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Royal Norwegian Council for Scientific and Industrial Research

NORSAR Research and Development

(1 July 1972-30 June 1973)

by

E.S. Husebye
Chief Seismologist

NORWEGIAN SEISMIC ARRAY

NORSAR

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CONTENTS

SUMMARY

The report covers the period 1 July 1972 - 30 June 1973 which is characterized by continuous improvements in event detection and location performance during routine operation of the array. The research efforts were aimed at improving the event detectability, and the potential exploitation of wave scattering effects for improving NORSAR's event detection and classification capabilities.

Work completed and in progress is presented in Chapter II. The first section deals with seasonal and diurnal noise level fluctuations plus changes in the character of the noise. Next, different types of array beamforming and optimum signal estimation techniques are discussed. The importance of so-called intrinsic time and amplitude anomalies or wave scattering (Chernov) effects in array data processing are also demonstrated. Finally, work on seismic verification problems is discussed briefly.

1. INTRODUCTION

The report summarizes the NTNF/NORSAR research and development efforts during the interval 1 July 1972 to 30 June 1973. In the first part of the period most attention was given to development work like software modifications and implementation of new data processing routines. For example, a supplementary event detection processor, based on so-called incoherent beamforming (Ringdal et al, 1973), was implemented in the on-line system in September 1972. For the purpose of editing a daily bulletin of seismic events, the required input data may be read directly from the detection log tape. Thus, a daily list of seismic events is now available every morning and covering the previous 24 hours, even if the Event Processor (EP) is behind its time schedule. Moreover, a status report of all data channels is generated daily and is available to users of NORSAR data.

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 optimum amplitude weighting of subarray beam signals, predictive decomposition models for explaining and predicting intrinsic phase shift and amplitude variations across the array, event detector false alarm rate fluctuations and signal-noise wavelet classification The detectability of the so-called incoherent event detector, part of the NORSAR on-line system, is superior to that of conventional beamforming in seismic regions characterized by complex P-signals. An evaluation study of NORSAR event detection and location capabilities, based on the array's routine performance in the interval Apr-Oct 1972 has been completed. One interesting result here is that the NOAA-NORSAR m_b magnitude discrepancy is a non-linear function of magnitude, i.e., NORSAR reports relatively too large m_b values for small events. Moreover, a bias analysis of NORSAR event magnitude estimates has also been undertaken. Several kinds of Vespagram analysis of core precursor phases indicate that these waves are not explainable in terms of the standard velocity models for the earth's core, while a realistic alternative is scattering sources in the lower mantle.

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 1972 - 30 June 1973 have been focused on event detection and classification problems. Presently, NORSAR reports in average 20 events per day, but recent research results indicate that significant improvements of the array's event detectability is still possible. An important problem here is the development of objective criteria for discriminating between weak P-signals and signal shaped noise wavelets.

Conditioned on the present NORSAR computer configuration, the most pressing event detection problems are considered solved. Thus, at the end of the reporting period more research effort could be spent on seismic event classification problems. For example, conventional discriminants criteria have been adapted to NORSAR data, but also so-called signal space expansion techniques are under investigation. In the reporting period a number of visiting scientists have been doing research at the NORSAR data center and part of this work is included in this report.

NORSAR Event Detector Threshold Setting and the False Alarm Rate

At NORSAR a significant trend in seasonal noise level variations occurs, and the same holds on a diurnal basis as demonstrated in Figs. 1 and 2. For example, extreme cases with a variation in noise power up to 18 dB in the frequency band 2.0-3.0 Hz within a few hours have been observed at a large number of NORSAR short period sensor sites. This simply means that the array's event detection capability is lower during winter than summer and also lower during the day than the night. In the latter case, there are roughly 20% more events detected during night time. Relevant data on the phenomena are presented

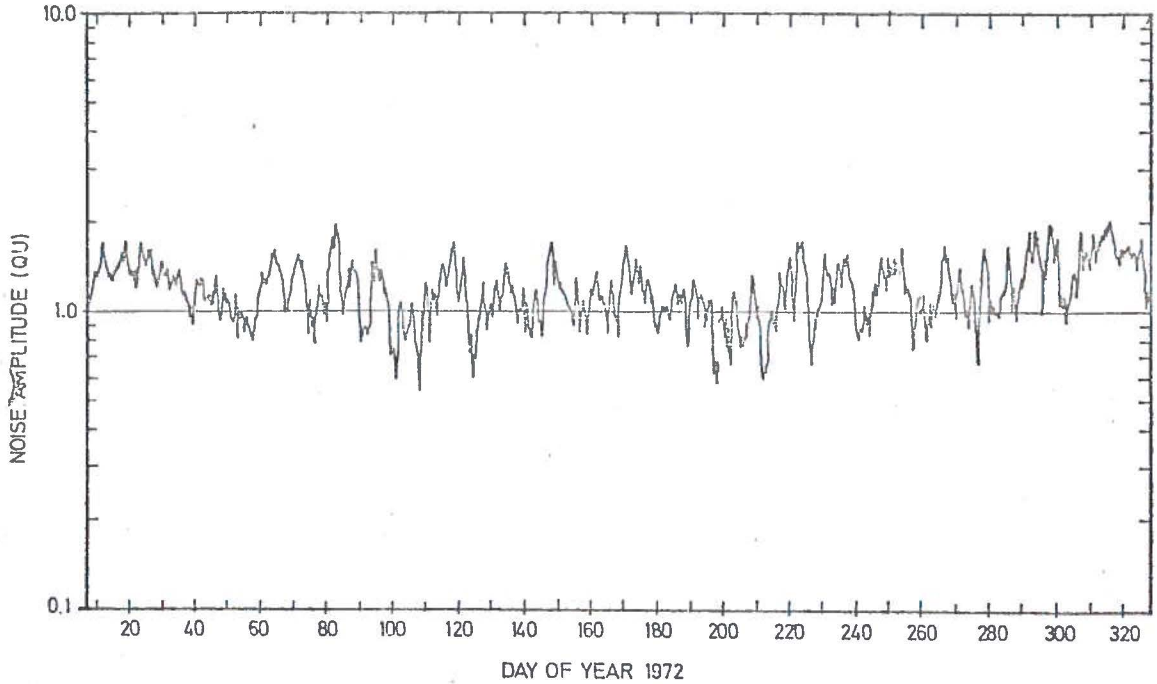

Fig. 1 Beam average of LTA for the time period 6 Jan - 23 Nov 1972. (LTA=Long Term Average, which is equivalent to linear power measured in a window of approximately 30 sec.) The sampling rate is 20 s/day and the frequency filtering of the data from which the LTA is computed is 1.2-3.2 Hz.

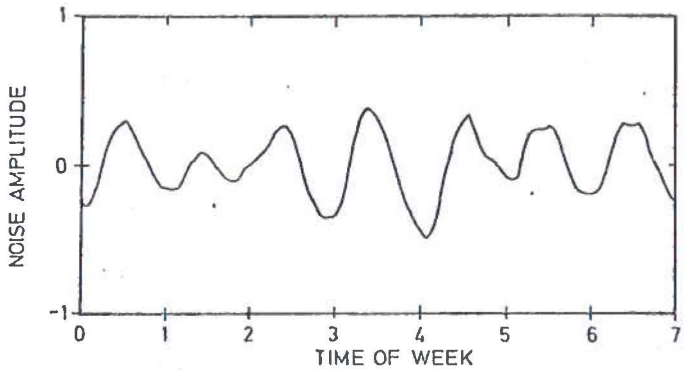

Fig. 2 LTA in relative units as a function of time of week, where day 1 is Sunday. (LTA as defined in Fig. 1) Average is made over 46 weeks, and a trend-removal is applied to the LTA time series by subtraction of daily averages. The sampling rate is 20 s/day, and the frequency filtering of the data from which the LTA is computed is 1.2-3.2 Hz.

and discussed in a recent report by Bungum and Ringdal (1973). Also, a similar study for long period noise is in progress.

An important but mostly ignored aspect of noise level fluctuations is that the statistical properties of the background noise change too. The same effect is also obtained by using filters with different passbands. Henceforth, from the theoretical studies of Rice (1944) and Cartwright and Longuet-Higgins (1956) we would expect that the noise wave train maxima would fluctuate between Gaussian and Rayleigh probability density distributions. In other words, the so-called false alarm rate would vary, i.e., the number of times pure noise wavelets trigger the event detector for a fixed SNR threshold (see Fig. 3). This phenomenon does not necessarily mean that relatively more noise wavelets are reported as seismic events under adverse noise situations

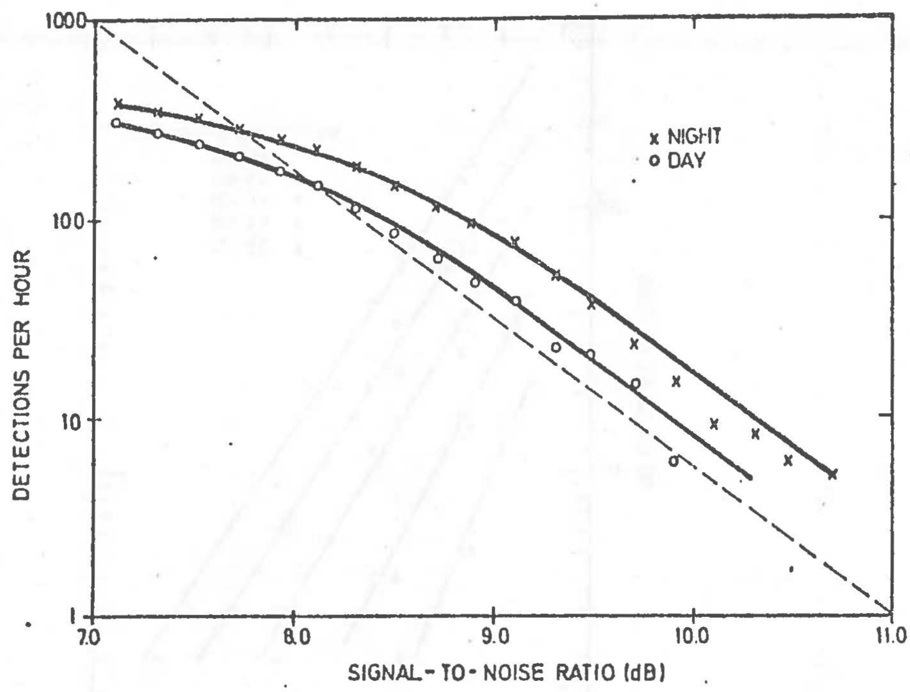

Fig. 3 Number of detections as a function of SNR for two time periods, covering one hour of day time and one hour of night time, respectively. The dashed line has a slope of -15.0.

as such a decision rests with the analyst. Instead, under favorable conditions too few events would be reported as the SNR threshold value in the event detector would be too large. The above problem was first considered by Lacoss (1972) who forwarded an approximately linear relationship between the noise stability parameter and the number of false alarms. The stability parameter was defined as the square of the noise level average relative to its variance. Steinert et al (1973) have continued this work, and the importance of the problem and also the potential gain by having a floating detector threshold setting are demonstrated in Fig. 4. Due to a limited data base the SNR threshold values range from 8 to 10 dB in the figure, while the corresponding values in the operational system are between 10 and 12 dB. Such an algorithm for the prespecified false alarm rate is feasible to implement in the NORSAR on-line system, and the expected gain expressed in equivalent SNR units would probably amount to around 0.5 dB. In addition, this routine would permit a more efficient computer capacity utilization.

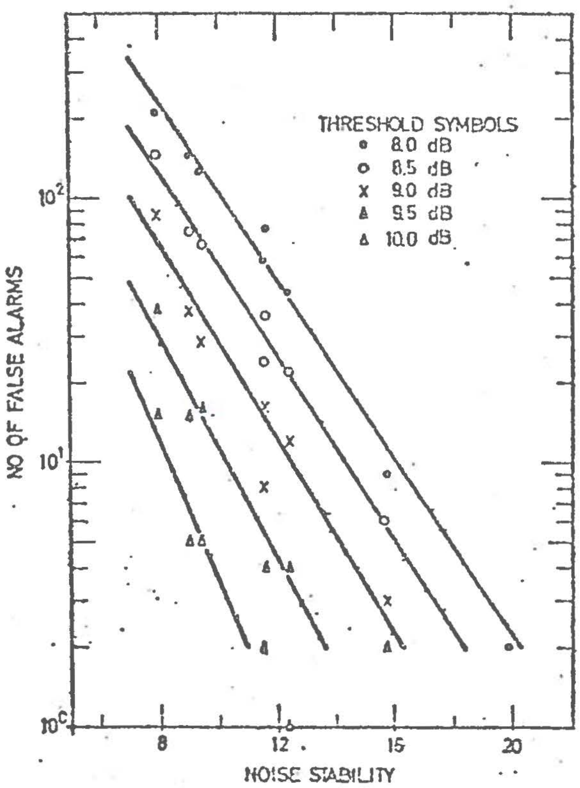

Fig. 4 False alarm rate versus noise stability for different event detector threshold values. Three different noise situations were analyzed, each corresponding to one hour of NORSAR on-line processing. For further variation of the noise structure, three different bandpass filters were also used.

Event Detector based on Envelope or Incoherent Beamforming

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, a supplementary event detector based on incoherent beams was implemented in the online system in September 1972. Results from the first two months of parallel operation of the so-called coherent and incoherent event detectors are presented in Fig. 5 and Table 1. The improvement in the array's event detectability amounts to around 15 per cent. For further details see the report by Ringdal et al, 1972.

The characteristic feature of a seismic array is real-time processing of data from a large number of sensors organized in a certain pattern on the surface of the earth. As is well known, when sensor separation increases, the signal similarity, in general, decreases. The consequence here is that when processing signals from a continental array or the global seismological network, the signal suppression is approximately equal to the noise suppression, resulting in a processing gain close to zero. One possible way to circumvent this problem might be to replace the individual signal trace by its envelope as we intuitively should expect this kind of signals to exhibit a large degree of

Zone No.	Name	EVENTS Total No.	COH.BF Only No.	INC.BF Only No.	COH.& INC. No.	COH.BF Total No.	%	INC.BF Total No.	%
1	Greece/Turkey	117	5	45	67	72	62	112	96
2	USSR/Centr.Asia	194	28	41	125	153	79	166	86
3	Japan/Kam./Aleu.	168	40	7	121	161	96	128	76
4	USA/Cent.America	64	31	1	32	63	99	33	51
5	Global I (All events)	1038	242	133	633	905	87	796	77
6	Global II (High Quality events)	546	24	25	497	521	95	522	95

TABLE 1

Events reported in the NORSAR seismic bulletin, 16 Sep - 15 Nov 1972. The table gives the total number and percent of events detected in different regions by the coherent and incoherent beamforming as well as the number of events detected only by one of these detectors.

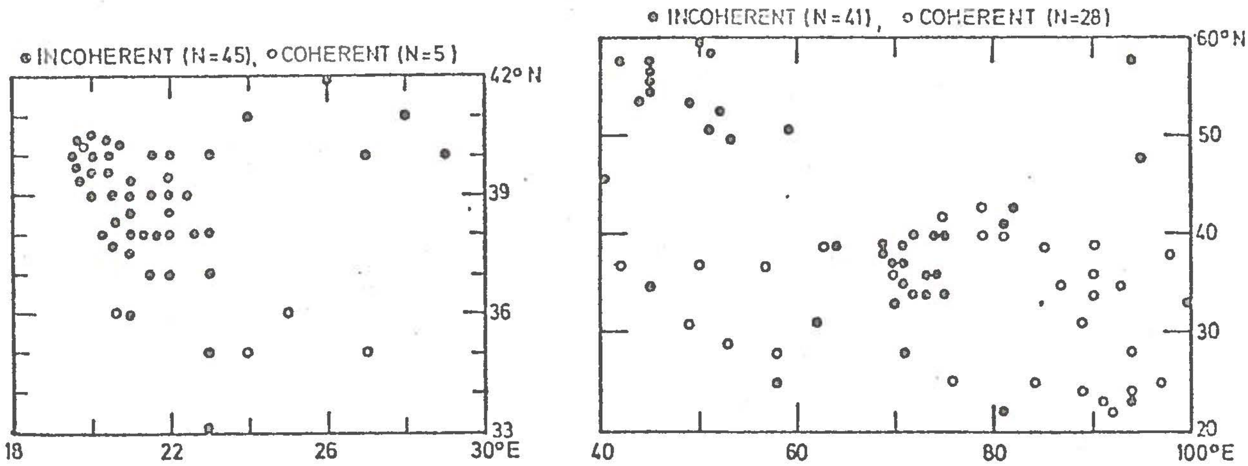

Fig. 5 Events reported in the final NORSAR bulletin which were detected by either the coherent or the incoherent detector, but not by both. The time period covered is 16 Sep - 15 Nov 1972, and typical SNR detection thresholds were 3.6 (coherent) and 1.6 (incoherent). The figures show detection performance in the Mediterranean and Central Asia & Russia areas.

signal similarity independent of sensor separation, seismometer type, etc. This hypothesis has been tested on WWSSN station records (two earthquakes and one explosion) and NORSAR subarray beams from many different events. The WWSSN beam pattern for an earthquake in Chile is shown in Fig. 6. Signal envelope similarity has been calculated through cross-correlation and coherency analysis. Typical cross-correlation values were around 0.75 units between WWSSN envelope signals. Similar results were obtained by joint analysis of 22 different NORSAR events in the distance range 3-145 deg. Moreover, using data on the P-wave amplitude variation in the teleseismic distance range and the theory for incoherent event detectors (Ringdal et al, 1972), reliable estimates on multiarray processing gains are obtainable. It is interesting to note that the above method may supplement previously proposed schemes based on joint detectability analysis of data from several arrays. The above topic is discussed in some detail in a recent report by Husebye et al, 1972.

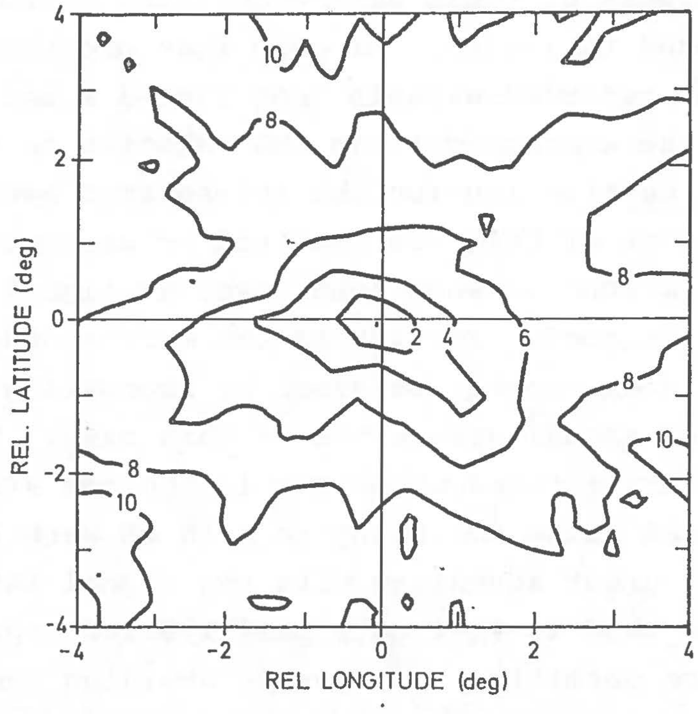

Fig. 6 Response pattern for the Greeley nuclear explosion in Nevada 12/20/1966 based on envelope traces for 19 WWSSN stations.

Optimal Beamforming

Beamforming or simple delay-and-sum processing is extensively used in analysis of P-waves recorded by the large aperture arrays NORSAR (Norway) and LASA (Montana). When the underlying assumptions of well-equivalized noise levels and identical signals between instruments is correct, the corresponding gain in SNR is optimum. In practice, these restrictive signal and noise models are not valid, thus degrading the final signal estimate and the event detectability of seismic P-waves.

In investigating this problem, we followed the line of development presented by Christoffersson and Janson (1973) where the interest is focused on the relation between signals at different instruments, i.e., the space spanned by the recorded signals. In a recent paper Christoffersson and Husebye (1973) introduced more generalized P-signal models during array beamforming and the corresponding least squares signal estimation techniques were described. The usefulness of these data processing schemes was also demonstrated in analysis of more than one hundred LASA and NORSAR recorded signals (see Tables 2 and 3 and Fig. 7). For LASA the average gain in SNR relative to that of conventional beamforming for the teleseismic event was around 3.7 dB. Most of this was obtained by accounting for noise level variations between subarrays, as signal coherency across the array is good. For NORSAR the corresponding SNR gain was approx. 2.5 dB, mostly obtained by accounting for the more complicated signal structures in this case. For local events, characterized by partly incoherent array signals, relative SNR gains amounting to 5-10 dB were usually obtained. A great advantage with the signal estimation techniques used is that both positive and negative signal weights are permitted thus partly avoiding destructive signal interference during beamforming of complicated or very weak signals.

No.	LASA EVENT PARAMETERS					PROCESSING GAIN			
	Date	Arr. Time h m s	Lat deg	Long deg	Mag m_b	IIA SNR	IIB dB	IIIA dB	IIIB dB
1	01/02/73	03.56.14.5	6N	82W	5.5	269.67	2.71	1.53	2.61
2	01/03/73	11.07.16.8	14N	110W	3.8	4.12	6.24	-1.52	6.63
3	01/03/73	11.14.17.0	16N	69W	3.8	11.77	3.01	0.73	3.46
4	01/04/73	01.31.56.6	5N	82W	3.7	7.26	2.44	-1.46	4.42
5	01/04/73	13.15.28.4	19N	109W	3.8	10.47	1.50	2.44	3.82
6	01/05/73	13.56.12.0	11N	62W	4.1	24.73	0.57	-0.41	1.33
7	01/05/73	14.55.13.2	17N	62W	4.1	13.34	6.50	1.80	5.60
8	01/06/73	07.11.19.0	16N	68W	3.4	5.65	1.54	0.59	2.26
9	01/06/73	12.23.35.5	11N	87W	3.4	6.25	2.31	0.46	2.34
10	01/06/73	20.08.06.3	11N	86W	3.4	1.99	6.42	-2.96	6.44
11	01/07/73	06.12.58.9	12N	87W	4.1	43.67	1.77	-0.76	2.12
12	01/08/73	04.12.15.0	3N	84W	3.3	2.66	4.66	-7.43	6.06
13	01/08/73	09.36.57.6	13N	87W	3.7	14.29	-0.16	-0.26	0.94
14	01/08/73	09.41.27.8	15N	96W	3.5	6.01	1.83	2.00	3.35
15	01/08/73	10.05.19.8	13N	98W	4.7	93.75	1.56	0.86	1.70
16	01/10/73	03.55.34.4	17N	93W	3.9	14.35	1.69	-3.93	2.72
17	01/10/73	20.17.16.4	9N	85W	4.5	30.95	5.19	-0.71	4.01
18	01/12/73	03.09.58.4	21N	108W	3.4	8.36	2.59	2.81	4.87
19	01/14/73	14.26.18.9	13N	90W	4.2	22.51	1.14	0.21	3.05
20	01/14/73	16.34.43.5	14N	92W	3.9	5.83	6.57	-3.86	8.47
21	01/15/73	05.25.56.9	11N	87W	3.8	11.28	2.50	1.92	3.39
22	01/15/73	17.38.30.8	20N	107W	3.7	5.08	4.97	-0.13	5.59
23	01/16/73	01.52.27.1	8N	82W	3.5	5.79	4.61	1.65	4.53
24	01/16/73	02.26.38.8	12N	88W	3.5	6.90	1.41	1.23	1.79
25	01/16/73	18.48.23.5	16N	97W	3.8	7.29	2.10	-1.94	2.13
Average gain values							3.03	-0.29	3.75

TABLE 2

Results of Model II A&B and Model III A&B signal estimation techniques used in analysis of 25 randomly selected LASA recorded earthquakes in the Central America region. (Model IIA=conventional beamforming; Model IIB= conventional beamforming using weights proportional to RMS-noise levels; Model IIIA=beamforming using signal amplitude weights; Model IIIB=beamforming using amplitude & RMS noise weights.) For Model IIA the SNR values are listed, while for the other models the gains in SNR relative to Model IIA are listed. The average epicenter distance and azimuth are 38 and 152 deg respectively. (Christoffersson & Husebye, 1973)

No.	NORSAR EVENT PARAMETERS					PROCESSING GAIN			
	Date	Arr.Time h m s	Lat deg	Long deg	Mag m_b	IIA SNR	IIB dB	IIIA dB	IIIB dB
1	01/16/73	18.29.02.4	36N	138E	4.2	12.78	2.23	3.50	4.13
2	01/16/73	19.01.59.0	37N	137E	3.8	3.35	-0.10	1.60	1.88
3	01/16/73	20.23.03.9	35N	143E	4.2	8.86	1.75	2.80	3.28
4	01/17/73	04.33.29.0	33N	138E	4.1	5.76	1.17	2.09	2.46
5	01/18/73	03.10.10.0	14N	144E	4.3	3.99	-0.64	-0.27	0.45
6	01/18/73	05.54.43.0	22N	143E	3.9	5.01	1.04	3.62	3.49
7	01/19/73	14.13.06.4	33N	139E	4.3	13.51	1.61	2.12	2.67
8	01/20/73	06.16.35.8	34N	141E	4.7	31.37	0.92	1.80	2.00
9	01/20/73	10.15.15.5	34N	141E	4.6	30.21	1.00	1.41	1.57
10	01/20/73	10.25.36.0	35N	140E	5.0	44.49	1.33	1.88	2.35
11	01/20/73	13.18.33.0	34N	140E	4.6	33.83	0.63	1.21	1.49
12	01/20/73	16.41.47.2	35N	140E	4.9	30.01	0.62	2.42	2.71
13	01/20/73	17.07.06.1	34N	140E	4.8	50.85	2.00	2.58	2.85
14	01/21/73	08.27.53.1	36N	140E	4.9	27.56	1.83	3.34	3.85
15	01/21/73	15.47.43.8	32N	139E	4.1	6.83	1.68	2.33	3.08
16	01/21/73	23.33.41.7	40N	141E	4.0	5.06	0.01	-0.41	0.00
17	01/22/73	06.47.28.4	27N	141E	4.0	6.79	1.42	2.09	2.24
18	01/22/73	08.53.42.4	43N	146E	4.1	12.32	0.98	5.00	5.27
19	01/22/73	10.18.54.0	32N	140E	3.9	2.57	1.21	-1.52	1.49
20	01/23/73	03.18.06.9	34N	143E	3.7	3.58	0.53	2.80	3.29
21	01/23/73	18.43.20.9	44N	148E	4.1	11.73	1.18	6.17	6.05
22	01/24/73	06.03.05.2	35N	141E	4.0	4.93	0.42	0.50	1.10
23	01/25/73	07.07.46.4	26N	139E	4.1	4.25	0.66	3.62	4.38
24	01/25/73	11.43.31.0	31N	139E	4.1	4.24	0.20	2.71	2.66
25	01/26/73	22.13.12.9	44N	147E	4.4	16.87	0.19	1.28	1.77
Average gain values							0.95	2.19	2.66

TABLE 3

Results of Model II A&B and Model III A&B signal estimation techniques used in analysis of 25 randomly selected NORSAR earthquakes in the Japan region. Symbol explanation as in Table 2. For Model IIA the SNR values are listed, while for the other models the gains in SNR relative to Model IIA are listed. The average epicenter distance and azimuth are 77 and 43 deg respectively.

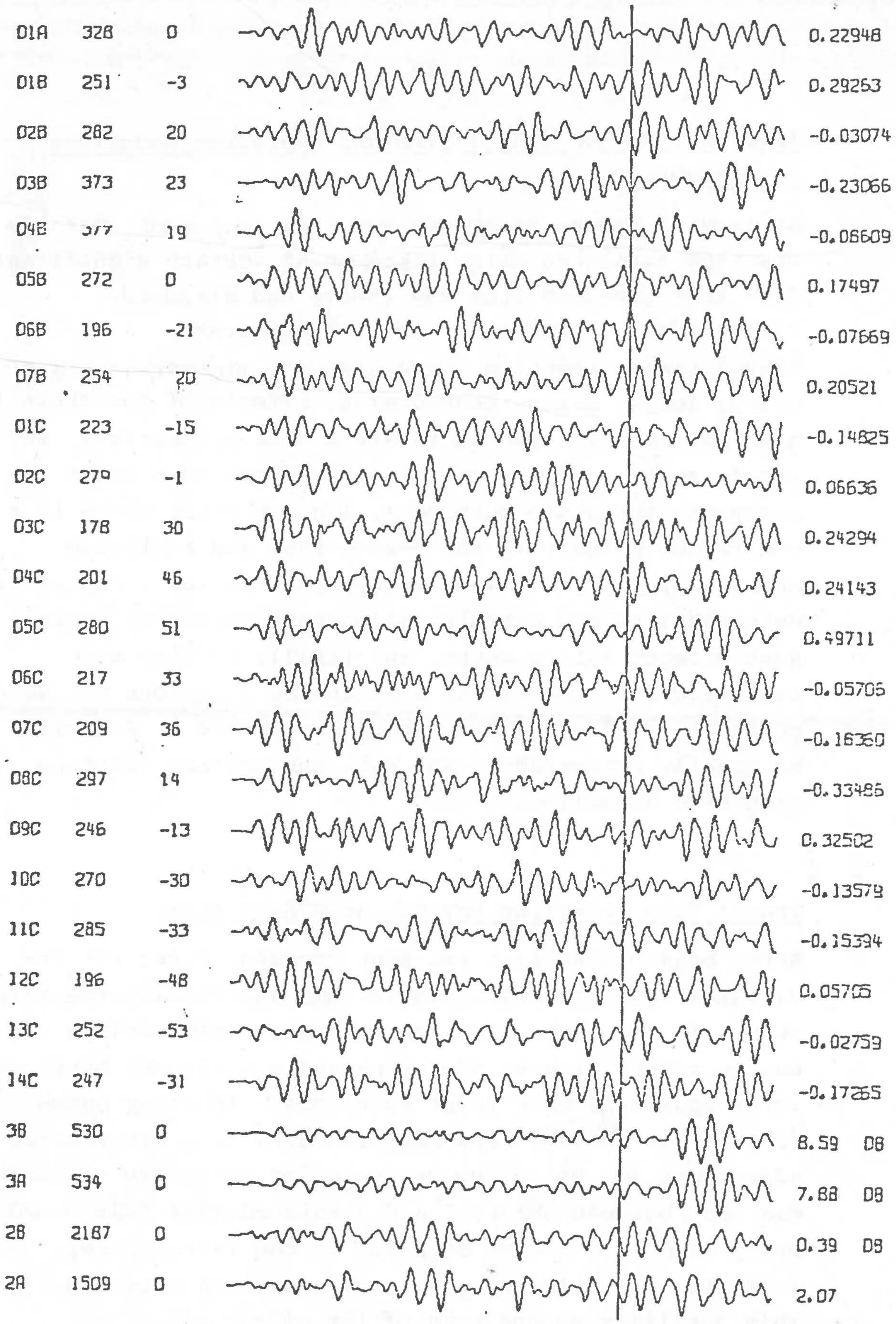

Fig. 7 Very weak Western Russia event recorded by NORSAR. Alternatively the signals may represent a side lobe detection of a local explosion in the Baltic Sea area. The columns to the left give subarray and array beam codes (the latter equivalent to II A&B, III A&B in Table 2), plot scaling factors and relative time shifts in dsec. The righthand column gives Model IIB subarray weights, SNR and relative gain in dB for the array beams. The signal portion marked with a line is 6.5 sec.

Intrinsic P-wave Travel Time and Amplitude Anomalies across NORSAR

As is well known, P-wave travel times and amplitudes as observed across an array like NORSAR deviate significantly from that expected from ray theory and standard earth models. Except for special subarray travel time correction files used for minimizing signal energy losses during beamforming, effects of the above types have been mostly ignored in array data processing. In recent months, considerable efforts have been spent on analyzing the above phenomena, i.e., whether there is a non-random pattern in the P-wave time and amplitude anomalies, the potential improvements in the array event detectability and classification performance by taking such effects into account, and finally to find more realistic earth models to explain the anomalous P-wave propagation effects. The results obtained so far will be briefly presented in the next subsections starting with time anomalies.

Travel Time Anomalies across the NORSAR Array

Array beamforming is a two-step process; first the individual subarray beams are formed, and finally the array beam. In the first case, the necessary time delays to ensure proper line-up of the sensor signals are based on least squares P-wave front solutions. In array beamforming the P-wave front solution used is a first order approximation, while the second order terms are the deviations between observed and predicted time delays (Δt_i) using so-called master events. In the latter case, anomalies amounting to ± 0.6 sec. have been observed. This justifies an analysis of the effect of ignoring second order terms in subarray beamforming.

The results obtained give that the subarray travel time anomalies exhibit a distinct regional pattern (see Fig.8) and that 95 per cent of the Δt_i observations have values less than 0.1 sec. The corresponding subarray beamforming losses are around 0.5-1.0 dB, with the exception of subarrays 05B and 07C (located on typical Oslo graben structures) where signal energy losses may amount to 2.0-3.0 dB.

Since the subarray time anomalies are non-random quantities, they should be predictable, so the following experiment was undertaken (Dahle et al, 1973). The travel time variation, T_i, across NORSAR is modeled as a function of two factors, namely, a trend effect, equivalent to the plane wavefront solution and a signal or wave scattering effect. The basic idea here is physically shown in Fig. 9, and the corresponding mathematical formulation is given in eq. (1).

$$T_i = T_o + U_x r_{ix} + U_y r_{iy} + S_i + n_i \qquad (1)$$

where r_{ix}, r_{iy} are position coordinates, U_x, U_y are trend components (slowness), S_i is scattering or Chernov (1960) effect, and n_i is the noise at the i-th site. The critical factor in this kind of analysis is the autocovariance functions typical for random media wave scattering models (Chernov 1960), and alternatively observed functional values.
To demonstrate the usefulness of the above approach, the arrival times at roughly half of the NORSAR sensors were predicted using observed travel times at the remaining SP instruments. Using actually observed travel time data as a reference base, most of the intrinsic travel time anomalies within a subarray are accounted for by inclusion of the signal effect term in eq. (1) as demonstrated in Fig. 10. Important, the minimum of the

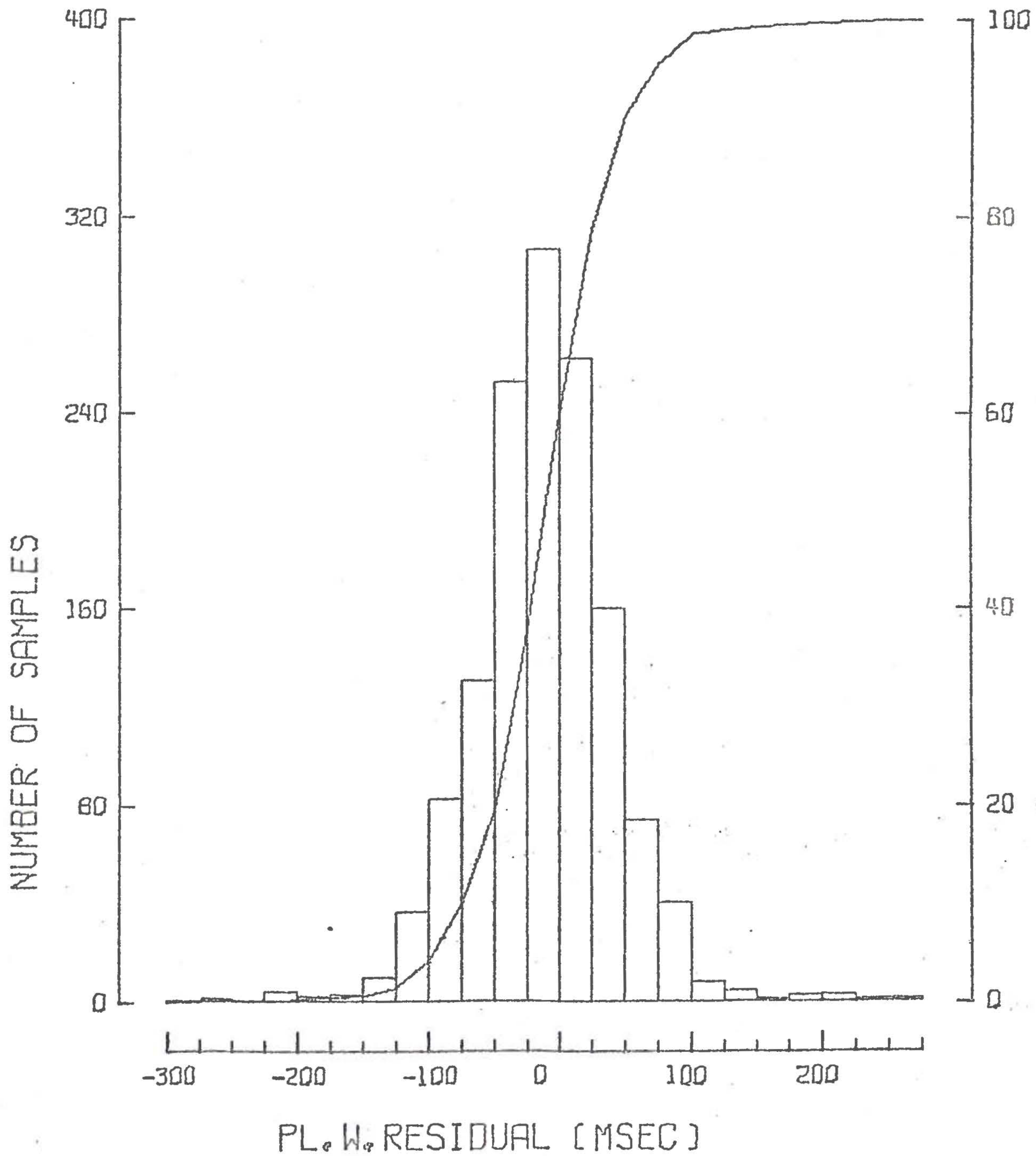

Fig. 8a Observed distribution of timing errors inside subarrays. Exact arrivals computed by iterative cross-correlation techniques on high quality signals.

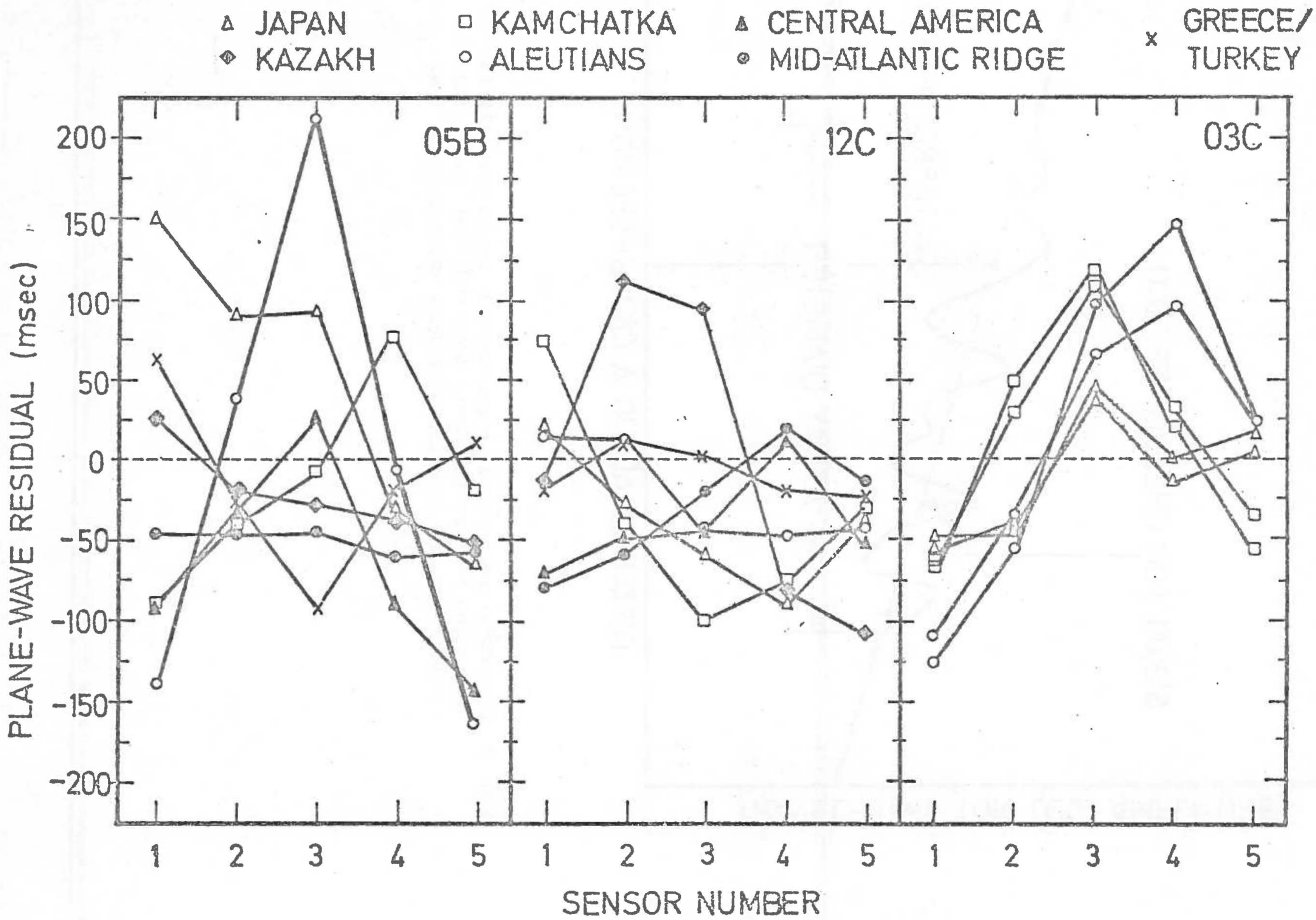

Fig. 8b Travel time anomaly patterns observed for different (symboled) events at subarrays 05B, 12C and 03C. Zero line corresponds to plane wave line-up. Reference is sensor 6 (center seismometer).

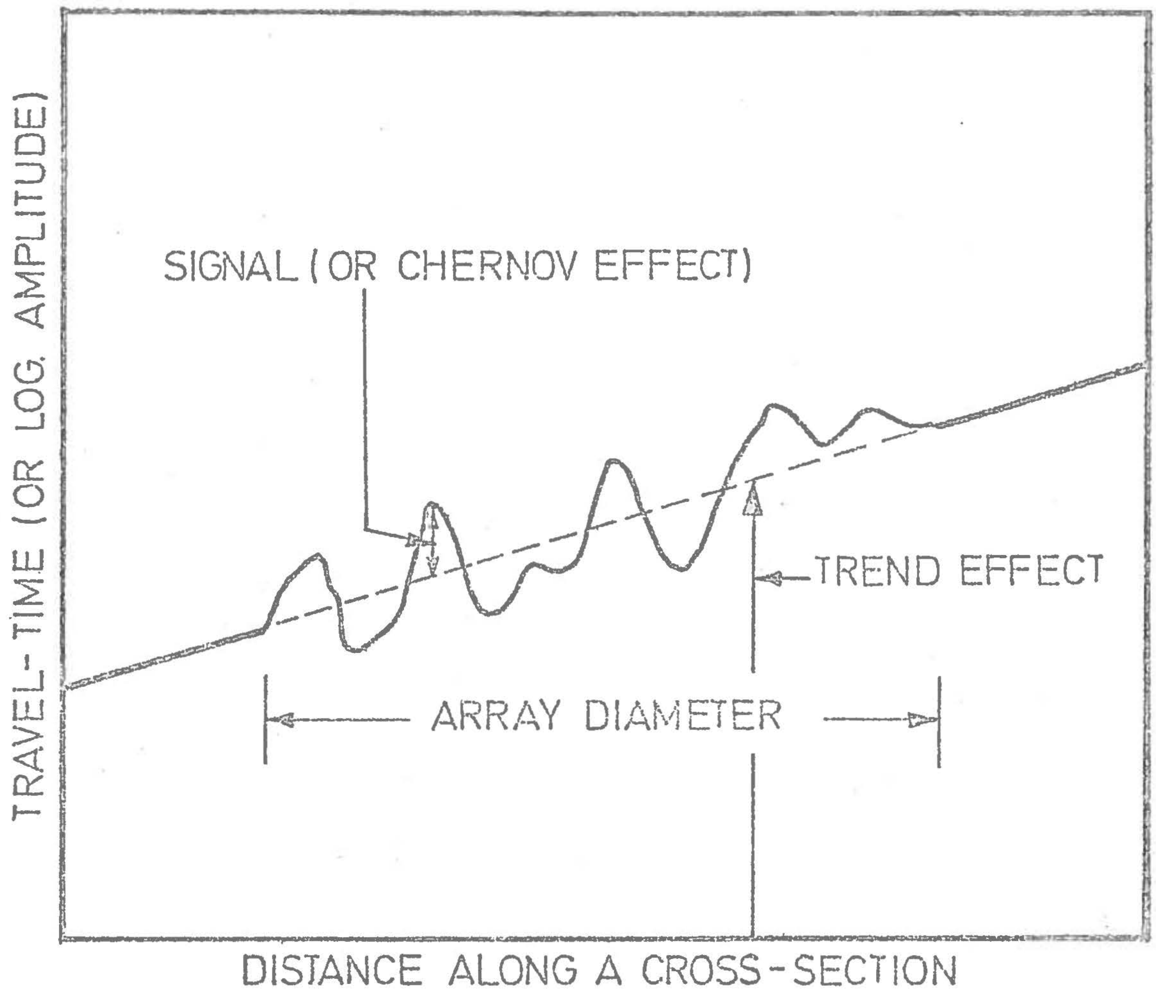

Fig. 9 Decomposition model of compressional seismic wavefield accounting for the intrinsic amplitude and travel time fluctuations observed across NORSAR seismometer sites.

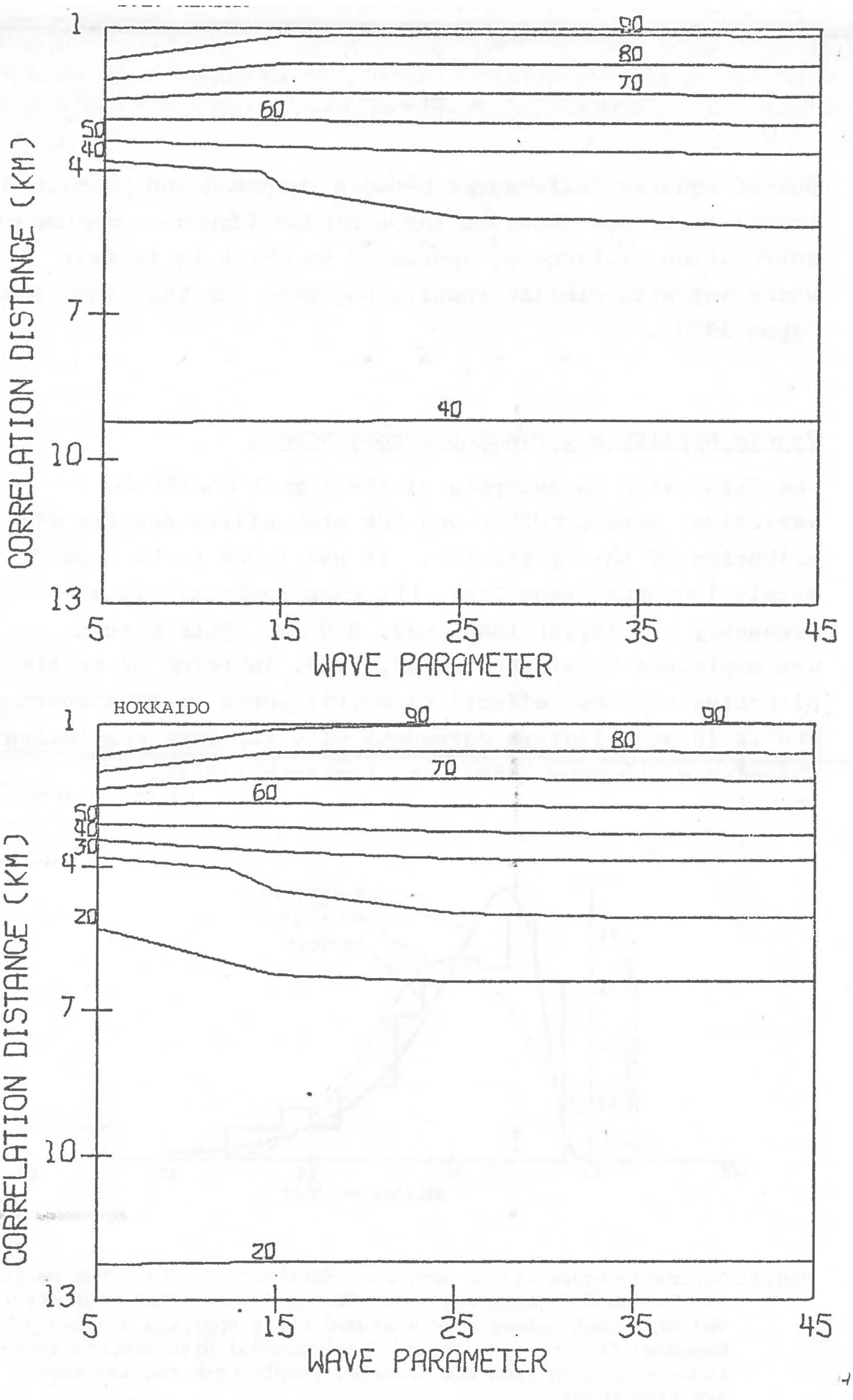

Fig. 10 Contour plot of sum of squared differences between observed and predicted travel time, including a scattering effect, measured in per cent relative to the same quantity neglecting scattering. Correlation distance and wave parameter as defined in Chernov (1960).

sum of squared differences between observed and predicted travel times was observed for a random (Chernov) medium with correlation distance of approx. 7 km which is in fair agreement with similar results obtained for LASA (Aki 1973, Capon 1973).

P-wave Amplitude Variation across NORSAR

The first step in analysis of the signal amplitude variations across NORSAR was the probability density distribution of this parameter. It was found to be approximately lognormal (see Fig. 11) when dominant signal frequency was larger than, say, 0.9 Hz. This result was explained by Ringdal et al, 1972, in terms of multiplicative response effects of multilayered earth structures and is in quantitative agreement with the wave scattering theories of Chernov (1960) and Tartarski(1961).

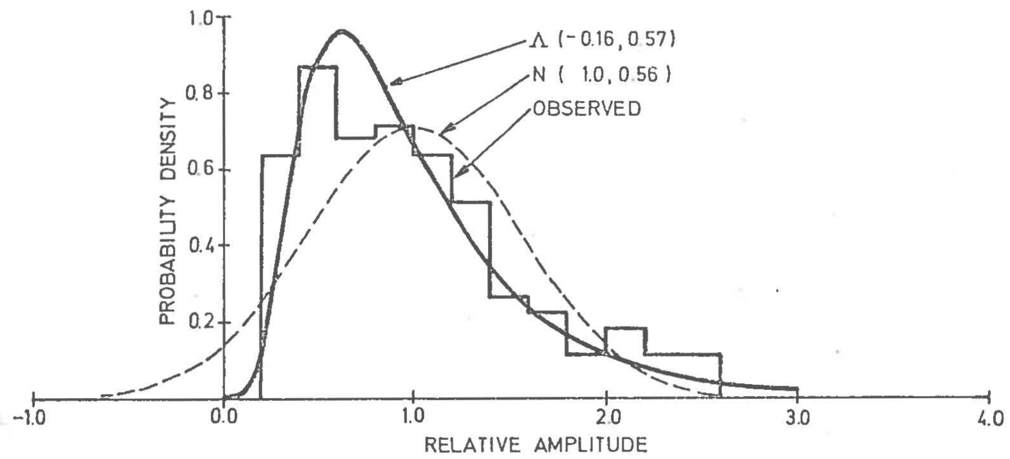

Fig. 11 Observed single sensor amplitude distribution for a Kamchatka earthquake occurring Jan 03 at 06.36.44 GMT (NORSAR bulletin). The amplitude values were measured after applying a 1.0-3.4 Hz bandpass filter. The normal and lognormal distribution functions estimated from the observed sample mean and variance are also shown.

Seemingly, the P-wave amplitude variation across NORSAR is random, but more detailed analysis of this problem reveals a distinct regional dependent pattern in the individual sensor or subarray beam amplitudes as demonstrated in Table 4.

Subarray Code	Subarray Ranking Scores							
	Greece-Turkey	Iran	Kam-chatka	Japan	Philip-pines	South Amer.	Fiji	Average Score
01A	3.8	9.3	8.3	12.2	10.7	6.6	4.4	7.9
01B	9.0	8.5	12.3	7.0	15.3	7.9	11.0	10.1
02B	9.8	5.1	1.3	7.1	18.5	13.9	4.4	8.6
03B	7.0	-	2.0	16.5	19.2	16.1	8.9	11.6
04B	8.5	12.6	13.6	-	16.9	12.9	12.9	12.9
05B	11.1	13.6	13.7	17.3	18.2	9.7	7.4	13.0
06B	10.6	4.7	-	12.0	11.7	4.9	21.6	10.9
07B	7.7	20.4	19.8	4.9	6.2	11.0	4.4	10.6
01C	15.7	17.9	5.4	1.1	3.8	-	18.9	10.4
02C	11.9	16.2	6.1	2.4	4.1	9.1	14.8	9.2
03C	19.3	16.7	5.3	8.1	3.0	19.2	1.1	10.4
04C	14.6	1.6	10.9	5.2	2.2	7.6	4.8	6.7
05C	15.9	10.2	9.7	2.6	7.6	5.9	17.4	9.9
06C	11.3	20.0	15.9	18.5	19.0	13.2	13.4	15.9
07C	7.7	14.9	19.3	13.0	12.8	17.4	20.5	15.1
08C	10.0	15.8	16.3	17.2	8.9	5.1	11.6	12.1
09C	10.7	7.6	3.3	13.0	21.1	14.0	16.0	12.2
10C	11.5	3.8	16.9	14.1	17.9	12.6	16.8	11.9
11C	13.9	8.0	19.4	13.8	8.0	15.3	14.1	13.2
12C	12.7	6.7	16.0	9.5	12.1	2.5	15.7	10.7
13C	14.9	3.2	5.7	16.3	2.4	10.6	2.1	7.9
14C	15.2	14.0	10.0	19.2	13.4	15.4	10.9	14.0
No. of Events	12	14	25	12	15	7	7	
Kendall Coeff. Concord.	0.31	0.86	0.92	0.84	0.92	0.54	0.98	
Chi-Square	77.1	240.8	460.9	201.6	290.5	76.1	129.5	

TABLE 4

Subarray ranking scores for different seismic regions. In all cases the results obtained are significant. For details on the non-parametric rank test, see Siegel (1956).

The prediction experiment of NORSAR observed travel time anomalies mentioned previously was repeated on amplitude data and some results are shown in Fig 12. It should be mentioned that the Chernov media parameters used in modeling the autocovariance functions and giving the best fit to the observational data are similar to the corresponding values obtained in the time anomaly experiment.

The optimal beamforming procedure (Christoffersson and Husebye, 1973) discussed in a previous section actually takes advantage of the skewness in the subarray amplitude distribution. However, this method is too complex for on-line data processing, but a viable alternative is using the simplified scheme of masking the weakest subarrays as demonstrated in Fig. 13. Presently, work is in progress to map the NORSAR subarray amplitude pattern in all seismic regions expressly for the purpose of 'zero-one' amplitude weighting during on-line array beamforming. The subarray amplitude pattern may also be instrumental in discriminating between very weak seismic signals and signal-shaped noise wavelets. Assuming that the above optimal beamforming procedure is used, the calculated weights should be matched against that expected for a given region. Preliminary results give that this method would be an important diagnostic tool in classifying weak signals - noise wavelets.

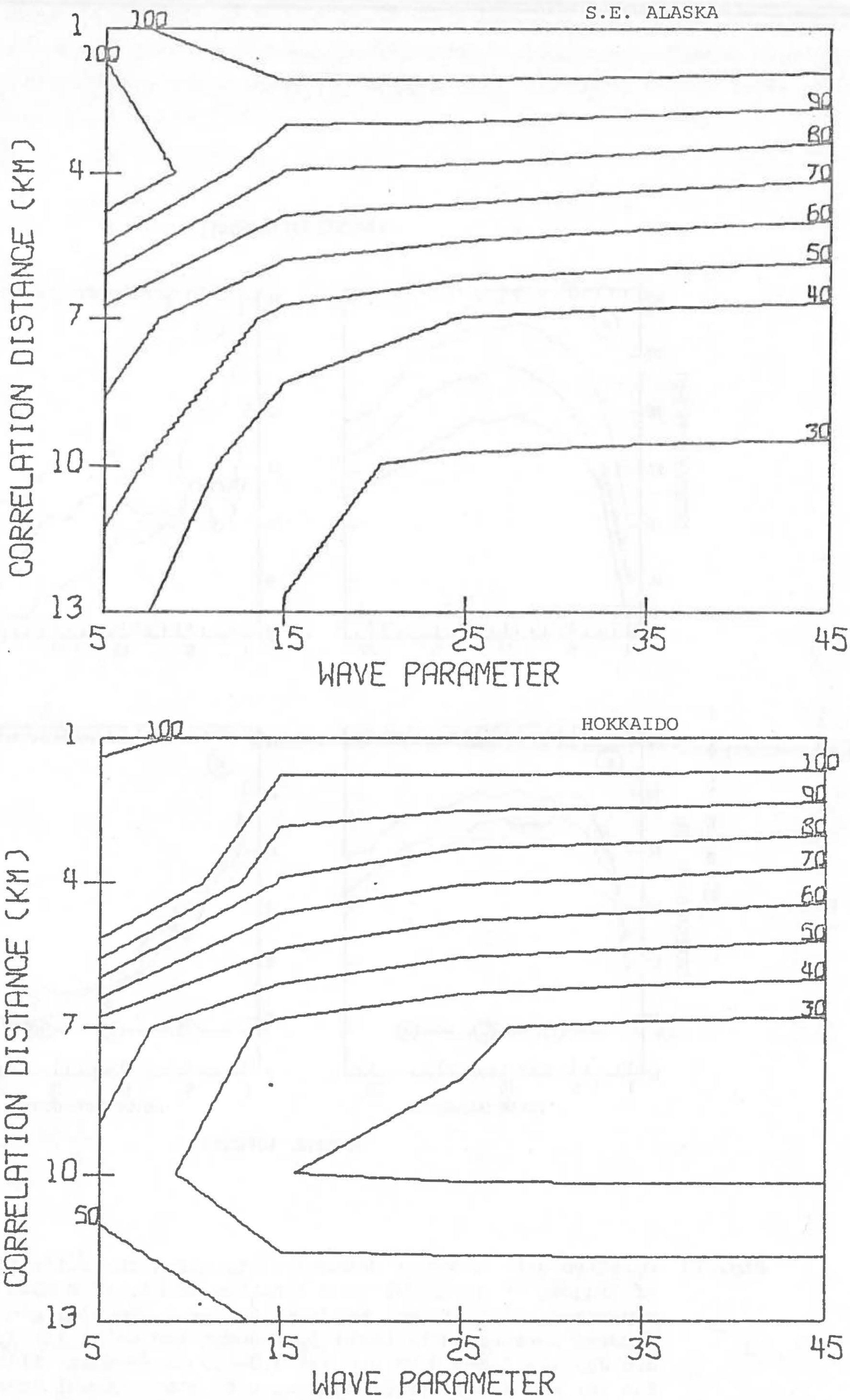

Fig. 12 Contour plot of sum of squared differences between observed and predicted log-amplitudes including a Chernov (scattering) effect, measured in per cent relative to sum of squared differences between observed and mean log-amplitude. Correlation distance and wave parameter as defined in Chernov (1960).

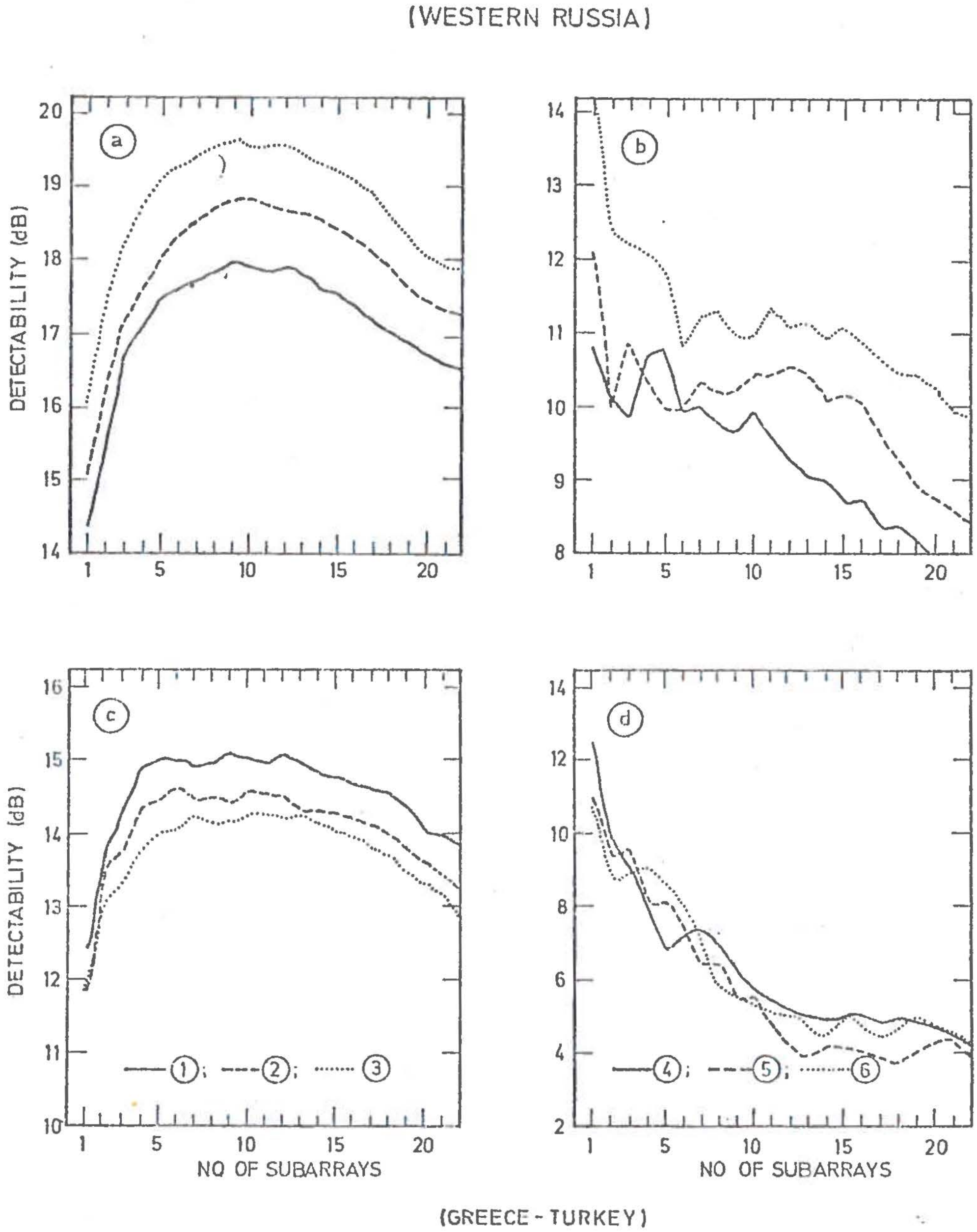

Fig. 13 Relative gain in event detectability using the definition of Ringdal et al (1972) as a function of no. of NORSAR subarrays for different bandpass filters. The (a) and (c) figures correspond to envelope beamforming using (1) 1.6-3.6 Hz, (2) 1.8-3.8 Hz and (3) 2.0-4.0 Hz bandpass filters. The (b) and (d) figures correspond to conventional beamforming using (4) 1.2-3.2 Hz, (5) 1.4-3.4 Hz, and (6) 1.6-3.6 Hz bandpass filters. The results were averaged over 12 and 11 events respectively for the Western Russia and Greece-Turkey regions. All the events analyzed were very weak, i.e., having SNR values between 2 and 4 and thus mostly reported by the envelope detector.

Seismic Wave Propagation in an Earth which is partly Modeled as a Random or Chernov Media

The typical features of the Chernov media are small perturbations amounting to a few percent of P and S velocities, density and the elastic parameters μ_x and λ. The corresponding wave scattering effect could be significant as shown by Haddon (1973) in a theoretical study of this problem. In case of seismic arrays this kind of data represents an excellent tool for observational evidence on seismic wave scattering hypothesis due to the large number of seismometers within a small area. For example, based on a thorough analysis of NORSAR recorded core precursor waves, Doornbos and Husebye (1972) concluded that the standard P-velocity model for the Earth's core probably was not quite correct. In more recent studies both Doornbos and Vlaar (1973) and Haddon (1973) attributed the above precursor waves to scattering effects in the deep mantle. Moreover, Aki (1972) and Capon (1973) have used array data for mapping the extent for which the crust and upper mantle beneath LASA could be considered a Chernov or random medium. In short, based on the evidence briefly discussed above, we feel confident that wave scattering effects could be used as a diagnostic tool in detecting and classifying weak seismic signals. We are planning to investigate most aspects of wave scattering effects, partly in cooperation with Dr. A. Christoffersson, Uppsala University, and Dr. R.A.W. Haddon, Sydney University.

Seismic Magnitude Investigations

The m_b magnitude parameter, measured on records of short period P-waves, is a convenient and widely used tool for ranking of earthquakes. More recently this parameter has become of critical importance in evaluating event detection and discrimination capabilities of various kinds of seismological stations and networks. The problem of a possible bias in the NORSAR estimation procedure of m_b magnitudes and also that used by the International Seismological Centre (ISC) in Edinburgh have been investigated by Husebye et al, 1973. The main results obtained are as follows (see also Table 5 and Fig. 14).

No. of Subarrays	dm(loss) (m_b-units)	dm(skew) (m_b-units)
3	0.28 ± 0.06	0.0 ± 0.01
6	0.23 ± 0.05	-0.01 ± 0.01
9	0.20 ± 0.04	-0.02 ± 0.01
12	0.16 ± 0.04	-0.03 ± 0.02
15	0.14 ± 0.04	-0.04 ± 0.02
18	0.11 ± 0.03	-0.05 ± 0.03
Operational 19≤No≤22	0.08 ± 0.03	-0.07 ± 0.03
Estimated skewness of subarray max. power distribution		1.26 ± 0.63
Estimated skewness for log-transformation of max. power		-0.10 ± 0.42
Correlation between signal loss and skewness effects		-0.40 corr. units
Sample size		222 events

TABLE 5

Estimated magnitude biases due to subarray power loss and skewed maximum power distribution, conditioned on the number of subarrays. The latter parameter represents a decreasing ordering of subarrays based on maximum power ranking.

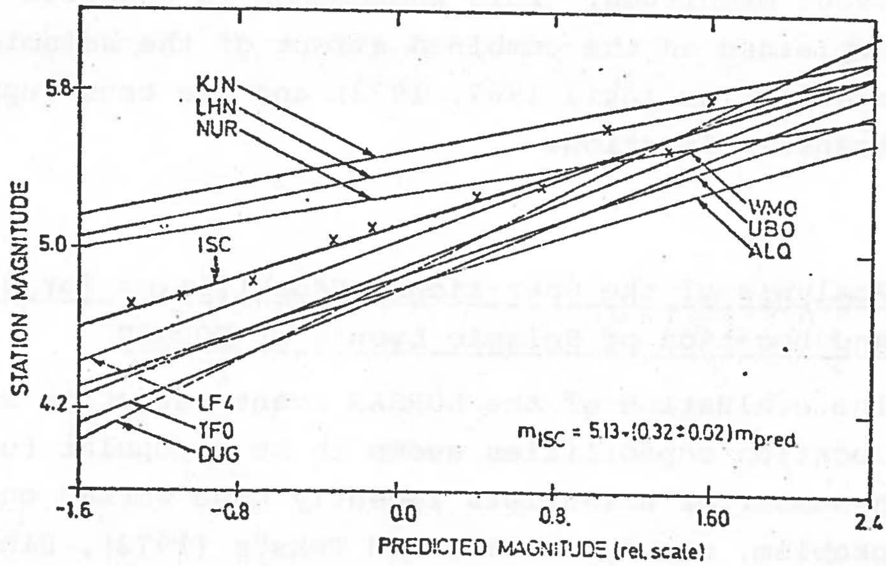

Fig.14 A comparison between event magnitudes as predicted from a multivariate analysis of ISC data for Japan, and that of the individual stations used in the analysis. The relationship between ISC reported magnitudes and predicted magnitude is also given. Dots are observed points for this line. This figure is based on 40 events occurring in the Japan region in 1968 and reported jointly by the 9 stations listed on the figure.

The signal energy losses observed during NORSAR P-wave beamforming do not in average affect its event magnitude estimates due to a skew, approximately lognormal, P-amplitude distribution across the array. A comparison between NORSAR-NOAA magnitude gave that the difference is largest at m_b~4.7 and then tapers off towards both small and large event magnitudes. A multivariate analysis of ISC data for Japan and the Aleutian Islands gave a consistent and linear relationship between the ISC event magnitude and that predicted from subsets of 5-9 stations in the m_b 4.0~6.0 magnitude range investigated. In this respect the ISC reported magnitudes are considered unbiased. We also found that the magnitude observations may be approximated by a normal distribution. In many cases the magnitude station correction term was not a constant but a function of event magnitude. This phenomenon is quantitatively explained as the combined effect of the seismic spectra scaling law (Aki, 1967, 1972) and the crust-upper mantle transfer function.

Analysis of the Operational Capabilities for Detection and Location of Seismic Events at NORSAR

The evaluation of the NORSAR event detection and event location capabilities seems to be a popular topic as a number of scientists recently have worked on this problem, namely, Shlien and Toksöz (1973), Ringdal and Whitelaw (1973) and Bungum and Husebye (1973). The differences in the results presented by the various authors are mainly due to data bases covering different time intervals. However, as Bungum and Husebye (1973) used both the most extensive and recent data, i.e., after improved time correction files, better bandpass filters, incoherent beamforming, etc., had been incorporated in the array's on-line system, we prefer to give a brief summary of their evaluation of NORSAR's event detection and location capabilities (see also Table 6 and Fig. 15 and 16).

Based on one year of data, Apr 1972-Mar 1973, the routine event detectability of the NORSAR array in Norway has been investigated in terms of 50% and 90% cumulative detectability thresholds which were derived from frequency-magnitude distributions. The best performance was observed for events in Central Asia and adjacent regions where the 90% cumulative detectability values are in the range 3.6-3.8 NORSAR m_b values. For teleseismic events the value is 3.8. For events with m_b

Region	Area	Events	Location Diff. (km)		Distance Diff. (km)		Azimuth Diff. (deg)	
			50%	90%	Average	St. Dev.	Average	St. Dev.
1	Aleutians-Alask.	157	135	330	24± 16	204± 12	0.32±0.06 *	0.79±0.04
2	West.North Am.	39	185	310	94± 15 *	95± 11	-0.69±0.20 *	1.26±0.14
3	Cent.Am.	61	430	830	-226± 36 *	278± 25	-2.28±0.32 *	2.53±0.23
4	Mid-At.Ridge	31	360	790	188±164	911±117	1.38±0.22 *	1.21±0.15
5	Med.-Middle East	120	220	650	14± 29	316± 20	-0.09±0.49	5.34±0.34
6	Iran-West.Russia	76	150	580	22± 35	303± 25	0.29±0.17	1.50±0.12
7	Cent. Asia	120	105	270	-38± 15 *	164± 11	0.04±0.07	0.72±0.05
8	South.east.Asia	42	130	340	134± 28 *	184± 20	0.13±0.11	0.70±0.08
9	Ryukuo-Philip.	166	195	610	-61± 27 *	343± 19	-0.71±0.10 *	1.30±0.07
10	Japan-Kamch.	255	95	260	-36± 8 *	125± 6	-0.28±0.06 *	0.94±0.04
11	New Guin.-Hebr.	87	380	1330	-152± 70 *	654± 50	0.46±0.33	3.09±0.23
12	Fiji-Kermadec	183	310	910	-216± 31 *	422± 22	-0.75±0.30 *	4.02±0.21
13	South Am.	33	390	680	11± 80	460± 57	1.47±0.35 *	2.01±0.25
14	Dist.range 30°-90°	1191	145	490	-30± 8 *	292± 6	-0.16±0.04 *	1.51±0.03
15	Dist.range 110°-180°	409	320	1020	-119± 25 *	504± 18	0.11±0.18	3.70±0.13

TABLE 6

Estimates of median and 90% location difference, and average and standard deviation of distance and azimuth difference between NOAA and NORSAR epicenter solutions, together with the standard errors in the latter estimates. An asterisk marks the regions where the distance or azimuth differences are significant on a 95% confidence level.

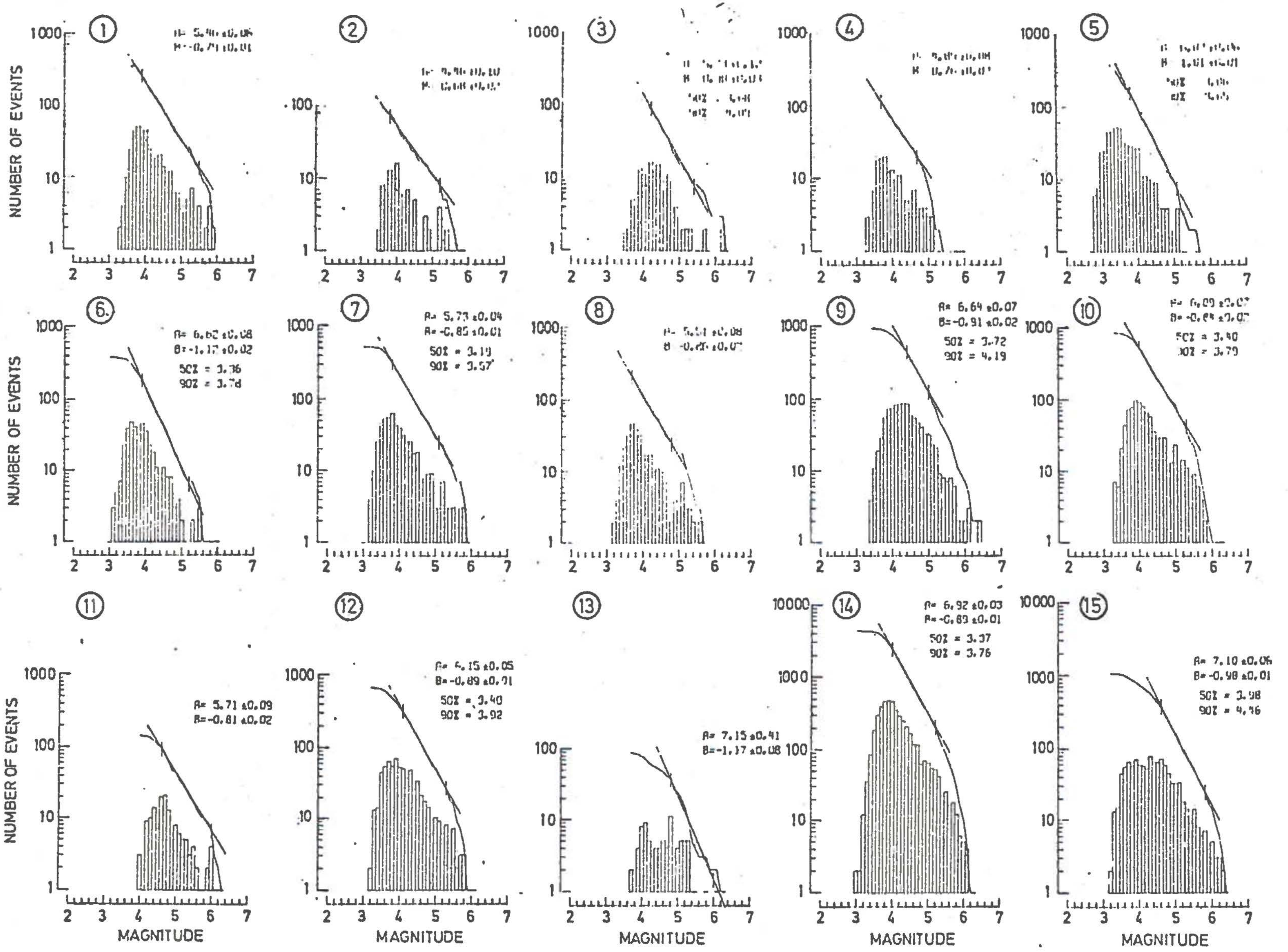

Fig. 15 Cumulative and incremental frequency-magnitude distributions for the 15 regions defined in Table 6. The straight lines are least squares fits through the data between the vertical bars.

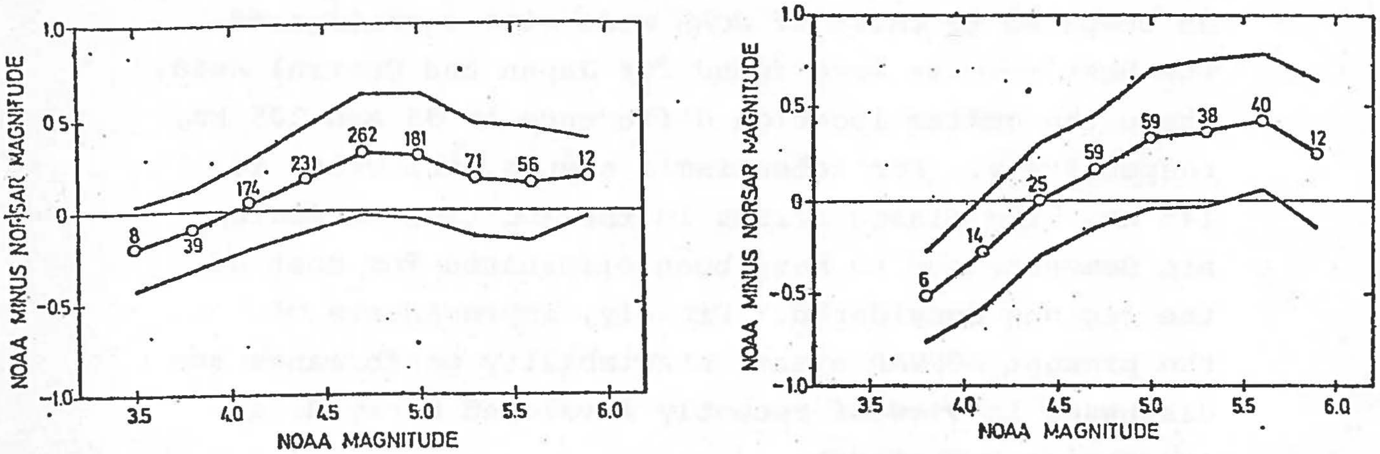

Fig. 16 Average difference between NOAA and NORSAR body wave magnitudes as a function of NOAA magnitude for all events with epicentral range $30^{o}-90^{o}$ and $110^{o}-180^{o}$ from NORSAR (regions 14 and 15 in Table 6). The averaging is done over bands of 0.3 magnitude units, the number at each data point gives the number of events, and the upper and lower bounds are the standard deviations.

above 4.0 NOAA reports the larger m_b value, while NORSAR reports the larger for events below m_b 4.0. The accuracy of NORSAR-estimated epicenter solutions as compared to those of NOAA were also investigated. The best results were found for Japan and Central Asia, where the median location difference is 95 and 105 km, respectively. For teleseismic events, the value is 145 km. The biased errors in the location estimates are demonstrated to have been eliminated for most of the regions considered. Finally, improvements of the present NORSAR event detectability performance are discussed in view of recently developed array data processing techniques.

Seismic Verification Research

So far our main research efforts have been aimed at improving the event detectability and location capability of the NORSAR array. Some investigations on the array's capability to discriminate between earthquakes and explosions have already been undertaken, although at the present stage only conventional classification criteria have been used in the analysis of relevant NORSAR data.

The main problem with the application of m_b : M_s criterion is to be able to detect the surface waves from small explosions and earthquakes. Three major signal enhancement techniques have been used in analysis of NORSAR surface wave data with good results, namely:

- Bandpass filtering centered at around 20 seconds, reducing the 6 second microseismic energy, which sometimes can be very strong in the winter.

- Beamforming, which works well if the noise is separated in azimuth from the signals. The signal similarity is always high.
- Matched filtering, which is a master event technique that takes advantage of the time invariance of recorded Rayleigh waves.

Fig. 17 shows the results from an m_b : M_s study where those techniques have been applied for signal enhancement. The lowest M_s reported is 2.5; however, at other times M_s 3.5 may not be detected due to variations in the background noise. Preliminary results from an m_b : M_s study at NORSAR have been published by Filson and Bungum (1972), and this work is continuing.

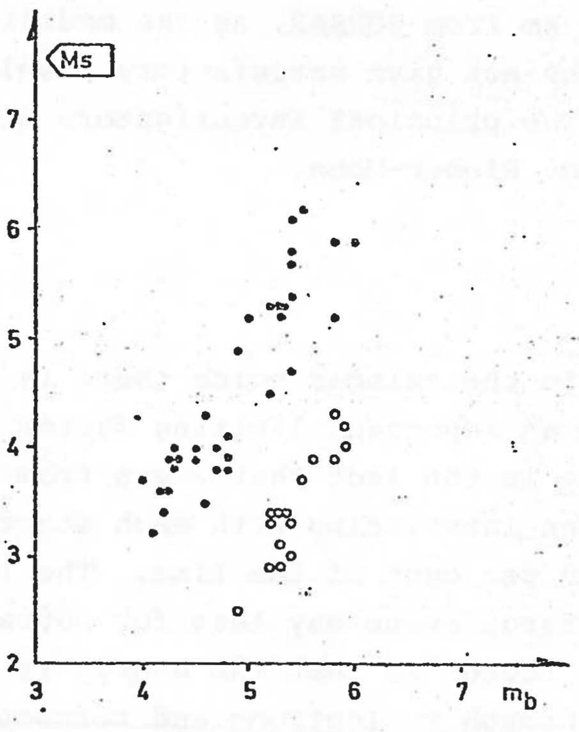

Fig.17 Body wave magnitude m_b versus surface wave magnitude M_s for events located by NORSAR in Central Asia during 1971 and 1972. Open circles indicate presumed nuclear explosions.

The m_b : M_s discrimination criterion works well for larger seismic events. However, the difficulty of detecting surface waves in the low magnitude range necessitates investigations of event classification capabilities based solely on P-waves. Modified versions of the complexity and third moment of frequency criteria have been tested on NORSAR recorded events - earthquakes located in Eurasia and North America. In the latter region event discrimination using P-waves only is relatively poor, and also the array's event detection capability is not specially good. On the other hand, preliminary results indicate that fairly good discrimination between earthquakes and presumed underground explosions is achievable for Eurasia. This statement is restricted to event distances larger than around 3,000 km from NORSAR, as the modified complexity criterion does not give satisfactory results for shorter distances. The principal investigators here are I. Noponen and D. Rieber-Mohn.

In addition to the seismic noise there is for long period waves an important limiting factor for the detectability in the fact that waves from two events are very often interfering with each other, maybe as much as 20 per cent of the time. The long period coda from a large event may last for hours, and another complicating factor is that the energy is often scattered in azimuth through reflections and refractions at continental margins. A study is now in progress, undertaken by H. Bungum and J. Capon (M.I.T. Lincoln Lab), where the energy distribution in the coda for a number of carefully selected events is studied at 20 and 40 second periods. The advantage of working at 40 second periods is that the multipathing there is much less severe and that the coda fall off more rapidly. On the other hand, some events may have energy only around 20 second periods. The results for NORSAR are comparable to those previously obtained for LASA by Capon (1972), although it seems that NORSAR data gives less variation in the way the coda around 40 second wave periods fall off with time.

3. MISCELLANEOUS

During the reporting period a number of scientists, whose names are listed below, have visited NORSAR Data Processing Center, Kjeller, for special research purposes.

D. Doornbos Utrecht University The Netherlands	1 Jul - 11 Sept 1972 8 Dec - 22 Dec 1972 12 Jun - 27 Aug 1973
I. Noponen Seismological Institute Helsinki, Finland	1 Jul - 19 Dec 1972 16 Feb - 25 Feb 1973 10 Jun - 20 Jun 1973
R.M. Sheppard M.I.T. Lincoln Lab Cambridge, Mass., U.S.A.	18 Sep - 27 Oct 1972
H. Ohlendorf Institut für Geophysik Kiel, West Germany	8 Sep 1972
H. Korhonen Oulu University Finland	16 Nov - 15 Dec 1972
S. Pirhonen Seismological Institute Helsinki, Finland	6 Nov - 20 Dec 1972
Professor Tsujiura, Tokyo, Japan	20 Dec 1972
M.L. Mäki Seismological Institute Helsinki, Finland	12 Dec - 15 Dec 1972
A. Christoffersson Statistical Institute Uppsala, Sweden	12 Feb - 23 Feb 1973 13 Jun - 7 Jul 1973
E. Hjortenberg Geodetic Institute Copenhagen, Denmark	21 Feb - 14 Mar 1973
J. Capon M.I.T. Lincoln Lab Cambridge, Mass., U.S.A.	16 May - 4 Jun 1973
J. Vermeulen Utrecht University The Netherlands	18 Jun - 14 Sep 1973

NORSAR scientists participated in the following seminars, congresses and meetings in the period 1 July 1972 - 30 June 1973.

13th General Assembly of the European Seismological Commission in Brasov, Romania, 30 August - 5 September 1972. Participants: K.A. Berteussen, H. Bungum, H. Gjøystdal, and E.S. Husebye. Altogether the NTNF/NORSAR group gave seven talks, which are listed below:

- K.A. Berteussen and E.S. Husebye, Seismicity in terms of event detection thresholds
- H. Bungum, Event detection and location capabilities at NORSAR
- H. Bungum, Array stations as a tool for microseismic research
- H. Gjøystdal, E.S. Husebye and D. Rieber-Mohn, One-array and two-array location capabilities
- H. Gjøystdal and E.S. Husebye, Noise suppression problems
- E.S. Husebye and F. Ringdal, Multiarray processing problems
- F. Ringdal and E.S. Husebye, Event detection problems using a partially coherent array.

Norwegian Geophysical Society in Nesbyen, Norway, 2-5 October. Participants: H. Bungum and E.S. Husebye. One talk was given.

American Geophysical Union, 54th Annual meeting, Washington, D.C., April 1973. Participant: K.A. Berteussen. One talk, "Bias analysis of NORSAR and ISC reported P-wave magnitudes", by K.A. Berteussen, A. Dahle and E.S. Husebye was presented.

Fourth Nordic Seminar on Detection Seismology, Helsinki, Finland, 12-14 June. Participants: H. Bungum, A. Dahle, H. Gjøystdal, E.S. Husebye, N. Marås, D. Rieber-Mohn, O. Steinert. The NTNF/NORSAR group gave ten talks, which are listed below:

- E.S. Husebye, A. Dahle and K.A. Berteussen, Analysis of possible non-random errors in NORSAR event magnitude estimates
- D. Rieber-Mohn and I. Noponen, New short period discrimination criteria used on NORSAR events
- H. Bungum and F. Ringdal, Diurnal variation of seismic noise and its effect on detectability
- O. Steinert, E.S. Husebye and H. Gjøystdal, Noise stability and false alarm rate at NORSAR
- E.S. Husebye, F. Ringdal and J. Fyen, On-line event detection using a global seismological network
- H. Gjøystdal, Array detection and location capabilities for events in Central Asia
- A. Dahle, P-signal variations within NORSAR subarrays
- F. Ringdal, E.S. Husebye and A. Dahle, Event detection problems using a partially coherent seismic array
- A. Christoffersson and E.S. Husebye, Amplitude weighting for optimal gain in SNR during array beamforming
- O. Steinert, Stability of array performance

Norwegian Geotravers Meeting, Bergen, Norway, 4-5 May 1973. Participants: K.A. Berteussen, H. Bungum, A. Dahle, H. Gjøystdal, E.S. Husebye. Three talks were given.

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