STATION CORRECTION ANALYSIS FOR SURFACE-WAVE MAGNITUDES OF NEW ZEALAND EARTHQUAKES

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SUMMARY

Station terms and standard errors are presented for 345 world-wide stations used in the determination of surface-wave magnitudes of 190 selected New Zealand earthquakes over the period 1901-1993 [1]. These will facilitate the estimation of surface-wave magnitudes of other earthquakes in the New Zealand region. The station terms and the residuals from the linear model used to estimate them are both found to be weakly related to the mean distance from the earthquakes recorded by each station. The horizontal and vertical components at a given site are treated as separate stations. The station term for the horizontal component tends to exceed that for the vertical component at mean distances in the 20°-40° range.

INTRODUCTION

This paper describes the station correction analysis for surface-wave magnitudes of a selection of 190 of the larger New Zealand earthquakes over the period 1901 to 1993 [1]. It follows a similar study [2, 3] carried out on a smaller selection of earthquakes with data from fewer stations. The methodology of the previous study has been followed in the main. An exception, discussed below, is in the treatment of the horizontal and vertical components at a single station.

The larger data set analysed in the present study allows station terms to be estimated for many more stations. It also offers the prospect of improved estimates of the station terms for the 96 stations included in the previous study.

Estimates of M_S are normally made only from data recorded at distances less than 160°, e.g., as practised in the ISC Bulletin. This would exclude data from many stations in Europe, as seen in Figure 1, reducing our data set for New Zealand earthquakes from 2040 station observations of M_S to 1577. However, as found previously [2], data at distances > 160° is made admissible by correcting for bias by calculating station corrections using analysis of variance.

METHOD

The data set used for this study has been described elsewhere [1], together with the computation of surface-wave magnitudes at each station from the seismograph records.

The estimation of station terms has been carried out simultaneously with the estimation of the surface-wave magnitudes, by fitting an analysis-of-variance model incorporating both earthquake terms and station terms. The model used is as follows [2]:

$$M_{ij} = m_i + c_j + e_{ij} \quad (1)$$

where M_{ij} is the magnitude of the ith earthquake computed from the seismographic record at the jth station, m_i is the "true" average magnitude of the ith earthquake, c_j is the fixed effect of the jth station, and the e_{ij} are independent normally distributed random errors with a common variance σ^2 that combines both observational inaccuracy and modelling deficiency. The modelling deficiency includes differences in the average attenuation along the paths to the stations, but as we are concerned solely with New Zealand events the paths to any given station will not vary greatly and the differences in average attenuation are therefore not expected to be large [2]. The above model is readily fitted by the method of ordinary least squares, although solving for such a large number of parameters (535) as are in the present study is demanding of computer memory. The size of the problem was substantially reduced by omitting from the data set, for model-fitting purposes, those stations which have only one observation. These stations contribute nothing to the estimation of magnitude, but their station terms can be estimated separately by $\hat{c}_j = M_{ij} - \hat{m}_i$, and their standard errors by $S(\hat{c}_j) = [S(\hat{m}_i)^2 + s^2]^{1/2}$, where $S(\hat{m}_i)$ is the standard error of the estimated magnitude and s is the residual standard deviation from model (1).

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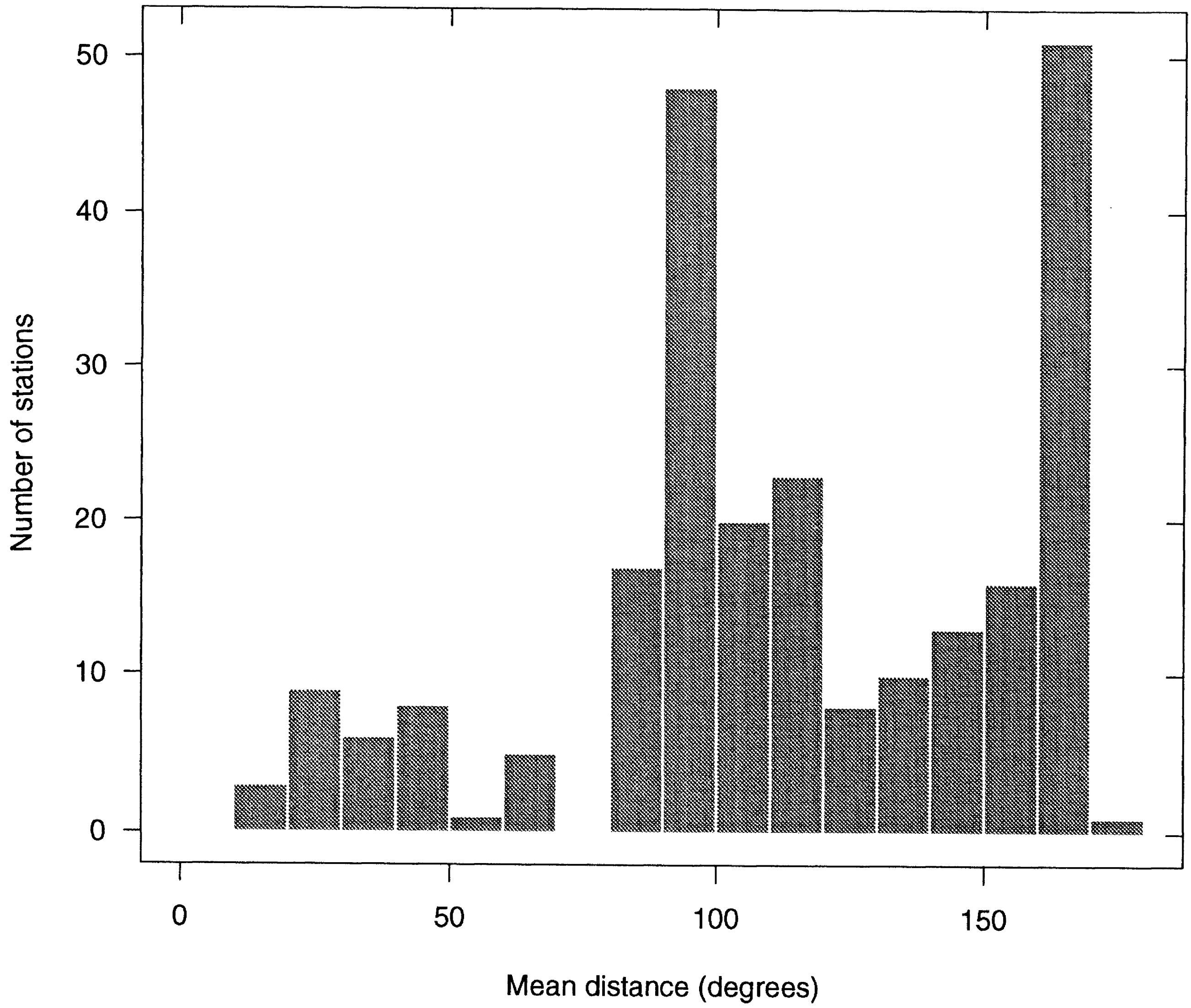

Figure 1 ***Histogram of mean distances from New Zealand earthquake sources of the stations outside of New Zealand used to determine surface-wave magnitudes.***

RESULTS

The station terms, $\hat{c}$, and standard errors, $S(\hat{c})$, are listed in Table 1, together with the mean earthquake-station distance, D (in degrees), and the number of observations, N, at each station. For stations included in the the previous study [2], the station terms do not differ greatly in most cases from the values given previously, but many of the standard errors are smaller because of the larger number of observations contributing to the estimates. The residual standard deviation from model (1) is given by $s = 0.200$.

The three or four letter station codes are those used by the ISC [4, 5]. In some cases a single letter code ("M" or "Z") follows the station code. Some earlier events were recorded on undamped Milne seismographs at certain stations. These observations have been treated as belonging to a different station from later recordings made at the same sites with damped seismographs, with an "M" added after the station code to distinguish the Milne instrument. Likewise horizontal and vertical components at the same site have been treated as separate stations in all cases, and a "Z" following the station code distinguishes the vertical component, where available. A somewhat different practice was adopted in the previous study [2], in which horizontal and vertical components were regarded as coming from the same station, and therefore averaged, except where they were found to differ significantly.

The linear model (1) does not allow independent estimation of all parameters; one parameter, or linear combination of parameters, must be fixed arbitrarily. As in the previous study [2], the station "UPP" (Uppsala) was chosen as a reference station and its station term arbitrarily set to zero, with a consequential systematic effect on all estimated magnitudes. Since the mean of the station terms turned out to be 0.001, the results are essentially the same as if the mean of the station terms had been set to zero.

The station terms and standard errors may be used to streamline the computation of surface-wave magnitudes of New Zealand earthquakes in future studies, by correcting each station observation and averaging all corrected observations to produce

Table 1: Station statistics and parameter estimates: Mean earthquake-station distance, *D*, in degrees, number of observations *N*, estimated station term $\hat{c}$, and standard error $S(\hat{c})$.

Station	D	N	$\hat{c}$	$S(\hat{c})$
AAS Z	70	2	0.22	0.151
ABE	164	4	0.12	0.111
ADE M	24	1	-0.56	0.259
ADE	31	1	-0.05	0.212
AFI	27	14	-0.27	0.071
AFI Z	27	10	-0.60	0.079
AGR	113	1	-0.14	0.211
AKU Z	154	2	0.23	0.150
ALG	173	7	0.19	0.087
ALQ	101	2	-0.06	0.151
ALQ Z	105	19	0.05	0.063
ANMO Z	106	2	0.27	0.151
ANN	150	1	0.47	0.207
ANN Z	150	1	0.27	0.207
ANR	122	1	-0.18	0.208
ANR Z	122	1	-0.03	0.208
APP Z	156	1	0.05	0.214
ARU	136	2	-0.12	0.149
ARU Z	136	2	-0.12	0.149
ASPA Z	37	24	0.06	0.060
BAK	140	11	0.43	0.080
BAK Z	139	5	0.35	0.087
BCAO Z	140	1	-0.31	0.214
BEO	159	12	0.09	0.069
BER	158	2	-0.04	0.152
BER Z	161	1	-0.24	0.209
BID M	168	2	0.30	0.205
BJI	96	16	-0.27	0.065
BJI Z	96	18	-0.16	0.064
BKS	96	6	-0.09	0.093
BKS Z	96	7	0.04	0.088
BLV	125	1	0.17	0.243
BMO	104	4	-0.38	0.112
BMO Z	105	5	-0.15	0.104
BNS Z	165	1	-0.23	0.208
BOM M	113	1	0.05	0.243
BOM	111	23	-0.07	0.056
BRA	159	1	-0.72	0.212
BRG	162	10	0.19	0.077
BRG Z	162	11	0.10	0.075
BRK Z	96	1	0.21	0.207
BRS Z	21	2	0.33	0.150
BRU	168	12	0.25	0.069
BRU Z	168	2	0.18	0.150
BTO	100	9	-0.21	0.079
BTO Z	100	2	-0.39	0.149
BUD	162	10	0.12	0.074
BUL	116	1	-0.28	0.208
BUL Z	116	2	0.13	0.150
CAL M	10	1	0.00	0.243
CAL	103	1	-0.03	0.211
CAP M	10	1	0.61	0.269
CAR	120	2	-0.07	0.150
CAR Z	120	2	0.03	0.150
CBD	133	1	-0.17	0.229
CBM Z	13	1	-0.35	0.209

Station	D	N	$\hat{c}$	$S(\hat{c})$
CDU	96	2	-0.29	0.151
CD2	96	6	-0.15	0.093
CD2 Z	96	8	-0.18	0.083
CEH Z	126	3	-0.19	0.126
CFF	167	1	-0.55	0.211
CHG Z	92	1	0.59	0.225
CLL Z	162	8	0.05	0.084
CMB	97	1	0.15	0.209
CNH	94	2	-0.16	0.150
CN2	95	12	-0.26	0.072
CN2 Z	95	15	-0.10	0.068
COL Z	105	1	0.03	0.210
COP Z	160	6	0.16	0.093
COR M	8	1	0.37	0.269
CPO	119	3	0.00	0.130
CPO Z	116	4	-0.09	0.115
CTA	31	1	-0.36	0.213
CTA Z	32	9	-0.09	0.085
CUL M	10	1	0.62	0.269
DAG	143	1	0.20	0.207
DAG Z	145	3	0.07	0.127
DBN	166	28	0.42	0.053
DBN Z	16	18	0.21	0.058
DJA	64	1	-0.12	0.222
DL2	93	4	-0.24	0.110
DL2 Z	92	8	-0.38	0.083
DOU Z	16	5	0.15	0.101
DUG Z	10	2	-0.12	0.149
DUR	167	1	-0.08	0.212
EDI M	166	2	-0.02	0.205
EGE	164	12	-0.01	0.071
ERE	141	1	0.11	0.208
ERE Z	144	1	0.27	0.207
FUR	165	2	0.28	0.151
FUR Z	164	3	0.10	0.124
FVM Z	116	2	0.39	0.152
GDH Z	138	1	-0.19	0.213
GLD Z	111	6	0.10	0.093
GOGA Z	117	1	0.45	0.209
GOL Z	112	8	0.03	0.083
GRA	165	1	0.15	0.213
GRE Z	165	1	-0.13	0.214
GRF Z	165	21	0.08	0.061
GRM Z	94	1	-0.02	0.207
GRO	144	1	0.07	0.207
GRO Z	144	1	0.47	0.207
GTA	104	6	-0.33	0.093
GTA Z	104	8	-0.14	0.083
GTT	165	9	0.11	0.079
GTT Z	165	4	0.23	0.099
GUA Z	60	2	-0.42	0.149
GUMO Z	61	6	-0.23	0.095
GYA	91	10	-0.29	0.076
GYA Z	92	10	-0.30	0.077
GZH	84	6	-0.30	0.093
GZH Z	85	6	-0.43	0.093

Station	D	N	$\hat{c}$	$S(\hat{c})$
HAM	164	9	0.38	0.079
HAM Z	164	4	0.24	0.110
HAU Z	167	1	-0.23	0.210
HEL	151	1	-0.23	0.211
HFS Z	156	5	-0.05	0.105
HHC	99	7	-0.22	0.088
HHC Z	99	9	-0.11	0.080
HLL	32	5	0.08	0.118
HLL Z	32	5	0.01	0.118
HLW	145	4	0.42	0.100
HOF Z	163	1	-0.04	0.208
HON Z	67	7	-0.39	0.088
HRV	139	1	-0.22	0.207
HRV Z	132	2	-0.12	0.152
HUR	160	2	-0.12	0.151
HYD	105	12	0.09	0.070
IRK	111	11	-0.37	0.072
IRK Z	111	5	-0.26	0.099
ISA Z	96	1	0.15	0.209
JCT Z	104	5	0.13	0.101
JEN	164	11	-0.02	0.071
JEN Z	164	9	0.03	0.081
JEN 2	164	9	-0.10	0.077
KAR	167	1	0.04	0.208
KAT	134	2	-0.08	0.149
KAT Z	135	1	0.27	0.207
KER	69	1	-0.62	0.211
KEV Z	148	1	-0.31	0.210
KEW M	138	2	0.06	0.205
KEW	168	6	0.34	0.093
KEW Z	166	3	0.28	0.125
KHC	164	14	0.04	0.069
KHC Z	164	15	0.11	0.067
KIR	149	13	0.04	0.068
KIR Z	150	14	0.10	0.066
KIS	153	1	0.06	0.208
KJF Z	149	2	0.13	0.150
KMI	93	14	-0.13	0.068
KMI Z	93	14	-0.01	0.069
KOD M	101	1	0.30	0.269
KOD	101	7	0.11	0.086
KRA	159	6	0.23	0.093
KRA Z	159	12	0.20	0.072
KSH	118	6	-0.05	0.093
KSH Z	119	5	-0.26	0.100
KSN	156	1	0.12	0.229
KUC	149	6	0.04	0.093
KUR	89	2	-0.04	0.149
KUR Z	89	2	-0.19	0.149
LEI	163	10	0.11	0.074
LEI Z	162	3	0.14	0.125
LEM	158	2	-0.02	0.150
LEN Z	150	1	0.05	0.214
LIC Z	145	12	0.03	0.075
LJU	164	3	0.15	0.124
LOR Z	170	2	0.24	0.152
LPA	90	6	-0.16	0.093
LPA Z	91	16	-0.02	0.065

Station	D	N	$\hat{c}$	$S(\hat{c})$
LPB	99	23	-0.06	0.057
LPB Z	99	28	-0.08	0.055
LSA	101	1	-0.12	0.207
LSA Z	101	1	0.08	0.207
LZH	100	14	-0.21	0.069
LZH Z	100	10	-0.29	0.078
MAG	103	1	0.27	0.208
MAK	145	2	0.00	0.152
MAK Z	150	1	0.03	0.214
MAT	82	4	-0.36	0.111
MAT Z	84	20	-0.37	0.061
MAW Z	63	1	-0.23	0.207
MBO	146	2	0.66	0.152
MBO Z	147	3	0.52	0.126
MCWV Z	127	3	0.06	0.125
MDJ	94	5	-0.17	0.100
MDJ Z	94	7	-0.16	0.088
MEL M	24	7	0.15	0.096
MEL	23	20	-0.04	0.065
MHC	96	2	-0.23	0.149
MHC Z	96	2	-0.23	0.149
MIAR Z	116	2	-0.01	0.150
MIR	48	1	0.43	0.208
MIR Z	48	1	0.45	0.208
MOS	149	4	-0.01	0.109
MOS Z	148	1	-0.03	0.207
MOX	164	17	0.06	0.063
MOX Z	164	18	0.07	0.062
MTA	144	1	0.77	0.207
MTA Z	144	1	0.87	0.207
MUN	49	3	-0.06	0.125
MUN Z	48	9	-0.17	0.080
NAI Z	126	1	-0.03	0.207
NDI	116	1	0.06	0.212
NDI Z	116	1	-0.06	0.212
NEW Z	106	4	0.36	0.110
NJI	88	1	0.08	0.209
NJ2	89	5	-0.32	0.100
NJ2 Z	89	6	-0.49	0.094
NNA Z	97	5	-0.41	0.100
NOU	18	1	0.28	0.213
NUR Z	152	9	0.00	0.084
NVL	68	4	-0.01	0.110
NVL Z	69	4	-0.01	0.110
NWAO	46	8	-0.39	0.088
NWAO Z	45	12	-0.41	0.075
OBN	149	3	-0.02	0.124
OBN Z	149	5	0.18	0.105
OSA	83	5	0.03	0.101
PAR	170	19	0.31	0.060
PAS Z	94	1	0.32	0.208
PER M	48	2	0.00	0.205
PER	46	3	0.37	0.127
PET Z	96	1	0.69	0.208
PMG Z	39	1	-0.07	0.214
PMR	105	2	-0.14	0.150
PMR Z	106	6	-0.16	0.093
POL	167	3	0.08	0.129

Station	D	N	$\hat{c}$	$S(\hat{c})$
POO	113	1	0.41	0.210
POT	164	3	0.24	0.131
PPT Z	45	2	-0.05	0.149
PRA	163	18	0.03	0.060
PRA Z	163	12	0.09	0.071
PRU	162	22	0.06	0.059
PRU Z	163	25	0.13	0.059
PUL	151	11	0.01	0.075
PUL Z	151	8	0.08	0.082
QIZ	84	6	-0.26	0.093
QZH	83	8	-0.26	0.083
QZH Z	83	7	-0.33	0.087
RAC Z	158	1	-0.12	0.207
RAR	26	13	0.01	0.072
RAR Z	28	14	-0.44	0.071
RIV	20	125	-0.06	0.042
RIV Z	20	92	-0.29	0.043
RJF Z	173	1	0.04	0.212
ROX	8	1	0.48	0.227
ROX Z	8	1	0.33	0.227
RSCP Z	122	6	-0.06	0.093
RSNY Z	131	9	0.09	0.080
RSON Z	124	7	0.03	0.088
RSSD Z	116	3	0.02	0.125
SAO Z	100	2	-0.06 -	0.150
SBA	38	36	0.04	0.055
SBA Z	38	34	-0.23	0.056
SDN Z	101	3	-0.10	0.124
SEM	122	1	-0.02	0.208
SEM Z	122	1	0.02	0.208
SHE	141	1	-0.13	0.207
SHE Z	141	1	0.57	0.207
SHI M	170	2	0.34	0.205
SIM	150	1	0.15	0.208
SIM Z	150	1	0.22	0.208
SIT Z	108	7	0.07	0.087
SJG	122	1	0.12	0.208
SJG Z	122	5	-0.15	0.101
SKA	157	1	-0.54	0.212
SKO	159	8	0.17	0.084
SKO Z	159	11	0.05	0.074
SLL Z	156	2	0.18	0.150
SLM Z	119	5	0.01	0.101
SLR Z	106	2	0.32	0.150
SMY Z	94	6	0.02	0.093
SNY	95	6	-0.27	0.093
SNY Z	94	9	-0.23	0.080
SOC	148	1	0.27	0.207
SOC Z	148	1	0.17	0.207
SPA	53	1	-0.07	0.209
SPA Z	50	26	-0.14	0.058
SRO	161	3	0.07	0.125
SSE	87	19	-0.18	0.063
SSE Z	87	25	-0.17	0.059
SSF	86	1	-0.21	0.213
SSH	86	1	0.11	0.209
SSPA Z	133	1	0.08	0.207
STR	167	14	0.26	0.067
STR Z	167	8	0.19	0.077

Station	D	N	$\hat{c}$	$S(\hat{c})$
STU	166	5	0.16	0.099
STU Z	166	5	0.25	0.099
SUV M	23	5	0.14	0.106
SUV	24	11	0.15	0.078
SVE	136	16	-0.05	0.067
SVE Z	136	7	-0.13	0.082
SYD M	20	3	0.12	0.144
TAS	127	18	-0.17	0.063
TAS Z	127	3	-0.68	0.125
TFO	101	1	0.41	0.232
TFO Z	100	4	-0.20	0.115
TIA	93	11	-0.25	0.074
TIA Z	93	10	-0.20	0.077
TIK	118	1	0.37	0.208
TIY	96	9	-0.19	0.080
TIY Z	96	9	-0.12	0.080
TLG	120	1	0.19	0.208
TLG Z	120	1	0.28	0.208
TNT M	127	2	-0.52	0.205
TPNV Z	98	2	0.10	0.150
TRI	166	3	-0.04	0.131
TUC	96	1	0.26	0.209
TUC Z	97	3	-0.23	0.128
TUL Z	115	3	0.29	0.124
UBO	107	3	-0.06	0.134
UBO Z	107	4	-0.09	0.118
UPA	114	1	0.13	0.209
UPA Z	111	3	-0.03	0.125
UPP	156	35	0.00	0.000
UPP Z	156	15	0.10	0.064
UZH	158	1	0.06	0.208
VIC M	103	1	0.57	0.243
VKA	162	2	-0.07	0.150
VKA Z	161	6	-0.03	0.093
VLA	92	6	-0.39	0.091
VLA Z	92	4	-0.42	0.109
WAR	157	1	-0.33	0.212
WAR Z	157	1	-0.11	0.212
WDC Z	97	1	0.15	0.209
WET Z	164	1	-0.46	0.212
WHN	90	10	-0.24	0.076
WHN Z	90	10	-0.28	0.077
WIE	164	6	0.08	0.091
WIE Z	163	4	0.00	0.109
WIN Z	119	2	0.24	0.152
WMOK Z	111	2	0.28	0.149
WMO	111	3	-0.08	0.131
WMO Z	110	6	0.15	0.097
WMQ	114	3	-0.23	0.125
WMQ Z	114	7	-0.27	0.088
XAN	96	11	-0.28	0.074
XAN Z	95	3	-0.27	0.124
YAK	107	1	0.17	0.207
YAK Z	107	1	0.17	0.207
YSS	94	2	-0.10	0.149
YSS Z	94	2	-0.17	0.149
ZOBO Z	99	9	-0.32	0.082
ZST Z	159	1	-0.34	0.207

a best estimate. Thus, if some earthquake not in the present data set [1] has observed magnitudes M_j at stations j=1, ... , n, then the surface-wave magnitude may be estimated by

$$\hat{m} = \sum_{j=1}^{n} \left(M_j - \hat{c}_j \right) / n \qquad (2)$$

where $\hat{c}_j$ is the station term obtained from Table 1. This estimate has standard error $S(\hat{m})$ given by

$$S(\hat{m}) = \left[ns^2 + \sum_{j=1}^{n} S\left(\hat{c}_j\right)^2 \right]^{1/2} / n \qquad (3)$$

Clearly, the greater the number of stations used, the smaller the standard error $S(\hat{m})$ will tend to be. The data in Table 1 allow an examination of possible relations between station effects and distance. In Figure 2 the station term is plotted against the mean distance of the station from earthquakes it recorded. Also plotted is a robust smooth trend line computed using the Splus function "lowess" [6]. It can be seen that the station term varies systematically with distance, being most negative (-0.07) at about 90° and most positive (+0.18) at about 173° (the greatest mean distance in the data set).

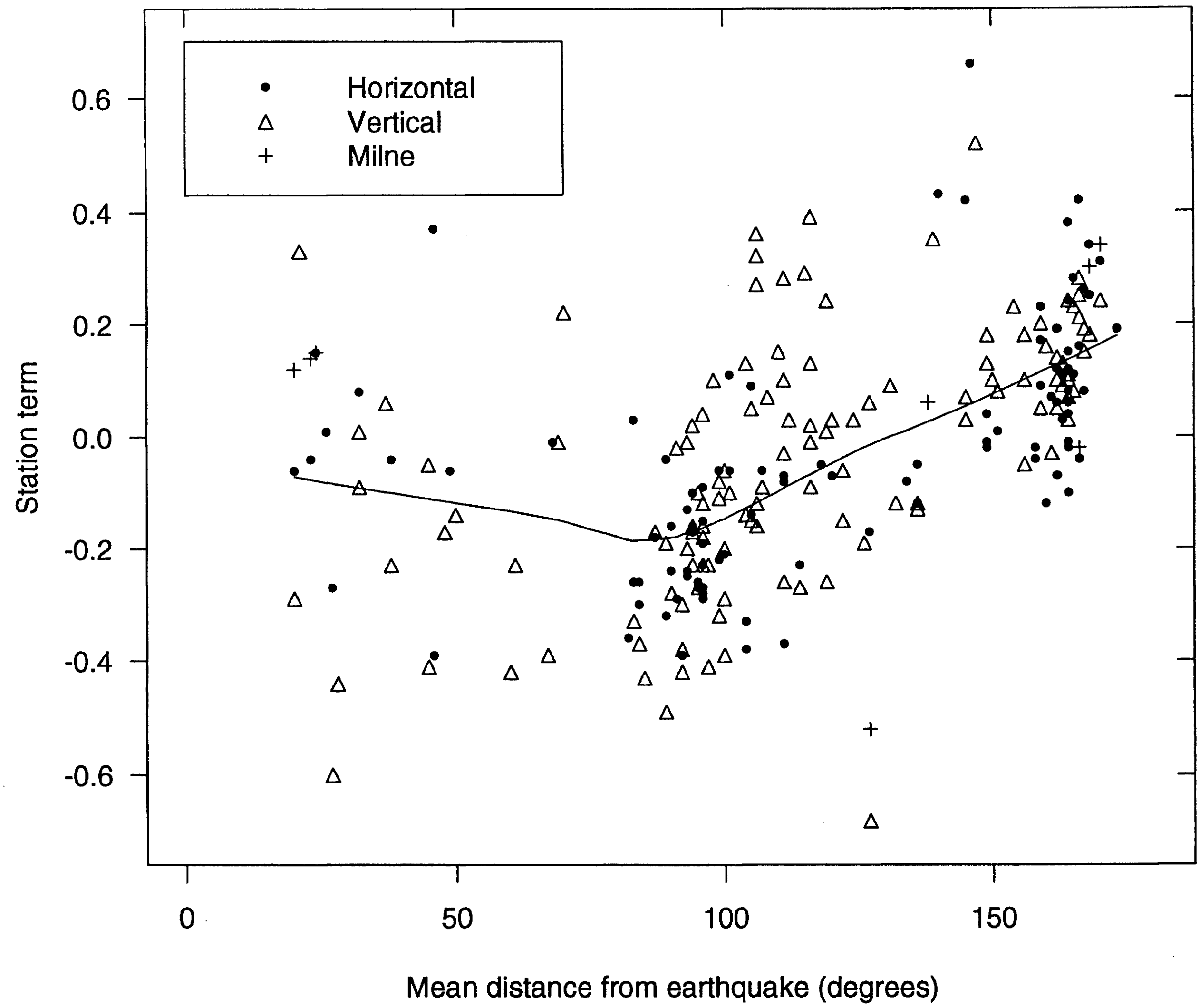

Figure 2 *Plot of station terms against mean distance, in degrees, of New Zealand earthquakes from the station, distinguishing horizontal and vertical components (damped seismographs) and undamped Milne seismographs. A robust smooth trend, computed using the Splus "lowess" function [6], has been fitted through all the data.*

The trend in Figure 2 is consistent with the expected second-order effects of the geometry of the world's surface on surface-wave attenuation. Surface-wave trains diverge out to distances of 90° and then converge between 90° and 180°. Hence the attenuation of surface waves will tend to be greater out to 90° and less between 90° and 180°, relative to the mean attenuation relation used for estimates of surface-wave magnitude at individual stations [1]. It should be no surprise, then, to see the decreasing trend in station terms out to 90° and the increasing trend from 90° to 180°.

The relatively small spread of station terms at mean distances greater than 150° suggests less variability in this range. This is confirmed by a plot of the absolute value of the residuals from model (1) against distance (Figure 3), again with an accompanying trend line. Here, the residual r_{ij} of the ith earthquake at the jth station is defined by

$$r_{ij} = M_{ij} - \hat{m}_j - \hat{c}_j$$

Figure 3 shows that the size of the residuals, although quite variable, decreases, on average, from about 0.13 to about 0.1, as the distance increases from about 90° to 173°. Thus, it is the stations at distances greater than 160° which contribute data of highest precision to the estimation of New Zealand surface-wave magnitudes, provided that station corrections are made. This is a significant result, since it is common practice to use only stations at distances in the range 20° $\leq D \leq$ 160° to estimate surface-wave magnitudes (e.g. the ISC Bulletin). The data at distances greater than 160° are particularly important for New Zealand earthquakes because they comprise about a quarter of the total available data. Their relatively high precision makes them even more important.

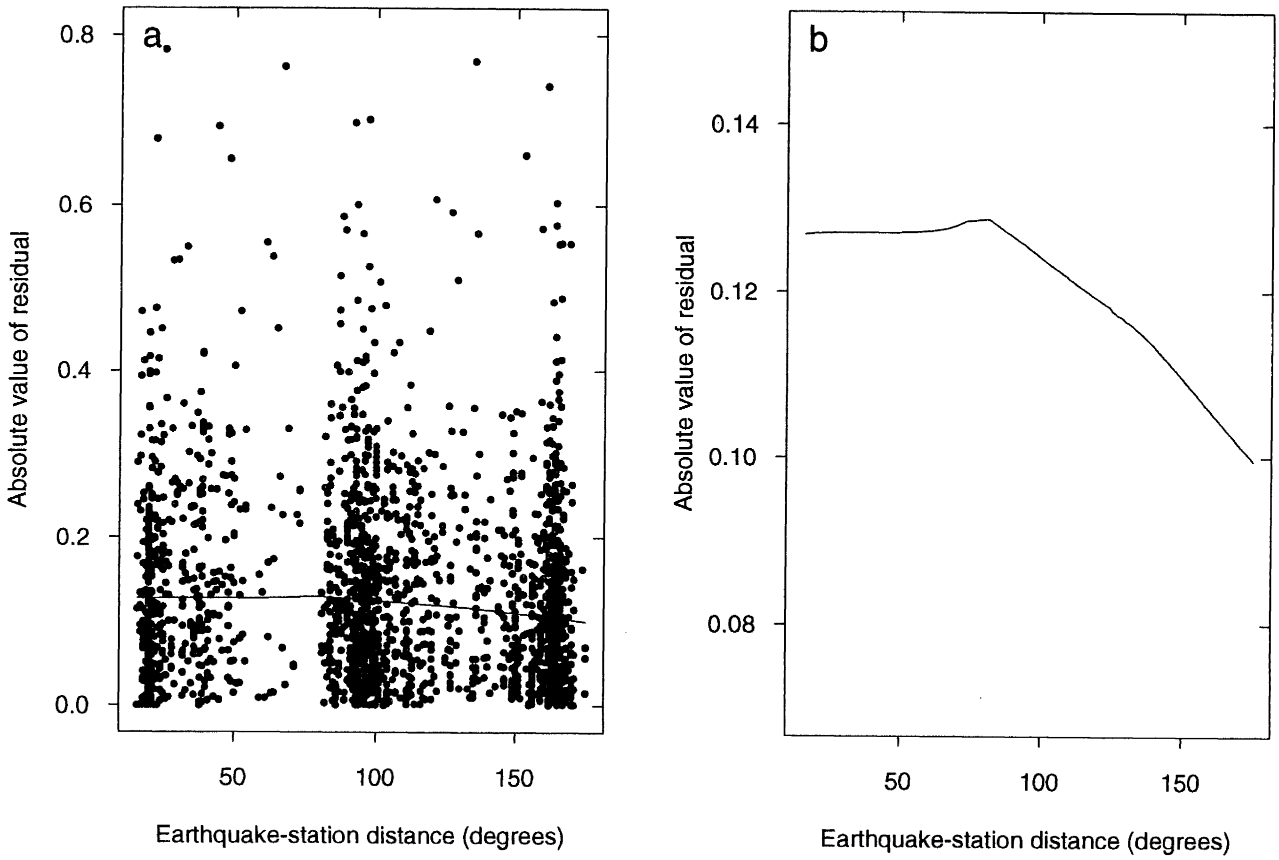

Figure 3 (a) Plot of absolute value of residuals from model (1) of station observations against distance, in degrees, from earthquakes to station. Also shown is a robust smooth trend computed using Splus "lowess" function [6]. (b) Trend from (a) on enlarged scale.

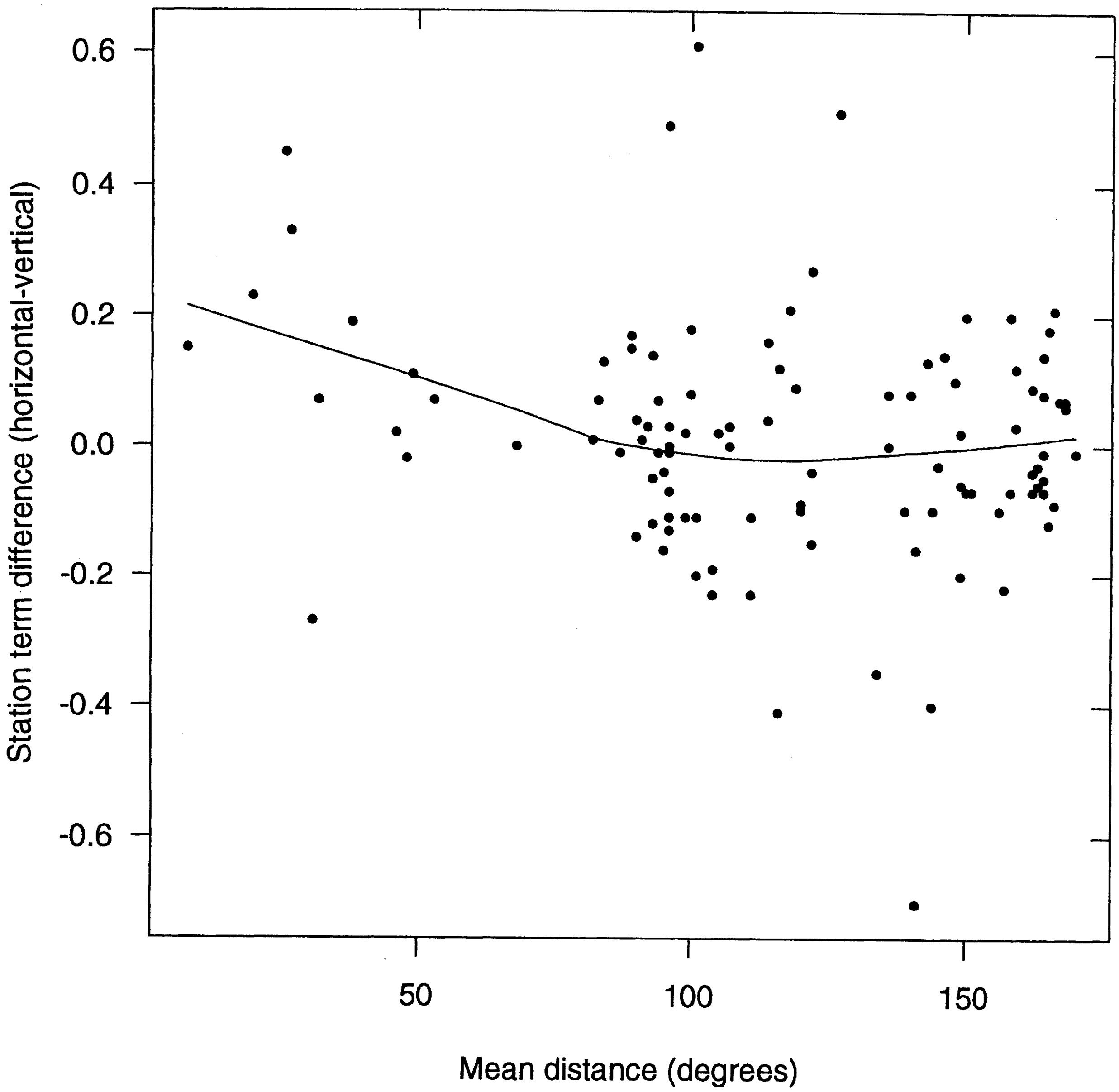

Figure 4 ***Difference of station terms estimated from the horizontal and vertical components recorded at a single site plotted against mean distance, in degrees, of New Zealand earthquakes from the site. A robust smooth trend, computed using the Splus "lowess" function [6], has been fitted through the data.***

Although we have no data from stations at, or close to, a distance of 180°, it is noted that near the antipode the maximum phases of surface wave trains can arrive simultaneously from different directions. For large earthquakes, this effect may occur within about 4° of the antipode, i.e. at distances $\gtrsim 176°$.

Enhancements of peak amplitudes by superposition are clearly possible in this situation, and focusing with strong amplifications of up to an order of magnitude, within 2° of the antipode, have been demonstrated [7] for body waves from the 1968 Inangahua, New Zealand, earthquake recorded in Spain. A surface-wave amplitude amplification by a factor of ten implies an overestimate of M_S by an increment of 1.0. Such data might be rejected as outliers [3], or data from distances $\gtrsim 178°$ could be systematically excluded.

The results include separate estimates of the station effects for both the horizontal and vertical components at 105 sites. This is a sufficiently large data-base to analyse for systematic differences between these two components. Overall, the station terms of the two components differ significantly at only five sites at the 1% level, and a further four sites at the 5% level. The former sites are "AFI" (Afiamalu, Samoa), "DBN" (De Bilt, The Netherlands), "RAR" (Rarotonga), "RIV" (Sydney) and "TAS" (Tashkent); the latter are "SBA" (Scott Base, Antarctica), "SHE" (Shanghai), "TFO" (Tonto Forest, Arizona), and "TUC" (Tucson, Arizona). For all of these sites except