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# DISTANCE-AMPLITUDE RELATIONSHIPS FOR LONG-PERIOD P, S, AND LR FROM MEASUREMENTS ON RECORDINGS OF THE LONG-PERIOD EXPERIMENTAL STATIONS

D. H. VON SEGGERN
Seismic Data Analysis Center
Teledyne Geotech, 314 Montgomery Street, Alexandria, Virginia 22314

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Measurements on long-period P, S, and LR phases were extracted from an eight-month data base for nine stations of the Long Period Experimental network. Amplitude-distance curves were plotted for P and S from shallow-focus events; these curves generally agreed with the commonly-used Gutenberg-Richter B factors. The amplitude-distance curve for LR was different in slope than the commonly-used correction curve for $M_S$; however, this difference would not be sufficient to affect routine network $M_S$ estimates by more than roughly .1 magnitude unit. over

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# DISTANCE-AMPLITUDE RELATIONSHIPS FOR LONG-PERIOD P, S, AND LR FROM MEASUREMENTS ON RECORDINGS OF THE LONG-PERIOD EXPERIMENTAL STATIONS

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## ABSTRACT

Measurements on long-period P, S, and LR phases were extracted from an eight-month data base for nine stations of the Long Period Experimental network. Amplitude-distance curves were plotted for P and S from shallow-focus events; these curves generally agreed with the commonly-used Gutenberg-Richter B factors. The amplitude-distance curve for LR was different in slope than the commonly-used correction curve for $M_s$; however, this difference would not be sufficient to affect routine network $M_s$ estimates by more than roughly .1 magnitude unit. The Q for 20-second LR implied by this new data is roughly 700, in contrast to the 300 implied by the accepted amplitude-distance curve.

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## INTRODUCTION

A large data base of visual long-period measurements on recordings of the Long Period Experimental (LPE) network of seismometers has been reported by von Seggern (1976). This network has the advantage of high magnifications due to rigid environmental control and emplacement at depth for the seismometers (Pomeroy et al., 1969). Thresholds for long-period phases were sufficiently low that copious data was accumulated at the SDAC while analyzing the first eight months of recordings in 1972 for the nine LPE sites then operating; these LPE thresholds were (in terms of 90% detection by $\geq$ 2 stations) roughly 5.7 $m_b$ for P, 5.5 $m_b$ for S, 5.4 $m_b$ for LQ, and 5.0 $m_b$ for LR, considering detection of all events worldwide (von Seggern, 1976). The nine stations operating during this period were: ALQ (Albuquerque, New Mexico), CHG (Chiang Mai, Thailand), CTA (Charters Towers, Australia), EIL (Eilot, Israel), FBK (Fairbanks, Alaska), KIP (Kipapa, Hawaii), KON (Kongsberg, Norway), OGD (Ogdensberg, New Jersey), and TLO (Toledo, Spain). Station KIP began operation on March 6, 1972; and FBK operated only until April 26, 1972.

Drawing on that LPE data base, this report will present the amplitude-distance relation of the two major long-period body-wave phases, P and S, and of LR near a period of twenty seconds. The LQ data was not considered sufficient in the period range near 20 seconds where $M_s$ is usually obtained. This deficiency occurred because available horizontal recordings were seldom aligned along the radial and transverse directions of motion, thus contaminating shorter periods of LQ motion with Rayleigh waves. In addition noise on the horizontal seismograph recordings was usually higher than on vertical ones. The data base of long-period measurements was associated with a merged list of NEIS, LASA bulletin, and NORSAR bulletin epicenters. Collation of presumably identical

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von Seggern, D. H., 1976, Final report on the analysis of recordings from the Very Long Period Experimental stations, SDAC-TR-76-1, Teledyne Geotech, Alexandria, Virginia (in press).

Pomeroy, P. W., G. Hade, J. Savino, and R. Chander, 1969, Preliminary results from high-gain wide-band long-period electromagentic seismograph systems, J. Geophys. Res. v. 74, p. 3295-3298.

epicenters was accomplished using criteria of less than 10° spatial separation and less than one minute time separation. No depth criterion was used in collating because of the general lack of such information in the LASA and NORSAR bulletins. The merged list comprised 5390 epicenters for the first eight months of 1972. Over one-half of these epicenters had phases recorded at one or more of the LPE stations.

## BODY WAVES

### Procedure

In the LPE data base (von Seggern, 1974) several thousand P amplitudes and S amplitudes were available for inferring long-period amplitude-distance relations. Only those phases from shallow-focus ($\leq$ 60 km earthquakes are considered because the data from deeper events was not considered sufficient to establish depth corrections. Since these phases represented events whose size extended over two or three orders of magnitude, some manner of normalizing the body-wave amplitudes among events was necessary to obtain meaningful displays of amplitude versus distance for these phases. We chose to normalize the body-wave amplitudes by the average $\overline{M}_s$ for the event, provided at least three stations had an $M_s$ estimate for the event. Body waves for events which did not meet this criteria were discarded. However, only a small part of the available P and S amplitudes were eliminated since the long-period, body-wave thresholds were at least one-half magnitude unit higher than the LR threshold (von Seggern, 1976), and since almost all events which had one or more reported long-period body waves also had at least three stations detecting LR. The level of LR generation should correlate well with that of the long-period body-wave generation by a shallow earthquake according to seismic source theory (Blandford, 1975; Gilbert, 1973; Douglas et al., 1973). Thus, normalizing long-period body-wave amplitude by $\overline{M}_s$ (log A/T-$\overline{M}_s$) should remove most of the scatter due to source factors. The number of amplitudes able to be normalized in this manner were 1279 for P waves and 2226 for S waves. No restriction was placed on period; the range extended from 5 to 80 seconds, with the majority of measured periods falling in the 20-30 second range, which is considerably longer than typical periods for long-period body waves seen on WWSSN recordings.

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Blandford, R. R., 1975, A source theory for complex earthquakes, Bull. Seism. Soc. Amer., in press.

Gilbert, F., 1973, The relative efficiency of earthquakes and explosions in exciting surface waves and body waves, Geophys. J. R. Astr. Soc., v. 33, p. 487-488.

Douglas, A., J. A. Hudson, and C. Blamey, 1973, A quantitative evaluation of seismic signals at teleseismic distance--III computed P and Rayleigh wave seismograms, Geophys. J. R. Astr. Soc., v. 28, p. 385-410.

Results

A plot of these amplitudes versus distance is shown in Figure 1 for P waves and Figure 2 for S waves. Amplitudes were grouped into 2° bins and averaged; the standard deviation of the mean amplitudes are indicated by error bars. For comparison we have included the Gutenberg-Richter (1956) tabulated amplitude terms for P and S waves. We note that their curves were compiled with phases having shorter periods than those in our data base; although the period range is not specifically stated, Gutenberg (1945a) implies that data for these curves had periods generally between 1 and 10 seconds.

Considering now the P-wave curves in Figure 1, we note that, although the general trend is similar, significant departures in our data from Gutenberg and Richter's occurs in the ranges 15°-18°, 38°-44°, and 91°-99°. For 15°-18° an explanation can probably be found in regional effects on amplitudes as the extent of the low velocity zone is critical here. No data is shown for $\Delta < 15°$ because of large standard deviations. For 38°-44°, there is no satisfactory explanation of the high values obtained by Gutenberg and Richter since geometrical spreading, the most important influence for long period P waves, causes only a very smooth, almost neglibible, decay in this range (Booth et al., 1974). For 91°-99°, our decay is not as great as that suggested by Gutenberg and Richter; recalling that our periods were quite long compared to Gutenberg and Richter, we can explain this facet of our data by the diffraction theory of Phinney and Cathles (1969) for P waves near the core. Overall, our curve is more similar to those of Willey et al. (1970) and Booth et al. (1974).

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Gutenberg, B., and C. F. Richter, 1956, Magnitude and energy of earthquakes, Annali de Geofisica, v. 9, p. 1-15.

Gutenberg, B., 1945a, Amplitudes of P, PP, and S and magnitude of shallow earthquakes, Bull. Seism. Soc. Am., v. 35, p. 57-69.

Booth, D. C., P. D. Marshall, and J. B. Young, 1974, Long and short period P-wave amplitudes from earthquakes in the range 0°-114°, Geophys. J. R. Astr. Soc., v. 39, p. 523-537.

Phinney, R. A., and L. M. Cathles, 1969, Diffraction of P by the core: a study of long-period amplitudes near the edge of the shadow, J. Geophys. Res., v. 74, p. 1556-1574.

Willey, G., J. R. Cleary, and P. D. Marshall, 1970, Comparison of least squares analysis of long and short period P wave amplitude, Geophys. J. R. Astr. Soc., v. 19, p. 439-445.

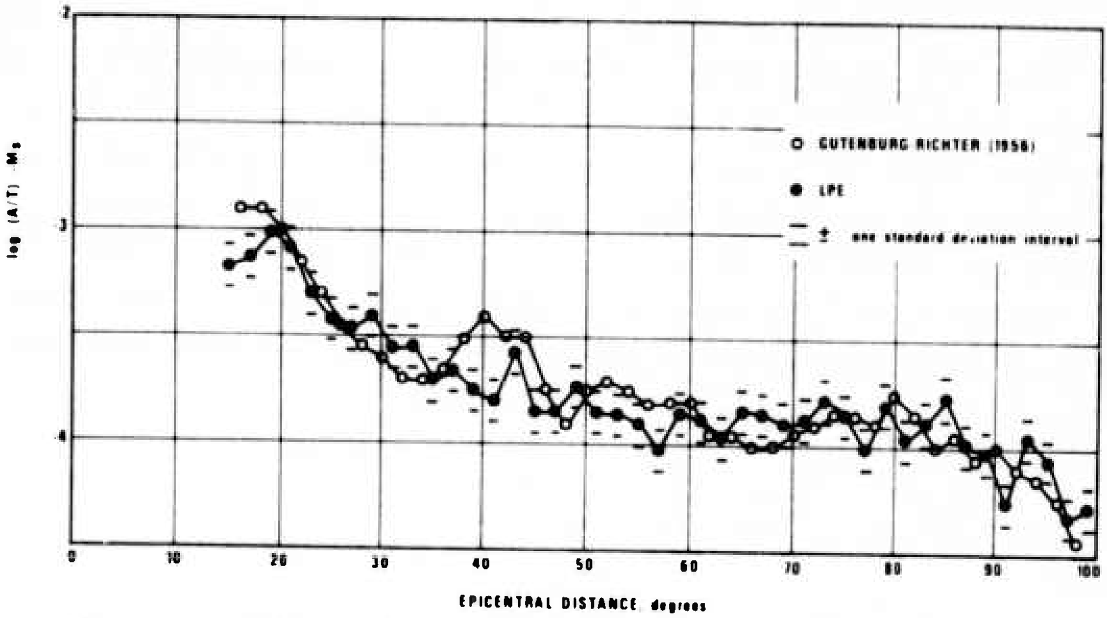


Figure 1. Amplitude-distance relation for long-period P waves from the LPE data base.

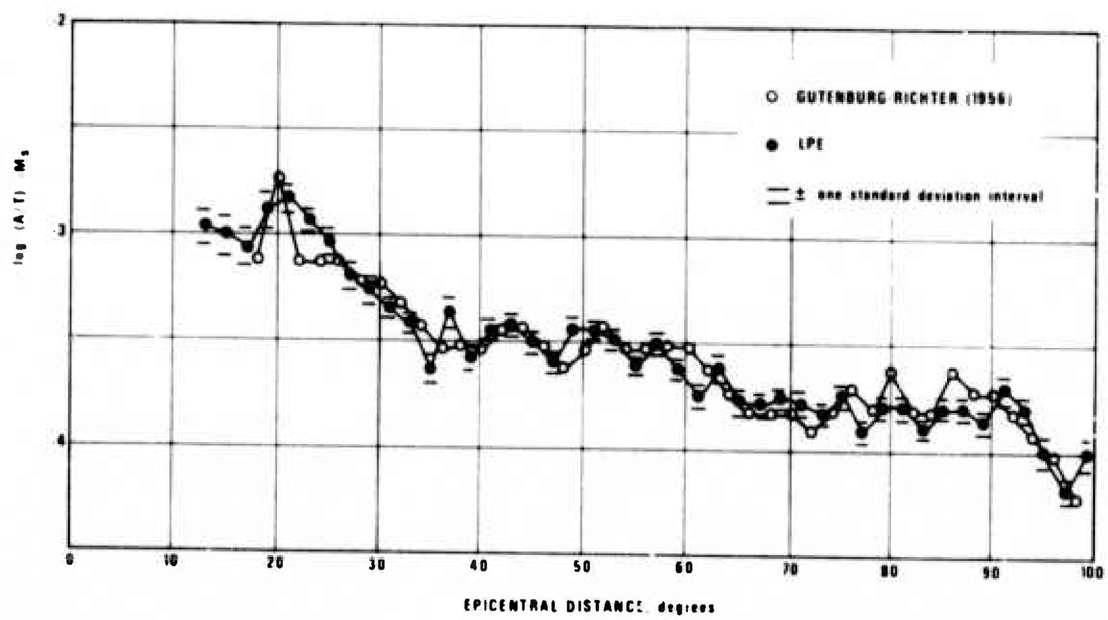


Figure 2. Amplitude-distance relation for long-period S waves from the LPE data base.

Turning now to the S-wave curves in Figure 2, we see that our data agrees with the Gutenberg-Richter curve satisfactorily except for $\Delta < 25°$ where, as for P waves, the regional affects of the low-velocity zone probably are causing the divergence. Data for $\Delta < 13°$ is not plotted because of large standard deviations. Again, there are no theoretical reasons for fluctuations in the curves beyond 25° and in fact, for our data, a very smooth curve could be drawn to lie within the 95% confidence limits of all the points (these limits would be approximately twice the standard deviation intervals shown). Other than the Gutenberg-Richter curve shown, there is no S-wave amplitude curve over this distance range to use as a basis of comparison.

## RAYLEIGH WAVES

### Data

For this section on LR, we shall describe the data base in more detail. The LR measurements used in this study were made peak-to-trough on the maximum of the Rayleigh-wave group in a period of 17-23 seconds. Roughly two-thirds of the data fell in the range 19-21 seconds. Many measurements were also made on LR outside these limits but are ignored in this study. The visually measured amplitudes were reduced to ground displacement using available magnification curves, and unlike the P and S amplitudes, were not divided by period for our purposes. We accepted measurements on horizontal recordings if none were available from the vertical, but only a tiny fraction of the LR data fell in this category. We also restricted our data to that associated with shallow-focus ($\leq$ 60 km) earthquakes; this, however, eliminated only a small part of the available data.

The data in general was considered to be of high quality since it was assembled by experienced analysts who demonstrated a very low false alarm rate (von Seggern, 1974) and who were operating in response to predicted LR arrival times from known epicenters made with a global group-velocity grid (Kimball, 1969). It might be expected though that amplitudes near the threshold of detection were contaminated by noise or were possible false alarms; such amplitudes would be reported for the smaller events and for larger epicentral distances. We were in fact forced by our choice of statistical analysis, as discussed in the next section, to limit the data to those events which had at least five LR amplitudes, restricted as stated above, in order to remain within the computer core capacity. This alone eliminated roughly one-half of the available data; but those events with four or less detections, being of smaller magnitude, would include most of the reported amplitudes of less quality. There remained 4456 LR amplitudes from 691 events for the analysis after all the criteria which have been mentioned were applied in restricting the data base.

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Kimball, B. C., 1969, Prediction of seismic surface-wave travel times, Technical Report 69-40, Teledyne Geotech, Garland, Texas.

### Statistical Model

We have followed Carpenter et al. (1967) in using the model:

$$A_{ijk} = S_i + F_j + R_k + e_{ijk} \quad (1)$$

where

$A_{ijk}$ = logarithm of observed amplitude,

$S_i$ = station effect,

$F_j$ = source effect,

$R_k$ = distance effect,

$e_{ijk}$ = random, normally distributed, error.

One can solve for the effects and their variances by least squares if the side conditions $\Sigma F_j = 0$ and $\Sigma R_k = 0$ are imposed (Scheffe, 1959).

The results from applying the above model must be judged against the adequacy of the model itself. Note that we have ignored any interactions which might arise due to non-uniformity of sources (radiation patterns from double couples) or from the heterogeneity of the earth (path effects on amplitude). Ignoring such interactions would be especially worrisome if the data were not evenly distributed as regards source, station, and distance. Tables I and II show the distribution of the data $A_{ijk}$ used in the least-squares solution for the effects in equation (1); examination of these tables reveals that no great concentrations of data occur, and therefore it seems apparent no large biases in the results should occur. We do point out some irregularities though, such as the large proportion of ALQ, OGD, and TLO data at 80° to 120° and a similar happenstance for CHG and CTA at 10° to 60°. These observed concentrations are of course due to the non-random pattern of seismicity over the earth. If significant interactions of opposite sign occurred between station and distance for these two groups, then the overall trend of the distance effects $R_k$ could be seriously biased. We do not, however, have sufficient geophysical knowledge

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Carpenter, E. W., P. D. Marshall, and A. Douglas, 1967, The amplitude distance curve for short-period teleseismic P waves, Geophys. J. R. Astr. Soc., v. 13, p. 61-70.

Scheffe, H., 1959, The Analysis of Variance, John Wiley and Sons, Inc., New York, New York.

TABLE I

Distribution of Observations by Distance and Station

| Distance | Number of Observations | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | ALQ | CHG | CTA | EIL | FBK | KIP | KON | OGD | TLO | Total |
| 0°-10° | 3 | 2 | 0 | 3 | 2 | 0 | 0 | 0 | 1 | 11 |
| 10°-20° | 10 | 7 | 63 | 24 | 8 | 0 | 8 | 0 | 12 | 132 |
| 20°-30° | 25 | 61 | 40 | 9 | 17 | 0 | 33 | 17 | 29 | 231 |
| 30°-40° | 28 | 35 | 72 | 17 | 10 | 42 | 13 | 69 | 12 | 298 |
| 40°-50° | 20 | 66 | 48 | 15 | 17 | 71 | 36 | 24 | 36 | 333 |
| 50°-60° | 70 | 48 | 29 | 32 | 18 | 102 | 20 | 39 | 13 | 371 |
| 60°-70° | 32 | 20 | 25 | 32 | 29 | 30 | 83 | 42 | 19 | 312 |
| 70°-80° | 37 | 35 | 40 | 46 | 39 | 64 | 62 | 48 | 40 | 411 |
| 80°-90° | 69 | 18 | 39 | 85 | 63 | 25 | 79 | 38 | 97 | 513 |
| 90°-100° | 91 | 44 | 18 | 58 | 21 | 37 | 37 | 42 | 73 | 421 |
| 100°-110° | 76 | 5 | 42 | 29 | 17 | 25 | 34 | 66 | 58 | 352 |
| 110°-120° | 75 | 7 | 15 | 70 | 6 | 16 | 59 | 61 | 27 | 336 |
| 120°-130° | 14 | 15 | 26 | 19 | 5 | 29 | 35 | 15 | 19 | 277 |
| 130°-140° | 22 | 7 | 6 | 26 | 5 | 9 | 39 | 21 | 15 | 159 |
| 140°-150° | 5 | 14 | 3 | 18 | 5 | 5 | 25 | 4 | 25 | 121 |
| 150°-160° | 0 | 7 | 3 | 37 | 4 | 1 | 10 | 3 | 46 | 112 |
| 160°-170° | 5 | 7 | 17 | 0 | 3 | 0 | 4 | 0 | 14 | 53 |
| 170°-180° | 4 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 6 | 13 |
| 0°-180° | 586 | 401 | 486 | 520 | 269 | 456 | 577 | 619 | 542 | 4456 |

TABLE II

Distribution of Observations by Seismic Region and Station

| Seismic Region | Number of Observations | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | ALQ | CHG | CTA | EIL | FBK | KIP | KON | OGD | TLO | Total |
| 1 | 37 | 20 | 28 | 33 | 16 | 29 | 35 | 38 | 34 | 270 |
| 2 | 7 | 3 | 6 | 3 | 0 | 6 | 6 | 6 | 6 | 43 |
| 3 | 5 | 2 | 5 | 3 | 2 | 4 | 4 | 5 | 4 | 34 |
| 4 | 6 | 1 | 5 | 4 | 6 | 3 | 6 | 8 | 8 | 47 |
| 5 | 13 | 6 | 6 | 7 | 4 | 11 | 14 | 15 | 15 | 91 |
| 6 | 17 | 5 | 8 | 8 | 6 | 10 | 18 | 17 | 17 | 106 |
| 7 | 4 | 1 | 1 | 1 | 2 | 3 | 4 | 4 | 4 | 24 |
| 8 | 31 | 10 | 19 | 30 | 8 | 23 | 30 | 30 | 30 | 211 |
| 9 | 3 | 1 | 3 | 3 | 1 | 2 | 3 | 3 | 3 | 22 |
| 10 | 10 | 9 | 11 | 13 | 6 | 9 | 9 | 13 | 9 | 89 |
| 11 | 3 | 2 | 1 | 2 | 2 | 3 | 2 | 3 | 2 | 20 |
| 12 | 43 | 30 | 43 | 33 | 19 | 39 | 37 | 42 | 34 | 320 |
| 13 | 8 | 4 | 6 | 5 | 3 | 6 | 4 | 8 | 6 | 50 |
| 14 | 27 | 22 | 27 | 22 | 16 | 19 | 27 | 28 | 24 | 212 |
| 15 | 44 | 24 | 41 | 31 | 15 | 43 | 35 | 43 | 26 | 302 |
| 16 | 16 | 14 | 18 | 15 | 12 | 12 | 18 | 19 | 11 | 135 |
| 17 | 4 | 5 | 4 | 2 | 3 | 3 | 5 | 5 | 5 | 36 |
| 18 | 14 | 11 | 14 | 10 | 10 | 7 | 14 | 14 | 12 | 106 |
| 19 | 43 | 41 | 41 | 45 | 25 | 37 | 53 | 50 | 49 | 384 |
| 20 | 2 | 5 | 5 | 5 | 3 | 4 | 3 | 6 | 4 | 37 |
| 21 | 14 | 15 | 17 | 13 | 5 | 15 | 16 | 15 | 12 | 122 |
| 22 | 28 | 28 | 25 | 27 | 9 | 21 | 28 | 27 | 23 | 216 |
| 23 | 6 | 6 | 9 | 9 | 1 | 8 | 7 | 7 | 7 | 60 |
| 24 | 17 | 16 | 21 | 21 | 8 | 15 | 14 | 19 | 13 | 144 |
| 25 | 3 | 0 | 2 | 3 | 0 | 3 | 3 | 3 | 3 | 20 |
| 26 | 6 | 4 | 6 | 8 | 3 | 4 | 7 | 6 | 5 | 49 |
| 27 | 3 | 3 | 4 | 6 | 4 | 1 | 5 | 5 | 6 | 37 |
| 28 | 6 | 5 | 6 | 7 | 3 | 6 | 8 | 8 | 7 | 56 |
| 29 | 15 | 17 | 9 | 14 | 5 | 16 | 20 | 16 | 18 | 130 |
| 30 | 14 | 5 | 7 | 14 | 6 | 11 | 15 | 15 | 13 | 100 |
| 31 | 6 | 1 | 2 | 5 | 3 | 4 | 7 | 7 | 7 | 42 |
| 32 | 51 | 26 | 22 | 47 | 24 | 25 | 44 | 54 | 53 | 346 |
| 33 | 20 | 21 | 19 | 19 | 12 | 13 | 19 | 19 | 19 | 161 |
| 34 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 35 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 36 | 1 | 1 | 0 | 0 | 1 | 0 | 1 | 1 | 1 | 6 |
| 37 | 3 | 2 | 2 | 2 | 1 | 1 | 3 | 3 | 3 | 20 |
| 38 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 7 |
| 39 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 40 | 5 | 4 | 2 | 6 | 3 | 2 | 6 | 6 | 6 | 40 |
| 41 | 2 | 1 | 2 | 2 | 0 | 2 | 2 | 2 | 2 | 15 |
| 42 | 3 | 1 | 1 | 2 | 2 | 1 | 2 | 3 | 3 | 18 |
| 43 | 13 | 7 | 16 | 14 | 6 | 12 | 14 | 14 | 12 | 108 |
| 44 | 12 | 6 | 9 | 6 | 7 | 11 | 10 | 13 | 12 | 86 |
| 45 | 3 | 2 | 2 | 3 | 2 | 1 | 2 | 3 | 2 | 20 |
| 46 | 4 | 3 | 4 | 5 | 2 | 3 | 5 | 4 | 5 | 35 |
| 47 | 6 | 4 | 3 | 4 | 1 | 3 | 5 | 5 | 4 | 35 |
| 48 | 7 | 6 | 4 | 7 | 2 | 4 | 6 | 6 | 2 | 44 |
| 49 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1-50 | 586 | 401 | 486 | 520 | 269 | 456 | 577 | 619 | 542 | 4456 |

to quantify the magnitude of such interactions, and the inclusion of them in the model would make it intractable for solution with our large body of data.

## Results

The station effects are estimated using equation (1) and are listed in Table III; the confidence limits, not listed, were all on the order of $\pm.02$ from the mean at the 95% level. The negative of these quantities would be applied as a correction to calculation of $M_s$ for routine seismological purposes although, except for OGD, the values are so small that applications of these corrections to network estimates of $\overline{M}_s$ would seem superfluous, especially since other effects, such as due to path and source non-uniformities and to measurement error, will dominate. The station effects of Table III reflect not just the structure near each station but the overall path effects for the signals recorded at each one, and so we cannot readily correlate the observed effects with those effects on Rayleigh-wave amplitudes predicted from the crustal structure at each site.

The solution for the $R_k$ effects in equation (1) are illustrated in Figure 3. The average global diminution of 20-second LR with distance is represented by these terms. We show, for comparison, the $-1.66 \cdot \log\Delta$ relation, arbitrarily scaled along the ordinate, which is the accepted (Vanek, 1962) relation for normalizing LR amplitudes in routine calculations of $M_s$ according to:

$$M_s = \log A + 1.66 \cdot \log\Delta - 130$$

where A is in millimicrons peak-to-trough and $\Delta$ is in degrees. The amplitude relation was first proposed by Gutenberg (1945b) in a slightly different form for $15° < \Delta < 140°$. Quite clearly, the LPE data deviates significantly from this line; and we have fitted the unweighted $R_k$ terms from 15° to 135° inclusive with a least-squares line as shown. The 95% confidence limits on the slope were $1.08 \pm .04$. A proposed $M_s$ formula, based on the LPE data, is given by

$$M_s = \log A + 1.08 \cdot \log\Delta - 0.22$$

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Vanek, J., A. Zatopek, V. Karnik, N. V. Kondorskaya, Yu. V. Riznichenko, E. R. Savarensky, S. L. Solov'ev, and N. V. Shebalin, 1962, Bulletin of the Academy of Sciences, USSR, Geophysics Series, No. 2 (February 1962), p. 108-111 (English translation).

Gutenberg, B., 1945b, Amplitudes of surface waves and magnitudes of shallow earthquakes. Bull. Seism. Soc. Amer., v. 35, p. 3-12.

TABLE III

Station Effects for the LPE Network

| Station | Effect |
|---|---|
| ALQ | +.04 |
| CHG | -.11 |
| CTA | -.04 |
| EIL | .05 |
| FBK | -.03 |
| KIP | -.11 |
| KON | .02 |
| OGD | .17 |
| TLO | .02 |

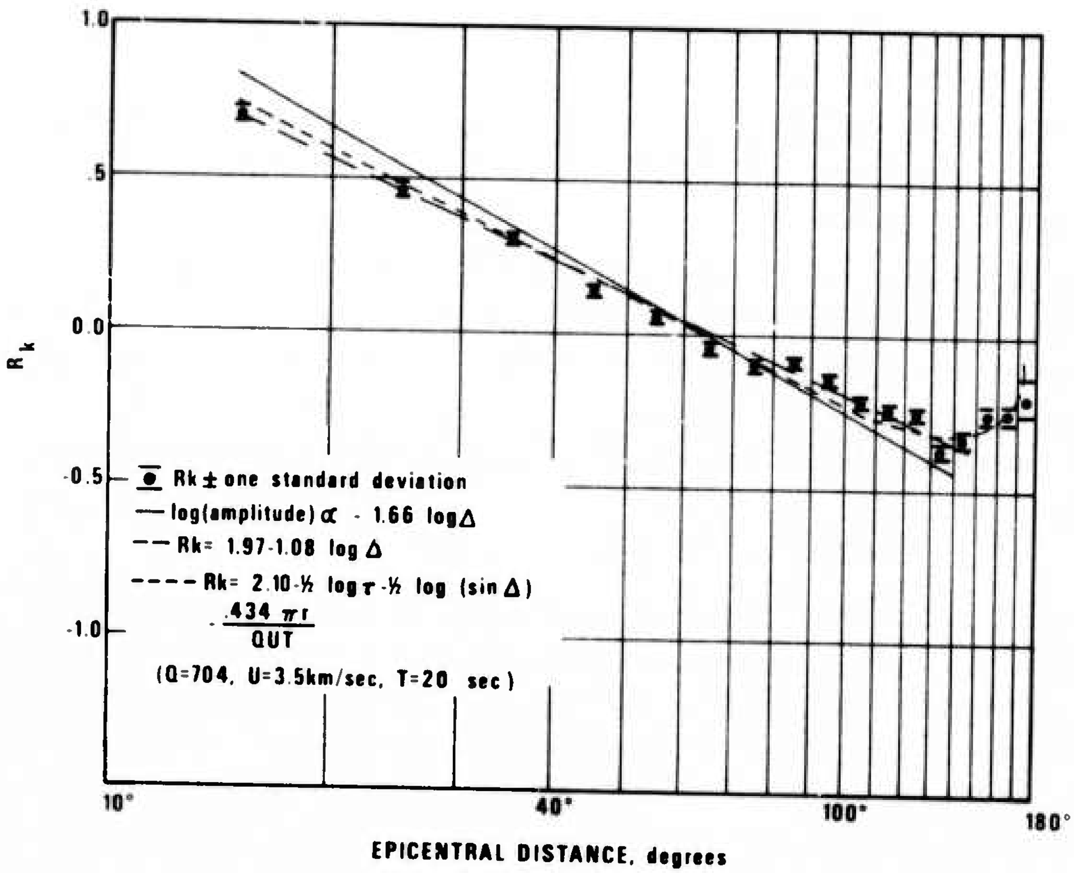


Figure 3. Distance effects from analysis of LPE LR data.

The constant was set by minimizing the average difference between old and new $M_s$ estimates for the 691 events in our data set; the two formulas give identical $M_s$ at $\Delta = 72°$.

The $R_k$ terms from 15° to 175° can be fit by the theoretical relation for surface waves propagating on a sphere; this relation involves the stationary-phase approximation, geometrical spreading, and attenuation (Sato, 1967):

$$R_k = cr^{-1/2} \sin^{-1/2} \Delta e^{\frac{-\pi r}{QUT}}$$

where c = constant

r = epicentral distance in km,

$\Delta$ = epicentral distance in degrees,

Q = quality factor,

T = period,

U = group velocity.

We shall set T = 20 seconds and U = 3.5 km/sec, a value appropriate as a global average for propagation of LR waves at a period of twenty seconds. Taking logarithms and rearranging the above, we have

$$R_k + \frac{1}{2} \log r + \frac{1}{2} \log (\sin\Delta) = \log c + (\frac{1}{Q}) (-.0195r).$$

This can be expressed in the simple linear regression form:

$$y_k = \alpha + \beta x_k$$

in order to solve for $Q = 1/\beta$. A fit to the data, as shown in Figure 3, assuming no error in the $R_k$ terms and applying equal weights, resulted in Q = 704 with 95% confidence limits of 597 and 857.

## Discussion

There is a serious discrepancy in the rate of amplitude diminution for 20-second LR between Gutenberg's (1945b) data and the LPE data. There is no other published study on the scale of Gutenberg's with which to compare these present results. We point out though that von Seggern (1975) has determined

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a Q for 20-second LR on the order of 500 using many great circle paths around the globe, and such an estimate of Q would agree with a value roughly halfway between those implied by the LPE data and by the Gutenberg data. It is impossible to determine if any significant bias exists in the result of Gutenberg since he does not list the epicenters used or the distribution of observation distances for each station; but with a group of 33 world-wide stations and over 1000 observations, it would seem that the data is sufficient to suppress any serious bias in his result. By contrast, we used 9 stations and over 4000 observations, again seemingly sufficient to suppress any serious bias. In both Gutenberg's and the present study, only periods near 20 seconds were allowed; and although Gutenberg took measurements from the horizontal recordings, this should make no difference. We postulate then that the true amplitude diminution lies somewhere in between and that unidentifiable station-path-source interactions peculiar to each study has caused the results to deviate in opposite directions from the underlying, true relation for LR diminution with distance. We emphasize that the differences, in the context of $M_s$ determination, are probably insignificant; for as Figure 3 shows, the maximum difference between the $-1.66 \log \Delta$ and $-1.08 \log \Delta$ relation would only be about .1 magnitude unit so that, in routine network estimation of $M_s$, values calculated by both formulas would agree very closely in all cases.

## CONCLUSIONS

Amplitude-distance curves formed using long-period P and S waves from a large LPE data base generally agreed with those published by Gutenberg and Richter (1956). In the case of long-period P, the LPE data agreed more with recent studies using LRSM and WWSSN data. In the case of long-period S, no other satisfactory curve for comparison is available. But in neither case are the curves given here or elsewhere sufficiently well-determined to promote abandoning the Gutenberg-Richter curves for a newer standard. Some smoothing of their curves based on geometrical spreading arguments might be desirable but still would not significantly affect network magnitude determinations using these phases. Our data appears to support the core diffraction affects on amplitude proposed theoretically by Phinney and Cathles (1969).

The amplitude-distance curve for 20-second LR derived from the LPE data is significantly different from Gutenberg's (1945b), amounting to +.15 $M_s$ unit at 15° and sloping down to −.09 $M_s$ unit at 140°. There is no obvious reason for this discrepancy. However, in the context of network estimation of $M_s$, this discrepancy can be safely ignored, with either Gutenberg's or the LPE formula giving nearly equivalent average $\overline{M}_s$ in all cases. The two formulas imply widely differing Q on a global scale though, roughly 300 for Gutenberg's and 700 for the LPE one; thus we feel that the two sets of data represent sampling of the earth's crust which cannot overlap to a great degree. A contribution to resolving this discrepancy could only come from a study using a large body of world-wide data; such data could be taken from the present NEIS files or possibly from the future files created by the Network Event Processor at the SDAC.

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