Royal Norwegian Council for Scientific and Industrial Research

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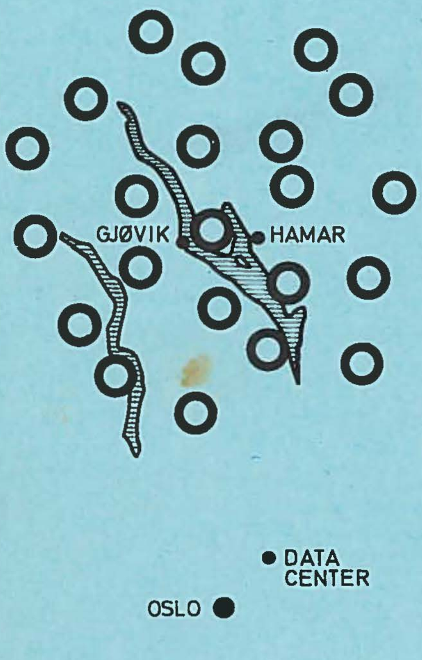

NORWEGIAN SEISMIC ARRAY

NORSAR

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NTNF/NORSAR
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Norway

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31 December 1970

The NORSAR research project has been sponsored by the United States of America under the overall direction of the Advanced Research Projects Agency and the technical management of Electronic Systems Division, Air Force Systems Command, through Contract No. F19628-70-C-0283 with the Royal Norwegian Council for Scientific and Industrial Research.

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Summary

In this paper we give a short description of NORSAR - the Norwegian Seismic Array. The on-line and off-line data processing systems are emphasized. Finally, some results of P-signal analysis are presented.

1. Introduction

Based on a request from Advanced Research Projects Agency (ARPA) the United States proposed to Norway the construction of a large aperture seismic array on Norwegian soil. The purpose of such an array was to provide data for research on seismological detection and classification problems, and also to provide event monitoring functions in the possible advent of a comprehensive test ban treaty. This happened in May 1967, and at the end of the year three small experimental arrays were in operation. The analysis of data from the preliminary systems gave promising results, and in May 1968 the Norwegian parliament approved construction of a large array northeast of Oslo. The cost of NORSAR and its operation to July 1972 is mainly covered by ARPA. Field work (expenses of $6 million and instrument installation were performed by the Norwegian Defence Research Establishment. For NORSAR Phase III, characterized by recording and data center operation and starting 7 July 1970, the local responsibilities rest with the scientific non-profit organization Royal Norwegian Council for Scientific and Industrial Research (NTNF). Federal Systems Division of IBM has developed the software for array monitoring, data acquistion and analysis on a routine basis. Electronic Systems Division, U S. Air Force Systems Command, acts as a consultant and technical advisor for NORSAR.

The array is planned to be fully operational in spring 1971, although interim SP data recording and analysis have been performed in long intervals both in 1969 and 1970. Although the system is not completed yet, we find it important to inform our colleagues about the hardware and software of the array, as well as the research activities associated with NORSAR data.

2. NORSAR Configuration and Instrumentation

NORSAR is located in southeastern Norway and comprises 22 subarrays (Fig. 1) each containing one LP (3-component) and 6 SP (vertical) seismometers. The latter are in outcrops or in shallow boreholes with depths ranging from 3-15 m. The types of LP instruments used at NORSAR are Geotech, model 8700C (horizontal) and model 7505B (vertical) which are moving coil, velocity type seismometers. The interconnected amplifiers are Ithaco, model 6083-82. The SP sensor used is a Hall-Sears HS-10-1/ARPA vertical seismometer. It is a spring-mass, velocity type instrument interconnected with a Texas Instrument RA-5 amplifier. Instrument response curves are given in Fig. 2. The NORSAR configuration indicates that the response of the array is fairly symmetric. The power is down about 20 dB at a wavenumber difference of 0.01 c/km, and the worst sidelobes are not more than about 5 dB above this level.

A brief outline of the geological structures in NORSAR siting area is given in Fig. 1. The pre-eocambrian rocks consist mainly of gneisses and granite. A sparagmite layer (probably 1-3 km thick) of eocambrian age is overlaying the pre-eocambrian rock complexes, but in some places even covers cambro-silurian sedimentary rocks. The Permian Oslo graben is characterized by plutonic rocks (mainly syenites and granites) and cambro-silurian sedimentary rocks. Preliminary analysis indicates that the geological structures as outlined above are reflected in the P-signal shape as a function of subarray site. For more details on the geology in the NORSAR area and Norway itself, we refer to Holtedahl (1960).

The crustal structures in Fennoscandinavia have been extensively studied by refraction shooting in recent years (see for example Sellevoll & Pomeroy 1968). In case of NORSAR, the Moho seems to have a somewhat complicated geometry according to most recent results (Kanestrøm, personal communication).

3. Data Transmission and Instrument Calibration

From the seismometers the recorded earth motions are transmitted through amplifiers at the top of the boreholes or pits and via trenched cables to the Central Terminal Vault (CTV) at the subarray center. The Long Period Seismometer Vault (LTV) is located nearby. The CTV is housing the Short and Long Period Electronic Module (SLEM) which multiplexes and digitizes the 9 seismometer outputs into a single bit stream. The sampling rate is 20 and 1 Hz for SP and LP seismometers respectively. To avoid aliasing effects, analog filters with high-frequency cut-off at 4.8 Hz are part of the SLEM. The data is then transmitted each 0.05 sec by means of ordinary telephone lines (2400 bauds) to the NORSAR Data Processing Center (NDPC) at Kjeller for further analysis.

It is, of course, a two-way data flow between the respective subarrays and NDPC, as time synchronization signals are sent to the SLEM each 0.05 sec. In addition, special commands may be sent to the SLEM from the Experimental Operations Console (EOC) for activating signal generators (sine pulses or pseudo random waves) to test and calibrate seismometers, SLEM and data transmission lines.

Drift of the LP seismometer mass position can be corrected remotely from NDPC by start and stop commands to small electromotors in these instruments. A display on the EOC enables the operator to check the status of any seismometer or subarray, and CTV and LTV information about open doors and possible water flow in the vaults can also be obtained.

Statistics on the performance of the transmission system will be printed out regularly, as an aid to localize and correct hardware errors which may always occur within a system of NORSAR's complexity.

The NORSAR transmission system, with a capacity of about 50 000 bauds of continuous data flow, makes NORSAR one of the largest on-line data transmission systems in Europe. In addition, one transatlantic link of 2400 bauds is used for on-line LP data transmission and communication between NORSAR and the data center in Alexandria, Virginia, for the LASA and ALPA seismic arrays.

4. Data Processing

The data received at NDPC is processed and stored on magnetic tape for a predefined retention period. The routine data analysis is performed in two steps, called detection processing (on-line) and event processing (off-line). The array monitoring and calibration functions are executed independently of the above analysis. Before we give an outline of the software system, it is appropriate to dwell briefly on the computers and peripheral equipment installed at NORSAR DPC, which are shown in Fig. 3. It is a dual computer configuration, i.e., the IBM 360/40 and related equipment such as tape and disc drives used for detection are identical to those for event processing. This means that continuous data recording and on-line analysis capabilities are retained also during the regular machine service periods. However, there is no duplicate of the Special Process System (SPS). Neither is there a duplicate of the EOC, but unlike the SPS this unit is not vital for the data recording and analysis.

4.1 Detection Processing

The Detection Processor (DP), outlined in Fig. 4, performs all functions associated with data acquistion and array monitoring. The DP also processes the incoming data in real time and decides whether or not a detection of a seismic event should be declared. The programs are divided in 7 tasks, where data acquisition and tape writing have the highest priorities. This will ensure that the recording takes priority over all other tasks in case of system overload. Several error checks are carried out in the SPS, which transfers data each 0.5 seceonds to the DP. Detected errors will be indicated on the output tape, thus ensuring the integrity of the recorded data. The SPS also performs some preprocessing of the seismometer signals, in order to relieve the DP of some processing load. This processing includes recursive filtering with two filters, A and B, and the forming of up to 20 subarray beams per filter for each of the 22 subarrays. These beams are slightly dispersed in order to decrease the maximum signal power loss in the subsequent array beamforming.

The Detection Processing task uses the subarray beams from the A filter as input to the array beamforming process. Up to 400 array beams may be formed by the DP, which includes options for additional filtering on the array beam level. These beams, which constitute the so-called Selected Surveillance, are steered towards the most interesting seismic regions. Due to the large aperture of NORSAR, this number of beams cannot cover adequately the whole teleseismic region of the array. A General Surveillance, using subarray beams from both filters, is therefore performed in parallel with the Selected Surveillance. It covers the whole teleseismic region, but with a lower detection capability.

The detection algorithm, performed individually on each subarray or array beam, is the following: The beam is rectified and integrated over a sliding time window (length around 2 sec), resulting in a short term average (STA). A long term average (LTA) is calculated by a recursive algorithm, thus providing a noise estimate which in principle is based on the history of the beam from the time the system was activated. The ratio STA/LTA is calculated at a specified rate for each beam. Whenever this ratio exceeds a certain threshold for a predefined number of successive times, a detection is declared on the corresponding beam. Fig. 5 shows an example of these calculations.

A seismic event may cause detections on several beams. This requires activation of a reduction process which in essence consists of finding the beam with the largest STA in the group of detections. In addition, it checks if the locations of the largest beams are close enough to ensure that it is not a false alarm. Whenever a detection has been declared, information consisting of start and end times, approximate location and size of the detected event, is written on the shared disk, which later will be read by the Event Processor.

The DP may also communicate with the EOC during on-line processing. Up to 8 signal traces can be displayed in real time on the Waveform Display, which can hold 45 seconds of data, including seismometer values and array beams. The Beam Display of the EOC can display in inverse velocity space all rectified and integrated array beams (or subarray beams) as enlighted squares with intensities proportional to the STA values.

4.2 Event Processing

The Event Processor (EP) outlined in Fig. 6 satisfies two objectives: first, the preparation of a daily seismic bulletin, and second, support of seismic research through the formation of a seismic data base. The EP receives the detections and the preliminary epicenter determinations from the DP, and it contains algorithms required to assign seismic phase identifications to the detections reported by DP, and to group the detection which belong to the same event. The EP also selects events for further processing, where different short period seismic parameters are extracted. It should be noted that so far routine processing of long period waves is not part of the NORSAR software system.

As Fig. 6 indicates, the output from the DP first enters the Event Process Controller (EPCON), which organizes the detections into event families in a Detection File. The EPCON then communicates with the Short Period Signal Processor (SPSP), which calls for raw data from High Rate Tape and for example regional corrections, from a permanent EP file in order to provide the EPCON with more detailed information about each event. The SPSP creates an EP Data File to produce a daily Seismic Bulletin, Event tapes, Plot tapes, a Summary Report, a Parameter Report, and a Detection/Bulletin report. The Output Processor also creates a Detection/Bulletin File, which the Editing Processor uses, together with the EOC and a 2260 Display Unit to allow the operator to edit the results, and, if desired, request extended processing.

The Event Processor Controller (EPCON) constitutes the main logic and control portion of the process. It starts with the merging of the DP detection groups from both the General and the Selected Surveillance beams, and the assignment of a seismic phase identification to each detection group. In order to keep the EP workload at a reasonable level, EPCON may change the EP threshold and thus determines whether a detection group shall be processed by the SPSP or not. This criterion depends on signal phase, amplitude, SNR, and the amount of computer time available in the processor. The EPCON also reviews selected results from the SPSP and modifies the initial phase identification if required, and it finally updates the Detection File for each detection group.

The Short Period Signal Processor (SPSP) is called upon by EPCON, and contains algorithms for extraction of more detailed information about the short period signal phases selected for further processing. The SPSP gives as output the wave parameters needed in the bulletin, waveform data, intermediate process results, and selected review parameters.

Included here is location in inverse velocity space, arrival time, depth phases with arrival times, and results of converting from inverse velocity space to geographical coordinate

The SPSP consists of three components, inverse velocity space estimation, waveform parameter extraction and event characterization. The location of the signal arrival in inverse velocity space is calculated by using the detection data as a starting point. The time alignment of the subarray beams which yields the array beam with the maximum SNR is determined by using a cross-correlation iterative technique for events with a sufficiently large SNR. Alternatively, the different subarrays are weighted according to the calculated correlation coefficients and SNR of the subarray beams. A linear sequential estimation algorithm is introduced for fitting a least squares plane wave to the derived delays. The resulting array beam and location in inverse velocity space are then passed on for further analysis.

Some basic signal parameters are extracted from the array beam waveform. The magnitude is determined by an algorithm based upon the assumption that the signal power is proportional to the kinetic energy of the P-waves, as the SP instruments are essentially velocity measurement devices. (The kinetic energy is included in the magnitude definition through the inclusion of the A/T term.) Arrival time is computed either by a threshold pick (emergent events) or by a model fit (impulsive events). The dominant period is estimated through a power spectral analysis, using the inverse of the frequency at which maximum power occurs. The signal amplitude is then calculated on the basis of dominant period and magnitude. Focal depth information is sought through the inclusion of a cepstrum analysis (see e.g. Cohen, 1970) on the array beam, taking into account the possibility of observing both pP, sP and PcP. This method has been developed to a stage where it succeeds for an acceptable number of events.

5. Data Analysis

An interim NORSAR data recording system comprising 18 SP seismometers from different subarrays became operational in Jan 1970. Data from about half a year has accumulated in this way, and preliminary analysis results will be discussed in this section.

The most important task has been to calculate precise time delays (Bungum & Husebye) and about 360 good events have been used. The measurements are computerized (IBM 1967) and performed in order to establish a library of regional time delay corrections (deviations from plane wavefronts). High accuracy in time delay data is essential, as estimated loss in array gain due to timing errors is (Steinberg 1965):

$$\text{Loss (in dB)} = 170(\sigma/\tau)^2$$

where σ is the standard deviation in the time delays and τ the dominant signal period. This effect has been verified empirically using 18 strong events from which the time delays were calculated accurately. The average signal power loss in the beamforming process was 2.0 ± 0.1 dB (probably due to signal incoherency), while the corresponding value for the delays calculated from a plane wave assumption was 5.7 ± 0.5 dB. This means that the average loss due to lack of steering delays was around 3.7 dB. On the other hand, noise suppression came close to the theoretical value for 18 uncorrelated sensors, namely, 12.6 dB. Measured time delay values vary, in general, between ± 0.5 sec across the array. Azimuth and $dT/d\Delta$ calculations give results which sometimes deviate significantly from those predicted from reported hypocenter parameters. Such anomalies should be attributed to heterogenities in the site and source regions.

Concerning signal similarity across the array, our results obtained so far indicate that this is to some extent dependent on the geology in the siting area (see Fig. 1). For example, signal coherency, measured through a 6 sec time window, is independent of station separation, and is distributed in an interval of 0.2 to 0.9 for signal frequencies above 2 Hz. However, within individual subarrays (data available limited to 01A and 01C) the geological structure is uniform enough to allow for signal coherency values around 0.7-0.95 in the whole frequency band. Therefore, signal power loss during beamforming on the subarray level is expected to be small, provided the time delays are sufficiently accurate.

Signal amplitude and maximum cross-correlation coefficients (sensor-beam combinations) vary considerably, but in general the highest values are found for sensors in the northeastern quadrant of the array. The worst case subarrays seem to be those situated in the Oslo graben (Fig. 1).

Power spectra calculated from P signals recorded at NORSAR are characterized by significant energy content for frequencies up to 4 Hz. Thus, in principle, NORSAR signals give more information about source parameters than corresponding, relatively low frequency LASA observations. However, on the beam level the difference between the two arrays is lesser as a significant part of the high frequency energy is lost due to small errors in the steering delays and signal incoherency. It should be noted that for many events the calculated regional corrections depend on signal frequency, i.e., type of bandpass filter used. Observed spectral minima for the individual subarrays are to some extent independent of source regions, and henceforth should be interpreted in terms of site structures. So far, satisfactory models for explaining this phenomenon have not been found.

A major objective of analysis on interim NORSAR recorded signals was optimal filter setting for the Detection Processor. The chosen procedures include spectral analysis (Fig. 7 and 8) and calculations of the SNR parameter through a large number of bandpass filters, where bandwidth and center frequency are perturbed in steps of 0.4 Hz. Typical results for the time domain analysis are displayed in Fig. 9. For a given bandwidth the SNR decreases both towards coherent noise (low frequency), and incoherent signal pulses (high frequency).

The most important single parameter is the lower cutoff point of the filter used. The final filter setting is a compromise between the above considerations, although this choice cannot be regarded as critical because of the large SNR peak area.

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Figure Captions

Fig. 1. NORSAR array configuration. The geological structures in the siting area are briefly outlined.

Fig. 2a. Short period system response.

Fig. 2b. Long period seismometer response.

Fig. 3. Hardware configuration of the NORSAR Data Processin Center (NDPC).

Fig. 4. NORSAR Detection Processor. Task numbers are encircled.

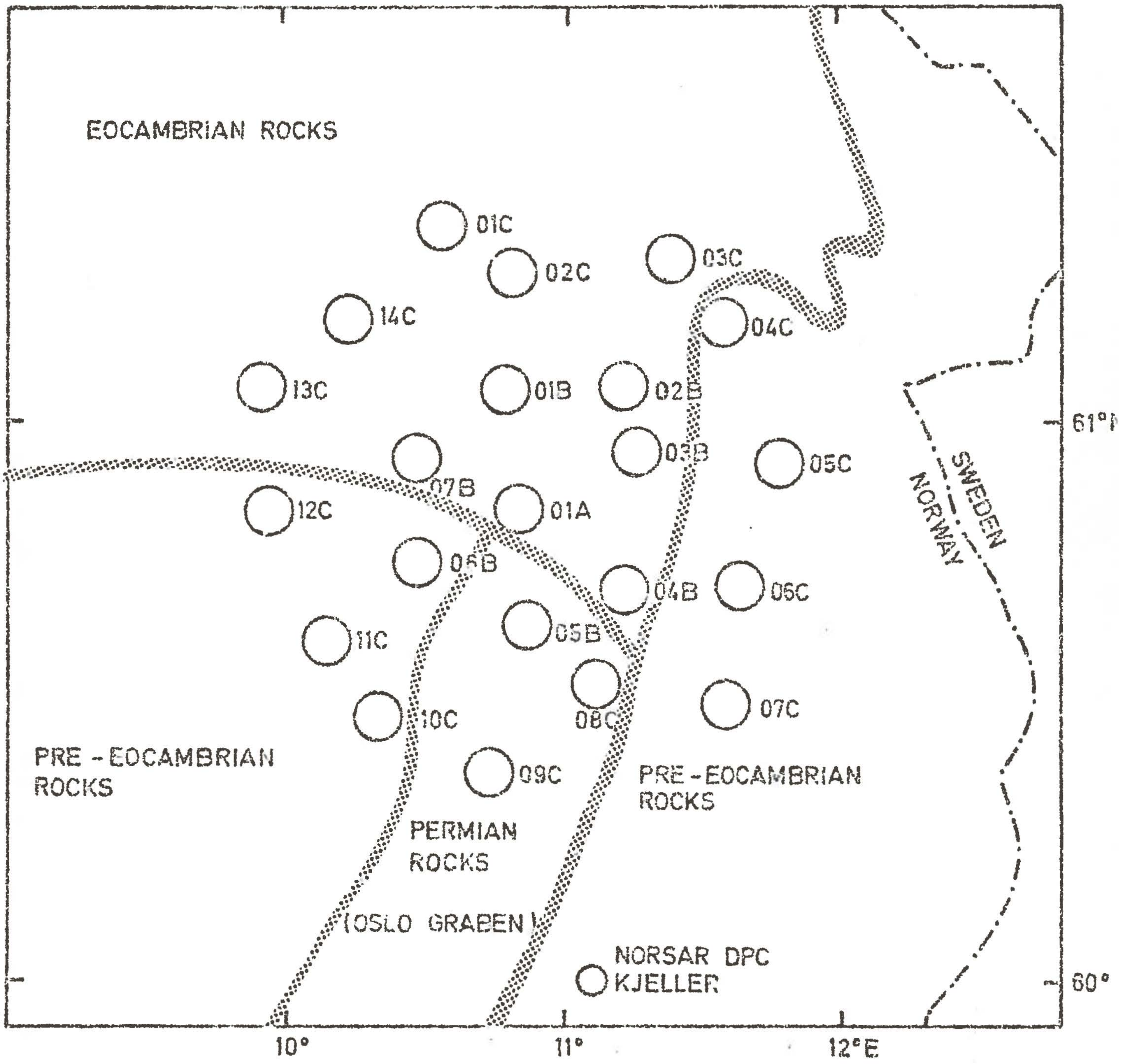
Fig. 5. Beam, STA, LTA and STA/LTA for earthquake from Tsinghai, China, 27 Feb 1970. Filtered 1.0-3.0 Hz. STA integration time is 1.8 sec, and LTA computation rate is 5/9 Hz. The short line above the STA/LTA curve indicates detection state, and the line crossing the curve is the threshold.

Fig. 6. NORSAR Event Processor.

Fig. 7. Unfiltered beam based on 18 subarray center seismometers for an earthquake at Honshu (29 Jan 1970, 06.03.22).

Fig. 8. Signal to noise ratio for the signal in Fig. 7. Th noise power is averaged over 4 blocks of 25.6 sec o data, and the signal power is estimated using a tapered 6 sec signal interval. In the latter case, zeroes are added to increase frequency resolution. The spectra are finally hammed.

Fig. 9. Signal to noise ratio for the signal in Fig. 7. The measurements are performed in the time domain, using a 30 sec noise interval and a 3 sec signal interval. The SNR parameter is computed through a large number of third order Butterworth bandpass filters, constituting the 'filter space'. The contour interval is 2 dB.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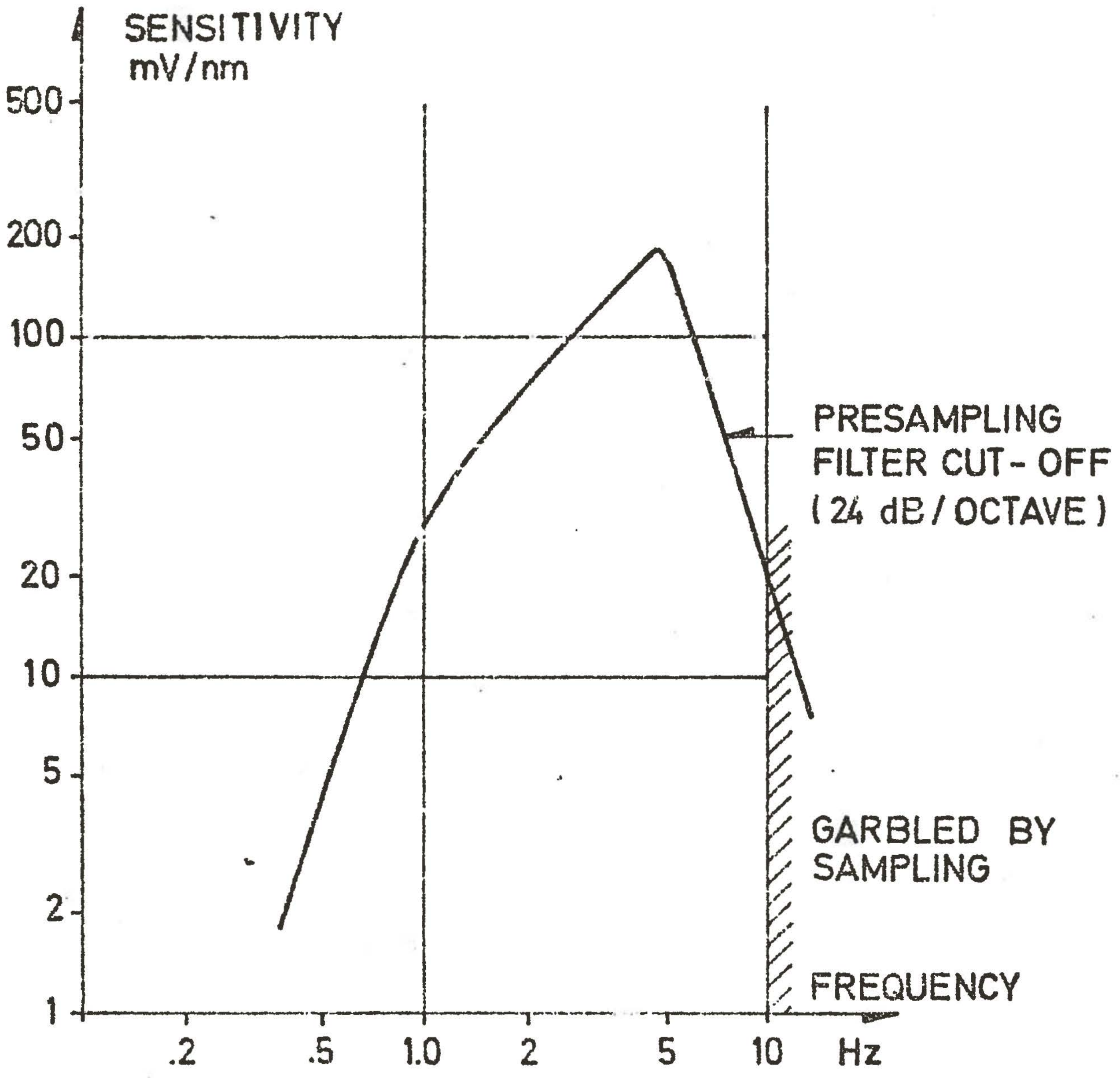
01C
02C
03C
14C
04C
13C
01B
02B
61°
03B
05C
07B
12C
01A
SWEDEN
NORWAY
06B
04B
06C
11C
05B
08C
07C
10C
PRE - EOCAMBRIAN ROCKS
09C
PRE - EOCAMBRIAN ROCKS
PERMIAN ROCKS
(OSLO GRABEN)
NORSAR DPC KJELLER
60°
10°
11°
12°E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mV/nm
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200
100
50
20
10
5
2
1
PRESAMPLING
FILTER CUT-OFF
(24 dB/OCTAVE)
GARBLED BY
SAMPLING
FREQUENCY
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.5
1.0
2
5
10
Hz

Fig. 2a

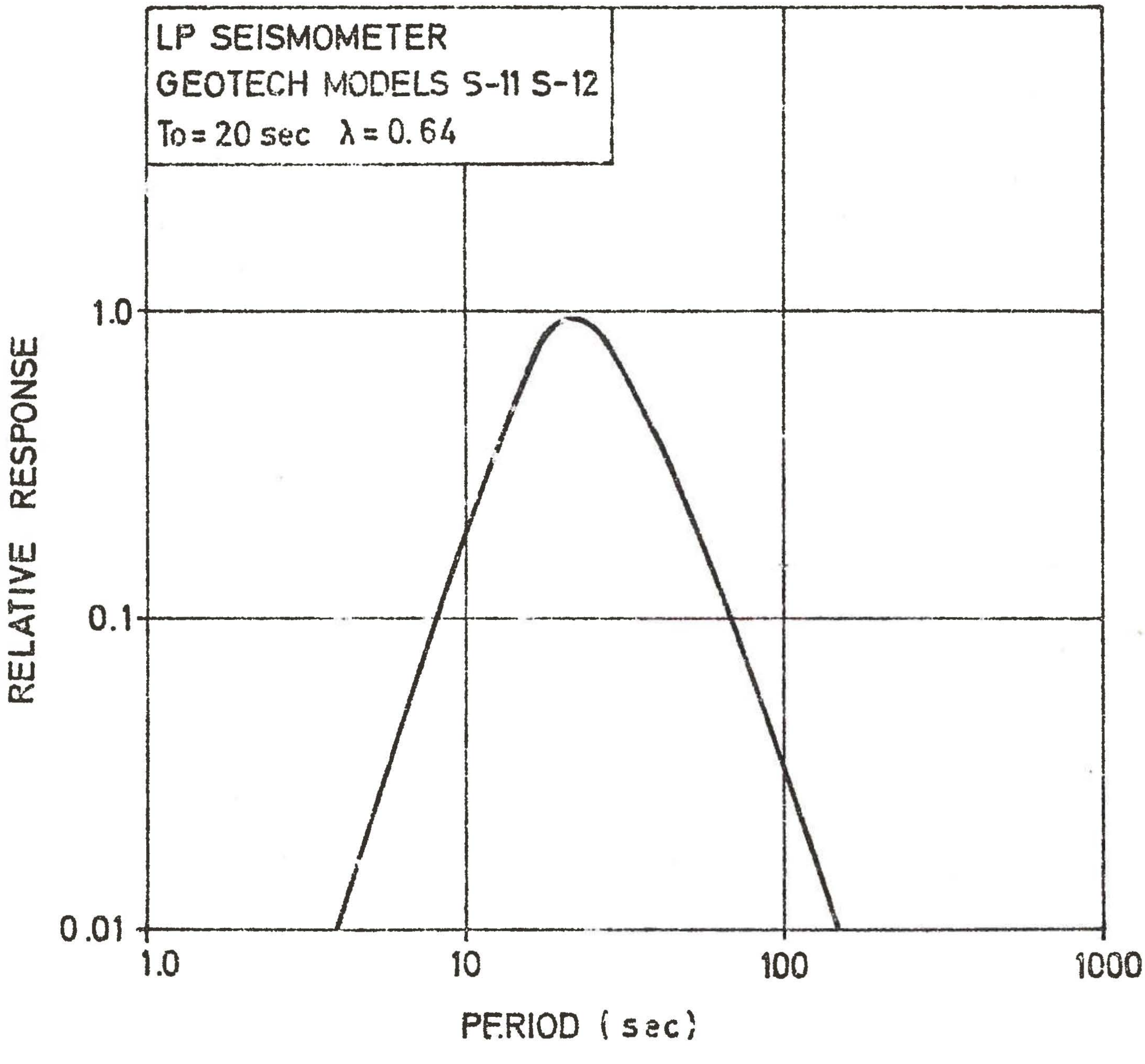

LP SEISMOMETER
GEOTECH MODELS S-11 S-12
To = 20 sec λ = 0.64
RELATIVE RESPONSE
1.0
0.1
0.01
1.0
10
100
1000
PERIOD (sec)

Fig. 2b

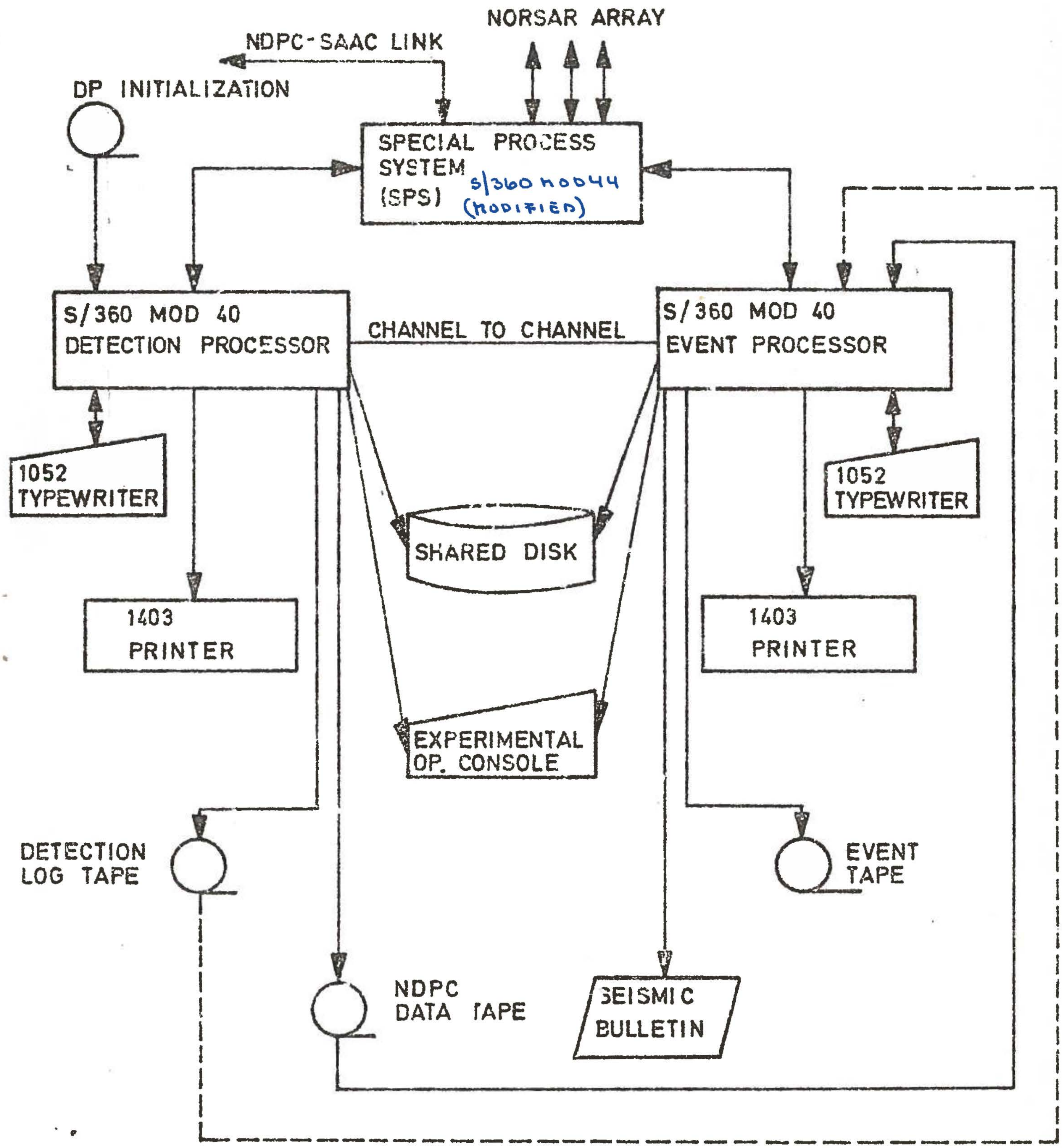
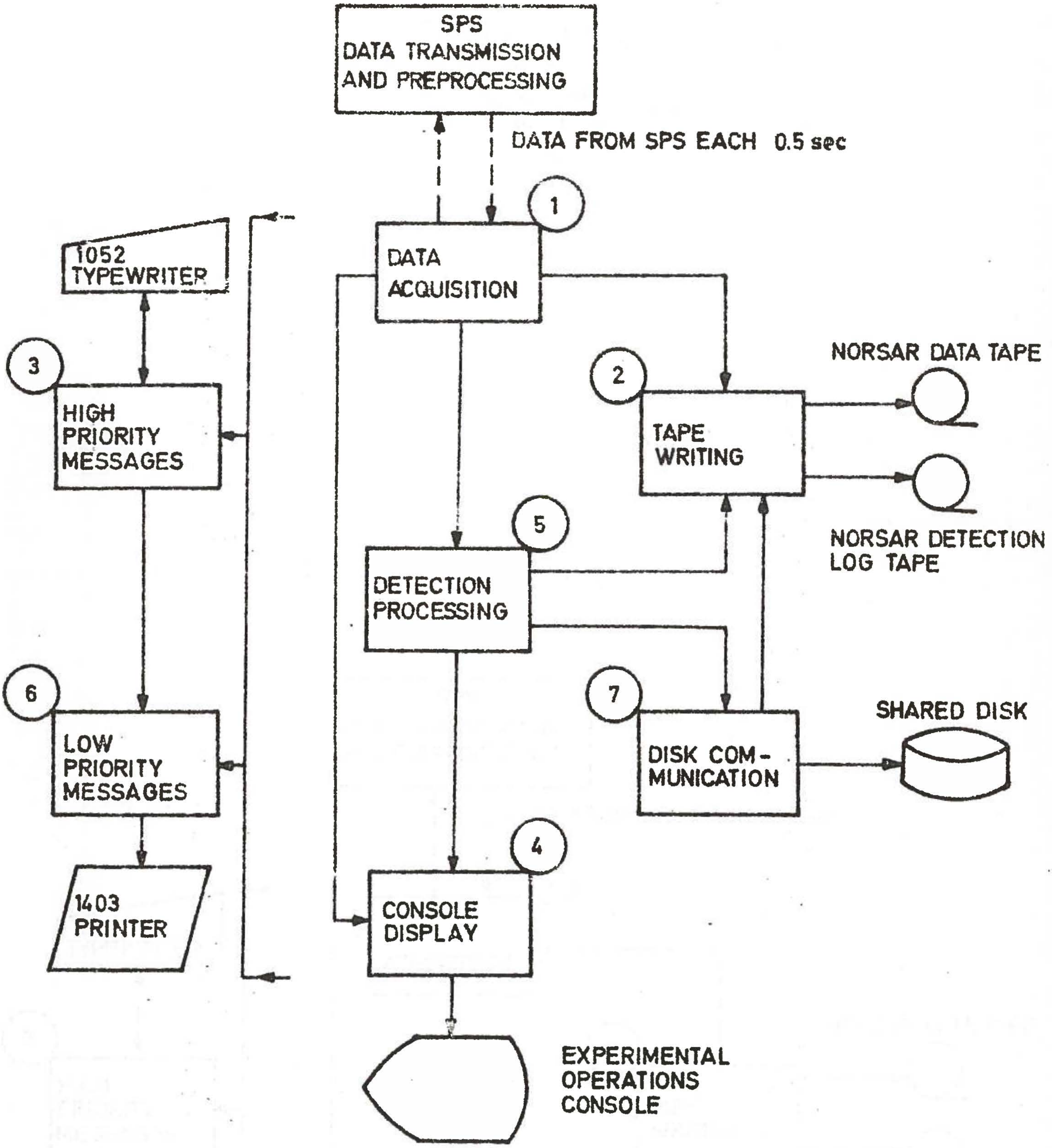

NORSAR ARRAY
NDPC-SAAC LINK
DP INITIALIZATION
SPECIAL PROCESS SYSTEM (SPS)
S/360 MOD44 (MODIFIED)
S/360 MOD 40 DETECTION PROCESSOR
CHANNEL TO CHANNEL
S/360 MOD 40 EVENT PROCESSOR
1052 TYPEWRITER
1052 TYPEWRITER
SHARED DISK
1403 PRINTER
1403 PRINTER
EXPERIMENTAL OP. CONSOLE
DETECTION LOG TAPE
EVENT TAPE
NDPC DATA TAPE
SEISMIC BULLETIN

Fig. 3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DATA TRANSMISSION
AND PREPROCESSING
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1
DATA
ACQUISITION
1052
TYPEWRITER
3
HIGH
PRIORITY
MESSAGES
2
TAPE
WRITING
NORSAR DATA TAPE
NORSAR DETECTION
LOG TAPE
5
DETECTION
PROCESSING
6
LOW
PRIORITY
MESSAGES
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OPERATIONS
CONSOLE

Fig. 4

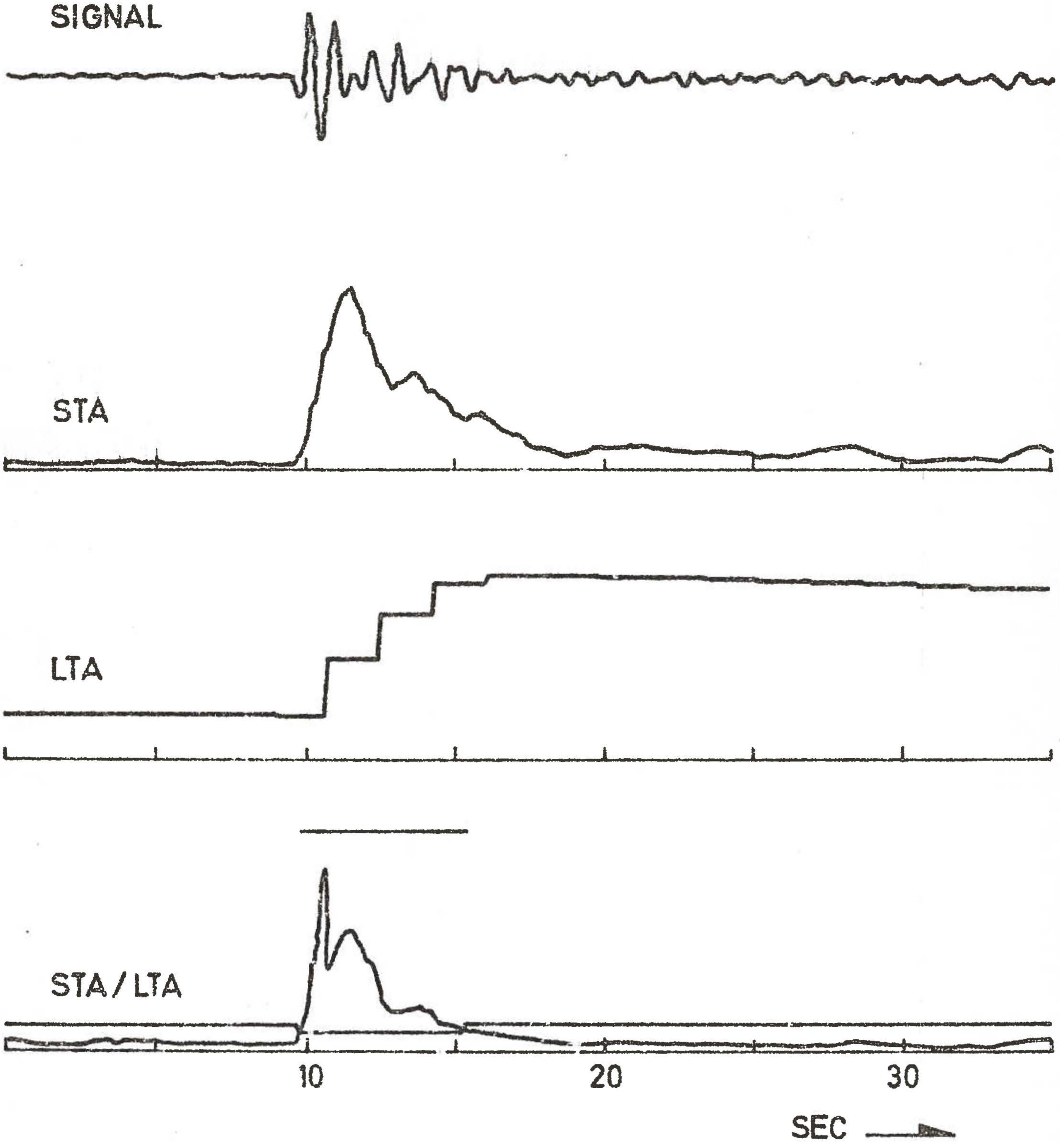
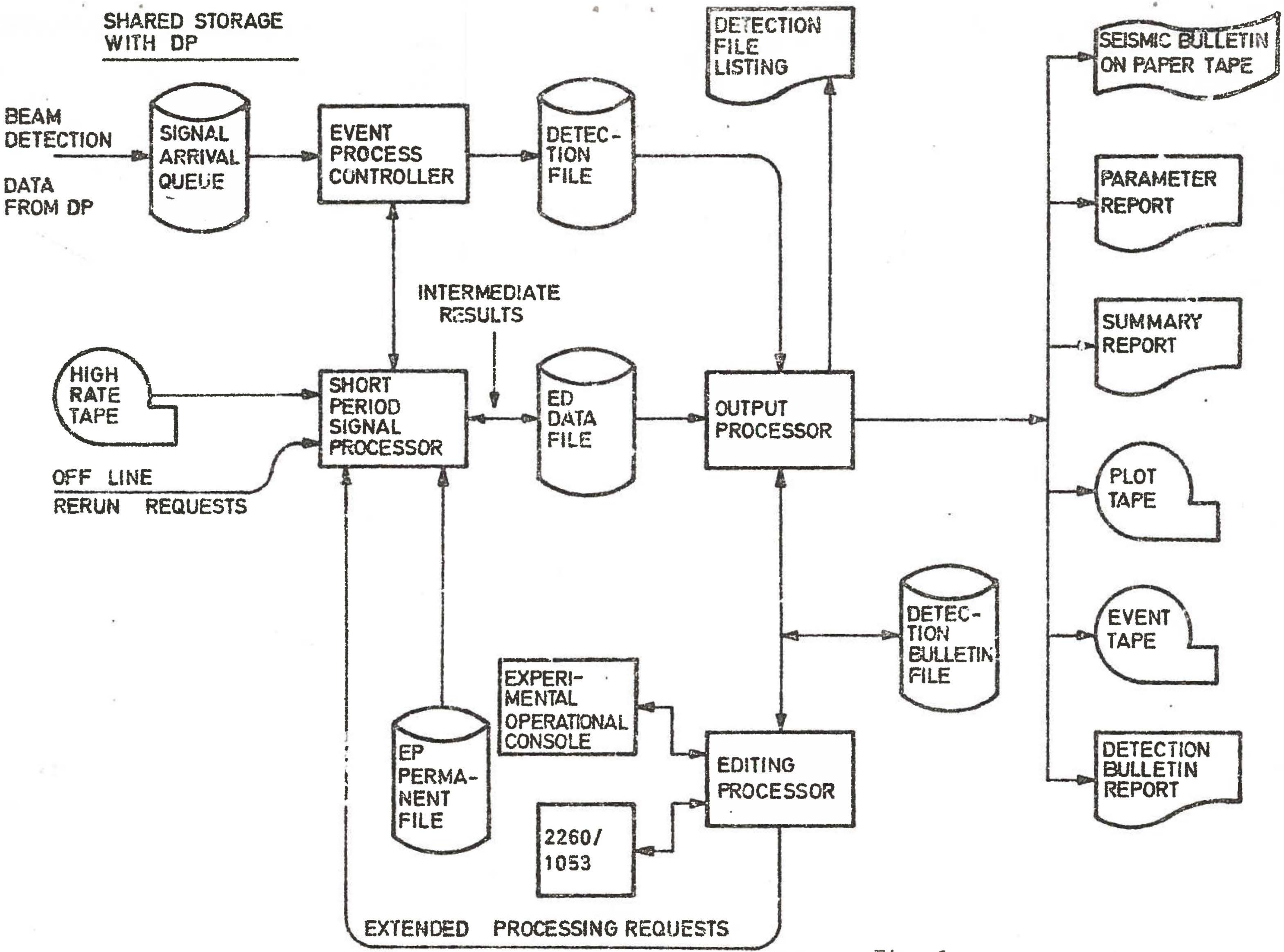


Fig. 5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BEAM DETECTION
DATA FROM DP
SIGNAL ARRIVAL QUEUE
EVENT PROCESS CONTROLLER
DETECTION FILE
DETECTION FILE LISTING
SEISMIC BULLETIN ON PAPER TAPE
PARAMETER REPORT
SUMMARY REPORT
INTERMEDIATE RESULTS
HIGH RATE TAPE
SHORT PERIOD SIGNAL PROCESSOR
ED DATA FILE
OUTPUT PROCESSOR
OFF LINE RERUN REQUESTS
PLOT TAPE
DETECTION BULLETIN FILE
EVENT TAPE
EXPERIMENTAL OPERATIONAL CONSOLE
EP PERMANENT FILE
EDITING PROCESSOR
DETECTION BULLETIN REPORT
2260/1053
EXTENDED PROCESSING REQUESTS

Fig. 6

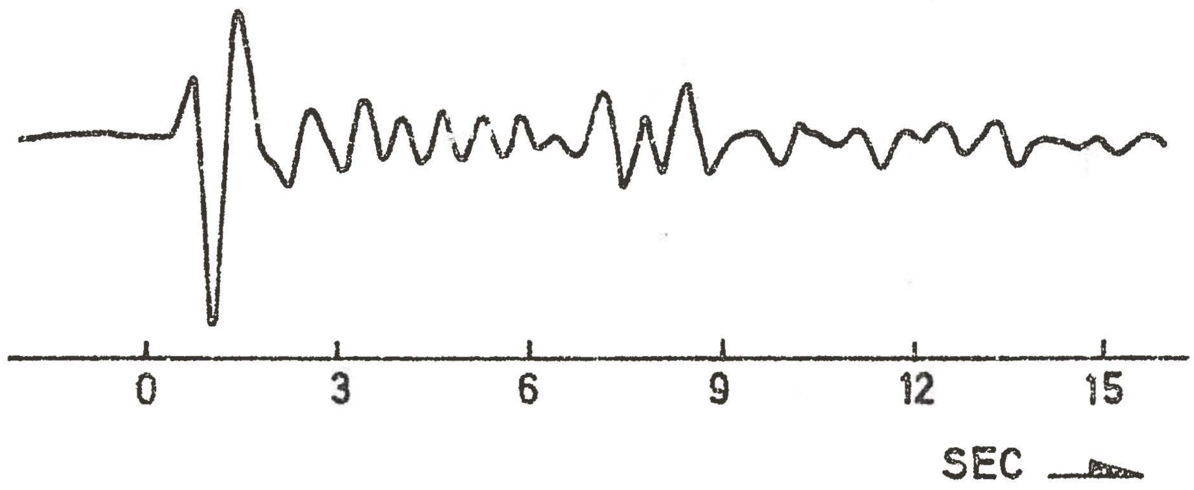


Fig. 7

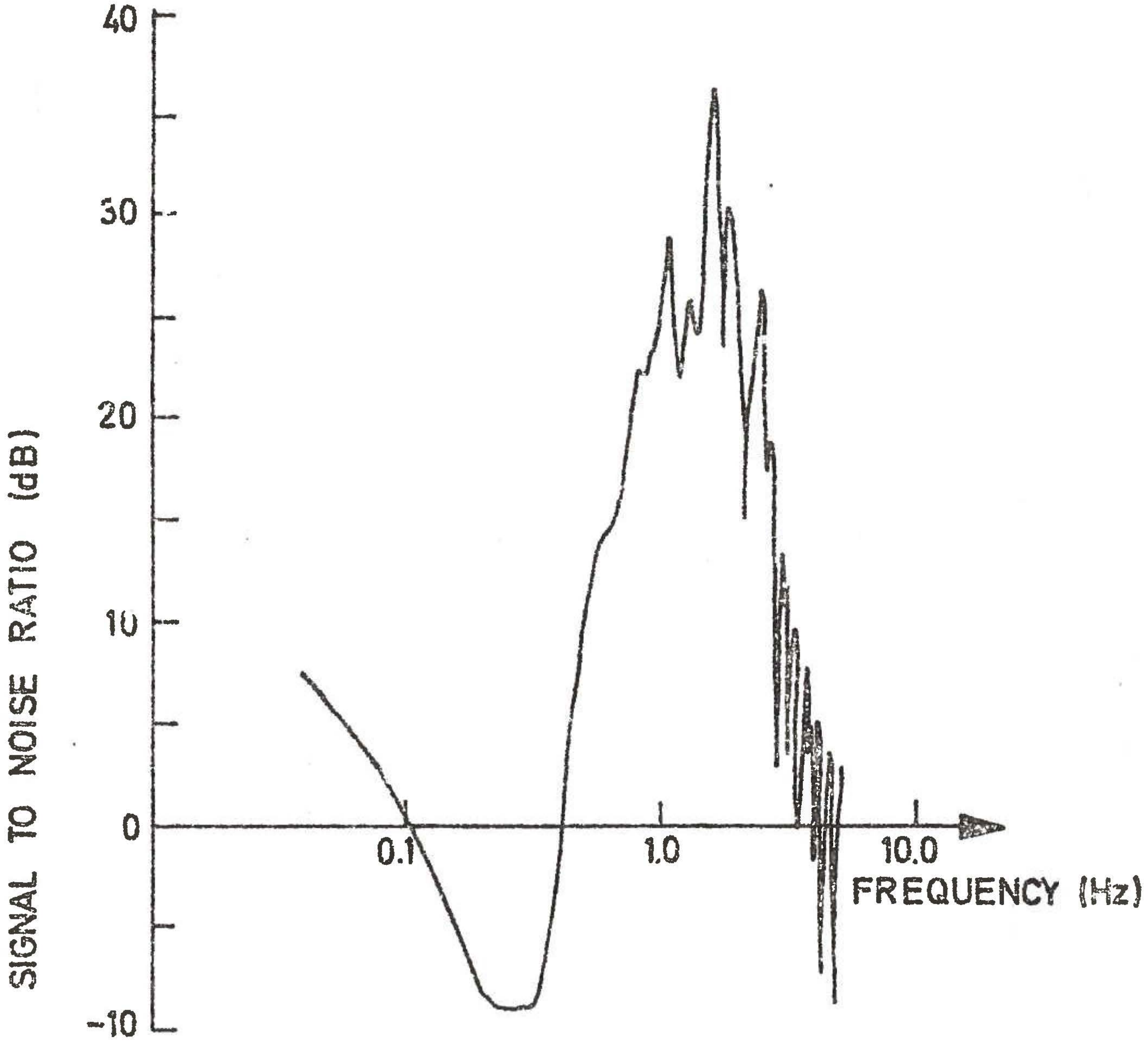
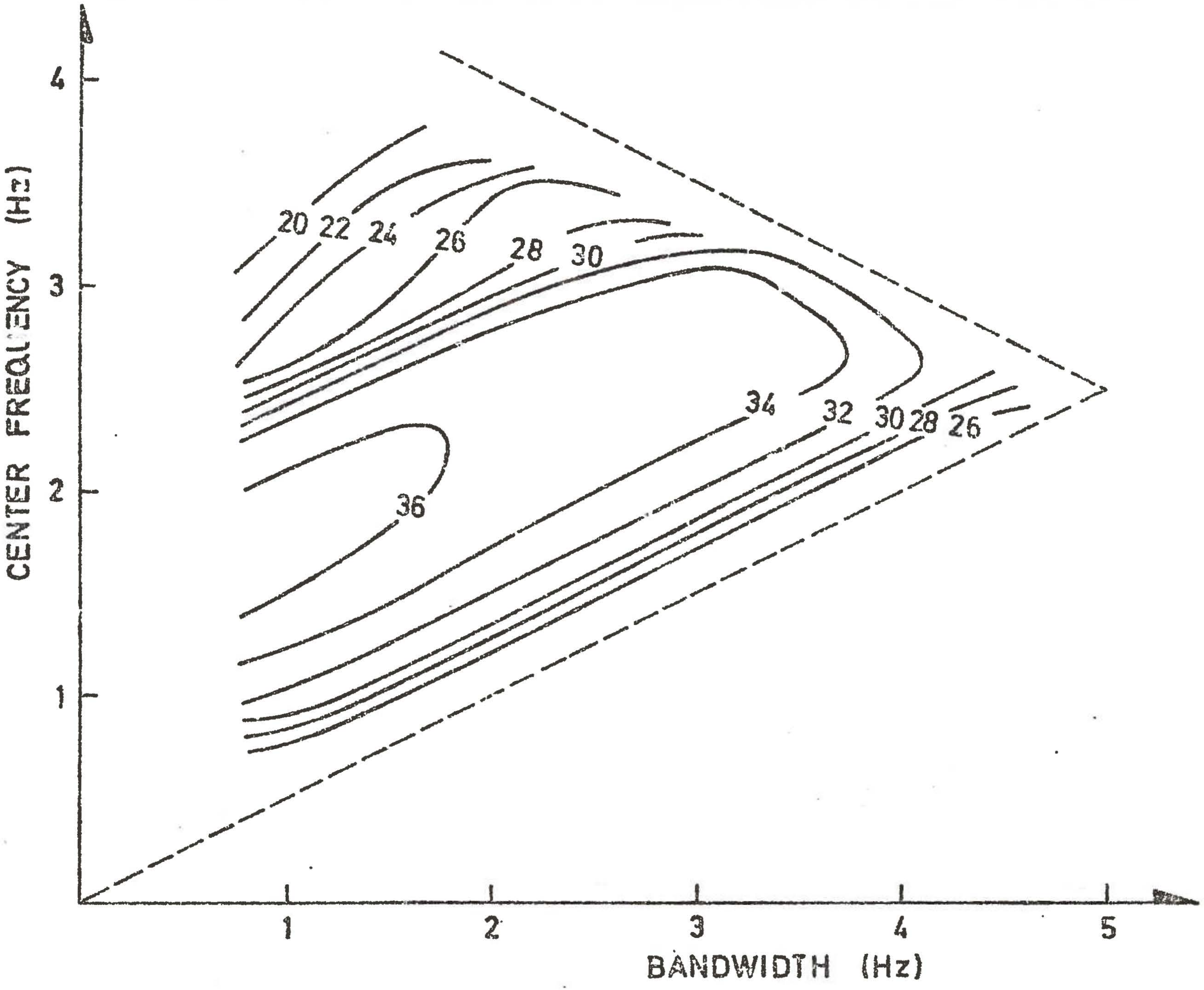


Fig. 3

Fig. 9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