

# Residual analysis of teleseismic P-wave energy magnitude estimates: inter- and intra-station variability

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## Abstract

Computing the magnitude of an earthquake requires correcting for the propagation effects from the source to the receivers. This is often accomplished by performing numerical simulations using a suitable Earth model. In this work, the energy magnitude  $M_e$  is determined considering theoretical spectral amplitude decay functions, computed over teleseismic distances considering the global Earth model AK135Q. Since the high frequency part (above the corner frequency) of the source spectrum has to be considered in computing  $M_e$ , the influence of propagation and site effects may not be negligible and they could bias the single station  $M_e$  estimations. Therefore, in this study we assess the inter- and intra-station distributions of errors by considering the  $M_e$  residuals computed for a large dataset of earthquakes recorded at teleseismic distances by seismic stations deployed worldwide. To separate the inter- and intra-station contribution of errors, we apply a maximum likelihood approach to the  $M_e$  residuals. We show that the inter-station errors (describing a sort of site effect for a station) are within  $\pm 0.2$  magnitude units for most stations and their spatial distribution reflects the expected lateral variation affecting the velocity and attenuation of the Earth's structure in the uppermost layers, not accounted for by the one-dimensional AK135Q model. The variance of the intra-station error distribution (describing the record-to-record component of variability) is larger than the inter-station one (0.240 against 0.159), and the spatial distribution of the errors is not random but shows specific patterns depending on the source-to-station paths. The set of coefficients empirically determined may be used in the future to account for the heterogeneities of the real Earth not considered in the theoretical calculations of the spectral amplitude decay functions used to correct the recorded data for propagation effects.

## Introduction

The basic idea behind the definition of earthquake magnitude is to provide a measure of an earthquake's "strength" (e.g., Richter, 1935). In order to obtain a parameter that is intended to characterize the seismic source, the propagation effects from the source to the receivers must be accounted for. When computing earthquake magnitudes using data from the teleseismic distance range, it is standard practice to apply corrections to the recorded seismograms which are assumed to be valid on a global scale (for a comprehensive review of this argument, see Bormann et al., 2002). Likewise, procedures to obtain moment tensor solutions (e.g., Dziewonski et al., 1981; Sipkin, 1994; Kanamori and Rivera, 2008) make use of a global average reference Earth model for the computation of synthetic seismograms. Such approximations are normally satisfied since the periods (wavelengths) considered in the teleseismic seismograms should not be significantly affected by the presence of small scale heterogeneities characterizing the Earth's structure. This is particularly the case for the moment magnitude  $M_w$  (Kanamori, 1977; Hanks and Kanamori, 1979) since, by its definition, it is computed by considering the long and very long periods of seismograms. However, when considering magnitude scales related to the medium and short period content radiated by a seismic source, such as the classical broadband body-wave  $m_B$  and the surface wave  $M_s$  magnitudes (Gutenberg, 1945a, b, and c; Gutenberg and Richter, 1956), the influence of propagation paths and local effects may be not negligible. In particular, the energy magnitude  $M_e = 2/3(\log_{10}E_S - 4.4)$  (Choy and Boatwright, 1995; Bormann et al., 2002; Choy et al., 2006), which requires the calculation of the radiated energy  $E_S$  (Haskell, 1964) and therefore the integration of the source spectrum over a broad range of frequencies, might suffer from biases due to these effects.

Since 1990, the global broadband station deployment has increased and made available a huge amount of digital data from globally distributed earthquakes, allowing the computation of  $M_e$  on a routine basis. Recently, Di Giacomo et al. (2010a, b) proposed a technique to compute  $M_e$  for rapid response purposes and tested it considering a large dataset. Owing to the dense sampling of a large volume of the Earth's interior by different source-receiver paths, it is now possible to assess the influence on  $M_e$  estimates of propagation and local effects not accounted for by one-dimensional (1D) models, such as AK135Q (Kennett et al., 1995; Montagner and Kennett, 1996), usually used to correct for the geometrical spreading and anelastic attenuation of the considered short to medium period teleseismic signals (i.e., P-waves in the frequency band 12.4 mHz - 1 Hz).

To accomplish this task, we perform a regression analysis on Me residuals considering a random effect model (Brillinger and Preisler, 1985), with the aim of isolating the local effects (inter-station errors) from all other sources of variability related to source and propagation effects (intra-station errors). We denote local effects as those related to the differences between the average 1D propagation model AK135Q and the real Earth properties over a depth range corresponding to a vertical or nearly vertical propagation of the seismic rays arriving at a given station from teleseismic distances. Moreover, after correcting the residuals for local effects by considering the station-to-station error distribution, we show some examples of specific source-to-station paths with peculiar error patterns, which in the near future may be used to apply specific source-propagation path corrections for Me estimations. In this way, the spectral amplitude decay functions calculated by Di Giacomo et al. (2008, 2010a) and based on a global average 1D model, might be corrected for effects due to Earth heterogeneities by applying a set of coefficients empirically calibrated for a number of representative source-to-station paths.

### **Dataset and residual distribution**

In this study, the residuals of single station Me determinations are considered. The residual is computed as the difference between the single station Me and the event average Me. The details of the calculation of our rapid Me values are described in Di Giacomo et al. (2010a,b) and are not repeated here. We only recall that Me is computed by analyzing teleseismic P-wave signals in the frequency domain (distance and frequency range within  $20^\circ < \Delta < 98^\circ$  and  $\sim 12 \text{ mHz} \leq f \leq 1 \text{ Hz}$ , respectively) and performing the correction for the propagation effects by means of theoretical spectral amplitude decay functions for different frequencies evaluated for the reference Earth model AK135Q. This way, the frequency-dependent energy loss experienced by the seismic waves during propagation is accounted for and the computation of  $E_s$  is obtained from the integral of the corrected power spectra. Fig. 1 compares examples of the theoretical functions (see Di Giacomo et al., 2008, 2010a) for 1 Hz (black lines) and 0.0625 Hz (gray lines) with the spectral amplitudes at the same frequencies observed for 11 earthquakes with Mw between 6.50 and 6.52. Although the theoretical curves are able to capture the overall trend in the data with distance, a significant scatter affects the distribution of the observations for each considered frequency. The aim of this study is to quantify and separate the contribution of local effects to this scatter from the contribution associated with all the other sources of variability, such as source characteristics (e.g., radiation pattern and

directivity effects) and propagation effects (e.g., significant deviation of the real Earth structure from the adopted average model for attenuation and velocity).

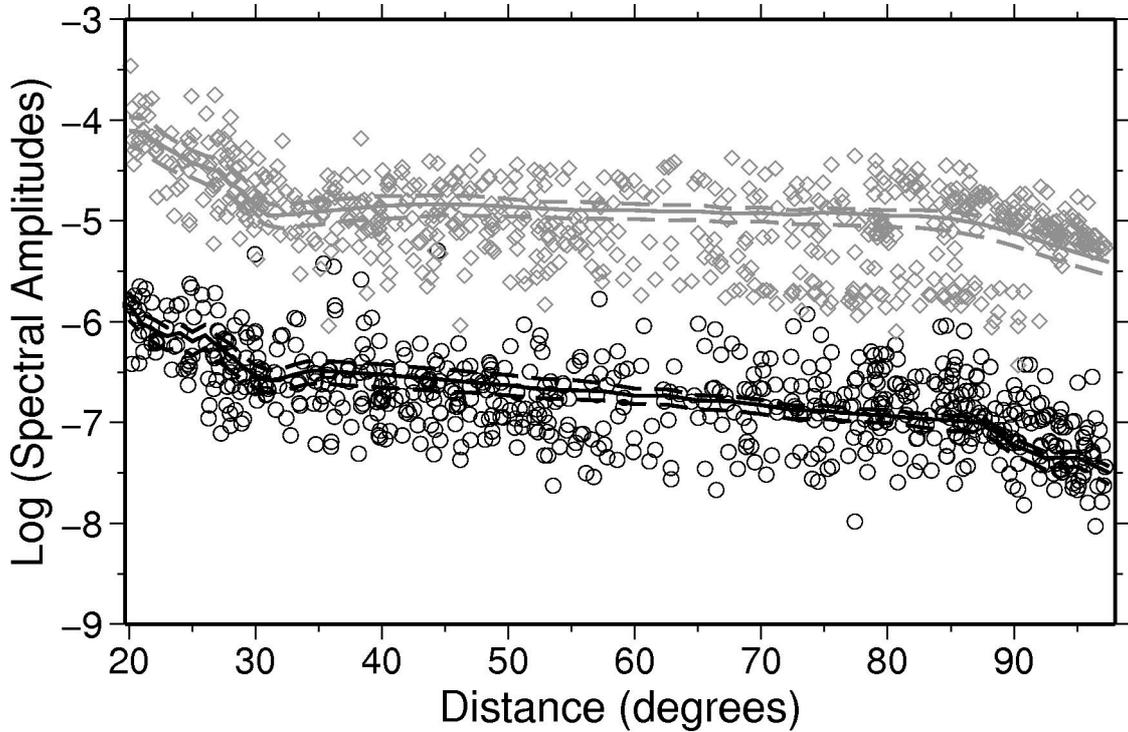


Fig. 1: Observed spectral amplitudes as a function of distance for frequencies of 1 Hz (black circles) and 0.0625 Hz (gray diamonds), considering 11 earthquakes of magnitude  $6.50 \leq M_w \leq 6.52$ . The median of the theoretical spectral amplitude decay functions at 1 Hz and 0.0625 Hz are the solid black and gray lines, respectively, along with their corresponding 15<sup>th</sup> and 75<sup>th</sup> percentiles (dashed lines).

The single station  $M_e$  values considered in this study are obtained by analyzing 1001 worldwide distributed shallow earthquakes ( $h < 70$  km). These earthquakes occurred between March 1990 and December 2008 and their magnitude range is  $5.5 \leq M_w \leq 9.3$ . Fig. 2 shows their geographical distribution together with the 476 seismic stations used to calculate  $M_e$ . In total, we obtained about 48,000 single stations  $M_e$  estimates. For 26% of the stations considered, recordings for less than 20 earthquakes are available. For 25% of stations, between 21 and 70 of the selected earthquakes were recorded while, for the remaining ~49%, more than 70 earthquakes can be analyzed. Finally, in the considered dataset, there are a few stations (CHTO, YAK, BJT, KMI and HIA) that recorded nearly 500 of the selected earthquakes.

Fig. 3 shows the  $M_e$  station residuals for different distance ranges. For each distance range ( $10^\circ$  wide with an overlap of  $5^\circ$ ) the average value  $\pm$  one standard deviation is also reported in each subplot. The standard deviations range from 0.270 for distances between 50 and 60 degrees, to 0.328 for distances between 20 and 30 degrees. The largest values are observed

over the two shortest distance ranges ( $20^{\circ}$ - $30^{\circ}$  and  $25^{\circ}$ - $35^{\circ}$ ), corresponding to rays traveling mainly through the most heterogeneous part of the Earth, that is the transition zone and upper mantle. The different contributions to the observed variability of the residuals are quantified by exploiting the size of the analyzed data set and the distribution of the considered stations and hypocenters, which allows us to sample a large proportion of the Earth's volume when looking at different source-to-receiver propagation paths.

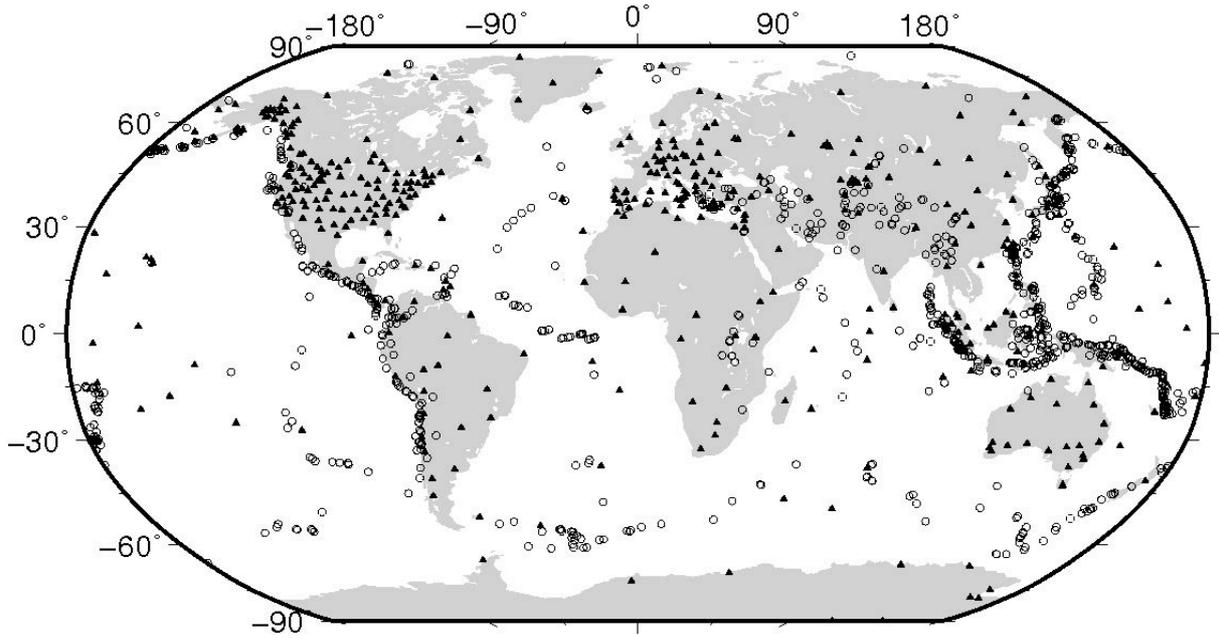


Fig. 2: Map showing the distribution of the 1001 earthquakes (circles) and the 476 seismic stations (triangles) considered in this work.

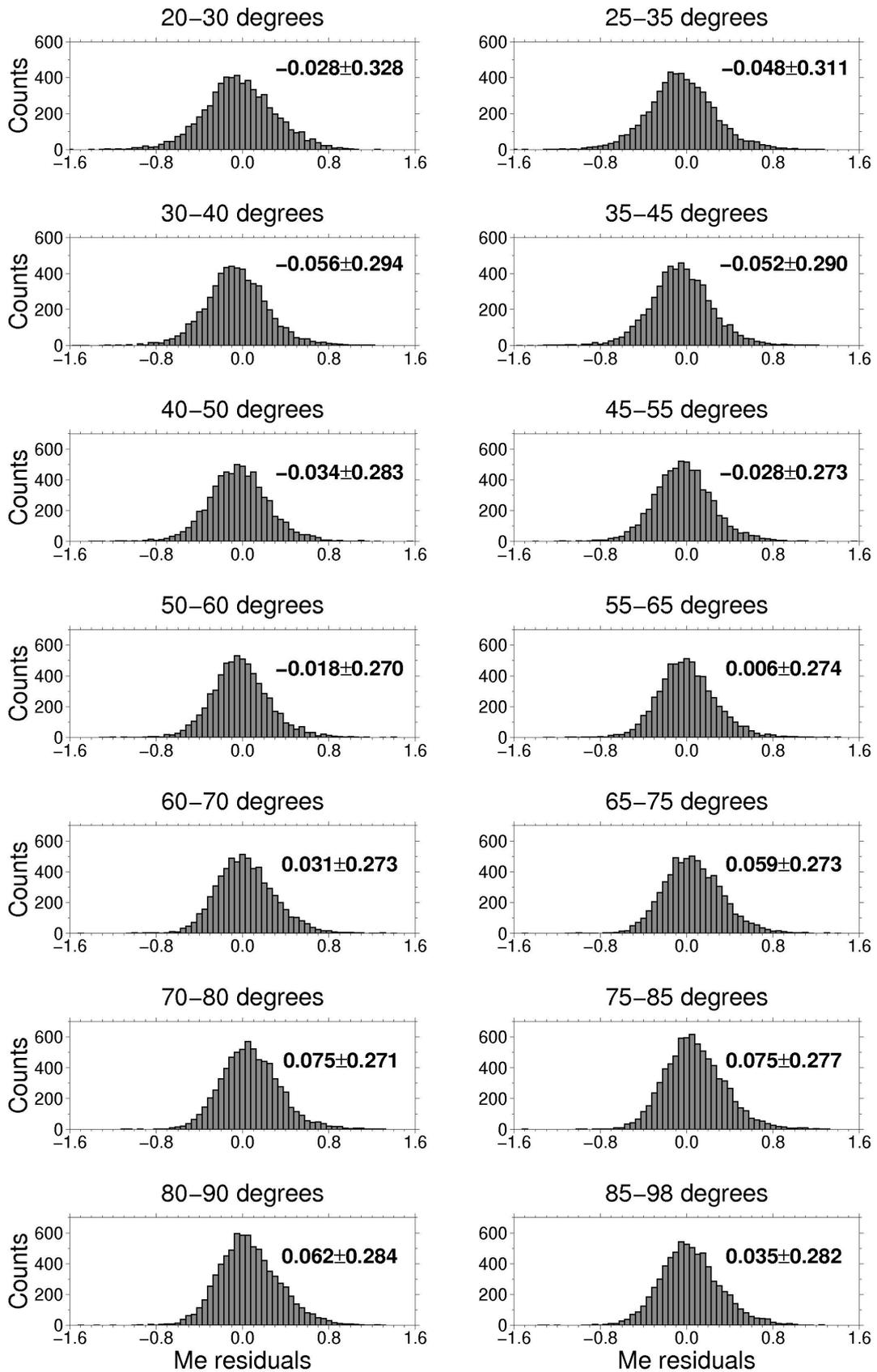


Fig. 3: Distributions of residuals for the complete dataset as a function of distance. In each subplot, the average  $\pm$  one standard deviation is also reported. See text for details.

## Inter-station and intra-station components of variance

We consider a mixed model (Brillinger and Preisler, 1985; Abrahamson and Youngs, 1992), usually used for the derivation of ground motion prediction equations, to describe the residual distribution between the event-magnitude and the single-station magnitude. In particular, we separate the residuals into fixed and random-effect components as follows:

$$M_{ij} - M_i = M_{ij} - \frac{1}{N_i} \sum_{j=1}^{N_i} M_{ij} = \delta_{ij} = \eta_j + \varepsilon_{ij}, \quad (1)$$

where  $M_{ij}$  is the magnitude estimate at station  $j$  for event  $i$ ,  $M_i$  is the average magnitude computed for event  $i$ ,  $N_i$  is the number of the stations that recorded event  $i$ ,  $\delta_{ij}$  are the residuals,  $\eta_j$  represents the inter-station variations (station-to-station component of error) and  $\varepsilon_{ij}$  represents the intra-station variations (record-to-record component of error). The distributions of error  $\eta_j$  and  $\varepsilon_{ij}$  are assumed to be independent and normally distributed with variances  $\sigma^2$  and  $\tau^2$ , respectively. The inter-station error  $\eta_j$  takes on a specific value for each station and accounts for the correlation between magnitude values estimated for different earthquakes at the same station. It describes a sort of site effect that can be due to either the instruments (e.g. incorrect calibration function) and/or to significant deviations between the uppermost part of the Earth structure beneath a given station and the global model AK135Q used to compute the Green's functions (Di Giacomo et al. 2008, 2010a). On the other hand, the intra-station error takes on a specific value for each source-to-station path and includes both propagation effects (e.g. lateral variations in the seismic velocity and attenuation not considered in the global model used for computing the Green's function) and source effects (e.g. radiation pattern effects). We apply a maximum likelihood approach (Abrahamson and Youngs, 1992) to determine the distribution of errors for the problem described by equation (1).

## Results

Fig. 4 shows the residual distribution  $\delta$  (top), the inter-station  $\eta$  (middle) and intra-station  $\varepsilon$  (bottom) error distributions, as well as their histogram distributions. Although the intra-station component of variance ( $\tau^2 = 0.240$ ) is the dominant one, the inter-station variability ( $\sigma^2 = 0.159$ ) is not negligible. In the following we first discuss the results regarding the inter-station variability, followed by the intra-station component of variability.

### 1) Inter-station distribution of error

The middle panel of Fig. 4 shows that, although the errors for a few stations (e.g. KHC, GRGR, SUW and LZH, as indicated in the figure) exceed 0.5 magnitude units (m.u.), most of the stations (~78%) show inter-station errors in the range  $-0.2 \leq \eta \leq 0.2$  (their geographical distribution is shown in Fig. 5, bottom). This result confirms how the AK135Q global velocity and attenuation model used to compute the Green's functions provide a reasonable average description of the propagation effects in the uppermost part of lithosphere, where the seismic rays reaching a given station are propagating almost vertically. The remaining ~22% of the stations with absolute inter-station errors larger than 0.2 are plotted in the upper panel of Fig. 5. We remind the reader that, apart from potential instrumental issues, a systematic overestimation of  $M_e$  at a given station (i.e., positive inter-station error) is expected if the correction for geometrical spreading and frequency-dependent attenuation overestimates the actual energy loss over the last part of the propagation path. Thus, the observation of a positive inter-station error means that the uppermost velocity and attenuation structure below a given station causes less energy loss than would be expected from the model AK135Q. In the case of underestimation of  $M_e$  (i.e., negative inter-station error), the opposite is true. The station showing the largest positive error is KHC, installed in the Czech Republic, while the largest negative error is obtained for station LZH, installed in China. It is worth noting that for these stations, large values of the residuals are observed systematically, regardless of the source position and strength, while neighboring stations, available at least for KHC, do not show such large values. We therefore hypothesize that such large inter-station errors are due to instrumental problems (e.g. miss-calibration).

Most of the stations with inter-station errors greater than 0.2 (Fig. 5, top) are located in the Europe/Mediterranean area, in Indonesia and in the Pacific and Atlantic oceans, whereas the main patterns of negative inter-station errors are located in Australia and the USA. Since the inter-station error, besides systematic instrumental errors, are related to propagation effects in the lithospheric layers below the stations, large absolute values of  $\eta$  for group of stations could hint at significant deviations between local lithospheric structure and the global AK135Q model. Although a direct comparison with percentage variations in P-wave velocity imaged by teleseismic tomography is not straightforward, a fair consistency between patterns of positive and negative inter-station errors with anomalies in the crust and upper mantle is found. For example, the inter-station distribution for North-America (Figs. 5a and 5b) shows a cluster of station with negative errors (i.e. single station magnitudes less than the average

magnitude) in the western United States in an area encompassing California, the Great Basin, the High Lava Plains, and the Yellowstone-Snake River plain hotspot, whereas positive errors are obtained for the Cascade region and in the central-southern United States. These patterns fit, to a first-order approximation, the velocity anomalies shown by Burdick et al. (2009). Similar observations for European stations can be made between the distribution of positive and negative inter-station errors and the variations in the lithosphere imaged by P-wave tomography (Koulakov et al., 2009). This is in particular the case for the stations characterized by negative  $\eta$  located in Crete and, to a lesser extent, in central Europe. Other stations (especially the ones located along the Apennines in Italy) do not show a good fit with the P-wave anomalies of Koulakov et al. (2009). Considering, however, that we analyzed P-waves over a broad period range (from 1 to 80 s) and that the velocity and attenuation models may be obtained using different period ranges as well as different wave types, we will not proceed further with these types of comparisons in order to avoid an over-interpretation of our results.

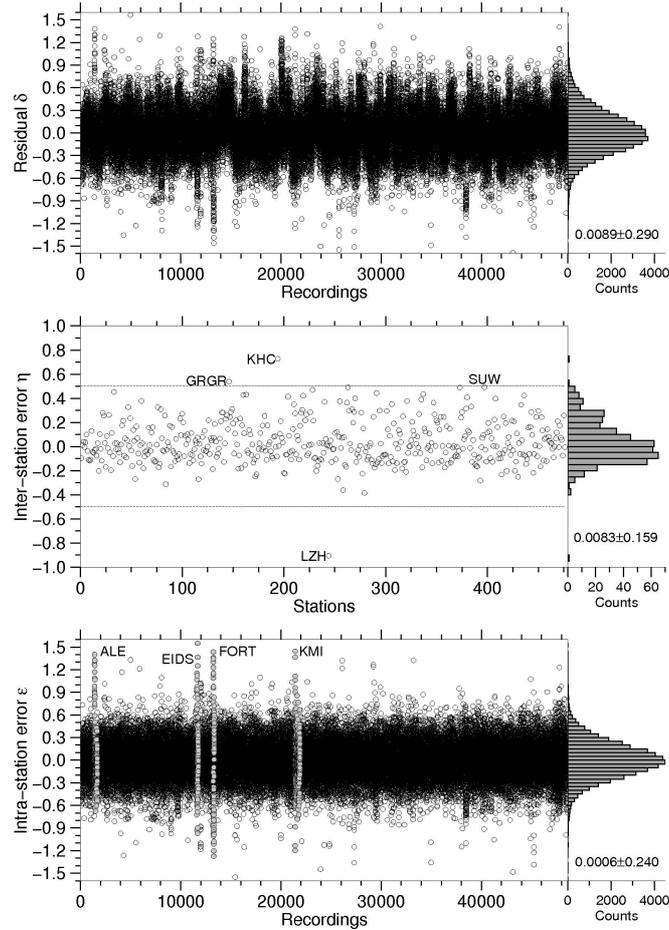


Fig. 4: Top: residual distribution  $\delta_{ij}$ ; middle: inter-station errors  $\eta_{ij}$ , with the names referring to the four stations discussed in the text with larger inter-station errors; bottom: intra-station errors  $\varepsilon_{ij}$  with the gray circles and corresponding names marking the stations with large values of intra-station errors. As representative example for these stations, station ALE is discussed later. For each panel, the histogram distributions and the mean  $\pm$  one standard deviation are also shown. The x-axes are sorted by station name.

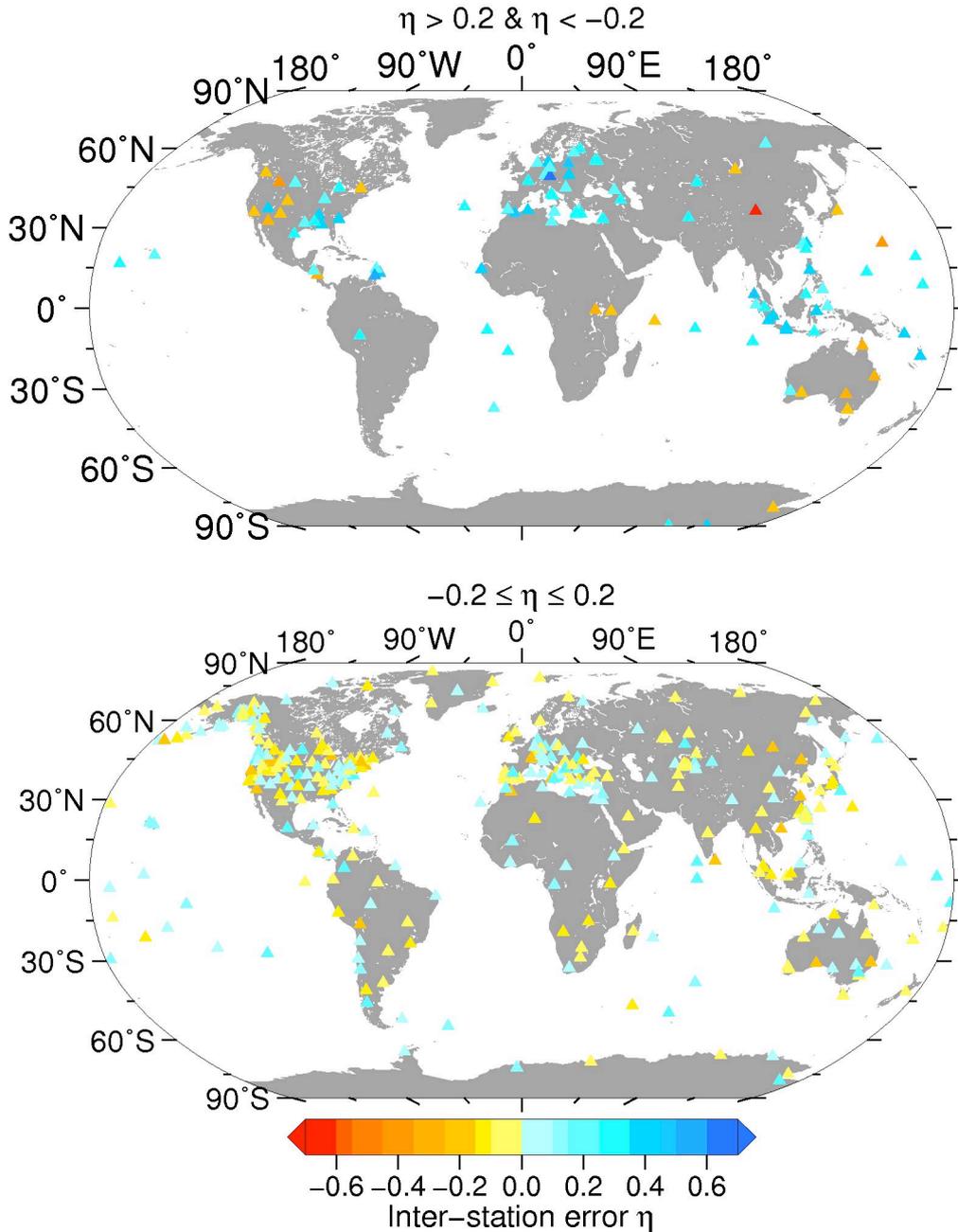


Fig. 5: Maps of the inter-station errors for the 476 station used in the regression analysis. Top: stations with absolute inter-station errors larger than 0.2 m.u. Bottom: inter-station errors within the range  $\pm 0.2$  m.u.

## 2) Intra-station distribution of error

The standard deviation of the intra-station distribution of errors is 0.24 (Fig. 4, bottom panel). Removing the inter-station errors from the residual distribution leads to a reduction of the variance with respect to the residual distribution shown in Fig. 3. This is shown in Fig. 6, where the intra-station errors are computed over different distance ranges as in Fig. 3, with a reduction of the dispersion observed over all distance ranges.

Some stations still present few recordings with large errors clustered in time. Fig. 7 exemplifies the case of station ALE, whose recordings are marked in gray in Fig. 4 (bottom

panel). The large errors correspond to earthquakes recorded between 1990 and 1993 while, after this date, the average intra-station error is almost zero. This may be due to some transitory malfunctioning of the station. Since the dependence on time of the residuals is averaged out when computing the inter-station error, this affects the intra-station error distribution. A similar behavior is also observed at a few other stations (EIDS, FORT, KMI) indicated in Fig. 4.

The intra-station variability can be related to propagation or source effects. Regarding the dependence on source, Fig. 8 shows the intra-station residuals versus distance for the entire dataset divided into their different fault plane solution groups (Zoback, 1992). The average and standard deviation of the intra-station distributions error for the different groups are very similar, suggesting that the magnitude estimates are not strongly affected, on average, by the source mechanism. This is also confirmed in Fig. 9, where the distribution of the intra-station errors for two stations, CHTO in Thailand and BJT in China, that recorded a large number of earthquakes do not show any significant trend with respect to the different fault mechanism groups. That is, the trend in the intra-station errors with both distance and backazimuth are independent of the focal mechanism. The observed scatter (similar for the different mechanisms) is related to the different propagation distances, suggesting that rays travelling at different mantle depths cross different lateral heterogeneities. This confirms the findings of Di Giacomo et al. (2010a) who showed on the example of the recent great doublet in the Kuril Islands (Ammon et al., 2008) that the source mechanism does not play a dominant role in the residual pattern when the average magnitude is computed over a broad range of azimuths and distances. In this sense, directivity effects, which according to Venkataraman and Kanamori (2004) may influence single station estimates of  $E_S$  by a factor of 2-3 (that is to say, 0.2-0.3 m.u.) and even more in some case, are expected to be averaged out. Moreover, considering also the fact that the distribution of intra-station errors does not show any dependence on magnitude (not shown here), we therefore discuss the intra-station error in terms of path distributions only.

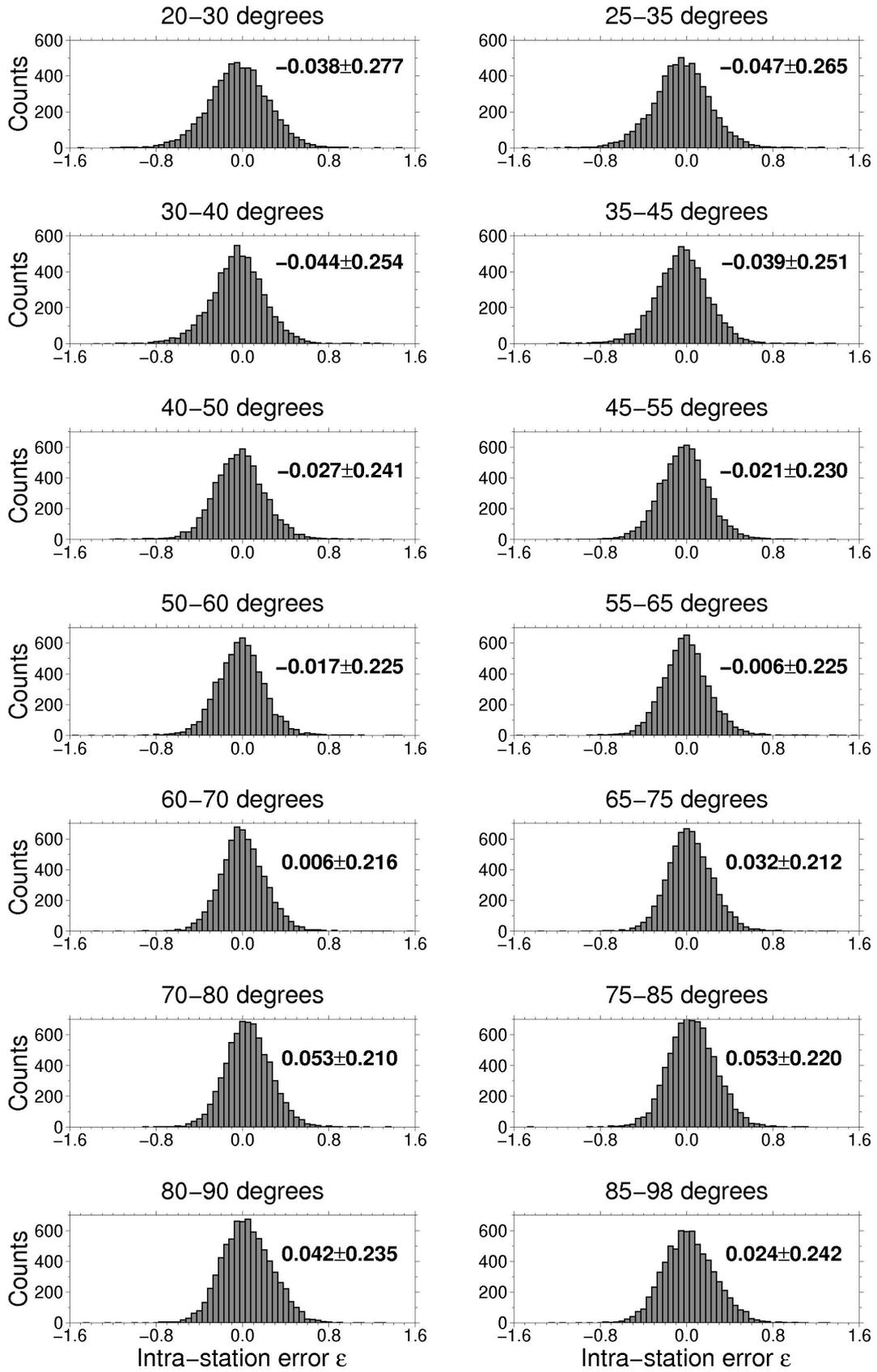


Fig. 6: Intra-station distributions for different distance ranges, as in Fig. 3. In each subplot, the average  $\pm$  one standard deviation is also reported.

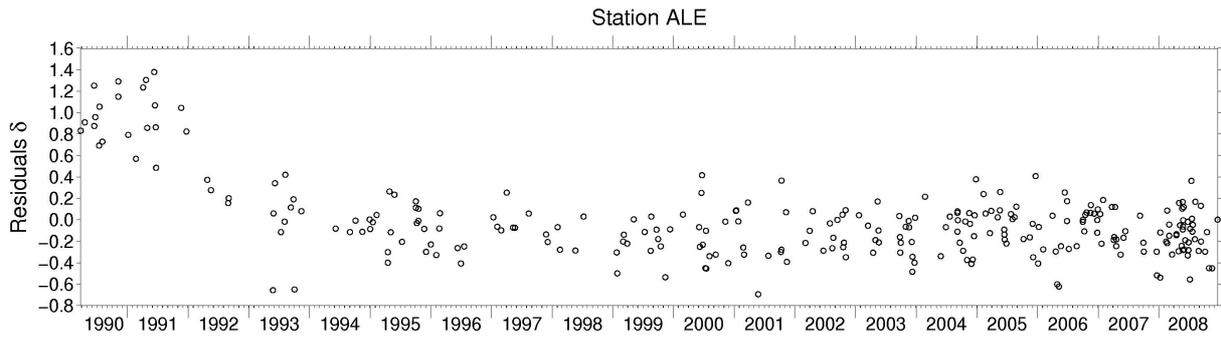


Fig. 7: Temporal distribution of the Me residuals  $\delta$  at station ALE (Canada).

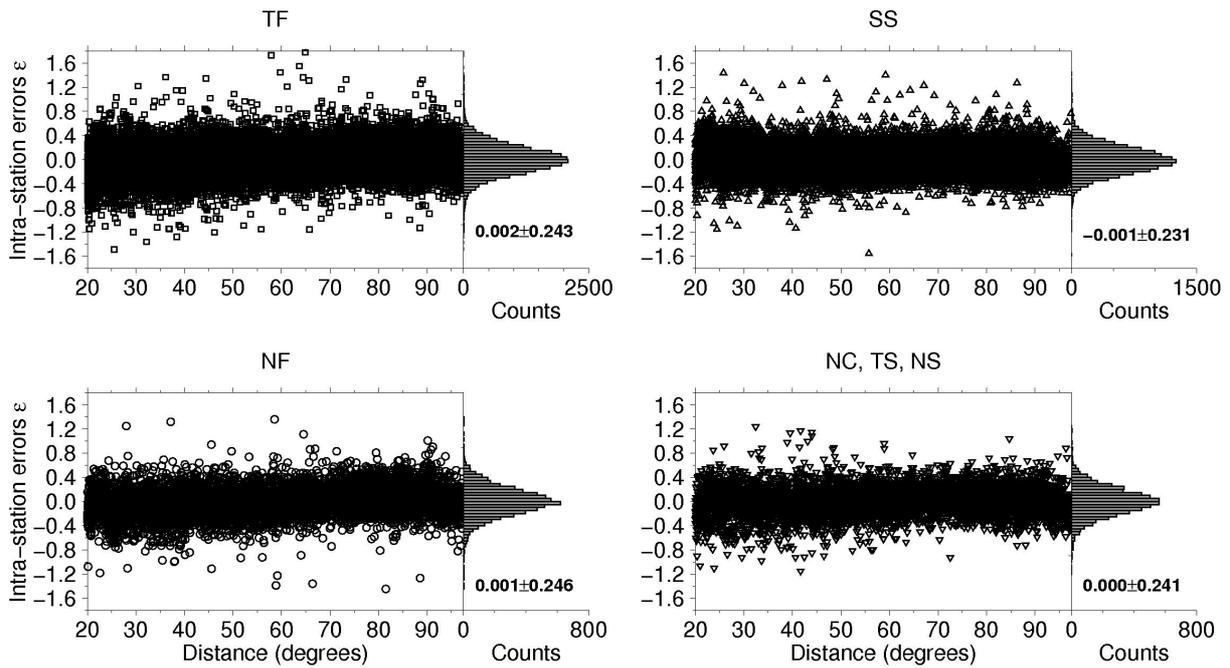


Fig. 8: Intra-station errors versus distance, grouped into the fault plane solution classes of Zoback (1992). TF identifies thrust, SS strike-slip, NF normal fault, NC not classified, TS thrust with strike-slip component, and NS normal with strike-slip component earthquakes, respectively. In each subplot, the average  $\pm$  one standard deviation is also reported.

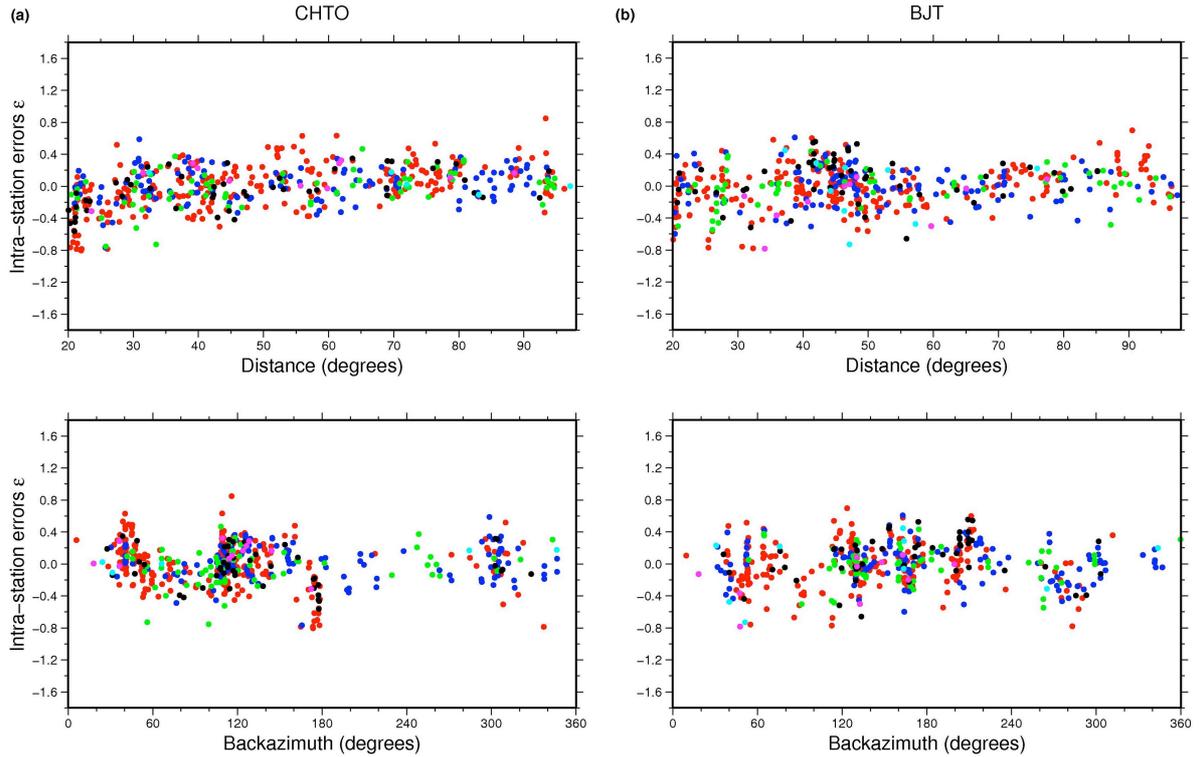


Fig. 9: a) Intra-station errors for station CHTO (located in Thailand), plotted using the fault plane solution groups of Zoback (1992). The upper panel shows the intra-station error distribution versus distance, the lower one versus backazimuth. The red points refer to TF, green to NF, blue to SS, black to NC, magenta to TS and cyan to NS earthquakes, respectively. b) The same as for a) but for station BJT (located in China).

To this regard, Fig. 10a shows the intra-station errors for station CHTO for the different travel paths. On one hand, for earthquakes occurring in an area that ranges from Hokkaido (Japan) in the south to the Kuril and Aleutian Islands in the north, the intra-station error is generally positive (only 7 negative values over 50 rays) spanning between -0.27 and 0.63. A similar pattern is found for the ray paths coming from the South Pacific Ocean, in the South-East quadrant of Fig. 10a. On the other hand, a clear cluster of negative intra-station error values is observed for earthquakes occurring in the Philippines Sea-Mariana Islands region with distances to CHTO less than  $\sim 45^\circ$ . This cluster can also be identified in Fig. 9a and a similar behavior also applies for some other stations. However, this apparent dependence on distance does not represent a systematic trend throughout the entirety of the dataset, as can for instance be seen in Fig. 9b for station BJT but also for stations not reported here. For rays arriving at station CHTO from the Indian Ocean, Eurasian plate and Africa, more data are necessary before patterns in the intra-station error distributions can be identified.

In Fig. 10b, we consider the propagation paths for 26 earthquakes that occurred in the Kuril Islands-Japan area (latitude between  $30.6^\circ\text{N}$  and  $52.1^\circ\text{N}$ , longitude between  $131^\circ\text{E}$  and  $150^\circ\text{E}$ ) and have been recorded by station BFO in Germany and TUC in the United States. The differences in epicentral distances for these earthquakes to the BFO and TUC locations

span between  $1^\circ$  and  $12^\circ$ . Noticeably, the rays travelling to BFO have nearly zero or positive intra-station errors ( $-0.007 < \varepsilon < 0.67$ ), whereas for the same earthquakes, rays arriving at TUC generally show negative values ( $-0.32 < \varepsilon < -0.03$ , with only one event having a relatively large positive  $\varepsilon$  of 0.29). As already mentioned, this outcome confirms what Di Giacomo et al. (2010a) observed for the great Kuril Islands doublet. The most probable cause for the distinct intra-station patterns of Fig. 10b lies in the difference in the cumulative propagation correction for rays travelling mostly along continental (station BFO) or oceanic (station TUC) paths. Similar observations can be made in Fig. 10c for stations ANTO and SCZ. Indeed, station ANTO shows  $-0.07 < \varepsilon < 0.45$  (only two events out of 23 having a negative  $\varepsilon$  but very close to zero) and station SCZ has  $-0.48 < \varepsilon < 0.19$  (only three events having positive  $\varepsilon$  between 0.14 and 0.19). Therefore, these examples provide hints that the compensation for the energy loss as calculated from the model AK135Q is overestimated for (continental) rays to BFO (ANTO) and underestimated for (oceanic) rays to TUC (SCZ).

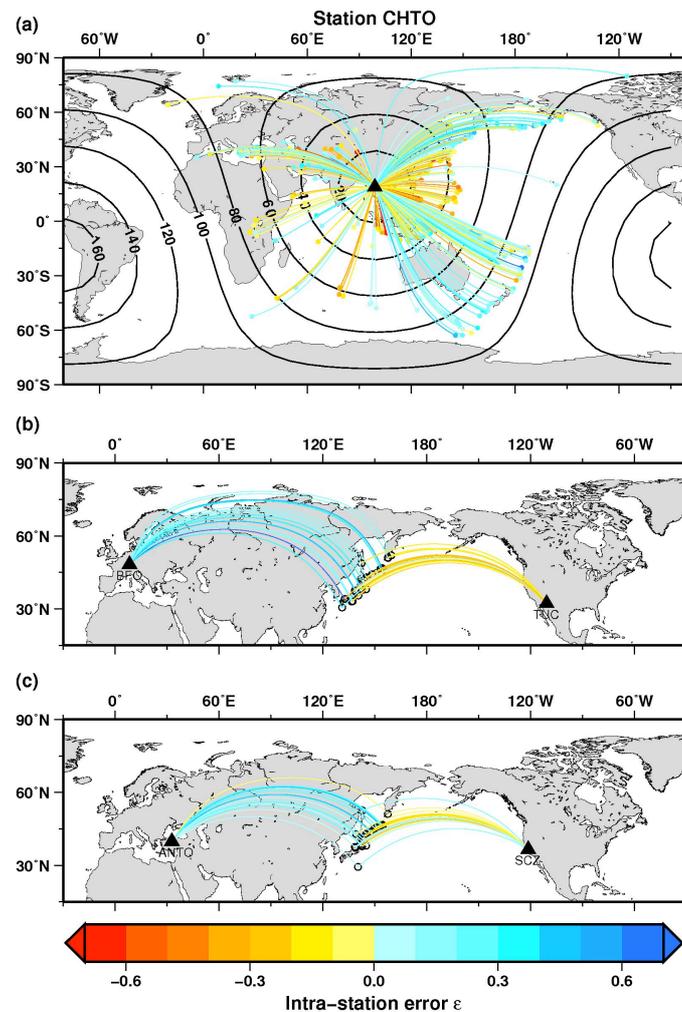


Fig.10: a) Intra-station errors for about 500 earthquakes recorded at station CHTO (black triangle). b) Intra-station errors for 26 earthquakes that occurred in the Kuril Islands-Japan region and were recorded by stations BFO (Germany) and TUC (USA); c) the same as for Fig. 10b for 23 earthquakes recorded by stations ANTO (Turkey) and SCZ (USA).

## Conclusions

Exploiting the redundancy of the information provided by the analyzed dataset (~48000 single station  $M_e$  determinations from ~1000 globally distributed earthquakes), for which the different source-receiver paths sample a large volume of the Earth's interior, we have been able to quantify the station-to-station (inter-station) and the record-to-record (intra-station) components of variability affecting our  $M_e$  estimations by performing a regression analysis on the resulting magnitude residuals. Bearing in mind that the correction for the various propagation effects of the P-wave signals in the frequency band 12.4 mHz – 1 Hz is performed by using theoretical spectral amplitude decay functions based on the average global model AK135Q, the results can be summarized as follows:

- The inter-station errors range within  $\pm 0.2$  m.u. for most (78%) of the analyzed stations and the variance of their distribution is 0.159. This suggests that the 1D model AK135Q provide a good average description of the propagation effects in the uppermost part of the lithosphere. For only a few stations, the inter-station error exceeds 0.5 m.u. in absolute value, most probably due to miss-calibration effects. The geographical distribution of the relatively large positive and negative inter-station errors can be reasonably well explained considering the shallow velocity structure anomalies observed by different authors (as discussed for North America and Europe).
- The variance of the intra-station distribution of error is 0.24 and is the largest component of variability affecting the  $M_e$  estimates. It is generally independent of fault plane geometry and the intra-station distributions for different fault plane solution groups do not show any significant trend with distance and backazimuth. On the other hand, the intra-station errors are not random with respect to the travel paths, and we found that the inter-station error may vary significantly at a given station for rays coming from different seismogenic areas. Moreover, oceanic and continental paths may show distinct inter-station error patterns for the same earthquakes. Large intra-station errors at a few stations are also due to important temporal variations in the original residuals distribution. This may be due to instrumental problems during particular time periods; hence the residuals themselves could be used as simple and quick indicators to detect such problems.

With the increasing number of stations deployed worldwide and, as a result, the increasing availability of seismic data, the outcomes of this study can be used in the near future to improve  $M_e$  estimates by applying sets of coefficients empirically determined to account for

the heterogeneities of the real Earth. Such heterogeneities may significantly influence the medium-to-short period teleseismic P-wave signals and are not considered in the theoretical calculations of the Green's functions used to correct the recorded data for geometrical spreading and anelastic attenuation given the 1D average global model AK135Q.

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