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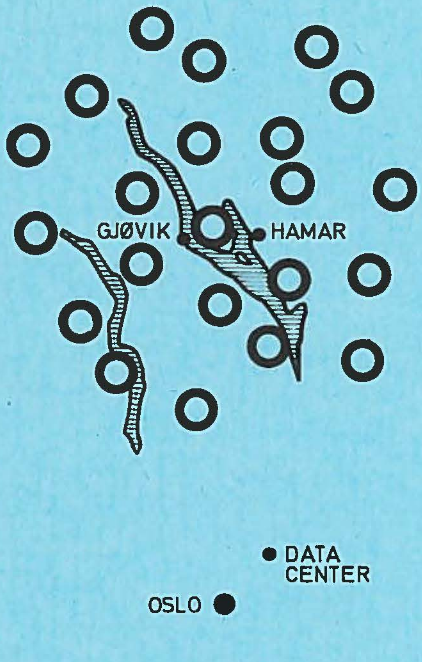
NORSAR Research and Development

(1 July 1971 - 30 June 1972)

by

E.S. Husebye
Chief Seismologist



NORWEGIAN SEISMIC ARRAY

NORSAR

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NORWAY

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This report has been reviewed and is approved.

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Technical Project Officer
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ESD Detachment 9 (Europe)

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CONTENTS

SUMMARY

This report covers the period 1 July 1971 - 30 June 1972 which is characterized by system developments and software debugging efforts and establishment of organizational procedures required for the routine NORSAR operation. The research efforts were aimed at system improvements, especially to increase the event detection capability, and array performance evaluation.

Work completed and in progress is discussed in Chapter II. The first five sections deal with event detection problems, while in the next four sections observed and predicted NORSAR event detection and location capabilities are discussed. Two studies on event classification problems are also included, and the last four sections cover structural investigations and long term noise variation investigations.

The most important single event in the reporting period was the seminar on Seismology and Seismic Arrays which took place in Oslo, 22-25 Nov 1971.

1. INTRODUCTION

The report summarizes the NTNF/NORSAR research and development efforts during the interval 1 July 1971 to 30 June 1972. In the first part of the period most attention was given to development work like software debugging and modification, and improving the operational procedures for the array. For example, a computerized log of the operational quality of the individual SP and LP seismometers has been created, and is a valuable supplement to data channel quality coding on the high rate tapes. Recording of NORSAR LP data on a special low rate tape became part of the real time operational system in November 1971. Similarly, on-line data transmission from SAAC to NDPC, comprising processed LASA SP and ALPA and LASA LP data, are stored on the new NORSAR low rate tape. A complementary event detector is under implementation in the Detection Processor.

Several modifications of the Event Processor (EP) have reduced the computer time per processed event from around 9 min. to around 3.5 min. without appreciable loss in the EP performance. As a result of the above work, the NORSAR operation became much more troublefree in 1972, thus providing much more time for research.

The research topics investigated or in progress are mainly aimed at system improvements and evaluation of the array's event detection and location performance. Also, some aspects of the event classification problem have been considered. Most attention has been given to improving NORSAR's event detection capability, and the work here comprised theoretical design of different types of seismic event detectors, parameterization of detectors for best-in-average performance, event detector false alarm rate fluctuations and potential SNR gains by using regionalized bandpass filters. The so-called incoherent event detector developed by NTNF/NORSAR personnel has proved useful for real-time multiarray processing problems, as demonstrated by analysis of three events recorded by WWSSN stations. Procedures for simulating array event detection and location capabilities have been worked out, including an off-line version of the on-line Detection Processor. A comparison between observed and predicted NORSAR event detection and location performance gave essentially identical results. Preliminary results on m_b:M_s classification capabilities for the NORSAR array have been obtained, and work on short period classification criteria has started. An analysis of single sensor amplitude variations across NORSAR favors a lognormal probability density distribution function. Vespagram analysis of core precursor phases indicates that these waves are inadequately explained by the standard models for the earth's core. Mislocation vectors observed for Fennoscandian arrays have been used for deducting an upper mantle model for the mentioned region. Also, some results on long term noise level variations have been obtained.

The above research topics and relevant results are described in the next chapter. In general only the main results are presented here, as further details are available in NORSAR Technical Reports or from papers published in professional journals.

2. RESEARCH EFFORTS

The research activities in the reporting period 1 July 1971 - 30 June 1972 have been focused on event detection, localization and classification problems. The NORSAR event detection performance was relatively poor in the fall 1971, mostly due to high noise level during the seasonal storms in the North Atlantic, so very much attention was given to the problem of improving the array's detectability.

Event Detection Algorithm

The mathematical formulation of the detection algorithm in use is as follows:

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

where t = STA sampling time, S(i) = array beam amplitude and IW = integration window length.

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

where t' = LTA sampling time, and the parameter $\eta = 5$ outside detection state (no signal present), and $\eta = 4$ in detection state. The ratio STA/LTA is calculated every time STA is updated. When this ratio exceeds the specified detection threshold a certain number Q of consecutive times, a detection is declared. Currently the values of IW, STA sampling rate are 15.5 and 1 respectively. In view of general detection theory, it was found that the optimal detector for the NORSAR system according to the Neyman-Pearson criterion is a square detector where a whitening filter is applied on the beam traces. However, from analysis of real and simulated seismic data we found that the gain was very modest by changing from a linear to a square detector, and the same applied to using an extra whitening filter in the NORSAR system. For further details on this problem we refer to a thesis by Berteussen (1972).

The False Alarm Rate of the NORSAR Detector

The false alarm rate at NORSAR does vary considerably with background noise level, and thus reflects fluctuations in the character of the noise. Otherwise, if the noise level increases with no change of spectrum, the false alarm rate will be unchanged as long as the detection threshold remains fixed. The above problem was investigated by R.T. Lacoss, Lin. Lab., M.I.T., during a visit to NORSAR DPC in April-May 1972. An idealized conceptual model has been formulated to help understand these false alarm fluctuations and to predict certain trade-offs (Lacoss 1972). For example, the false alarm rate under best noise conditions with a bandpass filter corner frequency of 0.9 Hz should be the same as for worst noise conditions and a filter having the lower corner frequency at 1.2 Hz.

A New NORSAR Event Detector

The P-signals recorded by NORSAR are only partially coherent across the array. This means that the expected gain in signal-to-noise ratio (SNR) which is proportional to the square root of number of sensors used is not obtained during array beamforming operations. The corresponding signal energy loss increases with increasing frequency, and may severely degrade the array's detectability of very short period P-waves. This problem may be partly circumvented by replacing or supplementing the array beam traces with the average of subarray beam traces. The relative advantages of using the so-called incoherent beams are modest signal losses, better estimates of the noise variance and good areal coverage. The noise suppression is small as compared to array beamforming, but could partly be compensated for by using high frequency bandpass filtering. As mentioned previously, an experimental event detector based on incoherent beams was implemented in the on-line system in Dec 1971. Preliminary results indicate that this new supplementary detector when completed, would improve the array's event detection performance by 10-20 per cent. A theoretical description of the incoherent detector and its operational performance has been prepared by Ringdal, Husebye and Dahle (1972).

Frequency Domain Filter Synthesis

In addition to the array SNR gain resulting from beamforming processing, additional noise suppression is obtainable by applying various types of filters. The performance of a large number of Wiener prediction error filters and Butterworth 3rd order bandpass filters have been checked on several types of frequency domain synthesized noise and P-wave models. In the latter case, the signal spectrum shape is fixed while the peak frequency is varied in frequency steps of 0.1 Hz.

The gain in SNR due to prediction error (PE) filtering is not very impressive except when the signal and noise are well separated in the frequency domain. The reason for this is simply that the above filter is essentially a noise-whitening filter. A single bandpass filter gives in general a somewhat better gain in SNR than a PE filter, but a stack of such filters is required for optimum performance. For example, the best-in-average filter has a passband of ca. 1.4-3.4 Hz, but might be 5 dB down in gain in comparison to other bandpass filters for extremely high and low frequency P-signals, like those from Central America and Central Asia, respectively.

Using the NORSAR observed distribution of the dominant P-signal frequency for recorded events in combination with relative filter gain in dB, we found that the array's event detectability may increase with roughly 10-20% if "optimum" bandpass filtering is used. The above work was undertaken by Gjøystdal and Husebye (1972).

Multiarray Processing Experiment

As the longitudinal seismic waves are not dispersive, the group and phase velocities are identical for the P signals. This means that under certain simple assumptions, i.e., the case in which the amplitude distribution of the component waves in the wave packet is Gaussian, the envelope y of the signal or disturbance is expressible as (Coulson 1961):

$$y = A(\pi/\sigma)^{\frac{1}{2}} \exp(-\pi^2(x-vt)^2/\sigma)$$

when A = amplitude scaling factor, σ = STD of the Gaussian distribution and x is distance. The half-width of the envelope is $(\sigma^{\frac{1}{2}}/\pi)$ and thus is a function only of the P-wave spectral bandwidth. In other words, we would expect the signal envelope to be very similar from one station to another, even if the signal shape may vary considerably. If this is true for seismic waves, then multiarray or global network processing would be feasible using an event detector similar to that of incoherent beamforming in use at NORSAR as discussed in a previous section.

The above hypothesis has been tested on WWSSN station records (two earthquakes and one explosion) and NORSAR subarray beams from many different events. Signal envelope similarity has been detected through cross-correlation and coherency analysis, and a typical value was around 0.75 units between WWSSN station data. Similar results were obtained by analysis of 22 different NORSAR events in the distance range 3-145 deg. The response pattern or global array beampacking was also calculated. In short, several kinds of multiarray processing are feasible if the P-signals are replaced by their envelopes. The results outlined above were obtained by Husebye, Ringdal and Fyen (1972).

One-Array and Two-Array Location Capabilities

Event location capabilities of a single array and of two arrays in terms of random and biased observational errors have been simulated on the computer. The approach was to obtain a Gaussian distribution of the parameters azimuth, slowness (DT/DΔ) and arrival time differences which are used in one and two array epicenter determinations. Specifying their mean values and variances, a large number of paired values of these parameters are simulated by using a random number generation routine. These observations determine a distribution of event locations in geographic space, from which the axes of the 95% confidence ellipse were calculated. In case of one array, the semi-axes of the confidence ellipse are tabulated as a function of epicentral distance, and fictive variances of observed azimuth and slowness. The joint event location capability for two arrays is easily computed but not tabulated due to the regional changes in the shape and orientation of the confidence ellipses. The above analysis was supplemented with epicenter determinations using real NORSAR and LASA data. In the West Indies area the average location error was found to be 310, 161 and 139 km for NORSAR, LASA, and NORSAR and LASA combined.

A model for individual subarray time corrections for the NORSAR array is used for simulating biased correction errors, which would be very large if left uncorrected. The results obtained roughly indicate that the array siting area may account for about 45 per cent of the observed slowness anomalies, but no improvement was obtained in the azimuth anomalies. The slowness bias makes it difficult to utilize the NORSAR DT/DΔ measurements for investigations of heterogeneities in the mantle. For further details on this problem we refer to a forthcoming paper by Gjøystdal et al (1973).

Evaluation of the Event Detection and Location Capability of the NORSAR array

The routinely analyzed NORSAR data from the first 6 months of regular operation, May-October 1971, has been evaluated. In this period about 8 events per day have been reported from the 30^o-90^o distance interval. This gives a 90% cumulative reporting threshold of about 4.1 NORSAR magnitudes, which is equivalent to about 4.3 NOAA magnitudes. The large variations in the seismic background noise cause large variations in the distribution of reported events per time unit. Out of the union of the events reported by NORSAR and NOAA in May-August 1971, 25% are reported by both, while 30% are reported only by NORSAR, 45% only by NOAA. A location comparison shows that 50% of the NORSAR locations are within 200 km of the NOAA location in the 30^o-90^o distance range. The biased errors in time delay and location estimates are demonstrated to be quite large, which indicates that significant improvements in the performance of the array can be expected when a better set of corrections for these errors is implemented.

The above investigation which is based on NORSAR data from 1971, was performed by Bungum and Berteussen (1972). However, during January 1972 a number of modifications and improvements were implemented in the Detection and Event Processor software systems thus necessitating a re-evaluation of the array's operational performance. The work was undertaken by Bungum (1972a) and an outline of the main results is as follows: Data published in the NORSAR seismic bulletin between February and June 1972 has been studied in order to find estimates of the detectability and location accuracy at NORSAR. The detectability is calculated from empirical frequency-magnitude distributions, and the 90%

cumulative detectability for the teleseismic zone ($30^\circ < \Delta < 90^\circ$) has been estimated at m_b 4.0, while values for different regions vary from 3.7 to 4.3. These are all NORSAR magnitudes. The magnitude bias between NOAA and NORSAR has been found to be 0.15 ± 0.31 in the teleseismic zone. In this zone, the median location difference between NOAA and NORSAR has been estimated at 160 km, with values for different regions ranging from 130 to 340 km.

Prediction of the NORSAR Array Event Detectability

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. In NORSAR's case, factors of importance are besides the noise level on the beam traces, the threshold to be exceeded before an event detection is declared and the relative signal losses inhibited in detection processing or NORSAR seismic surveillance. The starting point was to estimate the cumulative distribution of the linear noise power parameter STA and its relation to ground motion and henceforth event magnitude. The threshold parameter is no problem as it is a constant while an estimate of the relative signal loss was obtained by comparing Detection and Event Processor STA estimates for 800 recorded events. A comparison between observed (see Bungum 1972 a) and predicted events for several seismic zones are shown in Table 1, which is taken from a paper by Berteussen and Husebye (1972).

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	3.60	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 a) covers the interval Feb-June 1972.

Event Classification Applying the m_b-M_s Criterion to NORSAR Recorded Events

A study has been made by Filson* and Bungum (1972) of the capability of the Norwegian Seismic Array to discriminate between earthquakes and underground explosions occurring in Central Asia and western Russia. The ratio of surface to body wave magnitudes (M_s:m_b) has been used exclusively, and measurement of low amplitude surface waves. Beamforming and matched filtering were the signal enhancement techniques applied. Of 34 events in central Asia studied, 10 were identified as explosions, 22 earthquakes and 2 were unidentifiable because of high, long period background noise. Five events in aseismic western Russia, all presumed to be explosions, showed wide variation in M_s:m_b; two of these measurements being close to the earthquake population of central Asia.

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* J. Filson, Lincoln Lab., M.I.T., paid a visit to NORSAR Data Processing Center Oct-Nov 1971.

The $M_s:m_b$ measurements of central Asian explosions made in this and another study are compared with measurements of Nevada explosions. For a given m_b the latter consistently have higher M_s values. The possible causes of this are discussed and, depending on the cause, the array seems capable of detecting surface waves from an explosion of 4-16 kilotons yield at 40° distance in central Asia. Strong seismic noise variations in Norway make this long period capability time dependent.

Short Period Event Discriminants

The design of short period seismic event discriminants is principally aimed at manifesting typical source characteristics of underground nuclear explosions and earthquakes. A special problem here and typical for an array like NORSAR where the P-waves are only partially coherent, is the signal energy loss during ordinary data processing. For example, high frequency signal energy is strongly suppressed during conventional array beamforming, but preserved on the subarray beam level. Henceforth, our initial event discriminant efforts are focused on processing which minimized the loss of the important high frequency components in P-waves. Using the Fast Fourier Transform as a basic tool, power spectra of short period P-wave signals from 16 well-recorded earthquakes and underground explosions in Central Asia and in western North America were computed. The initial data preparation included a proper line-up of incoming signals and tapering the ends of the 6.4 sec transform windows used. The spectra were smoothed and the effect of the noise carefully removed. The computed spectra are the mean power of all 132 sensors in the NORSAR array (spectraform) and the power on the array beam. The ratio of the above two spectra (beam loss) increases sharply at frequencies above 1.5 Hz being in average 12 dB at 3 Hz Earthquakes and explosions were observed to have, in average, different shapes of spectrum. The observed spectraform spectra peaked between 1 and 2 Hz. The signal-to-noise ratio for the events in Central Asia peaked around 2 Hz, but was more flat for events in North America due to shift of energy towards lower frequencies. At frequencies above the spectral peak, spectraforming gave the most stable estimates, though a combined processing method, the average spectrum of subarray beams, also had high stability. The above work has been performed by Noponen*, Husebye and Rieber-Mohn (1972).

Time and Amplitude Anomalies on the NORSAR Subarray Level

An investigation is undertaken to map time delays and amplitude anomalies on the subarray level, and this means that all 132 NORSAR SP sensors' performances in this respect are jointly analyzed for the first time. The main results obtained so far are, according to A. Dahle, as follows. The single sensor amplitude varies tremendously across the array, a factor of 2 and 10 on the subarray and array level is not unusual. However, the interesting feature is that Kolmogorov-Smirnov hypothesis tests favor a lognormal probability distribution for the observed amplitude, and this is very clear for high-frequency signals (see also Ringdal et al 1972). Time anomalies across the subarrays defined as the difference between observed and predicted from Herrin's tables are in general small, i.e., the standard deviations were less than around 0.1 sec. The signal amplitude loss due to subarray beamforming is in average less than 1 dB and varies linearly as a function of the mean cross-correlation value.

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* I. Noponen, Helsinki University, visited NORSAR Data Processing Center in the intervals 16 Aug - 17 Dec 1971 and 20 May - 30 June 1972.

Vespagram Analysis of Core Waves

Some problems in the interpretation of core phases and their precursors have been studied by the analysis of PKP phases, recorded at the NORSAR array. A limited number of SKP phases has been used as an aid in the analysis. Processing techniques, suitable for the resolution of core phases in slowness and time are discussed, in particular the usefulness and limitations of the Vespa process in this connection. In the various techniques the effect of the structure under the array should be taken into account. The methods used reveal the refractions and reflections at the inner core boundary and also to some extent the more complicated character of the PKP precursors. Several representative examples of interpretation of the precursors are viewed in light of the observational results. The analysis is limited to $\Delta > 136^{\circ}$. In this range the results indicate that diffraction effects may play a more important role in the generation of the precursors than generally assumed. For more details, we refer to a paper by Doornbos* and Husebye (1972).

Upper Mantle Discontinuities in Scandinavia

During a research visit to NORSAR DPC, Dr. I. Noponen investigated slowness anomalies observed at array stations in Scandinavia, namely, NORSAR, Hagfors and the Helsinki tripartite station. His main results are as follows: (Noponen 1972): Systematic teleseismic P-wave slowness anomalies up to 1 sec/deg are observed at three array stations in Fennoscandia, NORSAR in Norway, Hagfors Observatory in central Sweden and the telerecording station at Helsinki in Finland. The slowness anomalies are smallest

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* Dr. D. Doornbos, Utrecht University, visited NORSAR Data Processing Center in the summers of 1971 and 1972.

at Helsinki and largest at Hagfors. Resulting event mislocations would exceed ten degrees at certain regions if no corrections were used. It is shown that an integration over the horizontal velocity gradient along the ray path near the receiver gives the slowness anomaly caused by that gradient. A given horizontal gradient produces an order of magnitude smaller mislocation when situated near the source than when situated near the receiver. It is concluded that a major part of the observed slowness anomalies can be explained by lateral changes in structures in the upper mantle and the crust under the arrays. In particular, an increase of the average vertical velocity in the upper mantle under the Scandinavian peninsula in the direction from oceanic towards continental areas is required by the slowness anomalies and by the travel time residuals of the conventional stations in the same region.

Microseismic Noise Studies

In a recent paper Bungum (1972 b) discusses different types and principles for microseismic noise investigations. The emphasis is on arrays like LASA and NORSAR which may be considered very efficient tools for analyzing the microseismic noise fields in the frequency-wavenumber domain. Another interesting topic discussed in the above paper is the long term variation of the NORSAR array beam noise level, which has a direct bearing on the array's event detectability as discussed in a previous section. Spectral analysis of short period noise level variations in the passband 1.2-3.2 Hz gives a significant peak at 1 c/day, and this reflects the diurnal noise variation.

3. MISCELLANEOUS

To mark the formal opening of the NORSAR array, a seminar on Seismology and Seismic Arrays was arranged in Oslo, 22-25 November 1971. A total of 69 scientists from 12 countries attended the meeting and altogether 28 talks were given. Twenty-two of the papers presented at the seminar have been edited by Husebye and Bungum (1972) in a special booklet titled Proceedings from the Seminar on Seismology and Seismic Arrays, Oslo, 21-25 November 1971.

Visiting Scientists

D. Doornbos, Utrecht Univ. The Netherlands	1 July - 30 September 1971
M. Perl, Hebrew Univ. of Jerusalem Israel	1 July - 27 August 1971 (NTNF Scholarship)
P. Basham, Ottawa, Canada	6-7 July 1971
E. Hjortenberg, Geodetic Inst. Copenhagen, Denmark	6-17 July 1971
H. Mach, Geotech/SAAC Alexandria, Va., USA	26-27 July 1971
J. Minear, Triangle Res. Inst. Raleigh, S. Carolina, USA	29 July 1971
I. Noponen, Helsinki Univ., Finland	16 August - 17 December 1971
I.P. Basilov, Moscow Univ., USSR	25-29 November 1971
W. Dean, Geotech/SAAC Alexandria, Va., USA	25-26 November 1971

C. Felix, IBM/SAAC, Alexandria, Va. USA	25 November - 3 December 1971
W.L. Gilbert, IBM/SAAC, Alexandria, Va. USA	25-26 November 1971
T. Harley, Texas Instr./SAAC Alexandria, Va., USA	25-26 November 1971
J. Hjelme, Geodetic Inst. Copenhagen, Denmark	26 November 1971
E. Hjortenberg, Geodetic Inst. Copenhagen, Denmark	17 November - 1 December 1971
I.P. Passechnik, Moscow Univ., USSR	25-29 November 1971
S. Pirhonen, Helsinki Univ., Finland	9 November - 12 December 1971
E. Hjortenberg Geodetic Inst. Copenhagen, Denmark	24 January - 12 February 1972
R.T. Lacoss, Lincoln Lab, M.I.T., Cambridge, Mass., USA	4 April - 8 May 1972
D.J. Doornbos, Utrecht Univ., Utrecht, The Netherlands	2 May - 30 June 1972
W. Ellis, IBM/FSD, Gaithersburg, Maryland, USA	8-26 May 1972
I. Noponen, Seismological Laboratory Helsinki, Finland	20 May - 30 June 1972
B. Söderström, Defense Research Inst., Stockholm, Sweden	29 May - 17 June 1972

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