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# Distance and station effects on UK shear- and Lg-wave amplitudes recorded in the range 0-600km.

Earthquake & Forensic Seismology and Geomagnetism Programme

Internal Report IR/03/55

BRITISH GEOLOGICAL SURVEY

INTERNAL REPORT IR/03/55

# Distance and station effects on UK shear- and Lg-wave amplitudes recorded in the range 0-600km.

D C Booth



*Key words*

Lg waves, Shear-wave amplitudes, UK seismic monitoring, earthquake magnitude, seismology.

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The author thanks Professor Alan Douglas, AWE for stimulating discussions and advice on the topic of this report, and also Alan and his colleague Mr John Young, AWE, for supplying the analysis of variance program used in this study. Brian Baptie and Lars Ottemöller are also thanked for comments which significantly improved the report.

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# Summary

The amplitudes of shear-waves and Lg-waves recorded at UK seismograph stations from local earthquakes in the range 0-600km have been subjected to an analysis of variance, allowing separation of the effects of earthquake size, distance and local attenuation near each station. The analysis of 385 amplitude readings at 28 stations from 39 earthquakes showed that the effects of both distance and station attenuation were statistically significant. Tables of corrections for both distance and station effects have been derived to allow local magnitude *ML* to be determined more accurately from horizontal and vertical component records. One set of tables allows the estimation of an *ML* which is consistent with the original Richter definition of *ML*, with a standard deviation which is smaller than that produced by the theoretical attenuation curve, defined according to attenuation in Southern California, which has customarily been used to calculate ML for seismic events in the UK. The improvement in accuracy is mainly due to the incorporation of station terms to correct for near-station attenuation, since the theoretical and observed variations of attenuation with distance are similar. This similarity implies that Southern California and the UK show a similar variation of distance-dependent attenuation, a surprising result in view of the differences in geology. Another set of tables will produce an *ML* which is consistent with the body wave magnitude $m_b$ determined by the International Data Centre (IDC) from station records of the Comprehensive Test-Ban Treaty Organisation's global monitoring network. These local magnitude estimates are consistently closer to $m_b$ (IDC) estimates than the UK bulletin estimates of local magnitude which are made with a standardised amplitude-distance curve and no station correction.

# 1 Introduction

Magnitude is one of the most important parameters associated with a seismic event. It is an objective measure of earthquake size, using instrumental measurements of ground motion with corrections for epicentral distance and source depth. Seismic wave amplitude attenuates with increasing distance, and so an appropriate distance correction must be applied to a ground motion amplitude measurement to provide a magnitude estimate. In the distance range 0°-20°, attenuation occurs in the crust and upper mantle and is region-dependent, and therefore a distance correction which takes account of local attenuation characteristics is required in any procedure to generate a magnitude value from local wave amplitude measurements.

The British Geological Survey (BGS) estimates the magnitude of earthquakes occurring in the region of the UK using a local magnitude *ML*. This scale is the same as that defined by Hutton & Boore (1987), following earlier work by Richter (1935), which uses the maximum trace amplitudes recorded on standard Wood-Anderson horizontal seismometers. The BGS operate Willmore Mk3 seismometers rather than Wood-Anderson seismometers, but given the responses of the two instruments, it is possible to produce equivalent Wood-Anderson seismograms from which the required amplitudes can be measured. The magnitude is calculated by taking the logarithm of the mean maximum wave amplitude recorded on two orthogonal horizontal seismometers, and adding a correction to allow for epicentral distance. The maximum trace amplitude is almost always in the shear-wave coda and corresponds to the crustal shear wave $S_g$, or the multiply reflected shear wave group $L_g$ which follows the Sg wave onset. Hutton and Boore (1987) have published a correction for distance which is based on observations in California, and the BGS has applied this correction when estimating local magnitude of UK events using amplitude measurements from its UK seismic monitoring network stations. The BGS recognises that seismic wave attenuation characteristics are likely to differ between California and the UK, so that application of the Hutton and Boore correction for the effect of attenuation of amplitude with distance will result in magnitudes being biased in some way with respect to those determined by independent global magnitude scales.

The UK region is seismically active, but few earthquakes of magnitude greater than 4.0 occur (with the exception of the North Sea Graben region), and the UK seismic monitoring network is primarily designed for the detection and analysis of relatively low magnitude events. Until recently, technical limitations imposed by the low dynamic range of the UK seismic network recording system meant that shear-wave amplitudes were often not measurable at stations near the epicentre when any relatively large (*ML*>3.5) event occurred, due to saturation of the recording system. For many years, this restriction limited the amount of data available for wave amplitude studies over a wide distance range, since small events are only observable over a limited distance range. However, as instrumentation has improved, and a network of strong motion accelerometer stations has been installed, sufficient data has become available for such a study.

In some circumstances, attenuation effects associated with a particular recording station may be present, and these may also bias the determination of magnitude at a station. In this report, we employ a technique employed by Carpenter et al. (1967) and others using analysis of variance to determine an amplitude-distance curve and station corrections for shear-wave amplitudes recorded at UK short-period seismic stations in the range 0-600km. We then use the Hutton and Boore's criteria, adapted from Richter (1935) to calibrate the correction to give a local magnitude consistent with Richter's original definition, which is based on observed amplitude values at UK stations. The corrections are also calibrated against independent measurements of $m_b$ derived for large UK earthquakes by the International Data Centre (IDC), Vienna to obtain a distance correction table which is appropriate for estimating a local magnitude *ML* equivalent to $m_b$(IDC).

The IDC is operated by the Comprehensive (nuclear) Test Ban Treaty Organisation (CTBTO) for the production and distribution of data for CTBT verification. The identification of a seismic event as an explosion from the use of seismograms alone is vital in monitoring compliance with the CTBT, since seismic techniques are required to monitor underground nuclear explosions, which are the most common type of nuclear tests. Explosions must be discriminated from much more commonly occurring earthquakes; this is a difficult task and no single discrimination technique has been found which is successful for all events. Probably the most successful technique so far has been the $m_b$:$M_S$ criterion (Marshall & Basham 1972) , which depends on the observation that for a seismic event with a given body wave magnitude $m_b$, the surface wave magnitude $M_S$ is larger for an earthquake than for an explosion. Application of the criterion requires that accurate measurements of $m_b$ and $M_S$ are available. For small events, $m_b$<4.0, few if any measurements of $m_b$ and $M_S$ may be available. For such events, the ability to determine an equivalent $m_b$ from locally recorded amplitudes may useful, particularly for a state signatory which wishes to provide discriminatory evidence in respect of a nearby event. It is therefore useful that a reliable estimate of $m_b$ for local events can be made, using seismic wave amplitudes recorded at local stations.

# 2 Method of Analysis

Following Carpenter et al. (1967) and Booth et al. (1974), we write the shear-wave amplitude recorded at a station as

$$\log_{10}A = b + s + r \quad (1)$$

where $A$ is the mean maximum shear-wave amplitude on two orthogonal horizontal seismometers, $b$ is a term proportional to source size, $s$ is a station effect, and $r$ is a distance effect.

The formula for magnitude according to Richter (1935) is

$$ML = \log_{10}A - \log_{10}A_0, \quad (2)$$

where $-\log_{10}A_0$ is a correction for the effect of distance, and is here given the simpler notation $B(\Delta)$. To allow for the possible effect of local station-dependent attenuation we introduce a station term $S$. Then

$$ML = \log_{10}A + B(\Delta) + S \quad (3)$$

It follows that

$$\log_{10}A = ML - B(\Delta) - S \quad (4)$$

and $\log_{10}A$ can be expressed as a sum of effects of source size, distance, and station structure.

To analyse the data I follow Carpenter et al. (1967) and Booth et al. (1974) and make the assumption that if $a_{ijk}$ is $\log_{10}A$ for the $j$-th station and the $i$-th earthquake in the $k$-th distance range then

$$a_{ijk} = b_i + s_j + r_k + c + e_{ijk} \quad (5)$$

where $b_i$ is a measure of the size (energy release) of the $i$-th earthquake, $s_j$ is the station effect for the $j$-th station, $r_k$ is the effect of distance, $c$ is a constant, and $e_{ijk}$ is an error. $b_i$, $s_j$, $r_k$ and $c$ can be estimated in the presence of this error by the method of least squares (on the assumption that the errors have zero mean) with the conditions

$$\Sigma b_i = \Sigma s_j = \Sigma r_k = 0, \quad (6)$$

where $b_i$ are summed over $n$ earthquakes, $s_j$ is summed over $q$ stations, and $r_k$ is summed over $l$ distance ranges. The problem corresponds to an analysis of variance of three effects: earthquake size, distance and station (structure). The distance correction $B(\Delta)$ and station correction $S$ in (3) are derived from the distance and station effects, $s_j$ and $r_k$ respectively.

We can write $B(\Delta) = -r_k + D$, (7)

where $D$ is a constant term which is added so that the magnitudes $ML$ computed using the revised curve agree on average with magnitudes computed by a specified agency. This gives the term $B(\Delta)$ in (3); the station correction $S$ which is to be added to $\log_{10}A$ and $B(\Delta)$ in (3) to form $ML$ is $-s_j$.

Also, from (3)

$$\text{ML} = \log_{10}A - r_k + D - s_j, \quad (8)$$

and from (5)

$$\log_{10}A - r_k - s_j = b_i + c,$$

so that for the $i$-th earthquake ML = $b_i + c + D$.

# 3 Results

### 3.1 ANALYSIS OF VARIANCE STUDY

Shear-wave amplitude measurements on vertical and N-S and E-W oriented horizontal seismometers were made from 40 UK earthquakes in the period 1996-2002, as recorded at 28 three-component stations in the BGS UK seismograph network. The locations of the events are shown in Figure 1 and the locations of stations in Figure 2. Four stations (BCC, HBL2, KEY2, LDU) are strong motion accelerometer stations. The range of distances was 0-600km and this range was divided up into 30 intervals of 20km length. As stated in section 1, BGS has consistently estimated *ML* using the mean maximum wave amplitude recorded on two orthogonal horizontal (H) seismometers, and these measurements of *ML* are published in their annual bulletins of seismicity for the UK. The present study has also used the vertical (Z) component amplitudes in order to determine if consistent local magnitudes can also be determined from vertical records alone. Use of vertical records would allow more stations to contribute to magnitude determination, since there are many more vertical stations than three-component stations in the BGS network. This is useful when small events generate measurable seismograms at only a few stations, since only one or none of these may be three-component stations.

The analysis of variance procedure described in section 2 above was applied to the data using a computer program developed by Prof. A Douglas of AWE Blacknest. The program generates tables of station effects $s_j$ and distance effects $r_k$ for the stations, and distance intervals, respectively. Application of Snedecor's F-test (Abramowitz & Stegun, 1972) to the station and distance variances shows that both are highly significant at the 0.1 percent level, for both horizontal and vertical component data. The statistics associated with the analysis are presented in Table 1. The variation of amplitude with distance ($r$ in equation 1) for horizontal and vertical amplitude measurements is shown in Figures 3 and 4, respectively, and the station corrections $S$ are given in Table 2.

### 3.2 CALIBRATION OF DISTANCE EFFECT FOR RICHTER LOCAL MAGNITUDES

It was noted in section 2 that a constant $D$ must be added to the distance correction formed from $r_k$ so that the magnitudes $ML$ computed using the amplitude-distance curve derived from observed amplitudes agree on average with magnitudes computed by a specified agency. I choose the baseline for the distance correction so that the magnitudes $ML$ are defined according to the Richter definition of local magnitude, subsequently modified by Hutton & Boore (1987), so that a $ML$ 3 event corresponds to 10mm of displacement on a Wood Anderson seismometer at 17km hypocentral distance. I denote this magnitude $ML^R$. In the UK, very few events are recorded at a distance of 17km, and so I take the equivalent original definition due to Richter (1935) that a $ML$ 3 event will correspond to 1mm displacement on a Wood Anderson seismometer at 100km hypocentral distance. I assume the Wood Anderson gain is 2080 (Bormann 2002), so that 1mm WA corresponds to 481nm, and a logA value of 2.68. I interpolate between the horizontal component distance effects determined for the ranges 80-100km, and 100-120km, to derive the value of 0.81 for the distance effect $r_k$ at 100km. It follows that for a $ML$ value of 3 at 100km hypocentral distance, the constant $D$ to be added to the distance correction, $-r_k$ , to form the distance correction $B(\Delta)$, must be 1.13 for horizontal component measurements. Similarly, $D$ for vertical component measurements is 1.08. The distance correction $B(\Delta)^R$ for evaluating the Richter magnitude $ML^R$ is given for both horizontal and vertical components in Table 3. Local magnitudes estimated using horizontal and vertical component records and associated station and distance corrections shall be suffixed *(H)* and *(Z)* respectively, when there is a need to identify them separately.

The formula for $ML^{BGS}$, specified for a measured displacement $A$ in nm at distance $r$ km in the Seisan analysis package (Havskov & Ottemöller 2001), is

$$ML^{BGS} = \log A + B(\Delta)^{BGS} = \log A + 1.11 \log(r) + 0.00189*r - 2.09 \qquad (9)$$

The $B(\Delta)^R$ distance corrections and the Hutton & Boore (1987) corrections $B(\Delta)^{BGS}$ used to compute $ML^{BGS}$ are compared in Figure 5. Discrepancies in the range 40-80km and 400-440 km are believed to reflect real anomalies in Lg wave propagation in the UK compared to California. Over the range 90 to 400 km the corrections are very similar, implying that the crustal attenuation properties of Southern California and the UK are similar for S-waves and Lg waves. This is a surprising conclusion as the geological structures are quite different.

$ML^R$ values were calculated for each station, and each event, which contributed the amplitude values used in the analysis of variance study, using equation 8 above, for both horizontal and vertical component amplitude values. Corresponding estimates of $ML^{BGS}$ were determined from the same amplitude values. The mean event magnitudes $ML^R$ and $ML^{BGS}$, and the corresponding standard deviations, are listed in Table 4 and $ML^R(H)$ is plotted against $ML^{BGS}(H)$ for each event in Figure 6. ($ML^R$ - $ML^{BGS}$) varies between 0.22 and –0.05 magnitude units, and 0.19 and –0.09 magnitude units, for horizontal and vertical component data, respectively. The respective average difference is 0.07 and 0.05 magnitude units. Note that the standard deviations of the sets of $ML^R$ values for each event are usually smaller than the standard deviations of the $ML^{BGS}$ values, and 35 standard deviations exceed 0.2 for $ML^{BGS}$ compared to only 4 for $ML^R$. This indicates that $ML^R$ will be slightly more consistent than $ML^{BGS}$. The similarity between the distance corrections used for $ML^{BGS}$ and $ML^R$ suggests that this is almost entirely due to the use of station corrections in the calculation of $ML^R$. It is seen that $ML^R(H)$ differs from $ML^R(Z)$ by about 0.2 magnitude units; this is due to the slight differences in the amplitude-distance curves for horizontal and vertical component amplitudes, combined with the definition of *ML* at 100km distance. $ML^R(H)$ is plotted against $ML^R(Z)$ in Figure 7; the best fitting straight line to this plot provides the following equation

$$ML^R(H) = 0.98ML^R(Z) + 0.25, \qquad (10)$$

which allows a consistent magnitude to be determined from a combination of horizontal and vertical component records. Note that since the baseline for the $ML^R$ scale has been set according to values for displacement for a specified magnitude observed in California, the $ML^R$ magnitudes will still be biased with respect to those determined by independent global body and surface wave magnitude scales.

## 3.3 CALIBRATION OF DISTANCE EFFECT FOR IDC MAGNITUDES

The constant *D* can also be computed so that the computed *ML* will be equivalent to the body wave magnitude $m_b$ in the Reviewed Event Bulletin (REB) published by the International Data Centre (IDC) of the Comprehensive Test-Ban Treaty Organisation. Event parameters for seven events occurring in the UK region have been published in the IDC REB. The location accuracy of three of these events is relatively poor as they occurred offshore, hence distance values for them may be inaccurate. Of the remaining four events, two were assigned an $m_b$ by three or more IDC stations, and the remaining two by only one IDC station. I have only used the two events which are well located and whose magnitude $m_b$ is relatively well determined by the IDC in determining D for an ML equivalent to the IDC $m_b$. For these events, $\log_{10}A - r_k - s_j$ in equation 8 above was determined for horizontal station seismograms and plotted against IDC $m_b$ magnitude. The assumption of a linear relationship between the corrected log(amplitude) and IDC mb allows a local magnitude $ML^{IMB}$ equivalent to the IDC mb to be calculated from BGS station seismograms.

$$ML^{IMB} = (\log_{10}A - r_k - s_j) + 0.60$$

In order to determine if $ML^{IMB}$ is consistent with the IDC $m_b$ values, the station and source corrections were used to estimate $ML^{IMB}$ for seven local events for which IDC $m_b$ estimates are available. These estimates, together with the equivalent BGS local magnitude estimates $ML^{BGS}$, which were calculated using the BGS procedure for *ML*, are presented in Table 5. Estimates of $m_b$ computed by the NEIC are also provided where available. For one event, there is an NEIC $m_b$ but not an IDC $m_b$. Note that the IDC $m_b$ magnitudes are consistently lower than the NEIC $m_b$ estimates, by about 0.3-0.4 magnitude units on average. This discrepancy is well known and is due to differences in the procedures used by the two agencies to calculate $m_b$. Data from four events (1, 5, 6 and 8) were used in the determination of the station and distance corrections. Table 4 shows that the $ML^{IMB}$ estimates are close to the $m_b$ (IDC) estimates, and $ML^{IMB}$ is 0.4 to 0.6 magnitude units less than $ML^{BGS}$. A significant discrepancy of 0.4 magnitude unit is observed between $ML^{NDC}$ and $m_b$(IDC) for event 5. This event occurred in the Bristol Channel and $m_b$(IDC) was determined by a single station (ARCES). *ML* as determined by IDC from records at distances less than 20º was 3.3, and the event was not published in the NEIC bulletin. Thus it is possible that the true magnitude is lower than 3.6 and the $m_b$(IDC) estimate is biased high due to path and site effects associated with this single station.

### 3.4 DISCUSSION

It is difficult to interpret the variation in station effect between stations in terms of shear-wave ($S_g$ and $L_g$) propagation characteristics. The station corrections in Table 2 differ significantly within groups of nearby stations and between horizontal and vertical components at individual stations. For example, the groups (BCC, BHH, ESK), (MCH, SSP, HBL2), (CWF, KEY2), and (HPK, LDU) all show wide disparity between individual horizontal station corrections, and BHH, CR2, HPK, MCH and ORE show very different sizes of correction for horizontal and vertical amplitudes. Relatively low station corrections for the accelerograph stations may be due to the recorded amplitudes being biased high since they only record large amplitudes from large magnitude events. A slight difference in the Wood-Anderson response generated for short-period seismometers compared to the accelerographs may also contribute to the differences, and this will be investigated. Future work will use measurements of $L_g$ from additional single component vertical stations to allow more UK network stations to stations to contribute to magnitude measurements, and measurements from regional events at distance ranges beyond 600km to extend the amplitude-distance curve for events recorded in the UK to 20˚ epicentral distance.

# 4 Conclusions

An analysis of shear-wave amplitudes from local earthquakes at stations of the UK seismic monitoring network has generated correction tables which allow the estimation of local magnitudes which are consistent with body wave magnitudes published in the bulletins of the CTBTO International Data Centre, as well as magnitudes which are consistent with the Richter definition of local magnitude. 385 amplitude readings from 39 local earthquakes recorded at 28 three-component seismometer stations and strong-motion accelerometer stations in the distance range 0-600km were used in this study. The effects on amplitude of source size, distance and near-station attenuation were separated using an analysis of variance technique. Local magnitude estimates made with the new correction tables, $ML^{IMB}$, are consistently closer to $m_b$ (IDC) estimates than the UK bulletin estimates of local magnitude which are made with a standardised amplitude-distance curve and no station correction. The new amplitude-distance curve and station corrections thus allow an estimate of $m_b$ (IDC) from local shear-wave data which can be applied to event discrimination studies. It should be noted that the NEIC and IDC do not calculate body wave magnitude $m_b$ in the same way. Thus $m_b$ (IDC) and $ML^{IMB}$ are currently underestimated by 0.3-0.4 units when compared with NEIC magnitudes. This situation may change in the future due to the NEIC making increasing use of data from CTBTO monitoring stations.

Local magnitude estimates according to the Richter definition of local magnitude, using appropriately adjusted distance correction tables from the new amplitude-distance curve and the new station corrections, show a smaller variance than the corresponding BGS values calculated from the Hutton & Boore (1987) formula. This is due to the application of station corrections to the calculation of ML, which have not been included so far in the standard BGS procedure for determining local magnitude.

# References

Most of the references listed below are held in the Library of the British Geological Survey at Keyworth, Nottingham. Copies of the references may be purchased from the Library subject to the current copyright legislation.

ABRAMOWITZ, M. & STEGUN, I.A. 1972. Handbook of mathematical functions. Dover Publications, Inc. New York.

BOOTH, D.C., MARSHALL, P.D., & YOUNG J.B., 1974. Long and short *P*-wave amplitudes from earthquakes in the range 0-114˚, *Geophys. J.R.astr.Soc.,*Vol. 39**,** 523-537.

CARPENTER, E.W., MARSHALL, P.D. & DOUGLAS, A., 1967. The amplitude-distance curve for short period teleseismic *P*-waves, *Geophys. J.R.astr.Soc.,* Vol. 13, 61-70.

HUTTON, K.L. & BOORE, D.M. 1987. The ML scale in southern California: *Bull.Seism.Soc. Am.*, Vol. 77, no. 6, p. 2074-2094.

MARSHALL, P.D. & BASHAM, P.W., 1972. Discrimination between earthquakes and explosions employing an improved $M_S$ scale, *Geophys. J.R.astr.Soc.,* Vol. 28, 431-458.

RICHTER, C.F. (1935). An instrumental earthquake magnitude scale. *Bull.Seism.Soc. Am.*, Vol. 25, 1-32.

HAVSKOV, J. & OTTEMÖLLER, L. (2001). Seisan: The earthquake analysis software, Version 7.2. Report Univ. Bergen, 260pp.

BORMANN, P. 2002. Magnitude of Seismic events. In *IASPEI New Manual of Seismological Observatory Practice*. BORMANN, P (editor). (Potsdam: GeoForschungsZentrum.) ISBN 3-9808780-0-7

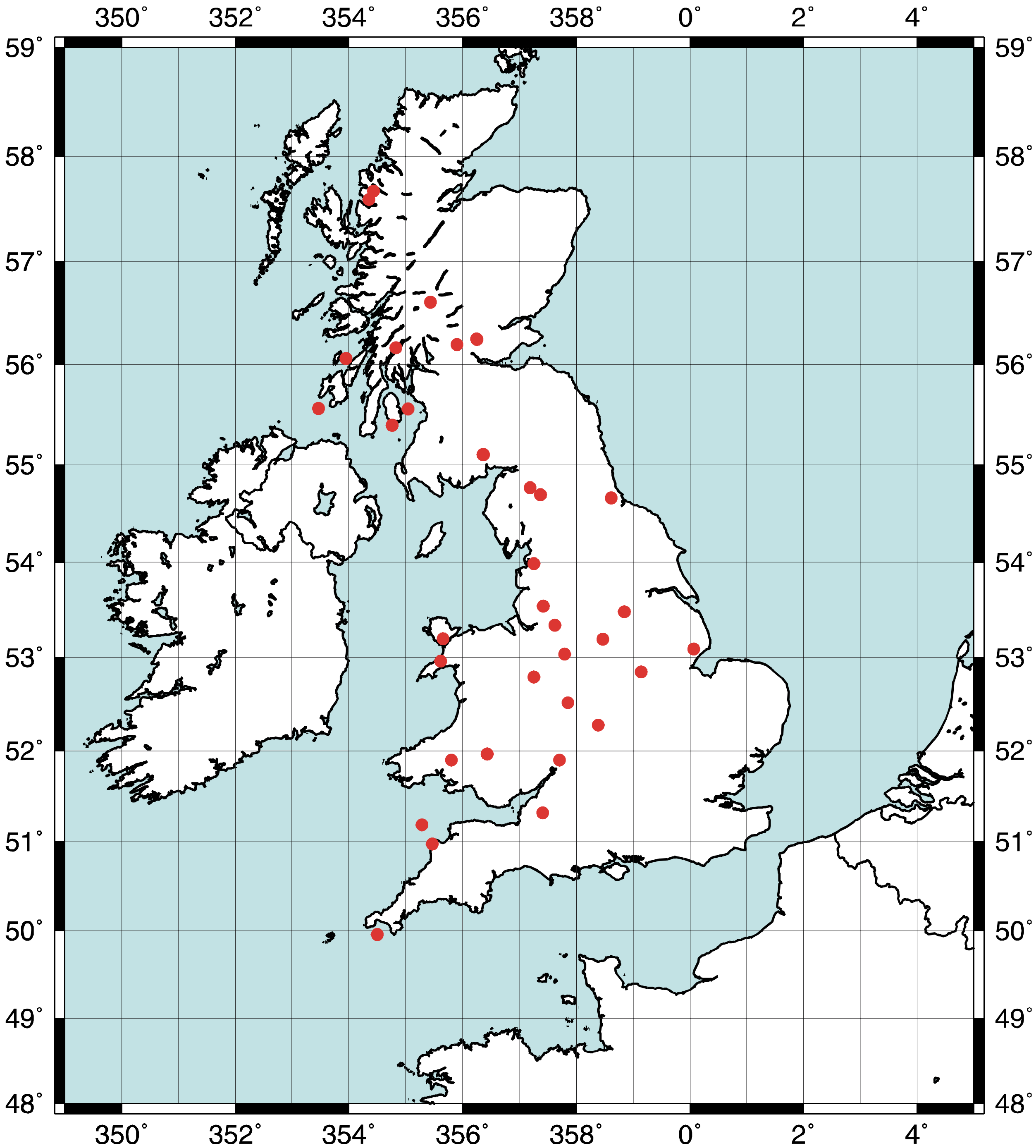


**Figure 1. Map of locations of earthquakes used in analysis of variance study.**

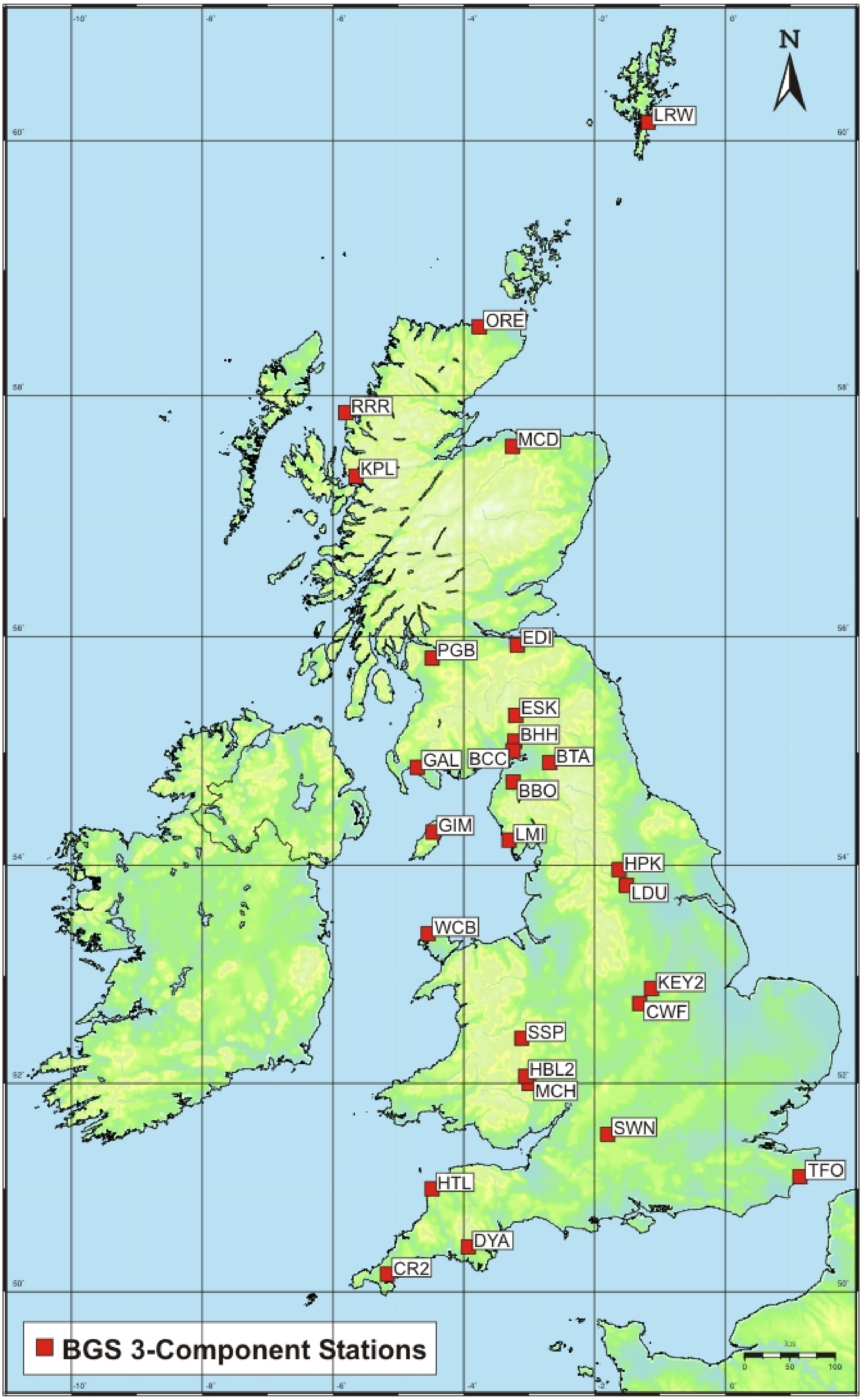


**Figure 2. Map of locations of three-component UK seismometer stations contributing data to the analysis of variance study.**

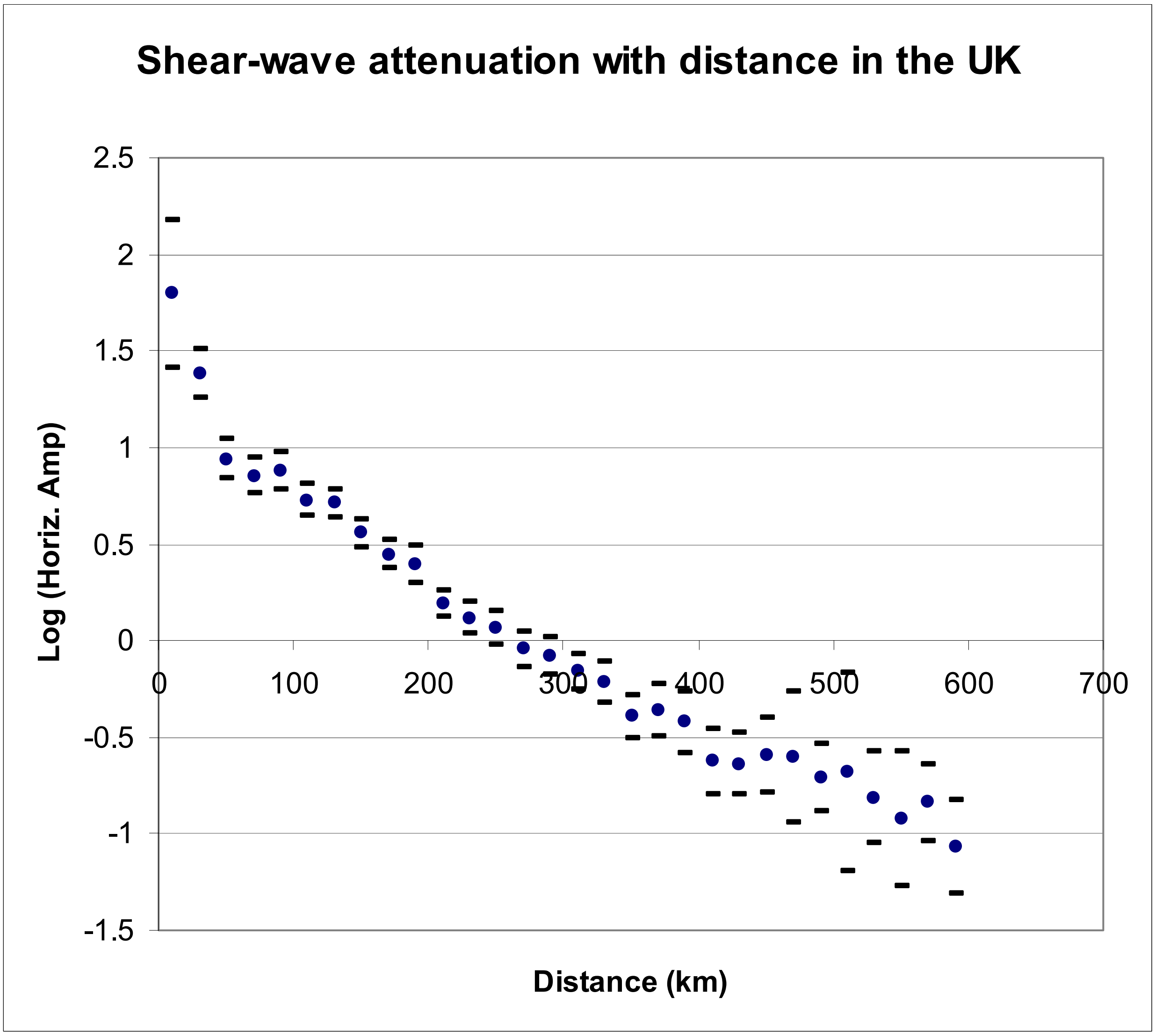


**Figure 3. Amplitude-distance variation of shear-waves in the UK region, from mean maximum amplitudes in horizontal component records. The 95% confidence limits at each 20km distance interval are indicated by the horizontal bars.**

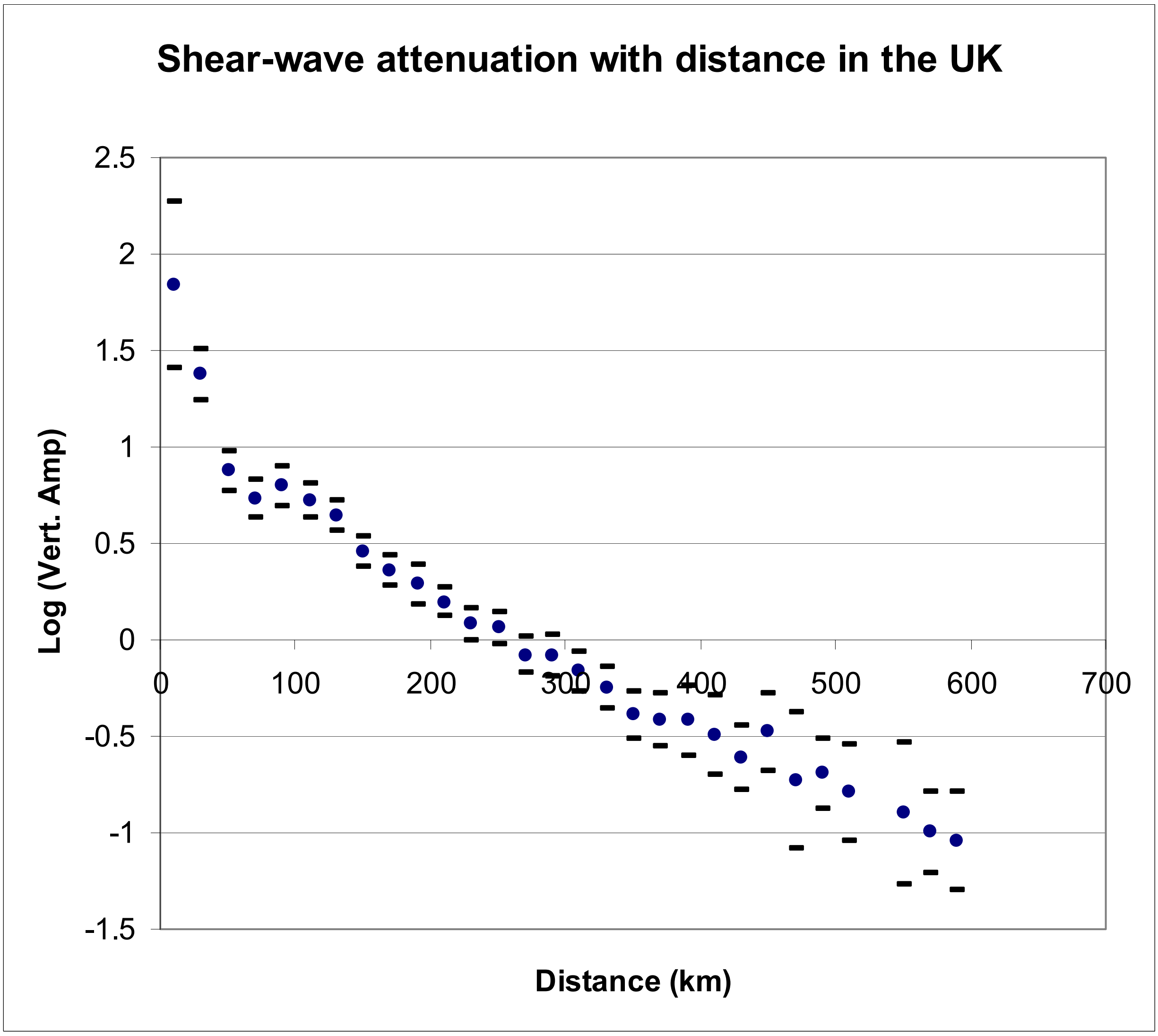


**Figure 4. Amplitude-distance variation of shear-waves in the UK region, from maximum amplitudes in vertical component records. The 95% confidence limits at each 20km distance interval are indicated by the horizontal bars.**

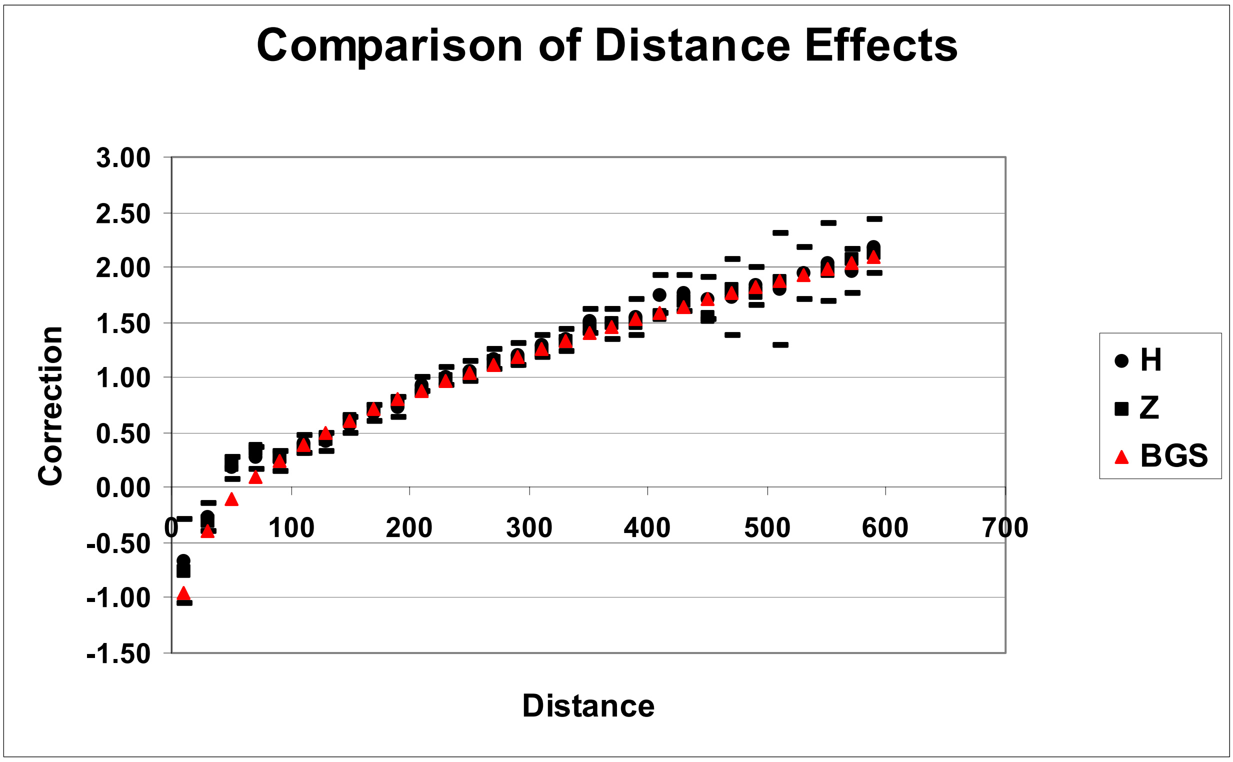


**Figure 5.** **Comparison of distance corrections** $B(\Delta)^{BGS}$ **, and** $B(\Delta)^{R}$ **for horizontal (H) and vertical (Z) amplitude measurements with associated error bars for H corrections, for the distance range 0 – 600km.**

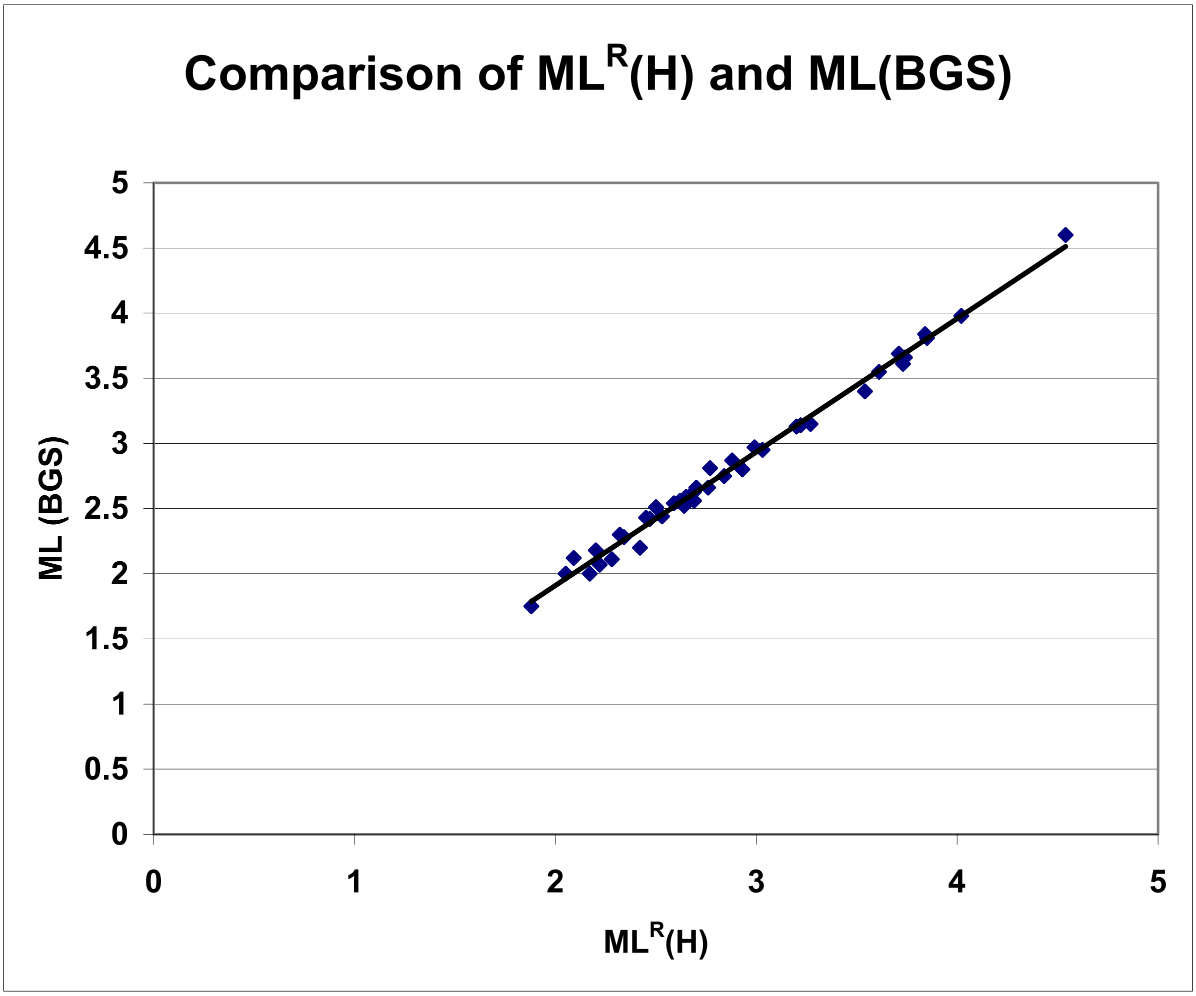


**Figure 6 Comparison of *$ML^R(H)$* and *$ML^{BGS}$* for the events used for the analysis of variance study (values given in Table 5). The straight line fit to the data has a slope of 1.02 and an intercept of -0.14.**

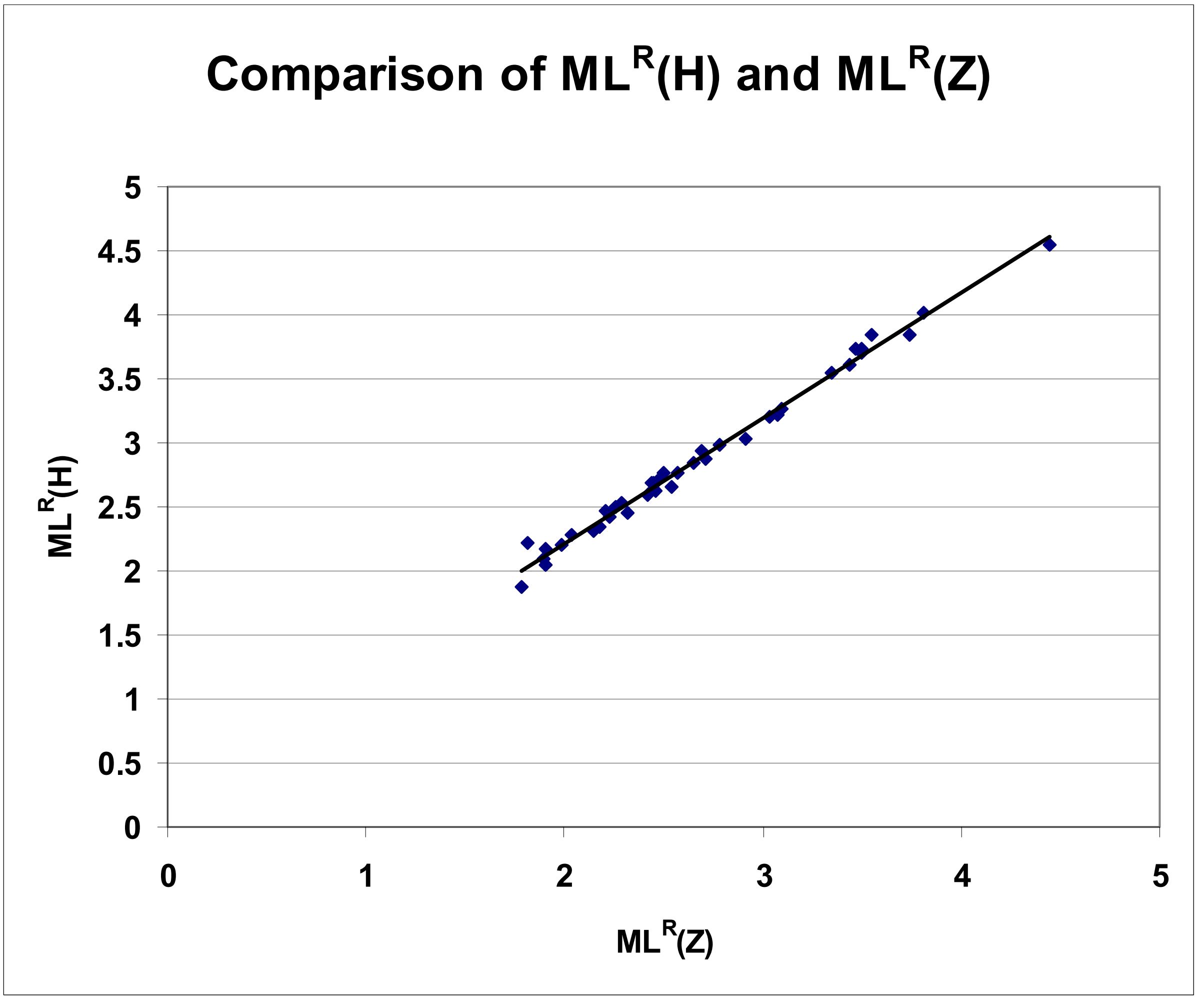


**Figure 7 Comparison of $ML^R(H)$ and $ML^R(Z)$ for the events used for the analysis of variance study (values given in Table 5). The straight line fit to the data has a slope of 0.98 and an intercept of 0.25.**

**Table 1 Statistics associated with the least squares analysis**

| | Horizontal | Vertical |
|---|---|---|
| Variance of a Single Observation | 0.0265 | 0.0282 |
| Total Degrees of Freedom | 300 | 282 |
| Sum of squares attributable to distance effect | 47.325 | 41.484 |
| Total degrees of freedom | 29 | 28 |
| Average square attributable to distance effect | 1.632 | 1.482 |
| Significance | <0.1% | <0.1% |
| Sum of squares attributable to station effect | 9.553 | 3.322 |
| Total degrees of freedom | 27 | 25 |
| Average square attributable to station effect | 0.354 | 0.132 |
| Significance | <0.1% | <0.1% |
| Constant | 1.744 | 1.594 |

**Table 2 Station Corrections with 95% confidence limits for application to log(Amplitude) measurements from horizontal (H) and Vertical (Z) component records. Strong motion stations are identified by an asterisk**

| Station | Correction (H) | Error (H) | Correction (Z) | Error (Z) |
|---|---|---|---|---|
| BBO | -0.03 | 0.07 | -0.06 | 0.07 |
| BHH | 0.24 | 0.07 | 0.05 | 0.07 |
| BCC* | 0.02 | 0.20 | -0.09 | 0.18 |
| BTA | 0.16 | 0.07 | 0.01 | 0.07 |
| CR2 | -0.22 | 0.12 | -0.01 | 0.12 |
| CWF | -0.16 | 0.09 | -0.16 | 0.09 |
| DYA | 0.09 | 0.14 | 0.11 | 0.15 |
| EDI | -0.12 | 0.08 | -0.19 | 0.08 |
| ESK | -0.23 | 0.07 | -0.04 | 0.08 |
| GAL | -0.22 | 0.08 | -0.07 | 0.09 |
| GIM | -0.19 | 0.07 | -0.05 | 0.07 |
| HPK | 0.37 | 0.10 | 0.08 | 0.11 |
| HBL2* | 0.24 | 0.17 | 0.20 | 0.20 |
| HTL | -0.05 | 0.10 | 0.08 | 0.12 |
| KEY2* | 0.36 | 0.20 | 0.17 | 0.25 |
| KPL | -0.18 | 0.09 | -0.09 | 0.09 |
| LDU* | 0.18 | 0.20 | | |
| LMI | -0.12 | 0.07 | 0.00 | 0.07 |
| LRW | -0.07 | 0.40 | | |
| MCD | 0.07 | 0.10 | 0.20 | 0.11 |
| MCH | 0.03 | 0.09 | -0.18 | 0.10 |
| ORE | 0.05 | 0.14 | 0.23 | 0.14 |
| PGB | -0.04 | 0.09 | -0.13 | 0.09 |
| RRR | -0.15 | 0.13 | -0.10 | 0.14 |
| SSP | -0.16 | 0.09 | -0.05 | 0.09 |
| SWN | 0.20 | 0.11 | 0.20 | 0.12 |
| TFO | 0.13 | 0.15 | 0.04 | 0.15 |
| WCB | -0.21 | 0.08 | -0.15 | 0.08 |

**Table 3 Distance corrections $B(\Delta)$ for application to log(Amplitude) measurements from horizontal component records to calculate $ML^{IMB}$ and $ML^{R}$**

| Distance (km) | $B(\Delta)^R$ (H) | $B(\Delta)^R$ (Z) | $B(\Delta)^{IMB}$ (H) |
|---|---|---|---|
| 0-20 | -0.67 | -0.76 | -1.20 |
| 20-40 | -0.26 | -0.30 | -0.79 |
| 40-60 | 0.19 | 0.20 | -0.34 |
| 60-80 | 0.27 | 0.34 | -0.26 |
| 80-100 | 0.25 | 0.28 | -0.28 |
| 100-120 | 0.40 | 0.35 | -0.13 |
| 120-140 | 0.42 | 0.43 | -0.11 |
| 140-160 | 0.57 | 0.62 | 0.04 |
| 160-180 | 0.68 | 0.72 | 0.15 |
| 180-200 | 0.73 | 0.79 | 0.20 |
| 200-220 | 0.94 | 0.88 | 0.41 |
| 220-240 | 1.01 | 0.99 | 0.48 |
| 240-260 | 1.06 | 1.02 | 0.53 |
| 260-280 | 1.17 | 1.15 | 0.64 |
| 280-300 | 1.21 | 1.16 | 0.68 |
| 300-320 | 1.29 | 1.24 | 0.76 |
| 320-340 | 1.34 | 1.33 | 0.81 |
| 340-360 | 1.52 | 1.47 | 0.99 |
| 360-380 | 1.49 | 1.49 | 0.96 |
| 380-400 | 1.55 | 1.49 | 1.02 |
| 400-420 | 1.75 | 1.57 | 1.22 |
| 420-440 | 1.77 | 1.69 | 1.24 |
| 440-460 | 1.72 | 1.55 | 1.19 |
| 460-480 | 1.73 | 1.81 | 1.20 |
| 480-500 | 1.83 | 1.77 | 1.30 |
| 500-520 | 1.81 | 1.87 | 1.28 |
| 520-540 | 1.94 | | 1.41 |
| 540-560 | 2.05 | 1.97 | 1.52 |
| 560-580 | 1.97 | 2.07 | 1.44 |
| 580-600 | 2.19 | 2.12 | 1.66 |

**Table 4. Comparison of Richter local magnitudes $ML^R$ and $ML^{BGS}$ and their standard deviations (S.D.) for all events used in the determination of station and distance corrections, for horizontal (H) and vertical (Z) component amplitude data.**

| Evt.DateTime | $ML^R$ (H) | S.D. | $ML^{BGS}$ (H) | S.D. | $ML^R$ (Z) | S.D. | $ML^{BGS}$ (Z) | S.D. |
|---|---|---|---|---|---|---|---|---|
| 9603072341 | 3.54 | 0.1 | 3.35 | 0.15 | 3.4 | 0.23 | 3.32 | 0.16 |
| 9604211828 | 2.22 | 0.13 | 1.81 | 0.15 | 2.07 | 0.13 | 1.76 | 0.17 |
| 9605060349 | 2.93 | 0.14 | 2.69 | 0.14 | 2.8 | 0.23 | 2.58 | 0.18 |
| 9605182101 | 3.2 | 0.13 | 3.03 | 0.15 | 3.13 | 0.14 | 3 | 0.2 |
| 9609200404 | 2.88 | 0.15 | 2.71 | 0.19 | 2.87 | 0.27 | 2.72 | 0.2 |
| 9610150542 | 1.88 | 0.24 | 1.78 | 0.23 | 1.75 | 0.28 | 1.6 | 0.12 |
| 9702042212 | 2.62 | 0.12 | 2.46 | 0.16 | 2.56 | 0.17 | 2.43 | 0.16 |
| 9702102309 | 2.77 | 0.11 | 2.5 | 0.06 | 2.81 | 0.18 | 2.48 | 0.08 |
| 9705172149 | 2.28 | 0.1 | 2.04 | 0.08 | 2.11 | 0.11 | 1.91 | 0.2 |
| 9707300834 | 2.84 | 0.15 | 2.65 | 0.2 | 2.75 | 0.23 | 2.58 | 0.31 |
| 9708261957 | 2.76 | 0.17 | 2.57 | 0.16 | 2.66 | 0.28 | 2.48 | 0.21 |
| 9710190242 | 2.5 | 0.07 | 2.26 | 0.18 | 2.51 | 0.16 | 2.28 | 0.15 |
| 9711080446 | 2.47 | 0.14 | 2.21 | 0.11 | 2.42 | 0.22 | 2.23 | 0.19 |
| 9802080551 | 2.34 | 0.09 | 2.18 | 0.09 | 2.28 | 0.18 | 2.16 | 0.11 |
| 9802171426 | 2.32 | 0.12 | 2.15 | 0.15 | 2.3 | 0.26 | 2.03 | 0.23 |
| 9803262051 | 2.69 | 0.14 | 2.45 | 0.15 | 2.56 | 0.29 | 2.34 | 0.34 |
| 9805030212 | 3.61 | 0.13 | 3.44 | 0.15 | 3.55 | 0.17 | 3.39 | 0.16 |
| 9805311255 | 2.53 | 0.07 | 2.29 | 0.07 | 2.44 | 0.1 | 2.25 | 0.16 |
| 9807200738 | 2.69 | 0.07 | 2.44 | 0.06 | 2.63 | 0.17 | 2.4 | 0.08 |
| 9807210716 | 2.17 | 0.14 | 1.91 | 0.14 | 2 | 0.21 | 1.76 | 0.2 |
| 9807311055 | 2.09 | 0.15 | 1.9 | 0.11 | 2.12 | 0.2 | 1.85 | 0.13 |
| 9808082207 | 2.05 | 0.17 | 1.91 | 0.17 | 2 | 0.24 | 1.81 | 0.2 |
| 9809150232 | 2.42 | 0.18 | 2.23 | 0.11 | 2.2 | 0.17 | 2.08 | 0.11 |
| 9901211110 | 2.99 | 0.11 | 2.78 | 0.12 | 2.97 | 0.24 | 2.78 | 0.13 |
| 9903040016 | 3.71 | 0.08 | 3.5 | 0.13 | 3.69 | 0.24 | 3.49 | 0.16 |
| 9906170220 | 2.7 | 0.06 | 2.47 | 0.07 | 2.66 | 0.18 | 2.45 | 0.12 |
| 9909010500 | 3.22 | 0.14 | 3.07 | 0.09 | 3.14 | 0.17 | 3.04 | 0.11 |
| 9910020350 | 2.59 | 0.17 | 2.42 | 0.09 | 2.54 | 0.27 | 2.35 | 0.18 |
| 9910251915 | 3.73 | 0.16 | 3.5 | 0.12 | 3.61 | 0.23 | 3.44 | 0.13 |
| 0002120851 | 3.03 | 0.19 | 2.91 | 0.19 | 2.95 | 0.29 | 2.83 | 0.29 |
| 0004240510 | 2.64 | 0.16 | 2.45 | 0.12 | 2.52 | 0.23 | 2.35 | 0.19 |
| 0006221436 | 2.65 | 0.08 | 2.54 | 0.12 | 2.59 | 0.14 | 2.51 | 0.09 |
| 0008080246 | 2.45 | 0.21 | 2.32 | 0.21 | 2.43 | 0.3 | 2.31 | 0.23 |
| 0009230423 | 3.84 | 0.11 | 3.55 | 0.08 | 3.84 | 0.22 | 3.56 | 0.13 |
| 0102251239 | 2.2 | 0.13 | 1.99 | 0.11 | 2.18 | 0.12 | 1.93 | 0.11 |
| 0105130826 | 3.27 | 0.19 | 3.09 | 0.21 | 3.15 | 0.27 | 2.98 | 0.38 |
| 0105312343 | 3.74 | 0.12 | 3.47 | 0.15 | 3.66 | 0.18 | 3.43 | 0.12 |
| 0110281625 | 4.02 | 0.1 | 3.81 | 0.14 | 3.98 | 0.23 | 3.82 | 0.22 |
| 0209222353 | 4.54 | 0.19 | 4.45 | 0.14 | 4.6 | 0.3 | 4.54 | 0.12 |
| 0210211141 | 3.85 | 0.13 | 3.74 | 0.16 | 3.81 | 0.22 | 3.74 | 0.19 |

**Table 5 Comparison of $ML^{IMB}$ and $ML^{BGS}$ with $M_B$ magnitudes estimated by IDC and NEIC.**

| No. | Date | Time | Latitude | Longitude | $m_b$ (agency) | $ML^{IBC}$ | $ML^{BGS}$ |
|---|---|---|---|---|---|---|---|
| 1 | 23/09/00 | 04:23 | 52.280 | -1.610 | 3.3 (IDC) | 3.3 | 3.8 |
| 2 | 08/12/00 | 05:54 | 59.944 | 1.934 | 4.3 (IDC) | 4.4 | 4.8 |
| | | | | | 4.7 (NEIC) | | |
| 3 | 14/03/01 | 22:20 | 58.252 | -0.695 | 3.2 (IDC) | 2.9 | 3.3 |
| | | | | | 3.3 (NEIC) | | |
| 4 | 07/05/01 | 09:43 | 56.596 | 3.248 | 3.6 (IDC) | 3.4 | 4.0 |
| 5 | 31/05/01 | 23:42 | 50.977 | -4.531 | 3.6 (IDC) | 3.2 | 3.7 |
| 6 | 28/10/01 | 16:25 | 52.846 | -0.856 | 3.7 (IDC) | 3.5 | 3.9 |
| | | | | | 4.2 (NEIC) | | |
| 7 | 14/02/02 | 1900 | 59.793 | 2.536 | 3.9 (NEIC) | 3.6 | 4.0 |
| 8 | 22/09/02 | 23:53 | 52.520 | -2.150 | 4.0 (IDC) | 4.0 | 4.7 |
| | | | | | 4.7 (NEIC) | | |