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Station Magnitude Corrections and Related Issues for Eastern Canada

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Abstract

Earthquake magnitudes are generally defined as an average (most often, the arithmetic mean) of magnitudes calculated at many individual seismograph stations. While some variation in station magnitudes stems directly from the seismic source (for example, radiation pattern or directivity) conditions beneath the recording station also affect the calculated value. For example, soft soils tend to amplify the seismic signal resulting in an apparent magnitude that is higher than the true value. By analyzing the differences between the magnitude determined at a specific station and the average magnitude for a large number of earthquakes, a site correction for the station can be determined. The intent of this study is to determine the station corrections for those seismographs routinely used in the calculations of magnitudes in eastern Canada. Corrections are determined for both the m_N and M_L magnitude scales. Additionally the magnitude residuals were further evaluated to determine whether they were dependent on parameters such as distance, azimuth or frequency. The effects of azimuth and frequency appear to be minimal. There does appear to be a distance dependency suggesting that the attenuation relation used in the magnitude calculation may need to be modified. Finally, several issues relating to magnitudes are raised, the resolution of which are beyond the intended scope of this paper.

Introduction

Earthquake magnitude is generally calculated by taking the mean value of magnitudes determined at individual seismograph stations. While there will always be some station magnitudes that differ from the mean because of factors related to the earthquake source, such as radiation pattern, there may also be stations that give consistently high or low magnitudes because of factors such as site conditions beneath the station or possibly an incorrect instrument response. Identifying these stations and applying an appropriate correction can result in more reliable magnitudes and also in larger numbers of stations being used to calculate magnitude as current practice is to exclude data that are significantly different from the average.

This study was undertaken to determine the station corrections for all eastern and central Canadian seismograph stations. The stations examined are those that are routinely used for the calculation of m_N, which is the standard magnitude scale for eastern Canada. Corrections for M_L at the same stations are also determined.

Earthquake magnitudes calculated at any given station may also be influenced by the path between the earthquake and station due to variations in Earth structure. These variations could result in station corrections that are dependent on azimuth or distance or both. The station correction may also be dependent upon the period at which the magnitude is calculated. These factors are investigated, preliminary results are presented for the m_N magnitude and some suggestions for future work are brought forward.

Data Selection and Analysis

Magnitude data from eastern Canadian earthquakes of magnitude 2.0 or greater from 2003-2007 whose magnitudes were calculated from amplitudes from five or more stations were evaluated. Corrections for m_N and preliminary corrections for M_L were determined independently. Because m_N is used primarily in eastern Canada, a longitude cut-off of 110º W was used when selecting the earthquakes to determine m_N corrections and only those stations which have been routinely used in m_N calculations were examined. In eastern Canada, M_L tends to be used only when m_N is inappropriate, in particular, when the epicentral distance is less than 50 km and for northern and offshore earthquakes with no significant Lg phase. The longitude restriction was removed for the M_L calculations but made little difference to the events selected.

The list of stations includes some that are located in the United States and Greenland. They are included because they are routinely used in the analysis of Canadian earthquakes. It should be noted that the corrections for these stations are based only on those earthquakes that appear in the Canadian earthquake database and some caution should be exercised if applying them to earthquakes occurring elsewhere.

The magnitude residual is defined as the difference (m(station)-m(event)) between the magnitude calculated at a specific station hereafter referred to as the station magnitude and the average magnitude for an earthquake hereafter referred to as the event magnitude. The station correction is the mean residual for a given station. When applied, it should be **subtracted** from the calculated station magnitude.

Although it is standard practice to quote magnitude to one decimal place, and may be sensible to do so when referring to event magnitudes, the digital data now available allow individual station magnitudes to be calculated with more precision. For the calculation stage of this project all event and individual magnitudes were recalculated to two decimal places. It is left to the user to decide how many significant digits to retain when applying the corrections. Standard deviations were also calculated and Student's T statistic (Abramowitz and Stegun (1965) was used to determine the width of the 99% confidence interval. All of these values as well as the number of events used to determine the corrections are provided in the Table. If the width of the 99% confidence interval is greater than 2 magnitude units, the field is left blank. Note that many stations, particularly in the north, are used far more often than it would appear from the Table but because many event magnitudes are calculated from fewer than five station magnitudes much of the data from some stations were excluded from the study.

Static Corrections

The static correction for each station is defined as the mean residual for the entire data set without considering possible differences related to aziumuth, distance, period or magnitude. It should represent the site conditions beneath the station but could potentially incorporate errors in the instrument calibration. If most of the earthquakes recorded by a station come from a single source zone the apparent static correction could also reflect source-specific path or radiation pattern effects.

For the most part the static station corrections summarized in the Table are small. That is they are less than 0.2 magnitude units, or within the range of the magnitude uncertainty associated with most of the earthquakes in the study suggesting that, on average, including station corrections in magnitude calculations would not have a significant effect on the event magnitude. Tests discussing the effect of including the station corrections are discussed later in the section entitled “Impact of Station Corrections on Event Magnitudes”.

There are no strong regional trends in the static corrections (Figure 1). There are a range of values for each region with the mean being close to zero. Stations in the Atlantic provinces are more likely to have negative (blue symbols) than positive corrections while the reverse is true for southern Ontario, but both regions are dominated by stations with corrections close to zero. Northern Ontario stations show the widest range of corrections with large differences sometimes observed between neighboring stations. It should be noted that in this region neighboring stations are separated by 10s to 100s of km. An attempt to better understand the underlying reason (for example, site, instrument, frequency dependence) for these differences by looking at magnitudes based on a wider range of periods and distances (such as M_S from large teleseisms) only served to confuse the matter more.

The same procedure was repeated for the M_L scale, which, in eastern Canada, is used primarily for offshore and northern earthquakes and those recorded at distances too close for the m_N scale to be appropriate. The results are also summarized in the Table. Although the exact numbers differ somewhat from the m_N corrections, for the most part they have the same sign.

It is standard practice to exclude or “X out” individual station magnitudes that appear to be outliers or not close to the mean. Magnitudes calculated at distances inappropriate to the magnitude scale used are automatically X’d out by the location program (S. Hayek, personal communication). In most other cases it is the analyst’s decision. The magnitude corrections discussed in this paper were calculated twice- first using only those readings that were used to determine the event magnitudes listed in the database and again using all available readings. For the most part, there was very little difference in the value of the mean residual although the standard deviation and width of the 99% confidence interval both increased when the X’d out values were included. For those stations with large mean residuals, the correction obtained when the X’d out stations were included is likely more representative, particularly if the uncertainty is small and the difference in the number of events used for the two sets of calculations is large; for those stations with small mean residuals it is less clear whether those readings should be included or excluded.

The practice of excluding outlier magnitudes is fairly standard yet questionable. When there is a high degree of redundancy at a particular azimuth and distance it probably makes sense to leave out any readings that are clearly different from the average. When there is little or no redundancy the best course of action is less clear. The normal variation in magnitude due strictly to radiation pattern can be quite significant and much larger than the normally allowed variation in magnitude. Directivity can also affect the apparent magnitude although it is generally only a significant factor for larger earthquakes. Furthermore, the magnitude residual pattern may provide information about the focal mechanism and/or directivity, which is lost if the magnitudes are excluded. It should be noted, however, that magnitudes that are calculated and then rejected are kept in the database with an “X” used to indicate that they were not used in the calculation of the event magnitude. When data from a station does not appear, it is less clear whether the data could not be used or whether it was simply not evaluated, the latter of which may occur on a regular basis when a station gains a reputation for giving magnitudes that are consistently higher or lower than the mean.

Parameter Dependent Corrections

Variations in magnitude residual as a function of azimuth, distance, period and magnitude were also evaluated. For this part of the analysis, only those stations with fifty or more available readings were considered. The calculations include the X'd out data. In this section, only the m_N scale is considered. No magnitude dependence of the residuals was observed and this parameter will not be further discussed.

Azimuth

Azimuthal corrections were determined by binning the data in 30º windows and calculating the mean residual as well as the standard deviation and 99% confidence interval. The calculations were performed twice with the mid-point of the window shifted by 15º to help ensure that the choice of window did not influence the outcome. Most stations show some degree of azimuthal variation but in almost all cases the 99% confidence intervals for each window overlap with the 99% confidence interval of the overall mean or static correction and are therefore not considered statistically significant. Note that when dealing with stations it is generally more common to use back azimuth (station to event direction) than azimuth (event to station direction). However, because the database is event oriented, azimuth is more readily available and was used for this part of the analysis.

Azimuthal variations are most likely caused by path and possibly by radiation pattern effects and thus would be expected to be similar at nearby stations, in which case stacking the data from several stations may highlight the pattern and reduce the uncertainty. Stacking was performed for several regional groups of stations. Before combining the data from multiple stations the individual station static correction was applied to each station magnitude leaving a second order residual which represents the deviation from the mean. This step helps ensure that site-specific effects are removed, that any azimuthal effects are emphasized and allows for more direct comparisons with nearby stations.

The results for most regions were equivocal. However, a small but strong azimuthal variation was observed for the stations in the Lower St. Lawrence Region (GASG, CNQ, GSQ, ICQ, MNQ, SMQ). The static correction for GASG was significant (see Table), but once removed, the resulting azimuthal pattern was remarkably similar to those for the other stations. The residuals for the stacked data and for the individual stations are very similar and show a statistically significant, higher than average, positive correction for the azimuthal range 240º-315º (Figure 2a), corresponding to earthquakes from the Gulf of St. Lawrence and Labrador Sea. There is a small but statistically significant negative correction for azimuths in the 45º-75º range corresponding to earthquakes in Charlevoix and western Quebec.

Stations in the two adjacent regions, the Charlevoix Seismic Zone (A11, A16, A21, A54, A61, A64, LMQ, shown in Figure 2b) and the Gulf of St. Lawrence (CHEG, MADG, TIGG, shown in Figure 2c), also show high positive residuals in the general azimuthal range where the residuals are high for Lower St. Lawrence stations. The Gulf of St. Lawrence stations appear to have azimuthally dependent corrections, but except at azimuths close to 300º, the variations are not statistically significant. Charlevoix shows very little azimuthal variation and has very well constrained corrections. In the azimuthal range 225º-270º the variation from the mean, while small, is positive and significant at the 99% confidence level.

In a few other regions, there are small azimuthal ranges over which the difference from the mean value is statistically significant but for the most part the apparent variations are not. Examples are shown for southern Ontario (Figure 2d), western Quebec (Figure 2e) and Melville Island (Figure 2f). In all cases, when there is a statistically significant range the correction itself is relatively small.

Note that the uncertainties indicated by the error bars in Figure 2 represent Student's T statistic which is related both to the variation of the individual residuals and to the number of data points. Generally, uncertainties of greater than 1 magnitude unit are indicative of a small sample size rather than a high degree of scatter.

Distance

When evaluating station corrections as a function of distance, a high degree of scatter was noted, but there were some ubiquitous trends. At almost all stations the variation with respect to the mean residual is positive at close distances and negative at greater distances. The station LMN is shown as a particularly clear example (Figure 3a) as are the data from the combined Lower St. Lawrence stations (Figure 3b) discussed in the azimuthal section. In the latter case, the azimuthal trend previously discussed is apparent as is the distance dependence. As for the azimuthal corrections, the static correction was applied to the data and the secondary residuals were evaluated. The most likely cause of the observed trend is that the attenuation relation used in the magnitude calculations is incorrect. Note that based on the recommendations of Wetmiller and Drysdale (1982) the Nuttli (1973) formula for distances greater than 4º is used for all distances. This practice might be the source of the apparently incorrect attenuation relation or there may be a need for an overall improved attenuation relation. The resolution of this problem is beyond the scope of this paper but will be explored in future projects.

Period

No strong correlation was noted between residual and period (Figures 4a-4d). Although the m_N scale was intended to be used at periods of close to 1 sec (Nuttli, 1973) in practice it is used at much higher frequencies (Figure 4). However, since the average magnitude for a given earthquake is based on data calculated at the higher frequencies this factor alone should not lead to significant residuals relative to an event magnitude but would not preclude period-dependent residuals over the range of periods typically used.

Comparing m_N and m_b, which are intended to be equivalent (Nuttli, 1973) and to be used for the same period range may provide more insight. A comparison of the two magnitudes for eastern Canadian earthquakes for which both were available (Fig. 5a) shows that they are generally not equal and that m_N is usually the larger of the two. The difference may be related to the practice of calculating m_N at higher frequencies. Since m_N and m_b are generally not calculated at the same stations a one-to-one comparison is difficult, but plotting station m_N's as a function of period against event m_b's (Fig. 5b) does not reveal any obvious correlation between frequency and magnitude difference, which would be seen as a systematic change in symbol color from left to right.

Plotting the residuals as a function of both distance and period (Figure 4) suggests that the distance dependence is more significant than any potential frequency dependence. This effect is more clearly seen in the plots for individual stations (Figures 4c and 4d) than when the data from all stations are grouped together (Figures 4a and 4b). Figure 4 does highlight that the average period at which a magnitude is calculated increase with increasing distance but the residuals for any given distance do not appear to be period-dependent. Note that since many individual data points would plot on top of each other, the mean residual for each period-distance combination is shown. The data for all stations have been binned by the distance windows noted in the figure caption. For the examples showing individual stations, all points are plotted. Periods are not binned.

A basic observation stemming from this part of the study inadvertently led to a change in the procedure for magnitude calculation. Many magnitude calculations were being performed at periods close to the sample rate of the instruments, which are not likely reliable indications of the true size of the earthquake and may, in some cases, represent noise spikes rather than true signal. Figures 6a and 6b show the number of station magnitudes for the data set used in this study as a function of period and distance. Note that the window used for binning the data is a function of distance: 5 km for distances of less than 100 km, 10 km for 100-500 km, 25 km for 500-1000 km and 50 km for greater than 1000 km. It can be seen that there are large numbers of amplitudes at periods as low as 0.02 sec and 0.04 and very few around the 1 sec period for which the magnitude scale was originally intended. Subsequent to this study, the analysis package used to determine earthquake locations and magnitudes has been modified to reject any magnitudes determined at periods of less than 0.1 sec.

Impact of Station Corrections on Event Magnitudes

A preliminary test was conducted to determine how much the inclusion of station corrections affects the event magnitudes. The first twenty events on the list for 2003 were initially selected and the data set was augmented by adding the first five events from each of the subsequent years. The magnitudes were calculated applying the static station corrections determined in this study. The X'd out stations were included and the corrections used were those derived including the X'd out magnitudes. For stations where a correction was not available a value of zero was used. The number of stations used to determine magnitude in this data subset ranged from five to seventy-one and the magnitudes ranged from approximately 2.0 to 4.5. The mean difference (corrected magnitude – original magnitude) is -0.002 with standard deviation of 0.04. Figure 7 shows the original and corrected magnitudes for this data set. While these results are not conclusive, they suggest that, on average, the improvement in the magnitudes by including station corrections is minimal. It may, however, be worthwhile to apply the station corrections for those stations for which the correction is large particularly if the correction is well constrained and/or the station is in a region where coverage is sparse. For consistency, however, the corrections should be applied all the time or not at all.

Standard deviations for instrumental event magnitudes are typically 0.1-0.3 magnitude units although the possible range is much wider. The list below summarizes all stations for which the absolute value of the station correction for m_N is 0.3 or greater. More information about the number of readings and uncertainties associated with these stations may be found in the Table.

ATKO	0.42	BANO	0.34
BRCO	0.34	DREO	0.71
DRWO	0.43	EPLO	0.34
EYMN	-0.56	GASG	0.72
GBN	-0.33	INK	-0.37
KSVO	0.30	LATQ	0.83
LDIO	0.64	LMN	-0.38
MGTN	0.41	MSNO	0.76
NSKO	0.40	ORHO	0.66
OTRO	0.84	PKRO	0.42
TORO	0.54		

Some effort was made to find reasonable explanations why these stations have high corrections. Many of the stations with high positive corrections are located on soft soil, glacial deposits or fill, which may amplify the signal. The stations BRCO, DREO, DRWO, GASG, MSNO, NSKO, ORHO, OTRO, PKRO and TORO fall into this category (CNSN, 2010; S. Hayek and I. Asudeh, personal communication). KSVO is on a loose, cracked boulder (S. Hayek, personal communication).

Several other stations with high positive corrections (ATKO, BANO, EPLO, LATQ, LDIO, MGTN), however, are situated on bedrock (CNSN, 2010; S. Hayek and I. Asudeh, personal communication) and the reason for their high residuals is less obvious. Instrument miscalibrations are a possibility but have not been proven. While the correction for BANO is very well constrained and based on a large number of earthquakes (see Table) the others are based on smaller data sets, ranging from 3 (LATQ) to 36 (EPLO) amplitude readings, and the widths of their 99% confidence intervals are 0.25 or larger. It may be worth re-evaluating these stations using additional data to verify whether the corrections are as high as they appear and whether they can be better constrained.

The station INK, located on bedrock, is used infrequently for m_N calculations and almost always for earthquakes at larger distances. The shortest distance in this data set is 1250 km. In the case of INK the high negative correction may be related to the observation that negative residuals tend to be more common at large distances rather than to something directly related to the site. The M_L correction for INK, which is based on a much larger data set, is also negative but is less than 0.1 magnitude units.

Station EYMN in the United States is another bedrock station with a negative correction. This station has been used for earthquakes covering a wide distance range and is consistently underestimating the magnitudes suggesting that the correction is a true site correction or that there is an instrument miscalibration.

GBN and LMN, both of which have negative corrections, are located on bedrock within the Appalachian geological province. In a recent study establishing ground motion models for Australia Somerville *et al.* (2009) noted that in the Lachlan Fold Belt, which may be analogous to the Appalachians, the preferred ground motion model more closely resembled that of tectonic, western North America than that for purely cratonic Australia or eastern North America. It might be worth investigating whether a different attenuation relation should be used for Appalachian paths than for other areas of eastern Canada noting also that results presented earlier in this paper question the validity of that model in general and also bearing in mind that some other stations within the Appalachian geological province, such as GGN and HAL, have station corrections close to zero.

Conclusions

Station magnitude corrections have been established for seismograph stations operating in eastern Canada. For the most part, the corrections are within the normal uncertainty for event magnitudes in this region although there are some stations for which the corrections are significant. In most cases the large corrections can be tied to the local site conditions although there are others for which the reason is not readily apparent. For example, many of the stations with high positive corrections are location on soft soils. An evaluation of the corrections as a function of several other parameters has shown that, on average, azimuthal variations are not statistically significant. Nor are variations related to the period at which the magnitude is calculated. Variations related to distance, on the other hand, are more systematic and suggest that the attenuation relation used to calculate magnitude may be incorrect and should be re-evaluated. Preliminary efforts to recalculate event magnitudes with the station corrections applied show that the difference is generally insignificant. However, applying the corrections to those stations for which the correction is large may result in data from those stations not being routinely discarded and provide better azimuthal coverage for earthquakes in some regions. During the course of this project it was noticed that magnitudes were sometimes being calculated at periods close to the sample rate of the seismometer. The location-magnitude code has now been modified to automatically exclude magnitudes calculated at periods of less than 0.1 sec.

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Table
Station Corrections

stn	comp	m_N (no X'd out data)				m_N (all data)				M_L (no X'd out data)				M_L (all data)			
		# events	corr.	S. D.	99% conf. width	# events	corr.	S. D.	99% conf. width	# events	corr.	S. D.	99% conf. width	# events	corr.	S. D.	99% conf. width
A11	HHZ	70	-0.14	0.16	0.051	216	-0.26	0.23	0.041	5	-0.25	0.22	0.508	6	-0.16	0.29	0.481
A16	HHZ	92	-0.02	0.17	0.047	219	0.03	0.26	0.046	7	0.01	0.57	0.864	8	0.01	0.53	0.673
A21	HHZ	167	0.05	0.18	0.036	269	0.02	0.26	0.041	9	0.26	0.21	0.249	10	0.25	0.23	0.243
A54	HHZ	181	0.04	0.17	0.033	315	0.14	0.27	0.039	9	0.25	0.25	0.296	10	0.23	0.25	0.265
A61	HHZ	180	-0.04	0.15	0.029	327	-0.04	0.26	0.037	9	0.18	0.49	0.582	12	0.10	0.45	0.414
A64	HHZ	149	-0.01	0.16	0.034	269	0.01	0.25	0.040	7	-0.03	0.29	0.439	8	-0.04	0.28	0.355
ACTO	HHZ	28	0.13	0.11	0.058	104	0.13	0.25	0.065	0				0			
AKVQ	BHZ	21	-0.09	0.12	0.076	40	-0.15	0.20	0.087	6	0.13	0.00	0.000	0			
ALFO	HHZ	149	-0.09	0.17	0.036	245	-0.09	0.28	0.047	0				0			
ALGO	HHZ	7	0.17	0.35	0.530	164	0.60	0.34	0.069	0				0			
ALLY	BHZ	0				0				0				0			
AP3N	BHZ	26	0.00	0.11	0.061	53	0.00	0.15	0.056	4	0.02	0.28	0.947	8	-0.01	0.22	0.279
ARVN	BHZ	21	0.05	0.16	0.101	24	0.07	0.15	0.087	0				0			
ATKO	HHZ	10	-0.01	0.30	0.325	32	0.42	0.58	0.285	0				0			
BANO	HHZ	37	0.21	0.25	0.113	165	0.34	0.32	0.065	0				0			
BASO	HHZ	4	0.10	0.05	0.169	15	0.04	0.17	0.133	0				0			
BATG	HHZ	32	-0.04	0.14	0.069	78	0.03	0.32	0.096	4	0.05	0.10	0.338	7	-0.02	0.22	0.279
BELQ	HHZ	5	-0.12	0.11	0.254	15	-0.17	0.18	0.142	0				0			
BINY	BHZ	16	-0.09	0.19	0.144	31	-0.24	0.24	0.120	0				0			
BMRO	HHZ	1	0.08	0.00		6	-0.01	0.10	0.166	0				0			
BRCO	HHZ	3	0.36	0.23	1.620	66	0.34	0.22	0.072	0				0			
BOXN	BHZ	7	-0.07	0.10	0.152	21	-0.11	0.23	0.146	1	-0.04	0.00		1	-0.08	0.00	
BUKO	HHZ	85	0.05	0.15	0.043	142	0.00	0.16	0.035	0				0			
BULN	BHZ	50	-0.04	0.13		78	-0.05	0.16	0.048	0				1	0.28	0.00	
BWLO	HHZ	5	0.07	0.06	0.138	13	0.01	0.11	0.096	0				0			
CHEG	HHZ	10	-0.15	0.09	0.097	47	-0.25	0.25	0.099	6	-0.08	0.20	0.360	12	-0.18	0.20	0.184
CHGQ	HHZ	0				2	-0.04	0.00	0.000	0				0			

		m_N (no X'd out data)				m_N (all data)				M_L (no X'd out data)				M_L (all data)			
stn	comp	# events	corr.	S. D.	99% conf. width	# events	corr.	S. D.	99% conf. width	# events	corr.	S. D.	99% conf. width	# events	corr.	S. D.	99% conf. width
CLWO	HHZ	38	0.10	0.14	0.063	92	0.07	0.22	0.061	0				0			
CNQ	EHZ	278	0.08	0.20	0.031	346	0.08	0.27	0.038	7	0.00	0.15	0.227	12	-0.01	0.14	0.129
CODG	HHZ	0				11	-0.01	0.43	0.422	2	-0.22	0.08		8	0.03	0.53	0.673
COWN	BHZ	10	0.00	0.15	0.162	26	0.02	0.17	0.094	2	0.26	0.36		3	0.19	0.28	1.160
CRLO	EHZ	392	0.02	0.16	0.021	415	-0.01	0.18	0.023	0				1	-0.11	0.00	
CTLN	BHZ	2	-0.25	0.17		9	-0.18	0.17	0.195	2	-0.07	0.39		2	-0.10	0.42	
CTNY	BHZ	0				0				0				0			
DAQ	EHZ	343	0.04	0.18	0.025	418	0.08	0.22	0.028	3	0.12	0.28	1.972	3	0.16	0.27	1.119
DAWY	BHZ	0				0				35	-0.06	0.23	0.107	405	-0.04	0.31	0.040
DELO	HHZ	87	0.08	0.16	0.046	155	0.00	0.26	0.054	0				0			
DPQ	EHZ	427	0.15	0.19	0.024	479	0.16	0.23	0.027	3	-0.19	0.12	0.497	3	-0.17	0.14	0.580
DREO	HHZ	0				2	0.71	0.04		0				0			
DRLN	BHZ	48	-0.13	0.19	0.080	71	-0.18	0.29	0.092	23	0.09	0.33	0.198	32	0.12	0.36	0.177
DRWO	HHZ	0				5	0.43	0.17	0.342	0				0			
EDM	BHZ	1	-0.04	0.00		1	-0.08	0.00		27	-0.13	0.27	0.147	68	-0.02	0.35	0.113
EEO	EHZ	62	0.01	0.17	0.058	354	-0.04	0.19	0.026	2	-0.20	0.18		2	-0.18	0.21	
ELFO	HHZ	28	0.25	0.09	0.048	64	0.22	0.16	0.054	0				0			
ELGO	HHZ	14	-0.02	0.20	0.167	45	-0.02	0.28	0.113	0				0			
EPLO	HHZ	12	-0.08	0.14	0.131	36	0.34	0.55	0.253	0				0			
ERPA	BHZ	14	0.02	0.21	0.176	20	-0.12	0.26	0.170	0				0			
EYMN	BHZ	5	-0.20	0.22	0.508	28	-0.56	0.67	0.356	0				0			
FCC	BHZ	72	-0.09	0.22	0.048	104	-0.14	0.29	0.075	6	0.05	0.22	0.396	51	0.31	0.33	0.125
FFC	BHZ	0				2	0.13	0.52		0				0			
FNBB	BHZ	2	0.00	0.01	0.905	0				38	-0.26	0.23	0.103	303	-0.07	0.30	0.045
FRB	BHZ	96	0.06	0.18	0.048	143	0.07	0.23	0.050	32	-0.07	0.31	0.152	40	-0.06	0.30	0.130
GAC	BHZ	31	-0.07	0.22	0.110	129	-0.29	0.33	0.076	0				3	-0.07	0.06	0.249
GAC	EHZ	383	-0.09	0.17	0.023	427	-0.13	0.21	0.026	2	-0.24	0.16		5	-0.09	0.16	0.322
GALN	BHZ	2	-0.17	0.01	0.905	9	-0.19	0.20	0.230	0				0			
GASG	HHZ	6	0.35	0.13	0.234	60	0.72	0.19	0.066	0				2	0.40	0.33	
GBLN	BHZ	0				7	0.17	0.31	0.478	1	0.15	0.00		1	0.11	0.00	
GBN	HHZ	15	0.02	0.12	0.096	49	-0.33	0.33	0.128	6	-0.23	0.22	0.396	12	-0.29	0.23	0.212

		m_N (no X'd out data)				m_N (all data)				M_L (no X'd out data)				M_L (all data)			
stn	comp	# events	corr.	S. D.	99% conf. width	# events	corr.	S. D.	99% conf. width	# events	corr.	S. D.	99% conf. width	# events	corr.	S. D.	99% conf. width
GGN	BHZ	119	0.03	0.28	0.068	163	0.02	0.34	0.070	16	0.11	0.24	0.182	21	0.18	0.36	0.228
GIFN	BHZ	81	-0.04	0.16		165	-0.04	0.14	0.029	0				33	-0.13	0.30	0.145
GLWN	BHZ	11	0.07	0.16	0.161	25	0.07	0.20	0.119	0				0			
GRQ	EHZ	392	0.00	0.16	0.021	434	-0.02	0.20	0.025	2	-0.01	0.23		2	0.01	0.26	
GSQ	EHZ	194	-0.14	0.18	0.034	284	-0.18	0.23	0.035	11	0.06	0.27	0.271	14	0.00	0.33	0.273
GTO	EHZ	59	0.04	0.24	0.084	76	-0.01	0.26	0.080	0				2	1.88	0.00	
HAL	EHZ	42	0.10	0.22	0.093	56	0.07	0.33	0.119	12	-0.22	0.21	0.196	14	-0.20	0.24	0.128
HRV	BHZ	8	-0.01	0.18	0.238	12	-0.10	0.27	0.249	0				0			
HSMO	HHZ	31	-0.01	0.13	0.065	61	0.03	0.20	0.069	0				0			
ICQ	BHZ	190	-0.07	0.18	0.034	263	-0.07	0.23	0.037	12	0.04	0.23	0.215	14	0.04	0.23	0.190
ILKN	BHZ	1	-0.22	0.00		5	-0.17	0.24	0.483	1	-0.27	0.00		1	-0.17	0.00	
ILON	BHZ	119	0.08	0.15	0.036	198	0.01	0.18	0.033	14	0.00	0.25	0.207	33	-0.01	0.24	0.116
INK	BHZ	4	-0.37	0.15	0.507	4	-0.37	0.15	0.507	18	-0.07	0.28	0.196	382	-0.06	0.25	0.033
INUQ	BHZ	11	0.16	0.12	0.118	11	0.16	0.12	0.118	3	-0.02	0.03	0.124	4	-0.09	0.11	0.293
IVKQ	BHZ	22	-0.05	0.17	0.105	51	0.05	0.23	0.087	7	0.00	0.32	0.456	9	-0.02	0.28	0.322
JERN	BHZ	1	-0.07	0.00		3	0.11	0.17	0.704	1	0.32	0.00		1	0.42	0.00	
JOSN	BHZ	45	0.09	0.12		57	0.09	0.13	0.046	0				1	0.21	0.00	
KAPO	BHZ	113	-0.06	0.22	0.054	138	-0.12	0.23	0.051	0				3	0.13	0.25	1.036
KASO	HHZ	3	0.01	0.10	0.863	9	0.10	0.30	0.345	0				0			
KGNO	BHZ	172	0.02	0.14	0.028	177	-0.02	0.17	0.033	0				0			
KILO	HHZ	56	0.08	0.24	0.086	111	-0.02	0.29	0.072	0				0			
KLBO	HHZ	84	-0.01	0.15	0.043	126	-0.06	0.18	0.042	0				0			
KNDN	BHZ	0				17	-0.13	0.18	0.130	1	-0.09	0.00		1	-0.13	0.00	
KSVO	HHZ	22	0.22	0.21	0.129	35	0.30	0.29	0.135	0				0			
KUGN	BHZ	26	-0.04	0.11	0.061	37	-0.01	0.16	0.072	1	-0.09	0.00		1	0.30	0.00	
KUQ	EHZ	63	0.02	0.20	0.067	87	0.01	0.21	0.060	23	-0.17	0.28	0.168	27	-0.29	0.36	0.196
LAIN	BHZ	39	-0.01	0.11	0.048	60	-0.01	0.15	0.052	2	-0.18	0.45		5	-0.09	0.46	0.927
LATQ	HHZ	0				3	0.83	0.27	1.119	0				0			
LBNH	BHZ	55	-0.09	0.20	0.073	96	-0.17	0.25	0.067	0				0			
LDIO	HHZ	2	0.04	0.10		17	0.64	0.39	0.282	0				0			
LG4Q	EHZ	151	-0.07	0.20	0.043	200	-0.12	0.23	0.042	23	0.12	0.23	0.138	29	0.12	0.29	0.151

		m_N (no X'd out data)				m_N (all data)				M_L (no X'd out data)				M_L (all data)			
stn	comp	# events	corr.	S. D.	99% conf. width	# events	corr.	S. D.	99% conf. width	# events	corr.	S. D.	99% conf. width	# events	corr.	S. D.	99% conf. width
LINO	HHZ	31	0.12	0.17	0.085	83	0.05	0.27	0.079	0				0			
LMN	BHZ	85	-0.13	0.24	0.069	165	-0.38	0.37	0.075	16	0.03	0.29	0.218	24	0.07	0.33	0.192
LMQ	BHZ	285	0.06	0.17	0.026	409	0.07	0.23	0.029	13	0.11	0.21	0.183	17	0.12	0.22	0.159
LONY	BHZ	10	-0.10	0.18	0.195	12	-0.14	0.21	0.202	0				0			
MADG	HHZ	4	-0.11	0.16	0.543	13	-0.08	0.23	0.200	0				3	0.12	0.19	1.575
MALG	HHZ	10	0.03	0.12	0.130	21	0.14	0.15	0.095	1	0.01	0.00		6	0.18	0.38	0.631
MALO	HHZ	64	0.11	0.25	0.084	119	0.02	0.32	0.077	1	-0.02	0.00		1	0.02	0.00	
MCKN	BHZ	5	0.21	0.24	0.619	15	-0.01	0.31	0.024	2	0.01	0.17		2	0.04	0.27	
MEDO	HHZ	53	-0.03	0.14	0.052	87	-0.08	0.23	0.065	0				0			
MGTN	BHZ	4	0.34	0.13	0.440	6	0.41	0.17	0.282	0				0			
MLON	BHZ	8	-0.03	0.11	0.145	20	-0.08	0.18	0.117	2	-0.03	0.18		2	0.00	0.28	
MNQ	EHZ	278	-0.01	0.18	0.028	324	0.00	0.20	0.029	10	-0.07	0.15	0.162	15	-0.04	0.16	0.122
MNT	BHZ	158	-0.06	0.18	0.037	185	-0.08	0.23	0.044	0				0			
MOQ	EHZ	242	-0.09	0.21	0.035	272	-0.09	0.22	0.035	1	-0.15	0.00		1	-0.11	0.00	
MPPO	HHZ	170	0.09	0.17	0.034	257	0.04	0.27	0.044	0				0			
MRHQ	HHZ	139	-0.04	0.16	0.036	190	-0.05	0.19	0.036	0				1	0.00	0.00	
MSNO	HHZ	1	0.07	0.00		18	0.76	0.27	0.189	0				0			
MUMO	HHZ	1	-0.09	0.00		8	-0.28	0.37	0.470	0				0			
NANO	HHZ	18	-0.09	0.13	0.091	50	-0.13	0.24	0.092	0				0			
NATG	HHZ	35	-0.06	0.18	0.082	73	-0.10	0.26	0.081	3	-0.16	0.09	0.634	6	0.05	0.27	0.448
NSKO	HHZ	0				13	0.40	0.30	0.261	0				0			
NUNN	BHZ	34	0.09	0.17	0.081	44	0.12	0.17	0.070	0				0			
ORHO	HHZ	0				4	0.66	0.22	0.586	0				0			
OTRO	HHZ	1	0.08	0.00		35	0.84	0.36	0.168	0				0			
OTT	EHZ	114	0.08	0.18	0.044	140	0.09	0.22	0.049	0				0			
OTT	HHZ	37	0.00	0.18	0.082	63	-0.02	0.19	0.064	0				0			
PECO	HHZ	102	0.04	0.13	0.034	150	0.03	0.19	0.041	0				0			
PEMO	HHZ	114	0.07	0.18	0.044	227	0.10	0.32	0.056	0				0			
PKLO	HHZ	39	-0.01	0.16	0.070	72	-0.12	0.25	0.078	0				0			
PKME	BHZ	0				42	-0.04	0.28	0.118	0				0			
PKRO	HHZ	3	0.14	0.27	1.901	89	0.42	0.30	0.084	0				0			

stn	comp	m_N (no X'd out data) # events	corr.	S. D.	99% conf. width	m_N (all data) # events	corr.	S. D.	99% conf. width	M_L (no X'd out data) # events	corr.	S. D.	99% conf. width	M_L (all data) # events	corr.	S. D.	99% conf. width
PLIO	HHZ	49	0.04	0.21	0.081	76	-0.04	0.20	0.061	0				0			
PLVO	HHZ	147	0.11	0.19	0.041	218	0.12	0.20	0.035	0				0			
PNPO	HHZ	35	0.02	0.13	0.061	58	-0.05	0.22	0.078	0				0			
QCQ	EHZ	82	-0.02	0.17	0.050	96	-0.04	0.19	0.051	0				1	-0.22	0.00	
QILN	BHZ	129	0.01	0.17	0.039	213	0.03	0.21	0.038	17	0.22	0.36	0.260	39	0.24	0.28	0.123
RES	BHZ	44	-0.15	0.27	0.111	105	-0.21	0.32	0.082	26	-0.13	0.30	0.167	113	0.09	0.30	0.074
RLKO	HHZ	4	0.06	0.03	0.101	15	0.03	0.27	0.212	0				0			
ROMN	BHZ	0				2	0.21	0.20		1	0.06	0.00		1	0.06	0.00	
RSPO	HHZ	116	-0.05	0.14	0.035	161	-0.10	0.16	0.033	0				0			
SADO	BHZ	292	-0.02	0.17	0.026	317	-0.07	0.20	0.029	0				4	-0.07	0.13	0.346
SCHQ	BHZ	75	-0.16	0.22	0.068	134	-0.24	0.27	0.061	26	0.00	0.26	0.144	34	-0.04	0.28	0.133
SEDN	BHZ	76	0.03	0.15	0.046	100	0.04	0.17	0.033	0				3	0.67	0.31	1.285
SFJD	BHZ	2	0.12	0.69		2	0.20	0.64		11	-0.08	0.33	0.331	13	-0.11	0.23	0.296
SILO	HHZ	64	-0.01	0.21	0.070	145	-0.20	0.34	0.074	8	-0.06	0.16	0.211	11	-0.02	0.19	0.186
SJNN	HHZ	2	0.19	0.07		4	0.24	0.09	0.240	5	0.02	0.24	0.554	7	0.09	0.27	0.385
SMQ	EHZ	248	0.05	0.22	0.036	308	0.07	0.25	0.037	22	0.05	0.26	0.161	27	0.06	0.31	0.169
SNQN	BHZ	8	0.14	0.14		19	0.06	0.23	0.155	0				0			
SOLO	EHZ	54	-0.06	0.20	0.073	90	-0.14	0.21	0.059	1	-0.44	0.00		1	0.36	0.00	
SRLN	BHZ	85	-0.02	0.12		158	-0.01	0.15	0.031	8	0.23	0.23	0.291	23	0.17	0.27	0.162
STCO	HHZ	7	0.11	0.21	0.318	46	0.02	0.30	0.120	0				1	-0.21	0.00	
STLN	BHZ	44	-0.10	0.17		71	-0.05	0.19	0.060	0				3	0.31	0.28	1.169
SUNO	HHZ	37	0.08	0.16	0.073	62	0.04	0.21	0.071	0				0			
TALB	HHZ	0				0				0				0			
TBO	EHZ	35	-0.03	0.20	0.094	72	-0.12	0.30	0.094	0				0			
TIMO	HHZ	11	0.03	0.16	0.161	30	-0.02	0.22	0.112	0				0			
TOBO	HHZ	43	-0.13	0.12	0.050	82	-0.19	0.17	0.050	0				0			
TORO	HHZ	2	0.29	0.47		36	0.54	0.20	0.092	0				1	0.17	0.00	
TIGG	HHZ	7	-0.04	0.21	0.318	25	0.04	0.32	0.182	0				1	-0.61	0.00	
TRQ	EHZ	351	-0.01	0.14	0.019	407	-0.01	0.19	0.024	0				1	-0.08	0.00	
TULEG	HHZ	0								1	-0.48	0.00		2	-0.56	0.16	
TYNO	HHZ	13	0.13	0.16	0.141	63	0.12	0.24	0.081	0				0			

stn	comp	m_N (no X'd out data) # events	corr.	S. D.	99% conf. width	m_N (all data) # events	corr.	S. D.	99% conf. width	M_L (no X'd out data) # events	corr.	S. D.	99% conf. width	M_L (all data) # events	corr.	S. D.	99% conf. width
ULM	BHZ	28	-0.10	0.15	0.080	60	-0.16	0.34	0.118	0				29	0.10	0.32	0.167
VIMO	HHZ	69	0.00	0.20	0.064	136	-0.12	0.29	0.065	5	0.20	0.13	0.262	6	0.21	0.14	0.232
VLDQ	BHZ	238	-0.17	0.20	0.034	291	-0.24	0.21	0.032	0				2	0.29	0.37	
WAGN	BHZ	31	0.11	0.18	0.090	42	0.10	0.18	0.076	0				0			
WBO	EHZ	295	-0.03	0.15	0.023	315	-0.04	0.18	0.026	0				1	-0.20	0.00	
WEMQ	HHZ	22	0.03	0.20	0.123	44	0.01	0.25	0.103	3	-0.07	0.68		5	0.07	0.53	1.068
WLVO	HHZ	46	0.06	0.11	0.046	99	0.01	0.21	0.056	0				0			
YBKN	BHZ	32	0.02	0.13	0.064	37	0.04	0.12	0.054	0				0			
YKBO	SHZ	1	-0.11	0.00		3	-0.03	0.06	0.249	1	0.11	0.00		1	0.11	0.00	
YKB1	SHZ	0				2	0.00	0.04		0				0			
YKB2	SHZ	0				2	0.06	0.05		0				0			
YKB3	SHZ	0				2	-0.06	0.01		0				0			
YKB4	SHZ	0				2	-0.01	0.01		0				0			
YKB6	SHZ	0				2	-0.05	0.06		0				0			
YKB7	SHZ	1	0.13	0.00		3	0.06	0.11	0.456	0				0			
YKB8	SHZ	0				2	0.00	0.12		0				0			
YKB9	SHZ	1	-0.09	0.00		3	-0.04	0.09	0.373	1	-0.07	0.00		1	-0.07	0.00	
YKR1	SHZ	0				2	0.01	0.02		0				0			
YKR2	SHZ	0				2	-0.01	0.07		0				0			
YKR3	SHZ	0				2	0.09	0.06		0				0			
YKR4	SHZ	0				2	0.00	0.04		0				0			
YKR5	SHZ	0				1	0.04	0.00		0				0			
YKR6	SHZ	0				1	0.08	0.00		0				0			
YKR7	SHZ	0				2	-0.06	0.13		0				0			
YKR8	SHZ	0				2	-0.05	0.04		0				0			
YKR9	SHZ	0				2	-0.03	0.11		0				0			
YKW1	BHZ	0				1	0.02	0.00		0				4	-0.02	0.53	1.412
YKW2	BHZ	0				0				0				4	0.18	0.15	0.400
YKW3	BHZ	6	-0.15	0.12	0.216	11	-0.14	0.16	0.157	29	0.23	0.15	0.078	212	0.20	0.24	0.043
YKW3	EHZ	42	-0.13	0.18	0.076	68	-0.18	0.17	0.055	44	0.13	0.20	0.052	352	0.22	0.28	0.039
YKW4	BHZ	0				1	0.21	0.00		0				3	0.27	0.04	0.166

		m_N (no X'd out data)				m_N (all data)				M_L (no X'd out data)				M_L (all data)			
stn	comp	# events	corr.	S. D.	99% conf. width	# events	corr.	S. D.	99% conf. width	# events	corr.	S. D.	99% conf. width	# events	corr.	S. D.	99% conf. width
YOSN	HHZ	0				0				0				0			
YRTN	BHZ	60	0.14	0.14	0.049	117	0.15	0.24	0.058	8	0.29	0.33	0.419	11	0.24	0.24	0.235

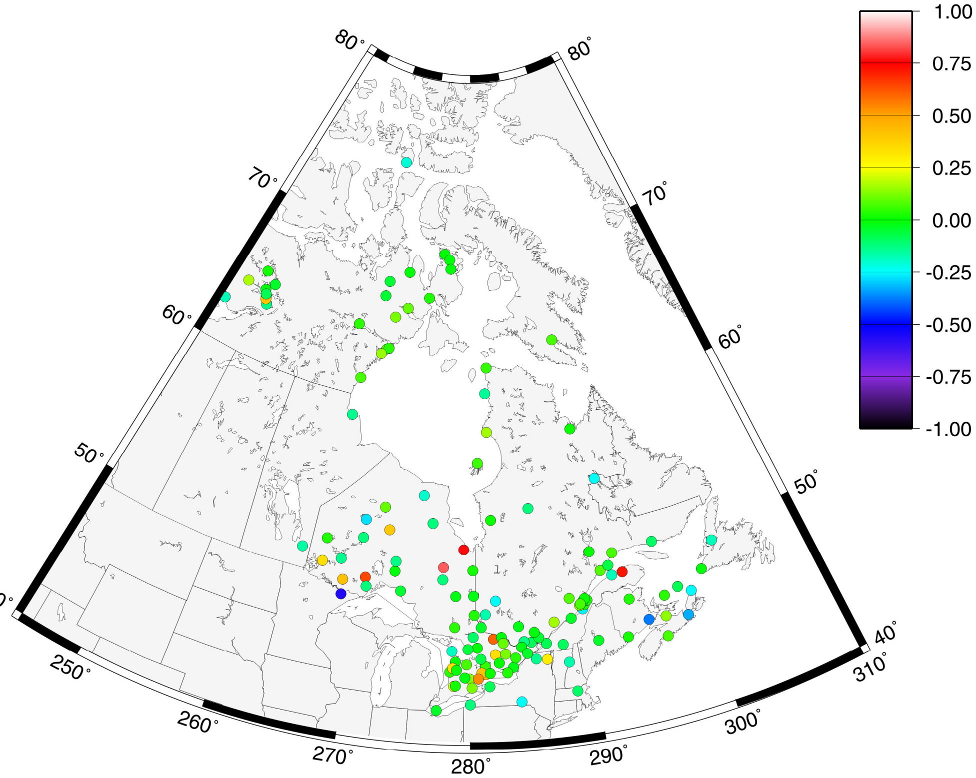


Figure 1: Static station corrections for the m_N magnitude scale. Details about the number of data points used and the uncertainty associated with each station may be found in the Table.

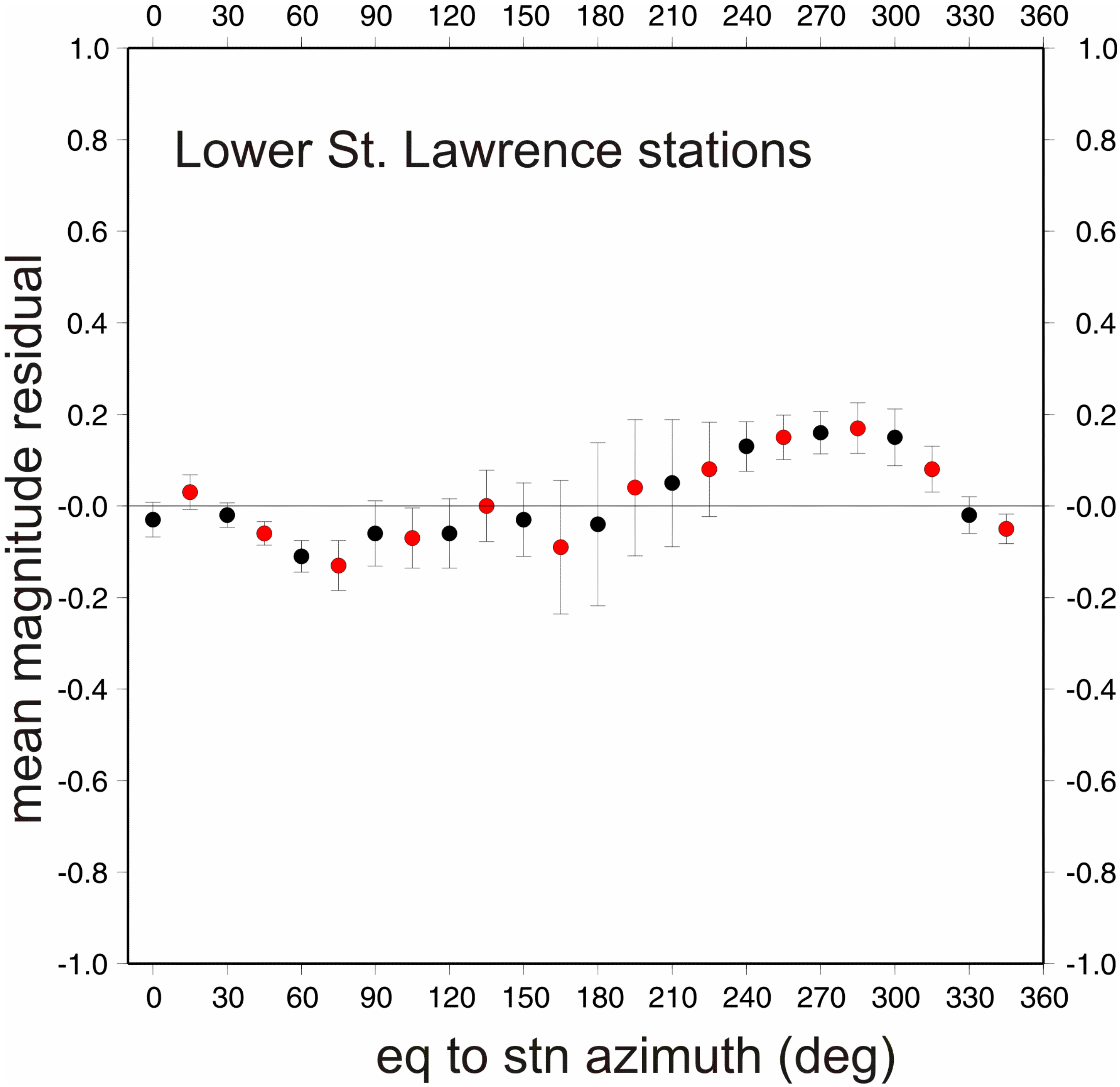
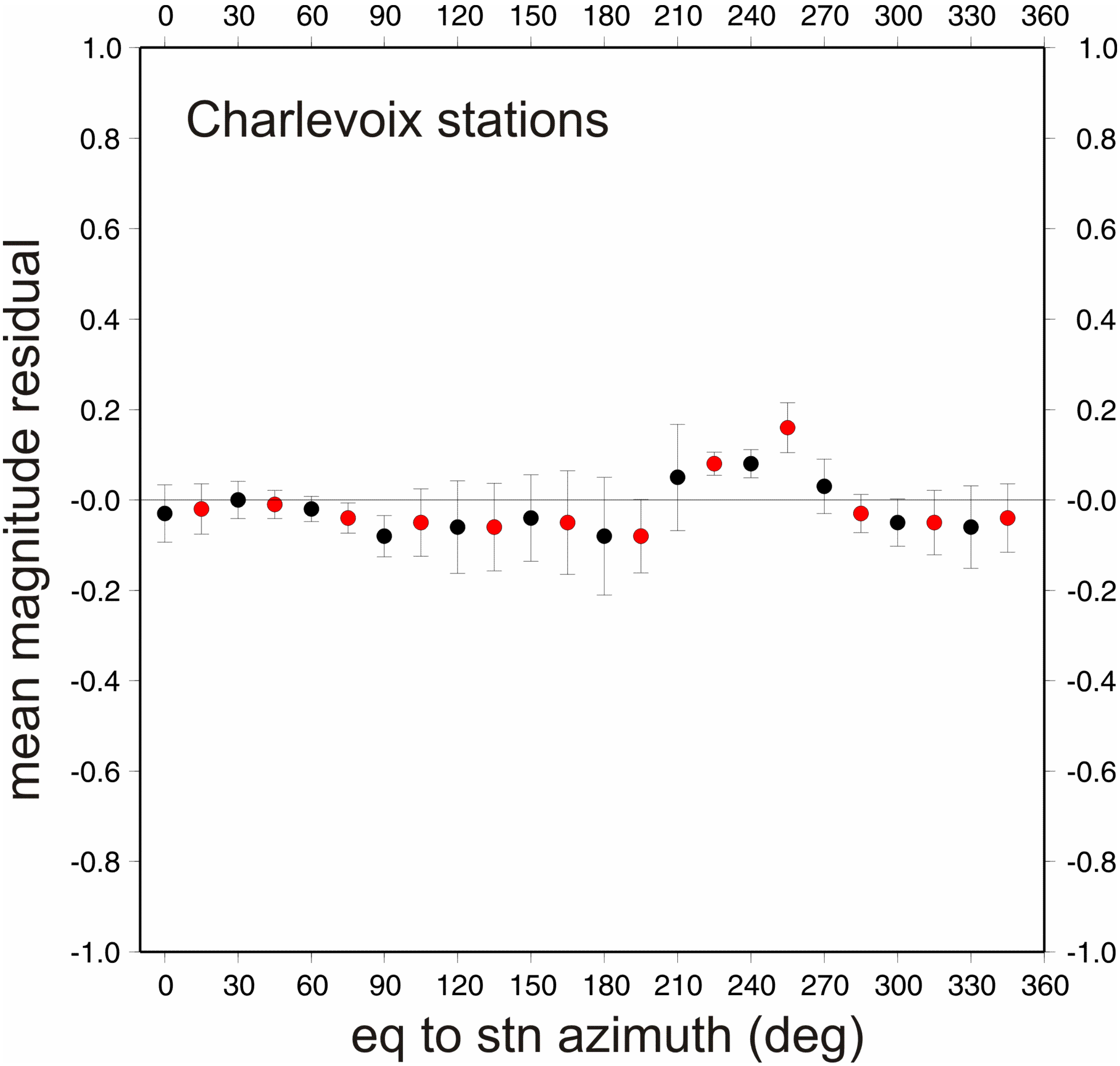
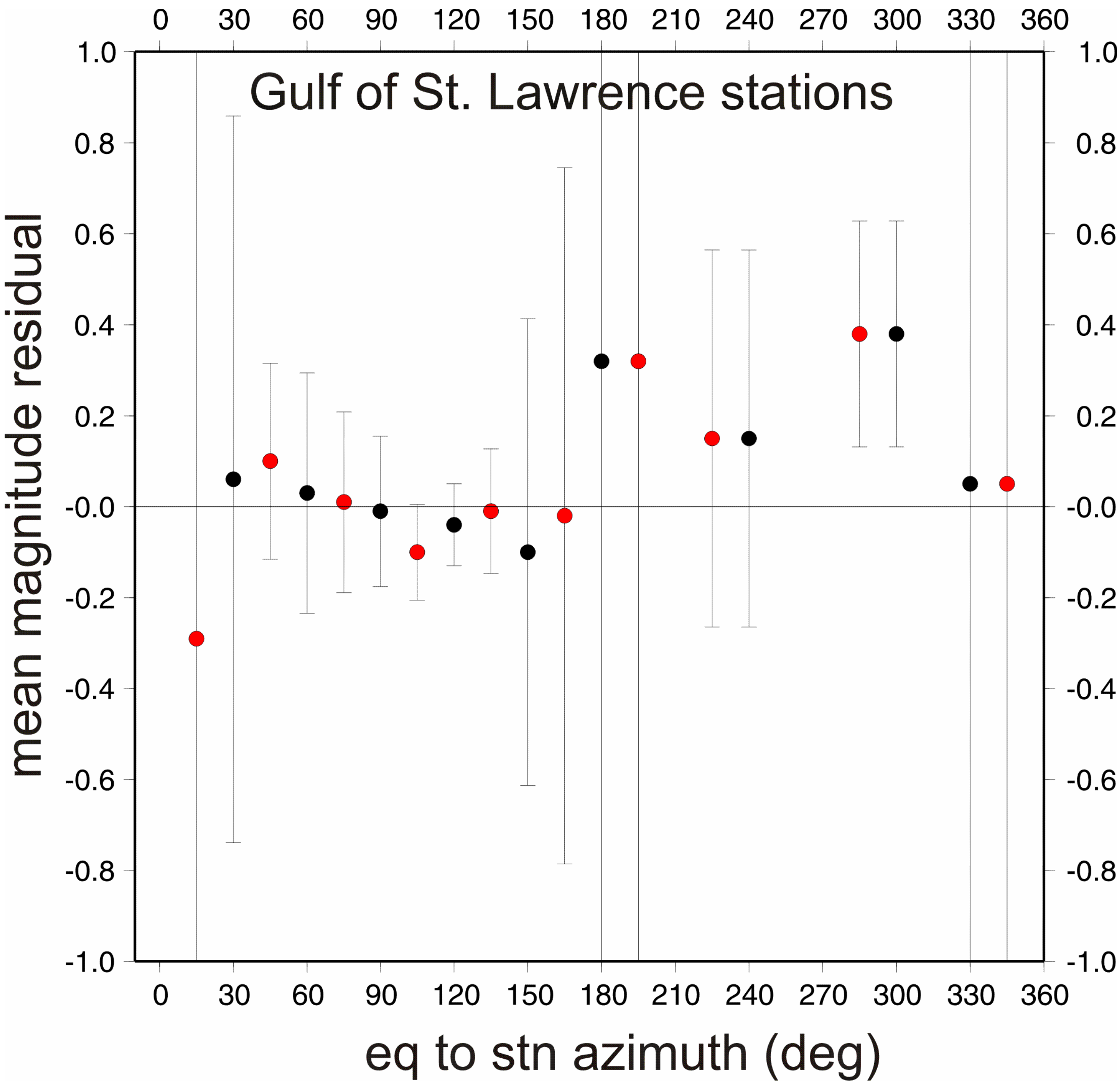


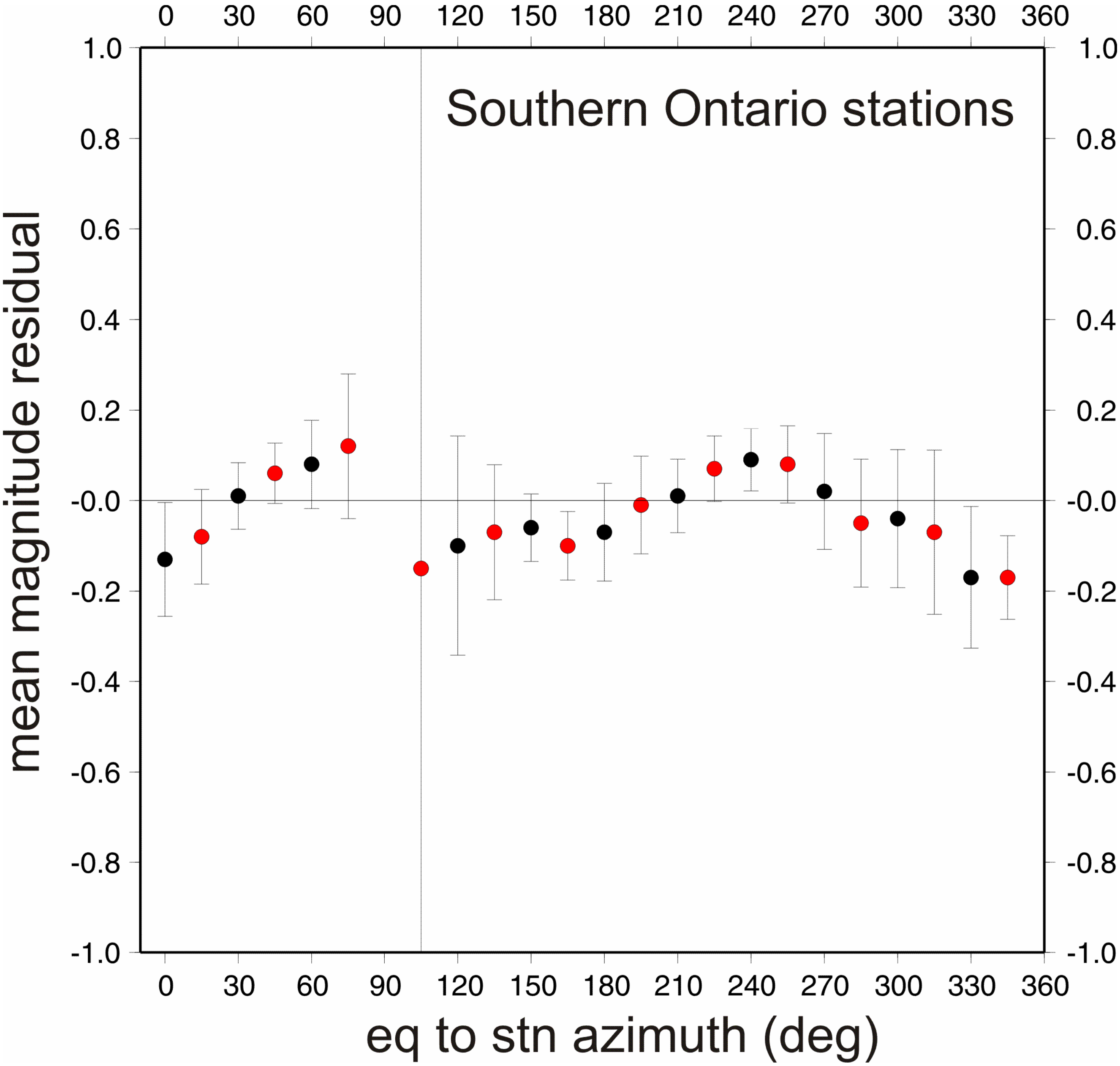
Figure 2: Mean magnitude residuals as a function of azimuth after the static station correction has been removed. Data have been stacked and binned in 30º bins with the points plotted at the midpoint. The error bars show the 99% confidence interval. The black and red dots represent windows with different midpoints. That is, there is no overlap in data between adjacent dots of the same color, but adjacent dots of different colors contain some of the same data points. (a) combined Lower St. Lawrence stations (CNQ, GASG, GSQ, ICQ, MNQ, SMQ)



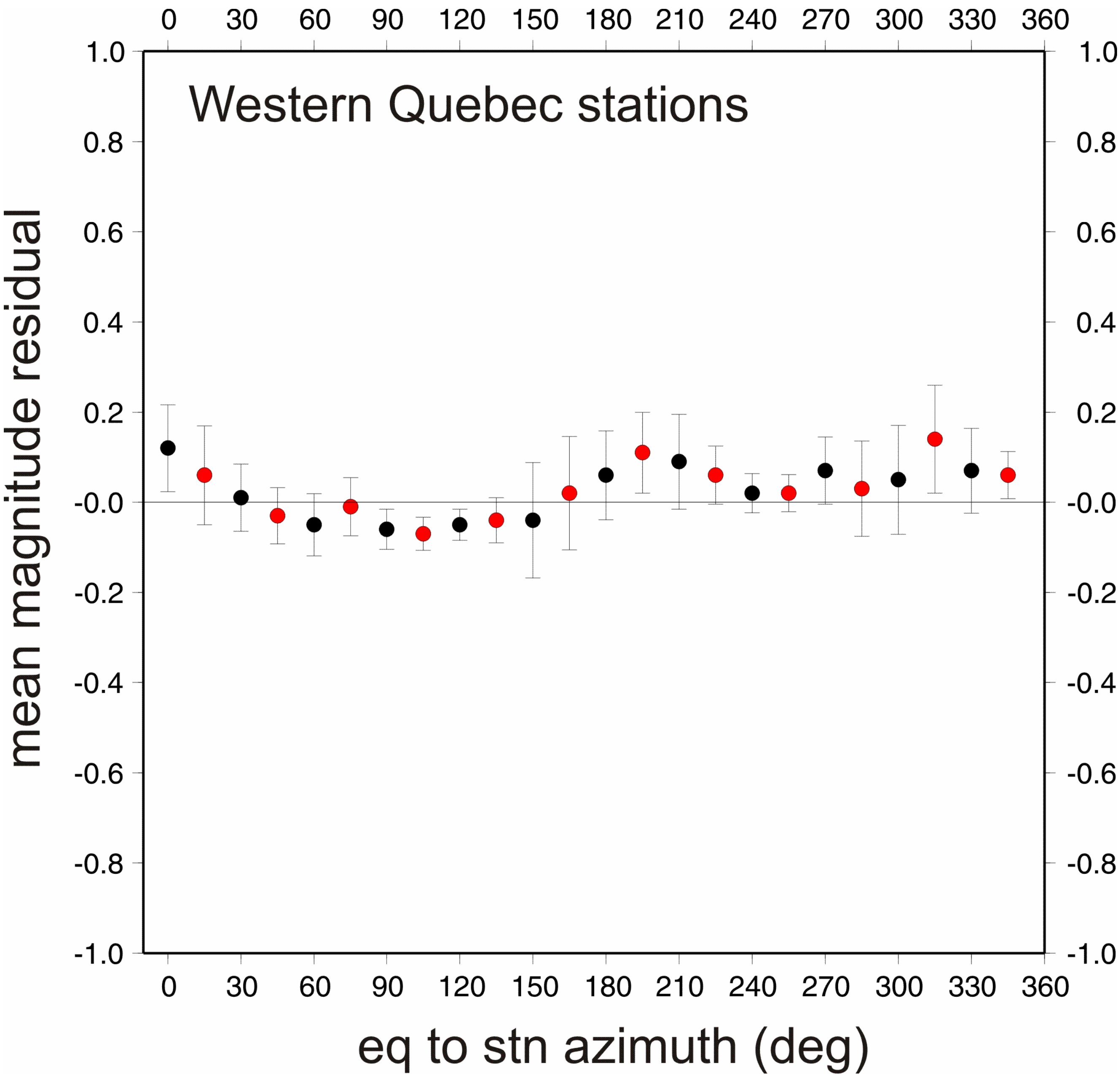
2(b) combined Charlevoix stations (A11, A16, A21, A54, A61, A64, LMQ)



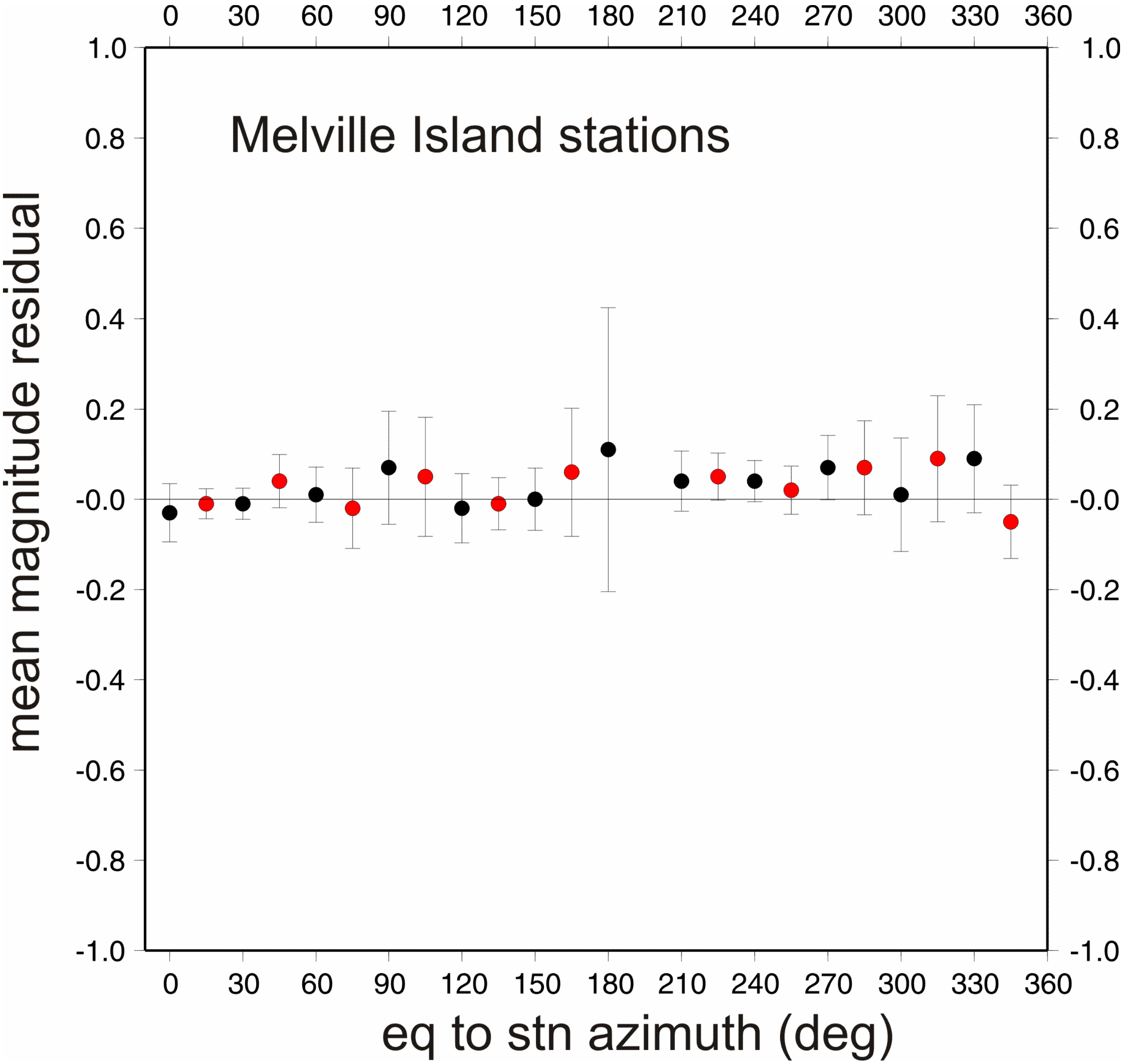
2(c) combined Gulf of St. Lawrence stations (CHEG, MADG, TIGG)



2(d) southern Ontario (ACTO, PKRO, STCO, TORO, TYNO, WLVO)



2(e) western Quebec (MNT, MRHQ, TRQ)



2(f) Melville Island (AP3N, GIFN, ILON, SRLN).

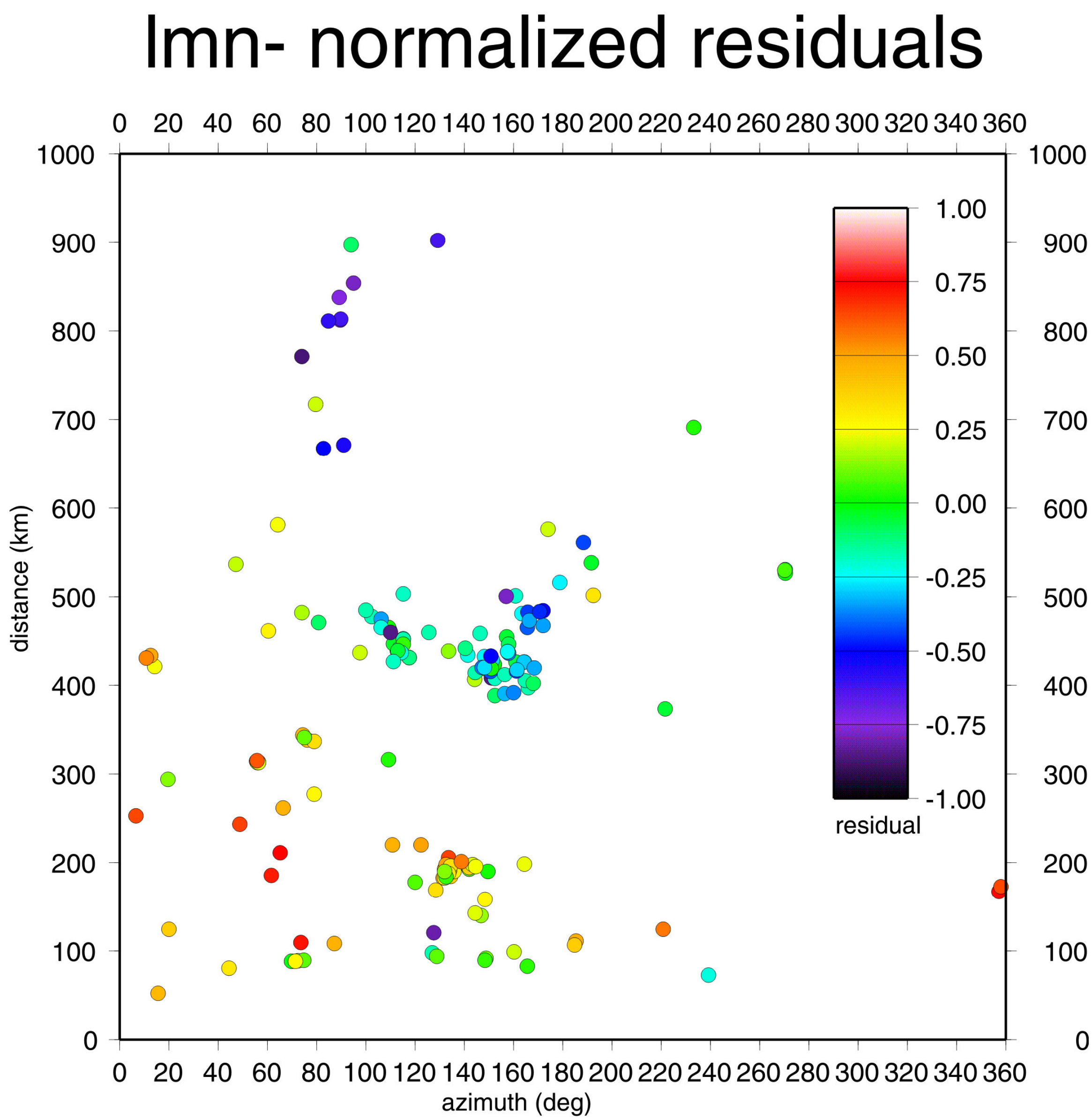
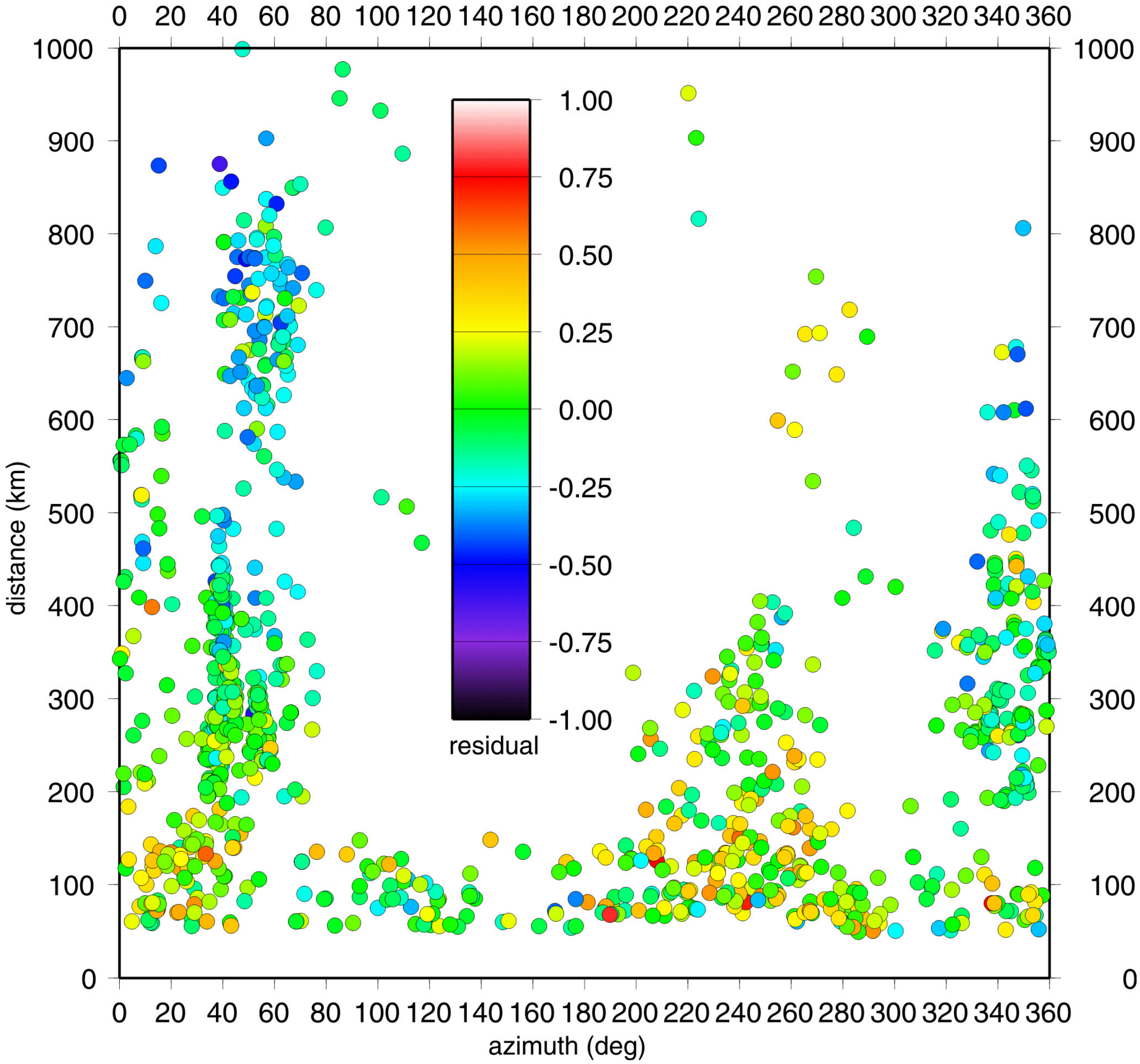


Figure 3: Magnitude residuals as a function of azimuth and distance. The static station correction has been removed leaving a residual representing the variation from the mean. (a) station LMN and

lsl- normalized residuals



3(b) the combined data set from several stations in the Lower St. Lawrence (CNQ, GASG, GSQ, ICQ, MNQ, SMQ)

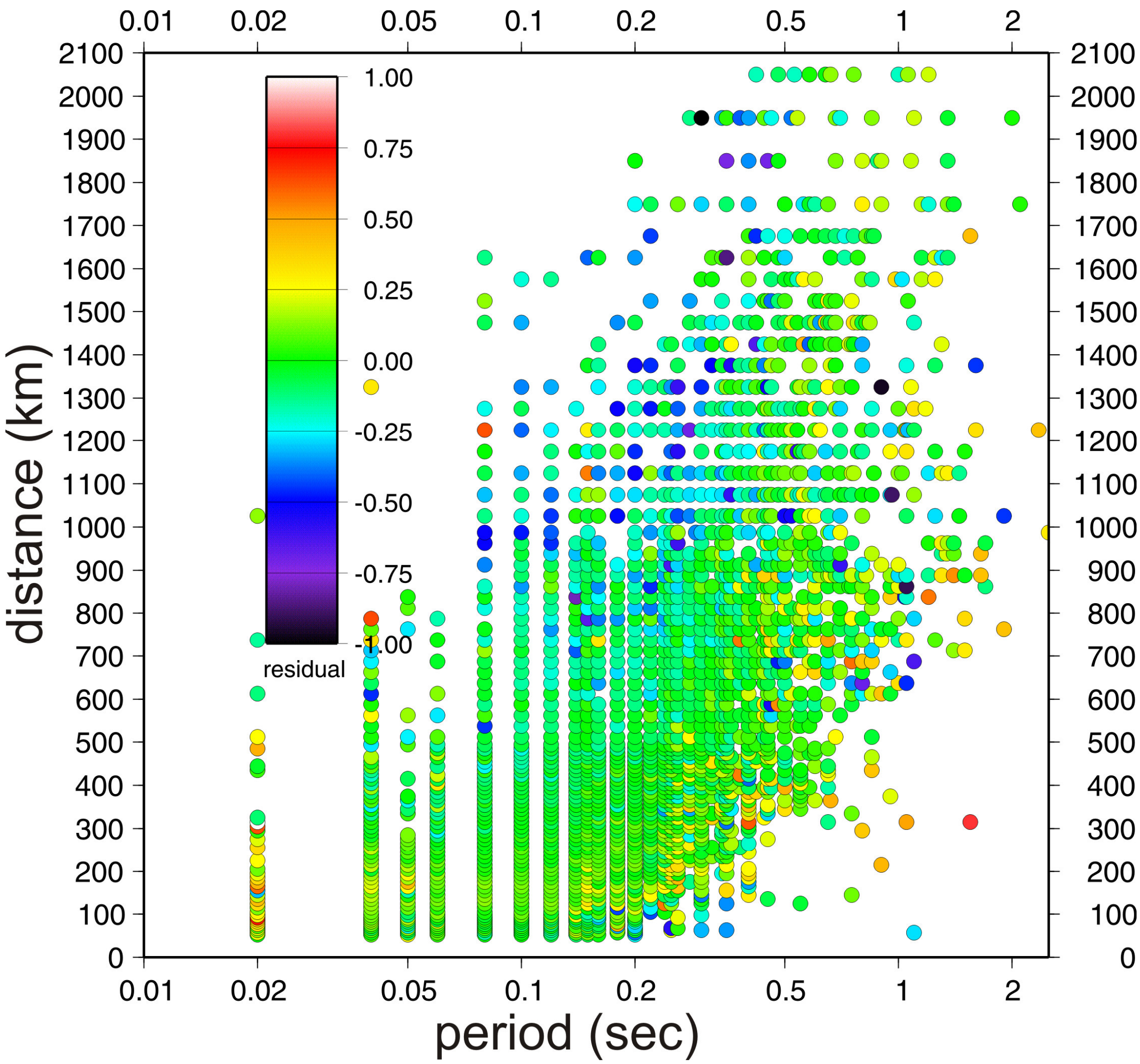
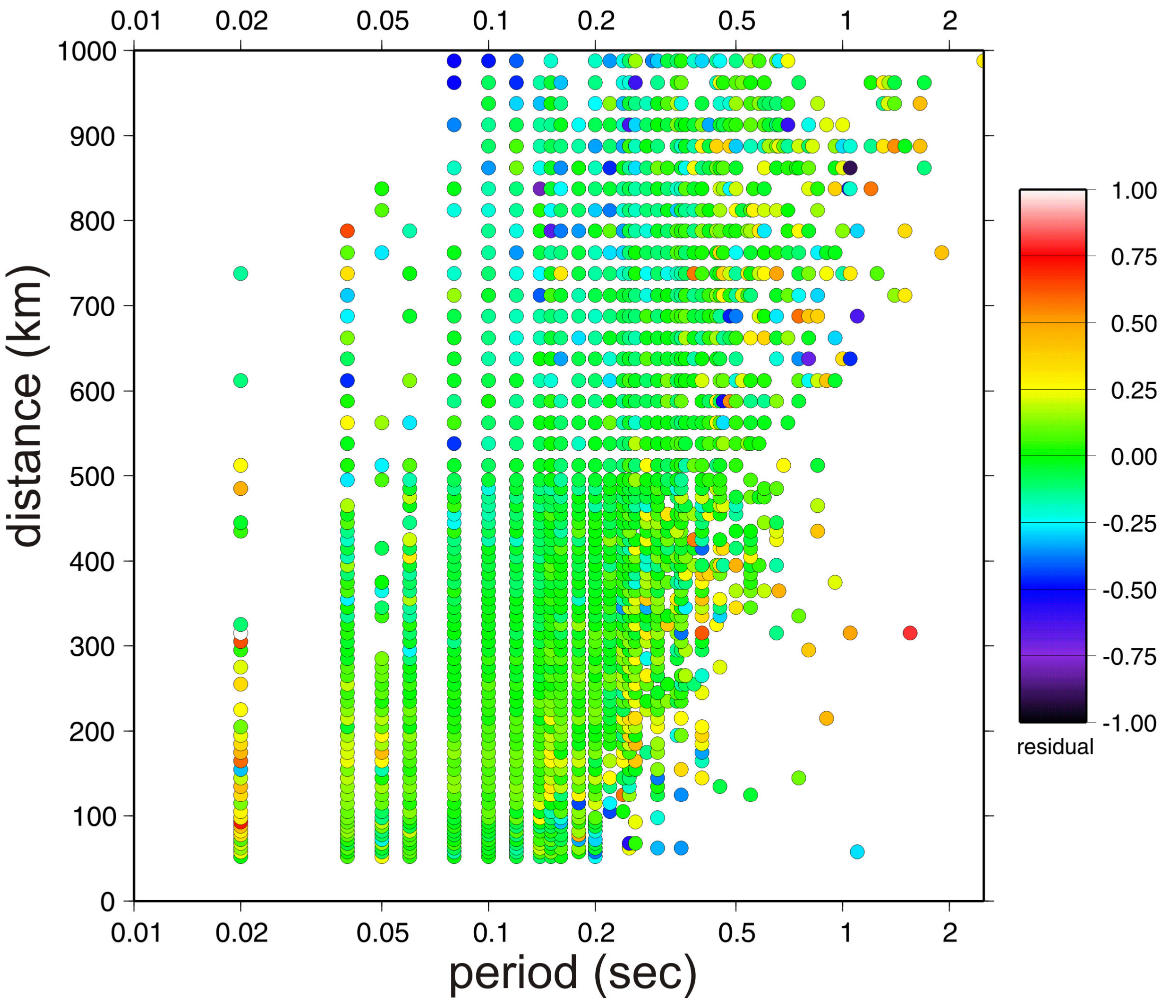
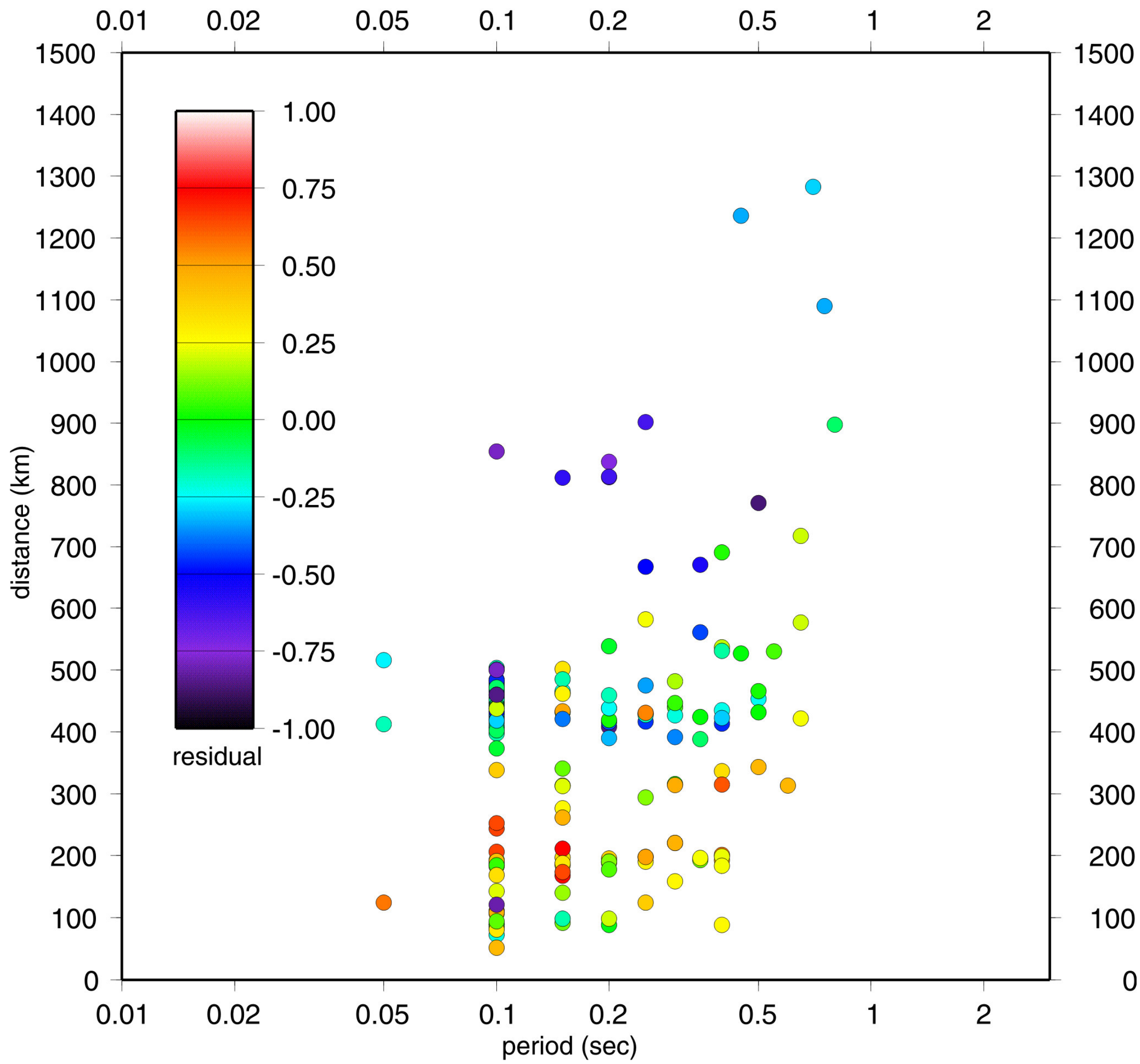


Figure 4: Magnitude residuals as a function of period and distance. The average value for each period-distance window is shown. Data points in parts A and B are binned by distance range which windows of 5 km for distances of less than 100 km, 10 km for 100-500 km, 25 km for 500-1000 km and 50 km for distances greater than 1000 km. Periods are as recorded in the data base. (a) the complete data set to distances of 2100 km

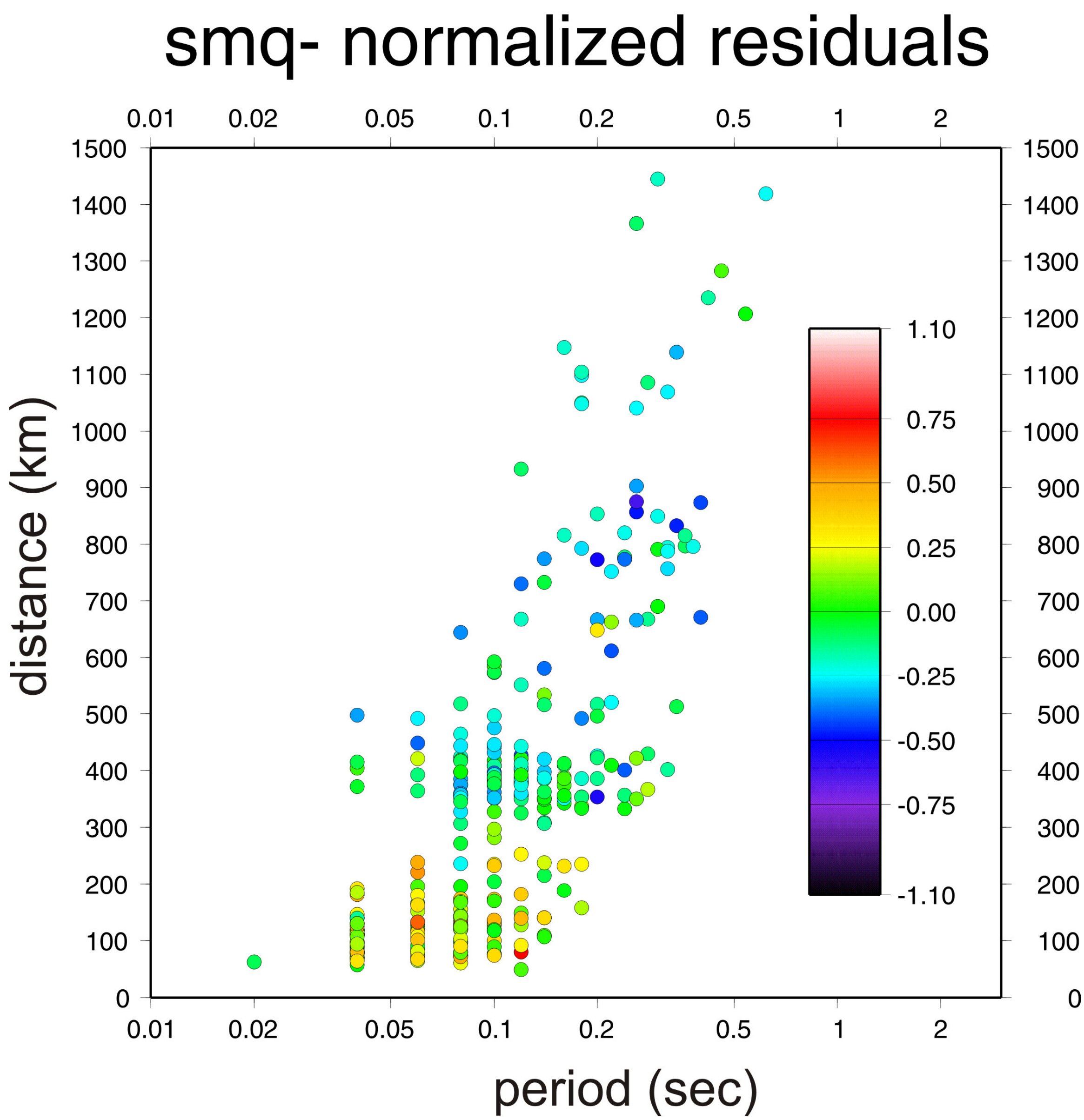


4(b) the complete data set to distances of 1000 km

lmn- normalized residuals



4(c) station LMN



4(d) station SMQ.

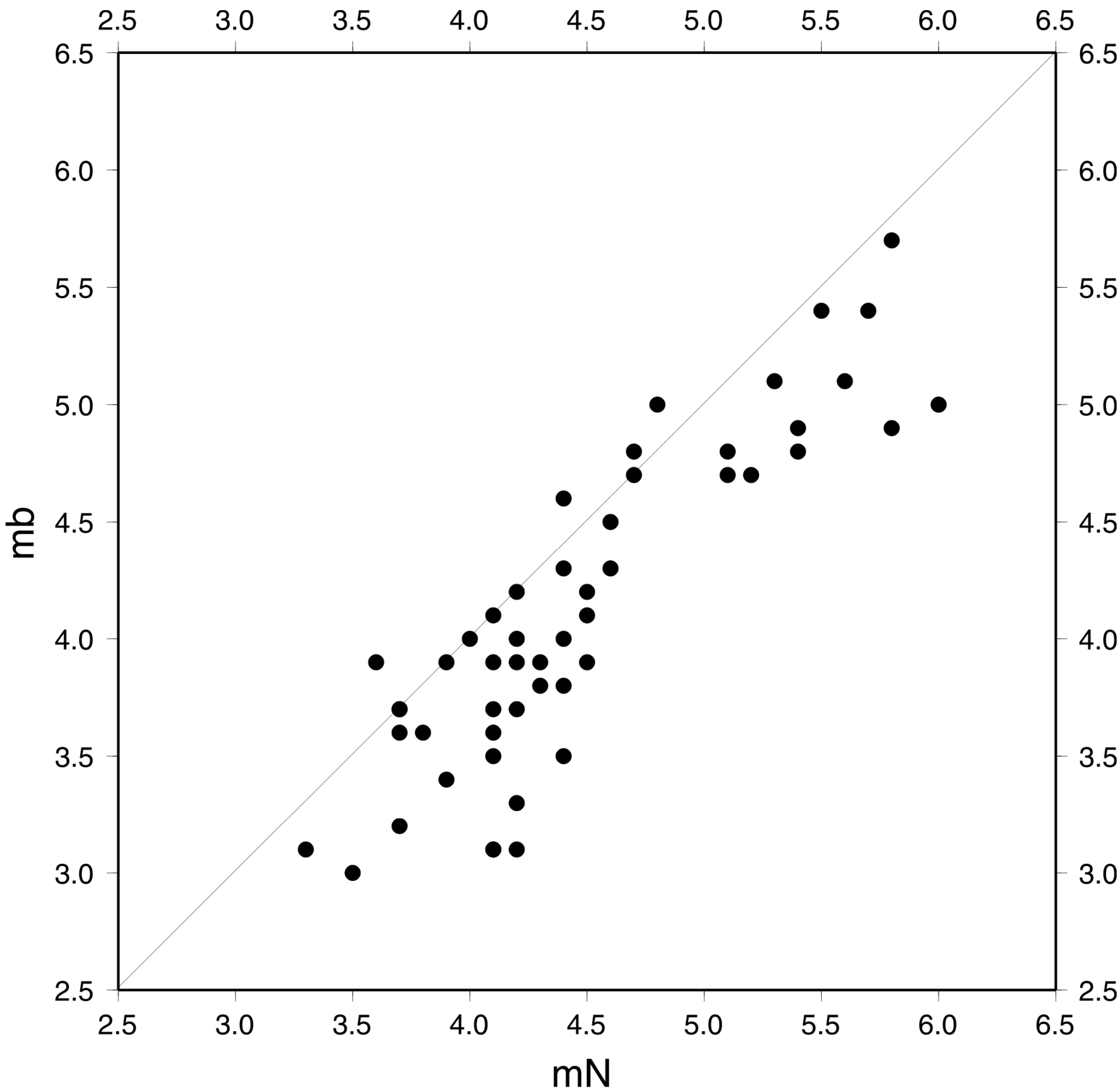
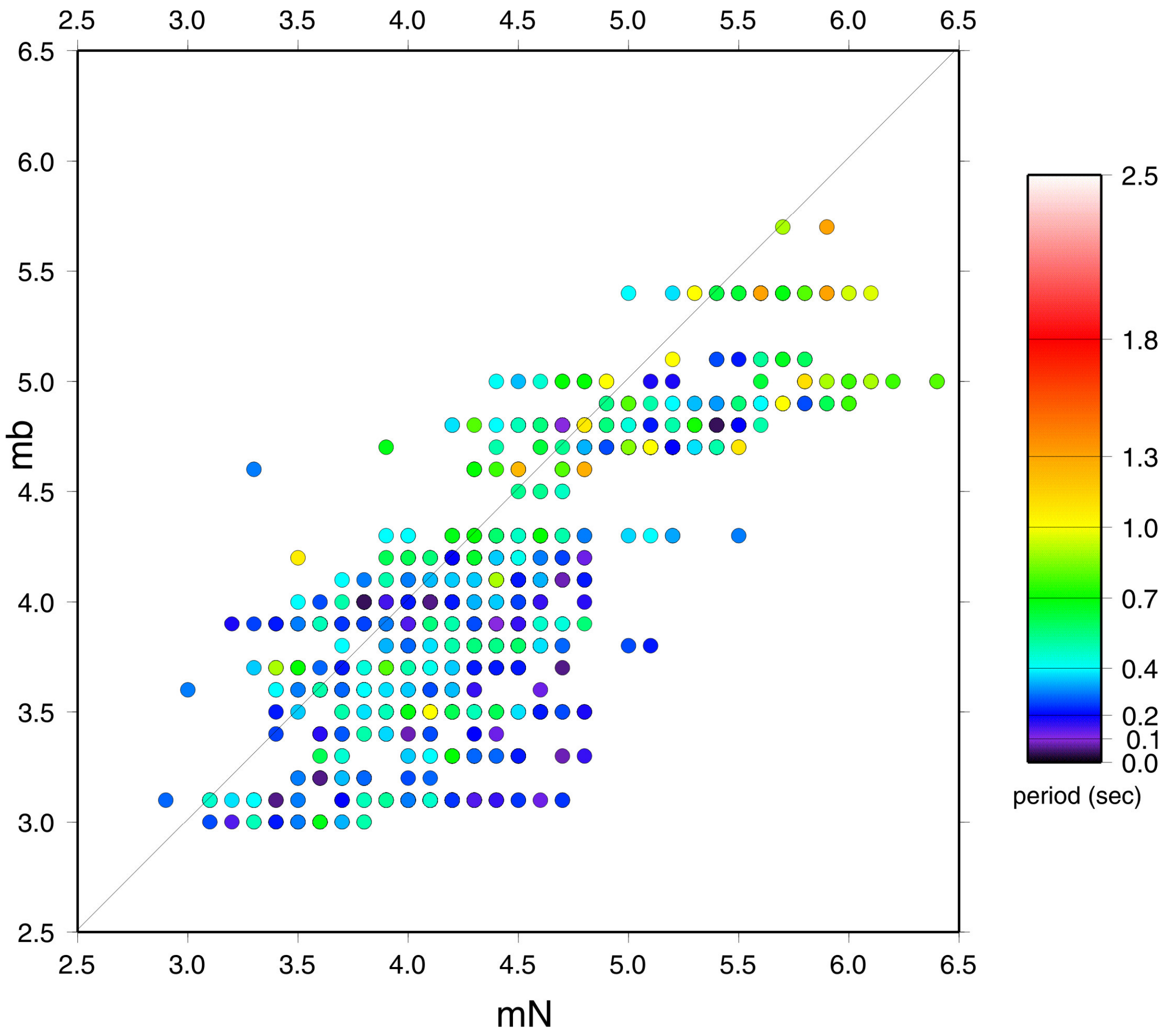


Figure 5: A comparison of m_N (x-axis) and m_b (y-axis) for earthquakes in this study for which both magnitudes are available. The diagonal line represents $m_N = m_b$. (a) comparison of event magnitudes



5(b) comparison of m_N station magnitudes to m_b event magnitudes. The color of the symbol indicates the period at which the m_N magnitude was calculated.

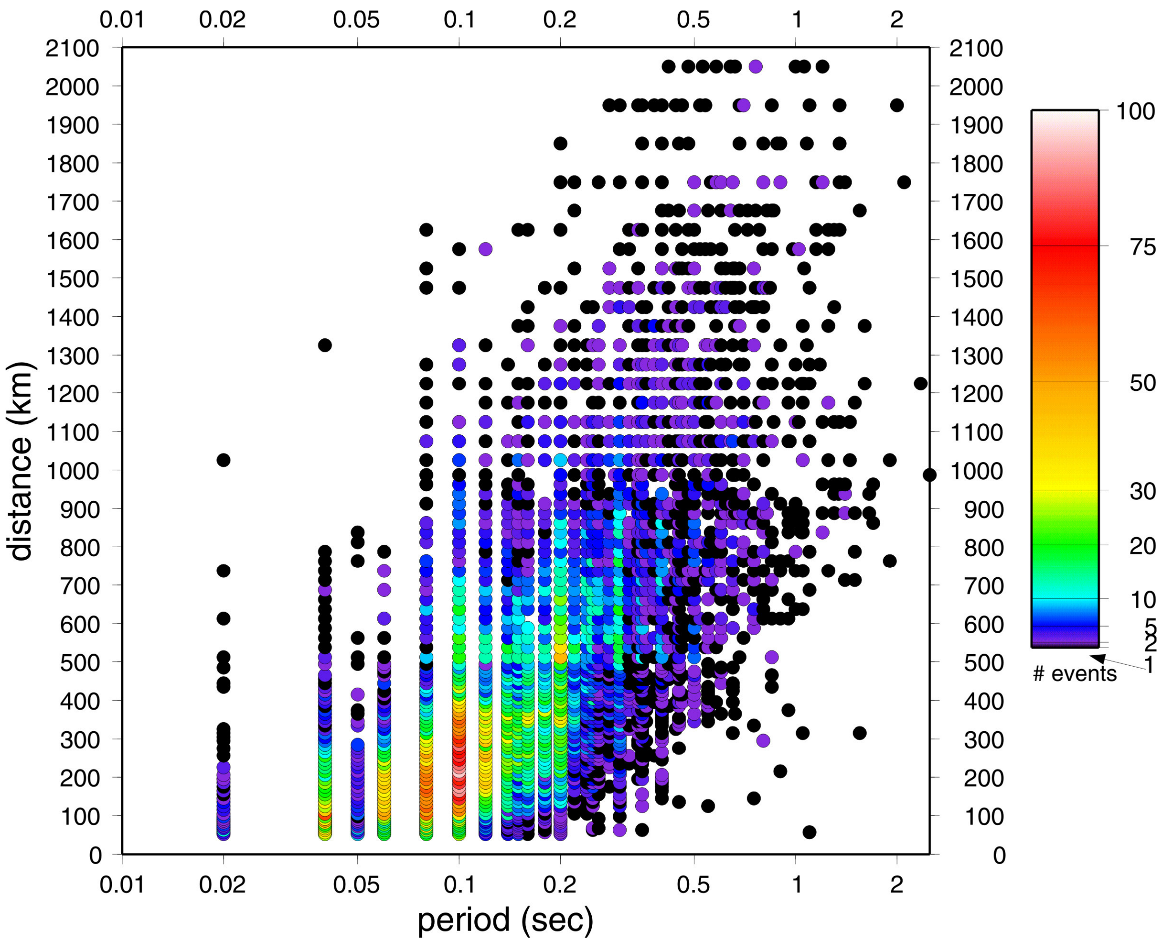
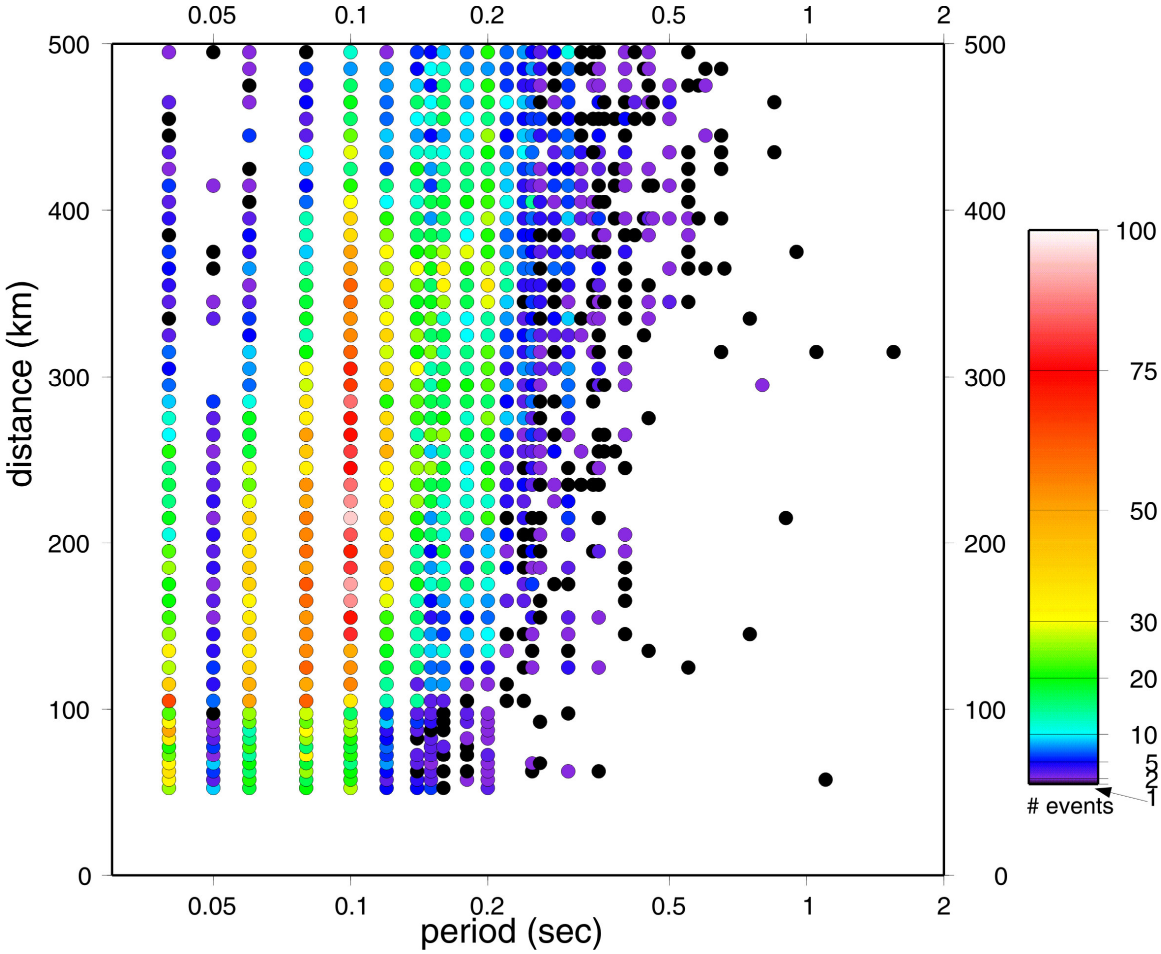


Figure 6: The number of station magnitudes for this data set as a function of period and distance. Distance windows used for binning the data are 5 km for distances of less than 100 km, 10 km for 100-500 km, 25 km for 500-1000 km and 50 km for greater than 1000 km. (a) all data to distances of 2100 km



6(b) periods of 0.04-2 seconds and distances to 500 km.

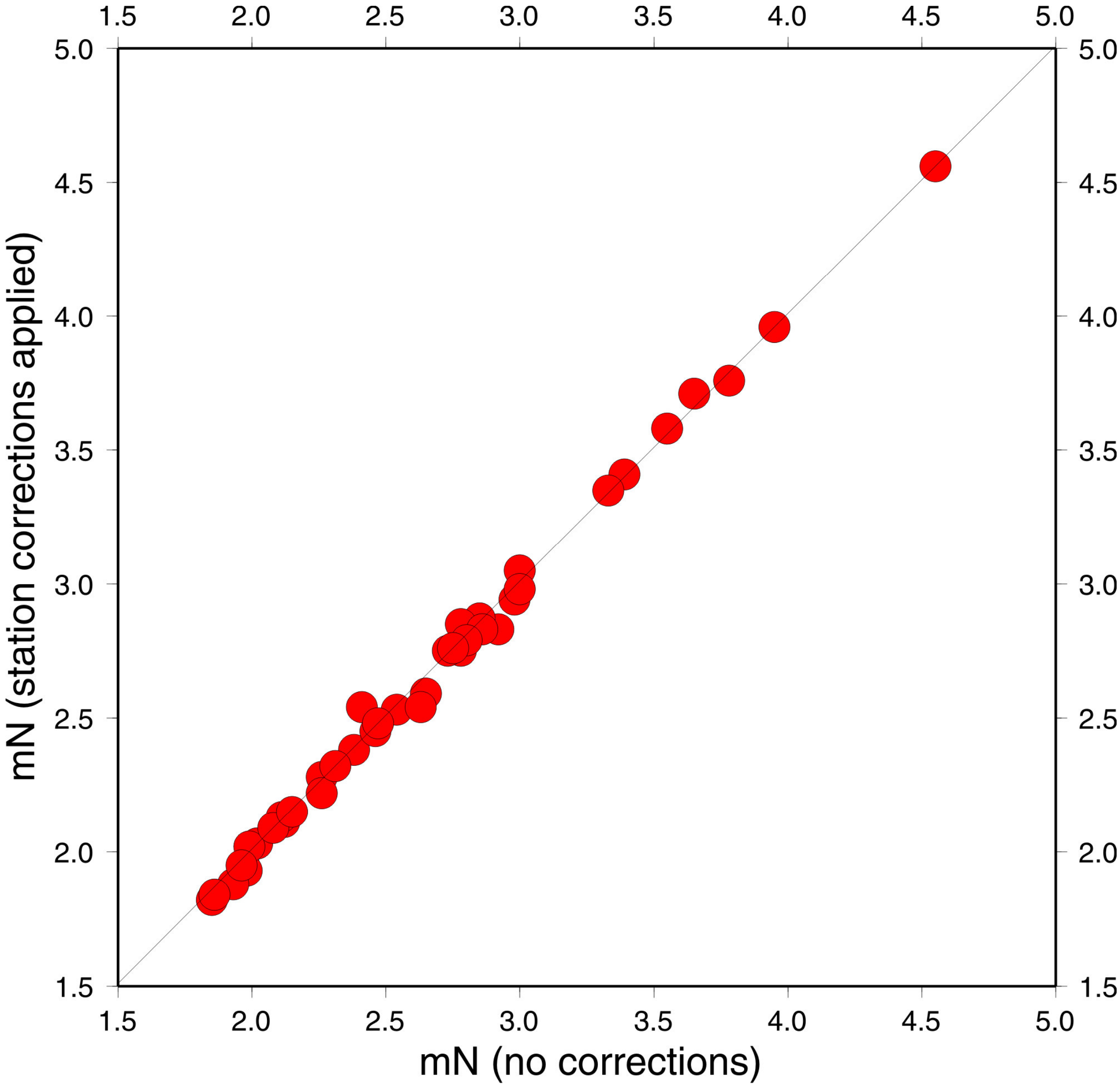


Figure 7: A comparison of original m_N magnitudes (x-axis) to those with the station corrections applied (y-axis) for forty selected earthquakes as discussed in the text. The diagonal line represents equal magnitudes.