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P-Wave Amplitudes and Sources of Scattering in m_b-Observations*

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Abstract. Regional comparisons of NORSAR and LASA reported m_b show significant variations between the two arrays even for small source regions. Dividing the observed variance equally between the two stations, we obtain standard deviation of each array's m_b estimates ranging from $\sigma=0.21$ (Central America) to $\sigma=0.40$ (Kurile Islands) and averaging 0.30 for 6 regions studied. These values are significantly higher than those generally inferred using PDE observations for large events. A possible explanation is that the low dominant frequency of signals from large events generally is subject to less amplitude scatter, and this is further supported by results presented on the frequency dependency of amplitude patterns across NORSAR.

Key words: Seismology – Earthquake magnitude – P-wave amplitudes – Scattering – Signal frequency content.

1. Introduction

The large scatter between individual station m_b determinations for a given seismic event is a problem of considerable importance in earthquake-explosion discrimination as well as other aspects of seismology. Attempts to correlate anomalous station amplitudes with regional geology or earthquake radiation patterns have generally had little success, so the tendency of recent works is to attack this problem by statistical means. For example, it is common practice to estimate "network" m_b by averaging over the individual station m_b values, and this method works quite satisfactorily for large earthquakes, as the m_b-observations have an approximate Gaussian distribution. This approach, however, would in many cases create a positive bias if only a few stations within the network detect the event.

The maximum-likelihood estimation method described by Ringdal (1976) partly alleviates this bias problem. However, a successful application of this technique requires that the standard deviation σ of the world-wide magnitude

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distribution is known, or at least can be assumed to lie within fairly narrow limits. In recent years, several studies have been performed to estimate σ based on world-wide m_b-observations of large events, most of them using WWSSN data. Veith and Clawson (1972) found $\sigma = 0.35$ using a smoothed distance-amplitude relationship. Evernden and Kohler (1976), also using large events, have studied the effects on σ when compensating for regional crustal structure and station site geology. Their conclusion is that values of $\sigma = 0.21$ and 0.15 can adequately represent m_b standard deviations on a world-wide basis for single stations and small arrays, respectively. These authors also argue on the basis of the low σ values that network magnitude bias is unimportant for the $M_s - m_b$ discriminant for networks as described by Evernden (1971).

An important question is to what extent world-wide m_b scattering observed for large earthquakes (say $m_b \geqq 6.0$) is representative for small events (say $m_b \leqq 5.0$), which are the ones of most interest both in seismic discrimination and when considering network bias problems. The procedure of looking at world-wide magnitudes of a given event is not suitable to study this problem. Instead, we choose the indirect approach of comparing m_b values of the sensitive arrays LASA and NORSAR for events from selected regions, assuming independence of their respective m_b estimates. Also, we will investigate the effects of signal frequency contents on the amount of amplitude variation by observing the amount of scatter in various frequency bands across the NORSAR array.

2. Basic Assumptions

When establishing a statistical model for station magnitude distribution, a major point is how to deal with station corrections. In general, signal amplification factors and thereby station m_b values are lowest for sites situated on hard rock and highest on soft sediments. The actual m_b bias in each case relative to some reference system can in principle be evaluated by comparing a large number of m_b values from widely distributed earthquakes. A different type of station correction is the regional m_b bias. This is defined as the average bias, again relative to a reference system, for events from one particular region. It is by definition tied to ray path and "average" source mechanisms, and may often vary quite strongly even for small changes in azimuth and distance (Berteussen, 1975).

A model to describe the station-region bias problem in statistical terms can be established as follows. Assume that magnitudes of a set of seismic events from various regions are measured at each station in a seismic network. Let m_{ij} denote the "true" magnitude of the i-th event within the j-th region, and let M_{ijk} denote the measured magnitude of this event at the k-th station. (Capital letters denote random variables.) We set:

$$M_{ijk} = m_{ij} + s_k + r_{jk} + Z_{ijk} \quad \begin{array}{l} i = 1, 2, \ldots, p_j \\ j = 1, 2, \ldots, q \\ k = 1, 2, \ldots, r \end{array} \tag{1}$$

where s_k is the site dependent station bias, r_{jk} is the regional bias and Z_{ijk} is a residual term which is assumed to be $N(0, \sigma_{jk}^2)$. There is clearly no a priori reason to assume all variances σ_{jk}^2 to be equal, and, as we shall see, there appears to be significant regional variations of this parameter. In the following, however, we mostly choose to operate with an "average" variance σ^2 for σ_{jk}^2, for reasons of simplicity.

Three different models for seismic magnitude distribution may now be established, each corresponding to a different level of a priori knowledge.

Model 1: Station and Regional Bias Terms Known

This model is in effect Equation (1) above, and we have:

$$\begin{aligned} E(M_{ijk}) &= m_{ij} + s_k + r_{jk} \\ \mathrm{Var}(M_{ijk}) &= \sigma^2 \end{aligned} \quad (i, j, k) \in \mathbf{D} \tag{2}$$

where **D** denotes the set of indices from Equation (1).

Model 2: Only Station Bias Term Known

In this model, we randomize the regional correction by assuming that r_{jk} represents a realization of R_{jk} which is $N(0, \sigma_R^2)$. Thus

$$\begin{aligned} M_{ijk} &= m_{ij} + s_k + R_{jk} + Z_{ijk} \\ E(M_{ijk}) &= m_{ij} + s_k \qquad (i, j, k) \in \mathbf{D} \\ \mathrm{Var}(M_{ijk}) &= \gamma^2 = \sigma^2 + \sigma_R^2 \end{aligned} \tag{3}$$

Model 3: Complete Randomization

In a way similar to Model 2, we substitute s_k by S_k which is assumed to be $N(0, \sigma_S^2)$:

$$\begin{aligned} M_{ijk} &= m_{ij} + S_k + R_{jk} + Z_{ijk} \\ E(M_{ijk}) &= m_{ij} \qquad (i, j, k) \in \mathbf{D} \\ \mathrm{Var}(M_{ijk}) &= \tau^2 = \sigma^2 + \sigma_R^2 + \sigma_S^2 \end{aligned} \tag{4}$$

A comment on the normality assumptions made above is in order. The tendency of magnitude values measured at different stations within a homogeneous network for any given event to follow a normal distribution has been established in different contexts by several authors (for references, see Freedman 1967; von Seggern, 1973; and Ringdal et al., 1972).

The statistical models established above assume that the networks considered are homogeneous, and can be related to either a number of arrays or a network of single stations. It is reasonable to assume that the variances σ^2, σ_R^2, and σ_S^2 will in general be larger in a network of the latter type, and we will look at such examples later. In the following, we shall mostly be concerned with Model 1, which in a sense represents the idealized condition of minimum variance in station m_b estimates. We will also consider the incremental variance of Model 2, while Model 3 will not be discussed in detail further.

3. Variance in m_b Estimates for Large Arrays

In this section we compare m_b observations from LASA and NORSAR. We assume that the respective m_b measurements are statistically independent, and, as before, that the respective variances relative to the "true" m_b are equally large in the two cases. We will mainly consider limited source regions which in effect means that the analysis is restricted to Model 1 above. Now, considering Equation (1) and setting $k=1$ for LASA, $k=2$ for NORSAR, we obtain for the i-th event of region j:

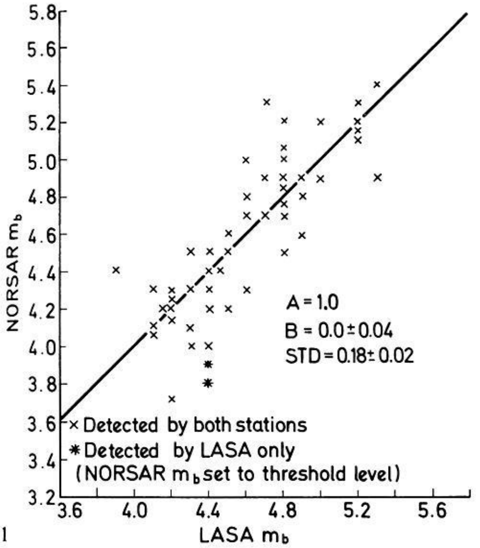
$$M_{ij1}-M_{ij2}=(s_1-s_2+r_{j1}-r_{j2})+(Z_{ij1}-Z_{ij2}) \qquad (5)$$

Consequently, the variance in m_b differences between LASA and NORSAR equals $2\sigma^2$.

We first consider the case of two earthquake sequences, from South of Honshu, Japan, December 3–20, 1972, and Kurile Islands, June 17–30, 1973, respectively. Figures 1 and 2 show plots of NORSAR m_b vs LASA m_b for 50 randomly selected events from each sequence. A striking observation from the two figures is the much larger variance for the Kurile Islands earthquakes. The orthogonal standard deviations, which from our assumptions represent the σ value of either station in Model 1, is 0.28 for this sequence as compared to 0.18 for the Honshu one. It is instructive to perform a similar experiment over larger source regions. Figures 3 and 4 give plots of NORSAR vs LASA m_b for 50 randomly selected events during 1974 and 1975. Figure 3 covers Honshu and South of Honshu (regions 226–233 in Flinn et al., 1974) while Figure 4 represents the Kurile Islands regions 220–222. Again, the σ values are substantially higher for the general Kurile Islands area; 0.40 versus 0.22 for Honshu. Table 1 gives a summary of similar statistics computed for 6 different source regions at teleseismic distances from both LASA and NORSAR. The value of σ shows significant regional variation, and averages about 0.30 m_b units. We also note that the relative bias in m_b between LASA and NORSAR on the average is modest.

A physical explanation of the large spread in σ, e.g., between Kuriles and Honshu, is not easy to establish, since several mechanisms may have contributed. A possible suggestion is that source mechanisms and radiation patterns may be more stable for Honshu earthquakes. Another reasonable hypothesis would be that the crust and upper mantle in the Kuriles are of a more complex nature than at Honshu, thus possibly enhancing focusing/defocusing and selective absorption effects.

The technique described above does not allow us to evaluate directly the parameters of Model 2, since the overlapping zone of the detection windows of LASA and NORSAR is too limited. However, data from Bungum and Husebye (1974) give an indication on the variation of r_{jk} within large-scale seismic regions. Their Table 4 lists average PDE-NORSAR m_b differences, which range from 0.07 to 0.46 for 10 regions at teleseismic distances from NORSAR. Considered as a set of random numbers, the standard deviation of these values is 0.11 m_b units, which then could be used as an estimate of σ_R for the NORSAR array, assuming large-scale regionalization. This value of σ_R is small relative to the value of $\sigma=0.30$ found previously, and the parameter γ of Equation (3) will therefore be only slightly greater than σ for a large array.



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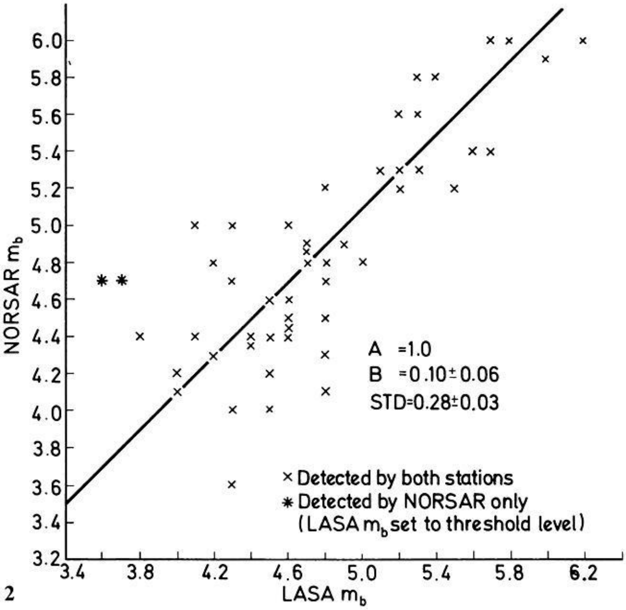

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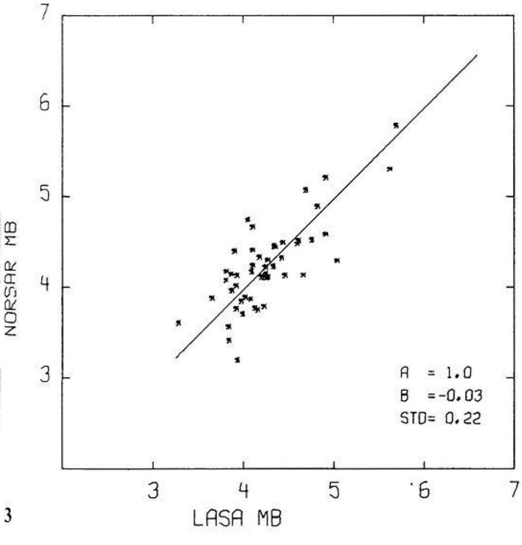

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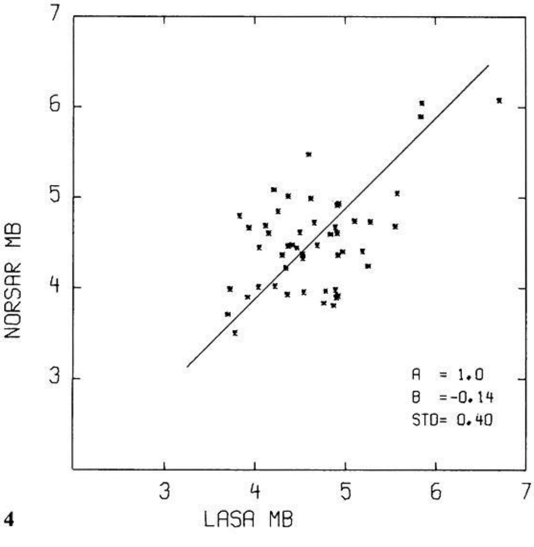

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Fig. 1. Comparison of NORSAR and LASA teported m_b for 50 events randomly selected from Honshu earthquake sequence Dec 3–20, 1972. The straight line has a slope of $A = 1.0$, and its intercept B (denoting the average difference m_b (NORSAR)-m_b (LASA)) and the orthogonal standard deviation relative to this line are also specified

Fig. 2. Same as Figure 1, but with events selected from Kurile Islands sequence, June 17–30, 1973

Fig. 3. Same as Figure 1, but with events selected from the general Honshu region during 1974 and 1975

Fig. 4. Same as Figure 1, but with events selected from the general Kurile Islands region during 1974 and 1975

Table 1. Regional statistics of LASA-NORSAR magnitude differences

General region	Corresponding Flinn-Engdahl regions	Number of events	Average m_b (LASA)-m_b (NORSAR)	St. dev. of m_b (LASA)-m_b (NORSAR)	St. dev. of each array m_b
S. Honshu	226–233	50	0.03 ± 0.04	0.31 ± 0.03	0.22 ± 0.02
Kurile Islands	220–222	50	0.14 ± 0.08	0.56 ± 0.06	0.40 ± 0.04
Kamchatka	217–219	50	-0.04 ± 0.06	0.39 ± 0.04	0.27 ± 0.03
Aleutian Islands	4–10	50	0.05 ± 0.07	0.46 ± 0.05	0.33 ± 0.03
North Atlantic Ridge	402, 403, 406	50	-0.08 ± 0.07	0.46 ± 0.05	0.32 ± 0.03
Central America	54–82	50	-0.09 ± 0.04	0.30 ± 0.03	0.21 ± 0.02
All above regions combined		300	0.00 ± 0.03	0.42 ± 0.02	0.30 ± 0.01

4. Variance in m_b Estimates for Small Arrays and Single Stations

Berteussen and Husebye (1974) have demonstrated that NORSAR amplitude patterns are very consistent for events within small source regions, although quite rapid changes may take place with larger shifts in epicenter. There is no reason to believe that this observation is not valid at other sites as well and the data presented by Pirhonen et al. (1976) are also indicative in this respect. This leads us to the very important conclusion that in Model 1, assuming small source regions, there is only negligible increase in σ from large arrays (aperture about 100 km) to small arrays (aperture about 10 km). We notice here that the relatively modest amplitude variations observed on the average *within* a NORSAR subarray (cf. Section 5), makes it reasonable to extend the preceding observation to assert that σ of Model 1 is essentially the same for large arrays, small arrays and single sensor stations.

The main benefit of arrays with respect to reducing the m_b scattering parameter appears in the context of Model 2, where regional corrections are randomized. Although so far we have not directly computed σ_R for small arrays or single stations, it is possible to get an indication of their incremental variance relative to a large array, again by looking at NORSAR data. In fact, selecting 32 random, widely spread array beam locations from Berteussen and Husebye (1974), extracting the bias values (on a logarithmic scale) of a given subarray (14C) relative to the array beam for each of these locations, and computing the standard deviation within this set of numbers, we found a value of 4.0 dB or 0.20 m_b units. This number is, incidentally, quite close to the average logamplitude standard deviation across NORSAR (4.4 dB) found by the above authors. Assuming that these NORSAR values are representative for other sites as well, we conclude that there is a significant difference between large arrays and small arrays (comparable to NORSAR subarrays) in m_b variance if regional corrections are unknown. A similar conclusion is obviously valid for single stations relative to large arrays. On the basis of the previous estimate of γ in Equation (3) for large arrays and the above observations, we infer that a value of γ for small arrays and single stations in the range 0.35–0.40 is indicated.

5. Frequency Dependency of Amplitude Variations Across NORSAR

A topic not treated in detail in the studies cited in the previous section is the potential dependency of the P-wave amplitude scatter on signal frequency. We now address this problem in terms of narrow band filtering of NORSAR records. We also describe the scatttering across various subsets of the array, in order to investigate variance reductions in m_b estimates achievable by using arrays relative to single sensor stations. We note in passing that analyzing relative logamplitude data across NORSAR is close to analyzing relative m_b values at single sensors, due to the particular form of the instrument response curve at NORSAR (Bungum et al., 1971). In fact, a similar statement holds true more generally for stations equipped with velocity-type sensors, as the response of these instruments is roughly proportional to the term A/T (amplitude divided by period) that enters the definition of magnitude. Consequently, a good estimate of magnitude at such stations may be obtained without even measuring the dominant period T of the signal. The 10 events selected for analysis are listed in Table 2 and are all characterized by high signal-to-noise ratio (SNR) and impulsive signal waveforms. The following analysis was performed:

1. All sensor traces were filtered with six different 3rd order recursive Butterworth bandpass filters (for details see Fig. 7). For each filter, the maximum amplitude of each trace over a 20 s window was determined.
2. Three ways of grouping instruments were considered,
   a) Full NORSAR array
   b) Subarray
   c) Partial arrays (see Fig. 5).

Table 2. Events used for studying NORSAR amplitude variations

Event no.	Region	Reported by PDE						Reported by NORSAR			
		Date	Origin time	Latitude	Lngitude	depth	m_b	m_b	T (s)	Dist (deg)	Azi (deg)
1	Afghanistan-USSR border	06/26/71	22.23.29	36.3N	71.4E	127	5.0	5.3	0.5	45	95
2	Eastern Kazakh SSR[a]	06/30/71	03.56.57	50.0N	79.1E	0	5.4	5.2	1.0	40	77
3	Szechwan, China	08/16/71	04.58.00	28.9N	103.7E	N	5.5	5.6	1.0	64	75
4	Honshu Japan	04/26/75	03.14.37	39.6N	141.1E	100	5.3	5.3	0.8	72	45
5	South of Honshu, Japan	05/06/75	10.18.20	31.0N	141.7E	N	5.7	5.6	0.7	81	49
6	Southern Nevada[a]	06/03/75	14.40.00	37.3N	116.5W	0	5.7	5.6	1.2	72	323
7	Kirgiz-Sinkiang Border	03/16/76	06.19.02	40.4N	77.8E	N	5.2	5.2	0.7	44	88
8	Kurile Islands	04/03/76	19.14.11	44.3N	149.7E	N	5.0	4.9	0.8	69	35
9	Uzbek, SSR	04/08/76	12.03.41	40.2N	64.1E	N	5.1	5.2	0.9	36	98
10	Off coast Hokkaido, Japan	04/11/76	02.53.02	43.9N	146.3E	97	5.1	5.4	0.7	71	38

[a] Presumed explosion

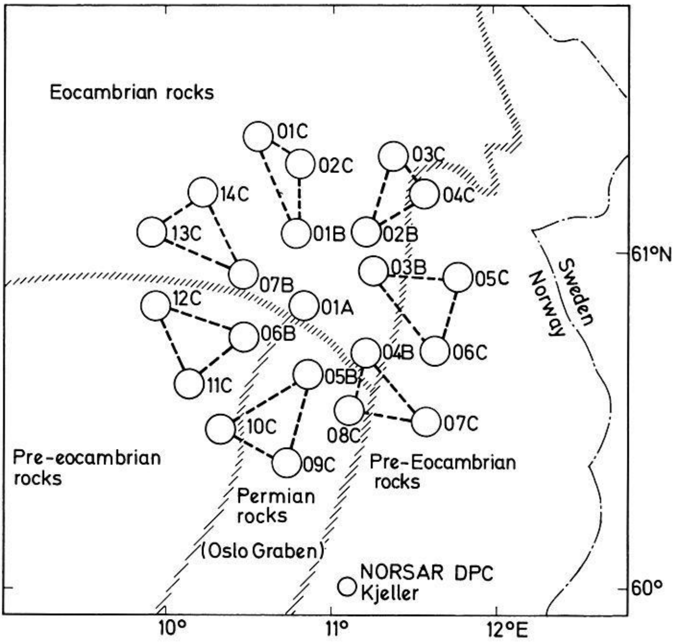

Fig. 5. NORSAR array configuration with outline of geology. Subdivision into partial arrays as used in the analysis are indicated by stippled boundaries

3. Within each type of grouping, the standard deviation of the logamplitudes was computed for each event in each filter band. Because of low signal energy at some frequencies, standard deviations for a and each group under c were estimated from the upper half of the amplitude distribution (using a Gaussian model), while the standard deviation for b was estimated as the median of the 22 individual subarray values.

The results for each individual event are listed in Table 3, while the average values for the narrow-band filters are shown in Figure 6. It is clear from these data that a very strong frequency dependency exists. The standard deviation of logamplitudes across the full NORSAR array increases from 2.8 dB at 0.6 Hz to 5.4 dB at 2.2 Hz. In the filter band 1.2–3.2 Hz used for event detection we find a value of 4.7 dB, which could be compared to the average value of 4.4 dB reported by Berteussen and Husebye (1974) using subarray beams. A noteworthy feature of Figure 6 is the significant difference in scatter across the full array, the partial arrays and the subarrays. In particular, the low variance across the average subarray indicates that there is little to be gained in terms of variance reduction in Model 2 by employing small arrays (comparable to NORSAR subarrays) rather than single instrument stations. The tapering off at high frequencies noticeable in Figure 6 is likely due to back-scattering and multipathing effects. Figure 7 illustrates this point for one of the events, an earthquake from Szechwan Province, China.

Table 3. Standard deviations (dB) of logamplitudes for individual events and filter bands within the NORSAR full array, partial arrays and subarrays (see also Fig. 5)

Event	Filter band (Hz)					
	1.2–3.2	0.4–0.8	0.8–1.2	1.2–1.6	1.6–2.0	2.0–2.4
Standard deviations within full array						
1	5.12	2.81	4.24	3.92	4.88	5.50
2	5.14	3.34	4.43	5.46	4.31	5.01
3	4.24	2.43	3.05	4.61	4.99	5.23
4	3.81	2.69	3.03	4.25	5.16	4.28
5	5.34	3.97	4.66	5.26	5.35	5.71
6	5.39	2.42	3.65	5.40	5.58	4.67
7	4.10	2.73	3.50	3.76	4.25	5.74
8	5.48	2.69	3.92	5.48	7.30	6.99
9	3.73	2.45	3.78	4.01	5.01	4.70
10	4.85	2.49	2.96	4.96	5.88	6.60
Average	4.72	2.80	3.72	4.71	5.27	5.44
Standard deviations within partial array						
1	2.95	2.23	2.66	2.72	3.36	3.39
2	2.01	2.37	2.39	2.85	2.54	3.27
3	2.43	1.98	1.68	2.84	3.44	3.77
4	3.80	2.47	3.55	4.22	4.89	4.26
5	4.67	2.43	3.24	4.69	4.62	4.01
6	3.48	1.66	2.21	3.42	4.63	2.94
7	2.52	2.02	2.65	2.67	2.98	3.44
8	2.94	2.23	2.23	3.37	3.70	3.40
9	2.71	2.11	2.40	3.13	3.20	2.70
10	3.21	1.92	2.67	3.22	4.34	3.90
Average	3.07	2.14	2.57	3.31	3.77	3.51
Standard deviations within subarray						
1	2.34	1.78	1.73	2.14	2.43	3.04
2	2.04	1.87	1.51	2.55	2.65	2.52
3	2.21	1.68	1.76	2.68	2.92	3.55
4	2.11	1.75	1.77	2.41	2.52	3.22
5	2.10	1.23	1.73	1.97	2.51	2.74
6	1.95	1.42	1.47	2.11	2.97	2.30
7	1.89	1.75	1.88	2.21	2.60	3.09
8	1.70	1.98	2.11	2.24	2.84	2.15
9	1.64	1.99	1.81	2.04	2.21	2.59
10	1.98	1.83	1.69	2.60	2.67	3.14
Average	2.00	1.73	1.75	2.29	2.63	2.83

6. Conclusions

Using a statistical model (Model 1) in which regional station corrections are assumed known, we have found a significant and possibly regionally dependent scatter between m_b values reported at the large arrays LASA and NORSAR.

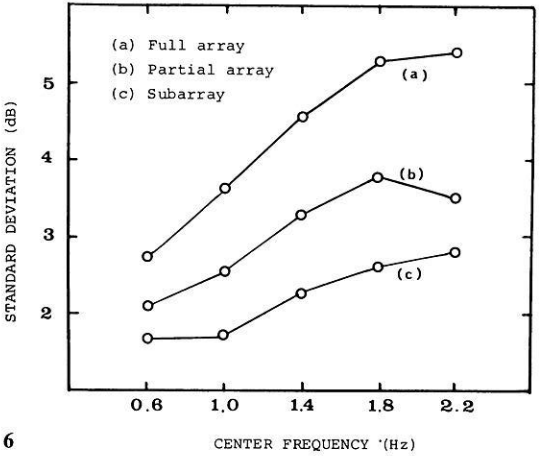

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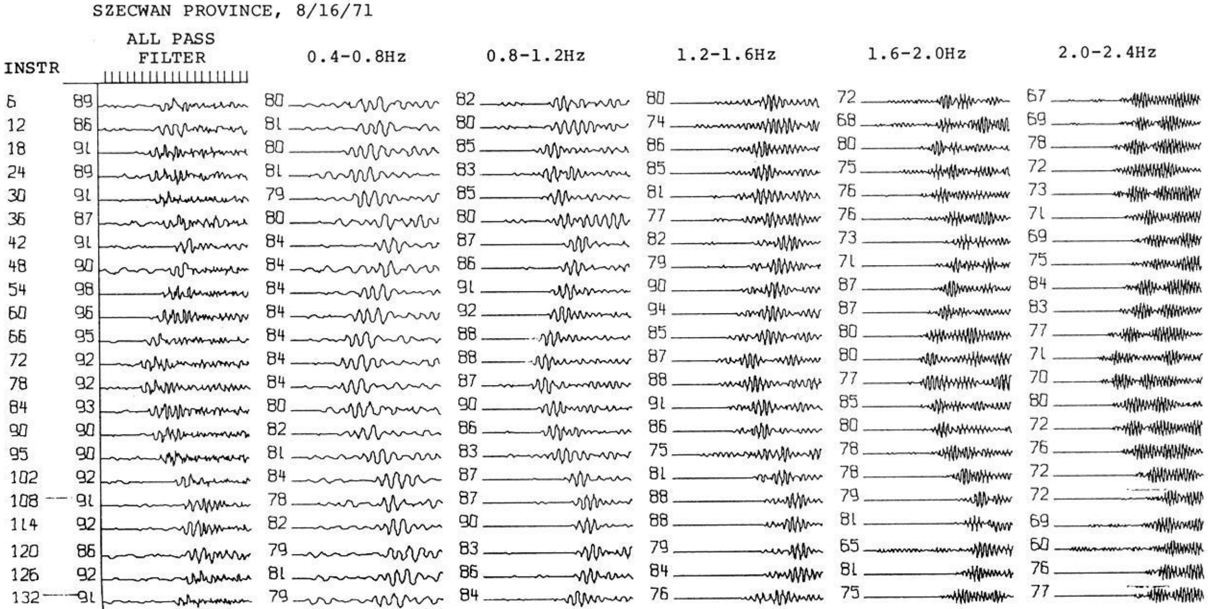
Fig. 6. Standard deviation of amplitudes (in dB) as a function of narrow-band filter frequency within the NORSAR array (a), within a partial array (b) and within a subarray (c). The numbers represent average values over the set of 10 events listed in Table 2

Fig. 7. Filtered waveforms showing P – wave arrivals at NORSAR for Event No. 3 in Table 2. One instrument from each of the 22 subarray has been selected and the traces are ordered according to alphabetical subarray sequence (01A through 14C). A time window of 20 s is covered, and the number in front of each trace represents its maximum amplitude in dB relative to 1 quantum unit



Analyzing 6 different geographic regions, we have estimated an average $\sigma = 0.30$ m_b units for the standard deviation around the "true" magnitude of each array m_b. At individual regions, σ ranges from 0.21 (Central America) to 0.40 (Kurile Islands). Little difference is found using this model in the value of σ for large arrays, small arrays and single sensor stations.

When assuming a model for which regional m_b corrections are unknown (Model 2), a marked increase in the variance takes place as the receiver aperture decreases. Based on the somewhat incomplete data available for analysis, it appears that a value of the standard deviation γ in the range of 0.30–0.35 m_b units would be adequate for large arrays, while a range of 0.35–0.4 is indicated for small arrays and single sensor stations. We emphasize that all of these values are based on observations of intermediate size earthquakes, mostly in the m_b range of 4.0–5.5.

Our results are incompatible with the assertions of Evernden and Kohler (1976) that $\gamma = 0.15$ and 0.21 can adequately represent the world-wide m_b scatter using small arrays and single stations, respectively. In fact, their values are even below the standard deviation of 0.22 m_b units observed for subarray beams across the limited aperture of the NORSAR array (Berteussen, 1975). We also note that our estimates appear high relative to those obtained by Veith and Clawson (1972). A possible explanation is the difference between world-wide m_b scattering of large events (studied by the above authors) and the smaller events studied here. That such a difference is very likely to exist can be inferred from the demonstrated frequency dependent increase in amplitude scatter across NORSAR, and noting that the earthquake source spectrum corner frequency generally increases with decreasing event magnitude (Aki, 1967; 1972; see also Husebye et al., 1974). Since the smaller earthquakes are of most interest for m_b bias considerations, we conclude that the standard deviations suggested in this paper are those most adequate to use both for network magnitude bias studies and to indicate the range of standard deviations to be considered in estimating m_b by maximum-likelihood techniques.

From a physical point of view, it is noteworthy that a significant residual scatter in m_b values exists even when local geology and near-receiver effects as well as average regional bias are eliminated (Model 1). The origin of this scatter must be found at or near the source. It is worth noting that radiation patterns in general do not correlate well with global P-wave amplitude data (e.g., Davies and Julian, 1972). Therefore, the dominant factor causing m_b variance appears to be selective absorption and fucusing/defocusing effects in the crust and upper mantle in the source region. Evidence in support of this statement comes from recent work by Haddon and Husebye (1977) who show that a significant part of the large NORSAR amplitude scatter originates in the lithosphere beneath the array. According to the reciprocity theorem of wave theory, a similar scattering would take place in a source region as seen by a global network. In fact, the source scattering is likely to be even stronger, as the NORSAR array is located in a stable tectonic area (the western extension of the Baltic Shield) while most earthquakes take place in structurally complicated plate boundary regions.

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