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Predicted and Observed Seismic Event Detectability of the NORSAR Array

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NORWEGIAN SEISMIC ARRAY

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Richard A. Jedlicka, Capt USAF
Technical Project Officer

PREDICTED AND OBSERVED SEISMIC EVENT DETECTABILITY OF THE NORSAR ARRAY

A drawback in many types of seismicity investigations is that an estimate of seismic event detection capability is not available or neglected. One interesting example here is that observed earthquake activity is higher during nights than in the daytime (Shimshoni 1972) which most probably reflects diurnal noise level variations (Flinn et al, 1972). Obviously, the event detection capability of an ordinary station or a seismic array is mainly governed by the noise level at the site under the assumption that instrument magnification is sufficiently high. Thus, in principle it should be possible to estimate the lower magnitude threshold for observable earthquakes for different epicentral distances for a given seismological observatory when its noise level variations are known. This problem is the topic of the letter.

We have here focused our interest on the event detectability of the NORSAR array in Norway, and will first dwell briefly on its automated procedures (Bungum et al, 1971) which define the system's operational noise level. The event detector is based on a large number of signal-to-noise ratio (SNR) tests on around 310 array beams which are deployed in all active seismic regions. For extra noise suppression, i.e., in addition to that proportional to the square of the number of array sensors, recursive bandpass filtering is applied on the beam traces. Moreover, a certain amount of signal energy loss occurs as the event epicenter and the nearest beam point seldom coincide and that short period P-signals are not perfectly coherent across a large aperture array. The event detection process itself is based on calculations of a short term (STA) and long term (LTA) linear power average through sliding

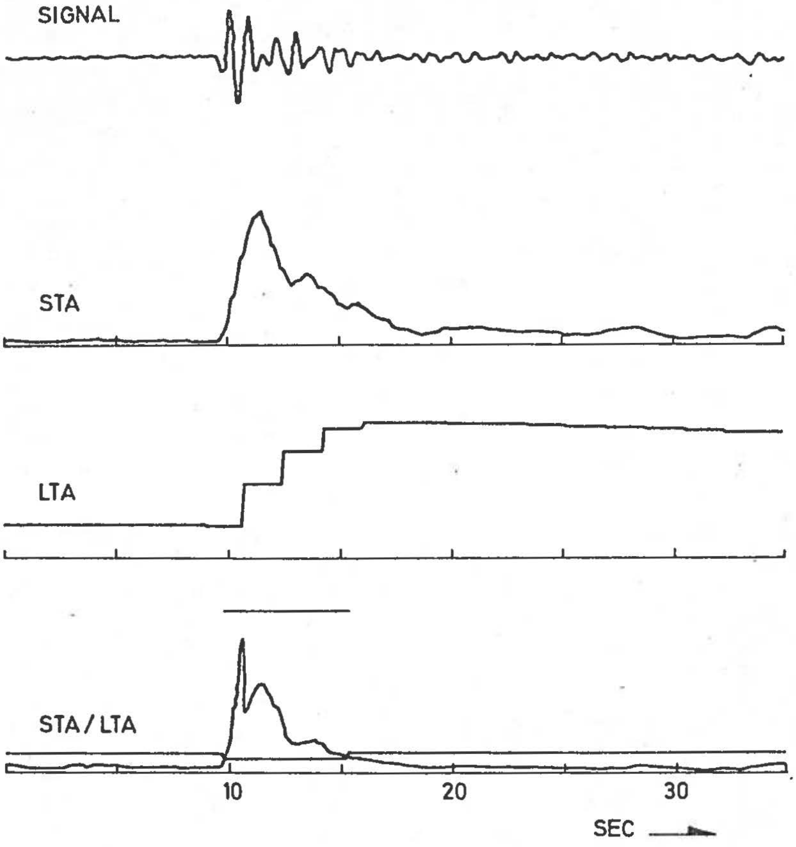

Fig. 1. Beam, STA, LTA and STA/LTA for earthquake from Tsinghai, China; arrival time Jan 27 1970, 10.59. 40.1 filtered 1.0-3.0 Hz. STA integration time is 1.8 sec and LTA computation rate is 5/9 Hz. The short line above the STA/LTA curve indicates detection state, and the line crossing the curve is the threshold.

windows. Whenever the ratio between these two parameters on a particular beam trace exceeds a predefined threshold, a detection is declared (see Fig. 1). The mathematical formulation is given in eq (1) and eq (2).

$$\mathrm{STA}(t) = \sum_{i=t-IW+1}^{t} |S(i)| \qquad (1)$$

$$LTA(t') = (1-2^{-\eta}) \cdot LTA(t'-IW) + 2^{-\eta} \cdot STA(t'-IW) \qquad (2)$$

where t and t' are STA and LTA sampling times in dsec, $S(i)$ is array beam amplitude, IW = integration window, and the parameter $\eta = 4$ or 5. For computational convenience a linear power detector is used, while a more common power detector PSTA/PLTA is easily defined from eq (1), i.e., STA replaced by PSTA and $|S(i)|$ by $S(i)^2$, etc. For noise and small signals we have $STA \sim (PSTA)^{\frac{1}{2}}$, and approximation used in this paper. (For Gaussian noise we have $STA = \sqrt{\pi/2} \cdot PSTA$).

The short term average is of special interest when an event is detected. The reason is that the STA parameter essentially is an estimate of the square root of the kinetic energy per unit mass of the signal and thus related to the dominating A/T term in the standard magnitude formula given below:

$$m_b = \log(A/T) + Q(\Delta,h) + S \qquad (3)$$

where A = signal amplitude, T = period, $Q(\Delta,h)$ = depth distance function for P-waves and S = station constant.

It has been shown (Anonymous, 1967) that the relation between PSTA and (A/T) is of the form

$$PSTA \sim \pi^2 (A/T)^2 \qquad (4)$$

To prove this equation, the starting point was the expression for the ground displacement $g(t)$ and ground velocity $v(t)$ respectively, i.e.,

$$g(t) = A\frac{2\pi}{T}t \qquad \text{and} \qquad v(t) = \frac{2\pi}{T}A \cos\frac{2\pi}{T}t \qquad (5)$$

The kinetic energy $E'(t)$ of an incremental mass δm beneath the seismometer is

$$E'(t) = \frac{1}{2}\delta m\ v^2(t) \qquad (6)$$

and the average, normalized kinetic energy is

$$<E(t)> \simeq \pi^2 (\frac{A}{T})^2 \qquad (7)$$

The average energy for sinusoidal ground displacement after compensating for the background noise can now be related to event magnitude through eq (3).

In the case of NORSAR, a direct approximation of the quantity A/T can be obtained as indicated in eq (4) or eq (7) as the instrument velocity transfer function is essentially flat in the frequency band 0.7-4.0 Hz. The validity of these equations has been checked by an analysis of 200 NORSAR events recorded during March 1972. The average difference between the PSTA and (A/T)-analyst magnitude estimates, measured on the same beam trace, was -0.008 and its standard deviation was 0.08 magnitude units.

The probability of detecting a P-signal with given log A/T and thereby a specific magnitude value (Felix et al, 1972), ignoring the $Q(\Delta,h)$ and S terms in eq (3), may be formulated as:

$$\text{Prob}\ (m_b) = \text{Prob}\ (20 \log A/T \geq NL+TH+SL) \qquad (8)$$

where NL = noise level in dB relative to 1 nanometer at 1 Hz, TH = the SNR value in dB to be exceeded before a detection is accepted as an event, and SL = signal loss during the on-line detector processing. It should be noted that m_b in this kind of analysis always refers to NORSAR P-wave magnitude.

In order to solve this equation we must know the cumulative probability density distributions (PDD) for the above parameters. It is no problem in the case of the TH parameter as it is a constant having a value of 11.5 dB in the time interval considered. An estimate of the PDD for the STA parameter on an individual beam trace (see Fig. 1) has been obtained from analysis of 2400 noise samples equivalent to 60 min of data in 6 different periods in the interval Dec 71 to Apr 72. The results are shown to the left in Fig. 2, and it should be noted that the 6 sub-samples always within the 2-98% probability interval.

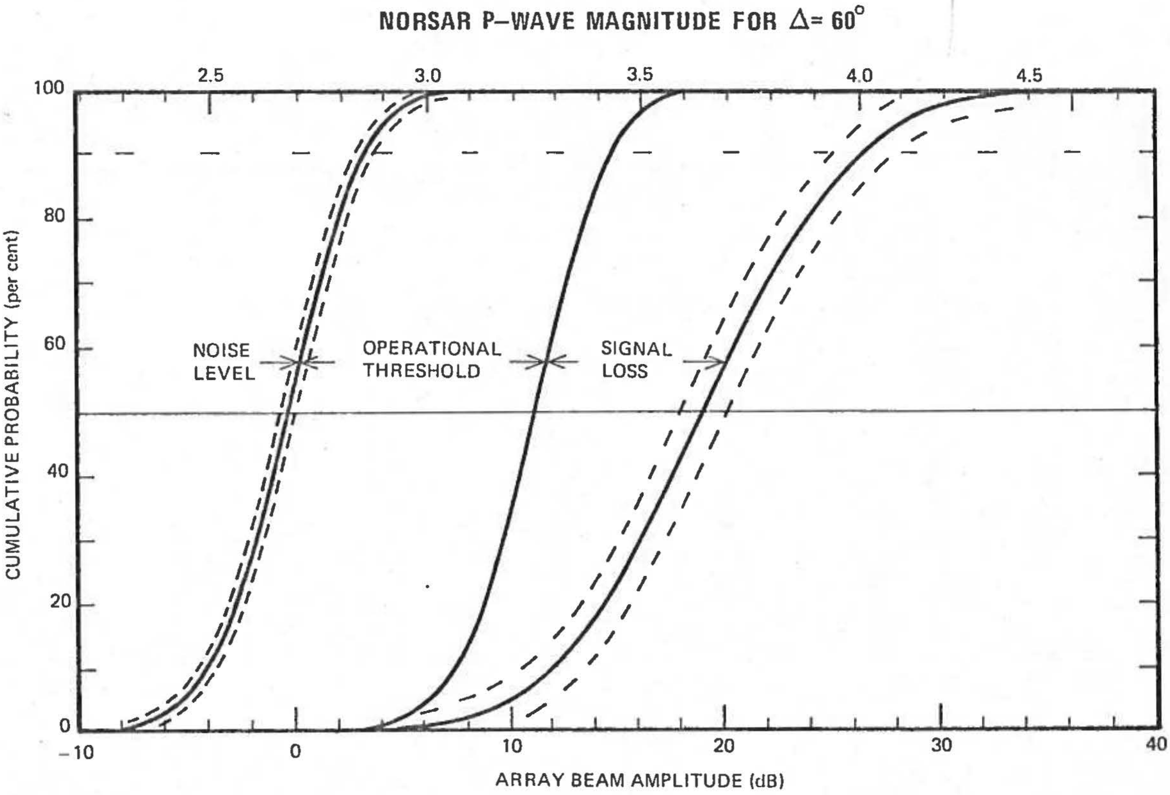

Fig. 2. The first or leftmost curve gives the observed cumulative noise distribution. The second or center curve is obtained by adding the operational threshold parameter of 11.5 dB to the first curve. The rightmost curve is the sum of the center curve and the observed cumulative loss distribution for Zone 1 in Table 1. The dotted lines show the 90% confidence intervals of the leftmost and rightmost curves.

fell inside the 90% confidence limits also included in the figure. The given STA distribution passed a lognormal distribution test at the 0.05 level.

The first NORSAR estimation of the magnitude of a specific event is the on-line STA calculation by the event detector. The final magnitude value is based on the analyst's measurements of P-wave amplitude and period after the best possible array beam has been found. In other words, the difference between log (A/T) and log (STA), which in this case is measured on different types of array beams, is an estimate of the signal losses encountered during the detection processing. In Fig 3 log (STA) versus log (A/T) for 800 NORSAR recorded events are plotted. As a rule, STA is significantly less than the corresponding A/T value, which is interpreted in

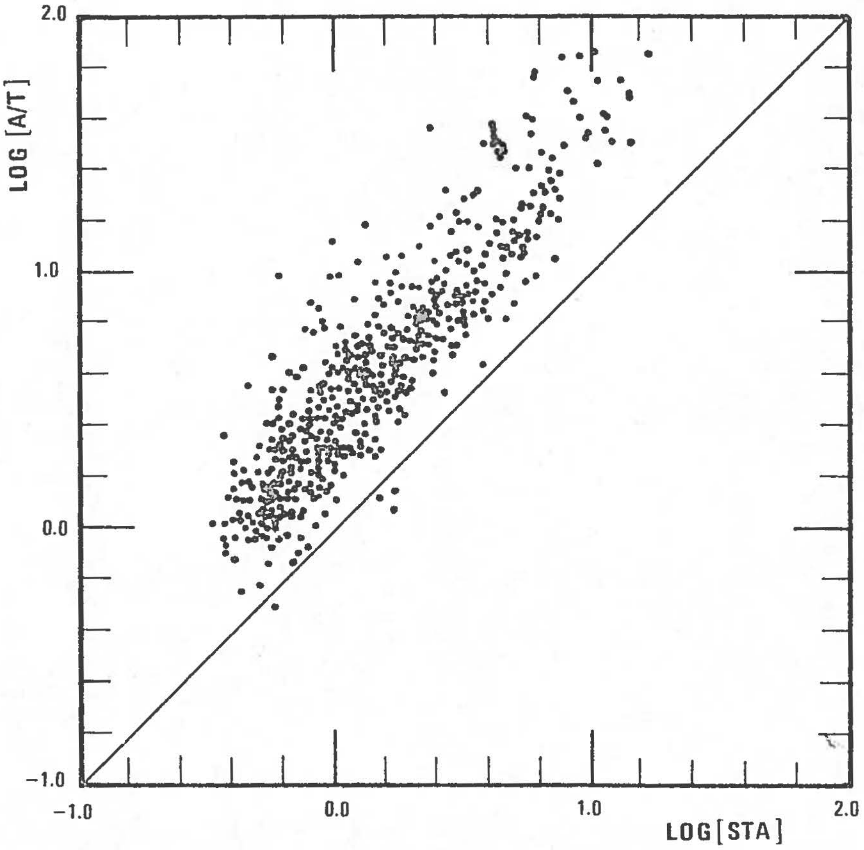

Fig. 3. Log A/T versus log STA after special scaling factors have been removed for 800 P-signals recorded in March and May 1972. The STA values are those measured on the actual array beam at signal detection, while the A/T values are those measured by the analyst after the best possible array beam has been formed.

terms of signal energy losses during the on-line event detection processing. Factors of importance here are the inevitable smoothing operations in the array software system, linear instead of square detector, a finite number of beams deployed (see Fig. 4), signal incoherency, travel time anomalies, etc. The cumulative STA distribution for signal losses for the events in Zone 1 in Table 1 is included in Fig. 2, where also the corresponding m_b magnitude for an epicentral distance of 60 deg is shown. The 50 and 90 per cent m_b probability event detection levels are given by solid and broken lines.

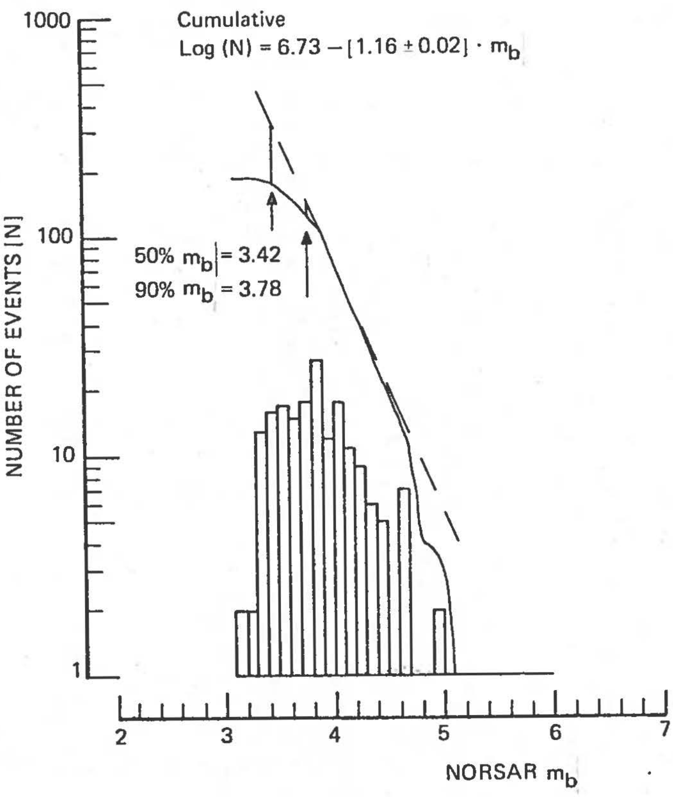

Fig. 4. NORSAR magnitude recurrence relation for observed events in Zone 8 in Table 1.

In short, using the given equations and at the same time having obtained PDD models for noise and signal losses during the event detection process, we are in a position to compute cumulative event detection capabilities of the NORSAR array.

We have also undertaken a comparison between predicted and observed event detection capabilities (Bungum 1972) in terms of NORSAR m_b thresholds, and the results are given in Table 1. For the individual regions, the PDD models of the signal loss parameter NS have been recomputed. In

ZONE		ZONE LIMITS		OBSERVED m_b LEVELS			PREDICTED m_b LEVELS		
No.	Name	Azi(deg)	Dist(deg)	No. of Events	50%	90%	No. of events for SL estimates	50%	90%
1	P-zone	0-360	30-90	1555	3.57	4.03	548	3.63	4.01
2	Atlantic	180-260	30-90	88	3.64	4.26	13	3.69	4.23
3	N.America	260-340	40-90	114	3.72	4.06	98	3.66	4.05
4	Aleutian Is.	340-15	30-90	131	3.40	3.90	17	3.62	3.95
5	Japan	15-70	50-90	738	3.66	4.07	236	3.61	3.95
6	C. Asia	40-110	30-90	211	3.21	3.69	58	3.45	3.87
7	Iran (1)	110-180	30-90	262	3.45	3.80	38	3.51	3.88
8	Iran (2)	110-130	35-50	188	3.42	3.78	31	3.49	3.83

TABLE 1

Observed and predicted m_b detectability levels for the NORSAR array. The observational data (see Bungum 1972) covers the interval Feb - June 1972.

the case of predicted magnitude levels, the $Q(\Delta,h)$ term in eq (3) was given a value corresponding to the average epicentral distance and normal focal depth for the events located within the respective zones. To ensure a sufficient number of events for computing the cumulative magnitude threshold level (see Fig. 4), the seismic zones considered cover very large areas. The only exception was the Iran zone, which was analyzed in some detail (Table 1). Both the observed and predicted event detection levels for the two Iran regions are very similar, which is somewhat contrary to expectations. The reason is that the seismic array event detectability is critically dependent on the number of array beams available and their deployment as illustrated in Fig. 5. With increasing separation between beam

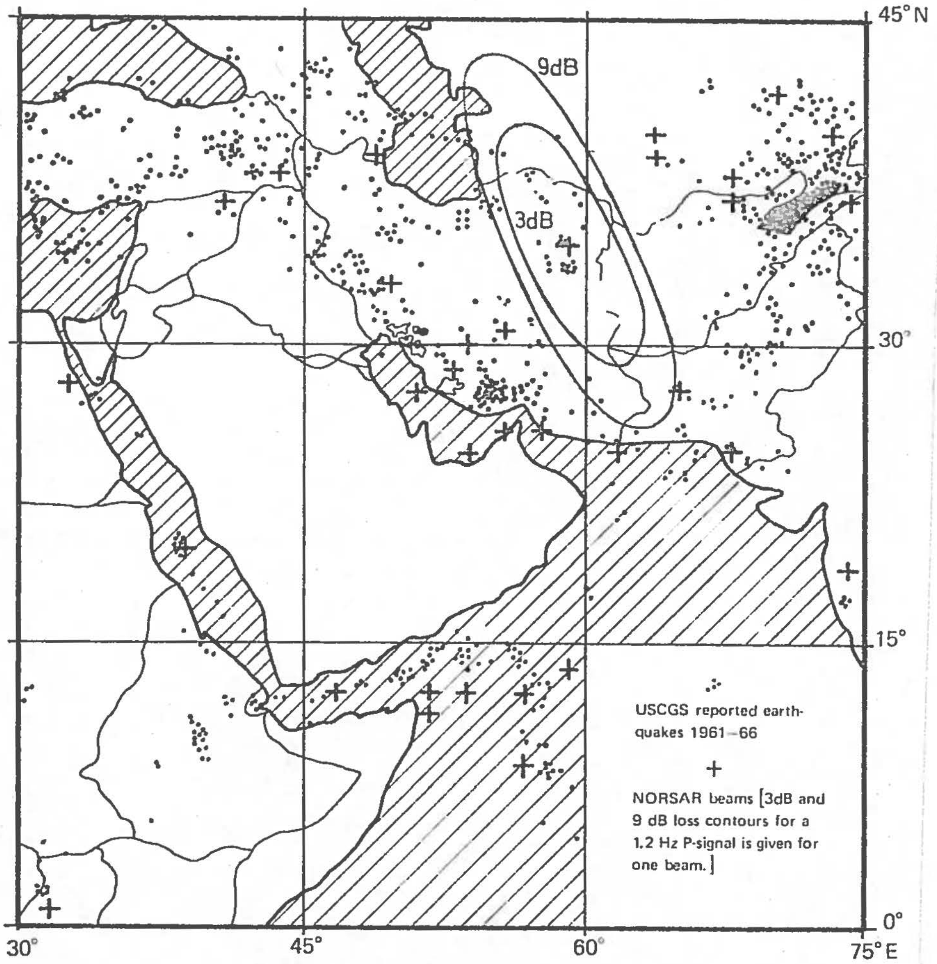

Fig. 5. Earthquake activity and NORSAR beam deployment in the Iran region. It should be noted that due to special array time delay corrections it is no simple relationship between beam locations and seismic activity.

and event locations, the signal loss during the event detection processing increases, and the corresponding m_b detectability effect may be roughly estimated from Fig. 2. An appropriate example here is that recently a supplementary event detector based on signal envelopes (Ringdal and Husebye 1972) was added to the NORSAR system. This detector which has a lower sensitivity but much better areal coverage than that based on array beams, resulted in a 10-15 per cent increase in the number of events reported by the NORSAR array. However, the array's 90 per cent cumulative detectability would probably decrease slightly, although we cannot prove this hypothesis due to lack of a sufficiently large data base.

From the experiments described above, it is quite clear that the event detection capability of a large array like NORSAR is hard to define properly except by limiting ourselves to small seismic regions. In our opinion it is preferable to define an operational event detectability which reflects the array's routine performance, and a potential event detectability. In the latter case, adequate beam coverage of the considered area is required and the array's software system parameters must be tailored to the seismic signals generated in that region. As demonstrated in this letter, reliable estimates of an array's potential event detectability may be predicted using the procedures outlined in this letter.

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