ATOMIC WEAPONS ESTABLISHMENT ALDERMASTON

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Earthquake Detection Statistics at Short Period Stations Using a Historical Data File (UK UNCLASSIFIED)

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CONTENTS

SUMMARY

Earthquake locations published by the International Seismological Centre (ISC) for the period 1964-83, together with recomputed magnitudes, are used to successfully predict the observed numbers and amplitudes of detected short period P waves at a selection of stations. Neglecting the contribution of "near regional" (Δ = 0 to 5°) seismicity and assuming identical detection thresholds, detection counts vary by more than a factor of 3 depending on global location. Estimated detection numbers at sites with low noise at short periods vary between 20 to 60 per day. For a station in a seismically active region, rough calculation suggests that nearby activity may double these figures provided the overall reporting threshold is $m_b 2.5$.

1. INTRODUCTION

The number and amplitudes of seismic disturbances detected at a seismological station depend on many factors. These include the magnitude distribution of both natural and man-made seismic sources, their spatial distribution with respect to the station, the effect of earth structure on seismic wave propagation to the station, and the presence of noise on the final recordings.

The logarithmic increase in earthquake numbers with decreasing magnitude predicted by the empirical Gutenberg-Richter (1) distribution suggests that detections should also increase without limit at smaller amplitudes. Noise reduces the ability to observe small signals however and ultimately results in a fall-off in detections. This ability is usually quantified by the station's detection threshold which at new station sites must be inferred from noise measurements (eg, appendix A). For existing stations, assuming the Gutenberg-Richter distribution is valid, the method of Kelly and Lacoss (2) can be used to estimate thresholds directly from the observed amplitude statistics. Conversely if the detection threshold is given and the factors outlined above are known, in principle it is possible to predict the amplitude distribution of detected signals.

In this report ISC earthquake locations for the period 1964-83, together with the maximum likelihood magnitudes, are used to estimate the amplitude distribution and total number of P wave detections at a selection of stations for which observational data is available. Agreement between predicted and observed statistics should provide confidence in the methods and data used. Reliable estimates of these statistics as a function of station location can be used to estimate data flow from any future global monitoring network such as proposed by the Group of Scientific Experts in Geneva (3).

2. THEORY

Seismicity is often quantified in terms of the Gutenberg and Richter (1) empirical magnitude frequency station:

$$\mathrm{Log}_{10} N_C = a - bm \quad \text{... (1)}$$

where N_C is the number of earthquakes with magnitude greater than or equal to m. Changing to the exponential form this is written:

$$\mathrm{Log}\, N_C = \alpha - \beta m$$

or

$$N_C = \exp(\alpha - \beta m) \quad \text{... (2)}$$

The "rate constants" (α,a) and "b values" (β,b) are related by

$$\beta = b\, \mathrm{Log}_e 10$$

$$\alpha = a\, \mathrm{Log}_e 10 \quad \text{... (3)}$$

The interval form of the magnitude frequency relation is obtained by differentiating the cumulative form (2). Hence the interval number of earthquakes N_I between magnitude m and m + δm is

$$N_I(m, m + \delta m) = -\,\delta N_C = \beta \exp(\alpha - \beta m)\, \delta m \quad \text{... (4)}$$

The ground amplitude of the SP P waves from a disturbance at distance Δ and depth h with body wave magnitude m_b are related in terms of the equation

$$m_b = A + Q(\Delta, h) - S \quad \text{... (5)}$$

where A is Log Ag/T; Ag is the ground displacement in nm; T the period in seconds; $Q(\Delta,h)$ the magnitude calibration function; S an (optional) station term.

If we consider a source of earthquakes, all at depth h, distance Δ, which follow the magnitude frequency distribution equation (4) then from equation (5) the interval distribution for the amplitudes is

$$N_I(A, A + \delta A) = \beta \exp(\alpha - \beta Q(\Delta,h) + \beta S) \exp(-\beta A)\, \delta A \quad \text{... (6)}$$

For a set of M sources with the ith source at depth h_i and distance Δ_i the resulting interval number is

$$N_I(A, A + \delta A) = \sum_{i=1}^{i=M} \beta \exp(\alpha_i - \beta Q(\Delta_i, h_i) + \beta S) \exp^{-\beta A} \delta A; \quad \text{... (7)}$$

assuming β is constant for all sources. Equation (7) shows that the signal amplitudes A follow the same exponential distribution as the magnitude frequency distribution equation (4). To obtain the numbers <u>detected</u> at a given location equation (7) must be multiplied by the probability Prob(A det) that an amplitude A is detected. Hence the interval number detected $N_D(A, A + \delta A)$ is given by

$$N_D(A, A + \delta A) = N_I(A, A + \delta A)\ \mathrm{Prob}(A\ \mathrm{det}) \quad \text{... (8)}$$

The total number of detections (per annum) follows by integrating over all amplitudes A. From equations (7) and (8)

$$N_{tot} = \sum_{i=1}^{i=M} \beta \exp(\alpha_i - \beta Q(\Delta_i, h_i) + \beta S) \int_{-\infty}^{\infty} \text{Prob}(A \text{ det}) \exp^{-\beta A} dA \quad \ldots (9)$$

Whether or not a signal is detected by a station is determined by the detection threshold which varies both spatially and in time. This variation is usually expressed in terms of a mean (50%) threshold μ and its standard deviation (SD) γ. If the detection threshold is assumed normally distributed then the probability Prob(A det) of detecting an amplitude A can be written

$$\text{Prob}(A \text{ det}) = \frac{1}{\sqrt{2\pi}\gamma} \int_{-\infty}^{A} \exp - \left[\frac{(X - \mu)^2}{2\gamma^2}\right] dX = \Phi\ (\mu, \gamma, A) \quad \ldots (10)$$

If the threshold parameters μ and γ are specified then an estimate of the number of detections at a station can be made using equation (9) provided the distance and depth of each seismic source (Δ_i, h_i) and the seismicity constants (α_i, β) are known. A simple procedure is to use the observed historical seismicity, each past hypocentre locating a source having the magnitude frequency distribution equation (2). If the seismic record is over Y years and is complete with unbiased magnitudes in the range m_1 to m_2, then each of the M hypocentres can be regarded as a source of 1/Y earthquakes a year following the distribution equation (2). The rate constant α_i is the same for all i and can be obtained using the relation

$$\frac{1}{Y} = \exp(\alpha_i - \beta m_1) - \exp(\alpha_i - \beta m_2)$$

ie, $$\alpha_i = - \text{Log}_e[Y\{\exp(- \beta m_1) - \exp(- \beta m_2)\}] \quad \ldots (11)$$

Since Δ_i and h_i are known then the distribution of amplitudes and their total number can be estimated using equations (8) and (9) respectively using an assumed value of β.

The theory outlined above is applicable to SP narrow band instrumentation and it is assumed that equation (5) successfully predicts observed amplitudes from m_b values. For most stations which report amplitudes to the ISC this assumption appears valid over most epicentral distances, but as figure 1 reveals, at short distances ($<5^{\circ}$) higher frequencies become increasingly important. Experience with the NORESS array (4) suggests that for propagation over shield regions over distances up to 1500 km, optimum detection thresholds occur at higher frequencies than the SP (1 to 2 Hz) band. Extension of the theory to include detection of near regional disturbances especially at higher (>2 Hz) frequencies is not attempted here, however, for several reasons. First the theory would have to take account of the source spectrum scaling law and the variation with frequency of the threshold parameters (μ, γ) and calibration function $Q(\Delta, h)$. None of these have been confidently established and will vary regionally. Furthermore to evaluate the contribution of near regional activity, extrapolation of the magnitude frequency law from the observational range m_b5.0 to 6.0 to less than m_b0.0 is required. For seismically active areas the large numbers arising from such extrapolation are extremely sensitive to the exact disposition of the sources and the form of the function $Q(\Delta,h)$. With these considerations in mind, analysis here is restricted to teleseismic and regional arrivals as observed on narrow band SP instruments.

3. COMPARISON OF PREDICTED AND OBSERVED DETECTION STATISTICS

A test of the above theory can be made by comparing the predicted station detection statistics with those observed by a sample of stations. Amplitude statistics published in an earlier report (5) provide a convenient dataset: these are for the large aperture NORSAR array (NAO) in Norway; the medium aperture arrays at Eskdalemuir (EKA) Scotland, Gauribidanur (GBA) India, Warramunga (WRA) Australia; and the small "VELA" array BMO in the USA. Amplitude frequency distributions of detections from all these stations have the general form expected from equations (8) and (10) above and values of b, μ and γ have been estimated using the method of Kelly and Lacoss in (2). These parameters are listed in table 1. To estimate the amplitude frequency distributions the distribution of potential seismic sources around each station, amplitude calibration factors and station terms S_j are required.

Hypocentres determined by the ISC provide the best available global definition of seismic sources. The hypocentres that can be used are those for earthquakes with magnitudes within the range m_{min} to m_{max} over which the catalogue is assumed complete and the associated values of m_b unbiased. Two sets of magnitude determinations were tried; the m_b values given by the ISC and those of Lilwall and Neary (6) computed using Ringdal's (7,8) maximum-likelihood procedure. For these two sets the ranges m_{min}-m_{max} are 4.95 to 6.25 and 4.8 to 6.2 respectively, the differences reflecting a rounding of 0.1 units and a positive bias in those of the ISC compared with the maximum-likelihood determinations. The world distribution of the earthquakes used is illustrated in figure 2. Suspected nuclear explosions have been deleted and the contribution of other man-made disturbances is effectively removed by the use of the lower threshold of around m_b4.8.

Amplitude calibration factors $Q(\Delta,h)$ are required for the total range of focal depth (0 to 800 km) and distance (0 to 180°). For teleseismic distances (30 to 180°) the curves published by Lilwall (9) are used here because they cover most of the range used for the maximum-likelihood m_b determinations, and also have been baselined to the Gutenberg and Richter (1) factors used by the ISC. At shorter distances the Veith-Clawson (10) factors are used subject to a rebaselining to give equivalent values for both sets at 30°. Station terms (S_j) applied at teleseismic distances (30 to 180°) correspond to those published in Lilwall (9) and are reproduced in table 1.

Estimated and observed detection counts are compared in table 1. Average detection numbers are overestimated by 50% where the ISC m_b magnitudes are used. For the maximum-likelihood magnitudes the estimated counts are in good agreement with the observed - they are on average only 8% less - confirming both that the method is valid and that the magnitudes are relatively unbiased. The largest differences are for Warramunga (WRA) Australia where the observed counts are 30% higher than the estimated (see also figure 7). It is noticeable that seismicity is concentrated at relatively short distances from WRA and in particular within 30° where the Veith and Clawson (10) calibration function $Q(\Delta,h)$ is likely to be in error. An average bias of only 0.12 units in values of $Q(\Delta,h)$ or the station term S would account for the 30% discrepancy.

The parameters b, γ and μ used so far, correspond to a best (maximum-likelihood) fit to the observational data for each individual station (5). Table 1 and figures 3 to 7 also show the results obtained for a compromise value for b and two values of γ. The value 0.95 chosen for b is the mean value obtained for the 5 stations by Lilwall and Douglas (5) and is higher than found for the largest arrays but somewhat lower than the median (0.98) found for a more comprehensive suite of (mostly non-array) stations. For γ the two values 0.20 and 0.25 reflect its observed variation (Ringdal (8), Lilwall and Neary (6)). For both pairs of (b, γ) μ is adjusted to the observational data using the Kelly and Lacoss (2) method. For (b, γ) = (0.95,0.20) the average estimated count (table 1) is 9% higher than observed whereas for (b, γ) = (0.95,0.25) it is 1% low. These statistics and the full detection curves illustrated in figures 3 to 7 indicate that satisfactory estimates of the observations are obtained over the range of values for γ and b tried.

4. GLOBAL VARIATION IN DETECTION STATISTICS

Estimates of the number of earthquake detections as a function of station detection threshold and global location is useful in the planning for dataflow from any future network for verifying a test ban treaty. Such estimates can easily be produced using the methods described above given values for b, the station threshold constants (μ, γ), and the station term S_j.

For b and γ, values of 0.95 and 0.25 are appropriate since they give the lowest average error in estimated counts for the sample of stations studied in the previous section. The value assumed for the mean threshold μ is important as it is determined by station noise levels which vary with location. Fortunately the form of equations (9) and (10) enable the results for alternative thresholds to be computed easily and a value of 1.0 (LogA/T units) is arbitrarily chosen here. This corresponds to a background noise level of 5 nm at one second period assuming 50% detection at a signal to noise ratio of 2:1 (see appendix A). Noise levels of 5 nm or less may be present at central continental sites, but microseismic noise near continental margins, means that arrays are necessary to effectively achieve this value (eg, EKA in appendix A). The station term S is assumed to be zero but, results for alternative values can easily be inferred using equation 9.

Figure 8 illustrates the contoured detection counts for a hypothetical station assuming values of 0.95, 1.0 and 0.25 for b, μ and γ respectively. The contours are based on individual counts computed for points on a grid each separated by approximately 10°. Results for oceanic locations are not included because the noise amplitude at one second is unlikely anywhere to be 5 nm or less. The contributions of sources at distances less than 5° have been omitted for the reasons already discussed and hence figure 8 will not reflect the true counts for stations situated within highly active regions. With this proviso figure 8 indicates that at most locations a station will detect about 1000 to 1500 earthquakes pa ie, 3 to 5 per day (pd). Globally this number varies by a factor of more than 3, however, with less than 750 pa in parts of Africa compared with greater than 2250 pa in SE Asia and N Australia. This difference reflects the location of the Circum-Pacific Seismic Belt with respect to the peaks and troughs of the amplitude distance curves. In the case of a central African station for instance, although most of the earth's continental landmass is within 95° nearly all the Circum-Pacific Belt falls within the core shadow.

Results for an alternative detection threshold μ can easily be deduced. Assuming b is near unity (ie, $\beta = 2.3$) then for equations (9) and (10) the Log_{10} counts can be found by simply subtracting the change in the threshold. For example a threshold μ of zero, representing the quietest station sites known, would result in an order of magnitude increase in the detections illustrated in figure 8. Such stations would generate data corresponding to 7500 to 22500 earthquakes pa (20 to 60 pd) depending on their location.

5. DISCUSSION

The results described give realistic estimates of the data flow expected from narrowband SP instruments situated in regions where local seismicity can be neglected. In seismically active areas large numbers of nearby earthquakes with magnitudes down to below zero magnitude are often recorded and their number may be many times that arising from more distant but probably more significant activity. In extreme cases where intense swarm activity occurs very near to a station, numbers can reach several thousand per day (eg, reference 13). Even in seismically quiet regions disturbances originating from mining and quarrying are often detected in large numbers especially if frequencies above the conventional SP passband are used. The use of high frequency recording at the NORESS array in Norway for example results in the detection of about 40,000 disturbances annually, mostly nearby (11). In the United Kingdom disturbances are observed at a rate of 10,000 pa on a high frequency (2 to 15 Hz bandpass) channel at the Eskdalemuir array (12). Nearly all can be shown to originate from human activity at epicentral distances of less than 500 km. Magnitudes are generally small and only 2% exceed $m_b 2.5$ or equivalent.

The above considerations indicate that for a global monitoring system, involving exchange of data on all detected signals, data flows arising from small disturbances adjacent to stations may exceed those arising from more distant activity by over an order of magnitude. Provided continuous recordings are available if required some procedure to reduce this flow is desirable. The use of a magnitude threshold, below which disturbances are not routinely reported, is a possible solution.

Where chemical explosions are the dominant local seismic disturbances then the number of signals exceeding a given threshold will depend on the nature of the human activities. The Eskdalemuir observations suggest that a $m_b 2.5$ reporting threshold would result in a substantial reduction in numbers to values below those originating from disturbances at larger distances (ie, roughly 200 locals pa compared with 1000 pa at larger distances). In the UK this threshold corresponds to tamped chemical explosions of approximately 10 tonnes (14).

It is useful to ascertain the extent that such a reporting regime would have in reducing the reported detections from a station situated in a seismically active belt. Approximate numbers can be inferred from the total number of earthquakes exceeding $m_b 2.5$ annually. Downward extrapolation of the world magnitude-frequency curves published by Lilwall and Douglas (5) and Ringdal (8) indicates that 150,000 to 250,000 such earthquakes occur each year. Assuming the higher count and that all occur uniformly on the Circum-Pacific and Alpine Belts (length $\simeq$ 50,000 km) then on average some 20,000 pa would be expected within 2,000 km of any point. Assuming 100% detection of these earthquakes (unlikely in tectonically disturbed zones) then the number is similar in magnitude to the maximum arising from more distant seismicity envisaged in the previous section. The use of an m_b2.5 threshold should therefore keep the average quantity of data resulting from near regional activity to within reasonable limits.

6. ACKNOWLEDGEMENTS

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APPENDIX A

COMPARISON OF 50% DETECTION THRESHOLDS AND NOISE MEASUREMENTS

In figure 9 detection thresholds and noise statistics for the array stations at WRA Australia and EKA Scotland are compared. The 50% detection thresholds are computed using the method of Kelly and Lacoss (2) based on amplitudes measured for detections made automatically by the on-line station processors (15). The noise data for one second periods and are the average of rms values measured on the best beam signals for 30 s prior to the detections.

An annual variation for EKA is noticeable and probably accounts for the relatively large value of the threshold standard deviation found for this station (0.28 for EKA compared with 0.19 for WRA - see table 1). The separation of the noise values from the 50% thresholds is 0.2 to 0.3 Log(A/T) units and provides a useful rule relating these quantities, at least for automatic event detectors.

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Table 1

Station Code In figures 3 to 6	Station Term	b Value	Threshold Parameters		Estimated Annual No. of Detections using m_b's computed by		Observed Annual Detections reference (5)
			γ	μ	ISC	Maximum Likelihood	
BM01	- 0.24	1.01	0.18	0.21	6400	4020	3720
BM02	- 0.24	0.95	0.25	0.23	5870	4220	
BM03	- 0.24	0.95	0.20	0.18	6210	4460	
EKA1	- 0.16	1.15	0.28	1.04	1259	800	900
EKA2	- 0.16	0.95	0.25	0.88	1560	950	
EKA3	- 0.16	0.95	0.20	0.83	1650	1060	
GBA1	- 0.22	0.92	0.26	0.59	4070	2390	2530
GBA2	- 0.22	0.95	0.25	0.59	4210	2450	
GBA3	- 0.22	0.95	0.20	0.54	4450	2870	
NA01	- 0.04	0.83	0.22	0.04	8250	5320	5404*
NA02	- 0.04	0.95	0.25	0.13	9400	5850	
NA03	- 0.04	0.95	0.20	0.08	9930	6530	
WRA1	- 0.18	0.91	0.19	0.36	14800	7970	11500
WRA2	- 0.18	0.95	0.25	0.33	15200	8060	
WRA3	- 0.18	0.95	0.20	0.27	16400	8710	

<u>Note</u>: * Detection count published in reference 5 increased to include PKP observations

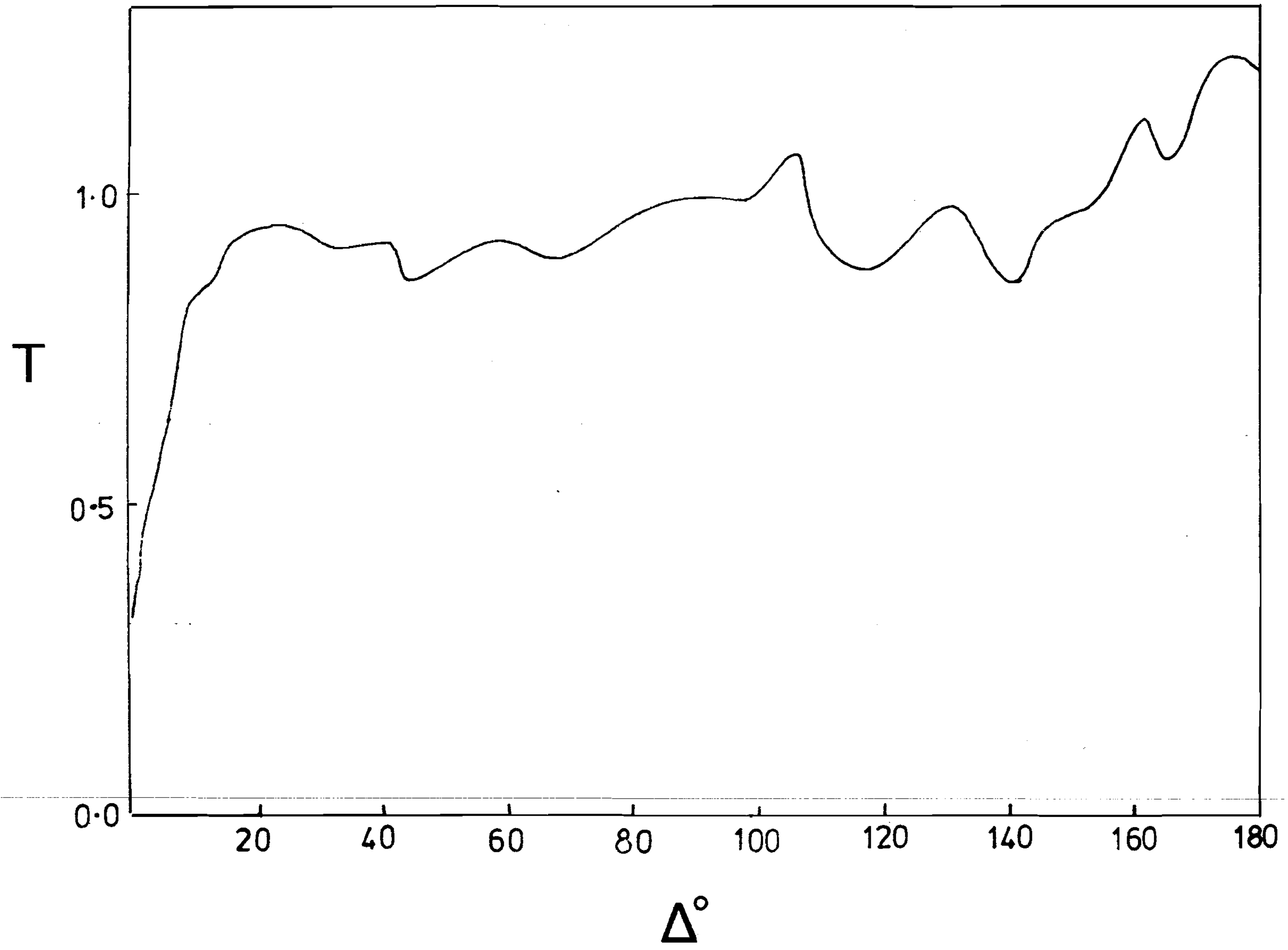


FIGURE 1.

Average period T(s) of p wave amplitude readings submitted to the ISC as a function of epicentral distance Δ. The conventional short period pass band maintains readings to near one second except for distances less than about 5°.

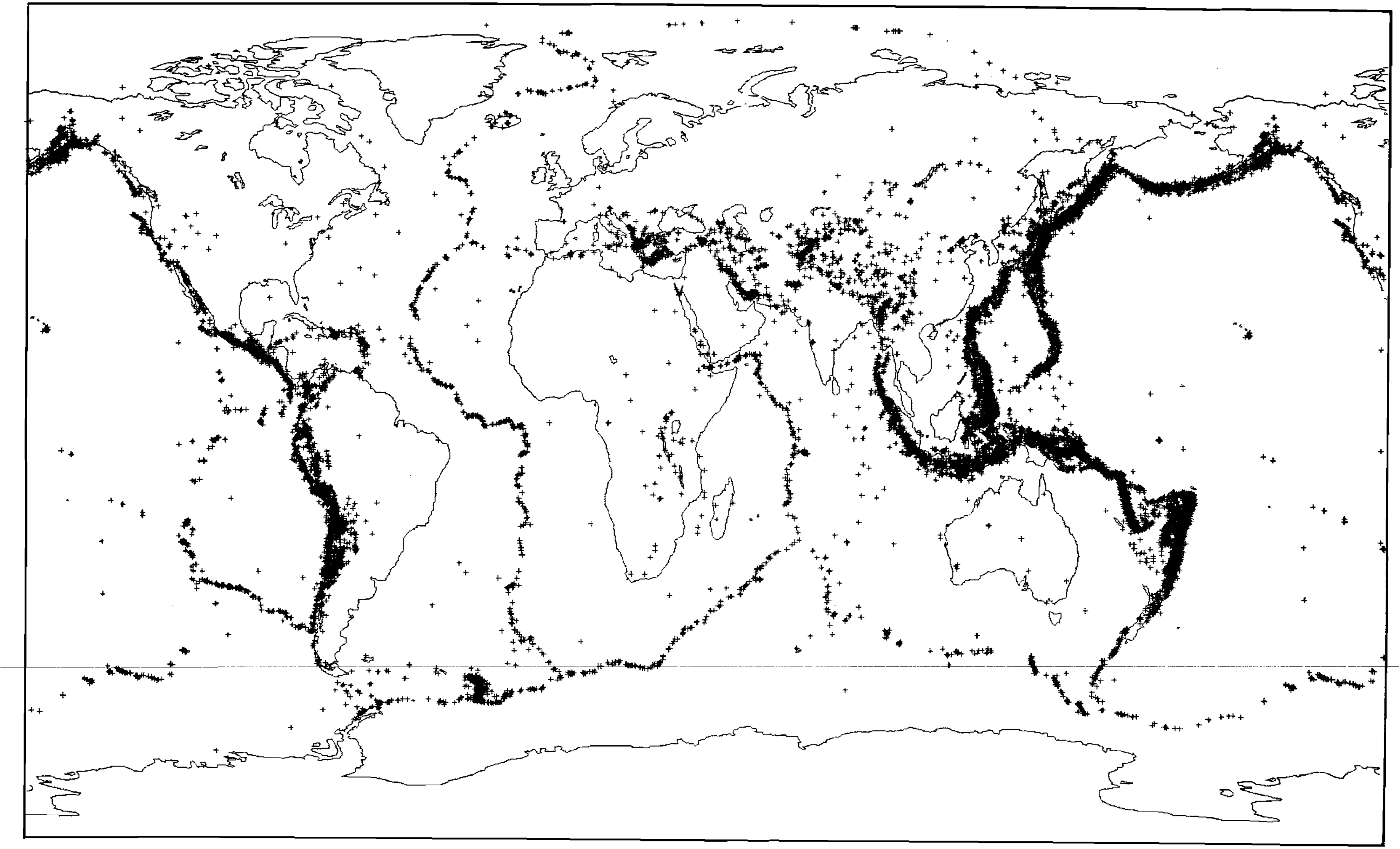


FIGURE 2. GLOBAL DISTRIBUTION OF ISC EPICENTRES 1964 TO 1983 HAVING MAGNITUDES m_b BETWEEN 4.8 AND 6.2 AS DETERMINED BY THE MAXIMUM-LIKELIHOOD METHOD (6,8)

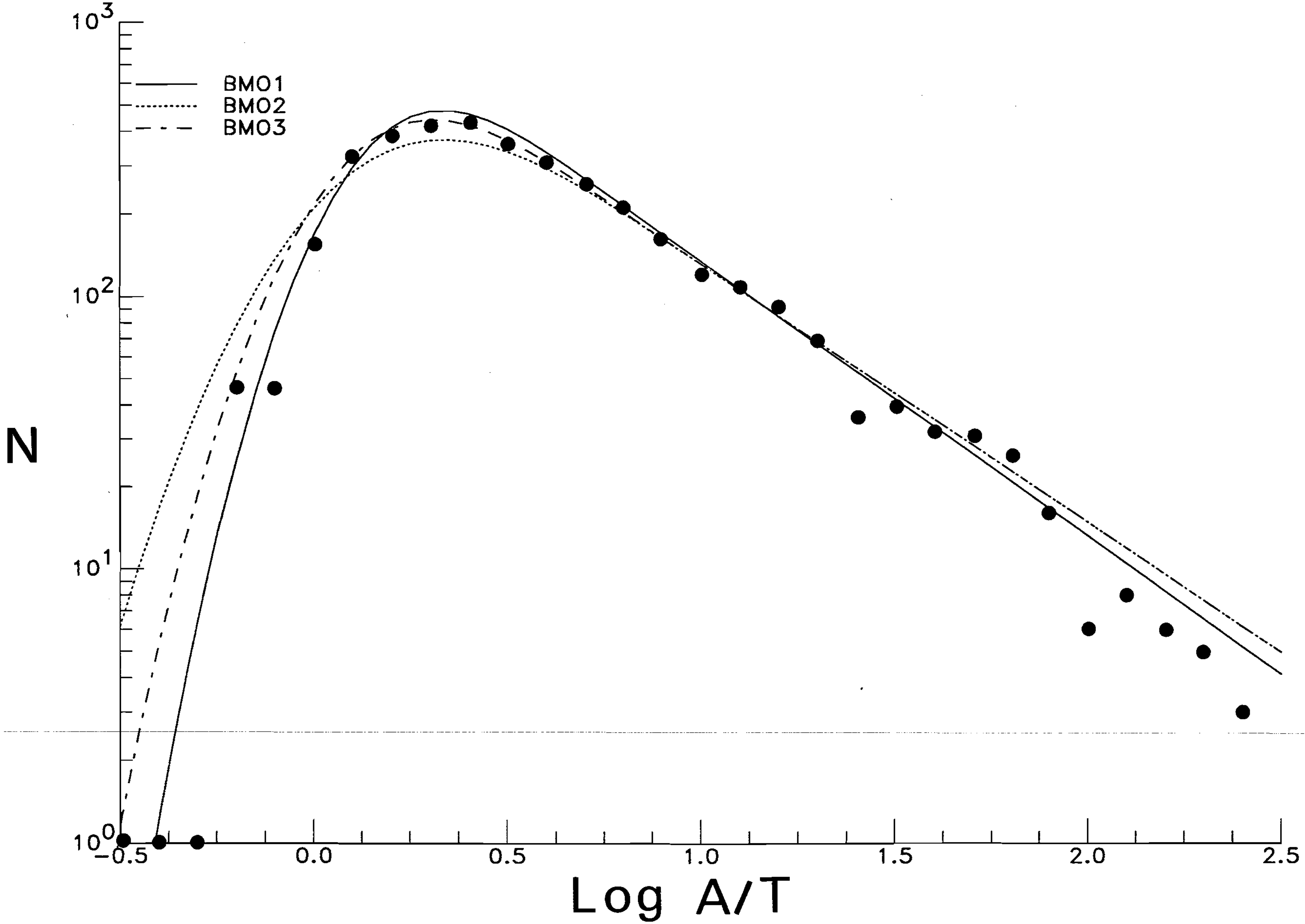


FIGURE 3. OBSERVED AND ESTIMATED AMPLITUDE STATISTICS FOR STATION BMO

Dots mark observed amplitude counts (5). Lines BMO1, BMO2 and BMO3 are predicted counts using parameters (b, γ, μ) given in table 1.

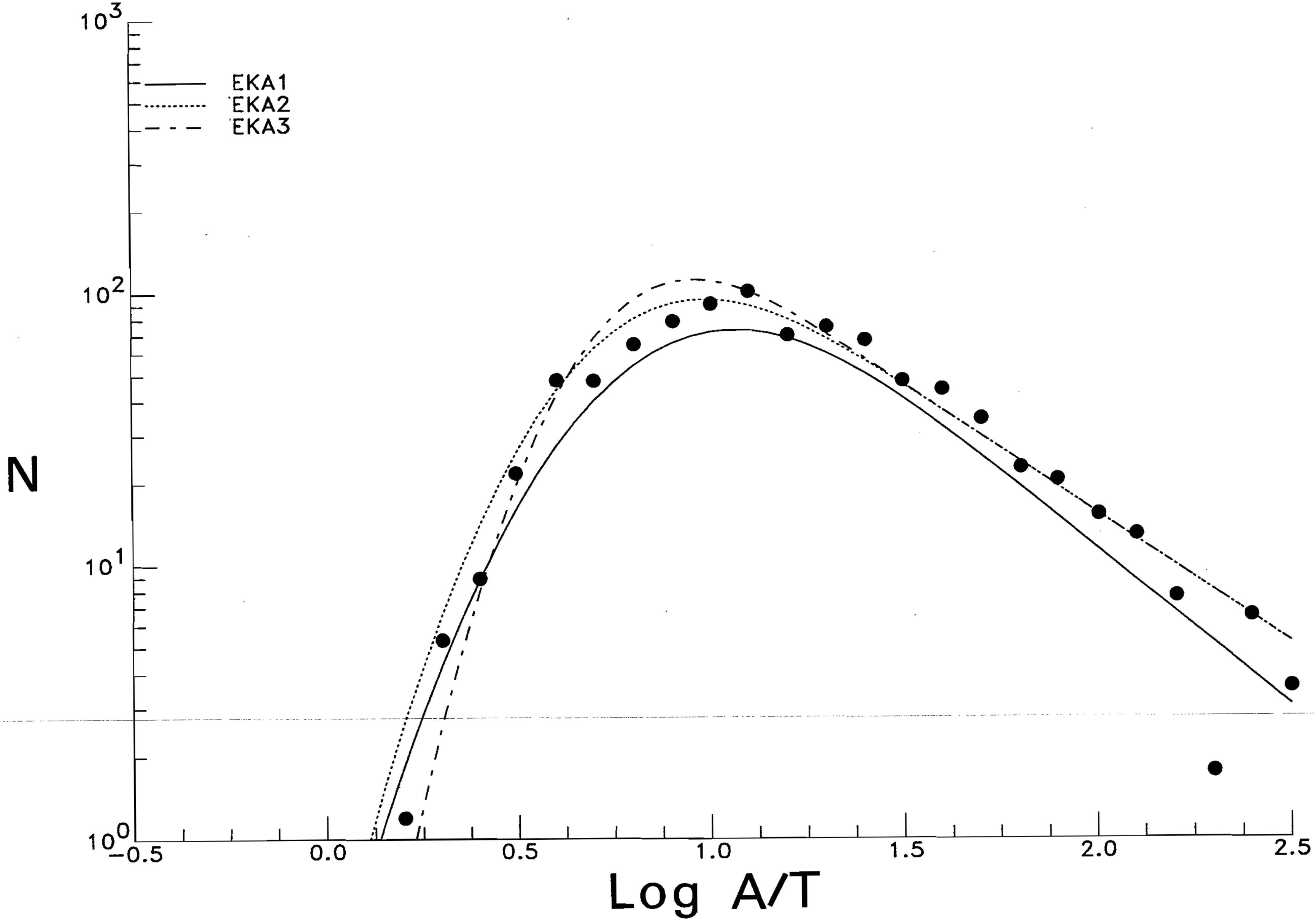


FIGURE 4. OBSERVED AND ESTIMATED AMPLITUDE STATISTICS FOR STATION EKA

Dots mark observed amplitude counts (5). Lines EKA1, EKA2 and EKA3 are predicted counts using parameters (b, γ, μ) given in table 1.

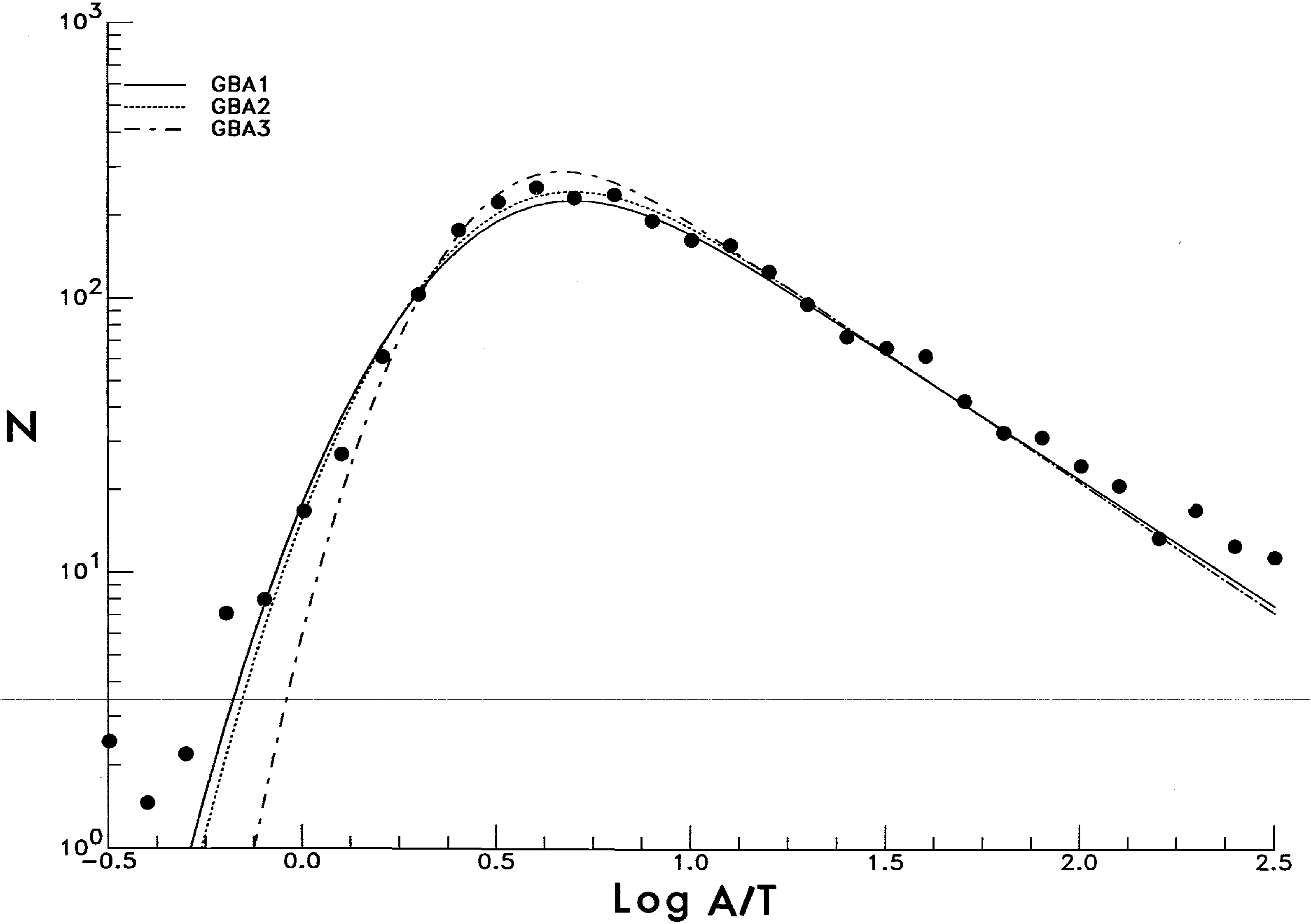


FIGURE 5. OBSERVED AND ESTIMATED AMPLITUDE STATISTICS FOR STATION GBA

Dots mark observed amplitude counts (5). Lines GBA1, GBA2 and GBA3 are predicted counts using parameters (b, μ, γ) given in table 1.

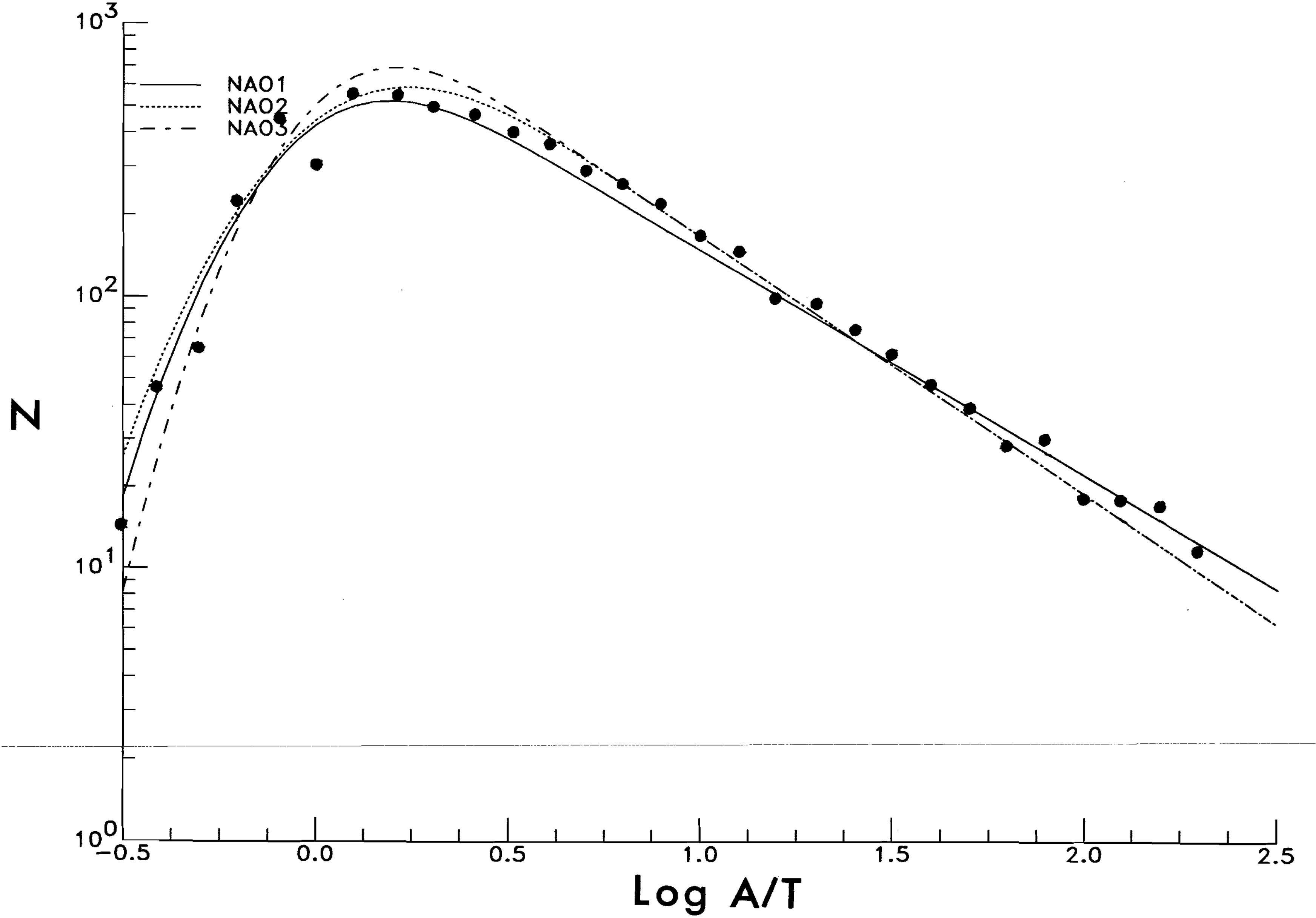
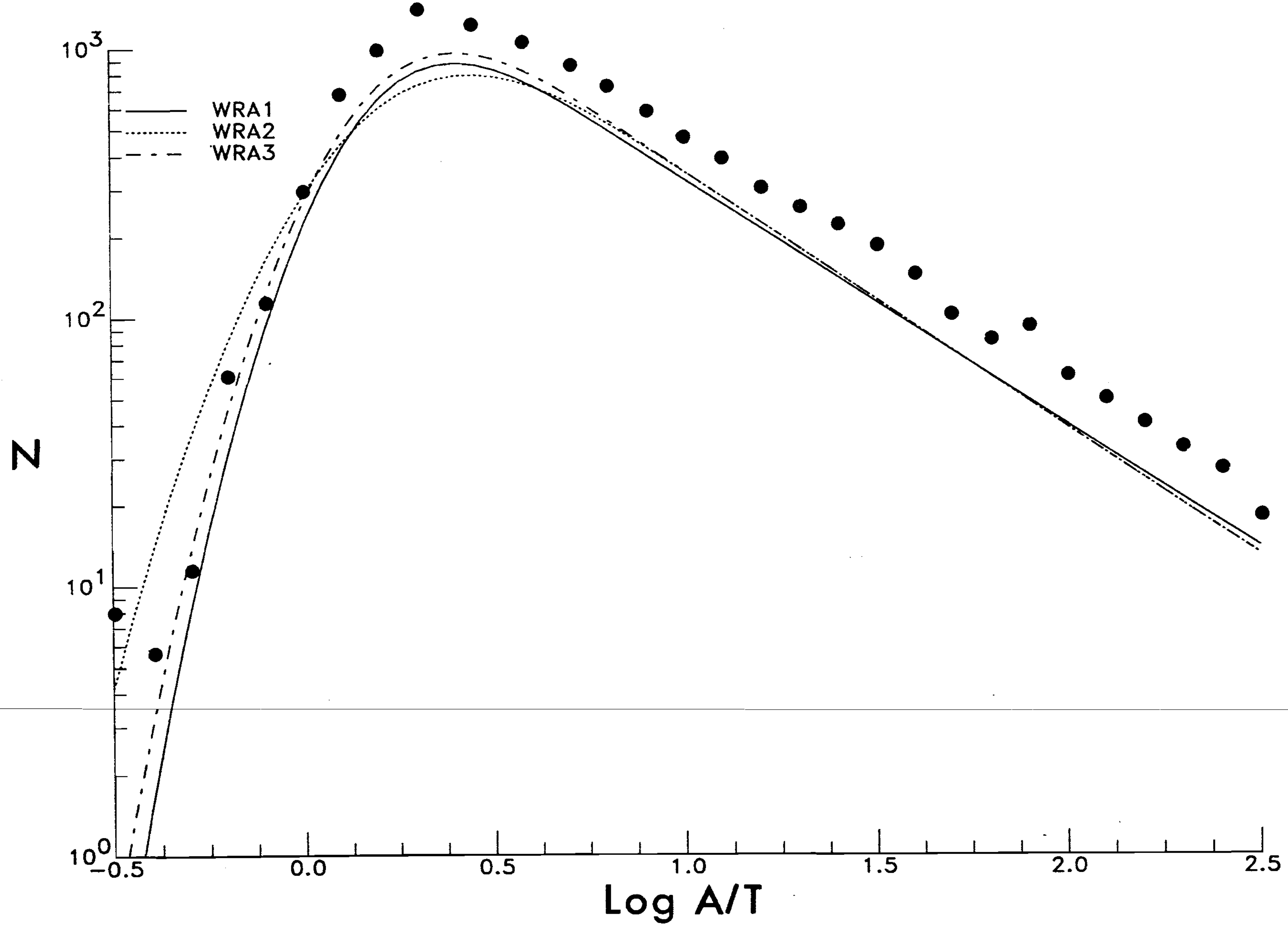


FIGURE 6. OBSERVED AND ESTIMATED AMPLITUDE STATISTICS FOR STATION NAO

Dots mark observed amplitude counts (5 but including PKP obs). Lines NA01, NA02 and NA03 are predicted counts using parameters (b, μ, γ) given in table 1.



<u>FIGURE 7. OBSERVED AND ESTIMATED AMPLITUDE STATISTICS FOR STATION WRA</u>

Dots mark observed amplitude counts (5). Lines WRA1, WRA2 and WRA3 are predicted counts using parameters (b, μ, γ) given in table 1.

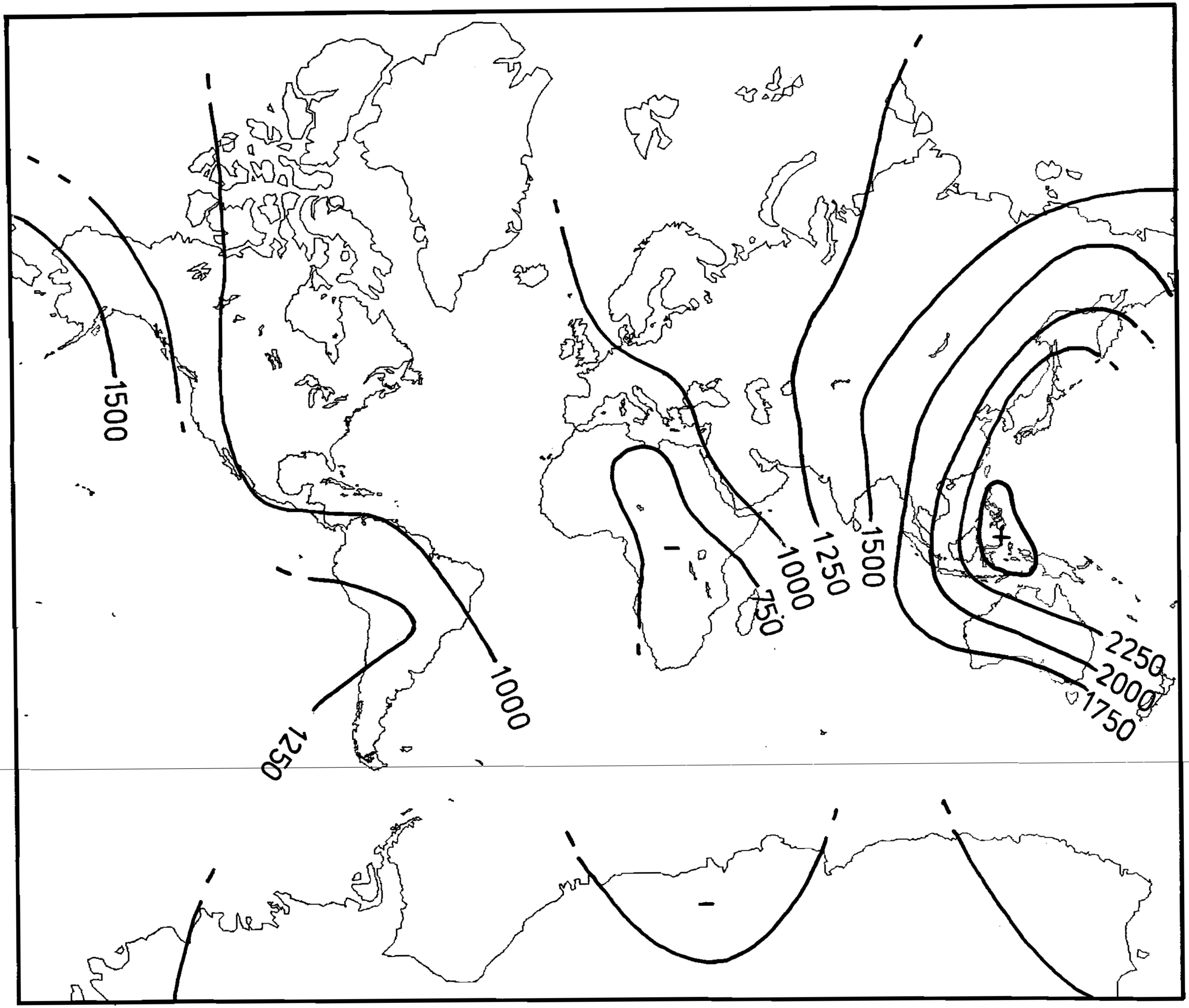


FIGURE 8. PREDICTED ANNUAL NO. OF DETECTIONS FOR A NARROWBAND SP STATION HAVING A MEAN (50%) DETECTION THRESHOLD CORRESPONDING TO A GROUND AMPLITUDE OF 10 nm (LogA/T = 1.0)

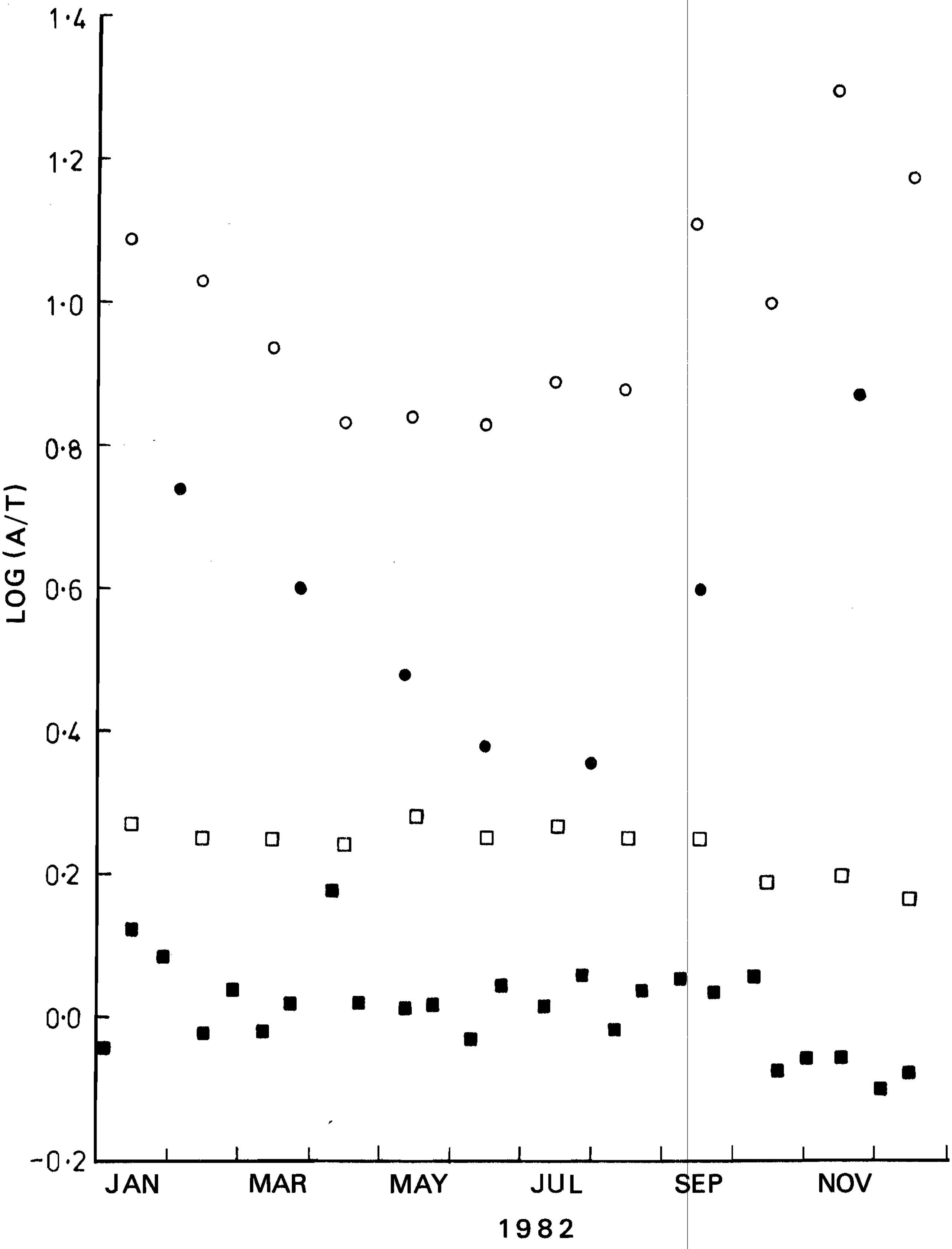


FIGURE 9.

Comparison of 50% detection thresholds and rms noise measurements at one second period for stations EKA (circles) and WRA (squares). The thresholds (open symbols) are estimated from the amplitude distribution of detected signals using the method of Kelly and Lacoss (2). Noise values (closed symbols) represent the average rms value for the array beams for noise preceding the detections. Units are in Log(A/T) units with A in nm and T in seconds.

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continue on separate piece of paper if necessary

Abstract

Earthquake locations published by the International Seismological Centre (ISC) for the period 1964-83, together with recomputed magnitudes, are used to successfully predict the observed numbers and amplitudes of detected short period P waves at a selection of stations. Neglecting the contribution of "near regional" ($\Delta = 0$ to 5^{o}) seismicity and assuming identical detection thresholds, detection counts vary by more than a factor of 3 depending on global location. Estimated detection numbers at sites with low noise at short periods vary between 20 to 60 per day. For a station in a seismically active region, rough calculation suggests that nearby activity may double these figures provide the overall reporting threshold is m_b2.5.

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