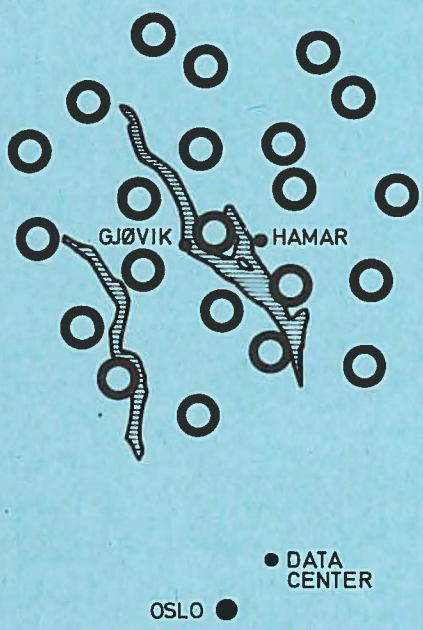23 34

Royal Norwegian Council for Scientific and Industrial Research

NORSAR RESEARCH AND
DEVELOPMENT
1 July 1970 - 30 June 1971

prepared by
Eystein S. Husebye
(Chief Seismologist)

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CONTENT

SUMMARY

This report covers the period 1 July 1970 - 30 June 1971 which is characterized by system developments and software debugging efforts, establishing of organizational procedures required for the routine NORSAR operation and research aimed at system improvements and array performance evaluation. The most important single event in the reporting period was that the NORSAR array became operational in March 1971.

In chapter II of the report which summarizes the joint efforts of the NTNF/NORSAR staff, development work and related topics are outlined. Emphasis is on the NORSAR software systems which main tasks are data recording on tape, event detection and routine analysis of recorded events. Research work completed and in progress is discussed in chapter III. The first 5 sections deal with typical NORSAR system subjects like time delay measurements, beam steering corrections and error location vectors, and filter setting for additional noise suppression during beamforming. The problem of defining a best-in-average event detection processor using real and simulated data, is discussed in section III, 6. Coherence and spectral analysis (section III, 7) are aimed on system improvements and also constitute a basis for array performance evaluation. A review of an investigation of the mantle structure is given in section III, 8. Appendix I and II give a preliminary set-up of the weekly bulletin and abstract of papers published in the reporting period.

I   INTRODUCTION

This report covers the interval 1 July 1970 to 30 June 1971, a period which is characterized by the successful completion of field installations and software developments. The array became operational in March 1971, thus marking a new period in the NORSAR project.

Even after routine recordings and processing of NORSAR recorded signals started, large efforts were still invested in software developments as a sizeable group from IBM (Federal System Division) remained at NDPC, Kjeller. That contract is to terminate Aug 31, 1971.

The transformation of the NORSAR array into an operational seis-
mological observatory has profoundly affected the research
and system development work. As of today we are actually
running the NORSAR array continuously, and this task in itself
represents an additional workload on the research group. The
system developments during the reporting period have been
within the frame of the designed software system and naturally,
in close cooperation with the IBM group. Moreover, the first
and significant steps for analysis of long periodic data have
been undertaken.

The research topics investigated or in progress, are oriented
towards system operation and evaluation. The above subjects
comprise travel time and wave velocity measurements and
feed-back of this information into the system. Spectral
analysis are used for estimating signal energy losses during
routine processing, and gains in SNR as a function of different
processing schemes. Several types of SNR measurements in the
time domain have been performed and the VESPA analysing
technique has been adapted to the NORSAR system. Most of
the above analysis is tied to Plan D or interim NORSAR data
which is based on recordings at a 10 Hz sampling rate from
18 seismometers in different subarrays. Also, long period
waves from a few events in Asia have been analysed on an
experimental basis.

II   SYSTEM DEVELOPMENTS

Originally NORSAR was planned to be operational in
1969, then in summer 1970 and finally in winter 1970/71.
As mentioned above, the array was completed in March 1971
when near continuous recording and routine processing of

incoming signals started. The above occasion represents
a major event for those involved in the development of the
NORSAR array, and naturally had a profound impact on the
NDPC staff. What we have in mind here is that actual
operation of a large and complex processing system which
NORSAR represents, requires establishing a large number of
daily working routines and procedures. (This involves first
of all the reporting and eliminating bugs in the software
system.) However, the real challenge is that the experience
gained by operating NORSAR should put us in a favorable
position for developing more fundamental system improvements.

During the reporting period our system development work
has taken place within the frame of the IBM system design
and in close cooperation with the IBM personnel attached
to NDPC. The most interesting parts of this work will be
discussed in some detail, and it is considered proper to
start with the data processing systems.

1. The Detection and Event Processor

The detection algorithm implemented at NORSAR is very
simple, and is essentially restricted to an SNR test on
the array or subarray beam level. On the other hand, as
more than 300 array beams are formed on-line, the detection
processor is rather complex. We have here participated
especially in making the programs more efficient and in the
optimum choise of detection algorithm and filter parameters.
These topics will be dealt with in greater detail in later
sections.

The performance of the Event Processor (EP) which handles
the routine analysis of events reported by the Detection

Processor (DP), is strongly dependent on typical seismic
parameters like steering delay corrections, observed
wavefront velocities, dominant signal periods, signal
coherency across the array etc. Henceforth, we became
very early involved in the parameterization of EP which is
so far mainly based on analysis of Plan D data. With the
completion of the field installations signals recorded by
the whole array became available so work has already started
on updating the above parameter set, emphasizing time delays
and velocity vector corrections.

The Event Processor is primarily designed for automated
analysis of events detected by the array. The quality of
the EP results here is somewhat dependent on SNR and the
complexity of the signals at hand, so a daily, visual
inspection and supervision by an analyst of the event
analysis is required. Special working routines have been
established, and an event summary is edited daily for NDPC
staff use. Moreover, we are planning to circulate in Aug/
Sep a weekly NORSAR bulletin to interested institutions
and seismologists. A likely bulletin setup is given in
Appendix I.

2. LP - Analysis System

Texas Instrument (TI) has developed a sophisticated software
package for analysis of long period (LP) waves recorded at
large arrays like LASA, ALPA and NORSAR. E. Husebye and
F. Ringdal spent approximately 4 weeks at SAAC, Alexandria
in early spring this year for training in usage and preparing
implementation of the off-line version of the TI package at
NDPC. The above task was successfully completed in June,
and includes creation of special NORSAR Low Rate Tapes
required for data input to the LP programs.

Visual inspection of analog records prior to analysis is considered essential for several reasons. First of all, the scientist wants to be sure that the type of signals under investigation, is actually recorded by the array, and second, that faulty sensors do not impair the final results. This especially holds for LP instruments which are less stable than the SP seismometers. A possible solution to the above problem is the usage of Develocorders which is limited to the recording of 8 sensor channels per instrument unit. However, it is considered a better idea to use the Experimented Operation Console (EOC) for display of recorded signals. We are presently working on a scheme which would permit off-line display of any sensor trace stored on high or low rate data tapes.

3. High Frequency Analog Filter

For short periodic signals recorded at NORSAR a sampling rate of 20 Hz is used, while the analog, anti-aliasing filters installed in the SLEM units have the 3 dB cut-off points at 4.8 Hz. With the above recording setup we may possibly lose significant source information as NORSAR P-waves are characterized by relatively much high-frequency signal energy. As part of an investigation of this problem Mr. Handsaker/ESD proposed temporary installation at one subarray of different analog filters having the 3 dB cut-off point at 8 Hz. Filters of the latter type were implemented at subarrays 03C in the end of May, 71 and will be transferred in Aug to subarray 08C. Preliminary analysis indicate the existence of a significant amount of high-frequency signal energy, i.e. above 4 Hz, but the spectral difference between 03C and the other subarrays is small in the whole frequency range. Moreover, high frequency signal energy is easily lost during beamforming, even on the single subarray level.

4. Seminar on Seismology and Seismic Arrays

A formal opening ceremony of the NORSAR array is scheduled
for November 1971, and will be combined with a seminar on
Seismology and Seismic Arrays. In the latter case, invitations
have been sent to individual seismologists and research
institutions in Europe and North America.

III RESEARCH TOPICS

The research activities in the reporting period have been
focused on NORSAR software system parameterization and
array evaluation. Most of the events used in analysis, were
recorded during the Plan D interim operation of the array.
At that time only 18 SP sensors from different subarrays
were operative. As mentioned previously, the whole array
became operational in Feb 71, but only a small number of
events from the latter period has been analysed so far.
It should be noted that computer program modifications due
to a larger data base and a new high rate tape format are
somewhat time consuming.

1. Errors in Time Delay Measurements

Simple delay and sum of sensors in a seismic array is an
effective method for noise suppression. However, unless
precise steering delays are available, much of the signal
energy is lost during the beamforming process too. We have
investigated possible error sources in time delay measure-

ments, which in case of NORSAR is based on an iterative
cross-correlation procedure. Parameters perturbed are
correlation window length and positioning, signal
frequency content and signal-to-noise ratio (SNR). The
results obtained (Bungum & Husebye, 1971) indicate that
relatively low frequency waves and using the very first part
of the P-signals give the most reliable and stable time
delay values. High frequency band pass filtering improves
SNR, but signal correlation and the precision in beam
steering correction decrease. Significant loss of high
frequency energy during beamforming seems to be unavoid-
able, and this result has been confirmed by frequency domain
analysis as will be demonstrated in a later section.

2. Beam_Steering_Delay_Corrections_and_Mislocation_Vectors

To avoid excessive signal losses during the NORSAR.event
detection processing, special steering delay corrections
must be an integrated part of the on-line system. Another
aspect is the mislocation vectors which represent the
difference between NORSAR's event locations and those
reported by NOAA. The latter information is required
for removing biased errors in estimated azimuth and
epicentral distance based on NORSAR data alone.

The basic data needed for calculating steering delay
corrections and mislocation vectors are relative P-arrival
times across the array for a large number of properly
distributed events and the corresponding focal parameters,
say, as reported by NOAA. In the former case, the measure-
ments are computerized and an iterative cross-correlation
procedure is used to ensure proper signal alignment, (Bungum

& Husebye, 1971). NORSAR event location is based on observed
P-wave velocity across the array and direction of approach
of the wavefront. These parameters are easily obtained by a
least squares fitting of a plane wavefront to the observed
arrival time.

The steering delay correction parameters are defined as the
difference between observed and calculated arrival times
across NORSAR. The reference model used, is that corresponding
to Herrin's 1968 tables. Altogether, 172 events have been
used in the above analysis, but the steering delay corrections
and mislocation vectors actually implemented in the processing
system are based on only 53 events. The reason for this is
primarily that a large number of the "excellent" events is
concentrated in a few very active seismic regions. It
should be noted that presently 331 NORSAR beams are deployed.
This means that only exceptionally will the actual beam locations
match those of the events used in this analysis. The re-
quired interpolation procedure is linear and performed in a
plane fitted through a set of three event correction points.
For convenience these calculations are tied to inverse
velocity coordinates instead of the conventionally used
latitude and longitude.

The Plan D sets of beam steering corrections and mislocation
vectors presently implemented in the Event Processor are not
quite satisfactory due to the small number of events used,
and the fact that data from only 18 subarrays were available.
Accordingly, we plan to update the DP and EP correction files
at the end of this year. This will include a complete new
set of time delays in DP and a reconsideration of the present
beam deployment. Finally, we should like to remark that the
above work was and is a joint undertaking by IBM/SAAC and
NDPC staff.

3. Earth Structure and NORSAR Travel Time Anomalies

From a seismological point of view the most interesting
aspects of travel time anomalies are the corresponding
structural inhomogeneities. The inversion of time delays
in terms of velocity anomalies is difficult as there is no
unique solution to this problem. In case of NORSAR we would
intuitively expect that this effect to some extent is re-
lated to the crustal structure in the array site area. In
view of the ambiguities involved in interpretation of time
delays, we decided on the following approach. If the delays
are at least partly of local origin, then some trend of
regularity in the observed data should exist. According to
Larner (1969) a good idea might be to project the individual
subarray time anomalies into a trend plane and choosing the
proper trend direction in a least squares sense, i.e., the
azimuth where the sum of squared differences between
consecutive observation points is the smallest possible.
This type of analysis has been performed on Plan D time
delay and signal power observations. Typical results obtained
here, based on average values of around 130 events in the
teleseismic distance range, are displayed in Fig 1 and 2.
Using more regionalized sample populations, a few exceptional
cases gave evidence for a secondary trend direction of
azimuth around 50 deg., or roughly normal to the former. The
dominating trend direction is parallel to the Oslo Graben
and the continental margin. The above results indicate two-
dimentional structures beneath the array, as also proposed
by Kanestrøm & Haugland (1971).

4. Location_Error_Vectors

Travel time anomalies across NORSAR may be taken as a
function of random and biased observational errors. The
latter explains the systematic, regional dependent mis-
locations of recorded events, which are removed in EP by
introducing the previous discussed inverse velocity
corrections. The problem, which we have tried to answer in
a quantitative way, is whether the bias in the time delays
across the array is due to structural anomalis in the siting
area or dominated by source effects. The procedure used was
to simulate event recording and location in the following way
The model for relative P-arrival time at the individual sub-
arrays is:

$$T_i = T_i(H) + CT_i(T) + T_i(R) \tag{1}$$

where T_i = arrival time at the subarray, $T_i(H)$ = arrival
time predicted from Herrin's tables, $T_i(T)$ = two-dimentional
trend correction as given in Fig 1, C = constant equal to
1.2, and $T_i(R)$ = random generated observational error assuming
a variance of 0.1 sec. A comparison of location errors based
on actually recorded events at NORSAR and simulated ones
through eq (1) exhibit a reasonable agreement as seen from
Fig 3 and 4. We may here conclude that the observed time
anomalies across the array are to a large extent, say 50%,
caused by structural inhomogeneities beneath the array.

5. Time_Domain_Filter_Analysis

It is well known that the spectral distribution of seismic
signals varies considerably from one region to another.
Also, the spectral content of the noise exhibit large time
variation as the array is located fairly close to the North

Atlantic ocean. This means that the signal-to-noise ratio (SNR), which is essentially the parameter used for event detection, is subject to both time and geographic space dependency. The main objective of this analysis was to find a physically realizable filter that could be applied to all incoming signals in real time. The performance of such a filter, with the requirement that it should give the best-in-average SNR for a large number of randomly selected events, should roughly match that of time-varying and regionalized filters.

The filters used were of two kinds, namely recursive Butterworth bandpass filters and sloping Lagrange differention filters. The former has the advantage of physical realizability and computational efficiency, while the latter may be used for flattening or whitening of the noise. Typical response curves of the above filters, are shown in Fig 5 and 6. Our results here show that the Lagrange filters alone do not suppress the noise efficiently enough, while a combination of Lagrange and Butterworth filter exhibit the best-in-average performance. However, if a few exceptional events are neglected, a third order Butterworth filter with a center frequency around 2.2 Hz and a bandwith of 2 Hz gives the largest SNR enhancements. Typical results of the above analysis are displayed in Fig 7 and 8. A joint consideration of performance and computational efficiency makes the above Butterworth filter the natural choise for use in NORSAR detection and event processing.

6. Event_Detection_Algoritm

The event detection procedure in the NORSAR system consists essentially of a near continuous signal-to-noise ratio (SNR) test on a large number of real time array beams which have been bandpass filtered for additional noise suppression. The problems of beam steering time corrections and the selection

of the best-in-average bandpass filter has been discussed in previous sections.

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

$$STA(t) = \sum_{i=t-IW+1}^{t} \left| S(i) \right| \qquad (2)$$

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

$$LTA~(t') = (1-2^{-\eta})~.~LTA~(t'-IW)+2^{-\delta}~.~STA(t'-IW) \qquad (3)$$

where t^1 = LTA sampling time, and the parameters (η, σ) = (5,1) outside detection state (no signal present) and (η, σ) = (4,0) in detection state. The STA is updated more frequently than LTA which means that t may differ from t^1. The ratio STA/LTA is computed every time STA is updated. When this ratio exceeds the detection threshold (THR) a certain number Q of consecutive times, a detection is declared (see Fig 9).

The analysis of the NORSAR detection process has mainly been focused on the problem of determining the best combination of STA window length (IW), STA updating interval (IUP), and the event declaration parameter Q.

We have used both NORSAR recordings and simulated data in the analysis. In the latter case Gaussian noise (before detection processing filtering) was generated by a random

number routine, while P-waves were taken as sinus modulated
Fourier signals. The advantage of this approach is large
data samples and that signal occurence is always known. The
method used, was to determine the receiving operating
characteristics (ROC) for each detector or parameter
combination, and then decide which one is the best. The ROC
is a plot of the probability of detection of signal, relative
to the corresponding probability of false alarm. The detector
that for a specified false alarm rate had the largest probability
of detecting a signal, was chosen as the best one. ROC-curves
for some of the simulated detector parameters are displayed
in Fig 10 . The set IW = 1.2, IUP = 0.4 - 0.6 and Q = 1
gave the best parameter combinations.

To ensure validness of the above results the detector was
tested using real data. In this case we made relative
intensive studies of individual events, concentrating on
the STA/LTA ratio as a function of time (see Fig 11). This
type of information is useful for calculating the change
in the STA/LTA threshold from one parameter combination to
another using the constraint that the detection capability
remained constant.

An important problem in event detection is the probability
of false alarms as a function of the STA/LTA ratio. In case
of NORSAR the number of event detection tests performed
during a 24 hour interval amounts to ca. $50 \cdot 10^6$. Results
obtained here, based on real data, are presented in Fig 12.
The resolution of the calculated cumulative distributions
of STA/LTA is at best 0.1%, roughly equivalent to three times
the standard deviations (SD) in a Gaussian population. To
avoid system saturation a false alarm rate around 5 times the
SD parameter must be considered, but no experimental data are
available for this extreme range and extrapolation is hardly

valid. However, the operative performance of the NORSAR Detection Processor indicates that extremal STA/LTA values have a non-Gaussian distribution.

Software limitations necessitate the use of a "linear" power detector and not a squared one which is optimal according to theory. Both types of detectors have been simulated, and for small signals the difference in detection capability is negligible (see Fig 13).

Finally, it should be noted that the event detector analysis gave the same results whether real or simulated data were used. This means that the noise and signal models considered gave a good approximation to actual NORSAR recordings.

7. Frequency_Domain_Analysis

Signal spectra and coherence has been estimated for the 22 Plan D events presented in Table 1. The computational procedure used, is based on the auto- and cross-correlation functions. The signal time window was 6.4 sec (10 Hz sampling) and the maximum lag in correlation 15%. Following Blackman & Tukey (1959) the number of degrees of freedom k can, for a reasonable smooth spectrum, be estimated as:

$$k = 2 \cdot \frac{Tn'}{Tm} = 2 \left(\frac{Tn}{Tm} - \frac{1}{3} \right) \tag{4}$$

where Tn = signal length and Tm = maximum lag. In our case k = 6 which is equivalent to a 90% confidence interval of ca 10 dB for the spectral estimate on the single sensor level.

In order to estimate the confidence interval for coherence, we refer to the tables of Amos & Koopmans (1963). Their results for k = 6 are given in Fig 14 and shows that at a 90% confidence interval, an observed coherence of 0.8 reflects

a true coherence somewhere in the interval between 0.60
and 0.94. However, spectral estimates based on the
average over a number of N sensor would have an improved
stability approximately proportional to $N^{-\frac{1}{2}}$.

Results of the coherence analysis are presented in Fig 15 - 17,
and brief comments are as follows. In the range 20 - 100
km observed signal coherence does not exhibit significant
distance dependence, i.e., subarray site anomalies seem to
dominate contrary to the expected effect of sensor separation.
The coherence function peaks around 1.0 Hz (typical value
0.7 units) and then slowly taper off with increasing
frequencies. The above results are in reasonable agreement
with corresponding time domain observation (same event
population) which gave a beam/sensor and sensor/sensor
correlation of 0.76 and 0.62 units respectively for a band-
pass filter of 0.8 - 2.8 Hz and a 6.4 signal window. It
should be noted that signal coherence vary considerably
from one event to another on the array level, while more
stable and significantly higher values are observed on the
subarray level (see Fig 17).

The spectral analysis clearly demonstrate the increasing
P-signal energy loss during beamforming as a function of
frequency, and results based on Plan D events are displayed
in Fig 18. A corresponding loss of ca 2 dB was obtained by
time domain beamforming, and is considered reasonable as
the Plan D event spectra have the maxima around 1.0 - 1.5 Hz.
Moreover, observed P-signal power exhibit large non-random
variations across the array as demonstrated in Fig 19.

The frequency domain analysis of NORSAR events has continued
after the array became operational, thus ensuring a

more representative data base than the "excellent" Plan D events
(Table 1) previously used. We have concentrated on various
kinds of power spectra which are related to processing methods
and system evaluation. For example, beam spectra represent
the square of the sum of sensor amplitude spectra, while the
spectraform represents the average of sensor power spectra.
For more details on computational methods and physical
implications, the proper reference is a paper by Lacoss and
Kuster (1970).

Different types of spectra and spectral ratios are presented
in Fig 20 - 23, and brief comments are as follows. Signal
loss during beamforming on the array level may be very large,
especially for frequencies above 2 Hz (Fig 20 - 22). In the
latter case, the expected gain in SNR amounting to 21.2 dB
for NORSAR is partly compensated by the suppression of the
high frequency signal components. On the subarray level the
situation is somewhat different as severe signal losses
commence around 3 Hz. The above results which are based on a
signal window length of 6.4 sec, are considered typical for
the NORSAR array. It should be noted that smaller beam
signal losses are observed for window lengths of 3.2 sec.
Moreover, during the on-line event detection process much
shorter signal lengths are used as discussed in the previous
section. Anyway, the essence of the above results is that
a spectraform method may be a viable alternative to beam-
forming - above a certain signal frequency - for detecting
small events. Moreover, the spectraform processing gives
a smaller noise variance, and thus simplify the false alarm
problem discussed in the previous section. Another factor
to be considered, is the noise level which is strongly
dependent on the weather situation in the North Atlantic
Ocean (see Fig 23).

8. P-velocity Discontinuities in the Earth's Mantle

The gross structure of the earth's interior is fairly well known, but we are still lacking information on the finer details, i.e. structural discontinuities of higher orders. We have investigated this problem using the Fennoscandian continental array and found evidence for vertical and lateral P-velocity discontinuities in the mantle (Husebye et al, 1971). The main results obtained are displayed in Fig 24.

9. Future Plans

The system parameterization work will continue in order to improve the beam steering correction files and event location. Minor modification of the present beam deployment will also be implemented. Evaluation of NORSAR's event detection and location capabilities is in progress. Both processed data like epicenter parameters of recorded events and more original data like beam and spectraform spectra are considered. The reason for the above approach to the evaluation problem may be illustrated by the following example. Presently, it seems that NORSAR's event detection capability is lesser than that of LASA, but also lesser than in general expected, which the spectral analysis (section III,7) indicate that improved performance could possibly be obtained by other types of detector processing schemes. In short, we must differentiate between the joint performance of the array and the present software system and the potential of the array itself. Corresponding evaluation work of the LP data will also be undertaken.

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TABLE CAPTION

Table 1 : The 22 events used in analysis.

EVENT NO	ARRIVAL TIME			MB	LAT	LONG	REGION
1	16 JAN 1970	08.15.27.9		5.6	60.3N	152.7W	SOUTH ALASKA
2	20 JAN 1970	00.49.08.9		5.1	53.8N	163.5W	UNIMAK ISLANDS
3	27 JAN 1970	10.59.40.1		5.1	34.9N	101.3E	TSINGHAI, CHINA
4	29 JAN 1970	06.14.58.3		5.1	36.0N	140.4E	NEAR EAST OF HONSHU
5	31 JAN 1970	11.54.21.2		5.3	4.1N	96.0E	NORTHERN SUMATRA
6	06 FEB 1970	00.22.14.0		5.6	54.6N	163.6E	OFF EAST KAMCHATKA
7	07 FEB 1970	23.47.53.5		5.0	47.3N	154.0E	KURILE ISLANDS
8	12 FEB 1970	02.01.25.1		5.4	29.4N	81.6E	NEPAL
9	16 FEB 1970	21.54.50.8		5.3	25.2S	178.3E	SOUTH OF FIJI
10	17 FEB 1970	05.59.10.6		5.9	9.8N	126.0E	MINDAN, PHILIP. ISLANDS
11	19 FEB 1970	07.20.31.3		5.5	27.4N	94.0E	EAST INDIA
12	27 FEB 1970	07.19.05.2		6.0	50.1N	179.6W	ANDREANOF ISLANDS
13	11 MAR 1970	22.48.50.8		6.0	57.5N	153.9W	KODIAK ISLANDS REGION
14	13 MAR 1970	17.39.16.0		4.6	51.7N	175.3E	RAT ISLANDS, ALEUTIANS
15	17 MAR 1970	01.37.15.6		4.9	26.3S	177.0W	SOUTH OF FIJI
16	22 MAR 1970	02.02.48.8		5.4	21.7N	73.0E	INDIA
17	26 MAR 1970	19.11.33.3		6.5	37.3N	116.5W	NEVADA
18	27 MAR 1970	04.39.16.3		5.2	5.6N	77.6W	NEAR WEST COLOMBIA
19	27 MAR 1970	05.10.20.0		5.2	49.8N	78.0E	EAST KAZAKH
20	28 MAR 1970	03.56.56.2		5.1	39.6N	75.4E	SOUTH SINKIANG
21	07 APR 1970	05.46.47.6		6.4	15.8N	121.7E	LUZON, PHILIPPINES
22	07 MAY 1970	04.20.42.8		5.1	14.6N	93.6W	OFF CHIPAS, MEXICO

FIGURE CAPTIONS

Fig 1;   Relative time delays across the NORSAR array.
         The given values are the average of the 130 Plan D
         events in the teleseismic distance range.

Fig 2;   Relative time delays and NORSAR Plan D configuration.
         MOHO depth contours as presented by Kanestrøm &
         Haugland (1971) are outlined. The subarrays 01A,
         03B, 04B and 05B are not included in the figure.

Fig 3;   Error in azimuth as observed and predicted from a
         simple time delay model.

Fig 4;   Error in slowness as observed and predicted from a
         simple time delay model.

Fig 5;   Amplitude response of Lagrange sloping filters used
         in analysis.

Fig 6;   Phase and amplitude response of a third order
         Butterworth recursive filter having a passband
         from 1.0 - 3.0 Hz for a 10 Hz sampling rate.

Fig 7;   SNR in dB for the array beam using both Lagrange
         and Butterworth filters for additional noise suppression.
         The broadness of the main beam lobe is noteworthy. The
         event used, no. 18 in Table 1, is a presumed explosion
         in eastern Kazakh.

Fig 8;   SNR in dB for the array beam using only the Butter-
         worth filter for additional noise suppression. The
         event used, no. 18 in Table 1, is a presumed explosion
         in eastern Kazakh.

Fig 9; Working principle of the NORSAR detection processor.
STA = short term average, LTA = long term average.
The line above the STA/LTA curve indicates detection
state, while the line crossing the curve is the
threshold.

Fig 10; Receiver operating characteristics determined from
simulated data. The numbers in brackets are STA
integration length in dsec, STA updating rate in
dsec, and event declaration parameter Q.

Fig 11; Integrated STA/LTA values as a function of time when
the system is in "detection state". The STA window
length was 1.2 sec, and the earthquake analysed
occurred in Sumatra 06/31/70.

Fig 12; Cumulative distribution of the STA parameter for a
single sensor and based on a noise sample of 1 hour,
July 23, 1970. STA integration length and updating
interval was 0.6 sec. The three curves correspond
to declaration parameter or Q values of 1,2 and 3
respectively. The 99 - 100% distribution interval
is enlarged.

Fig 13; Receiver operating characteristics for linear and
square detectors calculated from simulated data.

Fig 14; Coherence confidence area of 90% for six degrees
of freedom.

Fig 15; Average coherence between single sensors for
different frequencies as a function of sensor
separation. The data base is the 22 events in
Table 1.

Fig 16; Average coherence for beam/sensor and sensor/sensor combinations as a function of frequency for the 22 events listed in Table 1.

Fig 17; Results of coherence analysis for 4 events. Event I: Kurile Is., 22 May 1969; Event II: Fox Is., 7 May 1969; Event III: Lake Aral, 6 Dec 1969; Event IV: Kazakh expl., 30 Nov 1969. Subarray 14C corresponds to the experimental array Øyer, while NORSAR is NORSAR Plan D configuration.

Fig 18; Average beamforming loss as a function of frequency. Data base is the 22 events listed in Table 1.

Fig 19; Relative signal power across the NORSAR array. The given values are the average of ca 130 Plan D events in the teleseismic distance range.

Fig 20; Array beam and spectraform spectra for an earthquake in Szechwan 08/16/71.

Fig 21; Beamform-spectraform spectral ratio for an earthquake in Szechwan 08/16/71.

Fig 22; Signal-to-noise ratio for beamform and spectraform spectra for an earthquake in Szechwan 08/16/71.

Fig 23; Observed noise spectra at different days of the year. Variations in the noise level (LTA range) and detection processor filter setting are marked.

Fig 24   A new P-velocity model for the taper mantle.
Observed lateral velocity variation is represented
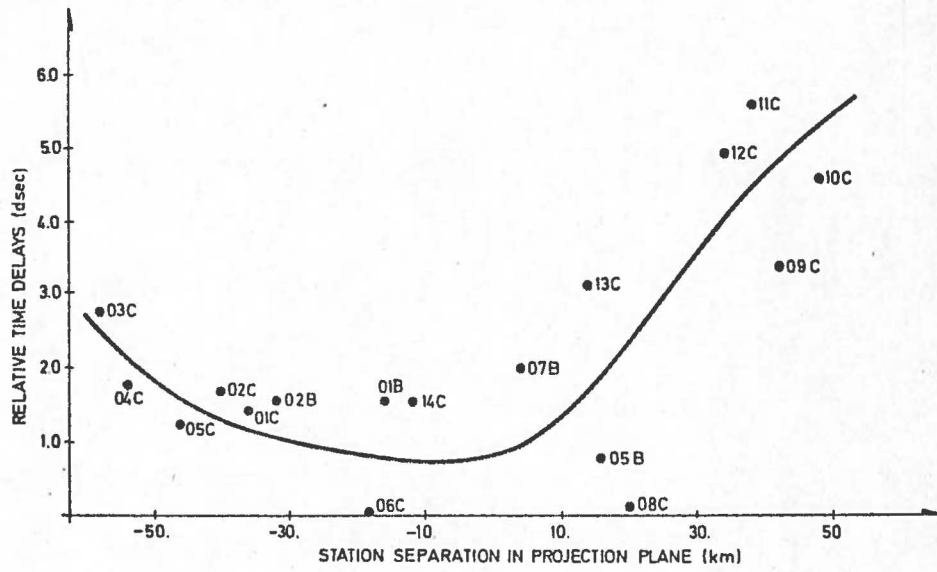by the NOR1 and NOR2 models respectively. The
standard model of Jeffreys-Bullen (1958) is included.

Figure 1

Figure 2
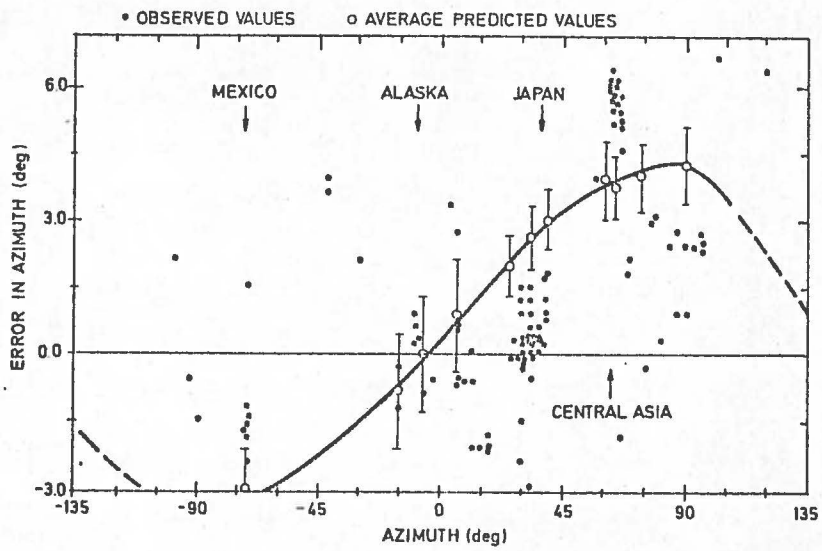
Figure 3

Figure 4

Figure 5

- 26 -

FILTER RESPONSE

Figure 6

EAST KAZAKH EXPL.
(SNR IN dB FOR BEAM)

12 dB/oct PREFILTERING

Figure 7

EAST KAZAKH EXPL.
(SNR IN dB FOR BEAM)
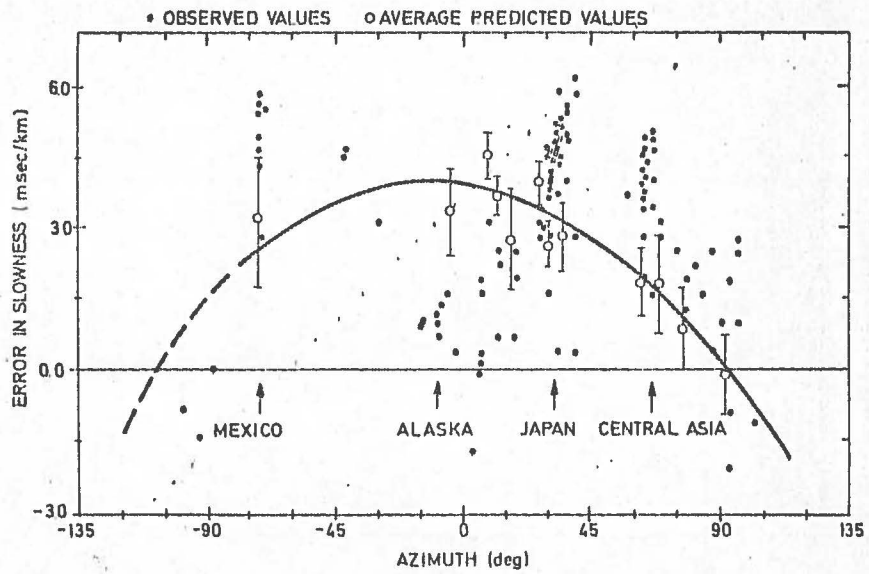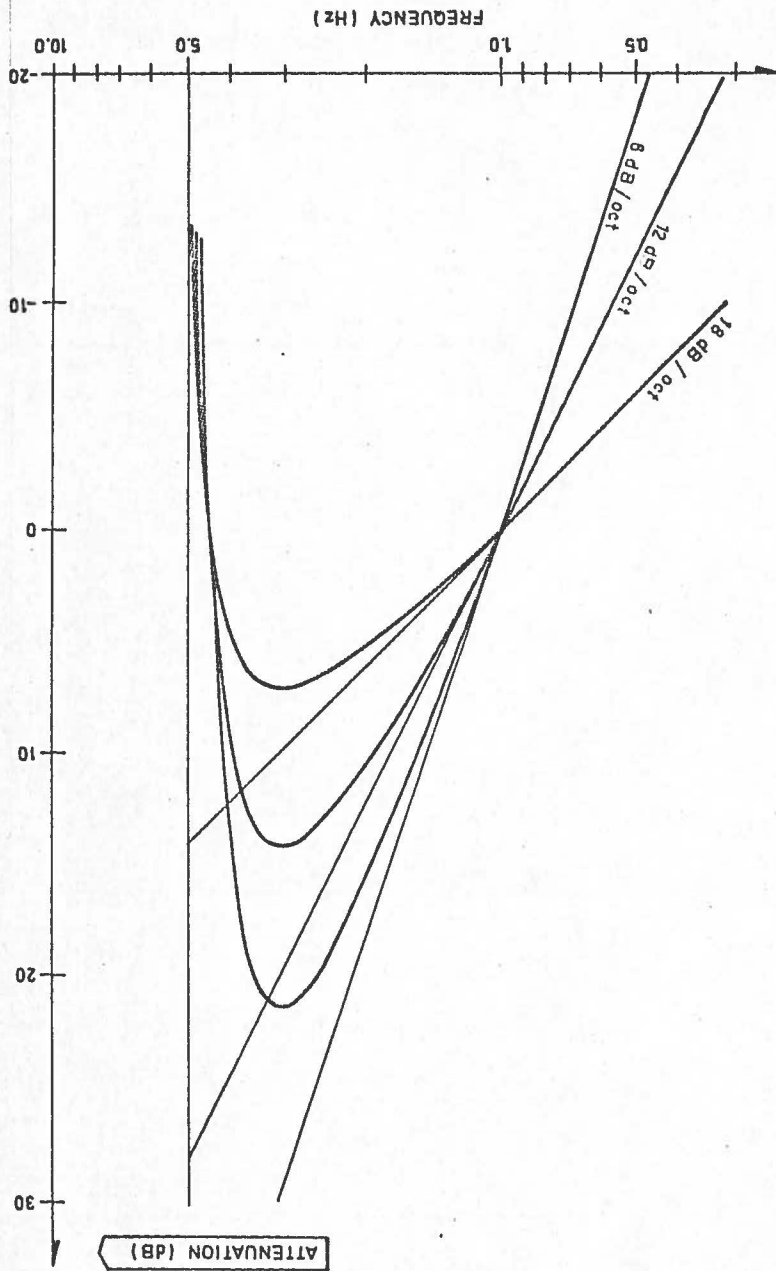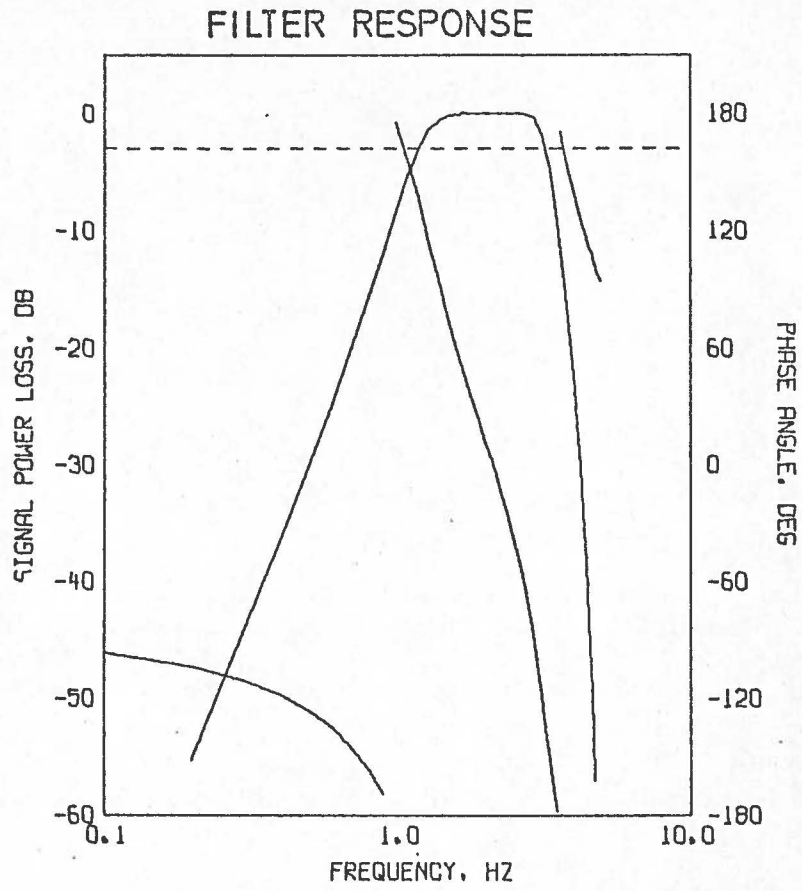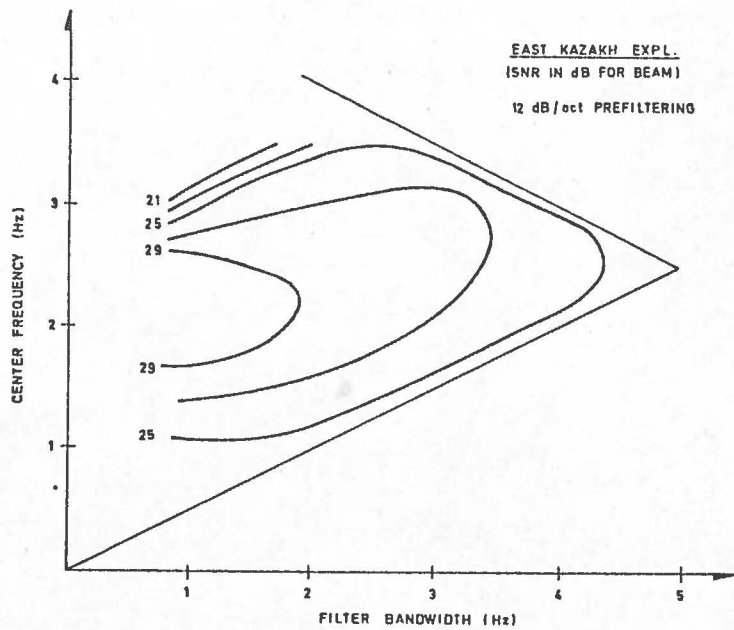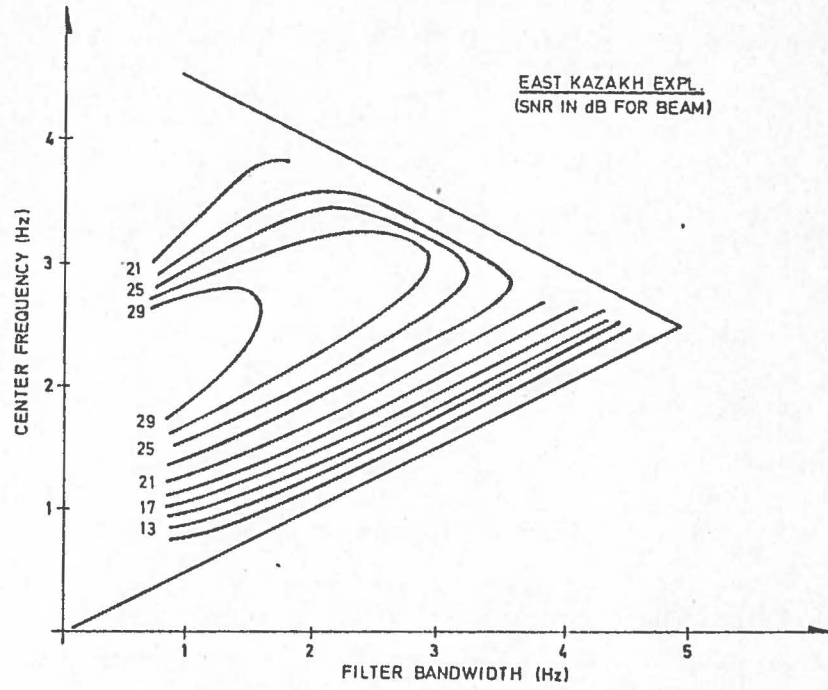
Figure 8

Figure 9

Figure 11

STA/LTA RATIO (dB)

TIME IN DETECTION STATE (sec)

Figure 10

FALSE ALARM PROBABILITY

DETECTION PROBABILITY

[24.6.1]

[20.9.1]

[18.8.3]

[18.6.1]

[12.8.1]
[12.4.1]
[12.6.1]
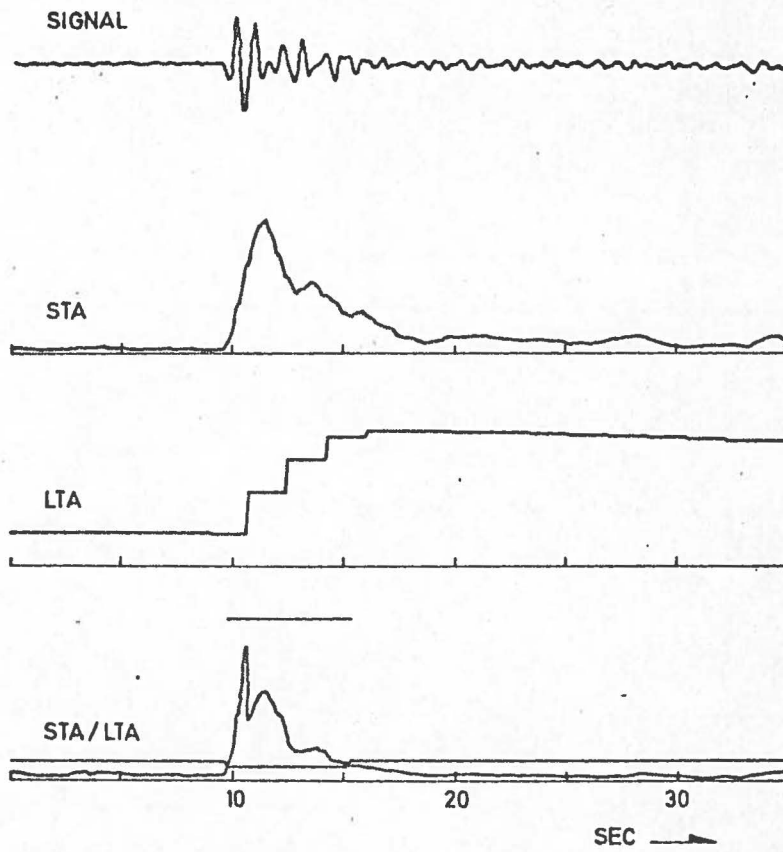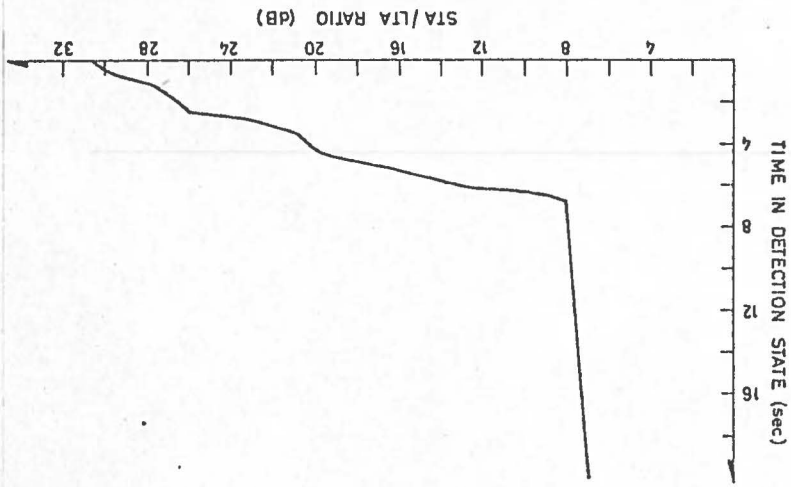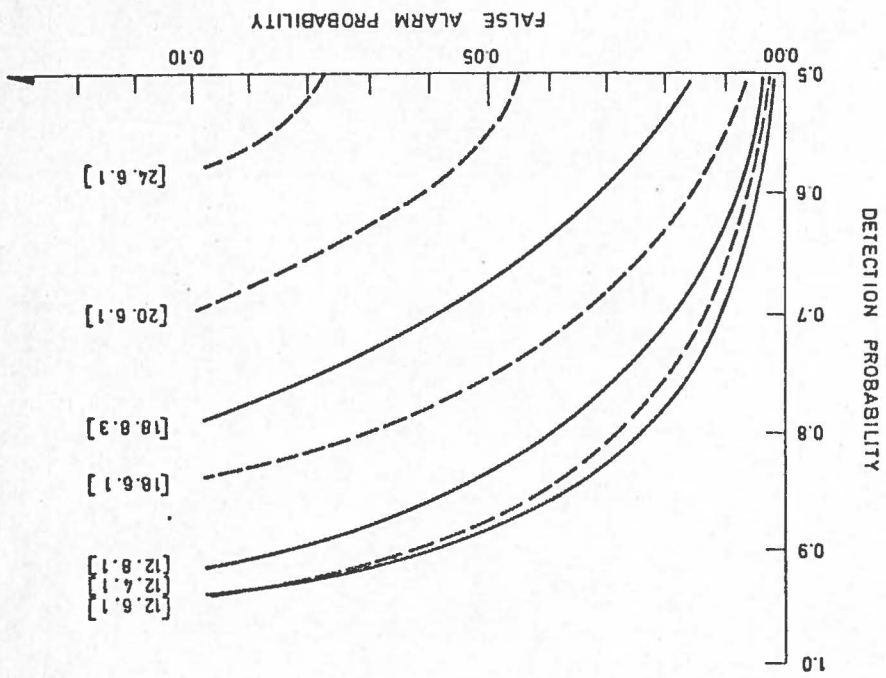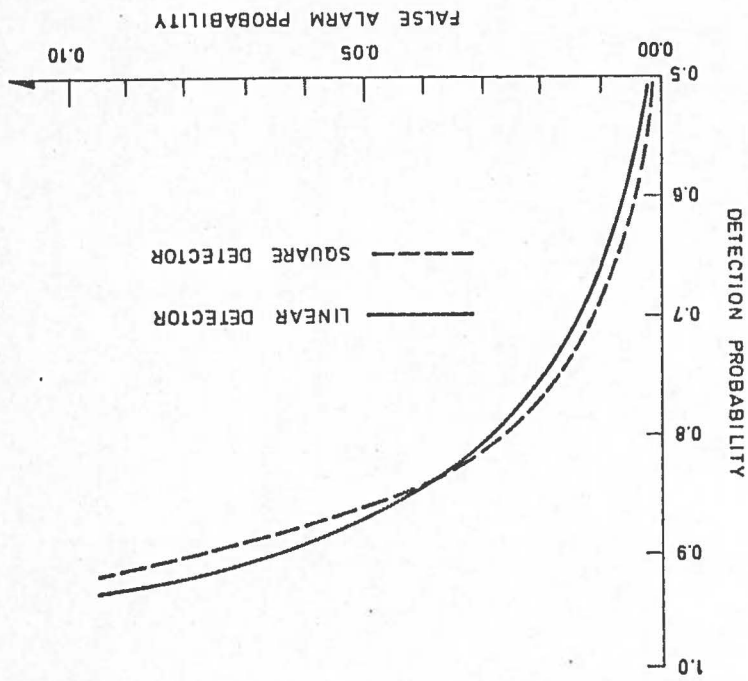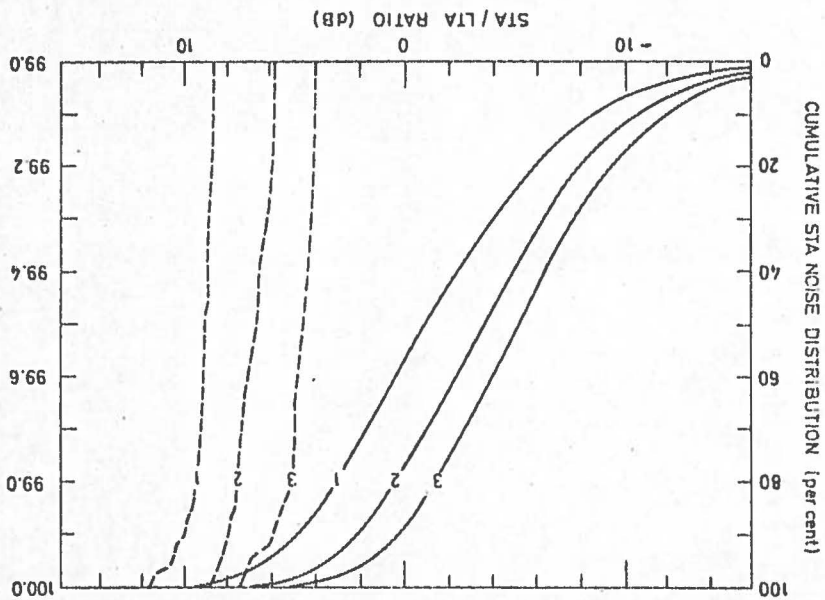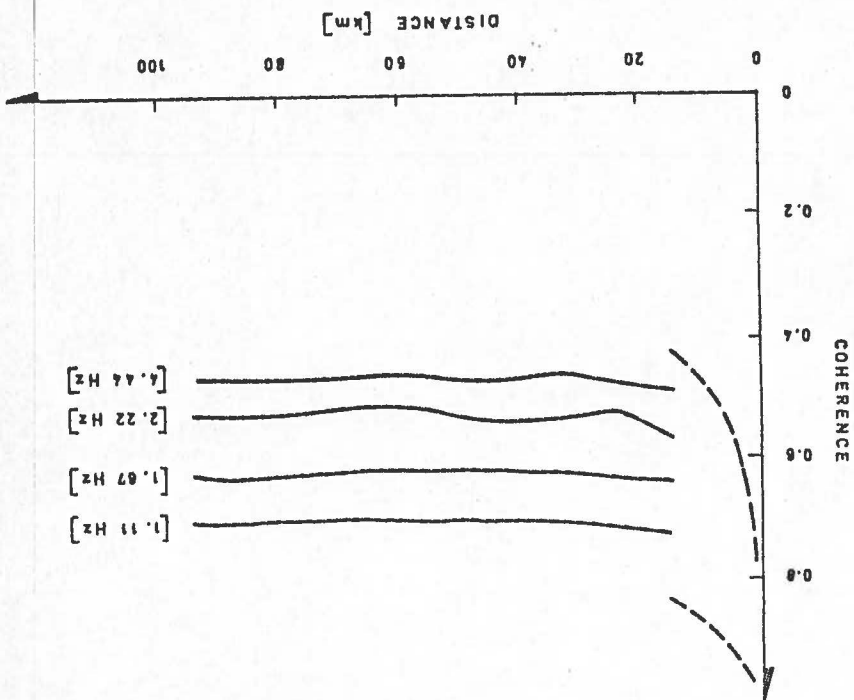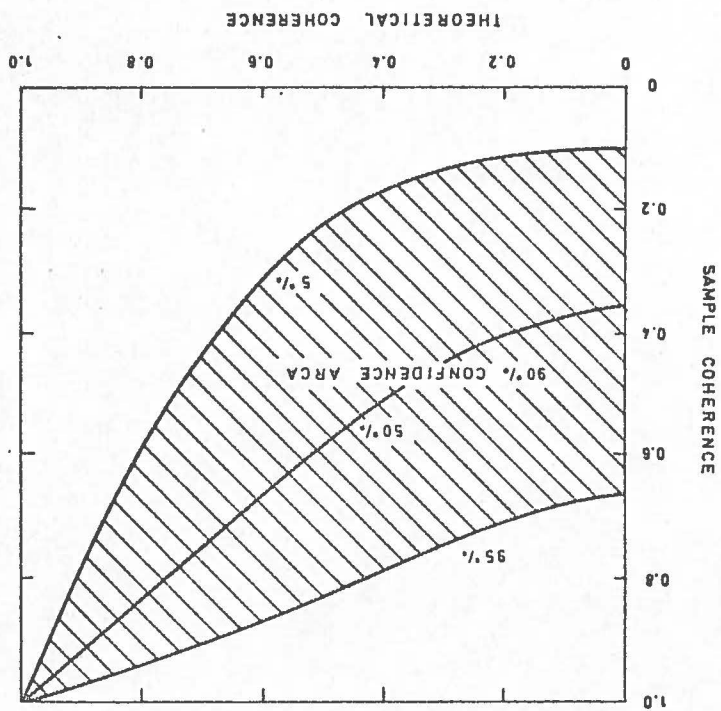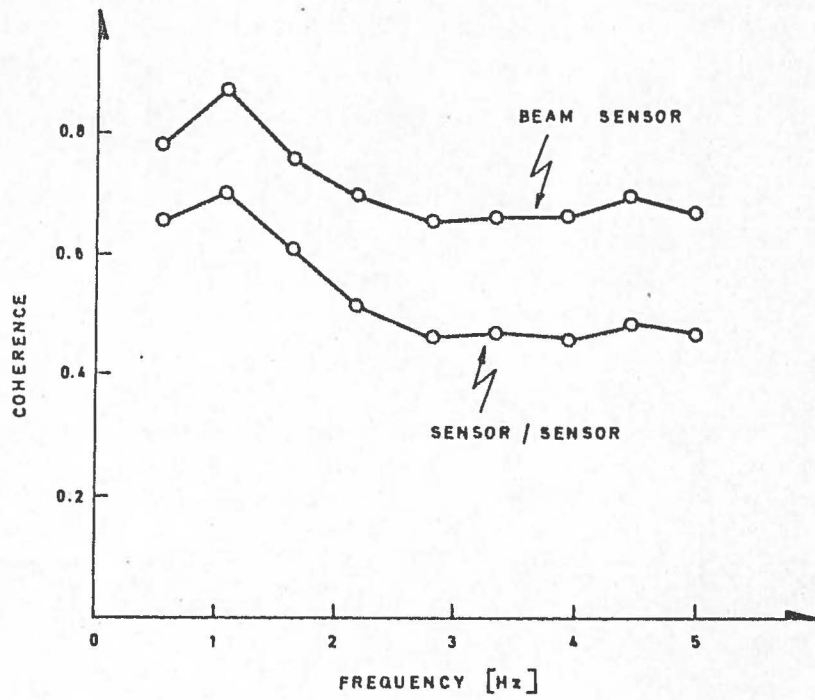
Figure 15

Figure 14

Figure 16
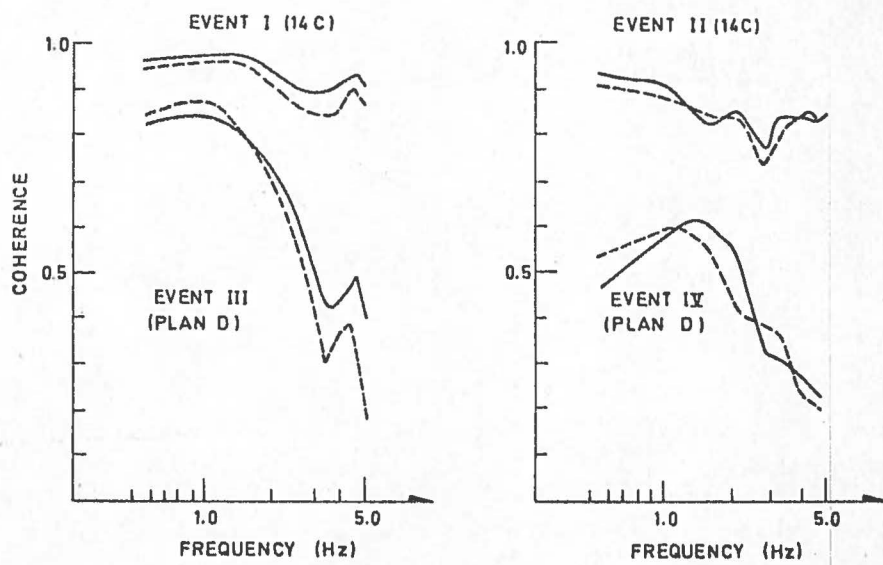
Figure 17
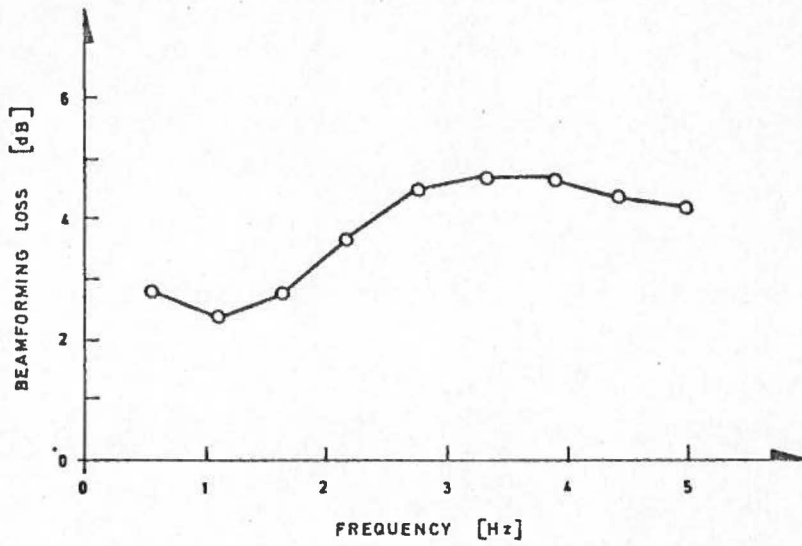
Figure 18

Figure 19

Figure 20

ARRAY BEAM ------
ARRAY SPECTRAFORM ——
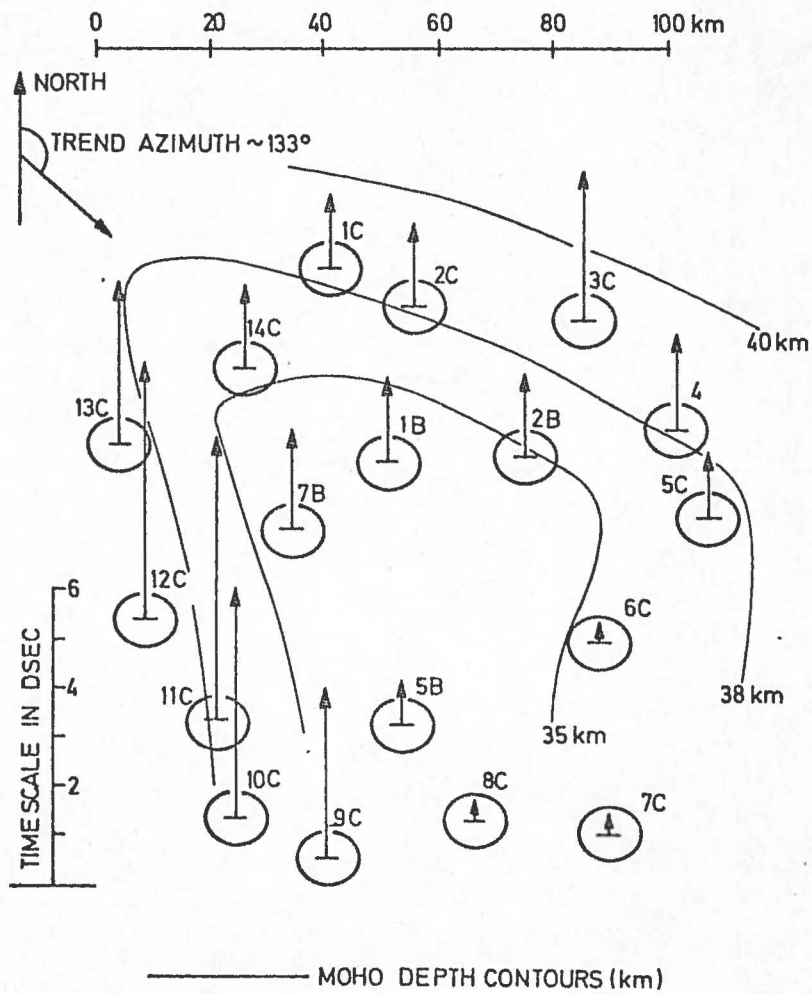
SPECTRAL DENSITY (dB rel. to 1nm²/Hz at 1.0 Hz)

FREQUENCY [Hz]

FREQUENCY
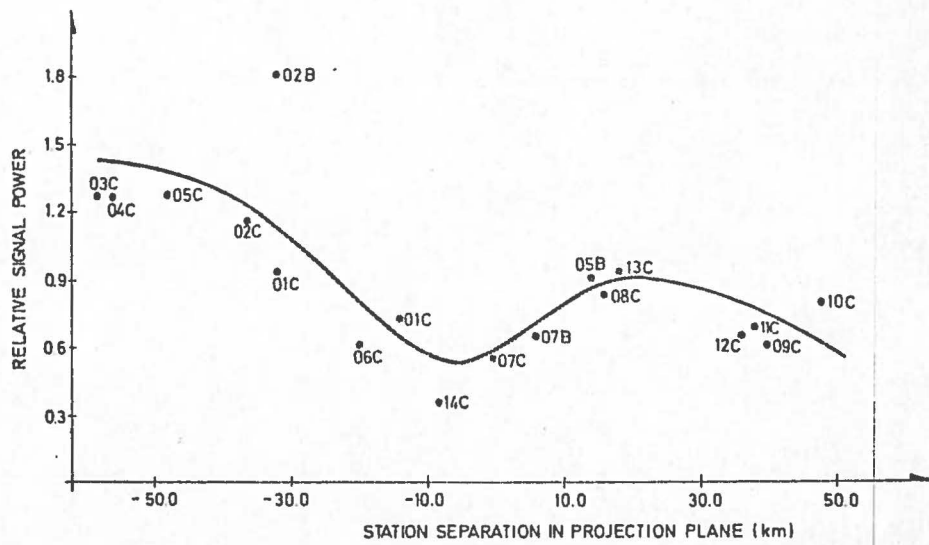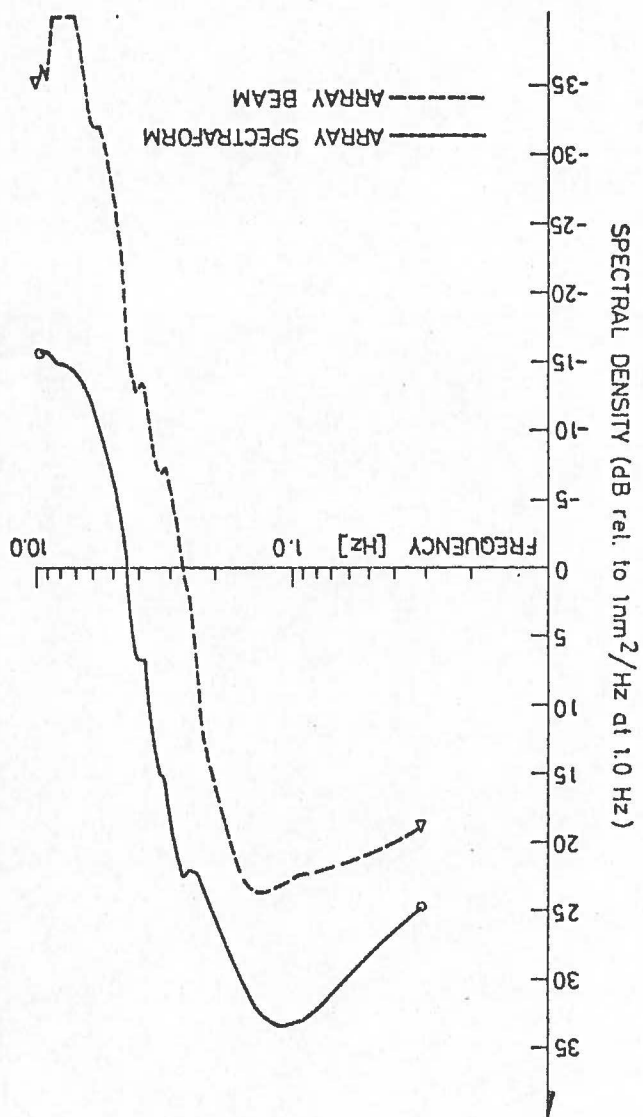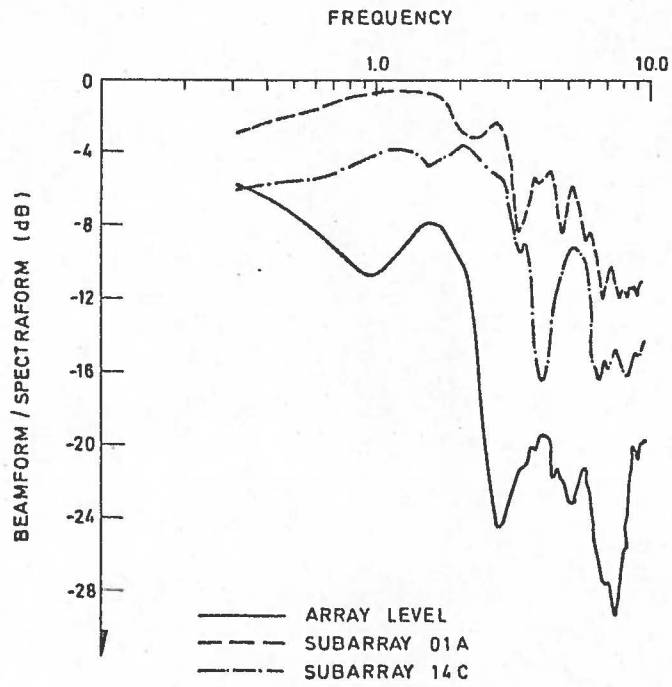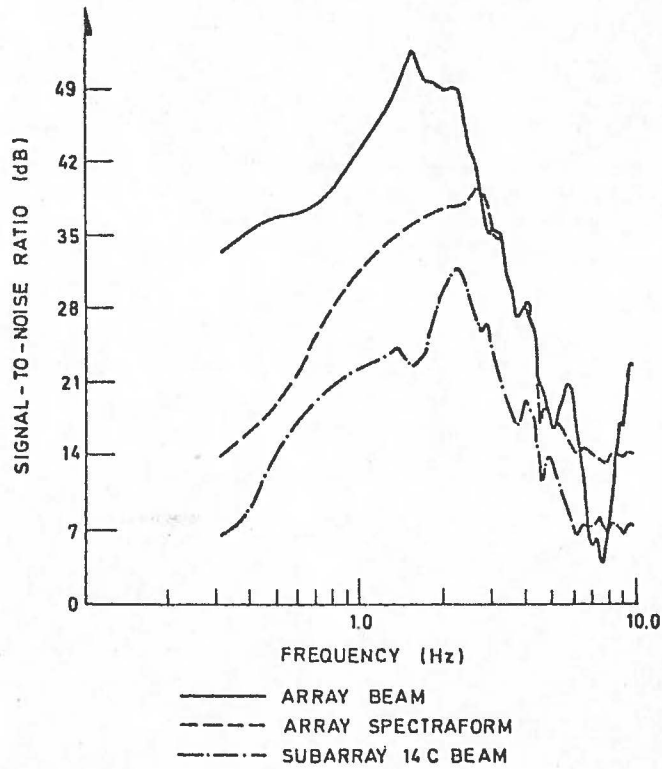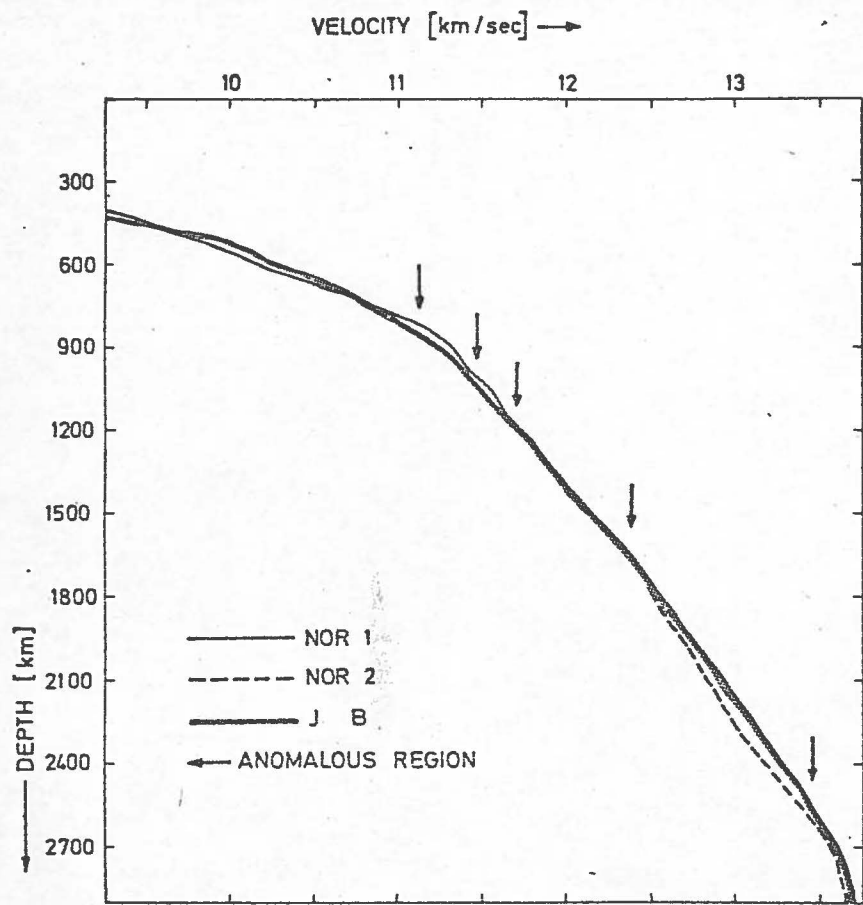
Figure 21

Figure 22

Figure 24
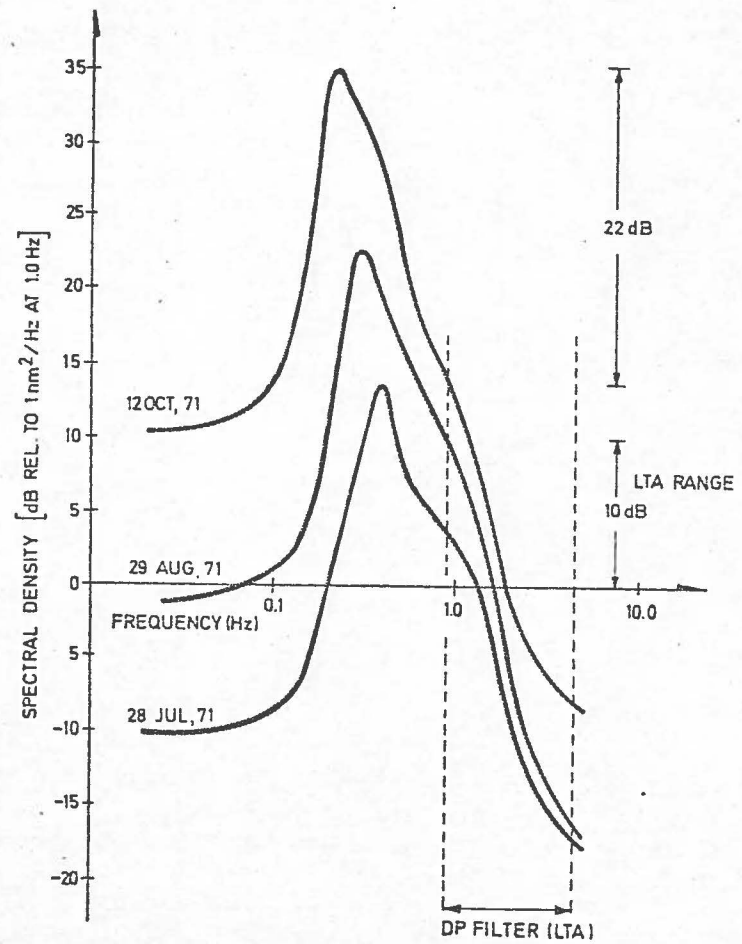
Figure 23

FOLLOWING EXPLAINS THE ENTRIES IN THE NORSAR EVENT SUMMARY

ARRIVAL TIME	ARRIVAL TIME (GMT)
REF	REFERENCE SUBARRAY FOR ARRIVAL TIME
PHS	PHASE NAME
AMP	ZERO-PEAK AMPLITUDE (NM)
PER	PERIOD (SEC)
VEL	APPARENT PHASE VELOCITY (KM/SEC)
DIR	DIRECTION OF WAVEFRONT APPROACH (DEG)
DEL	DISTANCE TO EPICENTER (DEG)
OR. TIME	ORIGIN TIME (GMT)
LAT	EPICENTER LATITUDE (DEG)
LONG	EPICENTER LONGITUDE (DEG)
MB	BODY WAVE MAGNITUDE
REGION	REGION NUMBER AND NAME (FLINN AND ENGDAHL)

PROCESSED INTERVAL(S)

13 JUL 0000 - 13 JUL 0706	15 JUL 0932 - 15 JUL 1500
13 JUL 1108 - 14 JUL 1027	15 JUL 1543 - 16 JUL 0349
14 JUL 1128 - 14 JUL 1624	16 JUL 0740 - 17 JUL 0718
14 JUL 1828 - 15 JUL 0738	17 JUL 0818 - 17 JUL 1838
15 JUL 0840 - 15 JUL 0923	17 JUL 1841 - 19 JUL 2400

DATA RETENTION TIME IS 9 MONTHS

NTNF/NORSAR
P.O. BOX 51
N-2007 KJELLER
NORWAY

ARRIVAL TIME	REF PHS	AMP	PER	VEL	DIR	DEL	OR. TIME	LAT	LONG	MB	REGION
16 JUL 20.27.41.5	01A P	3.0	0.6	13.8	94	48	20.19.06	35N	75E	4.3	302 EASTERN KASHMIR
16 JUL 21.52.54.0	01A P	34.4	1.5	23.3	299	86	21.40.19	15N	98W	5.2	65 OFF COAST GUERRERO, MEX.
16 JUL 22.27.11.1	01A P	22.4	1.2	18.3	42	73	22.15.44	39N	143E	5.0	229 OFF E COAST HONSHU,JAPAN
17 JUL 04.52.11.9	01A P	7.3	1.0	19.2	44	76	04.40.26	35N	143E	4.6	229 OFF E COAST HONSHU,JAPAN
17 JUL 05.44.44.3	01A P	141.7	1.0	17.7	90	81	05.32.33	7N	94E	5.9	704 NICOBAR ISLANDS REGION
17 JUL 05.54.40.9	01A P	204.5	1.3	9.3	91	19	05.50.29	56N	45E	5.3	724 WESTERN RUSSIA
17 JUL 12.43.57.0	01A	3.5	0.3								LOCAL
17 JUL 15.11.24.0	01A P	45.6	0.8	15.8	84	62	15.01.13	28N	92E	5.4	313 INDIA-CHINA BORDER REGION
17 JUL 19.39.22.0	01A P	2.2	1.0	18.6	43	74	19.27.50	38N	143E	4.1	228 NEAR E COAST HONSHU,JAPAN
17 JUL 19.41.23.4	01A P	7.7	1.0	18.1	42	73	19.30.00	40N	143E	4.6	229 OFF E COAST HONSHU,JAPAN
17 JUL 20.28.26.8	01A P	40.8	1.6	15.3	245	52	20.19.23	23N	40W	5.1	402 NORTH ATLANTIC OCEAN
18 JUL 00.09.16.4	01A P	1.9	0.5	11.7	119	27	00.03.36	42N	42E	4.2	367 TURKEY-USSR BORDER REGION
18 JUL 01.25.55.1	01A P	1.5	0.7	16.7	84	70	01.14.45	21N	97E	4.1	296 BURMA
18 JUL 05.10.01.8	01A P	2.7	0.8	17.4	20	63	04.59.37	54N	164E	4.2	219 OFF EAST COAST KAMCHATKA
18 JUL 07.13.17.0	01A P	0.8	0.8								
18 JUL 08.59.42.8	01A PKP	10.5	0.9	39.8	30	154	08.39.47	36S	180W	4.8	688 EAST OF NORTH ISLAND,N.Z.
18 JUL 11.22.49.6	01A PKP	4.1	0.9	30.6	21	144	11.03.19	26S	178W	4.2	171 SOUTH OF FIJI ISLANDS
18 JUL 11.25.39.3	01A PKP	5.6	1.0	35.7	25	149	11.05.57	30S	179W	4.3	178 KERMADEC ISLANDS
18 JUL 14.46.20.0	01A P	4.3	0.9	22.0	48	95	14.33.01	17N	147E	4.9	216 MARIANA ISLANDS
18 JUL 14.50.01.8	01A PKP	12.3	0.9	109.1	71	175	14.29.57	58S	178W	5.4	690 SOUTH OF CHATHAM ISLANDS
18 JUL 15.00.22.0	01A	2.2	1.0								
18 JUL 15.04.53.0	01A	3.5	0.9								
18 JUL 16.22.22.8	01A P	5.6	0.9	8.9	144	18	16.18.18	45N	25E	4.1	358 RUMANIA
18 JUL 19.29.08.9	01A P	2.3	1.1	23.3	307	88	19.16.23	17N	106W	4.3	64 OFF COAST MICHOACAN, MEX.
18 JUL 23.20.14.9	01A P	2.5	1.0	17.8	9	67	23.09.27	52N	179E	4.1	6 RAT ISLANDS, ALEUTIANS
19 JUL 00.33.32.4	01A PKP	10.2	1.2	40.7	55	158	00.13.27	43S	170E	5.0	161 OFF W COAST OF S IS.,N.Z.
19 JUL 00.43.49.8	01A PKP	5.8	0.9	31.1	210	144	00.24.19	69S	80W	4.3	692 SOUTHERN PACIFIC OCEAN
19 JUL 00.59.16.6	01A P	2.3	0.6	19.5	195	77	00.47.30	14S	9W	4.4	409 SOUTH ATLANTIC OCEAN .
19 JUL 06.28.05.0	01A P	4.0	0.8	13.9	91	46	06.19.44	38N	76E	4.3	321 SOUTHERN SINKIANG PROV.
19 JUL 09.25.26.0	01A P	2.8	1.1								
19 JUL 09.33.35.0	01A PKP	4.3	1.0	25.7	15	163	09.12.47	44S	173W	4.8	689 CHATHAM ISLANDS REGION
19 JUL 12.34.38.5	01A P	5.2	0.8	18.4	43	73	12.23.11	39N	143E	4.6	228 NEAR E COAST HONSHU,JAPAN
19 JUL 15.07.16.9	01A PKP	6.1	0.8	41.4	68	123	14.48.25	17S	139E	5.1	594 QUEENSLAND, AUSTRALIA
19 JUL 15.17.57.9	01A PKP	3.2	0.8	34.3	221	144	14.58.29	63S	88W	4.1	692 SOUTHERN PACIFIC OCEAN
19 JUL 15.57.41.1	01A P	8.1	1.8	15.8	48	59	15.47.46	49N	126E	4.3	658 NORTHEASTERN CHINA
19 JUL 17.10.00.0	01A P	2.0	1.1								
19 JUL 17.10.08.4	01A P	34.4	1.2	18.5	64	75	16.58.33	28N	121E	5.2	664 EASTERN CHINA
19 JUL 17.37.16.0	01A P	1.1	1.1								

APPENDIX II

H. Bungum and E.S. Husebye: Seismic arrays and data
handling problems. Union Geodésique et Geophysique
International, European Seismological Commission, pp. 4, 1971.

Abstract

To take full advantage of recent developments in
seismological theory and sophisticated interpretation
methods requires that high quality data are easily
available for research purposes. As of today, the
large number of seismological observatories in
operation, produce a tremendous amount of quantitative
data which are hardly accessible for the seismological
community. The latter problem prevails even for the
large aperture seismic arrays which are characterized
by a new seismic observation concept, advanced
recording and standardized analysis techniques. In
this paper we compare different types of seismic
wave recording systems, and discuss relevant data
handling problems. It is concluded that array
processing techniques could be adapted to ordinary
station networks, requiring coordination and
cooperation in seismograph operation on a regional
basis. In this way data quality and accessibility
could be improved, but at the same time reducing the
costs involved in running the global seismic network.

H. Bungum and E.S. Husebye: Errors in time delay measurements.
Pure and Appl. Geophys., 91: 56-70, 1971.

Abstract

Simple delay and sum of sensors in a seismic array is
an effective method for noise suppression. However,
unless we have precise steering delays, much of the
signal energy is lost during the beam forming process
too. We have investigated possible error sources in
time delay measurements, using a computerized cross-
correlation procedure. Parameters perturbed are
correlation window length and positioning, signal
frequency content and signal to noise ratio (SNR). Our
results indicate that relative low frequency waves and
using the very first part of the P-signals give the most
reliable and stable time delay values. High frequency
bandpass filtering improves SNR, but signal correlation
and the precision in beam steering corrections decrease.
Significant loss of high frequency energy during beam-
forming seems to be unavoidable.

H. Bungum og E.S. Husebye: Aspekter ved digital seismisk analyse, Ingeniør-Nytt, No. 5, Feb. 1971.

This paper gives (in Norwegian) a brief review of the fundamental principles of exploration seismology. Emphasis is on data handling and various kinds of digital filtering techniques, wave parameter extraction and methods of interpreting seismic data.

H. Bungum, E.S. Husebye and F. Ringdal: The NORSAR array and preliminary results of data analysis. In press. Geophys. J.R. Astr. Soc., pp. 14, 1971.

Abstract

A large aperture seismic array, NORSAR, has been constructed in Norway. The project, which started in the summer of 1967, is a joint undertaking by the governments of Norway and the United States of America. NORSAR consists of 22 subarrays, each equipped with one three-component long-period and six short-period instruments. The array diameter is around 110 km, while that of a subarray is approximately 8 km. In the data centre, which is located just outside Oslo, are installed 2 IBM 360/40 computers with peripheral equipment, a special-purpose computer, and an experimental operations console. Routine tasks performed at the data centre comprise array monitoring and calibration, data acquisition, on-line event detection and off-line event analysis. In this paper we give a technical description of NORSAR, emphasizing the software aspects of the array operation, and present some analysis results of P-waves recorded at NORSAR. For example, we have found that signal power and spectral characteristics vary across the array and seem to reflect local differences in the geological structures at the subarray sites. The recorded signals are found to be broadband and to contain significant energy at higher frequencies. Observed signal coherencies vary considerably across the array and are usually independent of station separation. Within the subarrays signal coherence is high and the waveforms exhibit little scattering.

H. Bungum, E. Rygg and L. Bruland: Short-period seismic
noise structure at the Norwegian Seismic Array. Bull. seism.
Soc. Am., Vol 61, pp. 357-373, 1971.

Abstract

Power spectral analysis in frequency-wavenumber space
and coherence studies in lag space have shown that the
noise recorded by the short period Øyer subarray at
NORSAR is critically dependent on the weather situation
in the North Atlantic Ocean. In addition to the low-
frequency noise from the west, there is observed 2-sec
microseisms from the Baltic Sea. Because of the non-
isotropic noise, the coherence is usually strongly
azimuthal dependent, being represented in lag space by
ellipses. Large time variations of the coherence are
demonstrated.

E.S. Husebye, R. Kanestrøm and R. Rud: Vertical and lateral
inhomogeneities in the earth's deep mantle. Union Geodésique
et Geophysique International, European Seismological
Commission, pp. 4, 1971.

Abstract

The gross structure of the earth's interior is fairly
well known, but we are still lacking information on
the finer details, i.e., structural heterogeneities
causing higher order discontinuities in seismic wave
velocities. The most fascinating aspect of this problem
is the possibility of having lateral velocity variations
in the deep mantle.

Support of the above hypothesis comes from recent
analysis of measured $dT/d\Delta$ values (Chinnery and
Toksöz 1967, Hales et al 1968, Johnson 1969) which
indicates azimuth dependence in the observations them-
selves and the individual studies present significantly
different results in certain distance intervals. A
joint analysis of several types of geophysical data
(Toksöz et al 1969) and P-wave diffraction studies
(Phinney and Alexander 1969) also favor the existence of
lateral inhomogeneities in the lower mantle. We have
investigated the above problems, using $dT/d\Delta$ data
which represents an efficient tool for such analysis.

Abstract

The gross structure of the Earth's interior is fairly well
known, but we are still lacking information on the finer
details, i.e. structural discontinuities of higher orders.
A powerful tool in investigations of this type of problem
is P-wave travel time, and specifically the parameter
$DT/D\Delta$. We have investigated this problem, taking advantage
of the concept of continental arrays. Reported arrival
time data (seismic bulletins) for the Fennoscandinavian
network have been used for direct measurements of apparent
velocity ($DT/D\Delta$) and direction of approach of P-waves
from 648 seismic events. Our observations are interpreted
in terms of vertical anomalies at depths around 850, 1050,
1250, 1700 and 2600 km where the velocity changes very
slowly with depth. The corresponding epicentral distances
are 35, 47, 53, 62 and 87 deg. In addition, we have strong
evidence for existence of lateral P-velocity variation
which amounts to around 0.1 kms^{-1} in the depth interval
1750-2300 km and the distance range is around 63-80 deg.
A comparison of our data with those presented by others
favours lateral velocity variations also at depths around
700-800 km and the corresponding distance range is 25-30
deg.