ROYAL OBSERVATORY, HONG KONG

Technical Note (Local) No. 62

EPICENTRE DETERMINATION OF DISTANT EARTHQUAKES IN HONG KONG

by

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Published January 1993

Prepared by

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550.34.06

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1. INTRODUCTION

Since the establishment of a network of three short-period seismographs by the Royal Observatory (RO) in 1979 to monitor earthquakes in the vicinity of Hong Kong, 19 earthquakes were felt by local residents in the subsequent 11 years, up to 1990. Of these 19 locally felt earthquakes, only three originated within Hong Kong. The remaining events occurred at distances which vary from 120 km to more than 1,100 km of Hong Kong (Table 1). Due to the large epicentral distances, many of these earthquakes could not be determined just based on the short-period seismograph records.

Being a member of the Pacific Tsunami Warning System, RO often receives P-arrival time (P-time) data in real-time from other seismological stations, including Matsushiro (MAT) of Japan, Guam (GUMO) of the Mariana Islands, and Yuzh-Sakhalinsk (YSS) of Russia whenever a significant earthquake occurs. If P-times from these 3 stations are available, it is then possible to locate the concerned earthquake together with local seismic data. In 1984, a program named EPILAR was developed to locate distant earthquakes using only P-time inputs. The formulation of the program will be discussed in the following section. Verification of the program has been carried out and the results will be presented in sections 3 and 4.

2. FORMULATION OF EPILAR

The formulation of EPILAR is rather similar to that pertaining to locating local earthquakes (Shun, 1992) in which the solution is determined by a least squares approach.

Suppose ϕ, λ, h, and T are respectively the geodetic (geographic) latitude and longitude, depth of the hypocentre and origin time for a given earthquake. The problem is to determine these 4 parameters given a set of arrival times t_k from stations at positions (ϕ_k, λ_k, h_k) (k = 1, 2, ..., n). For a given trial hypocentre (ϕ^*, λ^*, h^*) and a trial origin time T^*, a set of theoretical arrival times T_k (k = 1, 2, ..., n) can be obtained from the J-B Seismological Tables (Jeffreys and Bullen, 1940; SSB, 1980). Define

$$R = \Sigma_k (t_k - T_k)^2, \qquad k = 1, 2, ..., n \qquad (1)$$

as the residue which is a function of ϕ^*, λ^*, h^* and T^*. The method is to adjust the trial parameters such that the residue is minimized.

In EPILAR, theoretical P-times at 11 standard depth levels (0, 15, 20, 33, 96, 160, 223, 287, 413, 540, 667 km) are computed from second order polynomial equations which approximate the J-B P-travel time tables for 10 different epicentral distance (angular) ranges (DELTA = 0 - 9.9°, 10 - 19.9°, ..., 80 - 89.9°, and DELTA ≥ 90°). The epicentral distance DELTA between two locations with geodetic coordinates (ϕ_1, λ_1) and (ϕ_2, λ_2) is approximated by the great circle distance without taking into account the ellipticity of the earth:

$$\text{DELTA} \approx \cos^{-1} [\sin(\phi_1)\sin(\phi_2) + \cos(\phi_1)\cos(\phi_2)\cos(\lambda_2 - \lambda_1)] \qquad (2)$$

Furthermore, instead of minimizing R, $R' = \Sigma_{i,j} (t_{ij} - T_{ij})^2$ is minimized (Poon, 1985), where

$$t_{ij} = t_i - t_j, \quad \text{and} \qquad (3)$$

$$T_{ij} = T_i - T_j, \qquad i,j = 1, 2, ..., n \qquad (4)$$

Thus, the T^* terms are cancelled and for each depth level L, the point (ϕ_L, λ_L) with minimum residue $R'_{min,\,L}$ can be obtained by varying the trial parameters ϕ^* and λ^* over the vertices of a system of 3 nested grids:

	Grid Size	Grid Coverage
Coarse	$\delta\phi = \delta\lambda = 5°$	ϕ, λ = -60° to +60°
Medium	$\delta\phi = \delta\lambda = 0.25°$	ϕ, λ = -3° to +3°
Fine	$\delta\phi = \delta\lambda = 0.0125°$	ϕ, λ = -0.15° to +0.15°

The program starts computation at depth level 1 (i.e. earth's surface). The centre of the coarse mesh grid can be arbitrarily chosen but the default is 20°N 110°E. The coarse mesh grid is first used and the grid point (ϕ^*_c, λ^*_c) with the smallest residue is taken as the first approximation to the epicentral location. The process is then repeated by using the medium mesh grid centred at (ϕ^*_c, λ^*_c) to obtain a second approximation (ϕ^*_m, λ^*_m). Lastly, the process is repeated by using the fine mesh grid centred at (ϕ^*_m, λ^*_m) to obtain the point (ϕ_1, λ_1) with minimum residue $R'_{min,1}$. This entire process is again repeated for depth levels 2, 3, ..., up to level N if

(a) $R'_{min,N} > 1.1\, R'_{min,N-1}$, or

(b) the last depth level (i.e. N = 11) has been reached.

The location with minimum residue R'_{min} = minimum $\{R'_{min,L} : L = 1, 2, ..., N\}$ and the depth of the corresponding level (L_{min}) are taken as the final solution for the hypocentral position.

3. VERIFICATION OF EPILAR USING ACTUAL SEISMIC DATA

Methodology

EPILAR was verified using actual data pertaining to earthquakes which occurred during the one-year period July 1989 - June 1990 with magnitude greater than or equal to 5.0 on the Richter Scale and within 4,000 km of Hong Kong. A total of 56 cases were included in the study (Table 2 and Figure 1). P-times at overseas seismological stations were extracted from real-time earthquake messages received from the National Earthquake Information Center (NEIC) of the U.S. Geological Survey (USGS), Pacific Tsunami Warning Center (PTWC) and Alaska Tsunami Warning Center (ATWC) whenever they were available. P-times at RO (station code HKC) were extracted from preliminary analyses unless they could not be determined with confidence. In the latter cases, the P-times disseminated in the real-time "Tsunami Messages" were used. NEIC epicentral data were used as the "ground truth" in the verification.

EPILAR requires accurate geodetic coordinates of the seismological stations used in the computation. The original station data file which only contained coordinates for 40 stations was therefore updated and expanded to include 150 stations which appeared in real-time earthquake messages (Table 3). The station coordinates were extracted from ISC (1987). Due to limited computer resources, EPILAR was designed to accept up to 20 P-times in a single run. Therefore, whenever there were more than 20 P-times available from the messages, only the earliest 20 were used. The stations used in each individual case can be found in Table 2 and the geographical distribution of these stations is shown in Figure 2.

In the course of the verification, it was found that in some cases, stations with residues significantly greater than the rest had to be discarded to yield good solutions. Upon detailed checking, these cases can be explained by one of the following reasons:

(a) the stations with significantly large residues are more than 105° ($\approx$ 12,000 km) away from the epicentre and are located in the shadow zone. The arrival times given are therefore not pertaining to the P-waves but may be due to diffracted P-waves or PP-waves,

(b) the P-times were erroneous.

Unless otherwise stated, the station residues of the results presented in this report are all less than ± 5 s. Samples of the input and output files are shown in Appendices I and II respectively.

Results

The verification results of EPILAR are presented in Table 4. The computed epicentres at L_{min} and at 33 km depth are shown against the NEIC epicentres. Apart from case 31 (epicentre near the Andaman Islands), the location errors range between 0.1° and 6.4° (mean = 1.4°, standard deviation = 1.2°) for epicentres computed at L_{min} and between 0.1° and 9.7° (mean = 1.4°, standard deviation = 1.8°) for epicentres computed at 33 km depth. This result indicates that the accuracy of the epicentres computed at L_{min} and 33 km is about the same but the method of determining the epicentre at the level of minimum residue (which is computationally more expensive) has a smaller standard deviation in the errors. However, the location error for case 31 is very large (29° at both L_{min} and 33 km depth) and the computed epicentre is seriously wrong. The corresponding P-times were therefore extracted from the real-time messages for detailed examination (Table 5). Using the NEIC epicentre and origin time, the theoretical P-times at the five stations were derived from the J-B Seismological Tables and the differences between the theoretical and observed P-times are shown in Table 5. The P-time recorded by the station FBA (Fairbanks, Alaska) differs from the theoretical one by 8.0 s and is probably erroneous. After discarding the FBA P-time, EPILAR was re-run. However, the program gave good results only when certain central latitudes and longitudes were chosen for the coarse mesh grid (see section 2).

It was found that, for case 31, there were more than one local minima in the residue field. Therefore, although the global minimum should be in the vicinity of the actual epicentre, EPILAR erroneously identified the local minimum near 30° N 119° E as the epicentre due to the grid size of the coarse mesh being too large (Figure 3). In order to overcome this problem, EPILAR was modified to run with a 2-degree grid in the first iteration.

4. THE MODIFIED EPILAR AND ITS VERIFICATION

Due to limited computational power, the modified EPILAR consists of only two nested grid systems instead of three. The grid sizes and coverage are listed below:

	Grid Size	Grid Coverage
Coarse	$\delta\phi = \delta\lambda = 2°$	ϕ, λ = -52° to +52°
Fine	$\delta\phi = \delta\lambda = 0.1°$	ϕ, λ = -2.6° to +2.6°

Apart from the changes in the grid systems, the modified EPILAR is identical to the operational version.

Verification of the modified EPILAR was again carried out based on the 56 earthquakes selected in section 3 and the results are shown in Table 6. The use of a higher resolution coarse mesh grid enabled EPILAR to locate the earthquake of case 31 to within 2.5° of the NEIC epicentre. Although the modified EPILAR still obtains two local minima in the residue field (Figure 4), it successfully identifies the global minimum near the Andaman Islands. As a whole, the location errors range between 0.1° and 6.5° (mean = 1.4°, standard deviation = 1.2°) for epicentres computed at L_{min} and between 0.1° and 4.2° (mean = 1.2°, standard deviation = 1.0°) for epicentres computed at 33 km depth. In contrary to the results in section 3, the accuracy of the epicentres computed at 33 km depth is slightly better than that computed at L_{min}, both in terms of the mean errors and standard deviations.

As explained in section 1, RO often receives P-time data in near real-time from three other seismological stations: MAT, GUMO and YSS. In order to assess whether the modified EPILAR can accurately locate earthquakes which occur within 4,000 km of Hong Kong based on P-time data received from these stations, theoretical P-times at HKC and the three stations for epicentres (focal depth = 33 km) at the vertices of a 5-degree 17 x 17 grid system centred at Hong Kong were generated from the J-B Seismological Tables and input into the program. The computed epicentres were compared with the actual positions. Furthermore, to examine the effect of P-time errors on the location accuracy, three sets of theoretical P-times were considered:

(a) P-times accurate to the nearest second,

(b) P-times accurate to the nearest five seconds, and

(c) P-times accurate to the nearest ten seconds.

For each set, the verification results for epicentres computed at L_{min} and at 33 km depth were obtained and are shown in Figures 5 to 10. The mean errors pertaining to L_{min} (and at 33 km depth) increase from 0.3° (0.2°) for set (a) to 1.0° (0.9°) for set (b) and 1.5° (1.5°) for set (c). The corresponding maximum errors are 1.4° (0.8°) for set (a), 4.5° (5.5°) for set (b) and 7.8° (7.8°) for set (c). It is apparent that the mean errors increase with decreasing P-time accuracy and the accuracy pertaining to 33 km depth is marginally better than that for L_{min}. The earlier finding based on actual earthquake data seems to agree well with these results, bearing in mind that the average P-time accuracy achieved in near real-time is of the order of several seconds.

In Figures 5 to 10, the areas with location errors greater than or equal to 0.5° are shaded. It is obvious that the errors have a pattern which is related to the geometry of the four seismological stations. In particular, the errors are relatively small within the triangle formed by HKC, GUMO and YSS. Relatively large errors (of the order of several degrees) can be found anywhere outside this triangle but there is a tendency for them to cluster near Indonesia.

Five locally felt earthquakes which occurred during 1980 to 1987 were chosen for further verification of the modified EPILAR. The epicentres of these earthquakes are shown in Figure 11 and their details are included in Table 7. Although there were 18 locally felt earthquakes which occurred during 1980 to 1987, only these five were intense enough to have the P-waves recorded at the four stations (HKC, MAT, GUMO and YSS). All P-time data were extracted from the Bulletins of the International Seismological Centre (ISC) and input into the program. The epicentres computed at L_{min} and at 33 km depth are shown against the ISC epicentral locations in Table 8. The corresponding mean errors are 0.9° and 0.8° whereas the maximum errors are 1.2° and 1.6° respectively.

In order to compare the modified program with the operational version, the latter program was also run with the same set of P-time data and the verification results are shown in Table 9. The corresponding mean errors are now 1.4° and 8.5° whereas the maximum errors are 2.8° and 22.1° respectively. It is therefore obvious that the modified EPILAR performed much better than the operational version, especially for the cases of 1985 and 1987 which occurred over Luzon.

5. DISCUSSION

The verification results presented in section 3 indicate that although the operational EPILAR program can in general locate epicentres to within 2° on the average, its results could be seriously wrong (e.g. case 31).

Depending on the geometry of the seismological stations and the P-time accuracy, the residue field may contain more than one local minima. Even though the global minimum should lie in the vicinity of the actual epicentre, the program may not always be successful to find out the location of the global minimum. This situation can arise when:

(a) the grid size of the program is too large,

(b) the P-time data availability/coverage is poor, and/or

(c) some of the P-time data are erroneous.

Although it was mentioned in section 3 that erroneous P-times could be identified by considering the individual station residues, this method failed for the operational EPILAR for case 31.

The verification results in section 4 indicate that the modified EPILAR with a 2-degree coarse mesh grid performed significantly better than the operational program which has a lower resolution 5-degree coarse mesh grid. In particular, the serious error pertaining to case 31 resulted from using the operational program was reduced by the modified version. Although this suggests that the location errors may be reduced further by using finer mesh grids in EPILAR, it is too computationally expensive to run an even higher resolution version in near real-time. In fact, a single run of the modified version of EPILAR requires about 10 minutes on the Data General MV/20000 computer. For a finer mesh grid of 1°, about four times of computer time will be needed.

Using the modified EPILAR, reliable results can be obtained using only four P-time inputs (at HKC, MAT, GUMO and YSS) which are accurate to the nearest second. However, as the P-times may have errors of the order of several seconds, reliable results can only be obtained for epicentres within the triangle formed by HKC, GUMO and YSS. Nevertheless, for five locally felt earthquake cases, the modified EPILAR gave reliable results and also performed better than the operational version.

Manual seismogram analysis can help to tackle ambiguous cases and confirm the epicentre determined by EPILAR. P-times of the local short-period seismographs can be used to estimate the direction of a distant earthquake. The epicentral distance from Hong Kong can also be obtained from the J-B Seismological Tables if S-P times are available.

The capability of EPILAR in determining the focal depth of earthquakes was not explicitly considered in this study. However, the results in sections 3 and 4 show that the errors of the computed epicentres pertaining to the level of minimum residue (L_{min}) are not significantly less than those computed at 33 km depth. This may indicate that the accuracy of the computed epicentral locations does not depend very much on successful focal depth determination.

6. CONCLUSION

It was found that the operational EPILAR could yield very large errors in epicentral determination of distant earthquakes. The program was modified to have a higher resolution 2-degree coarse mesh grid and the epicentres determined by the modified version of EPILAR became much more accurate.

Using P-time data obtained from MAT, GUMO and YSS together with that of HKC, the modified EPILAR can be used in near real-time to determine epicentres within 4,000 km of Hong Kong. However, the results may still be affected by the three conditions discussed in section 5, namely, (a) grid size too large, (b) poor P-time data availability/coverage, and (c) erroneous P-time data. It is therefore recommended to also consider other local data, including P-times obtained from the local short-period seismographs and S-P times, in order to confirm whether the epicentres computed by EPILAR are reliable or not.

ACKNOWLEDGEMENT

The authors would like to thank Messrs. W.H. Leung and M.S. Chau for their assistance in the preparation of the figures and tables.

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Jeffreys, H. and Bullen, K.E.	1940	"Seismological Tables", Brit. Ass., Gray Milne Trust, London.
Poon, H.T.	1985	"Seismological Measurements in Hong Kong", Proceedings of Conference on Geological Aspects of Site Investigation Bulletin No. 2, Geological Society of Hong Kong, August 1985.
Shun, C.M.	1992	"Epicentre Determination of Local Earthquakes", Royal Observatory Technical Note (Local) No. 61.
State Seismological Bureau (SSB)	1980	"震相走時便查表", 地震出版社.

APPENDIX I

SAMPLE INPUT DATA FILE FOR EPILAR

```
 11.6 N   95.2 E   1153Z  10 JAN  1990
HKC 1158055
BRW 1205540
IMA 1206095
PMR 1206267
FBA 1206278
```

APPENDIX II

SAMPLE OUTPUT FILE OF EPILAR

```
          Program EPILAR begin processing at 15:44:38  on  9/16/91


EARTHQUAKE LOCATED BY NEIC AT  11.6 N  95.2 E   ORIGIN TIME  1153Z

 1 HKC    11 58  5.5     5.5   22.3036  114.1719
 2 BRW    12  5 54.0   474.0   71.3033 -156.7483
 3 IMA    12  6  9.5   489.5   66.0685 -153.6786
 4 PMR    12  6 26.7   506.7   61.5922 -149.1308
 5 FBA    12  6 27.8   507.8   64.9000 -147.7933

Origin Time : 11:55:48.3
Depth=   0Km  Lat.=   30.7 N  Lon.=   118.4 E  delta=     52.2276
Location from HKC is : Distance= 1023.8 Km Bearing=  23.2 Deg
  1 HKC   1126 5.5        -.01
  2 BRW   12 554.0       -1.03
  3 IMA   12 6 9.5        1.33
  4 PMR   12 626.7       -2.09
  5 FBA   12 627.8        1.80

Origin Time : 11:55:50.4
Depth=  15Km  Lat.=   30.5 N  Lon.=   118.7 E  delta=     51.8529
Location from HKC is : Distance= 1020.0 Km Bearing=  25.5 Deg
  1 HKC   1126 5.5        -.02
  2 BRW   12 554.0       -1.27
  3 IMA   12 6 9.5        1.34
  4 PMR   12 626.7       -1.89
  5 FBA   12 627.8        1.84

Origin Time : 11:55:51.1
Depth=  20Km  Lat.=   30.6 N  Lon.=   118.6 E  delta=     52.2373
Location from HKC is : Distance= 1018.8 Km Bearing=  24.8 Deg
  1 HKC   1126 5.5        -.02
  2 BRW   12 554.0       -1.24
  3 IMA   12 6 9.5        1.34
  4 PMR   12 626.7       -1.93
  5 FBA   12 627.8        1.85

Origin Time : 11:55:52.9
Depth=  33Km  Lat.=   30.4 N  Lon.=   119.0 E  delta=     52.8328
Location from HKC is : Distance= 1016.1 Km Bearing=  27.0 Deg
  1 HKC   1126 5.5        -.07
  2 BRW   12 554.0       -1.47
  3 IMA   12 6 9.5        1.35
  4 PMR   12 626.7       -1.71
  5 FBA   12 627.8        1.91

          Program EPILAR processing ended at 15:46:26  on  9/16/91
```

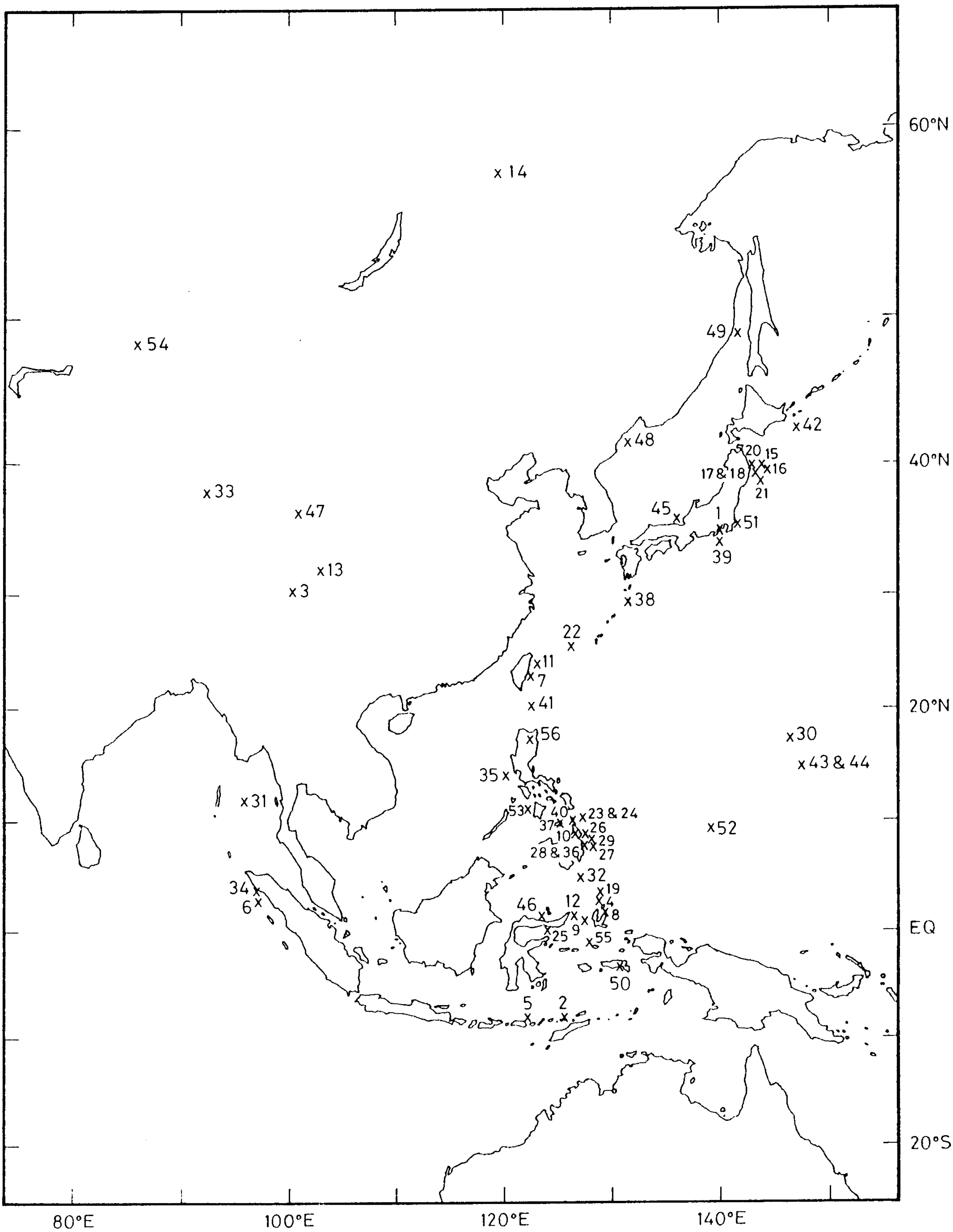

Figure 1 - Epicentres of earthquakes used for the verification of EPILAR
(The numbers shown refer to the case numbers in Table 2)

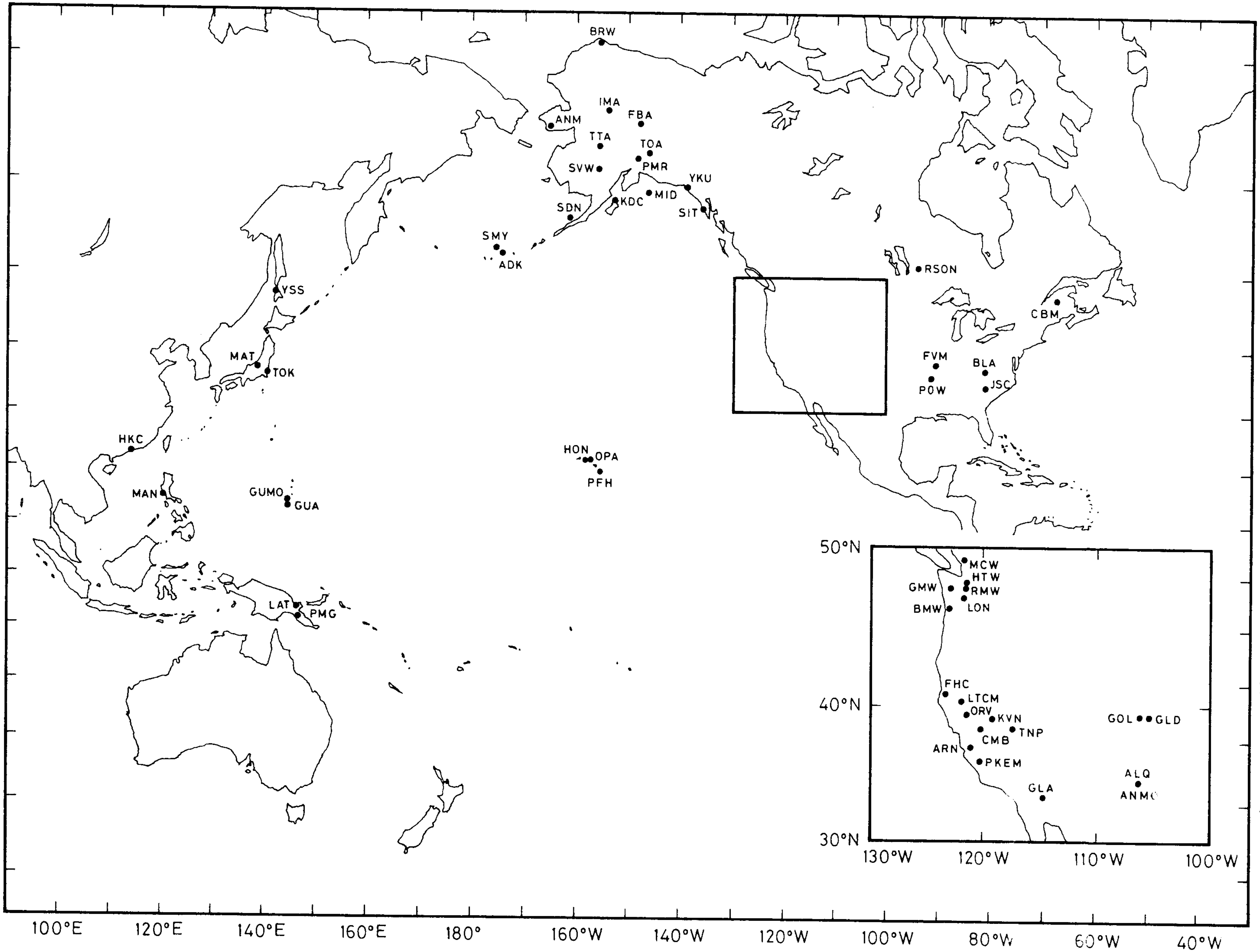

Figure 2 - Locations of seismological stations used in the verification of EPILAR

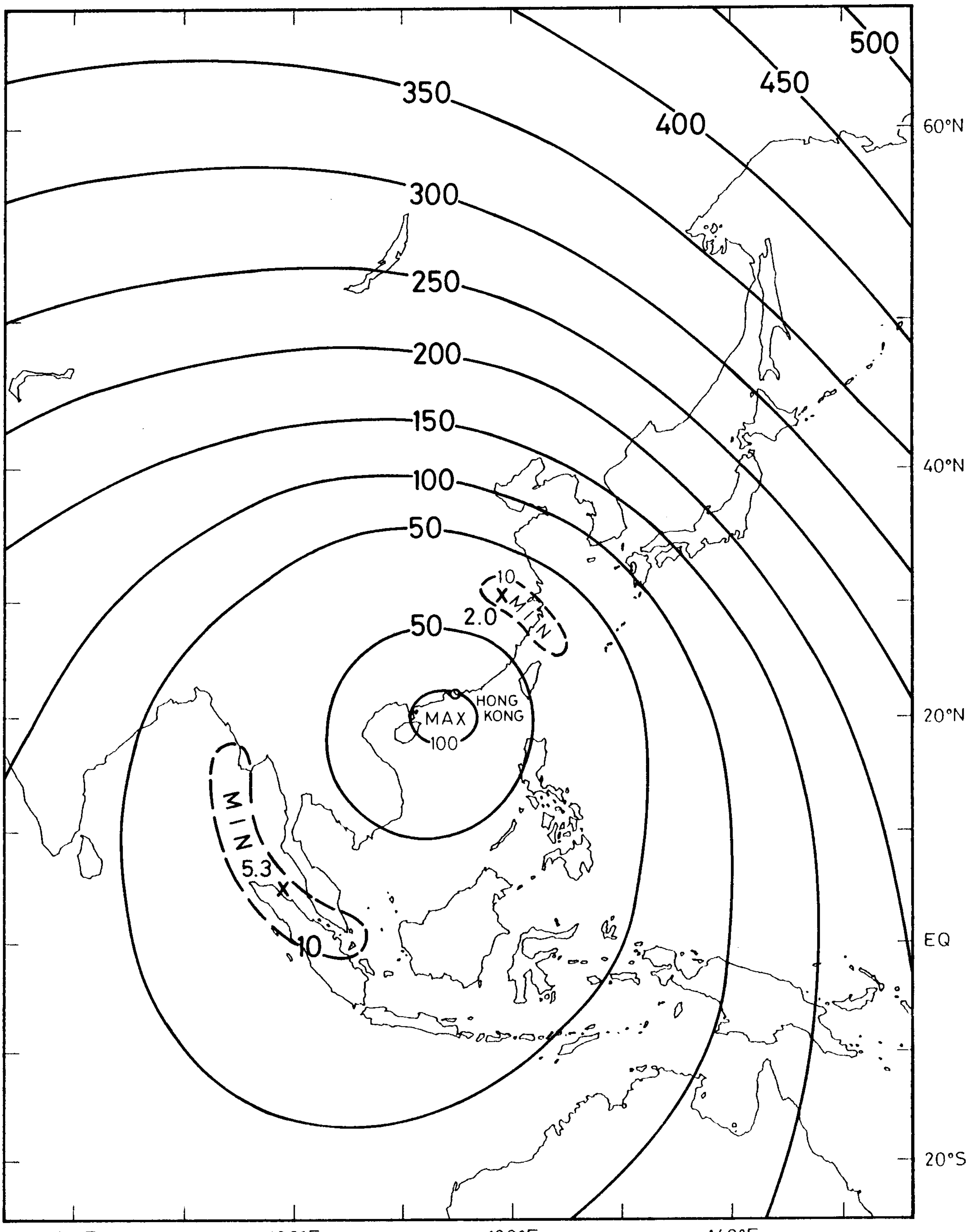

Figure 3 - Residue field (r.m.s., in s) of case 31 computed by EPILAR with 5-degree coarse mesh grid

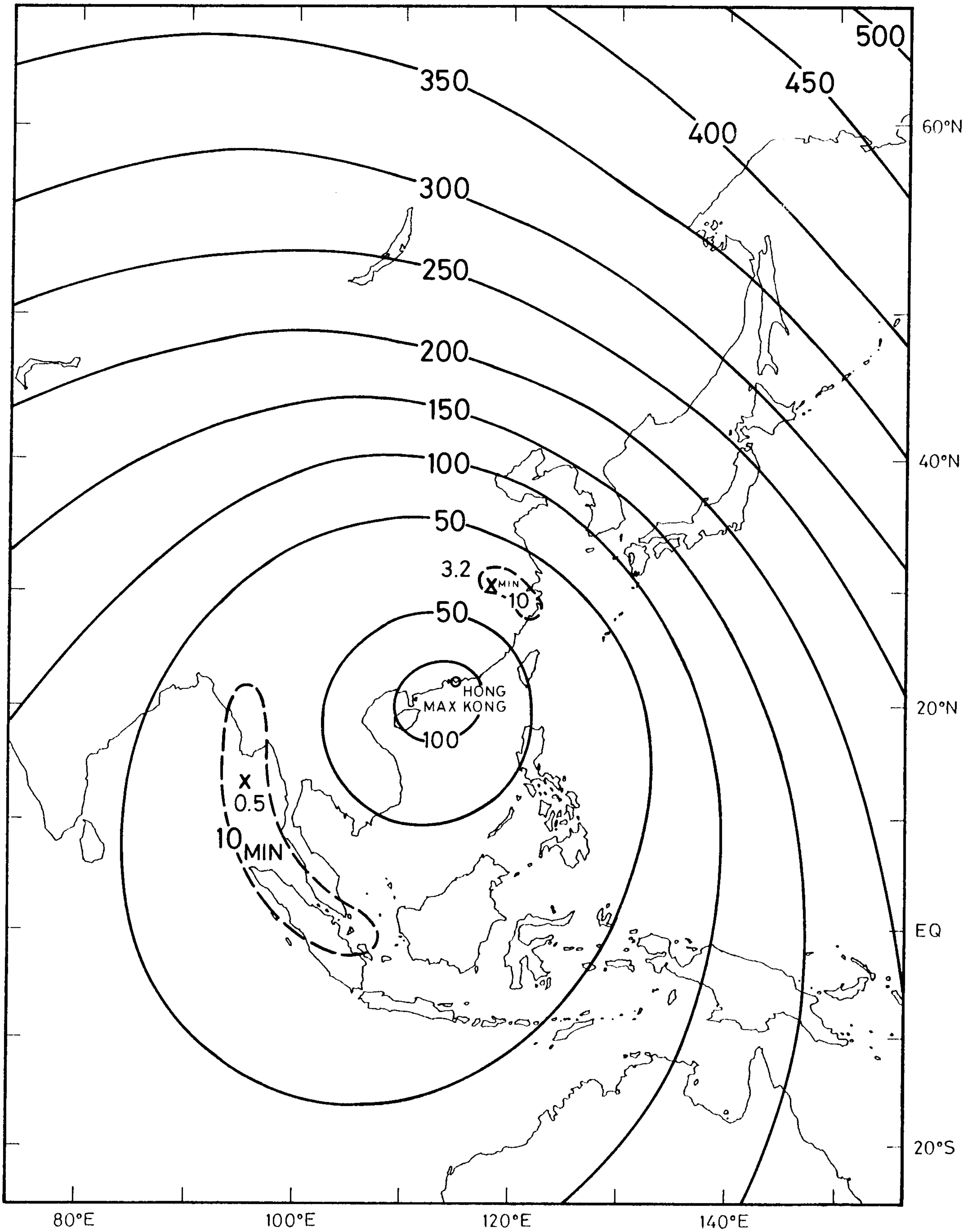

Figure 4 - Residue field (r.m.s., in s) of case 31 computed by the modified EPILAR with 2-degree coarse mesh grid

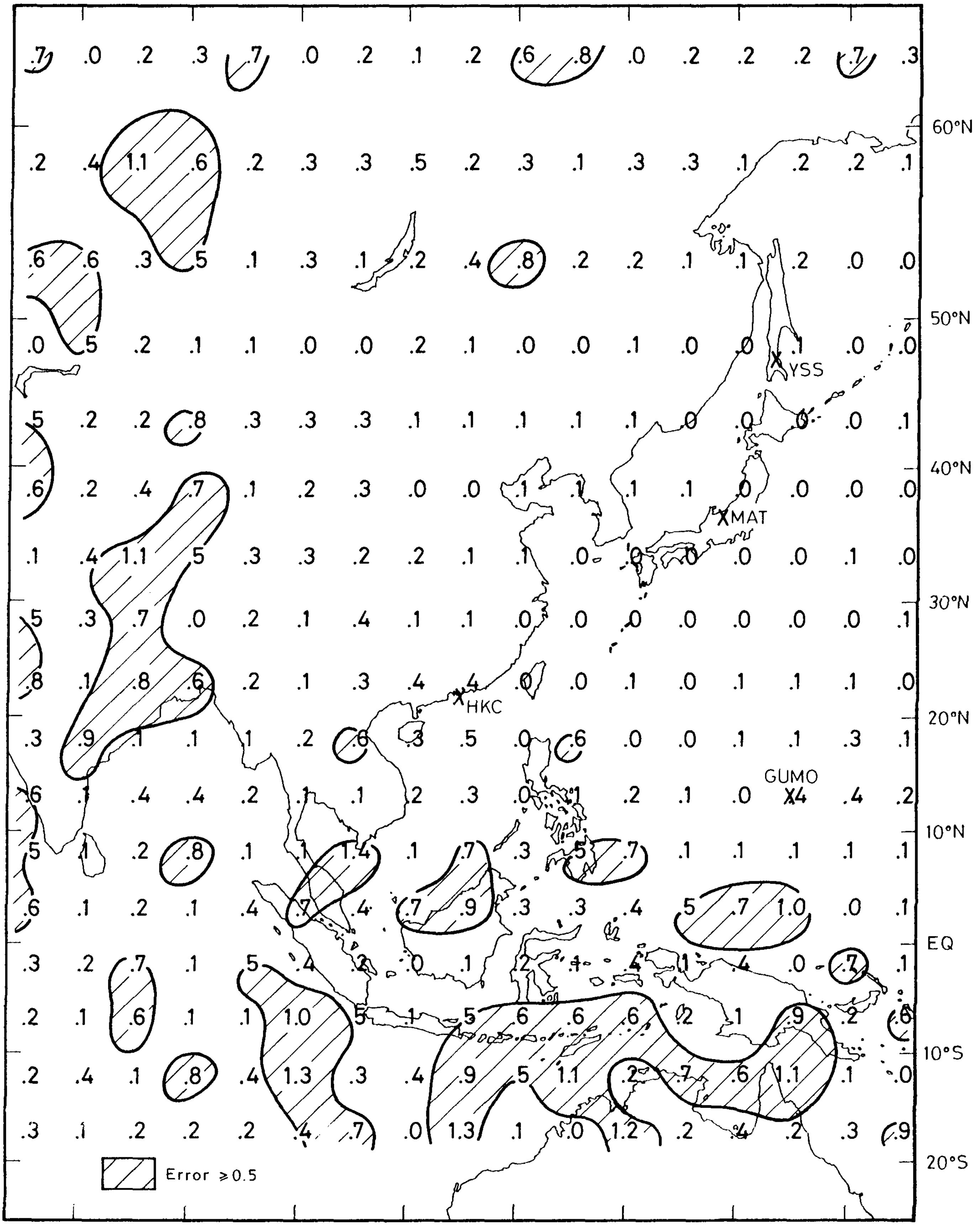

Figure 5 - Errors (in degrees) of epicentres computed at L_{min} by the modified EPILAR (P-times accurate to the nearest second) (Mean = 0.28 Maximum = 1.4 Standard Deviation = 0.29)

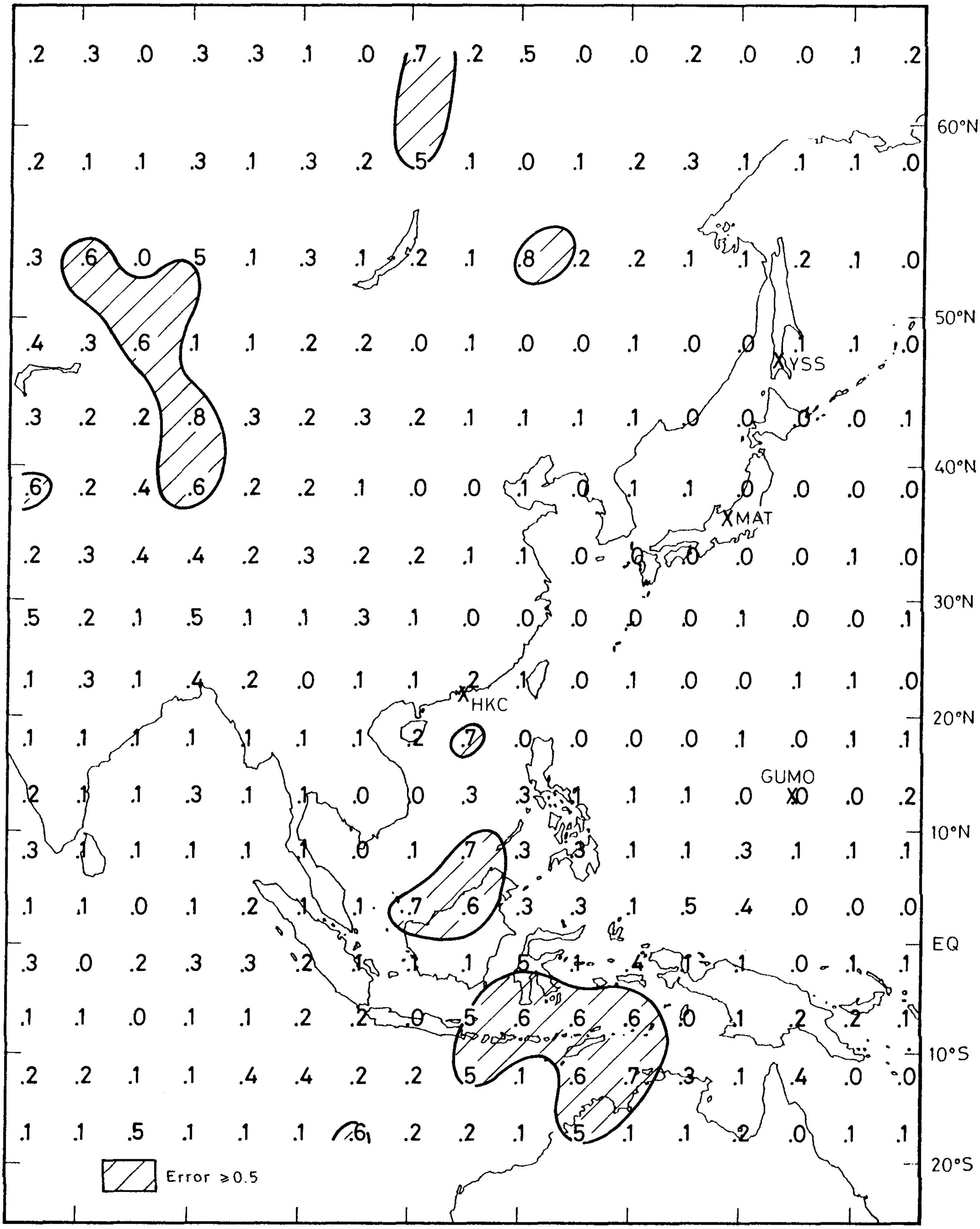

Figure 6 - Errors (in degrees) of epicentres computed at 33 km depth by the modified EPILAR (P-times accurate to the nearest second) (Mean = 0.17 Maximum = 0.8 Standard Deviation = 0.17)

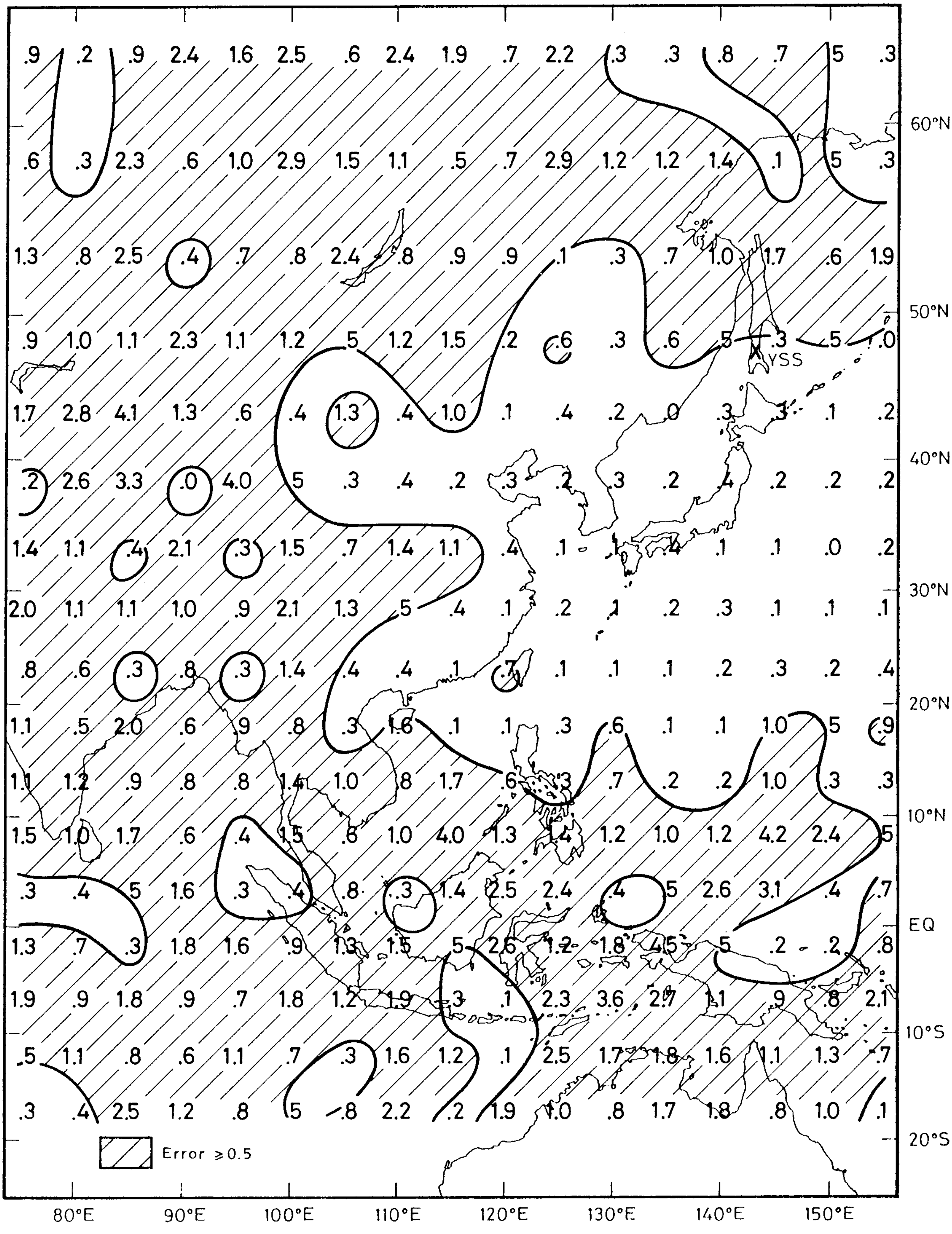

Figure 7 - Errors (in degrees) of epicentres computed at L_{min} by the modified EPILAR (P-times accurate to the nearest five seconds) (Mean = 0.97 Maximum = 4.5 Standard Deviation = 0.84)

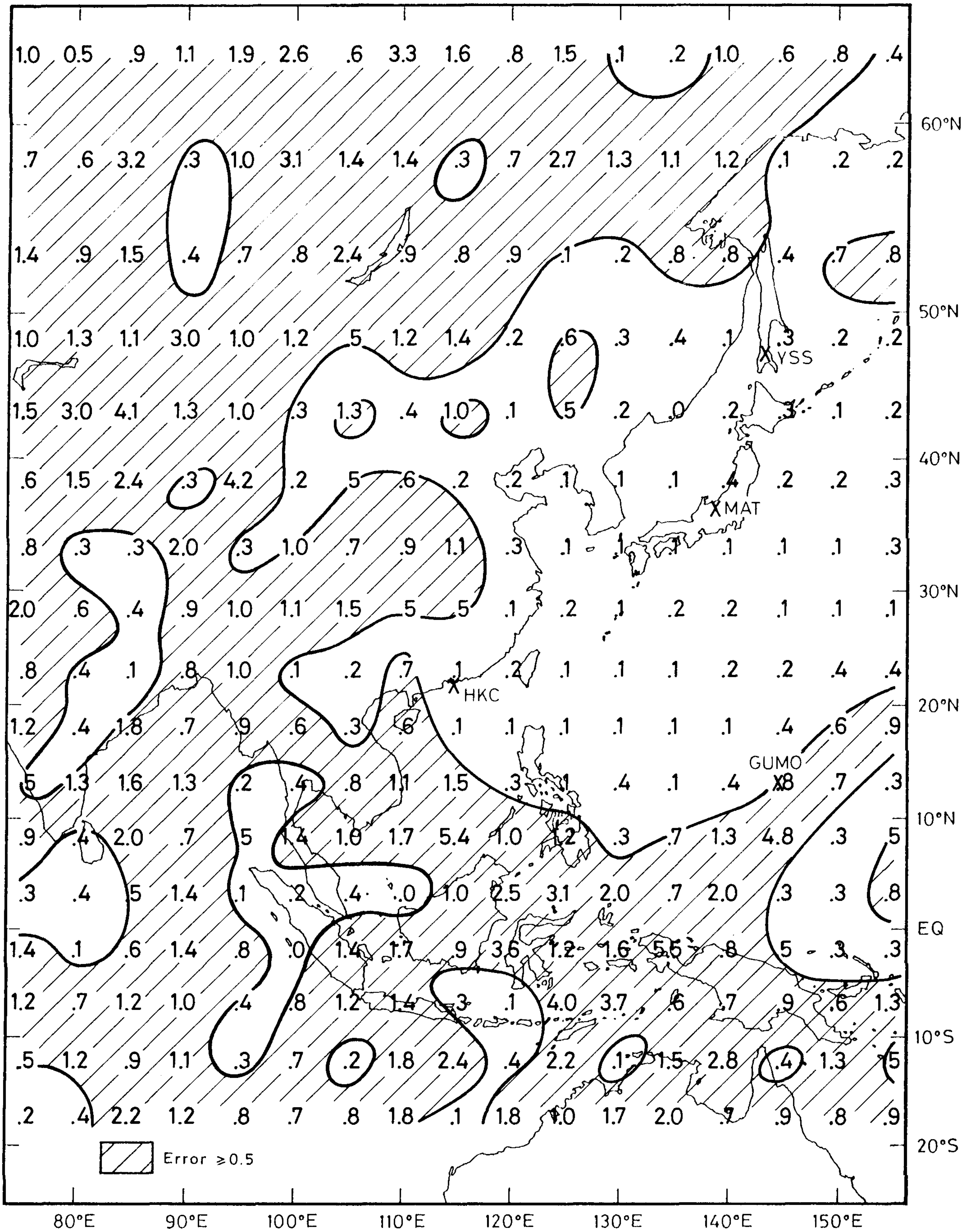

Figure 8 - Errors (in degrees) of epicentres computed at 33 km depth by the modified EPILAR (P-times accurate to the nearest five seconds) (Mean = 0.89 Maximum = 5.5 Standard Deviation = 0.91)

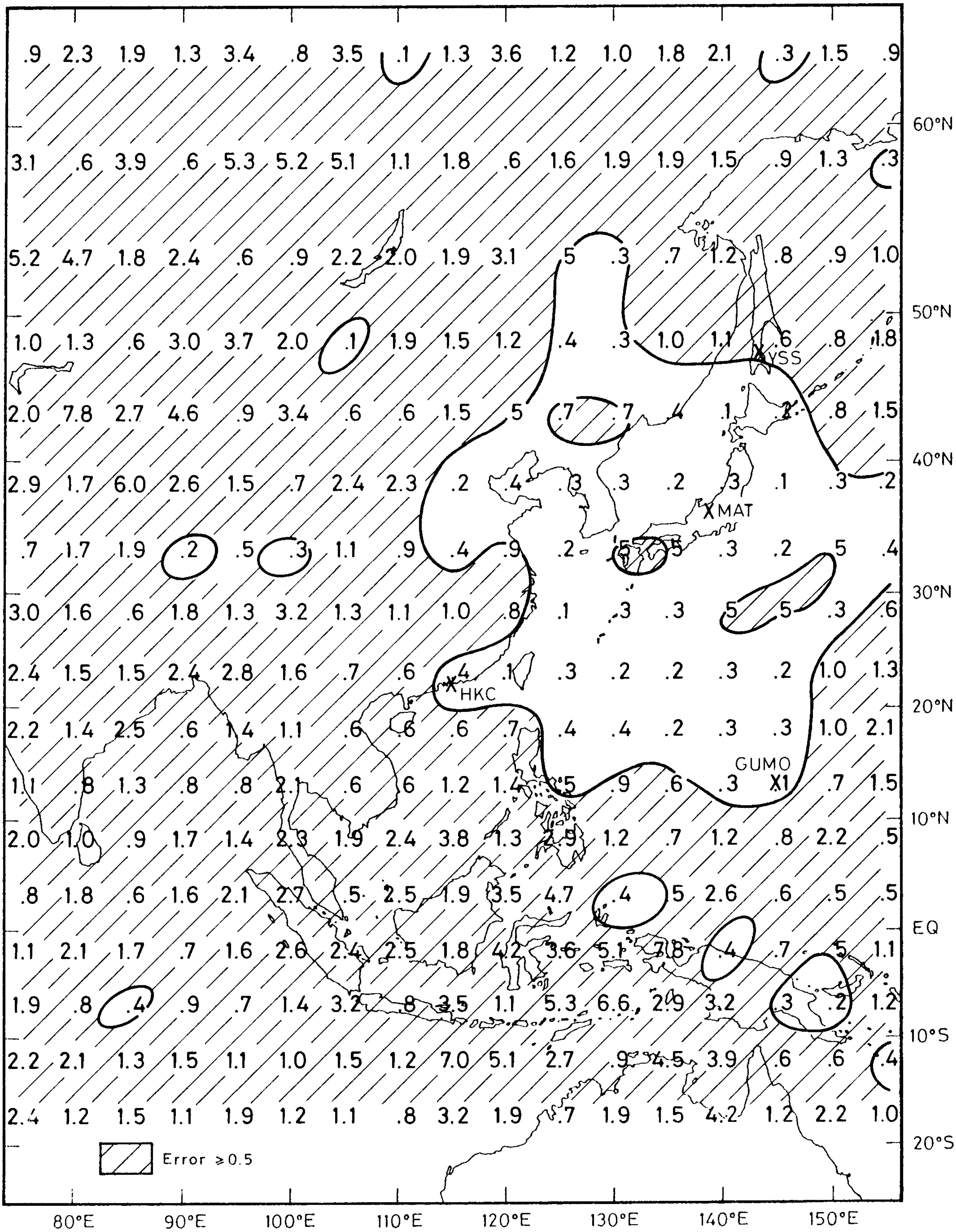

Figure 9 - Errors (in degrees) of epicentres computed at L_{min} by the modified EPILAR (P-times accurate to the nearest 10 seconds) (Mean = 1.54 Maximum = 7.8 Standard Deviation = 1.37)

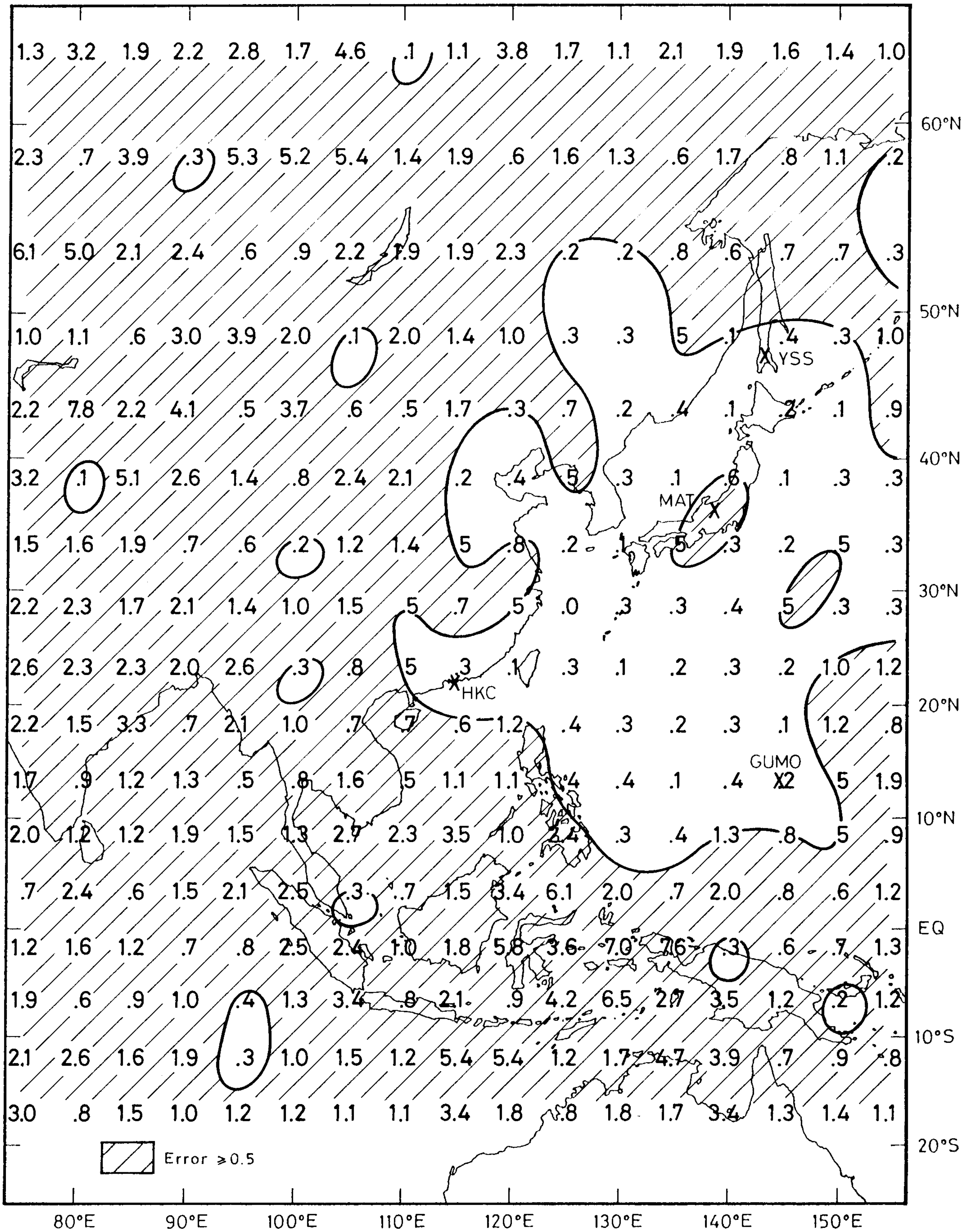

Figure 10 - Errors (in degrees) of epicentres computed at 33 km depth by the modified EPILAR (P-times accurate to the nearest 10 seconds) (Mean = 1.49 Maximum = 7.8 Standard Deviation = 1.41)

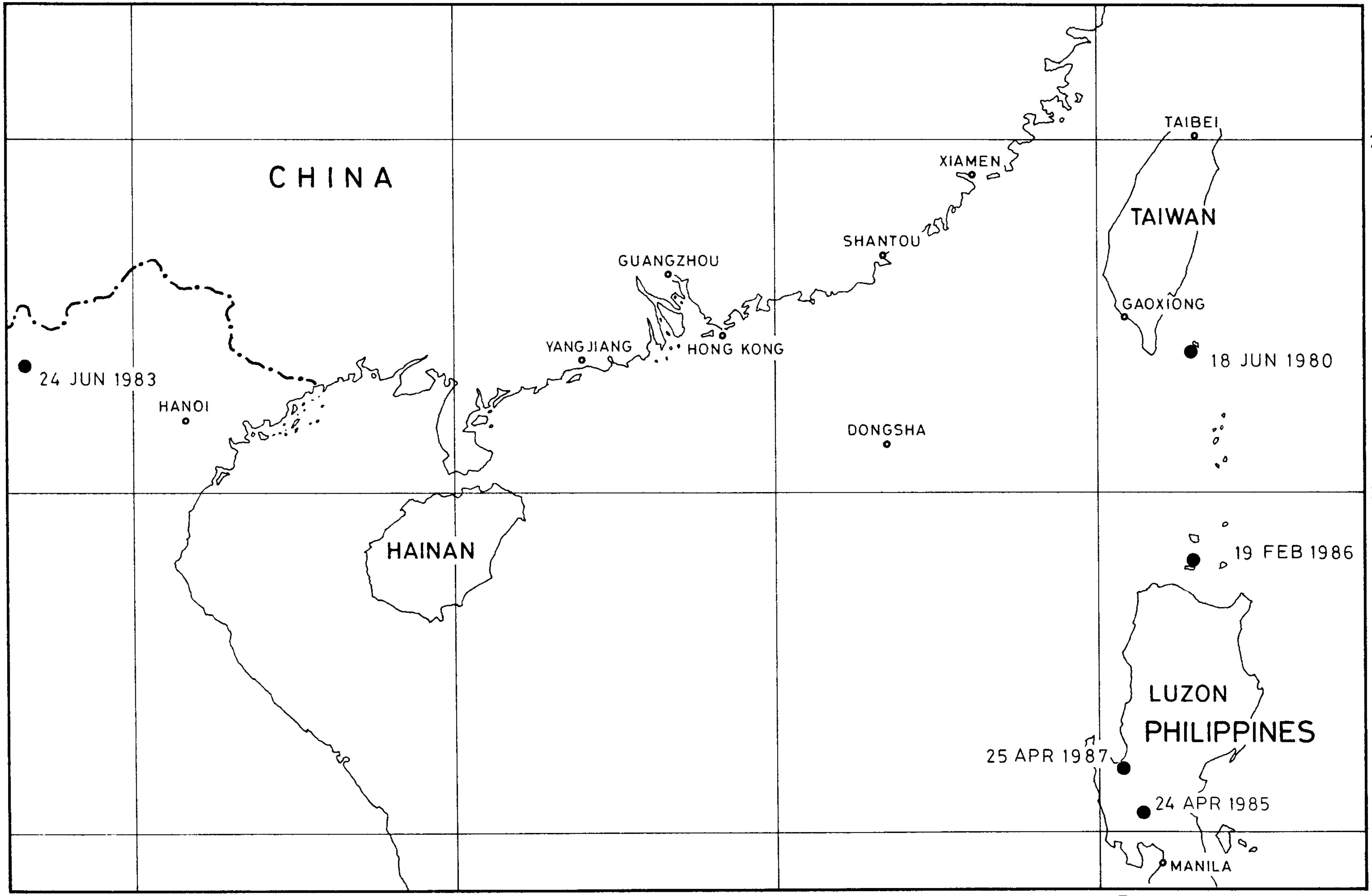

Figure 11 - Epicentres of locally felt earthquakes used for verification of the modified EPILAR

Table 1 - Felt Earthquakes in Hong Kong from 1980 to 1990

Year	Date	Time Recorded (HKT)	Intensity	Magnitude ML	Magnitude MS	Magnitude MB	Latitude (deg. N)	Longitude (deg. E)	Data Source#	Distance from Hong Kong (km)
1980	8 May 80	1038	II	4.5	4.0	-	23.3	117.5	GSB	360
1980	18 Jun 80	1734	II	-	-	5.7	22.0	121.4	ISC	750
1981	9 Apr 81	0904	III-IV	4.2	3.7	-	22.9	115.2	GSB	120
1981	4 May 81	1905	II	4.8	4.3	-	23.7	114.7	GSB	160
1982	25 Feb 82	0839	III-IV	-	3.9	4.4	24.8	114.8	ISC	280
1982	30 Aug 82	0423	III-IV	1.5	-	-	22.3	114.0	RO	17*
1982	7 Oct 82	2213	III-IV	1.5	-	-	22.3	114.0	RO	17*
1983	24 Jun 83	1521	IV	-	6.5	6.0	21.8	103.3	ISC	1120
1983	6 Dec 83	2225	IV	1.5	-	-	22.5	114.1	RO	25*
1985	24 Apr 85	0017	III-IV	-	-	6.3	15.3	120.6	ISC	1030
1986	28 Jan 86	0714	III-IV	-	5.1	4.5	21.7	111.8	ISC	260
1986	19 Feb 86	1942	III	-	5.8	5.7	19.0	121.4	ISC	840
1987	25 Feb 87	2229	II-III	-	-	4.1	21.7	111.7	ISC	260
1987	25 Apr 87	2019	III	-	-	6.1	15.9	120.3	ISC	960
1987	2 Aug 87	1708	III-IV	-	4.8	5.0	25.0	115.6	ISC	330
1987	3 Aug 87	0720	III	-	4.0	4.9	25.1	115.5	ISC	340
1987	15 Aug 87	0101	III	-	-	4.4	25.1	115.6	ISC	340
1987	15 Sep 87	1005	III	-	-	4.7	23.8	114.5	ISC	170
1989	26 Nov 89	0014	II-III	-	-	5.0	23.7	114.5	ISC	160

Data Source

GSB - Guangdong Seismological Bureau
ISC - International Seismological Centre
RO - Royal Observatory

* Epicentre located within Hong Kong and distance measured from the Royal Observatory

Table 2 - NEIC Epicentral Data and Stations Used for the Verification of EPILAR

Case Number	Date	Origin Time (UTC) HHMMSS	Latitude	Longitude	Depth (km)	Magnitude MB	Magnitude MS	Country/ Area	Stations Used
1	9 Jul 89	020909	34.9 N	139.4 E	5	5.0	5.0	Japan	HKC ADK PMR HTW GLA
2	14 Jul 89	204240	8.1 S	125.1 E	10	6.4	6.2	Indonesia	HKC MAT YSS SMY ADK SDN ANM TTA IMA GUMO PMR FBA
3	21 Jul 89	030916	30.0 N	99.5 E	36	5.5	5.3	China	HKC BRW IMA TTA SVW FBA PMR KDC TOA
4	22 Jul 89	050212	2.3 N	128.1 E	142	6.4	-	Indonesia	HKC MAT YSS ADK HON PMR HTW ARN GLA
5	31 Jul 89	170728	8.0 S	121.4 E	14	6.3	6.2	Indonesia	HKC MAT YSS SMY ADK SDN SVW TTA IWA GUMO TOA
6	2 Aug 89	102421	2.8 N	96.1 E	29	5.1	4.9	Indonesia	HKC SMY ADK TTA IMA SVW
7	3 Aug 89	113120	23.0 N	122.0 E	11	5.9	6.4	Taiwan	HKC MAT YSS ADK ANM BRW TTA SVW IMA KDC
8	6 Aug 89	063629	1.9 N	128.3 E	114	5.7	-	Indonesia	HKC HON PMR HTW
9	12 Aug 89	004011	0.8 N	126.8 E	51	5.7	-	Indonesia	HKC MAT SDN SVW TTA KDC SIT
10	12 Aug 89	164643	8.7 N	125.7 E	55	5.9	-	Philippines	HKC MAT PMR HTW
11	21 Aug 89	231241	24.1 N	122.5 E	43	5.6	6.3	Taiwan	HKC MAT TTA SVW IMA KDC PMR TOA SIT GUMO RMW ARN
12	6 Sep 89	144551	1.0 N	126.1 E	37	5.8	5.5	Indonesia	HKC MAT SMY ADK SDN SVW KDC PMR FBA TOA SIT
13	22 Sep 89	022551	31.6 N	102.4 E	15	6.1	6.1	China	HKC SMY PMR GUMO
14	25 Oct 89	202900	57.5 N	118.8 E	22	5.4	5.5	Russia	IMA TTA SVW FBA PMR TOA RMW GLA
15	26 Oct 89	170642	39.8 N	143.5 E	8	5.8	5.8	Japan	MAT YSS SMY ADK HKC ANM BRW IMA KDC PMR FBA OPA HON ARN KVN GLA ALQ
16	27 Oct 89	014555	39.8 N	143.7 E	9	5.8	6.2	Japan	HKC IMA HON RMW ARN KVN ALQ
17	29 Oct 89	052538	39.6 N	143.3 E	10	6.0	6.6	Japan	MAT YSS SMY HKC IMA RMW ARN KVN ALQ FVM BLA
18	29 Oct 89	155311	39.5 N	143.4 E	10	5.4	5.3	Japan	MAT HKC IMA RMW KVN ALQ FVM
19	1 Nov 89	094927	2.5 N	128.1 E	37	5.5	5.1	Indonesia	HKC MAT ADK SDN TTA SVW KDC IMA PMR TOA
20	1 Nov 89	182535	39.8 N	142.8 E	29	6.4	7.4	Japan	SMY HKC IMA PMR OPA RMW ARN KVN ALQ

Table 2 - NEIC Epicentral Data and Stations Used for the Verification of EPILAR (cont'd)

Case Number	Date	Origin Time (UTC) HHMMSS	Latitude	Longitude	Depth (km)	Magnitude MB	Magnitude MS	Country/ Area	Stations Used
21	4 Nov 89	201205	39.1 N	143.4 E	30	5.4	5.7	Japan	MAT YSS SMY HKC PMR KVN ALQ
22	6 Nov 89	151254	25.7 N	125.6 E	31	5.1	5.3	Ryukyu Islands	HKC ADK TTA SVW FBA
23	14 Nov 89	173934	10.1 N	126.5 E	33	5.3	4.7	Philippines	HKC SVW BRW IMA PMR FBA
24	8 Dec 89	102313	10.1 N	126.5 E	44	5.7	5.9	Philippines	HKC MAT ADK SDN TTA IWA PMR FBA TOA
25	9 Dec 89	203809	0.1 N	123.3 E	151	6.2	-	Indonesia	HKC MAT YSS SMY ADK SDN ANM TTA SVW RMW KDC IMA PMR FBA TOA
26	15 Dec 89	184345	8.3 N	126.7 E	24	6.2	7.3	Philippines	HKC MAT YSS SMY ADK HON TTA BRW KDC GUMO PMR FBA SIT BMW GMW SGO
27	16 Dec 89	102445	8.0 N	126.9 E	31	5.3	5.0	Philippines	HKC MAT IMA PMR
28	20 Dec 89	000821	8.1 N	126.8 E	21	6.0	6.3	Philippines	GUA HKC MAT ADK ANM SDN TTA KDC IMA PMR FBA SIT
29	20 Dec 89	083520	8.2 N	126.9 E	39	5.8	5.3	Philippines	HKC MAT PFH IMA PMR RMW ARN KVN
30	23 Dec 89	112403	17.4 N	145.8 E	162	5.9	-	Western Pacific	HKC ADK SDN ANM SVW TTA IMA PMR FBA TOA RMW CMB KVN GLA GOL ALQ
31	10 Jan 90	115321	11.6 N	95.2 E	33	5.3	5.4	Andaman Sea	HKC BRW IMA PMR FBA
32	12 Jan 90	152815	5.0 N	126.5 E	66	5.5	-	Indonesia	HKC TTA BRW KDC IMA PMR FBA TOA
33	14 Jan 90	030320	37.8 N	91.9 E	17	6.1	6.1	China	HKC MAT BRW ANM IMA PMR RMW KVN
34	22 Jan 90	172612	3.8 N	96.1 E	51	6.0	-	Indonesia	HKC SMY ADK BRW IMA TTA SVW
35	24 Jan 90	193331	14.6 N	119.5 E	23	5.6	5.7	Philippines	HKC ANM TTA IMA KDC PMR HON
36	1 Feb 90	183354	8.2 N	126.8 E	64	5.3	-	Philippines	HKC MAT IMA PMR
37	8 Feb 90	071532	9.7 N	124.7 E	31	6.2	6.6	Philippines	HKC MAT YSS ADK TTA BRW IMA KDC PMR GUMO FBA
38	17 Feb 90	022800	29.5 N	130.8 E	50	6.1	-	Japan	HKC MAT TTA SVW IMA KDC PMR FBA GOL
39	20 Feb 90	065340	34.7 N	139.4 E	13	6.1	6.4	Japan	TOK GUA HKC ADK TTA SVW IMA BRW KDC PMR FBA TOA ARN KVN CMB GLA ANMO FVM
40	26 Mar 90	224717	9.2 N	125.6 E	40	5.6	5.5	Philippines	HKC MAT ANM SDN SVW BRW IMA FBA TOA

Table 2 - NEIC Epicentral Data and Stations Used for the Verification of EPILAR (cont'd)

Case Number	Date	Origin Time (UTC) HHMMSS	Latitude	Longitude	Depth (km)	Magnitude MB	Magnitude MS	Country/ Area	Stations Used
41	30 Mar 90	004207	20.2 N	122.0 E	128	5.5	-	Luzon Strait	HKC ANM BRW TTA SVW IMA KDC TOA
42	31 Mar 90	193144	42.8 N	147.0 E	34	5.9	5.8	Japan	YSS MAT HKC
43	5 Apr 90	211239	15.2 N	147.5 E	32	6.5	7.5	Western Pacific	MAT PMG YSS HKC SMY ADK OPA HON PFH GUMO TTA IMA PMR BRW FBA SIT MCW RMW ARN KVN
44	6 Apr 90	145723	15.2 N	147.6 E	33	5.8	6.2	Western Pacific	HKC YSS ANM TTA IMA PMR FBA RMW ARN KVN
45	11 Apr 90	205113	35.5 N	135.5 E	369	5.7	-	Japan	HKC SMY ADK ANM SDN TTA SVW BRW IMA KDC PMR FBA TOA MID YKU RMW FHC
46	18 Apr 90	133919	1.2 N	122.8 E	28	6.2	7.4	Indonesia	MAN HKC MAT YSS ANM TTA SVW BRW KDC GUMO IMA FBA PMR TOA SIT
47	26 Apr 90	093719	36.0 N	100.2 E	33	6.6	6.9	China	HKC MAT YSS SMY IMA PMR SIT RMW KVN
48	11 May 90	131020	41.8 N	130.9 E	500	5.7	-	Sea of Japan	HKC MAT SMY ADK ANM SDN BRW TTA SVW IMA KDC FBA PMR TOA MID YKU SIT HON PFH RMW
49	12 May 90	045009	49.0 N	141.9 E	611	6.4	-	Russia	MAT SMY ADK HKC BRW TTA IMA KDC PMR LTCM SIT FHC ORV ARN CMB KVN TNP FBA RSON PKEM
50	25 May 90	020329	3.0 S	130.2 E	33	5.8	5.5	Indonesia	HKC MAT SDN SVW TTA IMA PMR TOA
51	1 Jun 90	012211	35.5 N	140.4 E	62	5.8	-	Japan	HKC MAT IMA PMR ARN KVN FVM ANMO
52	13 Jun 90	024408	9.5 N	138.2 E	20	5.5	5.0	Western Pacific	HKC SDN SVW IMA PMR FBA TOA
53	14 Jun 90	074053	11.3 N	122.2 E	15	6.0	7.0	Philippines	HKC MAT YSS SMY ADK TTA IMA PMR FBA GUMO SIT BMW LON NEW CMB KVN
54	14 Jun 90	124728	47.9 N	85.1 E	54	6.2	6.8	Kazakhstan	HKC YSS MAT SMY ANM IMA ADK TTA FBA SVW PMR TOA SDN NEW LON FHC KVN CMB GOL GLD
55	20 Jun 90	151729	1.1 S	126.8 E	33	5.5	5.8	Indonesia	HKC MAT SMY ADK SDN SVW TTA IMA PMR
56	21 Jun 90	143713	17.7 N	122.3 E	33	5.2	5.0	Philippines	HKC TTA SVW IMA PMR FBA TOA

Table 3 - Geodetic Coordinates of Seismological Stations Handled by EPILAR

Station Name	Station Code	Latitude	Longitude
Mount Abel	ABL	34.8508 N	119.2208 W
Adak	ADK	51.8837 N	176.6844 W
Ahua	AHA	19.3733 N	155.2650 W
Albuquerque	ALQ	34.9425 N	106.4575 W
Alto Anchicaya	ANCC	3.5153 N	76.8667 W
Nome	ANM	64.5655 N	165.3717 W
Albuquerque	ANMO	34.9462 N	106.4567 W
Apache	AP	34.8331 N	98.4358 W
Arnold Ranch	ARN	37.3493 N	121.5327 W
Arcevia	ARV	43.4985 N	12.9421 E
Baguio City	BAG	16.4108 N	120.5797 E
Branch Mt	BCH	35.1850 N	120.0842 W
Bhumibol Dam	BDT	17.2333 N	99.0500 E
Blacksburg	BLA	37.2113 N	80.4210 W
Boistfort Mt	BMW	46.4750 N	123.2281 W
Berlin	BNH	44.5906 N	71.2564 W
Bardonecchia	BNI	45.0527 N	6.6752 E
Bari-Castllana	BRT	40.8778 N	17.2036 E
Barrow	BRW	71.3033 N	156.7483 W
Boulder Array	BW06	42.7778 N	109.5556 W
Caribou	CBM	46.9325 N	68.1208 W
Cheung Chau	CCHK	22.2029 N	114.0243 E
Chiang Mai	CHG	18.7900 N	98.9769 E
Cairo Montenotte	CKI	44.4249 N	8.2799 E
Columbia Col	CMB	38.0350 N	120.3850 E
Charlottesville	CVL	37.9814 N	78.4608 W
Daniels Canyon	DAU	40.4125 N	111.2558 W
Davao City	DAV	7.0878 N	125.5747 E
Doyle Hill	DHN	42.8255 N	78.1930 W
San Damiano	DOI	44.5036 N	7.2454 E
Davenport	DPW	47.8706 N	118.2028 W
Dugway	DUG	40.1950 N	112.8133 W
Elco	ELC	37.2850 N	89.2270 W
East Machias	EMM	44.7329 N	67.4894 W
Fairbanks	FBA	64.9000 N	147.7933 W
Feldberg	FEL	47.8758 N	8.0127 E
Fickle Hill	FHC	40.8017 N	123.9850 W
Fukuoka	FKK	33.5800 N	130.3800 E
Forni Avoltri	FVI	46.5932 N	12.7809 E
French Village	FVM	37.9840 N	90.4260 W
Greenback	GBTN	35.6660 N	84.2110 W
Glamis	GLA	33.0525 N	114.8265 W
Golden	GLD	39.7506 N	105.2214 W
Gambarie	GMB	38.1675 N	15.8633 E
Gold Mt	GMW	47.5479 N	122.7863 W
Golden	GOL	39.7003 N	105.3711 W

Table 3 - Geodetic Coordinates of Seismological Stations Handled by EPILAR (cont'd)

Station Name	Station Code	Latitude	Longitude
Guam	GUA	13.5383 N	144.9117 E
Guam	GUMO	13.5878 N	144.8663 E
Guangzhou	GZH	23.0869 N	113.3439 E
Harts Bluff	HBF	32.9331 N	80.3777 W
Hinesburg	HBVT	44.3623 N	73.0650 W
Hong Kong	HKC	22.3036 N	114.1719 E
Honolulu	HON	21.3217 N	158.0083 W
Horqueta	HOQC	3.4680 N	76.6337 W
Howe Peak	HPI	43.7114 N	113.0972 W
Haystack Lookout	HTW	47.8035 N	121.7691 W
Indian Mt	IMA	66.0685 N	153.6786 W
Jayapura	JAY	2.5000 S	140.6667 E
Jenkinsville	JSC	34.2789 N	81.2581 W
Kaena	KAE	19.2892 N	155.1325 W
Kodiak Island	KDC	57.7478 N	152.4917 W
Kluang	KGM	2.0167 N	103.3181 E
Kipapa Oahu	KIP	21.4233 N	158.0150 E
Kailua-Kona	KKH	19.6642 N	156.0089 W
Kota Kinabalu	KKM	6.0453 N	116.2106 E
Kohala	KOH	20.1282 N	155.7795 W
Kaiserville	KVN	39.0510 N	119.1000 W
Lae	LAT	6.7125 S	146.9903 E
Black Fox	LBFM	41.3470 N	121.8903 W
Lembang	LEM	6.8333 S	107.6167 E
Liberty Hill	LHS	34.4792 N	80.8083 W
Longmire	LON	46.7500 N	121.8100 W
Tuscan Springs	LTCM	40.2083 N	122.1242 W
Isola Levanzo	LVI	37.9856 N	12.3374 E
Long V	LVNJ	40.8095 N	74.7650 W
Manila	MAN	14.6600 N	121.0780 E
Matsushiro	MAT	36.5417 N	138.2089 E
Macau	MCO	22.1219 N	113.5583 E
Mt Constitution	MCW	48.6797 N	122.8323 W
Monti di Nese	MDI	45.7772 N	9.7114 E
Monte Lauro	MEU	37.1011 N	14.9300 E
Maguayo	MGP	18.0076 N	67.0891 W
Morigerati	MGR	40.1376 N	15.5548 E
Middleton I	MID	59.4278 N	146.3388 W
Milo	MIM	45.2436 N	69.0403 W
Makaopuhi	MKA	19.3678 N	155.1642 W
Makassar	MKS	5.0667 S	119.6333 E
Monte Cimone	MME	44.1936 N	10.7000 E
Manado	MNI	1.4500 N	124.8000 E
Mt Sto Tomas	MSP	16.3500 N	120.5612 E
Marysvale	MSU	38.5133 N	112.1742 W
Noress Ar	NARO	60.7353 N	11.5414 E
Narrows	NAV	37.3167 N	47.5833 W
Newport	NEW	48.2633 N	117.1200 W
North Pit	NPH	19.4150 N	160.5143 W
Wright Ranch	NWRM	38.4570 N	122.8877 W

Table 3 - Geodetic Coordinates of Seismological Stations Handled by EPILAR (cont'd)

Station Name	Station Code	Latitude	Longitude
Olyphant	OLY	35.5030 N	91.4700 W
Opana	OPA	21.6906 N	158.0119 W
Oropa	ORO	45.6250 N	7.9803 E
Oroville	ORV	39.5550 N	121.5000 W
Osaka	OSA	34.6783 N	135.5217 E
Perris	PEC	33.8919 N	117.1607 W
Beijing	PEK	40.0403 N	116.1750 E
Pahoa Fire House	PFH	19.4969 N	154.9486 W
Harlau Ranch	PHAM	35.8360 N	120.3985 W
Pisa	PII	43.7212 N	10.5238 E
Potts Junction	PJG	13.5877 N	144.8663 E
Kettleman Hills	PKEM	36.0615 N	120.1090 W
Palomar	PLM	33.3534 N	116.8617 W
Port Moresby	PMG	9.4092 S	147.1539 E
Palmer	PMR	61.5922 N	149.1308 W
Powhatau	POW	36.1520 N	91.1850 W
Papeete	PPT	17.5690 S	149.5742 E
Parsons Mt	PRM	34.0833 N	82.3633 W
Pocatello Cr	PTI	42.8703 N	112.3702 W
Potsdam	PTN	44.5725 N	74.9828 W
Volcan Purace	PURC	2.3222 N	76.3617 W
Port Wells	PWL	60.8593 N	148.3348 W
Raibl	RBL	46.4417 N	13.5683 E
Revere	REVF	43.7400 N	7.3675 E
Rattlesnake Mt	RMW	47.4597 N	121.8053 W
Adirondack	RSNY	44.5483 N	74.5300 W
Red Lake	RSON	50.8589 N	93.7022 W
Black Hills	RSSD	44.1204 N	104.0362 W
Salo	SAL	45.6075 N	10.5262 E
Sapporo	SAP	43.0583 N	141.3317 E
Sand Point	SDN	55.3413 N	160.4972 W
Seoul	SEO	37.5667 N	126.9667 E
Santa Sofia	SFI	43.9210 N	11.8520 E
Sicignano	SGO	40.5583 N	15.3084 E
St George	SGS	33.1927 N	80.5118 W
Mt St Helens	SHW	46.1925 N	122.2367 W
Sitka	SIT	57.0569 N	135.3244 W
San Juan	SJG	18.1120 N	66.1500 W
Shemya	SMY	52.7308 N	174.1031 E
Songkhla	SNG	7.1733 N	100.6200 E
Samo	SOI	38.0721 N	16.0549 E
South Point	SPT	18.9818 N	155.6653 W
Sparrevohu	SVW	61.1082 N	155.6217 W
Table Rock	TBR	41.1417 N	74.2221 W
Terranova Sibari	TDS	39.6588 N	16.3379 E
Tsim Bei Tsui	THK	22.4878 N	114.0093 E
Tuckaleechee	TKL	35.6580 N	83.7740 W

Table 3 - Geodetic Coordinates of Seismological Stations Handled by EPILAR (cont'd)

Station Name	Station Code	Latitude	Longitude
Tangerang	TNG	6.1833 S	106.5000 E
Tonopah	TNP	38.0820 N	117.2180 W
Tolsona	TOA	62.1048 N	146.1723 W
Tokyo	TOK	35.7097 N	139.6972 E
Tatalina	TTA	62.9301 N	156.0116 W
Gordon Buttle	VGB	45.5157 N	120.7775 W
Villa di Villa	VVI	45.9829 N	12.4236 E
Wahaula	WHA	19.3317 N	155.0487 W
Wilmington	WNY	44.3910 N	73.8595 W
Yuen Ng Fan	YHK	22.3792 N	114.3354 E
Yakutat	YKU	59.5531 N	139.7286 W
Yuzh-Sakhalinsk	YSS	47.0167 N	142.7167 W

Table 4 - Verification Results of EPILAR (Operational Version)

Case Number	Date	NEIC Epicentres Latitude	NEIC Epicentres Longitude	EPILAR At L_{min} Latitude	EPILAR At L_{min} Longitude	EPILAR At L_{min} Error (degrees)	EPILAR At 33 km depth Latitude	EPILAR At 33 km depth Longitude	EPILAR At 33 km depth Error (degrees)
1	9 Jul 89	34.9 N	139.4 E	36.2 N	138.7 E	1.42	35.9 N	139.0 E	1.05
2	14 Jul 89	8.1 S	125.1 E	8.4 S	125.2 E	0.32	8.4 S	125.2 E	0.32
3	21 Jul 89	30.0 N	99.5 E	28.5 N	97.7 E	2.17	28.3 N	97.5 E	2.44
4	22 Jul 89	2.3 N	128.1 E	3.8 N	128.8 E	1.66	3.4 N	128.9 E	1.36
5	31 Jul 89	8.0 S	121.4 E	5.5 S	122.2 E	2.62	6.6 S	121.9 E	1.49
6	2 Aug 89	2.8 N	96.1 E	1.0 N	96.6 E	1.87	1.0 N	96.7 E	1.90
7	3 Aug 89	23.0 N	122.0 E	24.1 N	121.4 E	1.23	24.1 N	121.3 E	1.27
8	6 Aug 89	1.9 N	128.3 E	4.6 N	129.6 E	3.00	4.6 N	129.6 E	3.00
9	12 Aug 89	0.8 N	126.8 E	4.9 N	127.3 E	4.13	4.9 N	127.3 E	4.13
10	12 Aug 89	8.7 N	125.7 E	10.6 N	126.1 E	1.94	9.8 N	126.4 E	1.30
11	21 Aug 89	24.1 N	122.5 E	24.2 N	122.4 E	0.14	24.2 N	122.3 E	0.21
12	6 Sep 89	1.0 N	126.1 E	2.7 N	125.9 E	1.71	1.4 N	126.1 E	0.40
13	22 Sep 89	31.6 N	102.4 E	30.5 N	100.8 E	1.76	30.5 N	100.8 E	1.76
14	25 Oct 89	57.5 N	118.8 E	57.9 N	121.8 E	1.65	57.2 N	120.5 E	0.97
15	26 Oct 89	39.8 N	143.5 E	39.7 N	143.7 E	0.18	39.7 N	143.6 E	0.12
16	27 Oct 89	39.8 N	143.7 E	40.0 N	143.3 E	0.37	40.0 N	143.3 E	0.37
17	29 Oct 89	39.6 N	143.3 E	39.3 N	143.2 E	0.31	39.6 N	143.0 E	0.23
18	29 Oct 89	39.5 N	143.4 E	39.5 N	143.2 E	0.15	39.5 N	143.2 E	0.15
19	1 Nov 89	2.5 N	128.1 E	3.3 N	128.6 E	0.94	3.4 N	128.6 E	1.03
20	1 Nov 89	39.8 N	142.8 E	39.3 N	143.1 E	0.55	39.3 N	143.1 E	0.55
21	4 Nov 89	39.1 N	143.4 E	39.7 N	142.5 E	0.92	39.7 N	142.5 E	0.92
22	6 Nov 89	25.7 N	125.6 E	22.6 N	126.8 E	3.29	23.1 N	126.9 E	2.86
23	14 Nov 89	10.1 N	126.5 E	8.9 N	126.0 E	1.30	4.4 N	123.7 E	1.30
24	8 Dec 89	10.1 N	126.5 E	13.1 N	125.8 E	3.08	11.2 N	126.7 E	3.08
25	9 Dec 89	0.1 N	123.3 E	0.6 N	124.2 E	1.03	0.3 N	124.2 E	1.03
26	15 Dec 89	8.3 N	126.7 E	8.9 N	127.3 E	0.84	8.6 N	127.2 E	0.84
27	16 Dec 89	8.0 N	126.9 E	8.6 N	126.8 E	0.61	8.6 N	126.7 E	0.61
28	20 Dec 89	8.1 N	126.8 E	9.0 N	127.2 E	0.98	9.1 N	127.2 E	0.98
29	20 Dec 89	8.2 N	126.9 E	9.3 N	127.4 E	1.21	9.3 N	127.3 E	1.21
30	23 Dec 89	17.4 N	145.8 E	18.5 N	145.4 E	1.16	17.9 N	145.9 E	1.16

Table 4 - Verification Results of EPILAR (Operational Version) (cont'd)

		NEIC Epicentres		EPILAR Epicentres					
				At L_{min}			At 33 km depth		
Case Number	Date	Latitude	Longitude	Latitude	Longitude	Error (degrees)	Latitude	Longitude	Error (degrees)
31	10 Jan 90	11.6 N	95.2 E	30.5 N	118.7 E	28.81	30.4 N	119.0 E	28.98
32	12 Jan 90	5.0 N	126.5 E	0.3 S	123.0 E	6.35	0.3 S	123.0 E	6.35
33	14 Jan 90	37.8 N	91.9 E	38.1 N	93.2 E	1.07	38.1 N	93.2 E	1.07
34	22 Jan 90	3.8 N	96.1 E	4.9 N	96.9 E	1.36	3.3 N	96.9 E	0.54
35	24 Jan 90	14.6 N	119.5 E	18.3 N	119.8 E	3.71	11.2 N	110.2 E	9.68
36	1 Feb 90	8.2 N	126.8 E	9.2 N	127.1 E	1.04	9.4 N	127.1 E	1.24
37	8 Feb 90	9.7 N	124.7 E	10.5 N	124.6 E	0.81	10.0 N	124.8 E	0.32
38	17 Feb 90	29.5 N	130.8 E	29.6 N	130.6 E	0.20	30.1 N	130.2 E	0.79
39	20 Feb 90	34.7 N	139.4 E	34.5 N	139.2 E	0.26	34.6 N	139.1 E	0.27
40	26 Mar 90	9.2 N	125.6 E	10.2 N	126.1 E	1.12	10.2 N	126.1 E	1.12
41	30 Mar 90	20.2 N	122.0 E	20.6 N	122.5 E	0.62	20.5 N	122.5 E	0.56
42	31 Mar 90	42.8 N	147.0 E	44.1 N	142.2 E	3.72	43.2 N	144.6 E	1.80
43	5 Apr 90	15.2 N	147.5 E	15.1 N	147.6 E	0.14	15.1 N	147.5 E	0.10
44	6 Apr 90	15.2 N	147.6 E	16.0 N	147.5 E	0.81	16.0 N	147.4 E	0.82
45	11 Apr 90	35.5 N	135.5 E	35.4 N	135.7 E	0.19	35.4 N	136.0 E	0.42
46	18 Apr 90	1.2 N	122.8 E	2.8 N	123.4 E	1.71	1.7 N	123.1 E	0.58
47	26 Apr 90	36.0 N	100.2 E	35.7 N	100.3 E	0.31	35.7 N	100.4 E	0.34
48	11 May 90	41.8 N	130.9 E	41.8 N	130.8 E	0.06	43.7 N	128.5 E	2.59
49	12 May 90	49.0 N	141.9 E	49.1 N	142.0 E	0.11	50.9 N	140.3 E	2.16
50	25 May 90	3.0 S	130.2 E	1.4 S	131.6 E	2.13	1.7 S	131.7 E	1.98
51	1 Jun 90	35.5 N	140.4 E	35.2 N	140.7 E	0.39	35.3 N	140.7 E	0.26
52	13 Jun 90	9.5 N	138.2 E	7.9 N	138.2 E	1.60	5.2 N	138.2 E	4.30
53	14 Jun 90	11.3 N	122.2 E	12.0 N	122.2 E	0.70	11.6 N	122.2 E	0.30
54	14 Jun 90	47.9 N	85.1 E	48.2 N	85.5 E	0.40	48.2 N	85.6 E	0.45
55	20 Jun 90	1.1 S	126.8 E	2.3 N	126.9 E	3.40	0.7 S	127.4 E	0.72
56	21 Jun 90	17.7 N	122.3 E	19.6 N	122.8 E	1.96	17.0 N	121.9 E	0.80

	At L_{min}	At 33 km depth
Maximum	28.81	28.98
Minimum	0.06	0.10
Mean	1.89	1.94
Standard Deviation	3.85	4.04

Table 5 - Comparison of P-times Extracted from the Real-time Earthquake Messages and those Derived from the J-B Seismological Tables for Case 31

Station Code	Latitude	Longitude	Distance from epicentre (degrees)	P-time Extracted from Messages (UTC) HHMMSS.S	P-time Derived from J-B Tables (UTC) HHMMSS.S	Difference (seconds)
HKC	22.30 N	114.17 E	21.0	115805.5	115803.9	1.6
BRW	71.30 N	156.75 W	84.6	120554.0	120552.3	1.7
IMA	66.07 N	153.68 W	87.6	120609.5	120607.0	2.5
PMR	61.59 N	149.13 W	91.4	120626.7	120624.9	1.8
FBA	64.90 N	147.79 W	90.3	120627.8	120619.8	8.0

Table 6 - Verification Results of EPILAR (Modified Version)

Case Number	Date	NEIC Epicentres Latitude	NEIC Epicentres Longitude	EPILAR At L_{min} Latitude	EPILAR At L_{min} Longitude	EPILAR At L_{min} Error (degrees)	EPILAR At 33 km depth Latitude	EPILAR At 33 km depth Longitude	EPILAR At 33 km depth Error (degrees)
1	9 Jul 89	34.9 N	139.4 E	36.2 N	138.7 E	1.42	35.9 N	139.0 E	1.05
2	14 Jul 89	8.1 S	125.1 E	8.4 S	125.2 E	0.32	8.4 S	125.2 E	0.32
3	21 Jul 89	30.0 N	99.5 E	28.5 N	97.7 E	2.17	28.3 N	97.5 E	2.44
4	22 Jul 89	2.3 N	128.1 E	3.7 N	128.6 E	1.49	3.2 N	128.8 E	1.14
5	31 Jul 89	8.0 S	121.4 E	5.5 S	122.2 E	2.62	6.6 S	121.9 E	1.49
6	2 Aug 89	2.8 N	96.1 E	1.0 N	96.6 E	1.87	1.0 N	96.7 E	1.90
7	3 Aug 89	23.0 N	122.0 E	24.1 N	121.4 E	1.23	24.1 N	121.3 E	1.27
8	6 Aug 89	1.9 N	128.3 E	4.6 N	129.6 E	3.00	4.6 N	129.6 E	3.00
9	12 Aug 89	0.8 N	126.8 E	4.9 N	127.3 E	4.13	4.9 N	127.3 E	4.13
10	12 Aug 89	8.7 N	125.7 E	10.6 N	126.1 E	1.94	9.8 N	126.4 E	1.30
11	21 Aug 89	24.1 N	122.5 E	24.2 N	122.4 E	0.14	24.1 N	122.4 E	0.09
12	6 Sep 89	1.0 N	126.1 E	2.7 N	125.9 E	1.71	1.4 N	126.1 E	0.40
13	22 Sep 89	31.6 N	102.4 E	30.5 N	100.8 E	1.76	30.5 N	100.8 E	1.76
14	25 Oct 89	57.5 N	118.8 E	57.9 N	121.9 E	1.70	57.2 N	120.5 E	0.97
15	26 Oct 89	39.8 N	143.5 E	39.7 N	143.7 E	0.18	39.7 N	143.6 E	0.12
16	27 Oct 89	39.8 N	143.7 E	40.0 N	143.3 E	0.37	40.0 N	143.3 E	0.37
17	29 Oct 89	39.6 N	143.3 E	40.0 N	142.8 E	0.55	39.6 N	143.0 E	0.23
18	29 Oct 89	39.5 N	143.4 E	39.5 N	143.2 E	0.15	39.5 N	143.2 E	0.15
19	1 Nov 89	2.5 N	128.1 E	3.2 N	128.6 E	0.94	3.4 N	128.6 E	1.03
20	1 Nov 89	39.8 N	142.8 E	39.3 N	143.1 E	0.55	39.3 N	143.1 E	0.55
21	4 Nov 89	39.1 N	143.4 E	39.7 N	142.5 E	0.92	39.7 N	142.5 E	0.92
22	6 Nov 89	25.7 N	125.6 E	22.6 N	126.8 E	3.29	23.1 N	126.9 E	2.86
23	14 Nov 89	10.1 N	126.5 E	9.2 N	125.8 E	1.13	9.0 N	126.4 E	1.11
24	8 Dec 89	10.1 N	126.5 E	13.1 N	125.8 E	3.08	11.2 N	126.7 E	1.12
25	9 Dec 89	0.1 N	123.3 E	0.6 N	124.2 E	1.03	0.3 N	124.2 E	0.92
26	15 Dec 89	8.3 N	126.7 E	8.9 N	127.3 E	0.84	8.6 N	127.2 E	0.58
27	16 Dec 89	8.0 N	126.9 E	8.6 N	126.8 E	0.61	8.6 N	126.7 E	0.63
28	20 Dec 89	8.1 N	126.8 E	9.0 N	127.2 E	0.98	9.1 N	127.2 E	1.08
29	20 Dec 89	8.2 N	126.9 E	9.3 N	127.4 E	1.21	9.3 N	127.3 E	1.17
30	23 Dec 89	17.4 N	145.8 E	18.5 N	145.4 E	1.16	17.9 N	145.9 E	0.51

Table 6 - Verification Results of EPILAR (Modified Version) (cont'd)

		NEIC Epicentres		EPILAR Epicentres					
				At L_{min}			At 33 km depth		
Case Number	Date	Latitude	Longitude	Latitude	Longitude	Error (degrees)	Latitude	Longitude	Error (degrees)
31	10 Jan 90	11.6 N	95.2 E	13.7 N	95.7 E	2.16	13.3 N	95.1 E	1.70
32	12 Jan 90	5.0 N	126.5 E	0.1 S	122.5 E	6.48	8.4 N	127.9 E	3.67
33	14 Jan 90	37.8 N	91.9 E	38.1 N	93.1 E	0.99	38.1 N	93.2 E	1.07
34	22 Jan 90	3.8 N	96.1 E	4.7 N	97.0 E	1.27	3.3 N	96.9 E	0.54
35	24 Jan 90	14.6 N	119.5 E	18.3 N	119.8 E	3.71	18.6 N	120.7 E	4.16
36	1 Feb 90	8.2 N	126.8 E	9.2 N	127.1 E	1.04	9.4 N	127.1 E	1.24
37	8 Feb 90	9.7 N	124.7 E	10.5 N	124.6 E	0.81	10.0 N	124.8 E	0.32
38	17 Feb 90	29.5 N	130.8 E	29.6 N	130.6 E	0.20	30.1 N	130.2 E	0.79
39	20 Feb 90	34.7 N	139.4 E	34.6 N	139.1 E	0.27	34.6 N	139.1 E	0.27
40	26 Mar 90	9.2 N	125.6 E	10.2 N	126.1 E	1.12	10.2 N	126.1 E	1.12
41	30 Mar 90	20.2 N	122.0 E	20.6 N	122.5 E	0.62	20.5 N	122.5 E	0.56
42	31 Mar 90	42.8 N	147.0 E	43.2 N	144.5 E	1.87	43.2 N	144.6 E	1.80
43	5 Apr 90	15.2 N	147.5 E	15.0 N	147.7 E	0.28	15.0 N	147.6 E	0.22
44	6 Apr 90	15.2 N	147.6 E	16.0 N	147.5 E	0.81	16.0 N	147.4 E	0.82
45	11 Apr 90	35.5 N	135.5 E	35.4 N	135.7 E	0.19	35.4 N	136.0 E	0.42
46	18 Apr 90	1.2 N	122.8 E	2.8 N	123.4 E	1.71	1.7 N	123.1 E	0.58
47	26 Apr 90	36.0 N	100.2 E	35.8 N	100.3 E	0.22	35.7 N	100.4 E	0.34
48	11 May 90	41.8 N	130.9 E	41.8 N	130.8 E	0.06	43.7 N	128.5 E	2.59
49	12 May 90	49.0 N	141.9 E	49.1 N	142.0 E	0.11	50.9 N	140.3 E	2.16
50	25 May 90	3.0 S	130.2 E	1.4 S	131.6 E	2.13	1.7 S	131.7 E	1.98
51	1 Jun 90	35.5 N	140.4 E	35.2 N	140.7 E	0.39	35.3 N	140.7 E	0.26
52	13 Jun 90	9.5 N	138.2 E	7.7 N	138.3 E	1.80	7.6 N	138.3 E	1.90
53	14 Jun 90	11.3 N	122.2 E	12.0 N	122.2 E	0.70	11.6 N	122.2 E	0.30
54	14 Jun 90	47.9 N	85.1 E	48.2 N	85.5 E	0.40	48.2 N	85.6 E	0.45
55	20 Jun 90	1.1 S	126.8 E	2.3 N	126.9 E	3.40	0.7 S	127.4 E	0.72
56	21 Jun 90	17.7 N	122.3 E	19.6 N	122.8 E	1.96	17.0 N	121.9 E	0.80

	At L_{min}	At 33 km depth
Maximum	= 6.48	= 4.16
Minimum	= 0.06	= 0.09
Mean	= 1.38	= 1.17
Standard Deviation	= 1.20	= 0.97

Table 7 - List of Locally Felt Earthquakes for Verification of the Modified EPILAR

Date	Origin Time (HKT) HHMMSS	Latitude	Longitude	Depth (km)	Magnitude MB	Magnitude MS	Country/ Area
18 Jun 80	173221	22.0 N	121.4 E	71	5.7	-	Off east coast of Taiwan
24 Jun 83	151822	21.8 N	103.3 E	18	6.0	6.5	Northern Vietnam near Yunnan border
24 Apr 85	001511	15.3 N	120.6 E	181	6.3	-	Central Luzon
19 Feb 86	194023	19.0 N	121.4 E	39	5.7	5.8	Balintang Channel
25 Apr 87	201649	15.9 N	120.3 E	111	6.1	-	West coast of Luzon

Table 8 - Verification Results of EPILAR (Modified Version) for Five Locally Felt Earthquakes

	ISC Epicentres		EPILAR Epicentres					
			At L_{min}			At 33 km depth		
Date	Latitude	Longitude	Latitude	Longitude	Error (degrees)	Latitude	Longitude	Error (degrees)
18 Jun 80	22.0 N	121.4 E	22.2 N	120.8 E	0.59	22.3 N	121.3 E	0.31
24 Jun 83	21.8 N	103.3 E	22.2 N	105.4 E	1.20	21.7 N	103.8 E	0.47
24 Apr 85	15.3 N	120.6 E	16.0 N	121.0 E	0.80	16.5 N	121.7 E	1.60
19 Feb 86	19.0 N	121.4 E	19.6 N	121.7 E	0.66	19.5 N	121.3 E	0.51
25 Apr 87	15.9 N	120.3 E	16.7 N	120.9 E	0.99	16.7 N	120.9 E	0.99
			Maximum		= 1.20	Maximum		= 1.60
			Minimum		= 0.59	Minimum		= 0.31
			Mean		= 0.85	Mean		= 0.78
			Standard Deviation		= 0.22	Standard Deviation		= 0.47

Table 9 - Verification Results of EPILAR (Operational Version) for Five Locally Felt Earthquakes

	ISC Epicentres		EPILAR Epicentres					
			At L_{min}			At 33 km depth		
Date	Latitude	Longitude	Latitude	Longitude	Error (degrees)	Latitude	Longitude	Error (degrees)
18 Jun 80	22.0 N	121.4 E	22.2 N	120.8 E	0.59	22.3 N	121.3 E	0.31
24 Jun 83	21.8 N	103.3 E	22.2 N	105.4 E	1.20	21.7 N	103.8 E	0.47
24 Apr 85	15.3 N	120.6 E	14.5 N	118.9 E	1.83	0.9 N	103.6 E	22.12
19 Feb 86	19.0 N	121.4 E	19.6 N	121.7 E	0.66	19.5 N	121.3 E	0.51
25 Apr 87	15.9 N	120.3 E	14.6 N	117.7 E	2.83	4.4 N	105.0 E	18.93
			Maximum		= 2.83	Maximum		= 22.12
			Minimum		= 0.59	Minimum		= 0.31
			Mean		= 1.42	Mean		= 8.47
			Standard Deviation		= 0.83	Standard Deviation		= 9.90