DEVELOPMENT OF IMPROVED MAGNITUDE MEASURES FOR THE INTERNATIONAL DATA CENTRE

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ABSTRACT

Many of the most important issues in nuclear test monitoring at the International Data Centre (IDC), such as event screening, depend critically on the details of the definitions of the various magnitude measures to be employed by the IDC and their relations to the classical National Earthquake Information Center, International Seismological Centre, and Air Force Technical Applications Center magnitude measures, which have historically been used to assess seismic verification capability. Therefore, it is important that these IDC magnitude measures be well understood and carefully calibrated. During the past year, we have been continuing to refine the IDC m_b and M_S magnitude measures, as well as the associated M_S/m_b event screening criterion. A database of approximately 220,000 single station m_b observations recorded from some 25,000 earthquakes reported in the prototype IDC (pIDC) Reviewed Event Bulletin (REB) have now been statistically analyzed to obtain revised corrections for epicentral distance, focal depth, global station corrections for a prototype International Monitoring System network consisting of 89 currently operational stations and distance weighting factors for use in the estimation of a new, generalized m_b magnitude measure which incorporates both teleseismic and regional P wave data. The results of this statistical analysis indicate that the Veith/Clawson corrections for epicentral distance and focal depth employed at the pIDC are remarkably accurate in the teleseismic distance range, where they are clearly superior to the corresponding Gutenberg/Richter corrections, at least for events with focal depths of less than about 400 km. Furthermore, it has been found that application of the associated m_b global station correction factors leads to an average reduction of more than 40% in the variance of the network-averaged m_b values, which indicates that these derived corrections have a high degree of statistical significance. The application of these station correction factors also produces an average increase in the network-averaged m_b values of nearly 0.2 magnitude units, due to the fact that the REB m_b determinations are dominated by data from primary and array stations, which generally have positive station correction factors with respect to the prototype network average. It follows that the recommended M_S/m_b event screening criterion for use with the station-corrected, generalized m_b measure, m_b, is

$M_S(IDC) = 1.25\ m_b(IDC) - 2.45$

Key Words:: Seismic, Magnitude, IDC, Event Screening

OBJECTIVE

The IDC has the responsibility to characterize and measure seismic sources detected by the global network of stations of the IMS used to monitor the CTBT. Characterization of the size of detected events is important to many aspects of CTBT monitoring, including determination of detection thresholds, event screening (e.g. M_S-versus-m_b), and yield estimation for explosion sources. Furthermore, because of the large volume of events recorded by the IMS, IDC monitoring should be facilitated and made more consistent by automating magnitude measurement procedures. Therefore, the objective of this research program has been to expand and improve the magnitude measurement procedures used to characterize seismic sources at the IDC. We have been seeking to ensure that the magnitudes reported by the IDC are consistent with the definitions of seismic magnitudes and with previous magnitude measures and that they are free of regional biases and biases associated with measurement procedures. We have also been attempting to evaluate new magnitude measures which can help extract as much information as possible about the seismic sources in an automated processing environment. To accomplish these objectives, our efforts have been directed at improving the standard m_b, M_S, and regional magnitude measures currently employed at the IDC and at implementing and testing alternative source characterization procedures including moment tensor inversion, spectral magnitude estimation, and a generalized magnitude, combining teleseismic and regional P-wave amplitude measurements.

RESEARCH ACCOMPLISHED

During this past year, the effort on this project has focused primarily on revisions to the m_b estimation procedures, with particular emphasis on the development of improved corrections for epicentral distance and focal depth and the derivation of preliminary global m_b station correction factors for a subset of 89 currently operational pIDC stations which are scheduled to be included in the final IMS network. The data used in this study consisted of approximately 220,000 single station m_b observations from some 25,000 selected events reported in the pIDC REB. The distribution of these selected events with respect to m_b is shown in Figure 1, where it can be seen that it is approximately normal, with a mean value of about m_b = 3.8, with the overwhelming majority of the events falling in the range $3 < m_b < 5$.

The statistical model which has been used to analyze these magnitude data is a General Linear Model (GLM) in which the single station magnitude values $m_b(i,j,k)$, are represented as a general linear combination of the form (cf. Murphy and McLaughlin, 1998):

$$m_b(i,j,k) = m(i) + sta(j) + db(k) + e(i,j,k) \qquad (1)$$

where

m(i)	=	event magnitude
sta(j)	=	station correction
db(k)	=	correction to the specified dependence on epicentral distance (either Veith/Clawson or Gutenberg/Richter)
e(i,j,k)	=	error term

The system of equations (1) is solved using the Expectation Maximization Algorithm to minimize the residual error, subject to the constraints:

$$\begin{aligned} &\sum_j sta(j) = 0 \\ &\sum_k db(k) = 0 \qquad \text{for } 23^\circ < D < 92^\circ \end{aligned} \qquad (2)$$

The constraints (2) are employed to retain the average absolute levels of the event magnitudes for comparison purposes. That is, since the absolute levels of the single station magnitudes are set by arbitrary convention, any constant value could be added to all the single station magnitudes without affecting the error term in (1) in any way and, therefore, it is necessary to constrain the absolute levels of the correction terms for comparison purposes.

As an initial step in evaluating the m_b distance corrections, GLM analyses were conducted using single station magnitudes for the subset of shallow focus (h < 50 km) events obtained using both the Veith/Clawson (V/C) and Gutenberg/Richter(G/R) corrections for epicentral distance. The resulting perturbations to these two standard sets of distance corrections (i.e. db(k) in equation (1)) obtained from the GLM analyses are compared in Figure 2 over the teleseismic distance range extending from 23 to 92 degrees over which the corrections are constrained to average to zero in both cases. It can be seen from this figure that the corrections to the V/C factors are remarkably small over this range (i.e., generally less than ±0.05) and, more specifically, that they are significantly smaller than the corresponding correction to the G/R factors determined using the same data set. We conclude from these results that the V/C corrections for epicentral distance employed at the pIDC are remarkably accurate on average, and superior to the corresponding G/R corrections employed by the U.S.G.S. and ISC for the estimation of m_b, at least in this teleseismic distance range for shallow focus events.

The V/C corrections are found to be less satisfactory at distances less than and greater than those shown in Figure 2. This fact is illustrated in Figure 3 where the derived corrections to the V/C factors are displayed over the entire distance range extending from 2 to 100 degrees. It can be seen that these corrections are greater than 0.2 magnitude units near the 20 degree upper mantle triplication range and are as large as –0.5 magnitude units at the closest distances. Based on the results of Figures 2 and 3, we recommend retaining the V/C corrections for the epicentral distance range 23 to 92 degrees and have smoothed the corrections of Figure 3 for smaller and larger distances using a three point smoothing operator to obtain the final proposed corrections to the V/C factors for shallow focus events shown in Figure 4.

At the present time, a non-traditional regional magnitude measure based on initial P wave amplitudes in the 2-4 Hz passband observed at distances less than 20 degrees is being estimated at the pIDC and published in the REB as a local magnitude, M_L. However, the observed high degree of variability of the M_L magnitude measure with respect to the corresponding REB m_b values, together with its inconsistency with some of the more conventional regional magnitude measures published by the various countries participating in GSETT-3, has produced considerable confusion. This led Bennett et al. (1998) to investigate the feasibility of defining a new, generalized m_b measure that incorporates both regional and teleseismic observations. This is an attractive alternative for the IDC because, since an event must be detected by at least three primary station to be reported in the REB, most events incorporate at least some teleseismic data; and, in fact, m_b values were reported for more than 95% of the REB events during 1997.

In order to specify an optimum algorithm for combining teleseismic and regional observations to obtain a generalized m_b value, it is necessary to first examine the uncertainties in the derived epicentral distance correction factors as a function of distance. For example, the standard errors of estimate associated with the GLM shallow focus event distance correction estimates of Figure 3 are displayed as a function of epicentral distance as a dashed line in Figure 5. It can be seen that this measure of uncertainty is essentially constant, with an average value of about 0.28 in the teleseismic range extending from 23 to 92 degrees, and that it increases at shorter and larger distances. Therefore, we have constrained the standard error of estimate to the average constant value of 0.28 in the range 23 to 92 degrees and have smoothed the GLM results at shorter and longer distances to obtain the final epicentral distance dependence of the uncertainty represented by the solid line in this figure. Based on these results, a generalized network-averaged magnitude measure, m_b, has been defined as an inverse variance weighted average of the single station magnitude estimates. Note that for events recorded exclusively at teleseismic distances, where the weights are constant, the definition of the network-averaged magnitude value is unchanged from current practice, and the results will be identical to the existing REB m_b values. As is illustrated in Figure 6, it has been found that this generalized mb measure correlates better with the corresponding REB values than does the current pIDC M_L measure, even for events for which the number of regional observations equals or exceeds the number of teleseismic observations. On the basis of these results, we conclude that this generalized m_b magnitude measure can provide useful magnitude estimates for events which are not well-recorded by the available network of teleseismic stations, at least until such time as a more robust regional magnitude measure is defined and implemented at the pIDC.

Since the station correction factors are designed to be used in the estimation of generalized m_b values, a GLM analysis of the shallow focus event data was carried out with the distance corrections constrained to the revised Veith/Clawson factors obtained from the final, smoothed corrections of Figure 4. The resulting m_b station correction factors were found to range from approximately –0.7 to +0.5. Application of these correction factors to the observed single-station m_b values produces a significant reduction of more than 40% in the variance about the resulting network-averaged m_b values. Thus, it can be concluded that the derived corrections have a high degree of statistical significance.

Somewhat surprisingly, application of these station correction factors also produces a significant change in the absolute levels of the estimated m_b values. This fact is illustrated in Figure 7 which shows a histogram of the differences in m_b values computed with and without station corrections. It can be seen that the application of the station correction factors increases the resulting network-averaged m_b values by more than 0.18 magnitude units, on average. This offset seems puzzling at first glance, since by equation (2) the station corrections are determined under the constraint that they must sum to zero. That is, events recorded by all or most of the 89 station would be expected to have station-corrected m_b values which are the same on average as the corresponding uncorrected values. In fact, however, not all stations are equally represented in the REB. That is, for reasons of economy, data are not routinely recovered from secondary stations and the m_b determinations are dominated by data from the primary and array stations. The significance of this sampling bias with respect to the resulting network-averaged m_b values is indicated in Figure 8, which shows the station correction factors color-coded to distinguish between primary and secondary stations. Note that the station corrections for the primary stations are predominantly positive, averaging to a value of about +0.15, while those for the secondary stations are predominantly negative, with an average value of about –0.11. It follows that, since data from the primary stations dominate the REB m_b determinations, the application of the derived station correction factors generally increases the network-averaged m_b values, leading to the systematic offsets observed in Figure 7.

CONCLUSIONS AND RECOMMENDATIONS

A careful statistical analysis of a large sample of approximately 220,000 pIDC single-station m_b observations has been conducted in an attempt to formulate improved procedures for estimating network-averaged m_b values at the IDC. This analysis has led to the derivation of revised corrections for epicentral distance and focal depth, global m_b station corrections for a prototype IMS network consisting of 89 currently operational stations and distance weighting factors for use in the estimation of a new, generalized m_b magnitude measure which incorporates both teleseismic and regional P wave data. A notable result of this investigation has been the finding that the application of the derived global m_b station correction factors produces an average increase in the network-averaged m_b values of nearly 0.2 magnitude units with respect to the original REB values. This results from the fact that the REB m_b determinations are dominated by data from primary and array station which generally have positive station correction factors with respect to the prototype network average.

REFERENCES

Bennett, T. J., J. R. Murphy, R. W. Cook and B. W. Barker (1998), "Development of a Generalized m_b Magnitude Measure Incorporating Regional and Teleseismic P Wave Amplitude Observations from the IDC," Technical Memorandum to NTPO, May.

Murphy, J. R., and B. W. Barker (1996), "An Evaluation of the IDC/NEIS m_b Anomaly," Technical Memorandum to NTPO, September.

Murphy, J. R., B. W. Barker and M. E. Marshall (1997), "Event Screening at the IDC Using the M_S/m_b Discriminant," Technical Memorandum to NTPO, October.

Murphy, J. R. and K. L. McLaughlin (1998), "Comment on 'Empirical Determination of Depth-Distance Corrections for m_b and M_W from Global Seismograph Network Stations' by Guust Nolet, Steve Krueger and Robert M. Clouser," Geophys. Res. Lett., 25, 4269.

Veith, K. F., and G. E. Clawson (1972), "Magnitude From Short-Period P-Wave Data," Bull. Seism. Soc. Am., 62, 435-452.

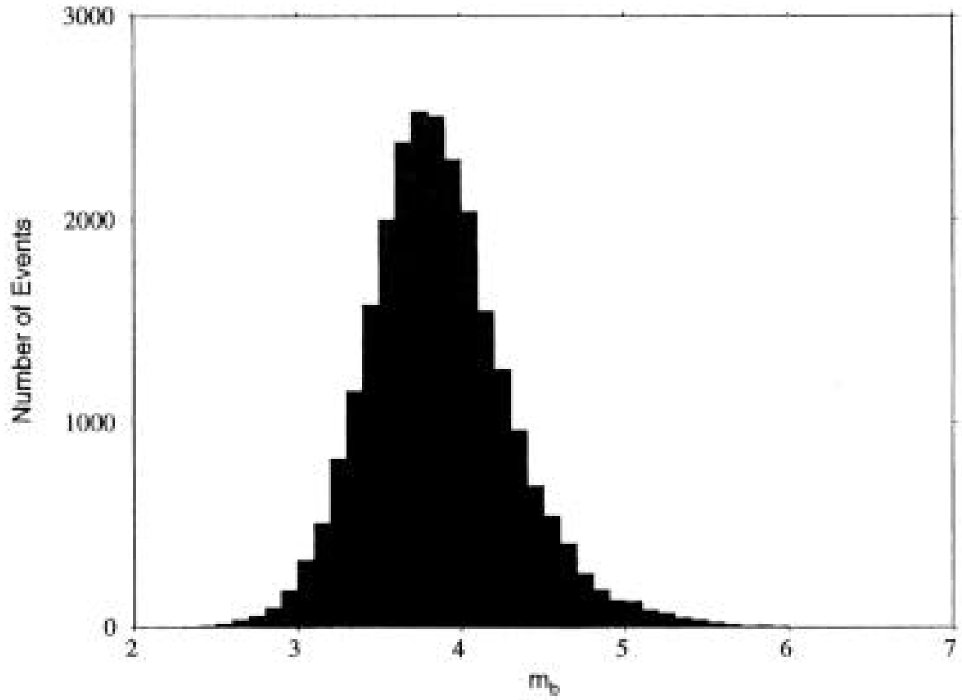

Figure 1. Distribution of the selected sample of events with respect to REB mb value.

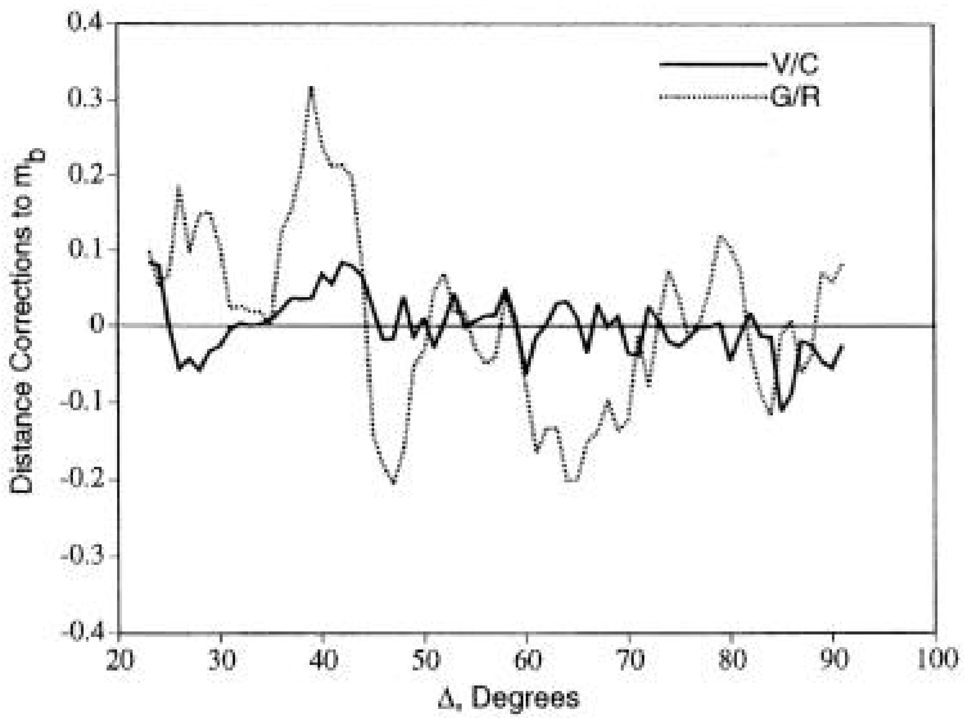

Figure 2. Comparison of corrections to V/C and G/R epicentral distance factors derived from GLM analyses of the same large sample of REB data recorded from shallow focus (h < 50 km) events, 23° < Δ < 92°.

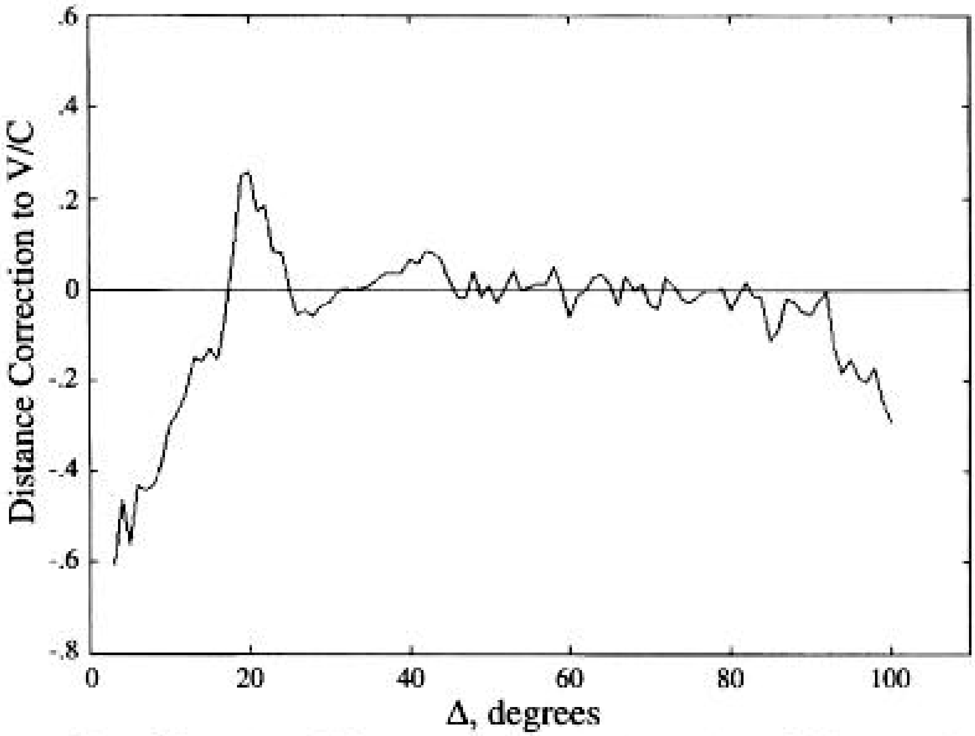

Figure 3. Corrections to V/C epicentral distance factors derived from a GLM analysis of a large sample of REB data recorded from shallow focus (h < 50 km) events, 2° < Δ < 100°.

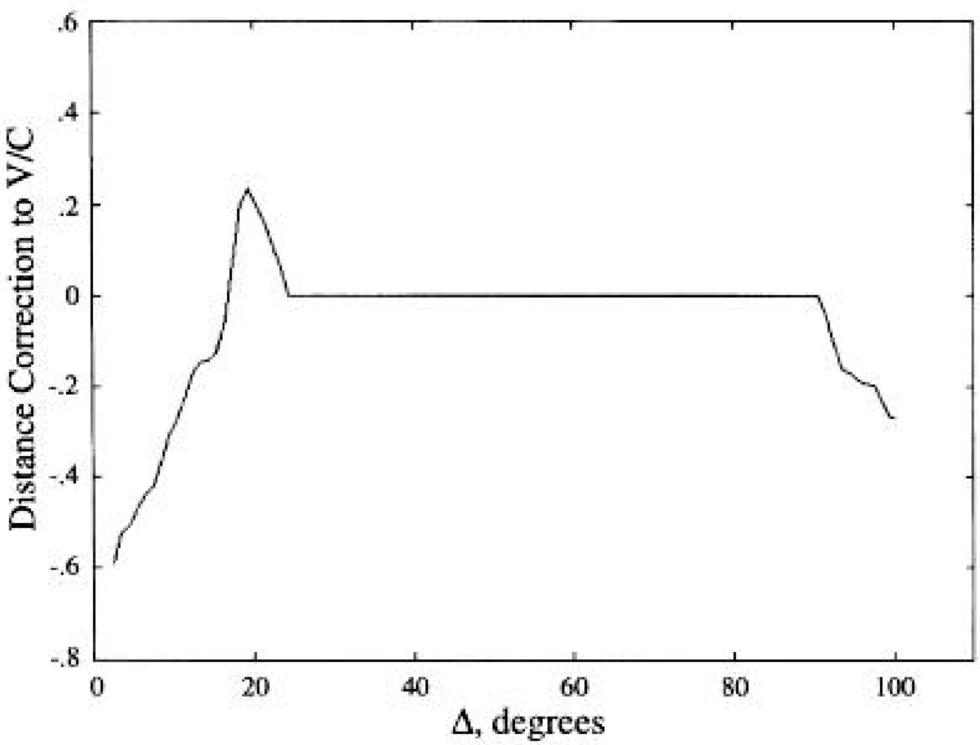

Figure 4. Final smoothed corrections to the V/C epicentral distance factors for shallow focus (h < 50 km) events, 2° <Δ < 100°.

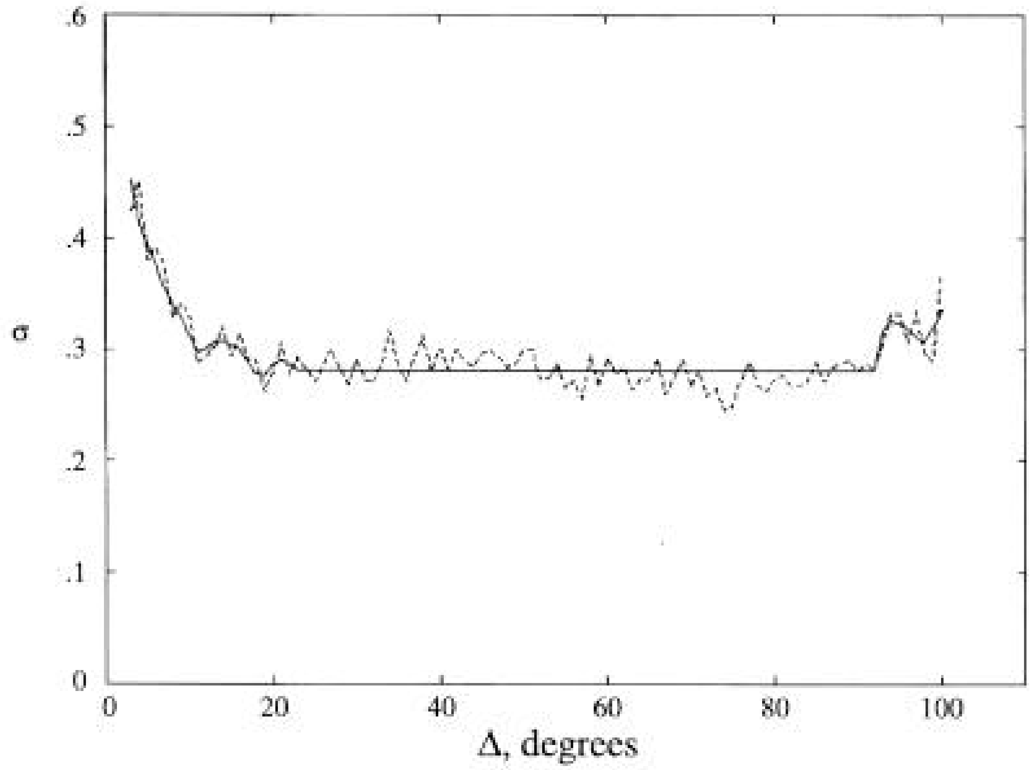

Figure 5. Standard errors of estimate (σ) as a function of epicentral distance for shallow focus events. The dashed line denotes the original GLM results, while the solid line denotes the final smoothed version adopted for generalized magnitude estimation purposes.

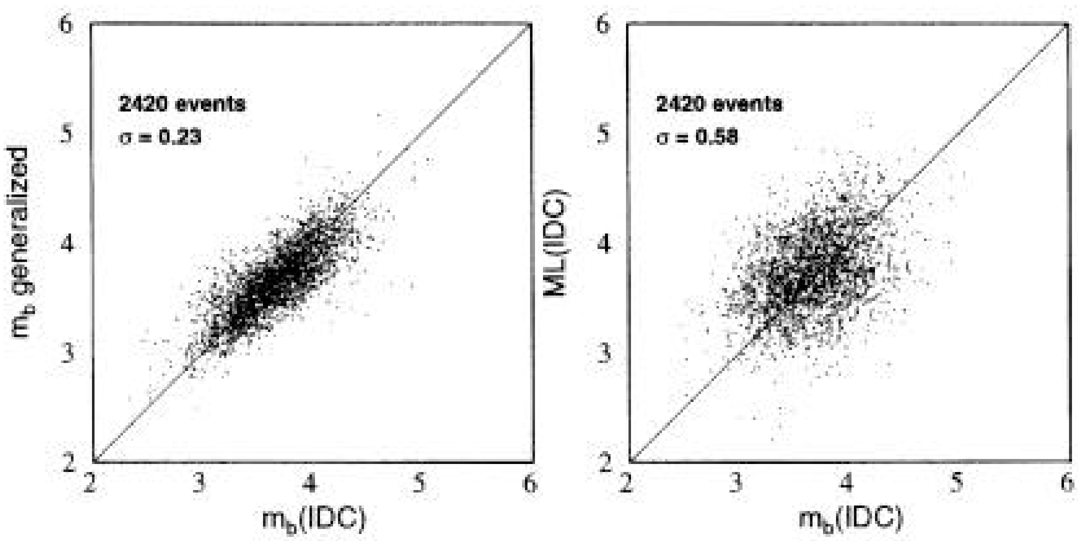

Figure 6. Comparison of generalized mb versus REB mb (left) with REB M_L versus REB mb (right) for a set of common events for which the number of regional observations equals or exceeds the number of teleseismic observations.

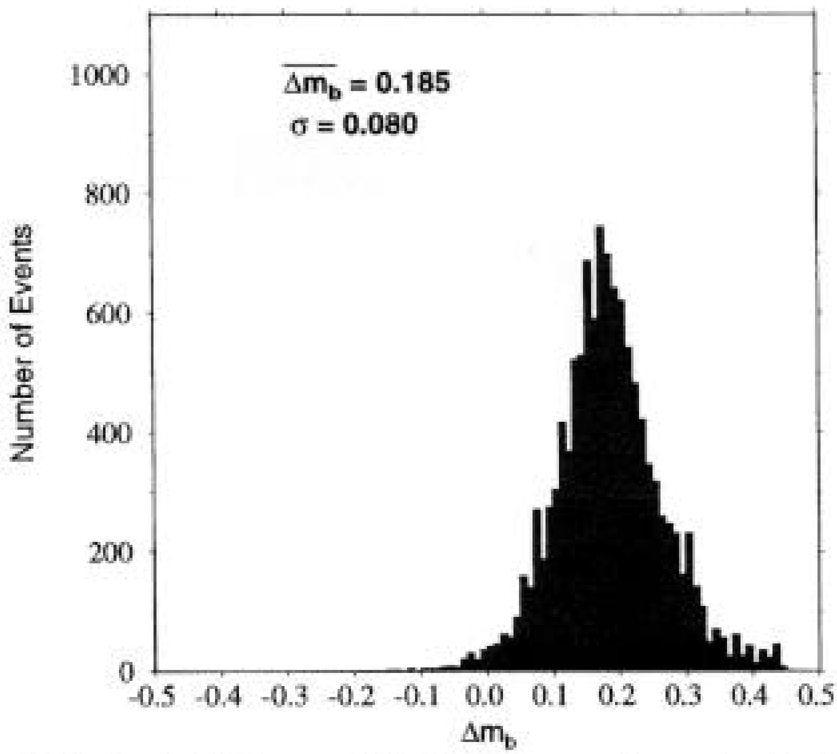

Figure 7. Distribution of differences in individual event network-averaged teleseismic mb values computed with and without station corrections, h < 50 km.

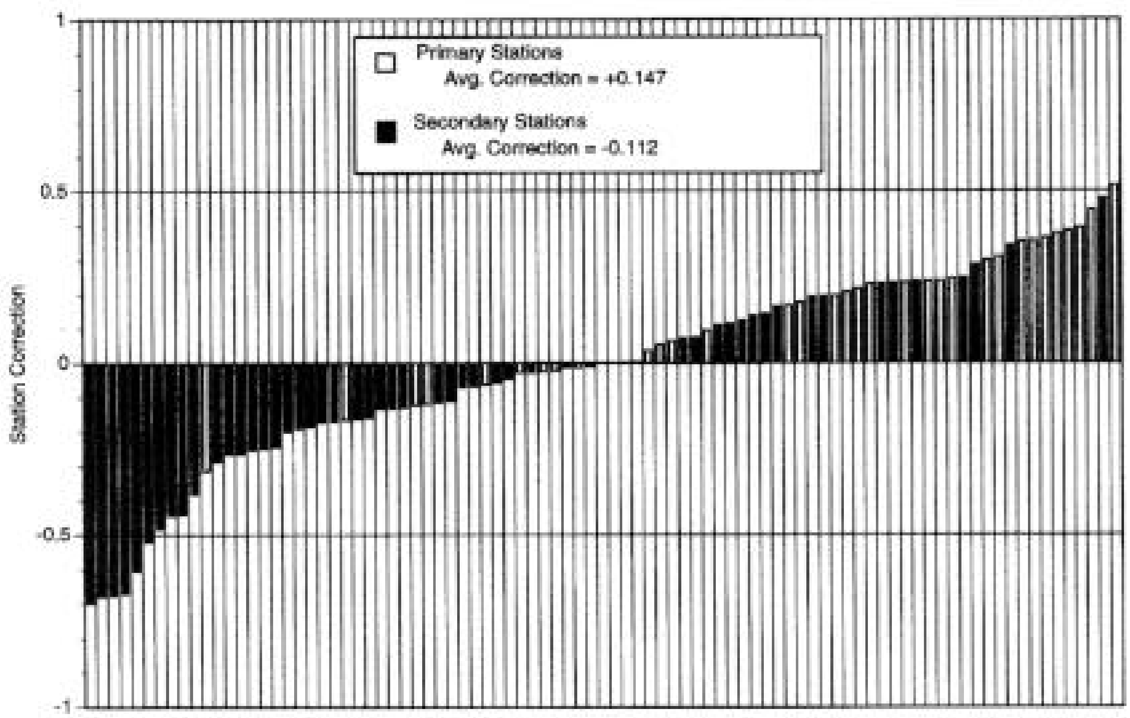

Figure 8. Estimated mb station correction factors for the 89 stations of the prototype IMS network color-coded to distinguish between primary and secondary stations.