NORSAR

FINAL REPORT

15 November 1986 - 14 December 1987

for project

DEVELOPMENT AND EVALUATION OF A NEW REGIONAL SEISMIC ARRAY IN FENNOSCANDIA

Edited by

Svein Mykkeltveit

Kjeller, 14 February 1988

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Sponsored by

Advanced Research Projects Agency (DOD)
ARPA Order No. 4950/7

Monitored by AFOSR under Contract No. F49620-87-C-0032

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION: UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT: APPROVED FOR PUBLIC RELEASE DISTRIBUTION UNLIMITED
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S): AFOSR-TR- 88-1009
6a. NAME OF PERFORMING ORGANIZATION: NTNF/NORSAR; 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION: AFOSR
6c. ADDRESS (City, State, and ZIP Code): POST BOX 51, N-2007 KJELLER, NORWAY	7b. ADDRESS (City, State, and ZIP Code): Building 410, Bolling AFB DC 20332-6448
8a. NAME OF FUNDING/SPONSORING ORGANIZATION: AFOSR; 8b. OFFICE SYMBOL (If applicable): NP	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: CONTRACT NO. F49620-87-C-0032
8c. ADDRESS (City, State, and ZIP Code): Bldg 410, Bolling AFB DC 20332-6448	10. SOURCE OF FUNDING NUMBERS: PROGRAM ELEMENT NO. 62714E; PROJECT NO. 4950; TASK NO. 10; WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)
(U) DEVELOPMENT AND EVALUATION OF A NEW REGIONAL SEISMIC ARRAY IN FENNOSCANDIA

12. PERSONAL AUTHOR(S) S. MYKKELTVEIT (ED.)

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final	FROM 15 Nov 86 TO 14 Dec 87	May 1988	56

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Array, Beamforming, Seismic
	08.11		

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This final report describes the work conducted by NORSAR in conjunction with project no. F49620-87-C-0032 during the entire contract period of 15 November 1986 - 14 December 1987.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: ☒ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION: UNCLASSIFIED
22a. NAME OF RESPONSIBLE INDIVIDUAL: Lt Col Bruce L. Smith	22b. TELEPHONE (Include Area Code): (202) 767-4908; 22c. OFFICE SYMBOL: AFOSR/NP

Form 1473, JUN 86 Previous editions are obsolete. SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

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SUMMARY

This final report describes work performed by NORSAR in conjunction with project no. F49620-87-C-0032 during the period 15 November 1986 - 14 December 1987.

In 1984, the NORESS regional array was installed in southern Norway. This contract provides for the deployment of another NORESS-type regional array in Norway, and the main purpose of this effort is to conduct research on how several regional arrays can be employed together using the pooled data in a simultaneous processing scheme.

A site for deployment of the new array was identified near Karasjok in northern Norway, and final approval by the relevant local authorities for permission to deploy an array at the designated site was granted in early July of 1987.

This report describes the work associated with the different tasks of the site preparation and field system deployment, the arrangements for satellite transmission of data from the array site to NORSAR's data processing center at Kjeller, and the installation of an interim system for acquiring and archiving data at Kjeller.

A central terminal building was constructed to house the core of the field system. Approximately 30 km of both fiber optic and power cables were trenched to connect the seismometer sites with the central building. 25 seismometer surface vaults were built, and a borehole for the broadband seismometer was prepared at the center of the array.

All essential site preparation work was completed by the end of August, so that the actual system installation could

start on 1 September. The field system deployment was completed on 28 September, and at the same time, the satellite link for transmitting the data to Kjeller was in place.

Data from the new installation were acquired and analyzed at Kjeller from 1 October. The analysis showed certain technical problems and needs for fine-tuning the system. These problems were solved during October, and the system was ready for regular operation from approximately 1 November.

The report also summarizes the efforts that went into the development of software for acquiring the data from the new array, and also the development of both a state-of-health monitoring system and software to be used for processing the data.

A final chapter is devoted to a preliminary assessment of the capabilities of the new array. The results from this study indicate that the new array fully matches the capabilities of NORESS in terms of regional detection, location and phase identification. The joint analysis of data from the two arrays has been shown to provide event location estimates that represent significant improvements over one-array estimates.

1. BACKGROUND

NORSAR has, through the past several years, conducted extensive research on the propagation of seismic phases and the structure of the seismic noise field at high frequencies. The emphasis has been on studying high frequency signals recorded in Fennoscandia (Scandinavia and Finland) for seismic events from Eurasia. The associated travel paths have been shown in various studies to provide extremely efficient propagation of high frequency energy. Since Fennoscandia is located within the same geologic plate boundary as the Soviet Union, such studies will provide important new insight with respect to the projected performance of possible future in-country stations in the U.S.S.R.

A major development was the installation of the regional seismic array NORESS in Norway in 1984. Results from evaluations of NORESS have been extremely encouraging, as the array has proved capable of taking advantage of the very efficient propagation of high-frequency seismic phases in Eurasia to provide a breakthrough in the detection and location of very small underground explosions at regional distances (0-2000 km). This research is particularly relevant in view of the possible deployment of several internal seismic stations on U.S.S.R. territory under future test ban treaties.

In order to assess the eventual capabilities of the new NORESS concept, it is necessary to conduct research on how several such arrays can be employed together, using the data in a simultaneous processing scheme. As an initial effort in this direction, we proposed in 1986 the development of a second such array in Fennoscandia. The decision was made to support the development of such a new array, and a site for this second regional array was identified near Karasjok in northern Norway, at a distance of about 1100 km from NORESS. This final report describes the work performed by NORSAR in conjunction with the installation and preliminary evaluation of the capabilities of this new array.

II. OVERVIEW OF WORK CONDUCTED UNDER THIS CONTRACT

The main objective of this contract was the site preparation and subsequent installation of a new regional array in northern Norway, to complement the existing NORESS array in southern Norway. The work also comprised the planning of and preparation for data transmission via satellite from the array site to Kjeller, where the data are acquired and processed. A preliminary assessment of the array capabilities is also part of the effort under this contract.

II.1 Site selection, site preparation and field deployment

The majority of the work under this contract was related to the preparation of the array site preceding deployment of the field system. Chapter III gives an overview of the work related to the selection of a site for the new array and the procedures for obtaining the approval of the local authorities, in order to enable us to go ahead with our plans. Chapter IV gives an account of the actual work performed in the field in preparation for the system deployment, and the chapter also summarizes the work conducted in installing the field system. This work was done in close cooperation between NORSAR personnel and representatives of the Sandia National Laboratories, who delivered the field system.

II.2 Satellite transmission of data

This contract called for an effort in planning for the transmission of data from the new array site to NORSAR's data processing center at Kjeller. Chapter V summarizes our work in this regard, and also gives details on initial operational experience. The actual costs of establishing the satellite link and the charges for transmitting data have been incorporated in a FY88 contract on the operation and further development of the new array.

II.3 Data acquisition and processing

The software for acquiring and processing the data from the new array was developed jointly by Science Horizons, Inc., San Diego, California, and NORSAR. Chapter VI summarizes these efforts and also gives details on the temporary arrangements for data acquisition and processing at Kjeller, as well as on the plans for a complete system to be acquired for these purposes.

II.4 Preliminary assessment of array capabilities

The background noise level of the new array site and the array's potential for noise suppression by beamforming have been checked using data from the initial period of operation. Furthermore, the event detection threshold and event location capability of the array have been assessed. In addition, the joint capabilities of the new array and NORESS have been addressed. The results are given in Chapter VII.

III. INITIAL WORK RELATED TO SITE SELECTION, PREPARATION OF SPECIFIC PLANS, AND APPROVAL BY LOCAL AUTHORITIES

III.1 Site selection and surveying

During field reconnaissance trips in the fall of 1986, a site was identified near Karasjok, Finnmark, in northern Norway that best conformed with our requirements. The site has the appropriate distance from NORESS, is located inland (away from noisier coastal areas) in an area of stable and mainly dry climate. The geology is an outcropping gabbro formation, which means high-velocity, high-density rocks all the way to the surface. Furthermore, the site is within one hour's drive from an airport (Lakselv) serviced by regular flights with connections to and from Oslo. The community of Karasjok (approximately 1500 inhabitants) is located 8 km from the array. The geographical coordinates at the center of this site are 69.535° N, 25.506° E.

Initial surveying was undertaken in late 1986. These measurements established that the deployment of an array with a geometry like that of NORESS was feasible at the designated site, with some minor local adaptations. The final surveying to pinpoint the ultimate seismometer locations was undertaken in June of 1987, after the snow cover had gone. Fig. III.1 shows the geometry of the new array and explains which channels are assigned to each of the 25 sites of the array configuration. Table III.1 gives the geometry numerically, with the cartesian coordinates of each position, relative to the vertical short-period instrument at the center (A0) of the array.

CID	SITE	COMP	NS(M)	EW(M)	ELEV(M)	INSTRUMENT
20	A0	SPZ	0	0	403	GS-13
60	A0	SPN	0	-1	403	GS-13
A0	A0	SPE	1	-1	403	GS-13
01	A1	SPZ	160	53	411	GS-13
02	A2	SPZ	-121	77	392	GS-13
03	A3	SPZ	-30	-149	402	GS-13
04	B1	SPZ	336	82	414	GS-13
05	B2	SPZ	97	294	397	GS-13
06	B3	SPZ	-269	189	376	GS-13
07	B4	SPZ	-225	-231	378	GS-13
08	B5	SPZ	158	-283	405	GS-13
09	C1	SPZ	690	81	381	GS-13
21	C2	SPZ	387	665	395	GS-13
61	C2	SPN	387	666	395	GS-13
A1	C2	SPE	385	666	395	GS-13
10	C3	SPZ	-214	673	376	GS-13
22	C4	SPZ	-616	229	377	GS-13
62	C4	SPN	-617	229	377	GS-13
A2	C4	SPE	-617	228	377	GS-13
11	C5	SPZ	-538	-296	374	GS-13
12	C6	SPZ	-81	-683	395	GS-13
23	C7	SPZ	530	-471	362	GS-13
63	C7	SPN	531	-470	362	GS-13
A3	C7	SPE	529	-469	362	GS-13
13	D1	SPZ	1491	135	395	GS-13
14	D2	SPZ	1143	972	366	GS-13
15	D3	SPZ	188	1651	331	GS-13
16	D4	SPZ	-858	1181	371	GS-13
0A	D5	SPZ	-1494	-233	351	GS-13
0B	D6	SPZ	-1347	-613	413	GS-13
0C	D7	SPZ	-607	-1360	413	GS-13
0D	D8	SPZ	392	-1443	368	GS-13
0E	D9	SPZ	1173	-778	359	GS-13
C2	E0	IPZ	-2	-5	356	KS-36000-04
C2	E0	IPN	-2	-5	356	KS-36000-04
C2	E0	IPE	-2	-5	356	KS-36000-04
C2	E0	LPZ	-2	-5	356	KS-36000-04
C2	E0	LPN	-2	-5	356	KS-36000-04
C2	E0	LPE	-2	-5	356	KS-36000-04

Table III.1 Configuration of the new Finnmark array, with channel identification (CID), site name, ground motion component recorded, cartesian coordinates relative to vertical instrument at A0, site elevation and instrument type. In addition to the channels in the short period (SP), intermediate period (IP) and long period (LP) bands defined in this table, the 3-component data from the element at site A0 are also recorded by a high-frequency (HF) system, using a sampling rate of 125 Hz. The sampling rates are otherwise 40 Hz for the SP data, 10 Hz for IP data and 1 Hz for LP data.

MAP OF ARRAY ELEMENT LOCATIONS

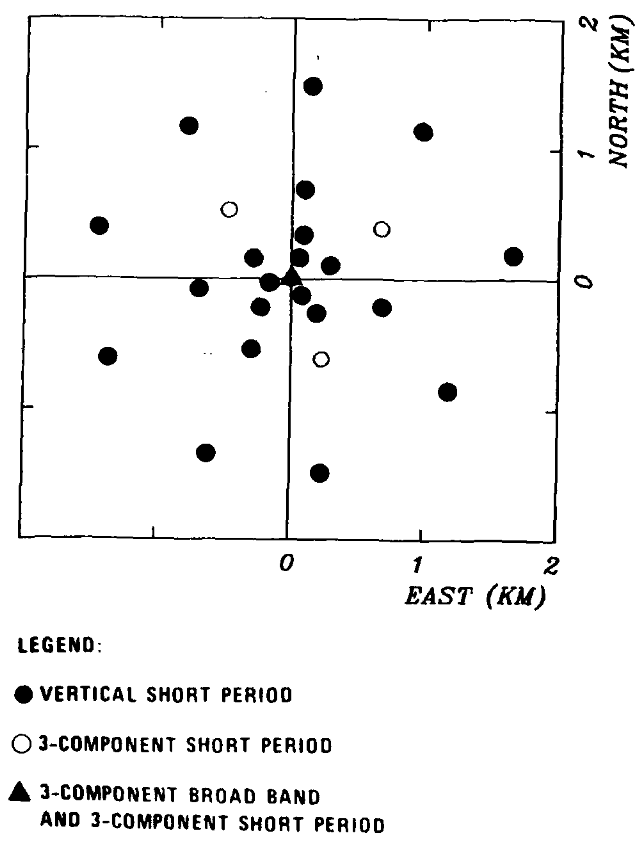


Fig. III.1 The geometry of the new array installed near Karasjok in Finnmark, northern Norway.

III.2 Plans for site preparation

During the spring of 1987, the work under this contract concentrated on working out detailed plans for all aspects of the site preparation work. This was done in close cooperation between the NORSAR staff and an engineering consultancy company that was contracted to assist us in this. During this planning period, regular consultations with Sandia took place, and Sandia representatives also visited the site in April, 5 months prior to the field installation phase. In writing the specifications for the site preparation work, experiences from the NORESS deployments in 1984 was heavily drawn upon. Still, it became clear that some work would have to be conducted in manners different from what was done for NORESS because of the environmental concerns that generally apply in the region of the new array. The conditions at the site are such that construction work and terrain traffic may easily cause unrestorable damage to vulnerable vegetation, etc. Also, the general area is to some extent used by the laplanders for their reindeer. For these reasons, we emphasized developing plans for site preparation work that represented a minimal impact on the environment, but that were still technically sound.

The detailed description of the various tasks related to the site preparation were made available to local construction companies in the form of tender documents, for public bidding.

III.3 Procedures for obtaining permission to deploy the array

It was necessary to obtain permission by both county and community authorities to install the array at the designated site. The general plans were submitted in February to the appropriate authorities for their approval. These authorities were responsible for collecting reports, reviews and statements on our plans in support of their own decisions. A considerable number of organizations were involved in the matter, and they all gave their statements by mid-June. The final approvals to our plans were granted in early July. In addition to obtaining these approvals, we arranged for the lease of the land (owned by the government) that is used for the installation, and negotiated with the organization of the laplanders on the subject of an annual compensation. The laplanders have traditional rights to use this area for their reindeer, and were consequently entitled to a compensation to account for the damage to the vegetation and other possible future reduction in the value of the area, relative to the laplanders' use of it.

IV. WORK RELATED TO SITE PREPARATION AND FIELD DEPLOYMENT

In this chapter, we describe the work conducted in relation to the various items of the site preparation, and the installation of the field system.

The actual work associated with the various site preparation tasks was done by local construction companies, following the public bidding. One (at certain periods more than one) NORSAR representative was present at the array site throughout the period to overlook and supervise both the progress of the work and the performance of the contractors. The work had to await the final approval of our plans by the authorities, and hence started in early to mid-July, for the majority of the work items.

IV.1 Construction of a central terminal building

The work associated with this task started in July by a helicopter lift to the central site in the array of all materials needed for the construction of the facility. The building was essentially completed by the end of August, so that the building with all its facilities could be used during the deployment of the field system in September.

Commercial power was provided by a new 2.5 km long power line built by the local electricity company. This line was completed in early October, and it was necessary to provide electricity by a diesel generator until the new line was in place.

The central terminal building has an instrument room for the hub equipment, two storage rooms and facilities for personnel visiting the site (living room, kitchen, washrooms, etc.). The building is insulated in order to maintain standard room temperature. The size of the building is approximately 80 m^2.

IV.2 Fiber optic and power cables

Approximately 30 km of armoured fiber optic and 30 km of armoured power cables were purchased in Norway. The entire shipment of cables was delivered in July and lifted by helicopter to the central site of the array. Each of the 25 single sites of the array geometry (see Fig. III.1) was connected with the central terminal building by one power cable and one fiber optic cable.

Approximately 15 km of trenches were needed to interconnect all seismometer sites with the central building. All cables were buried at a depth of 10 cm or more all over the array. The backfilling was done by hand, to avoid damage to the cables. The trenching operation was done with due care, to avoid damage to the terrain and the vulnerable vegetation.

IV.3 Seismometer surface vaults

The surface vaults for seismometers and the housing for the electronics at each seisometer site were carefully planned to meet both the technical requirements for field deployment of such equipment, and the constraints imposed by the environmental conditions. It was a requirement, among other things, that no rock blasting should take place in connection with this deployment, in contrast to what was done for the NORESS installation. Thus, we developed plans for installations directly on the bedrock, which in this area is exposed or covered by a very thin layer of overburden. Thus, each seismometer was placed inside a drum-shaped housing (three drums for each of the four three-component sites) and the electronics "blue box" was placed in a rectangular-shaped chamber next to the seismometer, with a styrofoam isolation material between the walls of the chamber and the blue box, to ensure that the blue box electronics do not experience temperatures below 0°C. The layer of styrofoam was planned to be sufficient to maintain temperatures above 0°C, even though the outside temperature drops to -40°C. This is possible because the electronics themselves dissipate heat corresponding to approximately 15W.

Adequate coupling of the seismometers to the bedrock was ensured by placing the seismometer on top of a small armoured concrete pad. The blue box housing was anchored to the ground and filled around by rocks and other material found at the sites, in order to provide protection and also provide a physical appearance tailored to the local environment.

IV.4 Borehole for broadband seismometer

The KS-36000 broadband seismometer was placed in a borehole at the center of the array (at the site denoted E0 in Table III.1). The borehole package is deployed at a depth of 50 m beneath the surface. A site survey conducted by NL Sperry-Sun International established the orientation of the holelock at the bottom of the borehole, for subsequent alignment of the horizontal seismometers in the north-south and east-west direction. The same survey showed that the borehole inclination is 1.03 degrees.

IV.5 Transportation issues

Our plans for the site preparation work were approved by the local authorities, subject to the condition that a helicopter be used for transportation of heavy equipment and materials, in order to prevent damage to the terrain and vegetation. Accordingly, helicopters were used to lift all cables and all materials for the terminal building to the array center. The material needed at the 25 seismometer sites was also transported by helicopter to each site.

The array electronics were shipped from Sandia in Albuquerque on 19 August via a military airlift, using a C-141 aircraft. The equipment arrived at the Bardufoss airport in northern Norway on 20 August, and was stored for a few days until it was picked up by a Norwegian Air Force C-130 aircraft, which took the load to the Lakselv airport, approximately 40 miles from the array site. All this equipment was available at the array center on the day of arrival of the Sandia representatives who came to participate in the array deployment work.

IV.6 Deployment of the field system

The site preparation work had progressed to a stage that allowed Sandia representatives to start installing the electronics immediately upon their arrival on 1 September. Approximately ten Sandia representatives were present at any time during the installation period. In addition, three NORSAR employees participated in the field system deployment. The installation work did not encounter any major problems, and towards the end of September all elements of the system were in place. This left about a week for systems integration testing before the installation crews left on 28 September.

The deployment work started by installation of the hub processor in the central terminal building. Next, all fiber optic connectors were mounted, both at the 25 vaults and in the terminal building, and the seismometer and the blue boxes were deployed at the sites. The final operation before systems integration testing was the lowering of the borehole instrument into the 50 m deep borehole.

V. SATELLITE TRANSMISSION OF DATA FROM THE NEW ARRAY

V.1 Work related to establishing the satellite link

A considerable effort went into the planning for the transmission of data from the new array site to NORSAR's data processing center at Kjeller. Based on previous experience with data transmission and taking into account the distance between Karasjok and Kjeller (nearly 1300 km), it soon became clear that the only feasible way of getting the data to Kjeller would be via satellite. Accordingly, we approached the Norwegian Telecommunications Administration (NTA) to obtain a quotation for a point-to-point satellite service betweem Karasjok and Kjeller, and to discuss technical matters related to such a service. NTA decided to offer such satellite service, based on their NORSAT-B concept. The domestic links based on NORSAT-B utilize transponders that NTA lease in Intelsat or Eutelsat satellites.

Representatives of NTA visited the Karasjok array site in June in order to familiarize themselves with the site. The ground station equipment needed for Karasjok was available at the array site on 16 September. Some days earlier, the necessary preparations for receiving data at Kjeller had been made.

After some days of physically establishing the link between Karasjok and Kjeller followed by end-to-end testing and fine-tuning of the equipment, NTA made the connection available for us to start transmitting seismic data from 25 September.

Science Horizons, Inc., San Diego, provided the communications interface between the data output from the field installation and the modem for satellite transmission. An interface of the same kind was also provided at Kjeller between the satellite receive modem and the data acquisition processor. This interface equipment also provides for multiplexing/demultiplexing of the two data streams from the array and the high frequency station of the field installation.

V.2 Initial operational experience

Regular traffic on the satellite link started on 1 October, but was initially restricted to periods with NORSAR personnel present at the array site. However, from 16 October, data were transmitted continuously over the satellite link, following NTA's installation of a facility that enables NTA to remotely control the transmit off/on switch at our ground station.

The experience with the quality of this link is extremely good, and there has been no problem whatsoever with the data recorded at Kjeller that can be attributed to the satellite link. During the testing of the link, it was established that the bit error rate was of the order or better than 1×10^{-7}.

VI. DATA ACQUISITION AND PROCESSING

VI.1 Development of software for acquiring and processing the data from the new array

At the beginning of this project, it was clear that the data handling and processing should utilize Sun workstation technologies and the UNIX operating system.

The development of the data acquisition and processing software for the new array has been a joint undertaking between Science Horizons Inc. and NORSAR. The software development was coordinated between the two organizations through several extended visits by NORSAR personnel to Science Horizons during the period January-July.

The approach taken during the development of the data acquisition software was to create a cyclic disk loop, comprising all seismic and state-of-health data. This is equivalent to what is done at NORSAR for the NORESS system. The acquisition software also includes a task for automatically reformatting the data into the CSS database structure by extracting the necessary data from the disk loop.

The efforts by NORSAR personnel related to developing data processing software focussed on refining the software written in conjunction with the NORESS developments. We also converted existing software to be able to run it in the Sun workstation environment. In addition, Science Horizons provided a set of basic stand-alone data manipulation and processing modules.

VI.2 The development of a state-of-healt sys‹ ›m for the new array

NORSAR assumed the responsibility of developing a state-of-health (SOH) system for the new array. Such a system was also developed for NORESS in 1984, and was installed on an IBM computer and has been used in the routine operation for reporting the technical status of the array. The new SOH program represents a significant extension of the functions of the NORESS SOH program, and is naturally adapted to the SUN/UNIX computing environment. The package is written in the C language and uses X-window graphics.

Some of the features in the new SOH system are a powerful command interpreter, input/output files in standard ASCII format, a profile for the program, flexible graphics presentation of traces and statistics, and different input modes (tape, disk). The program may be operated in either a graphic mode or numerical mode so information may be displayed on non-graphic screens. There has also been developed an input path for NORESS online data on the IBM system. The design of the program itself is modular and flexible so it is easy to add new commands and functions.

The SOH system is described in detail in a 107-page report written by Rune Paulsen, who developed the system. The report is available upon request.

VI.3 Temporary arrangements for data acquisition and processing at Kjeller

The purchase of a complete Sun-based system for acquiring and processing the data from the new array is one of the subjects of a FY88 contract with DARPA. According to present plans, such a system will be installed during April/May of 1988. Details on these plans are given in paragraph VI.5 below.

In order to receive the data from the new array until the ultimate system becomes available, an ad-hoc system, based on a Sun 2-processor, with approximately 700 Mb disk space and a tape drive, was installed at Kjeller in late September. This interim system was provided by Science Horizons Inc. The system enables us to acquire and archive the data from the new array, using the software described in VI.1. In order to process the data, the data tapes must be transferred to the IBM system, and the detection processing of continuous data is done in an offline mode.

VI.4 Initial experience with data quality

The new SOH program proved very useful during the installation and testing of the new array. We verified the recording system for the high frequency and array data using this program.

Data recorded at Kjeller during October revealed some technical problems with the field equipment. These problems resulted in numerous gaps in the data stream. The sources of these problems were identified during visits to the array site by NORSAR personnel, and corrective actions took care of almost all errors in the data.

From the end of the period of performance of this contract, the rate of errors in the data received at Kjeller has been low enough that it does not cause any problems to the detection processing performance.

VI.5 Plans for a complete system for acquiring and processing data from the new array

A considerable effort under this contract went into the design of the hardware aspects of the new data processing system. As mentioned above, this equipment will be acquired under a FY88 contract with DARPA.

Fig. VI.1 shows how the proposed data processing equipment will be integrated into and networked with already existing resources at NORSAR's Data Processing Center at Kjeller. The data acquisition systems for the NORSAR and NORESS arrays (not shown in this figure) are integrated into the total system in similar ways.

The data acquisition and processing systems (termed "FRS online" and "Research/Analysis/Data Exchange" in the figure) for the new Finnmark array are based on three Sun 3 computers. The bottom Sun 3/260 in the "FRS-online" box is interfaced to a CIM (Communication Interface Module) which receives data from the Finnmark field system via the satellite link. The communication protocol used is SDLC, which is also used for the NORESS installation. The CIM system can buffer up to 20 minutes of data. In normal operation, data are sent on to the Sun system without delays.

Recording of both high frequency (HF) and array data from the new Finnmark site will utilize disk loops that can hold 84 hours of array data and also 84 hours of HF data. One disk drive will be assigned to each of the two data types. The Sun 3/260 computer that handles the data acquisition task will also be running the state-of-health program described above to verify data quality and generate statistics on uptime, communication errors and calibration

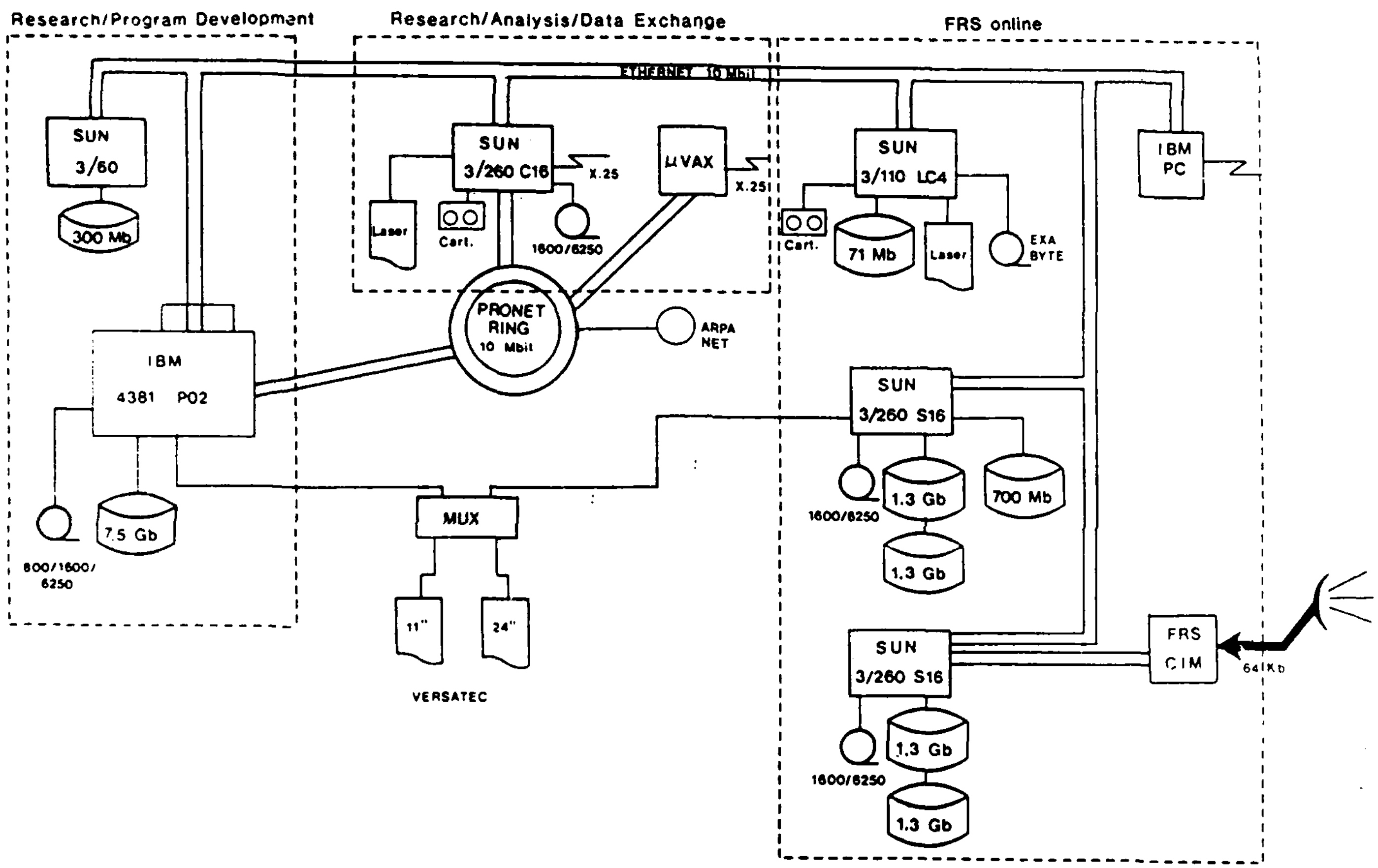


Fig. VI.1 The figure shows how the equipment for processing data from the new Finnmark regional array will be integrated into existing equipment at NORSAR's data processing center. Note that the current NORSAR/NORESS data acquisition system (based on IBM 4341 computers) come in addition to this figure.

results. All data will be permanently archived on tapes, in the NORESS format.

Data contained in the disk loops will be generally accessible using NFS. The data will also be accessible from the IBM system using NORSAR's network software for reading files that are stored on computers in the network.

The other Sun 3/260 system in the "FRS online"-box of Fig. VI.1 will be used for real-time processing and subsequent plotting of data. Relevant plots will be produced on the Versatec system. This Sun 3/260 computer is configured in exactly the same way as the acquisition computer, so it can act as a backup for the acquisition task.

The Sun 3/110 will be used for quality checking and array monitoring purposes.

The IBM/PC is the system currently being used for controlling critical tasks in the NORSAR/NORESS system. This system automatically calls the operator on duty in case of system failures. The FRS online system will be integrated into this alarm system. PC/NFS will be used to read current status directly from files stored in the Sun online system.

The third Sun 3/260 system will be used for data exchange, data analysis and program development.

VII. PRELIMINARY ASSESSMENT OF THE CAPABILITIES OF THE NEW ARRAY

This chapter gives a preliminary assessment of the capabilities of the new array and relates the results to previous NORESS studies. It should be emphasized at the outset that the available data from the new array at the time of this analysis cover only a period of a few weeks, and that a comprehensive assessment of the capabilities must await the collection of data cover a longer time span.

The new array was designed to be as closely as possible a copy of the NORESS regional array, which was established in southern Norway in 1984. The geometries of the two arrays are therefore practically identical (deviations between corresponding sensor positions are of the order of a few tens of meters, due to local terrain conditions), and the data outputs are the same for the two arrays. Fig. VII.1 shows the location of the two regional arrays in Norway, and also the location of the FINESA regional arrays in Finland, which was described by Korhonen et al (1987). The geometry of NORESS (and for most practical purposes, also the geometry of the new array) is shown in Fig. VII.2.

Data from the new array have been transmitted continuously via satellite to the NORSAR data processing center at Kjeller since October 1987. The data are subjected to automatic detection processing, with a beam deployment identical to the one used for NORESS.

Noise spectra

Fig. VII.3a shows corrected noise spectra for altogether 17 elements of the new Finnmark array (the vertical sensors at A0 and the C- and D-rings, see Fig. VII.2), taken at 00.00 GMT on day 315. For comparison, NORESS noise spectra for

REGIONAL ARRAYS IN FENNOSCANDIA

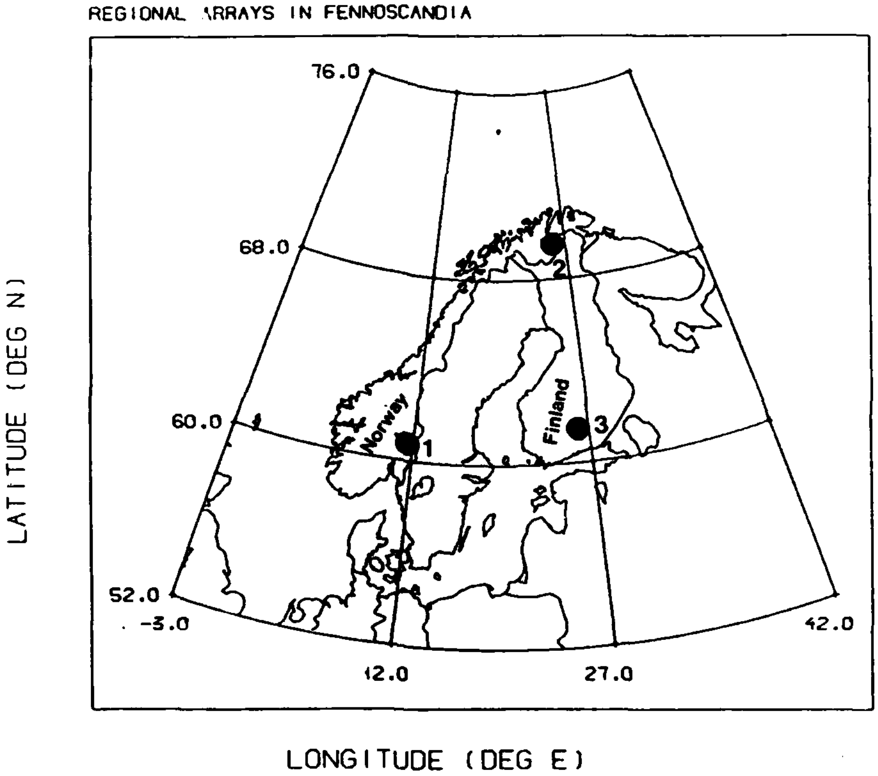
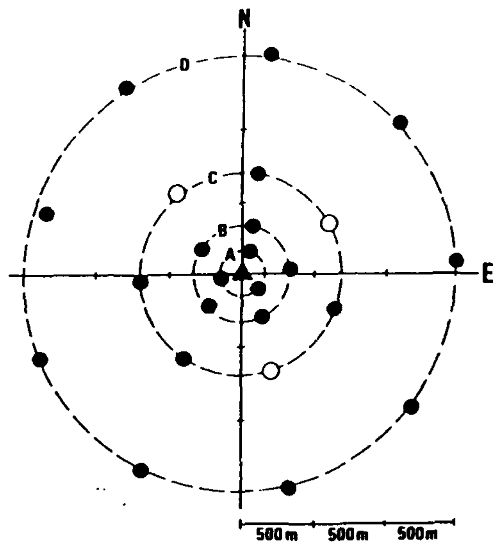


Fig. VII.1 The figure shows the network of the three regional arrays in Fennoscandia: 1. The NORESS array in southern Norway; 2. The new array in Finnmark, northern Norway; and 3. The FINESA array in Finland.



LEGEND:

● VERTICAL SHORT PERIOD

○ 3-COMPONENT SHORT PERIOD

▲ 3-COMPONENT BROAD BAND
AND 3-COMPONENT SHORT PERIOD

Fig. VII.2 The geometry of the NORESS array. The geometry of the new Finnmark array comes very close to being identical to that of NORESS; deviations between corresponding element positions are of the order of some tens of meters. The channel assignments (vertical only vs. three-component, short period vs. broadband) are identical for the two arrays. The short period instrument at the center of the array is denoted A0.

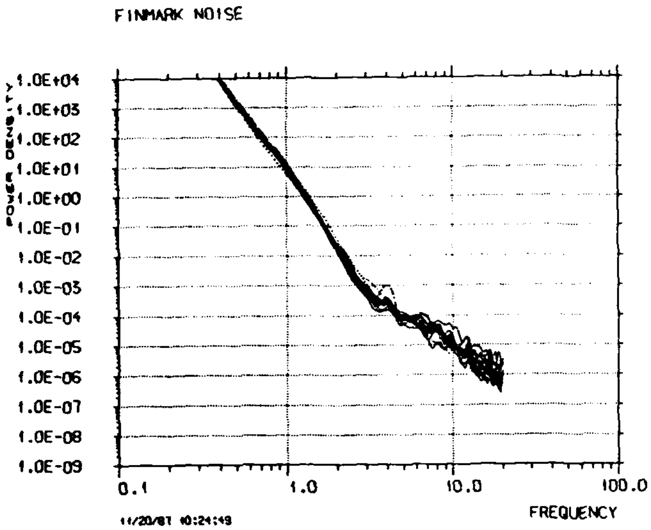


Fig. VII.3a Noise spectra corrected for system response for the Finnmark array for 17 vertical channels at A0, the C- and D- rings. The spectra are based on one minute of data at 00.00 GMT on day 315. The power density is in nm^2/Hz.

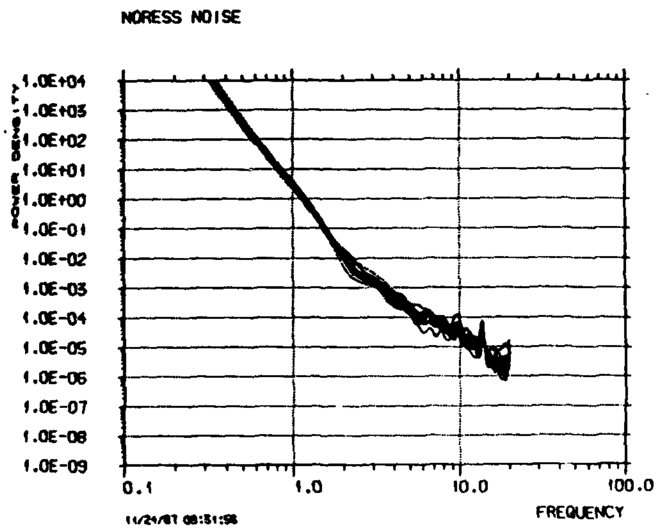


Fig. VII.3b Same as Fig. VII.3a, but for NORESS data taken at 00.15 GMT on day 315.

the same number of channels and taken at the same time, are shown in Fig. VII.3b. From these figures, it is seen that below 2.0 Hz, the Finnmark array experiences a higher noise level than NORESS, whereas above 2.0 Hz the Finnmark site is clearly the quieter.

The high noise level at low frequencies at the Finnmark site has been confirmed by other data and is typically even higher than shown in Fig. VII.3a. At the time of these spectra, the nearby coast of Finnmark experienced a wind force 4, which is moderate. The noise level at these low frequencies is generally believed to be governed by the passage of major weather fronts over the open ocean. Therefore, it should not be unexpected to find the higher microseismic noise levels at the Finnmark array, since this array is located closer to the coast than the NORESS array.

For the frequency range above 2 Hz, the noise level at the Finnmark site appears to be 3-5 dB below that of NORESS. A possible explanation here is that the noise in this band is lower at the northern site because of a lower population density and also lower level of traffic and industrial activities, compared to the NORESS site. These noise levels must also be rated as low relative to year-round averages for NORESS, as investigated by Fyen (1987).

Figs. VII.4a and 4b each show ten uncorrected spectra, taken hourly between 00.00 GMT and 10.00 GMT of day 315 for the Finnmark and NORESS arrays, respectively. Each single spectrum represents an average of 17 spectra for the vertical sensors of A0, the C- and D-rings. The NORESS spectra show the well-established (Fyen, 1986a,b; 1987) difference between night-time and day-time noise characteristics (particularly around 6 Hz). The Finnmark data are generally below those of the NORESS site for frequencies

FINNMARK AVERAGE NOISE 00-10

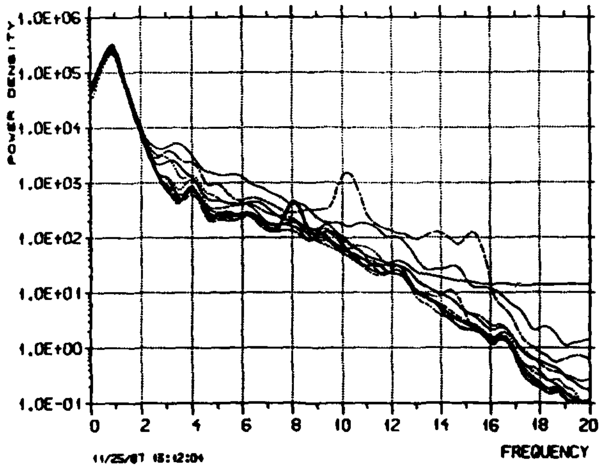


Fig. VII.4a Uncorrected noise spectra for the Finnmark array for ten one-minute intervals taken hourly between 00.00 and 10.00 GMT on day 315. Each spectrum represents an average of the 17 vertical sensors of A0, the C- and D-rings.

NORESS AVERAGE NOISE 00-10

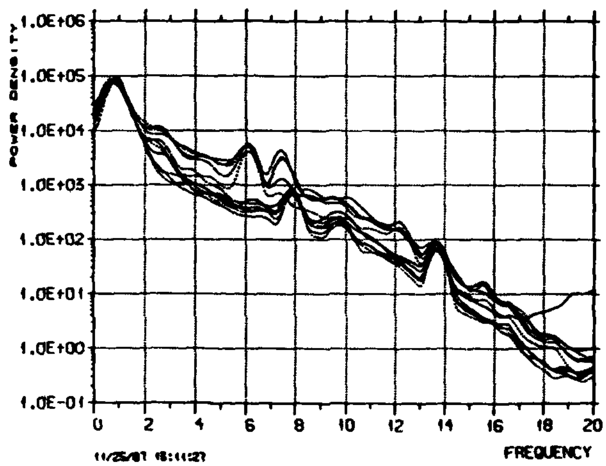


Fig. VII.4b Same as Fig. VII.4a, but for NORESS data taken hourly between 00.00 and 10.00 GMT on day 315.

above 2 Hz. The two or three curves with the higher noise power in Fig. VII.4a represent cases of high frequency noise bursts at the Finnmark site during daytime. These bursts are visually confirmed by careful inspection of the seismograms. A more comprehensive study is needed to clarify the origin of this noise. There is so far, however, no indication of constant noise sources like power plants and sawmills.

It should be emphasized again that in order to establish reliable estimates of ambient noise levels at the new array site, studies like those undertaken by Fyen (1986a,b; 1987) for NORESS are needed. The material analyzed so far, however, indicates that in the range of primary interest to regional seismic verification (i.e., above 2 Hz), the noise level at the new Finnmark array site is generally somewhat lower than the NORESS noise level.

Noise suppression by beamforming

The NORESS array has proved very proficient in the enhancement by beamforming of the SNR, yielding gains that are often of the order or even in excess of $\sqrt{N}$ (N being the number of sensors used in the beamforming). It has been shown that this success is largely due to the highly effective noise suppression that can be obtained by selecting appropriate sub-geometries for the various signal frequencies. As a first check on the new array's capabilities in this regard, noise suppression curves were computed and compared with corresponding results from NORESS.

In Fig. VII.5a, the noise suppression in the frequency range 0-20 Hz for vertical beamforming (no shifts introduced) is shown for three one-minute intervals taken hourly at 00.00, 01.00 and 02.00 GMT on day 315. The sub-geometry used is that of A0, the B- and C-ring instruments (13

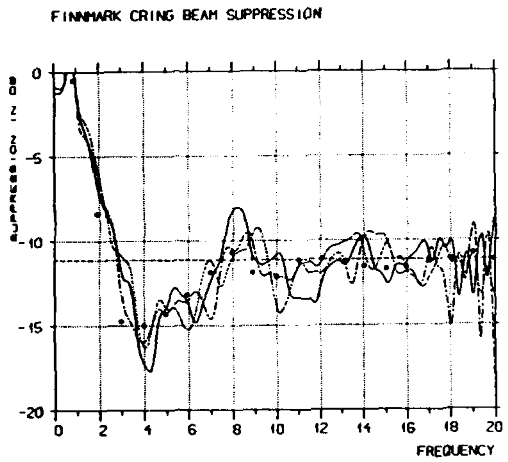


Fig. VII.5a Finnmark array noise suppression by beamforming for the sub-geometry comprising the A0, B- and C-ring sensors. To produce these curves, a vertical beam is formed and the spectrum for this beam is divided by the average of the single sensor spectra. The three curves result from one minute of data taken hourly at 00.00, 01.00 and 02.00 GMT on day 315. The dots represent typical NORESS noise suppression values for this sub-geometry. The horizontal line at -11.1 dB represents $\sqrt{N}$ suppression for 13 sensors.

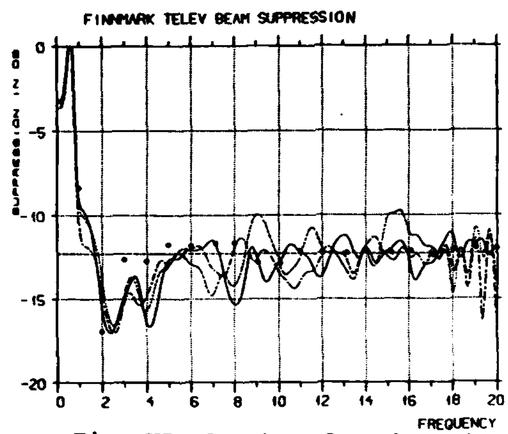


Fig. VII.5b Same as Fig. VII.5a, but for the sub-geometry comprising the sensors of A0, the C- and D-rings. The horizontal line at -12.3 dB represents $\sqrt{N}$ suppression for 17 sensors.

sensors). The dots in this figure represent average values for NORESS that are taken from Fyen (1986c). The $\sqrt{N}$ level is at about -11 dB, and the general impression left from this figure is that the new array is as effective in suppressing noise as NORESS, for this sub-geometry. For another sub-geometry, comprising the sensors of A0, the C- and D-rings, corresponding results are given in Fig. VII.5b. Again, we see that the noise suppression capability is comparable to or maybe even better than the average performance of NORESS. This strongly suggests that the spatial characteristics (e.g., correlation lengths vs. frequency) of the noise field are very similar to those found at NORESS. It has previously been established (Korhonen et al, 1987) that the NORESS and FINESA arrays exhibit strong similarities in this regard.

Analysis of data from two regional events located by the Finnmark array

As examples of regional events recorded on the Finnmark array, we present the records for two presumed mining explosions in the Kola peninsula of the USSR.

The C-ring seismograms for the first event are shown in Fig. VII.6. The event occurred at 67.6° N, 34.0° E (according to the University of Helsinki bulletin), at an epicentral distance of 408 km and an azimuth of 117.9°. The phases Pn, Pg, Sn and Lg can be clearly identified by visual inspection. These phases were subjected to wide-band slowness analysis, with results given in Figs. VII.7 and VII.8. We see that the phase velocities derived are in the expected range for these phases and that deviations from the "true" azimuth are within 6-7°.

Data for the second event are shown in Fig. VII.9. This event is located at 68.1° N, 33.2° E, at an epicentral

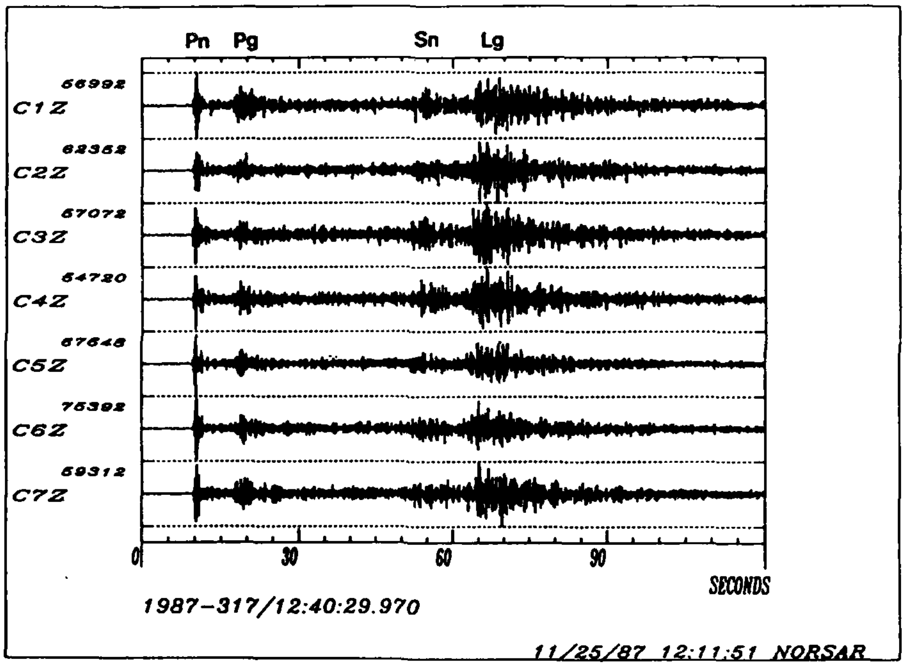
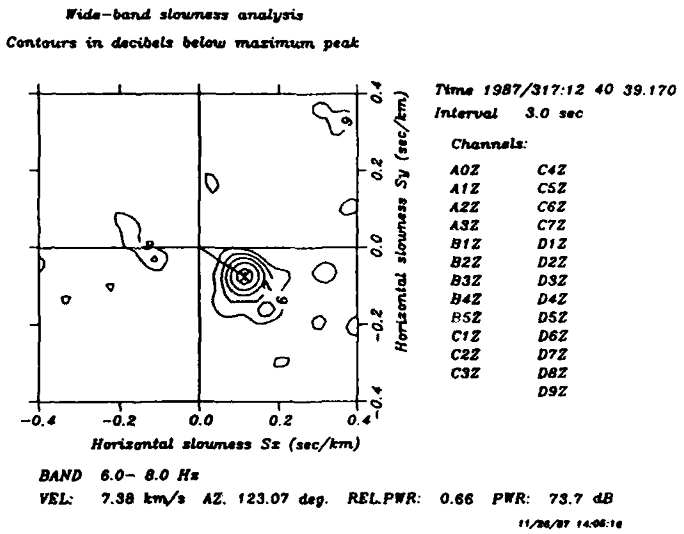


Fig. VII.6 Finnmark array data for a presumed mining explosion at 67.7° N, 34.0° E. The plot shows data for the vertical instruments of the C-ring.

Pn



Pg

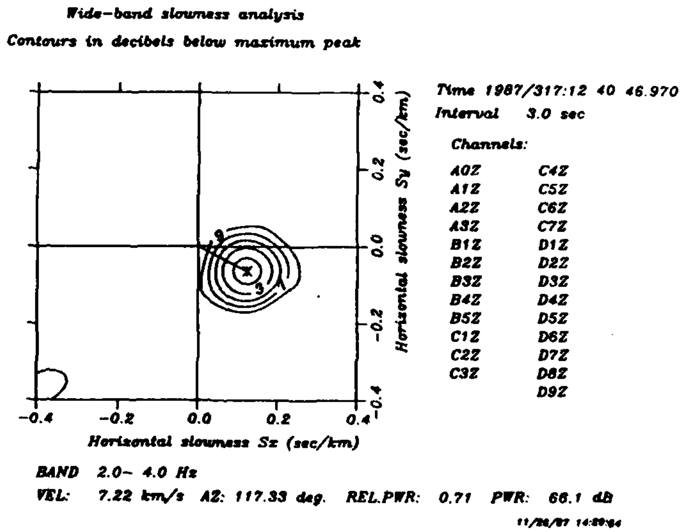


Fig. VII.7 Wide-band slowness spectra for the Pn phase (top) and Pg phase (bottom) for the event in Fig. VII.6.

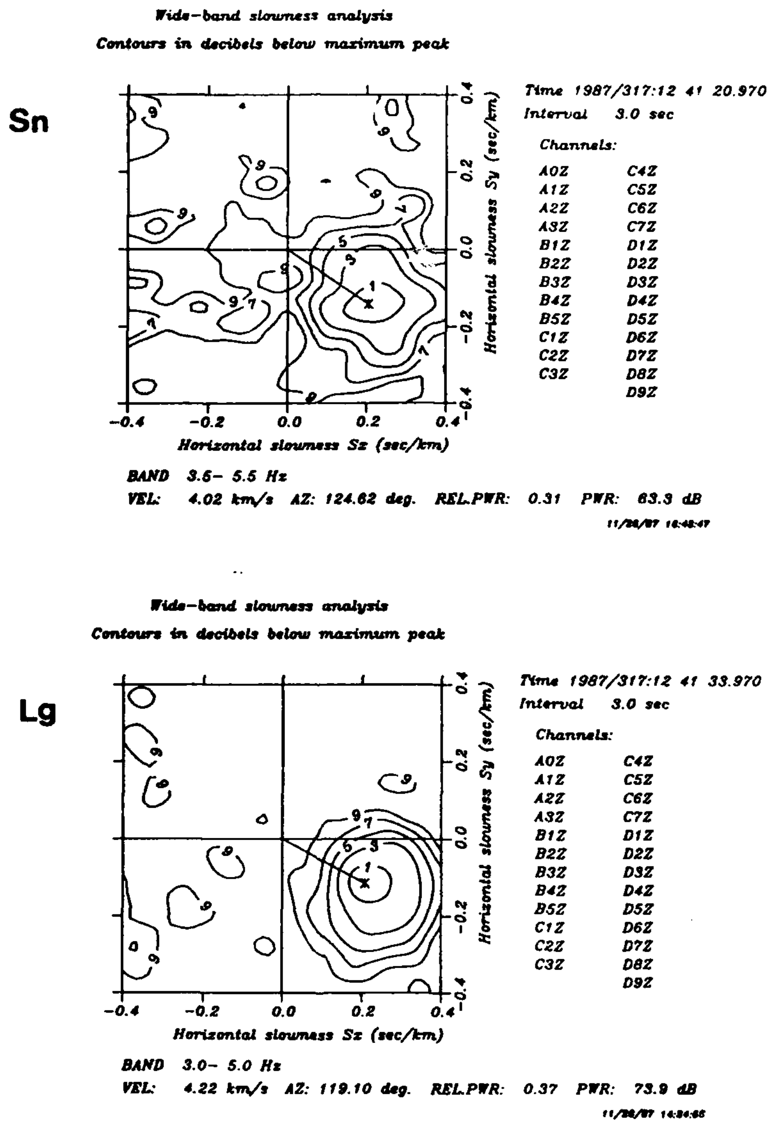


Fig. VII.8 Wide-band slowness spectra for the Sn phase (top) and Lg phase (bottom) for the event in Fig. VII.6.

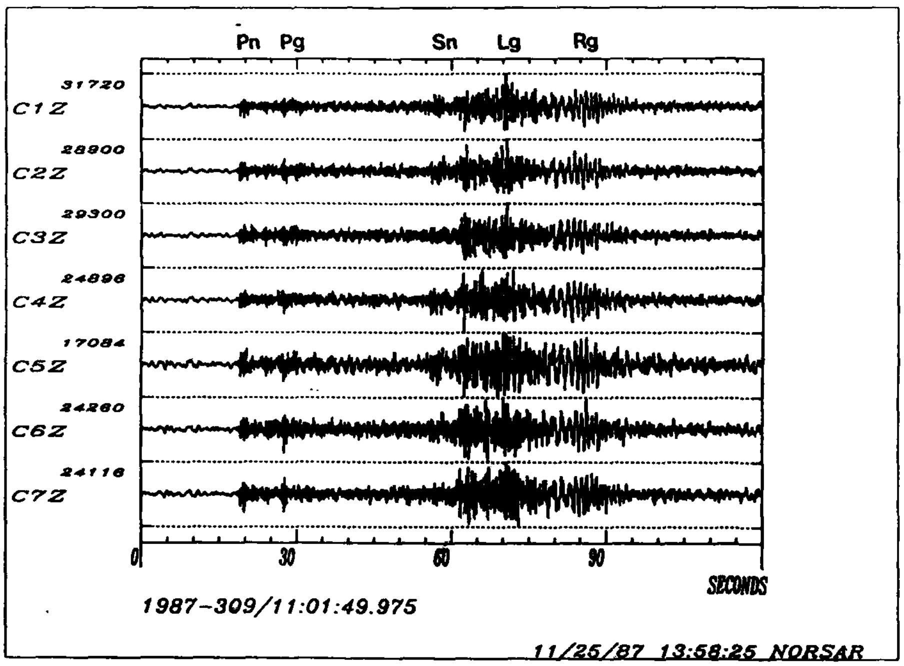


Fig. VII.9 Finnmark array data for a presumed mining explosion at 68.1° N, 33.2° E. The plot shows data for the vertical instruments of the C-ring.

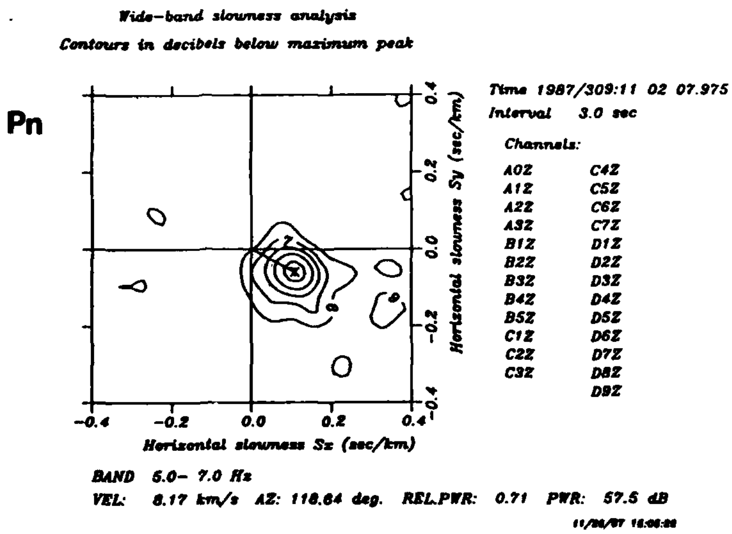
distance of 349 km and an azimuth of 113.7°. Besides the phases identified for the first event, we now also see a clearly developed Rg phase. It is of particular interest to note the difference between the two events in this regard, particularly since they are separated by not more than about 60 km. The occurrence of Rg waves in the records for events of epicentral distances of the order of 350 km also sharply contrasts what we have found at NORESS, where Rg waves are never observed beyond 100 km distance. The results of the wide-band slowness analysis of the phases Pn, Pg, Lg and Rg for this event are shown in Figs. VII.10 and VII.11. Again we see that the phase velocities are reasonable, and the azimuths deviate by not more than 5° from the "true" value.

Regional event detection

An initial study has been made comparing the regional event detection performance of the two arrays in Norway. A two-week period (31 Oct - 18 Nov 1987) was selected for this purpose, and analysis of RONAPP processing results for the two arrays was conducted. For both arrays, the beam deployments and thresholds were identical, and the same as those used for the past two years in regular NORESS operation.

Fig. VII.12 shows a map displaying all regional events located by NORESS during this time period, whereas Fig. VII.13 gives a similar map for the Finnmark array. We recall that in order for one array to locate a regional event, at least two phases (P and Lg) from that array must be detected and associated.

Comparing these two figures is quite instructive, and probably gives a reliable impression of what can be expected during long-term operation. The actual number of



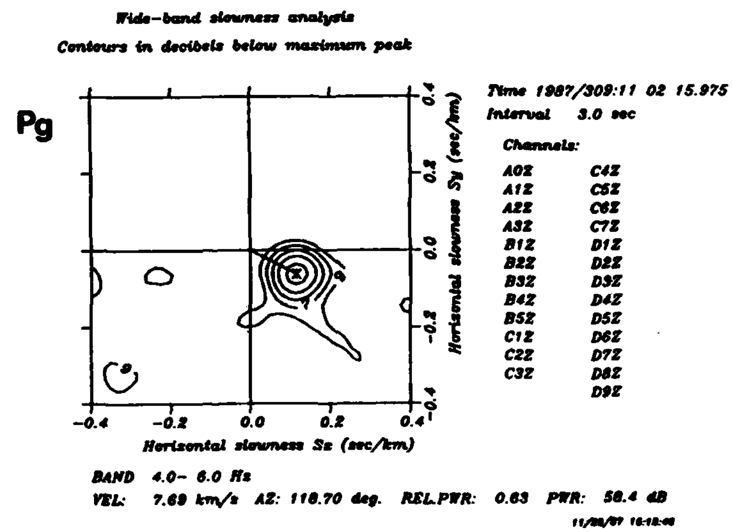


Fig. VII.10 Wide-band slowness spectra for the Pn phase (top) and Pg phase (bottom) for the event in Fig. VII.9.

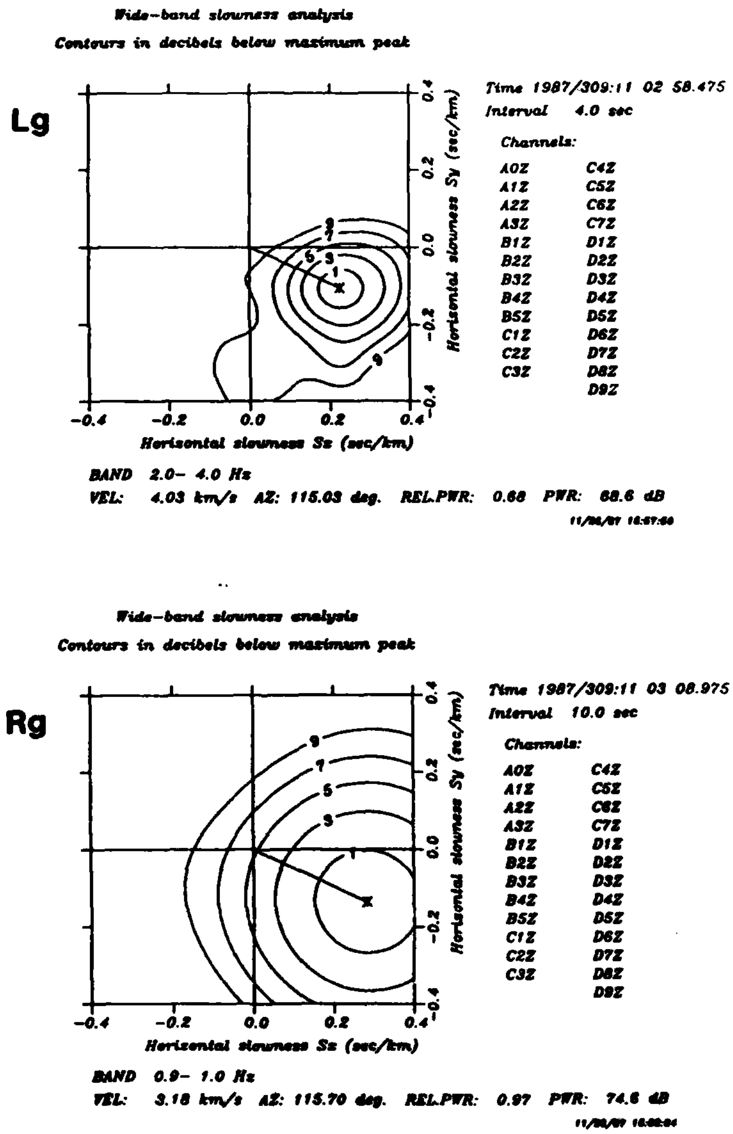


Fig. VII.11 Wide-band slowness spectra for the Lg phase (top) and Rg phase (bottom) for the event in Fig. VII.9.

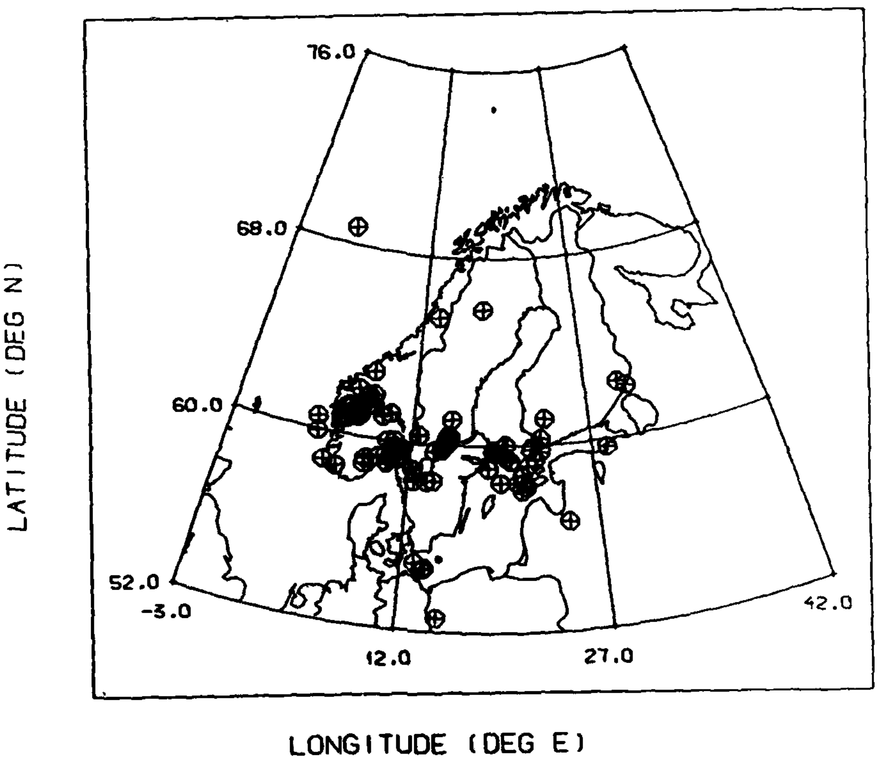


Fig. VII.12 Regional events located by the NORESS array during a two-week test period.

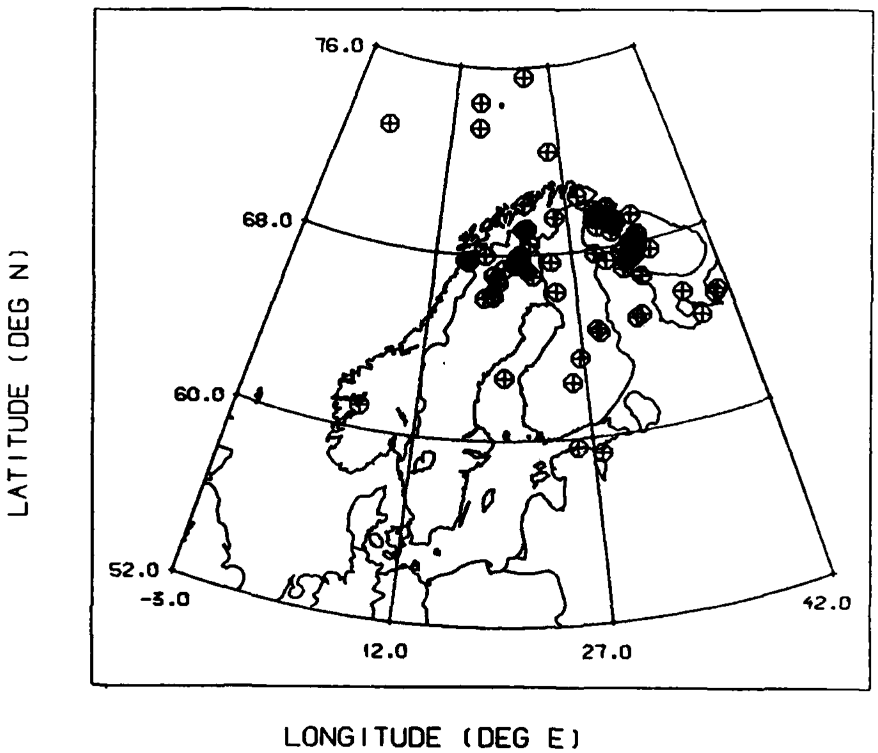


Fig. VII.13 Regional events located by the Finnmark array during a two-week test period.

located events is similar for the two arrays (NORESS 152, Finnmark 117). However, there is almost no overlap of the two populations; in fact only 8 events were located by both arrays. The large majority of located events are within 500 km of the respective arrays and represent in most cases presumed local explosions of low magnitude (M_L < 1.5). Sites where such explosions are clustered can be easily identified on the plots. It is noteworthy in particular that the Finnmark array detects and locates a large number of mining explosions in the Kola peninsula.

Fig. VII.14 shows a map of all events of estimated $M_L \geqslant 2.0$ located by at least one array. In those cases when both arrays located the same event, the location by the closest array was chosen. Events with at least one confirming phase (P or Lg) from the other array are encircled. Details pertaining to the figure are given in Table VII.1.

Compared to previous figures, it is clear that relaxing the criterion for "common" events to requiring only one confirming phase from the other array significantly increases the overlap of the populations. The majority of events in Fig. VII.14 are thus detected by both arrays. It is particularly interesting to observe the good performance for the event cluster near 65° N, 40° E, which is at a considerable distance from both arrays (700 and 1500 km, respectively). These events were in the magnitude range 2.5-2.7 and the locations have been independently confirmed by the Finnish network.

Regional detection threshold

The threshold capabilities of the new array have been evaluated based on the method described by Ringdal (1986). Using the Helsinki seismic bulletin as a reference, we have associated P-phases detected by the online procedure with

Reference array		NORESS	Finnmark
Total no. of events located by reference array		152	117
No. of events $M_L \geq 2.0$		31	42
No. of events $M_L \geq 2.0$ located by the reference array, detected or not detected by the other array	Both P and Lg	8	8
	P only	14	12
	Lg only	1	1
	Not detected	8	21

Table VII.1 Statistics of detected and located regional events for the two arrays in Norway during a two-week test period.

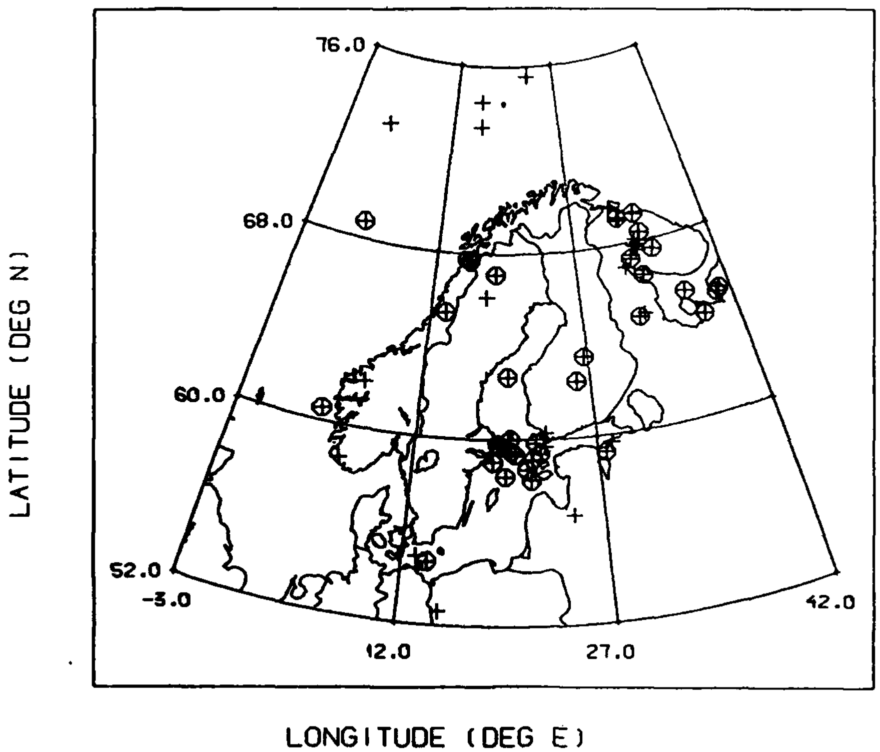


Fig. VII.14 Regional events of $M_L \geq 2.0$ located by at least one of the two arrays in Norway during a two-week test period. Events with at least one confirming phase from the other array are encircled.

the reported reference events. The results are shown in Fig. VII.15, which gives a histogram of the number of reference events at each magnitude, with the events detected by the Finnmark array marked specially. The figure further contains a detection probability curve with associated confidence limits, estimated by the maximum likelihood method of Ringdal (1975).

We note that the 90 per cent P-wave detection capability in the region studied (distance range 700-1400 km) is close to $M_L = 2.4$. This can be compared to the NORESS threshold of $M_L = 2.7$ found by Ringdal (1986) for the same region. It must be noted here that the reference events were on the average at a slightly greater distance in the case of NORESS, and this may largely account for the difference. Thus, we conclude that the new array appears to have a regional detection capability that at least matches that of NORESS.

Regional location capability

The capability of the new array to locate seismic events at regional distances has been evaluated and compared to that of NORESS. In addition, we have investigated the joint location capabilities of the two arrays. The data base for this study has comprised a set of seven regional events in October/November 1987, for which we have accurate independent location estimates computed at the University of Helsinki, on the basis of the Fennoscandian network of data.

For the purpose of estimating event location, we have used the program TTAZLOC developed by Bratt and Bache (1987). This program takes into account arrival times, back azimuth estimates and associated uncertainties, and incorporates these data into a generalized-inverse location estimation

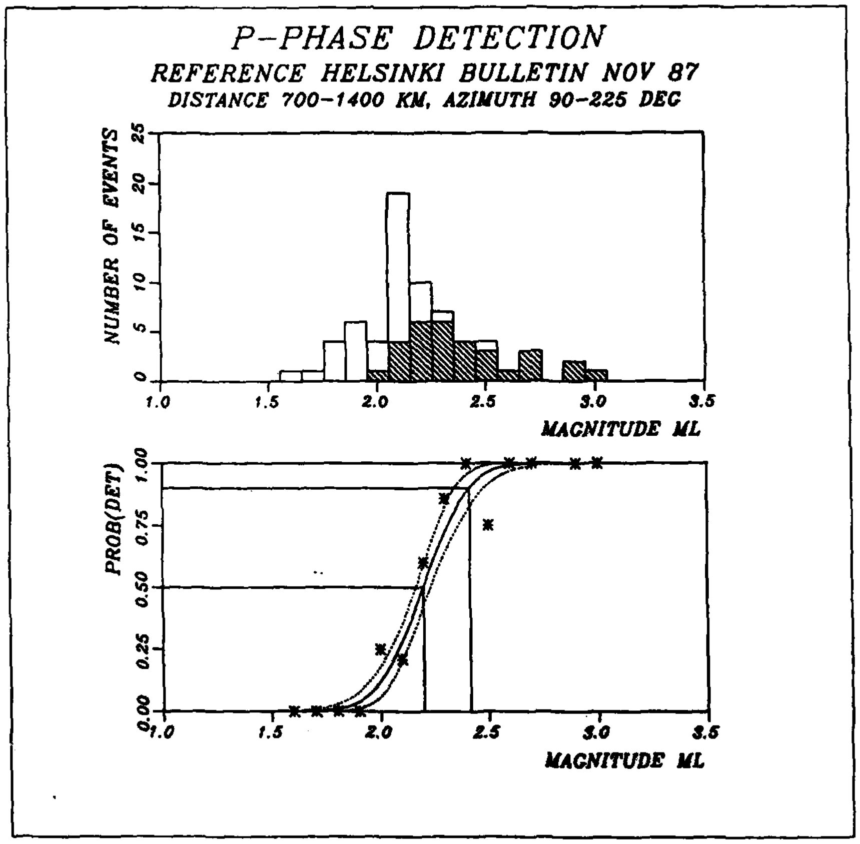


Fig. VII.15 P-phase detection statistics for the new array for regional events in the distance range 700-1400 km, using the Helsinki bulletin as a reference. The upper part of the figure shows the distribution of events by magnitude with detected events corresponding to the hatched columns. The bottom part of the figure shows the estimated detection probability curve as a function of magnitude, with the observed detection percentages marked as asterisks. The stippled curves mark the 90 per cent confidence limits.

scheme. TTAZLOC can be applied both to single-array and multiple-array situations, assuming that a sufficient number of phase detections is available.

Table VII.2 lists the events in the data base, together with the main results from the data processing. For each event both the network location and the joint two-array location has been listed, as well as the difference (in km) between the two estimates. For comparison purposes, the differences are also given between network location and locations computed on the basis of each individual array.

We note that the joint two-array location procedure produces excellent results, which on the average differ from the network estimates by only 34 km. In contrast, the error in the single array results are typically more than 100 km. It must be emphasized that six of these events are of very low magnitude (M_L 2.1 to 2.5), and all are at an appreciable distance from both arrays (see. Fig. VII.16). It is known from earlier NORESS studies that distant regional events are much more difficult to locate accurately than close-in events.

It is noteworthy that the above results have been obtained using arrival times and azimuths estimated automatically using the online RONAPP processing system. There is clearly a potential of improvement in using interactive analysis to extract more precise phase arrival times. Also by taking into account regional wave propagation effects, e.g., in a joint epicentral determination scheme, using nearby reference events, it is likely that increased accuracy can be obtained. On this background, the results are quite encouraging.

Event No.	Origin date, time		Mag. M_L	Network Location (1)		NORESS/Finnmark Joint Location (2)		Location "error" (2) - (1) (km)	Single array location "error" (km)	
				Lat.	Lon.	Lat.	Lon.		NORESS	Finnmark
1	10/31/87	10.09.08	4.2	61.11	4.51	60.84	5.35	54	33	191
2	11/02/87	13.28.00	2.5	61.40	31.60	61.74	31.18	43	277	154
3	11/03/87	22.35.12	2.3	68.37	15.21	68.02	16.56	67	269	125
4	11/06/87	08.25.21	2.1	66.51	14.87	66.45	14.93	8	15	27
5	11/10/87	11.06.58	2.2	59.63	22.36	59.60	22.13	13	93	148
6	11/10/87	12.29.01	2.3	61.50	30.40	61.58	29.80	33	21	84
7	11/13/87	12.15.20	2.3	59.30	27.60	59.35	27.84	15	86	92
							Averages	34	113	117

Table VII.2 Comparison of epicentral location estimates from NORESS/Finnmark array and the Fennoscandian network (reference to Helsinki bulletin) for a set of seven events. The location accuracy of each individual array is also given. Events 1, 3 and 4 are earthquakes; events 2, 6 and 7 are mining explosions and event 5 is a presumed underwater explosion.

Conclusions

The initial results from analyzing data from the new array show that it fully matches the capabilities of NORESS in terms of regional detection, location and phase identification capabilities. Some significant differences in phase characteristics have been observed between the two arrays; this confirms that optimum processing will need to take into account regionally based corrections. The joint analysis of data from the arrays has been shown to give significantly more precise event location estimates for weak seismic events than individual arrays, and a network of such arrays might be expected to provide further improvements.

We finally stress again that the results presented in this study are based on a very limited time interval of recording. Further assessments of the new array as well as the joint detection, location and identification potential of the two arrays will require a much more extensive data base, and will be the subject of further study.

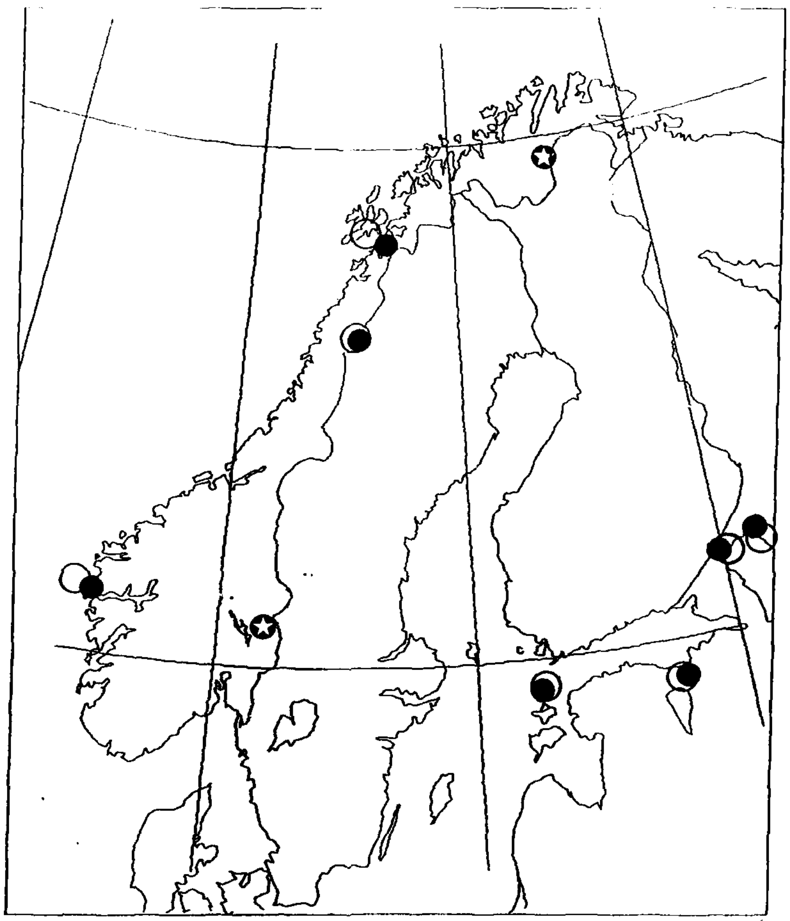


Fig. VII.16 Joint two-array location results for the events listed in Table VII.2. The open circles are centered at the epicenter locations computed at the University of Helsinki on the basis of Fennoscandian network data, whereas the filled circles are centered at the locations computed from the TTAZLOC program using data from the two arrays (marked on the figure). Note the excellent correspondence of the respective location estimates. The locations of the two regional arrays are indicated by special symbols.

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