changes in trend (Sieh & Natawidjaja, 2000). A total of 117
 114 seismic stations recorded 15 or more earthquakes within the window of events used in this study.
 115 The seismic stations are distributed around the southern part of Thailand, Peninsular Malaysia,
 116 Singapore and the Island of Sumatra (Indonesia). The station distribution spans latitudes 10° N –
 117 11° S and longitudes 93° E – 115° E and the earthquake epicenters are distributed over an area ~
 118 1,970,000 km² which is roughly the size of Mexico (Fig. 1a and 1b).

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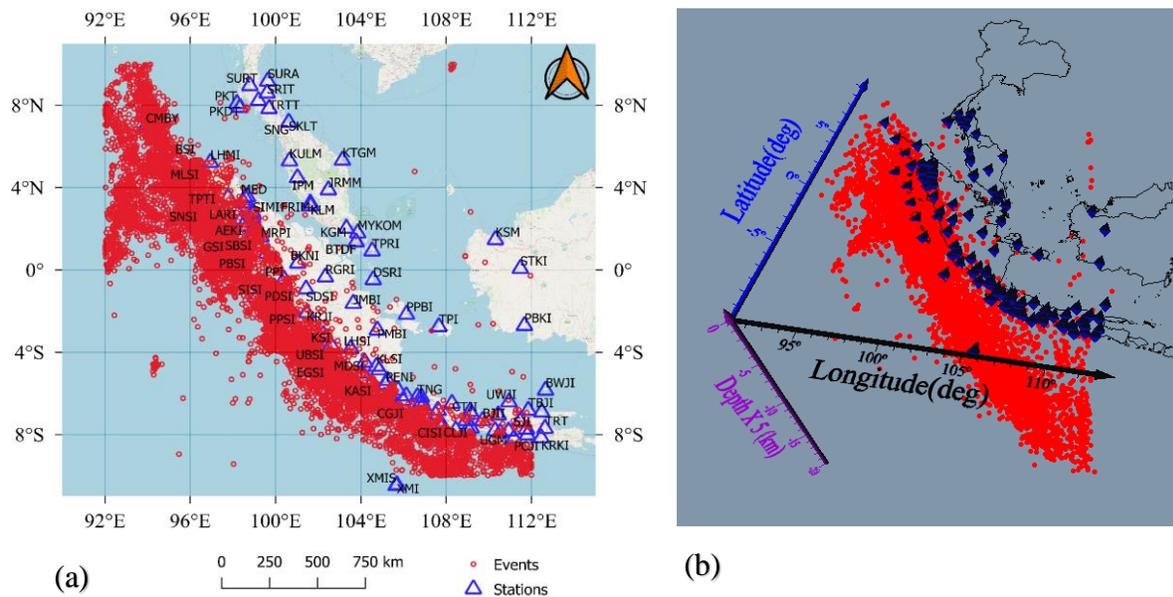
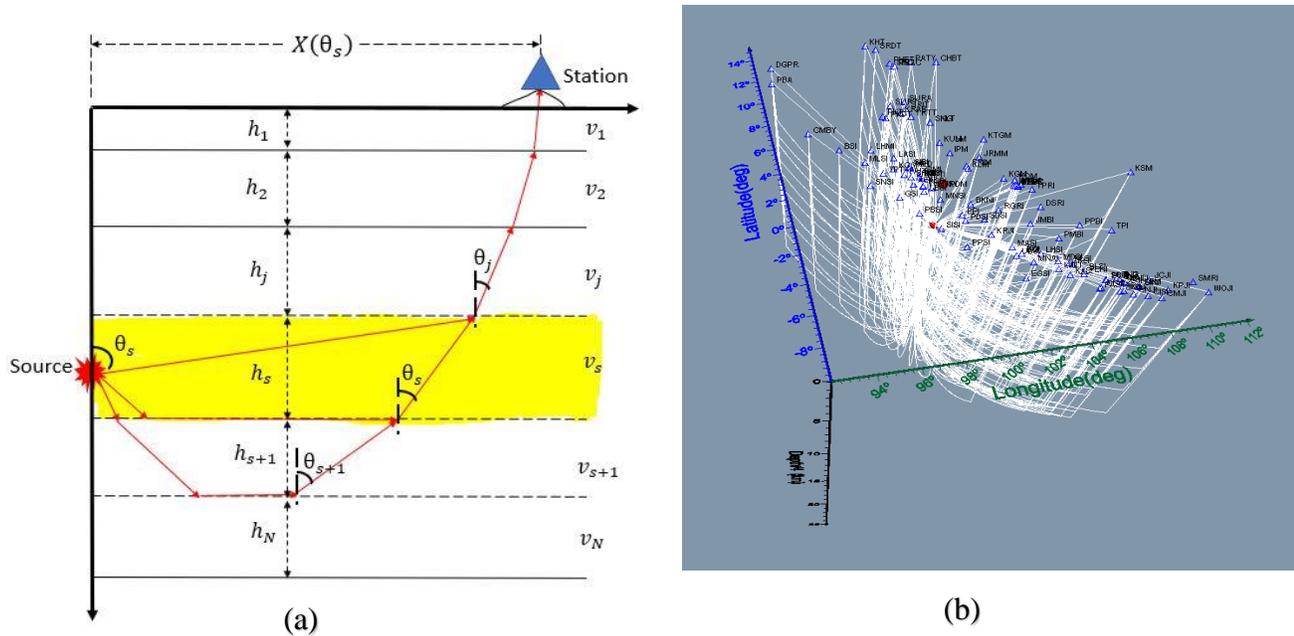


Figure 1. Distribution of 15,176 earthquakes and 117 seismic stations across the region. (a) epicenters (red circles) and seismic stations (blue hollow triangles) and (b) hypocenters (red circles) and seismic stations (blue solid triangles).

120 Phase picking from the IRIS waveforms is done with the SEISAN software (Havskov &
 121 Ottemoller 1999). The corresponding S-file from SEISAN is added to the BISC dataset. A new
 122 scheme (CONVT) developed in this study reads the combined file formats. The scheme operates
 123 within certain conditions which are predefined by the user (e.g., the limiting boundaries of the
 124 study area, the maximum depth of events, maximum epicentral distance and the residual limits).
 125 If the limiting boundaries of the study area are not set, CONVT will extract the limits from the
 126 largest and smallest values of latitudes and longitudes of the station list. Both the BISC dataset
 127 and the IRIS summary file formats can be converted into S-file format for entry into SEISAN

128 software. Since waveforms can be registered into SEISAN database, this conversion will be
 129 useful to validate reported arrivals from the waveforms in the SEISAN database. The routine
 130 extracts the number of stations with arrival time data and the combined dataset is converted to
 131 input format for a ray tracing algorithm (TRAVT) also developed in this study.

132 The ray tracing algorithm (TRAVT) is used to compute raypaths and traveltimes. The
 133 reported hypocentral parameters from both the BISC and the IRIS are used in this study. First,
 134 the station coordinates, the selected 1-D velocity model and the dataset are initiated within
 135 TRAVT. Then, a 3-D grid model is constructed from the selected 1-D velocity model using the
 136 parameterization technique introduced by Zhao et al. (1992). This technique has been used for
 137 tomographic studies (e.g., Zhao, 2012; Wang et al., 2017). Using the haversine formula, the
 138 epicentral distance is determined. The hypocentral distance and azimuth are also determined
 139 within TRAVT. The take-off angle for up-going rays from the source are determined by a
 140 subroutine (TRAYD) using the technique introduced by Kim and Baag (2002) that relates the
 141 take-off angle at the source to the horizontal distances covered by the seismic wave (Fig. 2a).
 142 This two-point ray shooting technique has been used by some authors (e.g., Kang & Kim, 2013;
 143 Osagie & Kim, 2013; Hong et al., 2017; Osagie, et al, 2017). Another subroutine (TRAYR)
 144 computes raypaths and traveltimes for refracted rays from all existing boundaries in the model.
 145 The ray with the shortest traveltime from the result of TRAYD and TRAYR is selected and the
 146 wave type is determined within TRAVT.



147 **Figure 2** (a) A schematic diagram showing raypaths (red arrow lines) for both direct and refracted
 148 rays in an N-layered model with the thicknesses h_j and velocities v_j . The source is at the layer with
 149 thickness h_s and velocity v_s and the station (blue triangle) is at some elevation. (b) Raypaths (white
 150 lines) from three sources (red sphere) to stations (blue triangles) for a 10-layer test model. The
 151 depth axis of (2b) is 55 times exaggerated.

152 The computed rays are constrained to bottom in each layer between interfaces and might
 153 be reflected off the top of the layer or turn within the layer to retain raypath with the shortest
 154 traveltime. Apart from boundary values, the various points are determined by a predefined value
 155 of step-length as the rays propagate from source to stations. A variable is defined that carries

156 information (latitude, longitude, depth, velocity, time from source, raypath length from source,
157 angle ray makes the vertical) at various points along the path step-length between source and
158 station. For refracted wave the variable index the boundary of refraction. The depth of refraction
159 for any boundary are adjustable within the scheme. TRAVT has the advantage of rapid
160 convergence resulting in less computational time and resources. The scheme can accommodate a
161 model with as many layers as required for computing traveltimes for local and regional
162 investigation of the sub-surface. This can be useful for both field seismic investigations,
163 generation of synthetic seismograms, determination of refraction depths and to estimate crustal
164 thicknesses/Moho depths. It can also be used for the forward calculation process of tomographic
165 inversions and has been successfully integrated into a tomographic scheme. The ability of the ray
166 tracing scheme to identify boundaries of refraction has been demonstrated with a fictitious 10-
167 layer test-model (Fig. 2b). Note that the depth axis is 55 times exaggerated compared with the
168 dimensions of the longitude and latitude axes.

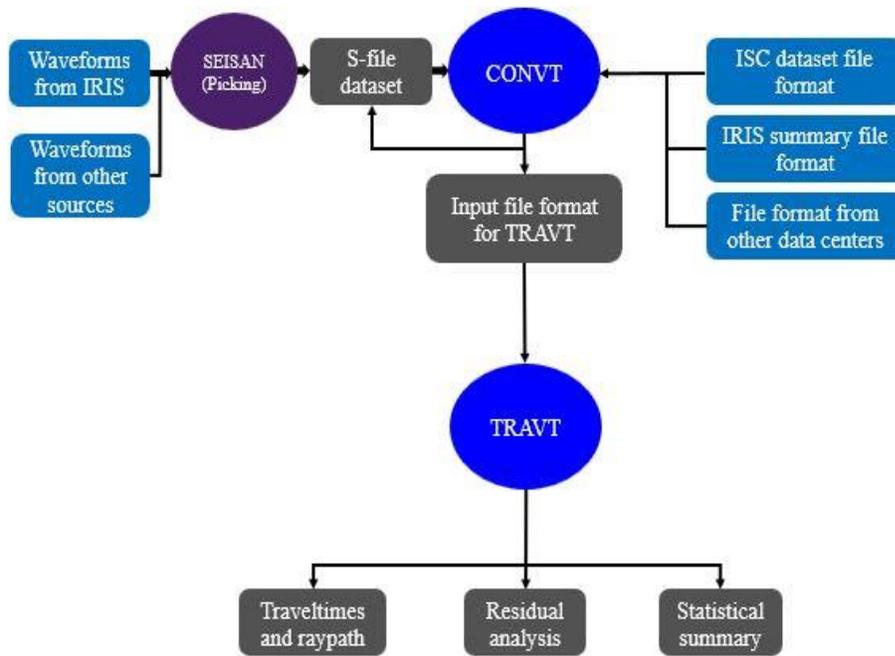
169 **3 Data**

170 Earthquakes (magnitude > 3.5 mb) used in this study spans latitudes 10° N – 10° S and
171 longitudes 92° E–114° E are confined to the top 100 km in focal depths. This selection is due to
172 the intention of the authors to carry out tomographic inversion of the area in the near future. The
173 data is obtained from two sources: (1) waveforms from Incorporated Research Institutions for
174 Seismology (IRIS) and (2) arrival time dataset from the Bulletin of International Seismological
175 Center (BISC). A software (JWEED) developed by Seismology Department at the University of
176 South Carolina (USC, 2012) is used to retrieve waveforms from the IRIS online free access
177 archive for the period between the year 2006 and 2018. This was the period of good waveform
178 data during the time of data collection in 2018. In 2018, this study also obtained all available
179 arrival time data from BISC between 1964 and 2016. The BISC data ended in 2016 as at the time
180 of data collection for this study. Review of the BISC data is usually about 24 months behind time
181 because arrival times are manually checked by BISC analysts (ISC, 2019). Later in 2019, the
182 revised BISC dataset until mid-2017 was added to the dataset. Picked phases from the IRIS
183 waveforms are combined with the dataset from the BISC to obtain a total of 15,212 events. The
184 combined dataset contains 82,325 are *P* wave first arrivals.

185 **4 Results and Discussion**

186 After the ray tracing scheme (TRAVT) has been validated with a test-model, traveltimes
187 and raypaths are computed using the IASP91 velocity model. The computed traveltime result of
188 manual picks from the IRIS waveforms are validated by the TauP Toolkit software for the same
189 velocity model, hypocenters and station distribution around the study area. The flowchart (Fig. 3)
190 shows the process from data collection, preparation, analysis and computation. Raypaths for P_g
191 and P_n phases calculated using the IASP91 model and station locations are shown in figure 4.
192 (note that the depth axis is 55 times exaggerated).

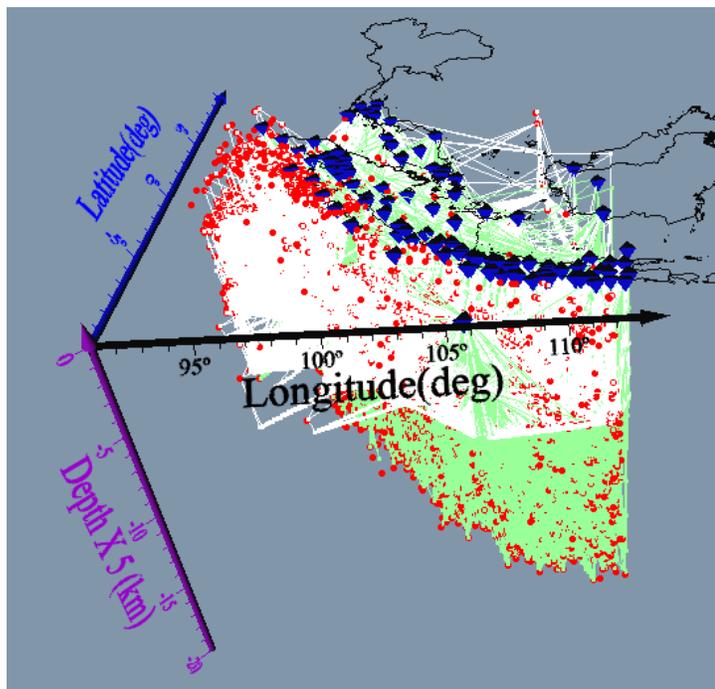
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194

195 **Figure 3** Flowchart of data collection, analysis and computation (blue circles are the algorithms)

196



197

198 **Figure 4** Some Ray path for P_g and P_n phase calculated using the IASP91 model (depth axis is 55
 199 times exaggerated). Red circles represent earthquake locations while blue triangles represent
 200 seismic stations. Green lines are direct raypaths and while lines are refracted raypaths.

201 The number of arrivals recorded by the stations range from 15 (MBSI) to 4877 (PSI). The
 202 traveltimes residuals are compared with the published result from the BISC for the same “Event

203 ID” and “Arrival ID”. The \mathcal{R} values are represented on a plot of θ against Δ for some selected
 204 stations which are arranged according to country and in decreasing number of arrivals (Fig. 5).

205 The stations at the northern end of this spectrum are within the southern part of Thailand.
 206 Arranged in order decreasing number of recorded arrivals are: SNG, TRTT, PKDT, SKLT,
 207 SRIT, SURT, SURA, KRAB and PKT. Station SNG indicate a relatively positive \mathcal{R} values (Fig.
 208 5a). TRTT and PKDT show similar negative \mathcal{R} for $\Delta > 750$ km (Fig. 5b and 5c). SKLT indicates
 209 a slightly more positive \mathcal{R} values for events between 500 - 750 km away and θ between $180^\circ -$
 210 270° (Fig. 5d).

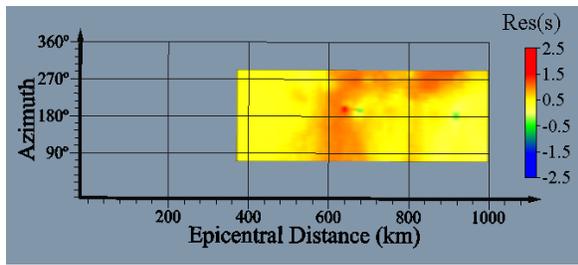
211 The ten stations within Peninsular Malaysia include: KULM, IPM, MYKOM, KGM,
 212 FRIM, KTGM, DSRI, KLM, JRMM, and KSM. Station KTGM is on the east coast of the
 213 Peninsula while the rest are on the west and central part of the Peninsula. Heterogeneity appears
 214 to be present when seismic waves travel toward stations KULM and IPM (Fig. 5e and 5f)
 215 respectively. A consistently positive \mathcal{R} values is observed for stations KGM and KLM (Fig. 5g
 216 and 5h) respectively, suggesting the presence of low velocity region with respect to the IASP91
 217 model in the SW direction from the stations. Stations KOM and KUM (IRIS station code names)
 218 are observed to be the same as stations MYKOM and KULM respectively on the BISC station
 219 list.

220 At the southernmost end of the Peninsula is Singapore with four stations: BTDF, BESC,
 221 NTU and KAPK. While station BTDF is on the BISC list, the other stations (BESC, NTU and
 222 KAPK) are only on the IRIS station list and appeared only on the hand-picked data. This is
 223 responsible for the fewer arrivals recorded for these stations. However, there appears to be a
 224 common trend in the observed velocity heterogeneities among the stations. Examples are shown
 225 for BTDF and BESC (Fig. 5i and 5j) respectively.

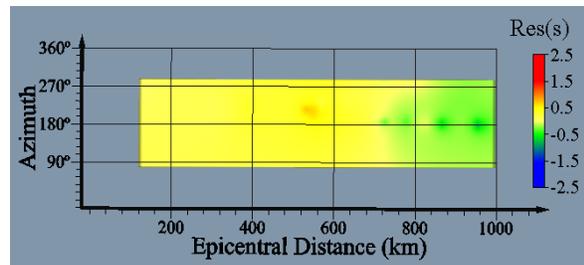
226 The two southernmost stations (XMI and XMIS) are situated in Christmas Island,
 227 Australia while the easternmost station (CMBY) is located in the Andaman Islands, India. The
 228 two Australian stations (Fig. 5k and 5l) show mild and similar heterogeneities. CIMB (Fig. 5m)
 229 changes from slightly positive to negative \mathcal{R} values when Δ is beyond 400 km.

230 Most stations used in this study are distributed around the Island of Sumatra in Indonesia.
 231 The stations show varying degrees of heterogeneities. Station PSI (Fig. 5n) recorded the highest
 232 number with 4877 arrivals. There is a consistent positive \mathcal{R} values for $\theta > 250^\circ$. However, the
 233 station shows a strong negative \mathcal{R} values for $\Delta > 800$ km and $\theta < 270^\circ$. GSI (Fig. 5o) shows some
 234 slight similarities with PSI in \mathcal{R} for $\Delta > 800$ km. Other stations within the Sumatra region show
 235 varying degrees of heterogeneities (e.g., Fig. 5p – 5t). Station LEM (Fig. 5t) shows consistent
 236 positive \mathcal{R} values at all θ , which suggest the presence of a low velocity structure around the station.

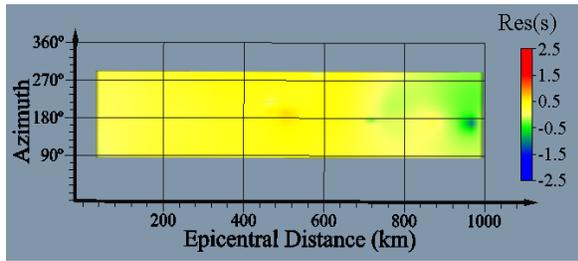
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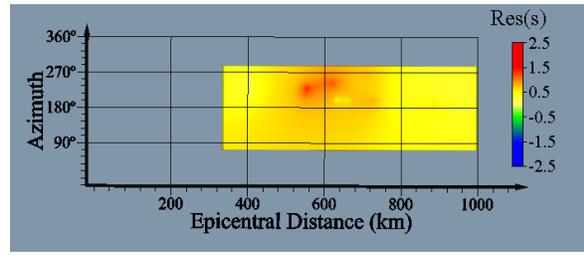
(a) SNG (Thailand - 846 arrivals)



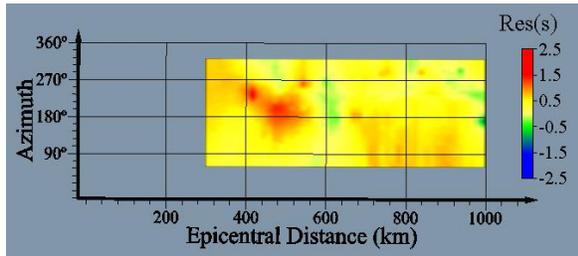
(b) TTRT (Thailand - 331 arrivals)



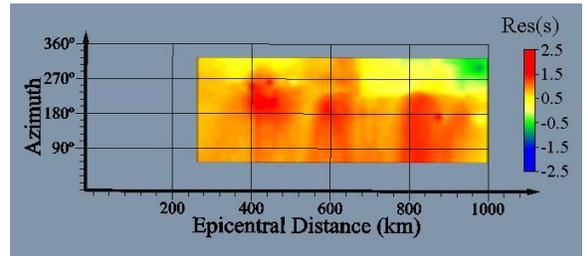
(c) PKDT (Thailand - 288 arrivals)



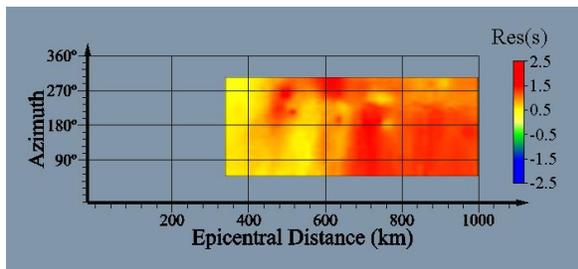
(d) SKLT (Thailand - 286 arrivals)



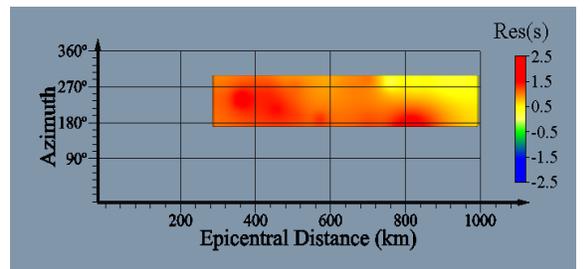
(e) KULM (Malaysia - 4568 arrivals)



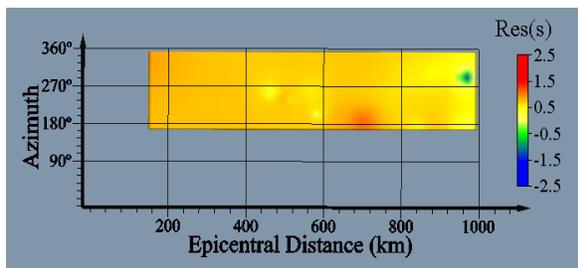
(f) IPM (Malaysia - 3268 arrivals)



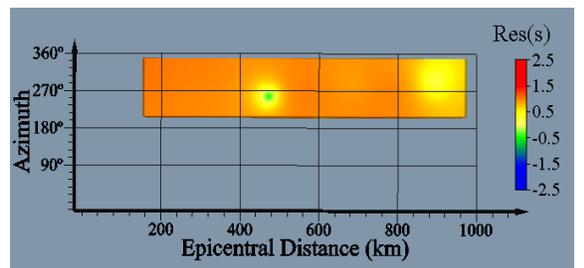
(g) KGM (Malaysia - 1424 arrivals)



(h) KLM (Malaysia - 158 arrivals)



(i) BTDF (Singapore - 230 arrivals)

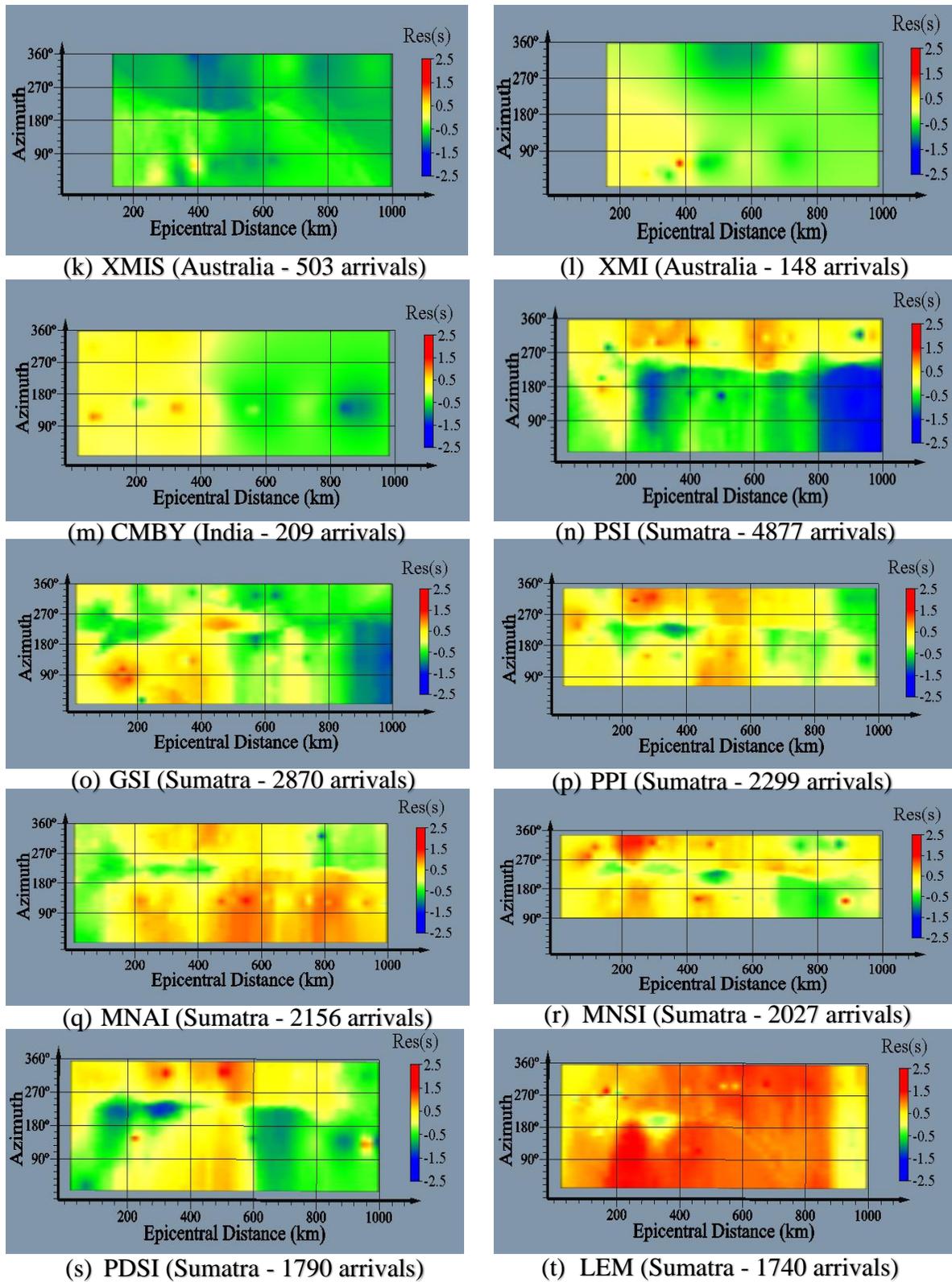


(j) BESC (Singapore - 70 arrivals)

238

239 **Figure 5** Plot of back-azimuth against epicentral distance for some stations within the study region.

240 The figures are arranged according to county and in decreasing order of arrivals.



241 **Figure 5** continues

242

243 **Table 1** Calculated (AR) from four back-azimuthal directions (columns 8 - 11). Columns 12 and
 244 13 are the overall calculated (AR) and BISC (AR) respectively for 117 stations distributed
 245 around the region. The stations are arranged according to country and in decreasing number
 246 of arrivals
 247

Sn	Stn Code	Lat [deg]	Lon [deg]	Z [km]	Country	NArv	$\theta \leq 90^\circ$	$90^\circ < \theta \leq 180^\circ$	$180^\circ < \theta \leq 270^\circ$	$270^\circ < \theta \leq 360^\circ$	AR-Cal [s]	AR-ISC [s]
1	XMIS	-10.4807	105.6519	0.2430	Australia	503	-0.29	0.00	0.00	-0.86	-0.47	-0.64
2	XMI	-10.4495	105.6895	0.2780	Australia	148	0.04	0.00	0.00	-0.78	-0.13	-0.17
3	CMBY	7.0109	93.9266	0.0100	India	209	0.08	-0.14	-0.26	0.73	-0.04	-0.18
4	PSI	2.8010	98.9240	0.9870	Indonesia	4877	0.15	-0.71	0.01	0.87	0.11	-0.08
5	GSI	1.3039	97.5755	0.1070	Indonesia	2870	0.56	-0.18	0.09	0.26	0.09	-0.13
6	PPI	-0.4568	100.3970	0.0000	Indonesia	2299	-0.14	0.23	0.03	0.57	0.29	0.12
7	MNAI	-4.3605	102.9557	0.1540	Indonesia	2156	0.08	0.50	0.04	0.31	0.32	0.15
8	MNSI	0.7955	99.5796	0.0000	Indonesia	2027	0.00	0.00	0.15	0.71	0.42	0.22
9	PDSI	-0.9118	100.4617	0.2760	Indonesia	1790	-0.08	-0.11	-0.34	0.40	0.02	-0.13
10	LEM	-6.8266	107.6175	1.2930	Indonesia	1740	0.96	0.99	0.79	1.04	0.96	0.77
11	KASI	-5.5236	104.4967	0.0000	Indonesia	1720	0.22	0.55	-0.36	0.29	0.24	0.05
12	MDSI	-4.4861	104.1783	0.0000	Indonesia	1685	0.00	0.76	0.42	0.56	0.57	0.39
13	LHMI	5.2288	96.9472	0.0030	Indonesia	1673	-0.09	0.30	0.51	0.48	0.46	0.29
14	BKNI	0.3262	101.0396	0.0650	Indonesia	1608	-0.18	0.30	0.46	0.60	0.49	0.34
15	SISI	-1.3265	99.0895	0.0000	Indonesia	1569	0.59	-0.15	-0.05	0.23	0.06	-0.10
16	KSI	-3.6517	102.5929	0.5390	Indonesia	1539	-0.86	0.34	0.07	0.49	0.34	0.21
17	LWLI	-5.0175	104.0589	0.9380	Indonesia	1533	0.71	0.87	0.15	0.62	0.57	0.38
18	TPTI	3.2600	97.1800	0.0090	Indonesia	1456	0.44	0.11	-0.30	0.30	-0.05	-0.29
19	KCSI	3.5220	97.7715	0.2050	Indonesia	1369	0.97	0.18	0.53	0.98	0.52	0.25
20	CISI	-7.5557	107.8153	0.5440	Indonesia	1349	0.68	0.23	-0.30	-0.24	-0.14	-0.41
21	TSI	3.5008	98.5645	0.0000	Indonesia	1335	-0.19	0.59	0.84	0.88	0.80	0.61
22	UGM	-7.9125	110.5231	0.3500	Indonesia	1208	0.65	0.31	0.13	0.69	0.41	0.13
23	PPSI	-2.7630	100.0096	0.0000	Indonesia	1204	0.24	0.27	-0.82	0.08	0.08	-0.03
24	CGJI	-6.6135	105.6929	0.0000	Indonesia	1143	-1.26	0.36	-0.33	-0.29	-0.08	-0.30
25	SDSI	-0.9324	101.4282	0.0000	Indonesia	1038	0.00	0.66	0.39	0.84	0.58	0.41
26	KLI	-4.8630	104.8567	0.0320	Indonesia	950	0.37	0.93	0.70	0.85	0.82	0.62
27	MLSI	4.2668	96.4040	0.0580	Indonesia	932	-0.19	0.09	0.30	0.22	0.20	-0.02
28	MASI	-3.1415	102.2396	0.3840	Indonesia	922	-0.34	0.87	0.21	0.67	0.60	0.42
29	CNJI	-7.3090	107.1296	0.0000	Indonesia	916	-0.02	0.34	-0.23	-0.30	-0.06	-0.33
30	SKJI	-7.0053	106.5563	0.1000	Indonesia	863	0.41	0.51	-0.30	0.38	0.31	0.05
31	BSI	5.4964	95.2961	0.1920	Indonesia	839	-1.17	-0.51	-0.07	-0.21	-0.36	-0.51
32	LHSI	-3.8267	103.5233	0.0000	Indonesia	831	-1.28	1.09	0.69	0.91	0.87	0.71
33	DBJI	-6.5538	106.7497	0.2110	Indonesia	827	0.31	0.91	0.45	0.62	0.65	0.40
34	SNSI	2.4089	96.3267	0.0140	Indonesia	808	1.00	0.22	0.26	0.10	0.22	-0.09
35	CMJI	-7.7837	108.4485	0.0000	Indonesia	760	-0.08	0.19	-0.12	0.13	0.07	-0.21
36	PBSI	-0.0547	98.2800	0.0000	Indonesia	756	0.59	0.24	0.08	0.43	0.37	0.09
37	PWJI	-8.0220	111.8039	0.0000	Indonesia	750	0.35	0.01	0.41	0.85	0.58	0.25
38	RPSI	2.6951	98.9240	0.0000	Indonesia	743	-1.35	-0.21	0.63	0.74	0.55	0.37

248
249**Table 1** continues

Sn	Stn Code	Lat [deg]	Lon [deg]	Z [km]	Country	NArv	$\theta \leq 90^\circ$	$90^\circ < \theta \leq 180^\circ$	$180^\circ < \theta \leq 270^\circ$	$270^\circ < \theta \leq 360^\circ$	AR -Cal [s]	AR-ISC [s]
39	SBJI	-6.1200	106.1300	0.0000	Indonesia	698	0.25	0.87	0.19	0.73	0.59	0.36
40	PCJI	-8.1947	111.1771	0.0000	Indonesia	693	-0.04	-0.47	0.28	0.60	0.38	0.07
41	BLSI	-5.3676	105.2452	0.1470	Indonesia	691	1.99	0.61	0.40	1.04	0.66	0.41
42	PPBI	-2.1616	106.1364	0.0640	Indonesia	676	-1.14	1.25	0.85	1.14	0.94	0.85
43	KRJI	-2.0912	101.4619	0.8110	Indonesia	671	0.00	0.69	0.24	0.83	0.59	0.41
44	KLSI	-4.6900	104.7300	0.0810	Indonesia	648	-1.52	0.82	0.68	0.92	0.82	0.64
45	SMRI	-7.0491	110.4407	0.2030	Indonesia	626	0.10	0.94	1.12	0.72	1.01	0.77
46	RGRI	-0.3491	102.3338	0.0410	Indonesia	608	0.00	0.98	0.75	0.66	0.76	0.64
47	TNG	-6.1717	106.6462	0.0140	Indonesia	584	0.15	1.10	0.75	0.76	0.83	0.47
48	TPI	-2.7563	107.6534	0.0250	Indonesia	536	-0.29	1.06	0.69	0.81	0.75	0.62
49	KPJI	-7.3330	108.9310	0.0000	Indonesia	533	1.19	1.12	0.98	1.18	1.07	0.77
50	PMBI	-2.9270	104.7720	0.0300	Indonesia	512	0.23	0.75	0.40	0.21	0.41	0.28
51	PENI	-5.5667	105.1710	0.2000	Indonesia	449	-0.48	0.70	0.86	1.22	0.98	0.19
52	KALI	-7.1064	106.6590	0.8100	Indonesia	366	0.13	0.41	0.09	0.54	0.49	-0.65
53	TPRI	0.9184	104.5263	0.0410	Indonesia	366	0.00	0.88	0.81	1.07	0.85	0.80
54	JMBI	-1.6335	103.6417	0.0000	Indonesia	364	0.00	1.20	0.82	0.94	0.86	0.76
55	PASI	-6.6894	105.5890	0.2200	Indonesia	347	1.28	0.39	-0.52	0.26	0.24	-0.49
56	WOJI	-7.8372	110.9236	0.0000	Indonesia	345	-0.10	0.14	0.28	1.01	0.46	0.17
57	YOGI	-7.8166	110.2949	0.1600	Indonesia	335	0.85	0.05	0.14	0.46	0.21	-0.01
58	CBJI	-6.4200	106.8500	0.0000	Indonesia	321	-1.18	-0.88	0.33	1.62	0.58	0.25
59	BJII	-7.3329	109.7096	0.6290	Indonesia	309	0.00	0.41	0.33	0.92	0.46	0.34
60	LARI	2.8856	98.1572	0.8200	Indonesia	285	0.00	0.24	0.28	0.99	0.46	-0.64
61	PULI	-6.3450	105.9760	1.3460	Indonesia	285	1.77	0.95	0.02	1.09	0.93	0.21
62	SJI	-7.7349	111.7669	0.7230	Indonesia	276	1.12	0.54	0.71	0.87	0.75	0.45
63	JCJI	-6.4900	108.2700	0.0000	Indonesia	270	1.22	-0.75	-0.36	1.34	-0.08	-0.33
64	GRJI	-6.9145	112.4793	0.0000	Indonesia	249	0.00	0.00	1.03	1.49	1.07	0.79
65	SINI	-7.0144	107.5000	1.0000	Indonesia	249	-1.46	0.83	0.55	0.87	0.78	0.35
66	MRPI	1.6125	99.3172	1.1000	Indonesia	230	-0.47	0.81	0.62	1.06	0.82	-0.30
67	PACI	-6.5928	106.9100	0.8500	Indonesia	228	2.46	1.01	0.69	1.08	0.97	0.58
68	TRT	-7.7040	112.6350	0.0000	Indonesia	228	0.00	0.00	0.68	0.99	0.79	0.47
69	AEKI	2.1017	98.4536	0.8400	Indonesia	219	0.00	0.03	0.05	0.43	0.17	-0.64
70	SIBI	3.2408	98.5044	2.0500	Indonesia	169	0.00	0.96	1.15	0.93	1.01	0.30
71	UWJI	-6.4191	110.9474	0.0620	Indonesia	165	0.00	0.65	0.89	1.32	0.90	0.68
72	NGJI	-7.3676	111.4612	0.0000	Indonesia	164	1.96	0.99	1.34	1.17	1.28	1.01
73	PCBI	1.8900	98.9253	1.0000	Indonesia	162	-0.13	-0.09	0.03	0.41	0.15	0.04
74	KRKI	-8.1583	112.4525	0.0000	Indonesia	142	0.00	0.00	0.62	1.11	0.77	0.49
75	TBJI	-6.8179	111.8481	0.0000	Indonesia	140	0.00	1.04	0.96	0.70	0.94	0.71
76	SEMI	2.4603	98.3917	1.7500	Indonesia	137	0.07	-0.50	0.17	0.58	0.02	-0.06
77	RBSI	-5.8445	105.7420	0.0000	Indonesia	133	0.00	0.53	-0.33	0.92	0.41	0.24
78	MED	3.5500	98.6833	0.0320	Indonesia	125	0.00	0.70	0.49	0.50	0.56	0.41

250 **Table 1** continues

Sn	Stn Code	Lat [deg]	Lon [deg]	Z [km]	Country	NArv	$\theta \leq 90^\circ$	$90^\circ < \theta \leq 180^\circ$	$180^\circ < \theta \leq 270^\circ$	$270^\circ < \theta \leq 360^\circ$	AR -Cal [s]	AR-ISC [s]
79	TRSI	2.0256	98.9594	0.9790	Indonesia	121	0.00	0.85	0.30	0.58	0.54	0.50
80	DJA	-6.1833	106.8362	0.0080	Indonesia	117	0.00	0.85	0.38	0.25	0.41	0.14
81	EGSI	-5.3526	102.2767	0.0360	Indonesia	108	-0.04	0.56	0.35	-0.20	0.10	-0.12
82	SIMI	2.6889	98.9469	1.6810	Indonesia	107	0.00	0.32	0.76	0.74	0.61	0.39
83	CLJI	-7.7187	109.0150	0.0460	Indonesia	91	0.00	-0.36	0.26	0.52	0.22	-0.03
84	SBSI	1.5500	98.8900	0.1470	Indonesia	90	0.33	-1.29	0.83	0.00	0.14	0.11
85	PBKI	-2.7047	111.6697	0.0740	Indonesia	88	0.00	0.64	0.93	-1.15	0.87	0.94
86	HUTI	2.3153	98.9711	1.6000	Indonesia	84	0.00	0.71	0.78	0.78	0.76	0.48
87	TGJI	-6.8679	109.1210	0.0440	Indonesia	65	0.00	0.12	0.50	2.05	0.60	0.40
88	BWJI	-5.8511	112.6578	0.0580	Indonesia	64	0.00	0.00	0.99	0.10	0.97	0.83
89	BBJI	-7.4626	107.6500	0.6150	Indonesia	55	0.00	0.58	-0.18	-0.04	0.21	0.32
90	CTJI	-7.0075	109.1836	0.1040	Indonesia	42	0.00	1.10	1.22	0.83	1.14	0.83
91	UBSI	-3.7611	102.2714	0.0280	Indonesia	39	0.00	0.24	0.29	1.01	0.50	0.34
92	SCJI	-7.6810	109.1689	0.0450	Indonesia	32	1.57	-0.29	0.76	1.18	0.50	0.18
93	STKI	0.0656	111.4772	0.0880	Indonesia	22	0.00	1.77	1.25	-1.09	1.17	1.29
94	MBSI	-3.7611	102.2710	0.0270	Indonesia	15	0.00	0.64	-0.64	0.49	0.24	0.21
95	KULM	5.2900	100.6500	0.0740	Malaysia	4568	1.60	0.67	0.60	0.33	0.58	-0.11
96	IPM	4.4795	101.0255	0.2470	Malaysia	3268	0.09	1.07	0.74	-0.02	0.58	0.39
97	MYKOM	1.7900	103.8500	0.0000	Malaysia	1528	0.00	0.61	0.69	0.64	0.68	0.61
98	KGM	2.0157	103.3190	0.1030	Malaysia	1424	0.06	1.10	0.97	0.98	0.98	0.78
99	FRIM	3.2370	101.6250	0.0980	Malaysia	722	0.00	0.95	0.63	-0.02	0.57	0.56
100	KTGM	5.3280	103.1340	0.0560	Malaysia	566	0.00	0.00	0.63	0.84	0.63	0.69
101	DSRI	-0.4793	104.5778	0.0580	Malaysia	491	-1.41	1.02	0.80	0.98	0.84	0.78
102	KLM	3.1025	101.6450	0.0460	Malaysia	158	0.00	1.42	1.25	0.08	0.87	0.62
103	JRMM	3.8867	102.4767	0.0720	Malaysia	59	0.00	1.72	1.02	0.04	0.66	0.53
104	KSM	1.4733	110.3083	0.0660	Malaysia	18	0.00	-0.76	0.00	1.25	0.40	-0.22
105	BTDF	1.3608	103.7729	0.0640	Singapore	230	0.00	0.59	0.69	0.75	0.71	0.68
106	BESC	1.3422	103.8513	0.0030	Singapore	70	0.00	0.00	1.08	0.76	0.91	0.91
107	NTU	1.3537	103.6852	0.0050	Singapore	65	0.00	0.00	1.05	0.74	0.89	0.89
108	KAPK	1.2967	103.8883	-0.0290	Singapore	62	0.00	0.00	0.91	0.94	0.92	0.92
109	SNG	7.1770	100.6170	0.0040	Thailand	846	0.26	0.90	0.76	0.83	0.77	-0.05
110	TRTT	7.8362	99.6912	0.0710	Thailand	331	-0.14	0.82	0.02	0.71	0.05	0.01
111	PKDT	7.8920	98.3350	0.0530	Thailand	288	-2.15	0.72	0.17	0.87	0.22	0.15
112	SKLT	7.1700	100.6200	0.0140	Thailand	286	-0.21	0.00	0.58	-0.32	0.54	0.50
113	SRIT	8.5955	99.6020	0.0580	Thailand	231	0.00	0.47	0.31	0.23	0.31	0.22
114	SURT	8.9577	98.7950	0.0260	Thailand	190	0.00	1.07	0.38	0.84	0.41	0.47
115	SURA	9.1663	99.6295	-0.0050	Thailand	110	0.00	1.02	0.48	1.92	0.50	0.56
116	KRAB	8.2215	99.1965	0.0580	Thailand	102	0.00	0.51	0.49	0.87	0.49	0.56
117	PKT	8.0800	98.1900	0.0000	Thailand	25	0.00	1.40	0.50	2.25	0.68	0.51

252 Station coordinates and the computed AR at the four θ directions (NE, SE, SW and NW)
 253 are shown in Table 1. Columns 2 - 13 respectively are: (2) station code, (3) station latitude (deg),
 254 (4) station longitude (deg), (5) station elevation (km), (6) Country where station is located, (7)
 255 number of arrivals recorded by station, (8) calculated AR (s) in the NE direction of θ , (9)
 256 calculated AR (s) in the SE direction of θ , (10) calculated AR (s) in the SW direction of θ , (11)
 257 calculated AR (s) in the NW direction of θ , (12) calculated AR (s) in all θ directions and (13) AR
 258 (s) from the BISC results.

259 **5 Conclusions**

260 Hypocentral parameters from the bulletin of International Seismological Center and the
 261 Incorporated Research Institutions for Seismology are combined to obtain a total of 15,212
 262 earthquakes. The selected earthquake data (magnitude > 3.5 mb) spans five decades and are
 263 confined to the top 100 km in focal depths. A total of 117 broadband stations is used to obtain
 264 82,325 first-arrival P waves within this window of events. A new algorithm for ray tracing in 1-
 265 D/3-D models have been developed and shown to accommodate any model with as many layers
 266 to compute traveltimes and raypaths for use in local/regional sub-surface investigations. The
 267 scheme has been successfully incorporated for forward calculations in a scheme for 3-D
 268 tomographic studies and will be useful for other applications like generating synthetic
 269 seismograms. Traveltimes are computed using the IASP91 model to all stations used in this
 270 study.

271 The average residual values at the four back-azimuthal directions (NE, SE, SW and NW)
 272 show varying degrees of heterogeneities. The two southernmost stations are in Australia with
 273 residual values ranging from -0.86 to -0.29 s. The easternmost station is in India and the values
 274 range from -0.14 to 0.73 s. The average residual values range from -2.15 to 2.25s for stations in
 275 southern Thailand, -0.76 to 1.60 s for stations in Peninsular Malaysia. Only station BTDF among
 276 the four Singaporean stations is listed on the bulletin of International Seismological Center
 277 station list. The other three stations (BESC, NTU and KAPK) are listed only in the Incorporated
 278 Research Institutions for Seismology station list. The average residual values for the stations in
 279 Singapore range from 0.59 to 1.08 s. Most stations used in this study are distributed around the
 280 Sumatra region of Indonesia. Their average residual values range from -1.52 and 2.46 s. Station
 281 PSI in Sumatra Island recorded the highest number of arrivals. A consistently positive residual
 282 values at all calculated angles and distances is observed for stations KLM and KGM located in
 283 the western corner of Peninsular Malaysia. This is also the case with station LEM which is locate
 284 in Sumatra. The result of this study will support routine location of hypocentral parameters
 285 within the region. The algorithm can be useful in generating synthetic seismograms and for the
 286 forward computational process of seismic tomographic studies.

287 **Acknowledgments**

288 The authors thank Kim Woohan for the use of his two-point ray tracing codes which was
 289 modified in a subroutine within our algorithm. The authors acknowledge the Bulletin of
 290 International Seismological Center (ISC) from where part of the arrival time data used in this
 291 study is obtained. Also, the facilities of IRIS Data Services were used for access to waveforms
 292 and earthquake catalog which form part of the data used in this study. Data used for the study is
 293 available at <https://data.mendeley.com/drafts/j2c8nmmnzt>. The algorithms (CONVT, TRAVT)
 294 developed in this study, seismic stations and the figures generated are available at
 295 <https://data.mendeley.com/drafts/bd82mtfgbc>.

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Direction-based P-wave Traveltime Residual Estimation for some Stations around Southern Thailand, Peninsular Malaysia, Singapore and Sumatra using a New Ray Tracing Algorithm

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ds02: OUTPUT2-RESIDUALS

Introduction

DATASET-1964-2018 is a text file of arrival time dataset for or earthquakes (magnitude > 3.5 mb) and confined to the top 100 km in focal depths that have occurred around the Sumatran Fault System spanning latitudes 10° N - 10° S and longitudes 92° E-114° E.

OUTPUT2-RESIDUALS is also a text file with the calculated first-arrival p wave residual values for 117 broadband stations around southern Thailand, Peninsular Malaysia, Singapore, Sumatra region of Indonesia, Australia and India

- Both ds01 and ds02 are text files;
- ds01 include hypocentral parameters, origin time, magnitude and event ID as well as first-arrival time picks of p waves from both the bulletin of International Seismological Center (BISC) and the Incorporated Research Institutions for Seismology (IRIS). ds02 include arrival ID (ARVD), Event ID (EVID), focal depth in km (DEP) calculated epicentral distance in km (DXD), calculated back-azimuth in angular degrees (BAZI), calculated residual in seconds (RESC) and BISC reported residuals (RESR);

- Phase picking from the IRIS waveforms is done with the SEISAN software. The corresponding S-file from SEISAN is added to the BISC dataset. A Fortran routine is used to compute traveltimes and raypaths;
- Seismic stations KOM and KUM (IRIS station code names) are observed to be the same as stations MYKOM and KULM respectively on the BISC station list