FOSR 68-1940

AD 676011

Research Paper No. 47

# Greenland Ice Cap Noise Studies Project Blue Ice

by

R. A. LENTON

June 1968

**THE ARCTIC INSTITUTE OF NORTH AMERICA**

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RESEARCH PAPER NO. 47

# FINAL REPORT:
# GREENLAND ICE CAP NOISE STUDIES
## PROJECT BLUE ICE

by

R. A. Lenton

ARPA Order No. 292-66
Project Code No. 6F10

This research was supported by the Advanced Research Project Agency
and was monitored by the Air Force Office of Scientific Research
under
Contract AF49(638)-1722

Arctic Institute of North America
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Washington, D. C. 20009

June, 1968

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# 1. INTRODUCTION AND ACKNOWLEDGMENTS

## 1.1 PROJECT BACKGROUND

In February, 1966, representatives of the Arctic Institute of North America, the Air Force Office of Scientific Research, Office of Aerospace Research, and the Advanced Research Projects Agency discussed the feasibility of conducting a seismic program in the high latitudes of the Greenland ice sheet as a part of the VELA-UNIFORM basic research program. The project received the full recognition of the Government of Denmark, and on February 17, 1966, the Arctic Institute entered into a contract with the Air Force Office of Scientific Research (SRPG) under Contract AF49 (638)-1722 to conduct seismic and related earth science studies. The title of the contract was "Greenland Ice Cap Noise Studies." A sub-contract was awarded Geotech Division of Teledyne, Inc., Garland, Texas for provision of research analysis of the results and seismic technicians for the field program. Through supplemental amendments to the basic contract the field program was continued through September 1, 1967. The code name Project "Blue Ice" was used for identification throughout the program.

## 1.2 PROJECT OBJECTIVES

This report discusses and reviews the observations made at the Inge Lehmann Station and on a traverse across the ice sheet of north Greenland under Project Blue Ice.

The objective was to establish a research facility within the area of 78 degrees north latitude and 40 degrees west longitude and to conduct research on seismic noise propagated through the ice sheet to determine the distortion on seismic signals propagated vertically through the ice sheet. To accomplish this an array consisting of four vertical seismometers and two three-component sets of long-period and short-period seismometers were used. The four vertical seismometers were installed in shallow bore holes approximately 60 m deep; the three-component sets of long-period and short-period seismometers were installed in chambers dug in the ice.

To make the best use of a facility so far removed from any cultural noise sources and located in a unique environment, other scientific activities were encouraged. Discussion is included of the environment, of data on the location, and of installation of the array.

The objective of the traverse (Blue Trek) during the second year of the project was to find a site as seismically noise free as the Inge Lehmann Station but as close to Thule Air Force Base as possible. In order to meet this objective, observations of the seismic noise field were taken at five temporary stations along a line from Inge Lehmann to Thule Air Force Base.

## 1.3 ACKNOWLEDGMENTS

Acknowledgment of the assistance of field personnel can best be summarized by listing the many participants. The author was in charge of operations throughout the project and is greatly indebted to Dr. Erik Hjortenberg, Dr. Eduard Douze, Mr. Gerald W. Johnson, Mr. Johannes Wilhjelm, Mr. Peter Bingham, and Mr. R. Iverson of the U. S. Army Map Service for their contribution and assistance in the preparation of this report. The field personnel for the various phases of the project are given below.

### Field Party Summer 1966

| | | |
|---|---|---|
| Ralph A. Lenton | Field Leader | The Arctic Institute of North America (AINA) |
| James B. Pranke | Assistant Field Leader | AINA |
| Richard H. Ragle | Glaciologist | AINA |
| Benjamin W. Fletcher | Assistant Glaciologist | AINA |
| Frank C. Layman | Polar Mechanical Specialist | AINA |
| David Donoho | Polar Mechanical Technician | AINA |
| Robert C. Nowosad | Chief, Drilling Operations | AINA |
| O. Layne Churchman | Senior Seismic Technician | Geotech Division of Teledyne, Inc. |
| Ian A. Harris | Seismic Technician | Geotech |
| Johannes Wilhjelm | Magnetician | Meteorological Institute, Denmark |
| Michael Davis | Field Assistant | AINA |

### Visiting Scientists

| | |
|---|---|
| Dr. Wilford Weeks | U. S. Cold Regions Research & Engineering Laboratories |
| Mr. Steven Mock | U. S. Cold Regions Research & Engineering Laboratories |
| Dr. Erik Hjortenberg | Geodetic Institute, Denmark |
| Dr. Eduard Douze | Geotech |

## Winter-over Party. October 1966 to February 1967.

| | | |
|---|---|---|
| Frank C. Layman | Station Leader | AINA |
| Lloyd Gallagher | Field Assistant, Magnetics | AINA |
| Peder Knudsen | Field Assistant | AINA |
| O. Layne Churchman | Seismic Technician | Geotech |

## Relief Party. February-April 1967.

| | | |
|---|---|---|
| Ralph A. Lenton | Leader | AINA |
| O. Layne Churchman | Seismic Technician | Geotech |
| Freidrich C. Belzer | Polar Mechanical Specialist | AINA |
| Peter Upton | Field Assistant, Magnetics | AINA |
| Leo Ingversen | Field Assistant | AINA |
| Christian Danielsen | Magnetician | Meteorological Institute, Denmark |

## Summer Party. May-September 1967.

| | | |
|---|---|---|
| Frank C. Layman | Station Leader | AINA |
| C. Norman Coleman | Deputy Leader (May) | AINA |
| Peter Upton | Field Assistant, Magnetics/Meteorology | AINA |
| Richard N. Chapman | Seismic Technician | Geotech |
| Leo Ingversen | Field Assistant | AINA |
| Leif Svelgaard | Magnetician | Meteorological Institute, Denmark |

## Visiting Scientists

| | |
|---|---|
| Dr. Robert Robbins | Stanford Research Institute, California |
| Dr. Elmer Robinson | Stanford Research Institute, California |
| Dr. Knud Lassen | Meteorological Institute, Denmark |

## Blue Trek Traverse

| | | |
|---|---|---|
| Ralph A. Lenton | Leader | AINA |
| Dr. Erik Hjortenberg | Magnetics/Seismology | Geodetic Institute, Denmark |
| O. Layne Churchman | Seismic Technician | Geotech |
| Freidrich C. Belzer | Polar Mechanical Specialist | AINA |
| Gerald W. Johnson | Surveyor | AINA |
| Michael Davis | Field Assistant | AINA |

| | | |
|---|---|---|
| Major Durward D. Young, Jr. | Project Scientist | Air Force Office of Scientific Research<br>SRPG |

**Coordinator, Thule Air Force Base**

| | |
|---|---|
| Mr. Gerald Pagano | AINA |

Special acknowledgment is due to the aircrews of the 17th Troop Carrier Squadron, Alaskan Air Command, who made the project possible by their professional skill and their keen interest in the project's objectives.

The Arctic Institute of North America wishes to express its gratitude for the participation and assistance of all who had a part in this very worthwhile effort.

# 2. INGE LEHMANN STATION

## 2.1 GENERAL DESCRIPTION

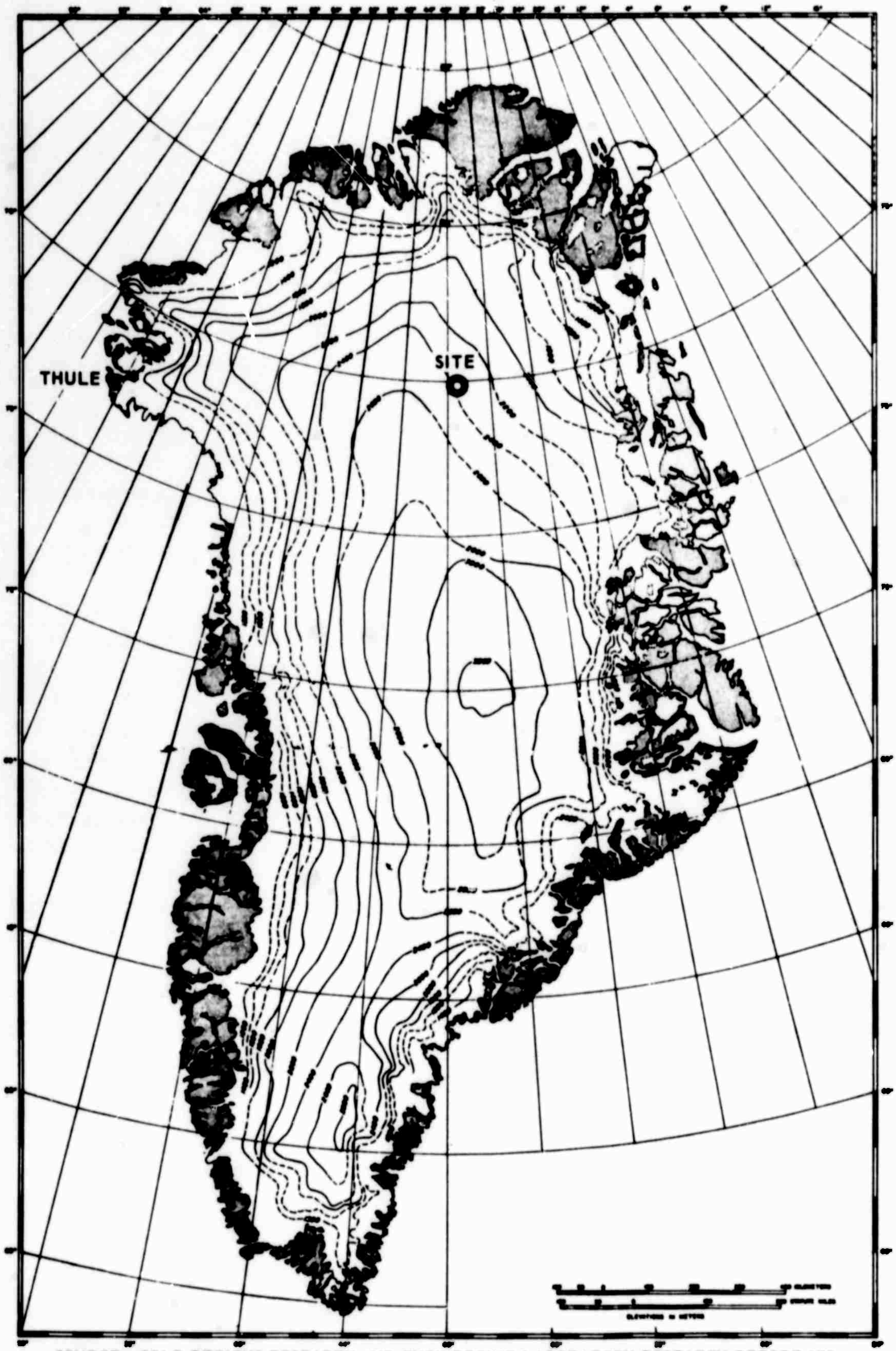
The island of Greenland has an area of 2,186,000 km$^2$ (844,000 mi$^2$) of which 85 percent is ice covered and represents about 12 percent of the total ice cover on the earth's surface. It has a maximum surface elevation of 3290 m (10,800 ft) and a mean surface elevation of 2135 m (7005 ft). The mean thickness of the ice cover is 1515 m (4979 ft). To obtain maximum distance from all sources of cultural and natural noise for the seismic noise study, the area of operations was centered in the northern sector of the ice sheet.

Inge Lehmann Station is located 730 km (455 mi) east of Thule, (77° 55' 20" N., 39° 13' 58" W.) at an elevation of 2402 m ± 6 m (7880 ft ± 20 ft), twenty kilometers southwest of the abandoned "North Ice" station of the British North Greenland Expedition, 1952-54 (Figure 1). The mean annual surface temperature is -32.5°C. In winter strong radiational cooling of this elevated snow surface causes surface temperatures to fall to -50°C and below, while in summer the glacier efficiently holds the surface temperatures close to freezing. The location is in what is generally considered a dry snow zone, i.e., where all precipitation falls as snow. Accumulation observations taken in the area (Lister, 1961, p. 170) give a mean annual accumulation of 38 cm.

The surface in the Inge Lehmann area is relatively flat with a general slope of about 5 degrees to the east. Local and regional relief is limited to gentle undulations resembling a modified swell and swale topography with wave lengths of about three to eight kilometers. The only small scale surface forms observed are sastrugi or snow dunes which are the products of wind action and rarely exceed 6 to 20 cm heights. Analysis of recordings taken at Inge Lehmann showed that the depth of the ice to bedrock at the station is approximately 2800 m.

### Establishment of the Station

The initial touchdown to establish the station was made on June 19, 1966. Within six days the basic camp was set up and the number of personnel was brought up to a full strength of ten. As soon as the minimum requirements of the station were filled, drilling for the seismic installation began.



SOURCE: COLD REGIONS RESEARCH AND ENGINEERING LABORATORY RESEARCH REPORT 170.

Fig. 1 Location of Inge Lehmann Station

On the afternoon of August 17 a dedication ceremony was held at the station. The station was named in honor of the distinguished Danish seismologist, Dr. Inge Lehmann, who has performed considerable seismic research in the United States. Attending the dedication ceremony were representatives from the following organizations:

Government of Denmark
Meteorological Institute of Denmark
Geodetic Institute of Denmark
Advanced Research Projects Agency, U. S. A.
Belgian Embassy, Washington, U. S. A.
U. S. Air Force Office of Scientific Research
Arctic Institute of North America
Teledyne Industries, Geotech Division
17th Troop Carrier Squadron, Alaskan Air Command, Elmendorf Air Force Base, Alaska
Thule Air Force Base, Greenland

## Station Construction

Originally, the base station was to provide accommodation and workspace for a ten man crew operation through the summer. When it was decided to continue the operation through the winter, the original station was increased in size to include a garage, additional storage and workspace.

The basic units consisted of two twenty-foot long, skid mounted trailers manufactured by Northland Camps, Idaho to meet the low temperature requirements of construction for use in polar areas. One trailer served as a cooking, messing and recreational facility. The other housed four personnel, the scientific recording equipment, and a washroom-shower which doubled as a darkroom for the development of photographic records.

These two trailers were positioned to provide a vestibule workspace between them. The roof of the vestibule was formed of 18 ft beams and covered with 1/4" plywood. A polyurethane-backed canvas made as a large paulin covered the roof and sides. The floor of this area was laid independently of the trailers to allow for any possible settling movement. The snow melter unit, store lockers and a portable workbench were housed in this area.

A Jamesway tent extended from one end of the vestibule served as a dormitory and communications area. The Jamesway is a frame type insulated tent with plywood flooring. This prefabricated structure is easily constructed and does not pose any problems from a climatological viewpoint for those using it during the summer. To increase the insulation for winter use it was covered on the outside with plywood and allowed to become partially buried, thereby sealing the floor panels from the wind.

In changing the station from summer to winter use the vestibule area was enclosed by extending out from the trailers a building which encompassed the generator room and effectively doubled the size of the covered work area. This provided space for the parking of the bombardier tractor and the two snow toboggans. In addition extra shelf storage for food and other supplies was erected along the walls. The area was heated from the generator room and an average temperature of 25°F was maintained through the winter.

## Electrical System

The generator plant consisted of two diesel driven generators which were rated at 12.5 kw, 120-240 v, 60 cycle. The units were used on a rotation basis, and the wiring was installed to permit the use of one or both units, according to the power demand, through a rotary switch in the generator room. Power from the generators was distributed through number six, three conductor low temperature cable to individual instrument panels and circuit breakers in each trailer.

Two auxiliary gasoline driven generators of 500 and 2500 w, 120 v, 60 cycle were used for outside operations. At the time of closing the station both diesel units were drained and winterized. A 2500 w gasoline unit was located by the emergency exit and is connected to selected lights throughout the station.

## Fuel and Heating System

Inge Lehmann was heated by diesel burning, forced air flow heaters in each trailer, and a pot burner stove in the Jamesway. The diesel fuel used was Grade DF-A Arctic type delivered to the station in barrels. In future operations the bladder type fuel tank should be used, since bulk delivery is available in Thule. The fuel was pumped from the outside storage area to the holding tanks for heater and generator consumption, and gravity fuel flow was used throughout the buildings. All fuel tanks were left full when the station closed. An auxiliary portable electrically fired forced air flow heater using kerosene or diesel fuel was used in the garage area when required.

## Trash Disposal

The trash disposal area was located northeast of the station. To prevent a large accumulation of garbage and trash, the dump was burned over regularly. Since prevailing winds of the location are from the west, it was unlikely that fire would spread from the area to the main camp.

## Water System

A small compact snow melter, filled daily, provided all the water requirements of the station. The water was pumped into holding tanks located in each trailer unit. The snow melter held approximately 250 gallons of water and was kept full at all times to provide a fire fighting capability in addition to the dry charge fire extinguishers located throughout the station. All water systems were drained and cocks left open when the station closed.

## Communications

The communications system at Inge Lehmann operated in the HF and VHF bands on frequencies compatible with the 1983rd Communications Squadron, Thule, and the 17th TCS, Alaskan Air Command. It consisted of Collins Transceivers model KWM2A for long distance HF operation and a Skycrafters AM122 multiphone for short range VHF aircraft operation. The equipment was installed in the Jamesway. Various antennae for different frequencies were located to the west of the station and directed toward Thule.

Schedules with Thule Airways were maintained at 0000, 1200 and 1800 GMT (Greenwich Mean Time) daily. Using voice transmission, weather, seismograms and other traffic were exchanged. When conditions permitted, telephone calls could be placed through a phone patch system at Thule direct to Washington, Alaska and elsewhere. This proved to be a very effective part of our communications capability.

The HF frequency used was monitored by Thule AFB on a twenty-four hour basis, providing Inge Lehmann with instant contact should an emergency arise. During aircraft operations between Thule and the station, constant watch was maintained on the HF frequency for relaying flight information. For ranges up to fifty miles the VHF frequency was used to transmit local weather and other pertinent flight information.

Emergency procedures were established whereby a maximum period of no contact for 72 hours would be permissable between stations. At the end of this period an aircraft would be dispatched to the station to investigate. This rule did not apply in known cases of radio blackout which can frequently occur in these latitudes. Several of these periods were recorded at Inge Lehmann, such as one in May, 1967 lasting for five days.

## Transportation

Equipment was moved around the station by using a Bombardier J5 tractor. U. S. Army type one ton sleds were used for cargo and were stripped of all unnecessary parts to keep the weight at a minimum. Although the J5 tractor performed successfully, the larger track surface on the next model in this series would have given an advantage during the period of very soft top surface snow which occurs in the height of the summer.

For personnel movement two Polaris cruiser model snow toboggans were used between the drill sites and the main camp. These towed small tote sleds for gear and lightweight equipment.

## Logistics

Inge Lehmann Station is accessible by oversnow journey from Thule but such a method of travel is not considered practical in this day of air transportation. Logistic support of the project was efficiently discharged by the 17th Troop Carrier Squadron of the Alaskan Air Command, stationed at Elmendorf AFB, Anchorage, Alaska. All missions were flown in Lockheed Hercules C130 aircraft fitted with ski landing gear for landing on snow surfaces.

Sixty tons of equipment, supplies and personnel were flown in eight missions to establish the station. After the station was established, resupply and movement of visiting personnel were maintained by a bi-weekly air schedule.

During the winter darkness emergency flights were the rule and a rudimentary runway lighting system was installed for such emergencies. The highlight of the winter over crew was the flight made on Christmas Eve to airdrop essential spare parts and personal mail.

Regular flying began in late February, 1967 with the relief of the winter over crew and continued throughout the summer supporting the station and the Blue Trek traverse party until the last flight on September 2, 1967 when Inge Lehmann Station was closed.

## Meteorology

Surface weather parameters covering temperature, sky conditions, barometric pressure, wind speed and azimuth were recorded daily at the main synoptic hours. The observations were passed to Thule Air Weather Service for inclusion in their routine forecast analysis. Additional observations were taken prior to and during aircraft operations.

Observations recorded about 12 years ago at "North Ice" (British North Greenland Expedition 1952-54) compared with those of Inge Lehmann Station show that little change in the general climatic conditions for the two periods has occurred.

### Temperature

The mean average temperature for the year was minus 22°F with a maximum of 32°F and a minimum of minus 75°F recorded. Table I indicates the mean monthly values computed from records at both stations. Large fluctuations in temperature are characteristic of the ice sheet in general and show markedly in Figure 2 which indicates the temperature recorded at 1200 GMT daily throughout the year. These fluctuations were more pronounced during the colder months with a range of up to 40 degrees during a 24-hour period.

### Wind

Wind speed and azimuth were recorded at the five-meter level above the snow surface. The percentage frequency of calm ($<$ 1 mile per hour) was very low, such observations occurring only during the summer months. This infrequency of calm reduced the occurrence of extremely low temperatures. Although the wind was predominantly downslope, the prevailing direction of 250 degrees was occasionally interrupted by frontal winds from other directions, including strong upslope winds, for periods of several hours. The data in Table II show the computed mean wind speed recorded at North Ice and Inge Lehmann Station. Figure 3 indicates the wind speed and azimuth recorded at 1200 GMT daily. The maximum wind speed recorded for the year was 75 miles per hour on February 15th.

### Cloud Cover

Cloud cover at Inge Lehmann Station was greatest during the warmer months. The mean cloudiness during the summer was approximately 45 percent. Almost all cloud forms known were observed over the station. Cloudiness affected visibility by reducing the subdued shadows and at times eliminating all traces of them, making it difficult to judge distances on the nearly featureless white surface. Occurrence of thin stratus clouds on bright days accentuated the glare of the snow surface. Reduced visibility occurred with low-lying clouds close to the surface, and with night radiation fogs which dissipated when temperatures rose during the days. Radiation fogs were very prevalent in the early spring and late summer months. Except for the occasional occurrence of blowing snow and fog, visibility at the station was usually good.

## 2.2 CORE DRILLING AT INGE LEHMANN

### Purpose

The primary purpose of the core drilling was to provide four holes set out in predetermined positions to accommodate the vertical seismometers.

## TABLE I. MEAN MONTHLY TEMPERATURE VALUES (°F)

| Station | Jan | Feb | Mar | Apr | May | June | Jul | Aug | Sept | Oct | Nov | Dec | Avg |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Inge Lehmann (1966-67) | -45.9 | -44.6 | -49.9 | -36.0 | -1.0 | +9.4 | 17.2 | 10.1 | -13.3 | -22.1 | -42.5 | -51.2 | -22.5 |
| North Ice (1953-54) | -42.0 | -44.0 | -45.0 | -26.0 | -5.0 | +9.0 | 14.0 | 8.0 | -15.0 | -34.0 | -40.0 | -43.0 | -22.0 |

## TABLE II. MEAN WIND SPEED (MPH)

| Station | Jan | Feb | Mar | Apr | May | June | Jul | Aug | Sept | Oct | Nov | Dec | Avg |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Inge Lehmann (1966-67) | 15.8 | 16.3 | 13.7 | 16.9 | 16.2 | 10.2 | 13.2 | 12.3 | 11.8 | 17.7 | 15.9 | 15.2 | 14.6 |
| North Ice (1953-54) | 18.1 | 18.4 | 18.1 | 17.4 | 13.6 | 11.6 | 15.8 | 17.9 | 17.1 | 17.1 | 18.9 | 17.3 | 16.6 |

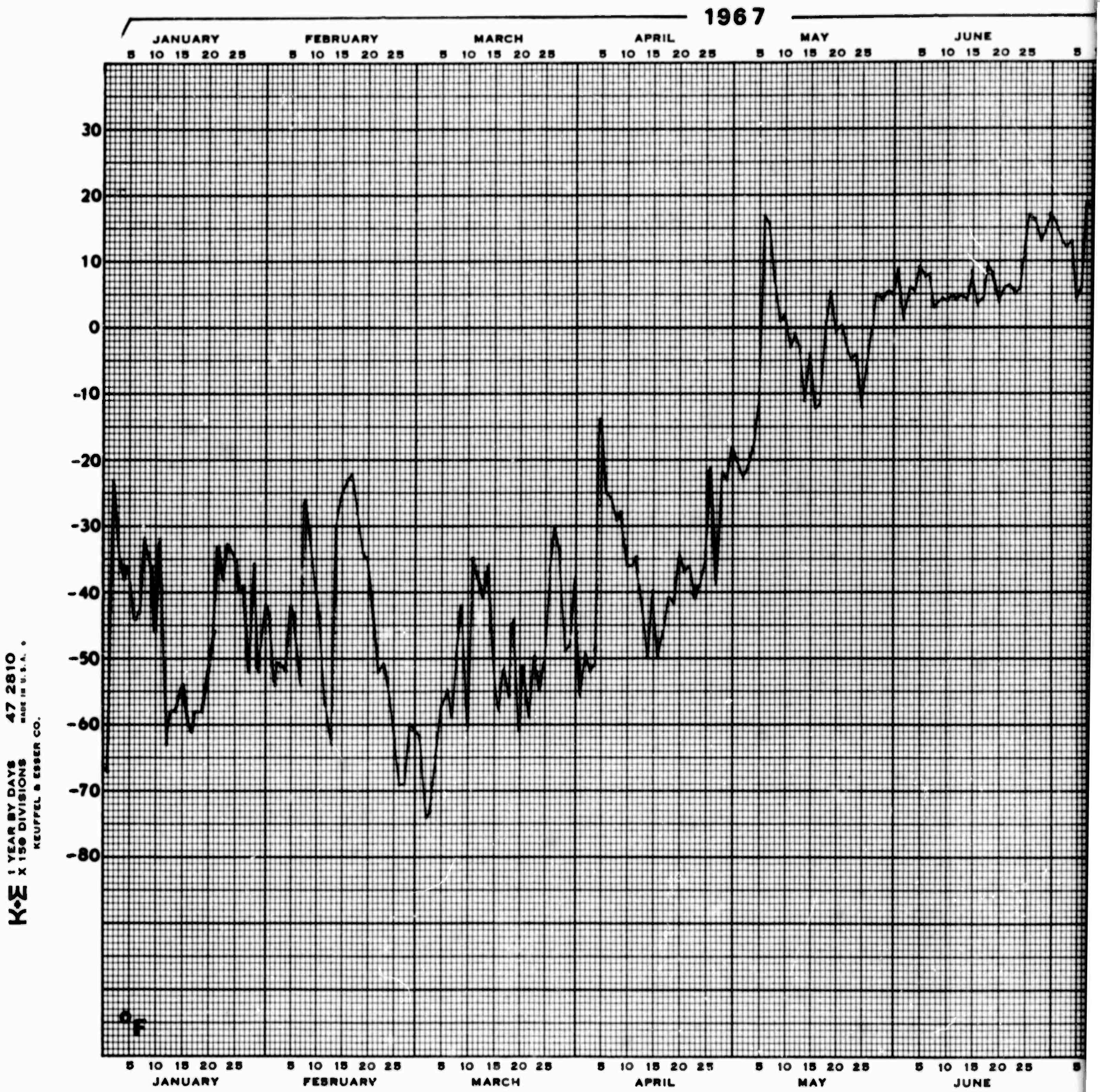
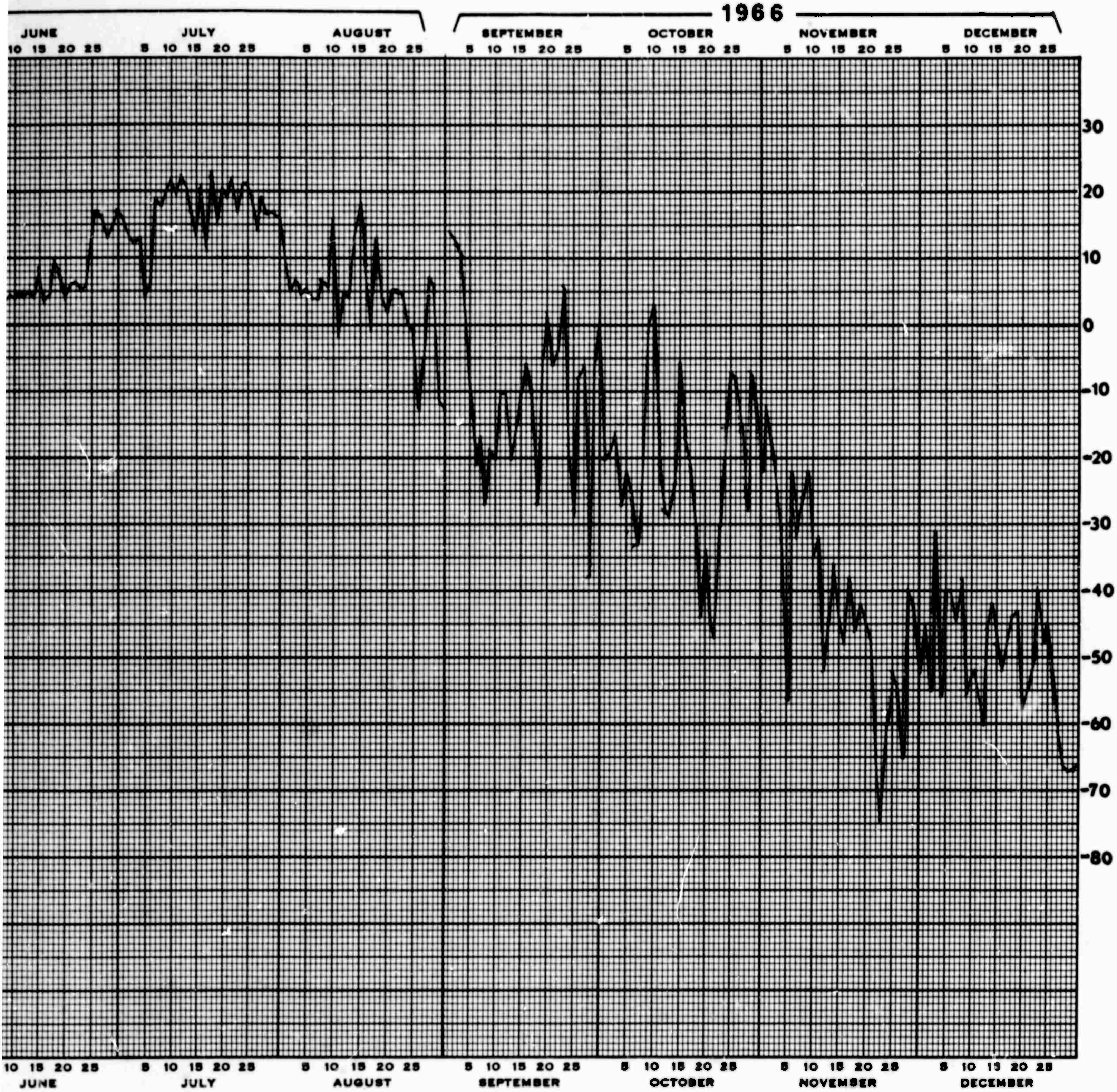


FIGURE 2 DAILY TEMPERATUR

INGE LEHMANN

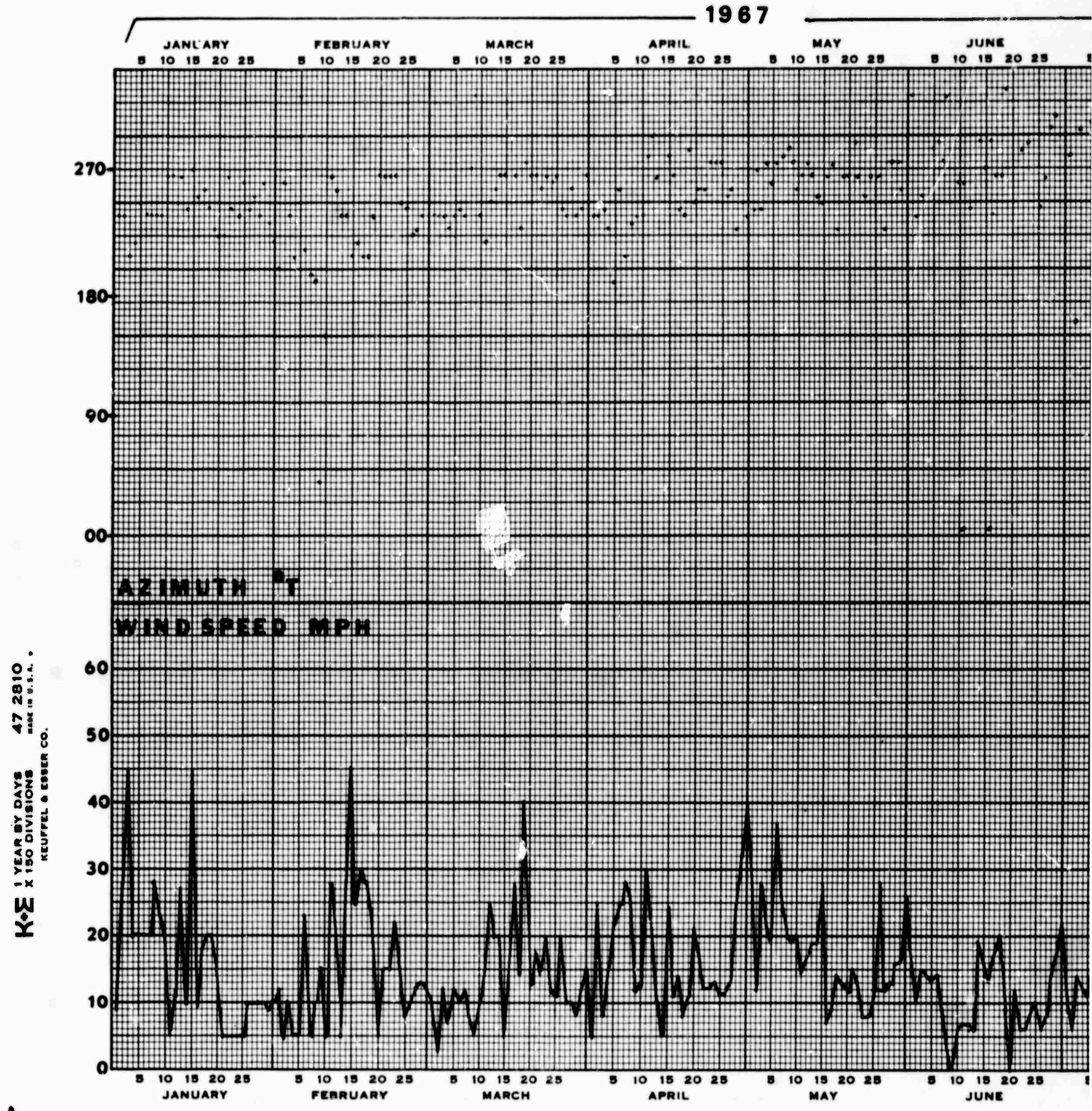
A



MPERATURE AT 1200 GMT,

E LEHMANN STATION

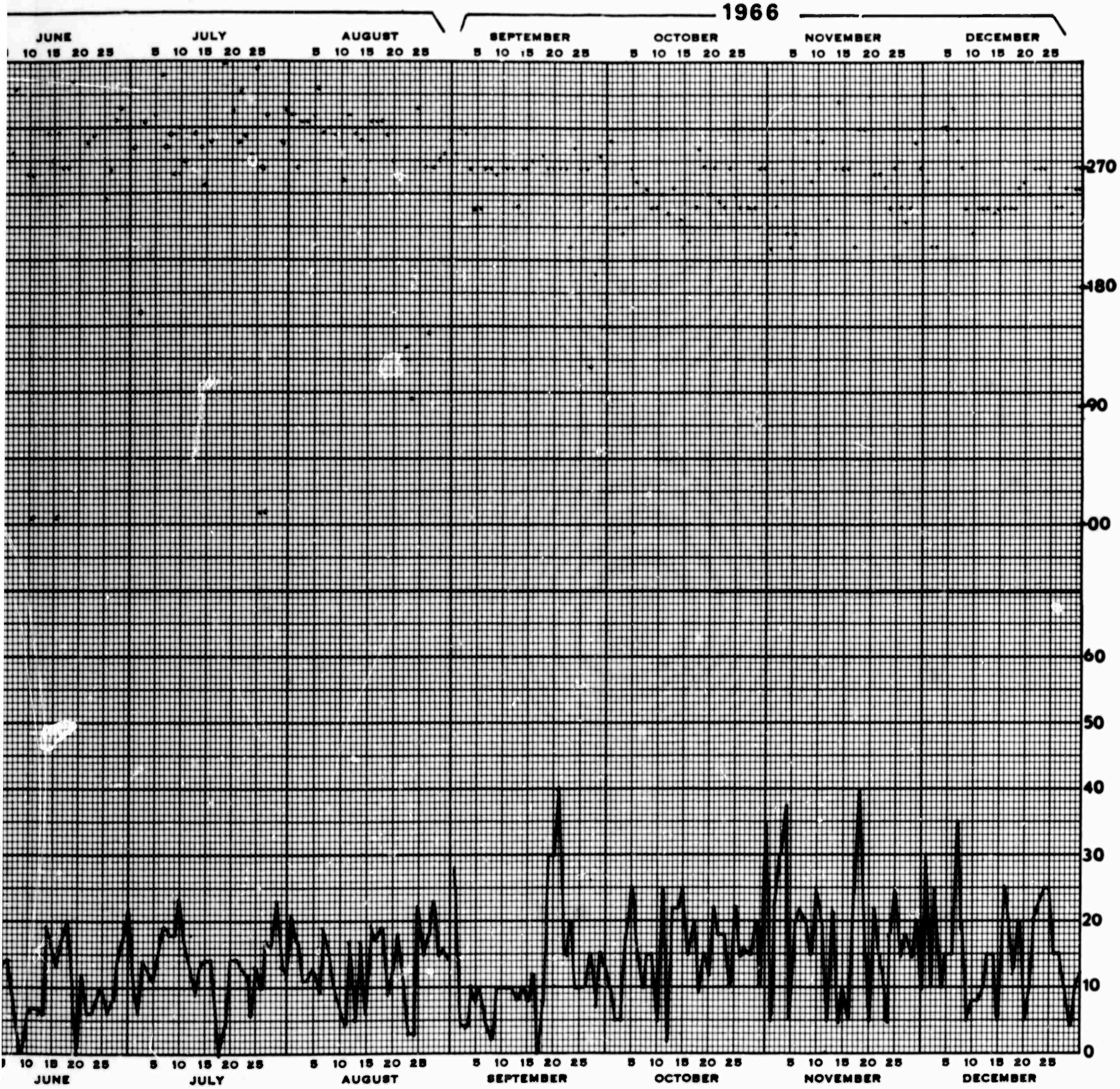
B



A

FIGURE 3 DAILY WIND SPEED AND A

INGE LEHMAN



EED AND AZIMUTH AT 1200 GMT,

IGE LEHMANN STATION

B

The depth of the holes were to be in the zero permeability zone. It is in this zone where the average density is 0.828 $g/cm^3$, that by definition firn becomes glacier (blue) ice. At Inge Lehmann the zone was reached at a mean depth of sixty meters.

A secondary but important purpose was the collection of core samples throughout the entire depth of the holes. This collection not only enabled us to determine densities, but also supplied us with very valuable material for later study.

## Equipment

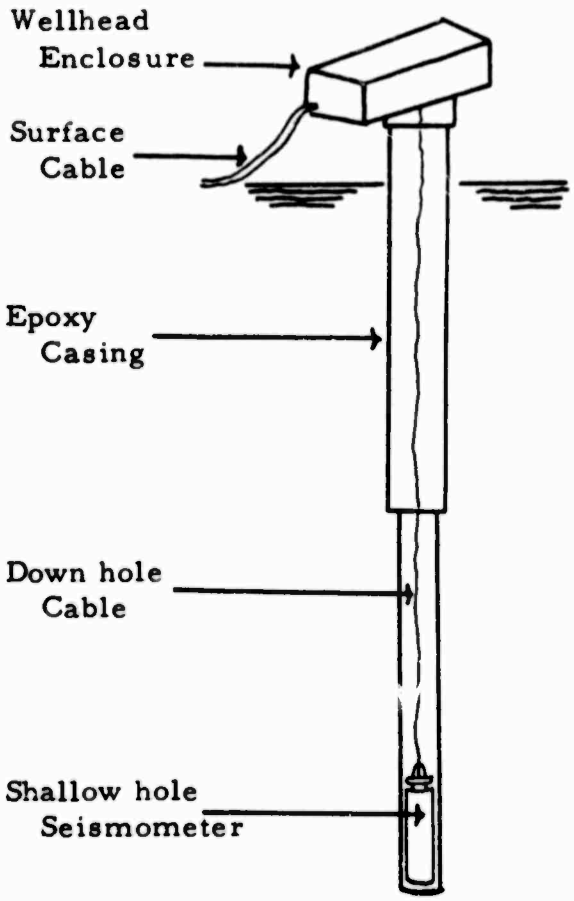
Although several different types of drilling rigs are capable of drilling the required holes, not all are suitable for use or transportation under the conditions present on the ice sheet. Acceptable rigs were examined and the heavy duty Hillbilly model manufactured by the Acker Drill Company was chosen. This rig in its basic form is a self-contained unit, easily operated by a small crew, and easily transported from place to place. For our project a few changes and additions were made to the rig by the manufacturer.

The power source was changed from the usual gasoline engine to a diesel unit of the type used to drive the generators at the station, thereby cutting the costs and maintenance of a large variety of spare parts. To obtain very low speeds for drilling in the ice, a second high-low gear box as well as the usual four speed shift was installed and a full base plate sled was bolted to the underside of the skid plates to facilitate the transportation of the rig between drilling locations. In addition, a self-supporting tripod was used rather than a rig-mounted derrick. Each leg of the telescoping tripod was twenty-nine feet long when extended, providing a usable height of twenty feet when the tripod was in position over the hole.

Unlike the normal rig which is usually placed on top of a crib for drilling, it was decided to build a drilling platform of two by fours and plywood, which would hold the tripod and most of the other drilling equipment together with the rig itself. The platform was twenty-four by twenty-four feet overall, made up in four sections for ease of transportation. These sections were held together during drilling operations by overlapping sections of plywood. This provided us with a very stable platform on which to carry out the drilling operations.

In order to support the wellhead enclosure and the down hole cable, the nature of the firn required casing the hole to a depth of eighteen meters. Standard six inch epoxy well casing was used. To the top of this the wellhead enclosure was affixed.

Two sizes of auger barrel patterned after the 3" SIPRE auger design of the Cold Regions Research and Engineering Laboratories were used. The larger barrel was 7 7/8 inches in diameter and six feet long. This was used for the upper eighteen meters of each hole. The smaller barrel was 4 7/8 inches in diameter and was manufactured in two lengths, six and ten feet. All barrels were fitted with removable bit heads, baskets and core lifter rings to enable the collection of undisturbed core samples. The ten foot, small diameter barrel was discarded when it was found to bend under pressure, causing deformation of the hole and further difficulty in raising the string.



## Operation

Working with ice creates special problems for the design of drilling machinery, due to the imponderable factors in the behavior of the drilling tools at depth. Even though several techniques have been developed for ice augering, no one had previously used the kind of equipment selected. For this reason it was not possible to detail definite drilling procedure. Two factors very important to this kind of drilling are the revolutions of the auger and its downward travel rate. Several tests were conducted, varying both the rotation speeds and the travel rates. The optimum rotation rate varied between twenty-four and fifty-two revolutions per minute. In almost all cases the lower rpm rates gave the best results.

With the hydraulic pressure control at 2000 lbs, the downward rate of travel ranged from two to eight inches per minute. Between zero and one hundred feet it was possible to drill over thirty feet per eight hour shift. From one hundred to one hundred and fifty feet the rate decreased to twenty feet and below this depth it again dropped slightly to fifteen feet per shift.

This method of drilling is possibly a little slower than other techniques, but where good core sampling is required along with depth-density control, it cannot be surpassed. If an expanded array is to be placed at Inge Lehmann Station the continuous flight augering method should be used as deptn/density control is now established.

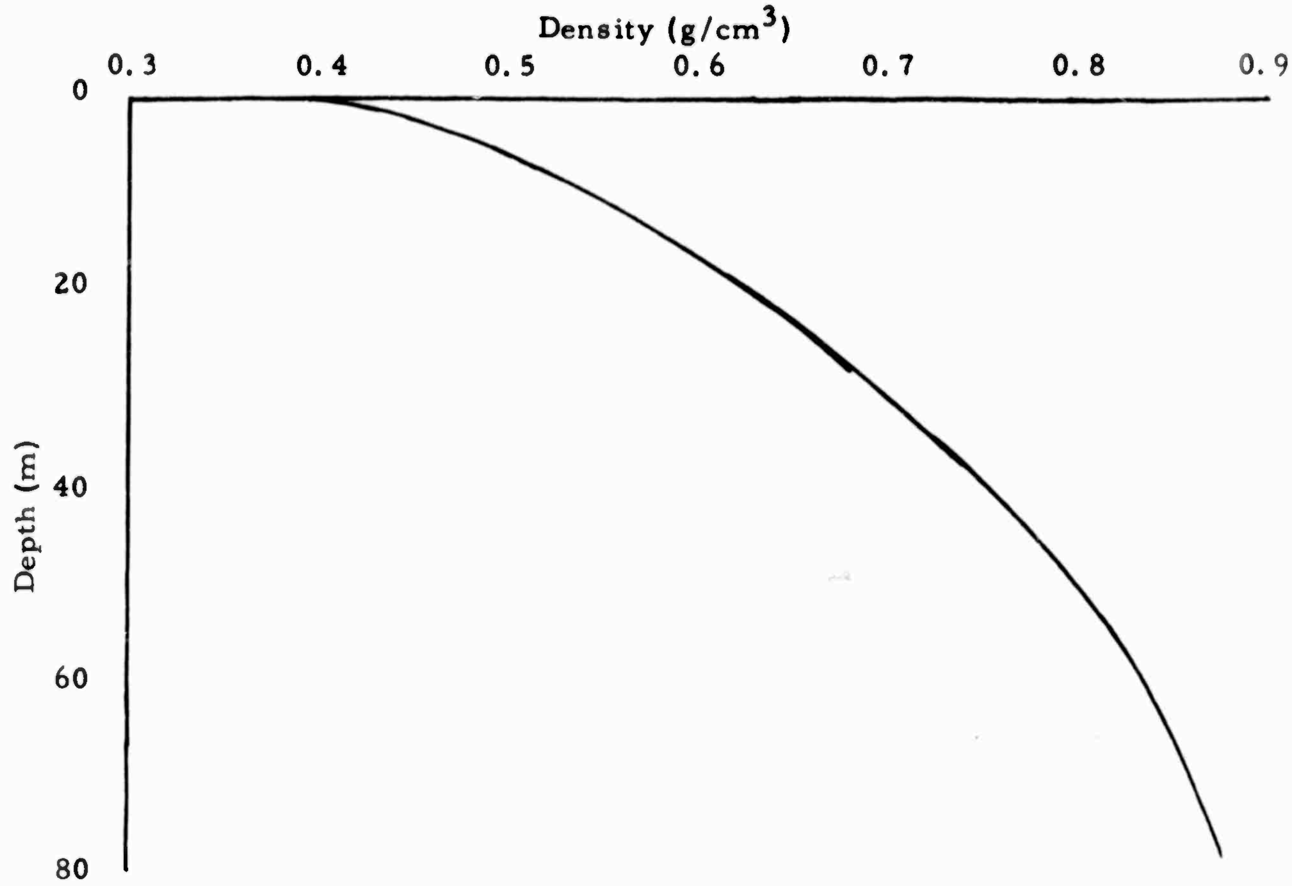


Fig. 4 Depth-density Curve, Inge Lehmann Station

## 2.3 SEISMIC INSTRUMENTATION AND INSTALLATION

The seismic array used for the noise study consisted of four downhole short-period seismometers. The Geotech model 20171A moving coil seismometer is designed to operate in shallow holes at pressures up to 500 p.s.i. and at tilt angles as great as ten degrees. The instrument is capable of long-term operation at temperatures of 120°F, and demonstrated satisfactory operation at bottomhole temperatures encountered of minus 33°F. It has a natural frequency response adjustable from 0.75 to 1.05 hertz and a natural period adjustable from 1.33 to 0.95 second. For this study the period was set at one second. These seismometers were located at the centre and apices of an equilateral triangle.

Initial layout of the array was made using a landing compass and later surveyed in by tellurometer and theodolite. The distance for each leg of the array was controlled by the length of the cable per reel. The surface cable used was REA type PE23, a semi-armoured six pair telephone cable, the same as that used in the Montana Large Aperature Seismic Array.

To ensure that the shielding and insulation would not crack due to extremes of cold, the complete drum of cable was heated by hot air using a Herman Nelson heater. After warming, the cable was attached to a snow toboggan vehicle and pulled off the reel to the seismometer location. The buried cable was marked by flagged bamboo poles at 300 ft intervals from borehole to the recording trailer. On the completion of the coring of each borehole, the seismometer was lowered into position using a 7H4 multi-conductor double armoured cable as the down hole cable, the necessary connections being made at the wellhead junction box.

A three-component surface seismic station was installed 685 meters to the north north west of the center borehole seismometer in a chamber dug out of the snow at a depth of five meters. Short-period signal detection was accomplished using Geotech Model 18300 seismometers. These seismometers can be used as vertical or horizontal detectors depending on whether the spring suspension is attached or detached. The conversion is simple and can be made in the field.

During March-April 1967 a second surface chamber was dug at eight meters to accommodate a three-component long-period system comprising two Geotech Model 8700C vertical seismometers and one Model 7505A horizontal seismometer. These seismometers required much more extensive chamber preparations than the short-period system, but arrangements are made so that final adjustments to seismometer free period, mass centering, and dampening can be made remotely after the chamber has been sealed, greatly reducing setup time. Also, operation after setup is simplified, because parameters can be adjusted without direct access to the seismometer.

The remainder of the seismic instrumentation was housed in the instrument trailer. Data was recorded on a 14 channel SlowSpeed Magnetic-Tape Recording System Geotech Model 19429. This system records with a tape speed of 0.03 i.p.s. in IRIG format.

Signal amplification and level control was provided by the Amplifier Control Unit, Geotech Model 19800. Six Photocell Amplifiers Model 19718 are installed in the control unit. System response is controlled by filtering the amplifier output and by adjusting the seismometer parameters.

Station time and WWV standard time were provided by the Timer-Programmer Unit, Model 19754.

A special installation was required for the photocell amplifiers to prevent extraneous disturbances caused by personnel movement in the instrument trailer, thus necessitating isolation of the amplifiers from the trailer. A hole fifteen centimeters (six inches) in diameter was cut in the trailer floor which allowed a five foot section of 8.9 cm (3 1/2 in) diameter

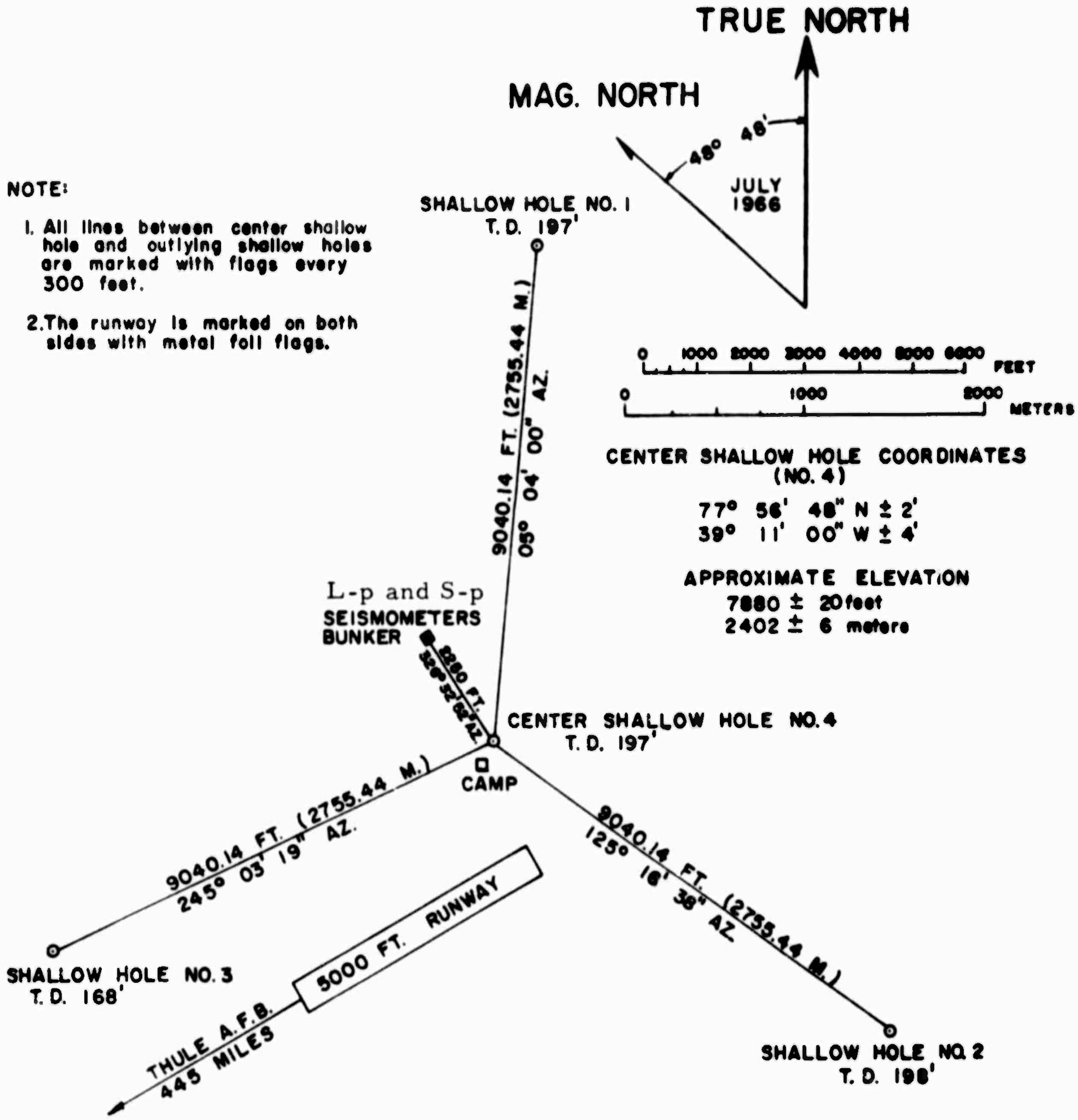


Fig. 5 Inge Lehmann Site Layout

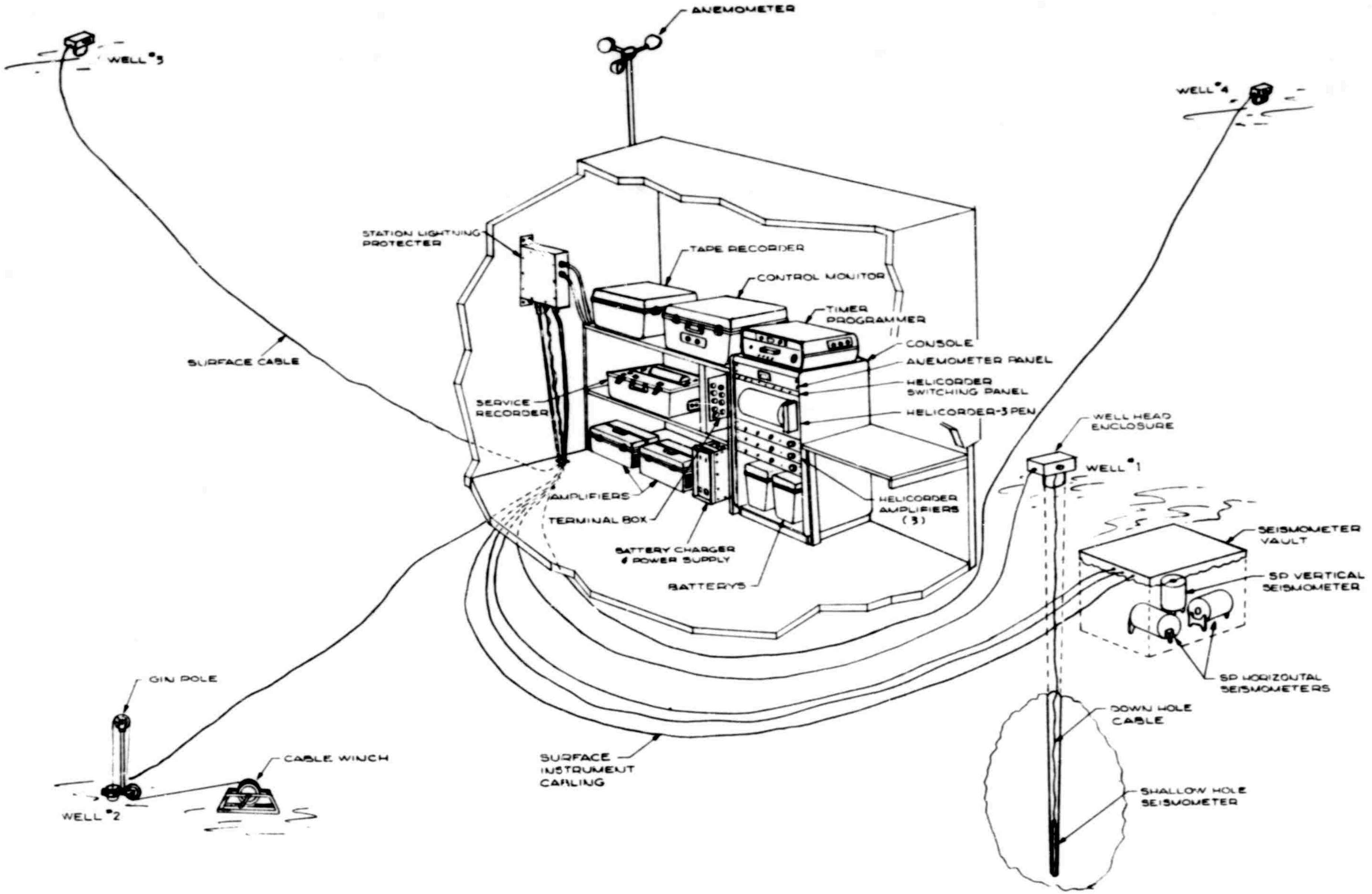


Fig. 6 Inge Lehmann Seismic Instrumentation

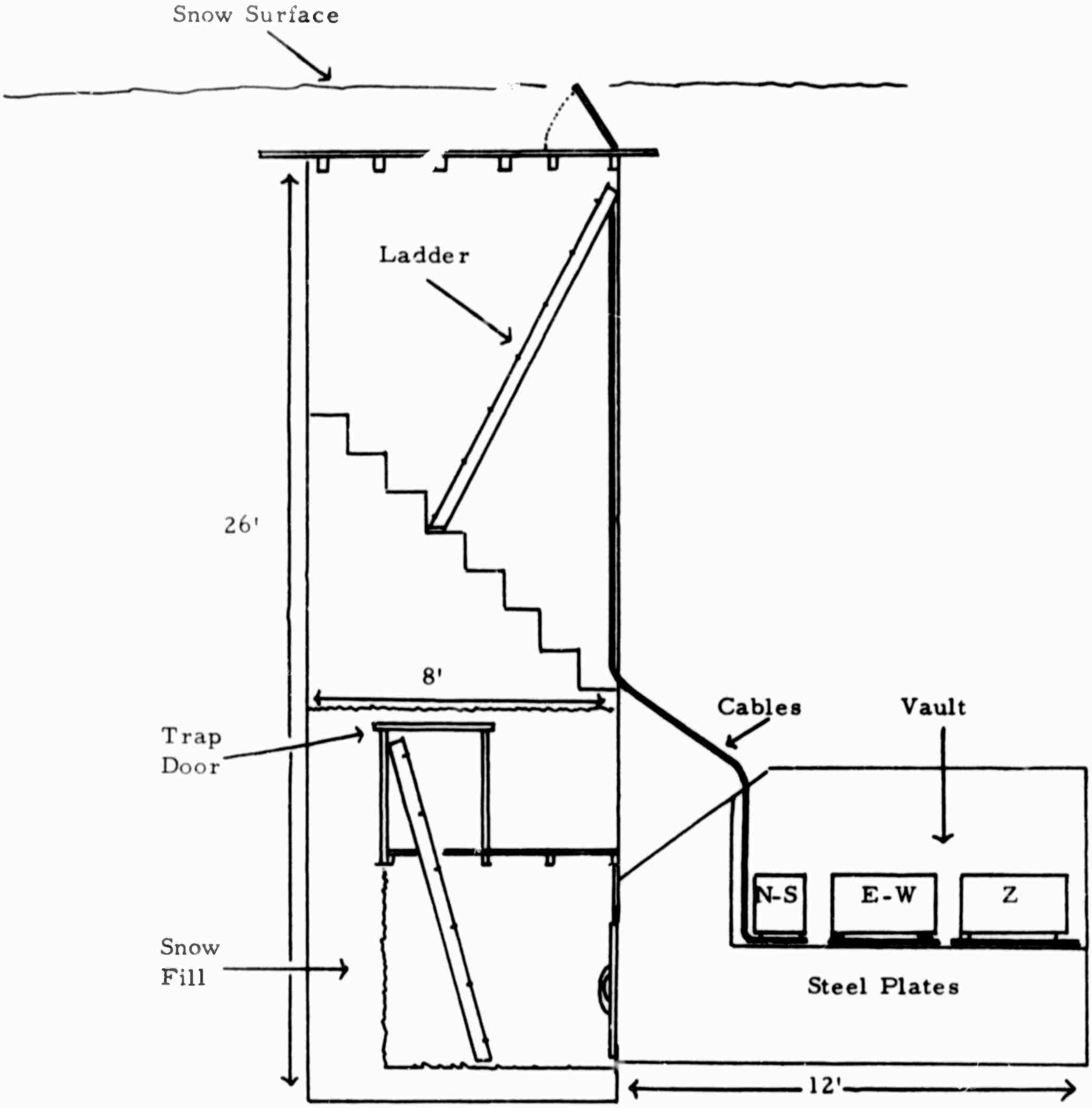


Fig. 7 Side View of Long Period Vault
Inge Lehmann Station

pipe to be frozen into the snow to a depth of 1.2 m (4 ft) below the trailer floor. A platform was fixed to the top of the pipe large enough to accommodate the amplifier and control units which house the photocell amplifiers.

A Helicorder Model 2484-3 was used to record individual seismometers, providing a paper record for day-to-day visual analysis of events. These events were then coded and relayed by radio to the U.S. Coast & Geodetic Survey Seismological Center at Rockville, Maryland for inclusion in their daily seismic event bulletin.

The taped record was despatched by air to Garland, Texas for detailed analysis and storage in the LRSM library.

System accessories included the equipment necessary to calibrate, monitor and maintain the system.

## 2.4 ANALYSIS OF SEISMIC NOISE DATA

### Short-period Noise

#### Spectra of Short-period Noise

The noise level recorded at the bottom of the shallow boreholes (approximately 60 m) is comparable with that obtained at some of the best stations in the continental United States. Figure 8 shows the power spectrum of the noise, the power at 1.0 sec period is close to 1.0 $m\mu^2$/cps, decreasing rapidly towards the shorter periods and increasing rapidly towards the longer periods. Figure 9 shows the seismograph response. For periods less than 2.0 sec, the noise was approximately time stationary during the time covered by the data. This point is illustrated by figure 10, which shows spectra of the noise taken 1 week apart during August and September 1966. The minor peaks in the spectra at these shorter periods are not significant, considering the confidence levels of the results and the presence of some tape noise. For periods greater than 2.0 sec, the noise changes appreciably with time (see figure 10). Only one of the spectra shows the peak at 6.0 sec period which is commonly found in spectra of continental sites; visual examination of the records confirms that waves of this period were rarely recorded with large amplitudes during the summer. However, during the winter months these waves were often predominant in the recordings. This difference between summer and winter is almost certainly caused by the presence of large storms in the northern Atlantic. For the period range of 5.0 to 2.0 sec, a number of peaks are present in each spectra; however, with the possible exception of the one at 2.9 sec, none of them appear to be time stationary.

When the first spectrum of the noise was obtained, it was thought

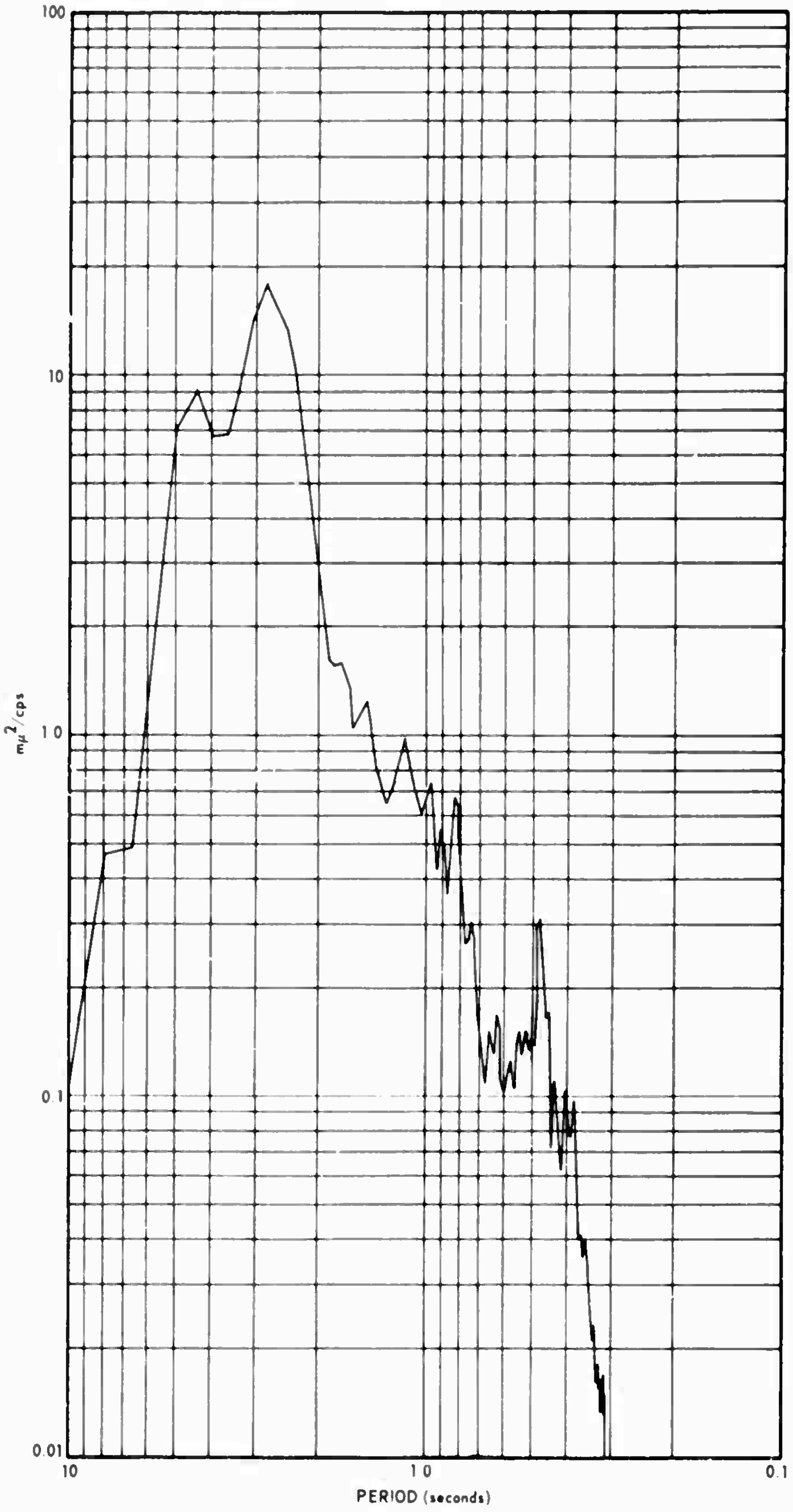


Figure 8 Power spectrum of the short-period seismic noise at Station Inge Lehmann, Greenland

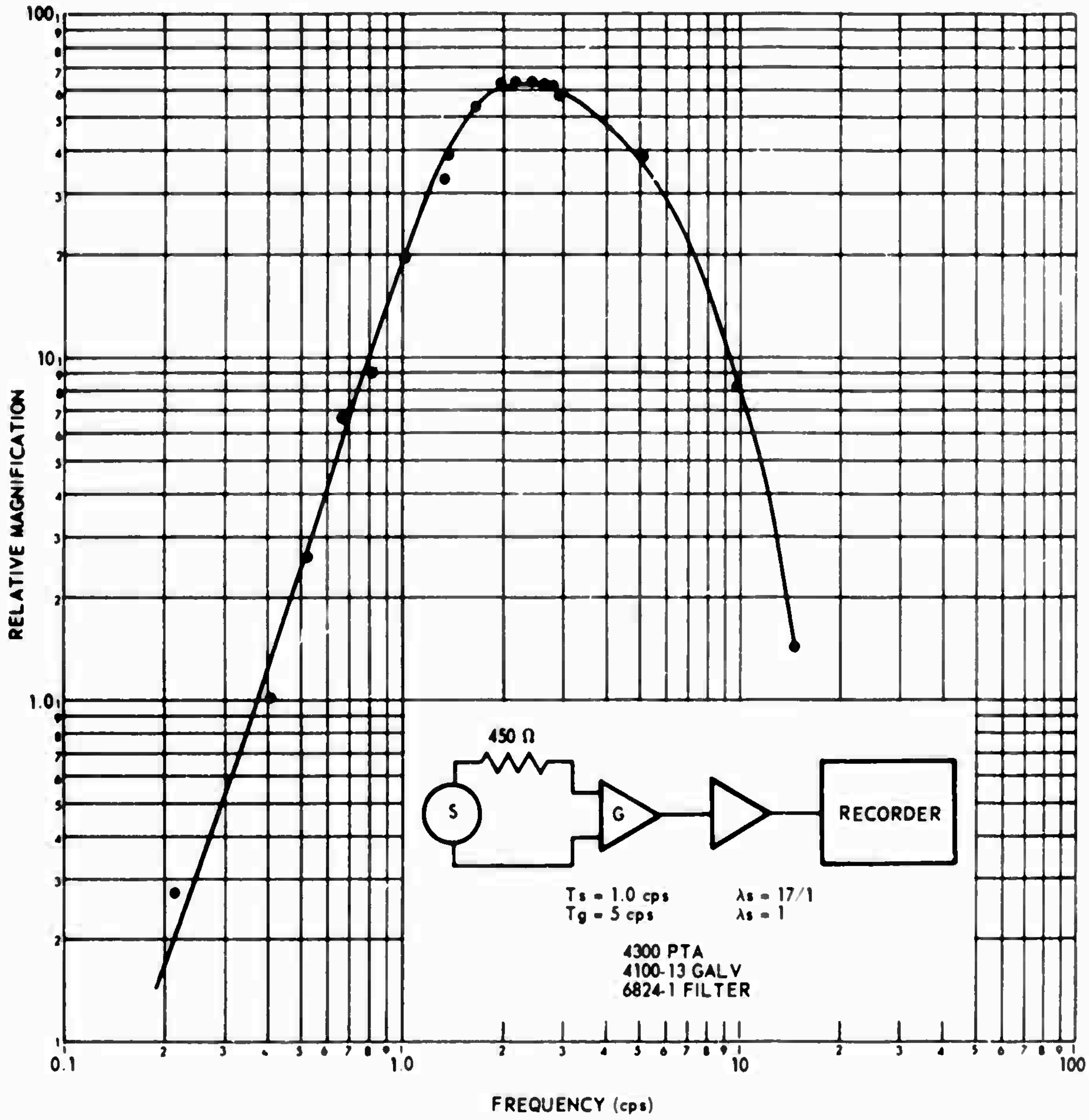


Figure 9  Frequency response of short-period borehole seismographs at the Inge Lehmann Observatory

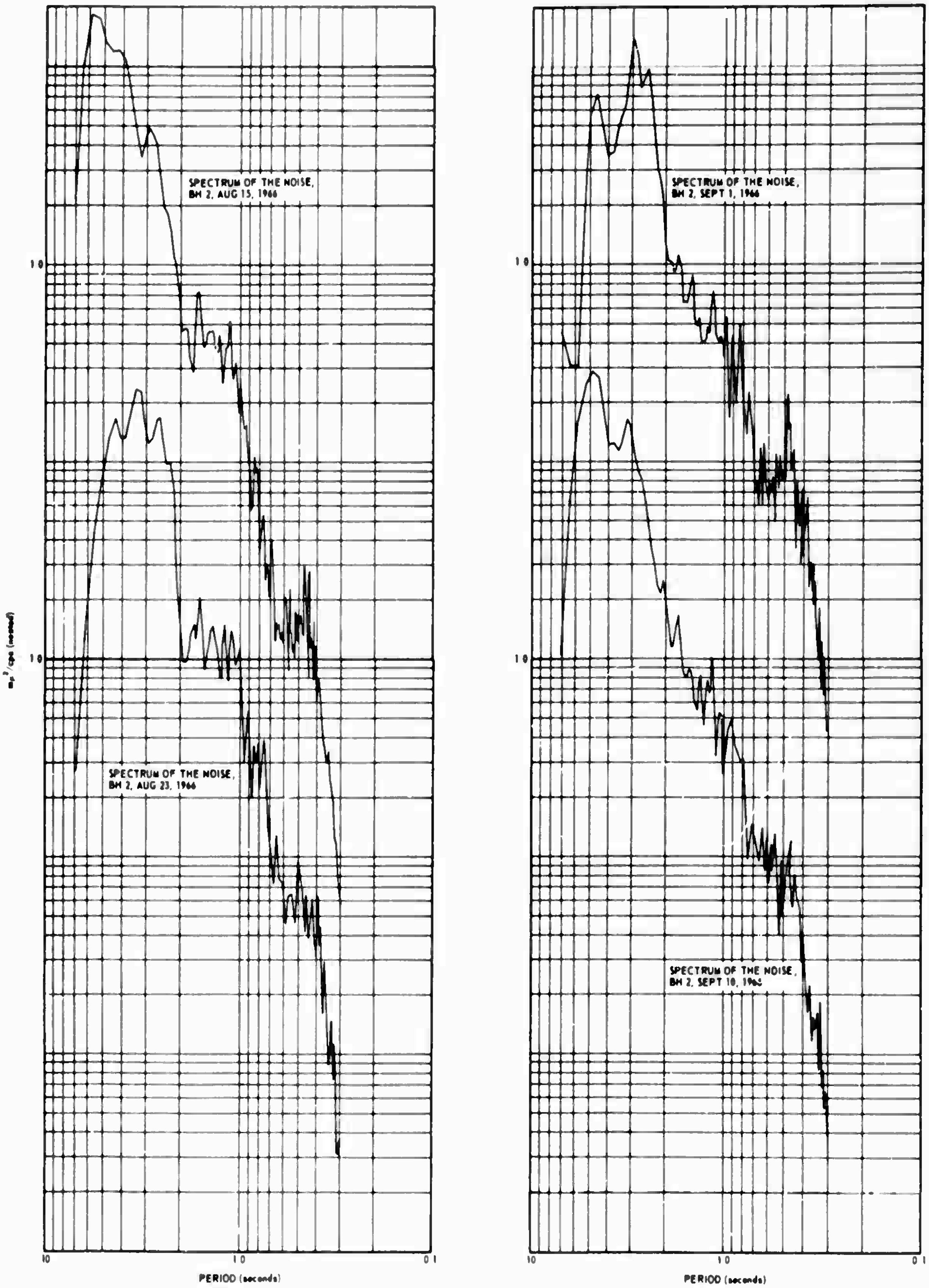


**Figure 10** Nested spectra of the short-period noise recorded at Station Inge Lehmann, Greenland

that the peaks might be connected with Airy phases of surface waves controlled by the low-velocity ice layer. The dispersion curves for Rayleigh and Love waves were computed assuming an ice thickness of 2.8 km and an estimate of the crustal thicknesses and velocities. The fundamental and first Rayleigh modes both have lows in the group velocity curves at close to 3.0 sec period (see figure 11). These low values are caused by the low-velocity layer. Although it is still possible that some waves at the peaks in the spectra are controlled by the ice layer, the variability of the periods at which the spectral maxima are found indicates that the source is the controlling factor. As will be discussed later in the report, no phase velocities that agree with the theoretical one were found in the noise. It appears likely that surface waves which are essentially trapped in the ice layer will be rapidly attenuated. The author is not aware of published attenuation coefficients for elastic waves in ice at the frequencies recorded. However, extrapolation of attenuation values for higher frequencies indicates that ice has a low Q (high attenuation). This feature probably explains the low-noise levels; the higher frequencies of surface waves in the band of interest (around 1.0 sec period) will be trapped in the ice and highly attenuated. The longer periods travel with most of their energy content in the deeper rocks and will attenuate less rapidly.

Examination of the recordings has revealed no high-frequency events such as would be expected if any breaking of the ice under or near the station occurred. It therefore appears that the ice under the station is deforming plastically. Some of the high-frequency noise may originate from this flow, but if so, it produces a relatively constant background.

The original short-period vault was located very close to the camp. Appreciable high-frequency noise was observed. This noise was completely eliminated by placing the vault 685 meters from the camp; this feature supports the argument that high attenuations are responsible for the low-noise levels.

In general, the noise levels increased somewhat during the winter months as can be seen by comparing the spectra shown in figures 10 and 12.

As discussed again in the section on wind noise, this increase is not related to the wind velocities on the ice sheet. It must be assumed that almost all the noise for all periods originates in the oceans and that the increase in noise levels is connected with the storms in the ocean. It must be noted that the noise levels shown in figure 12 are representative of the highest noise levels recorded during the winter and that numerous days during the winter had noise levels as quiet as those obtained during the summer.

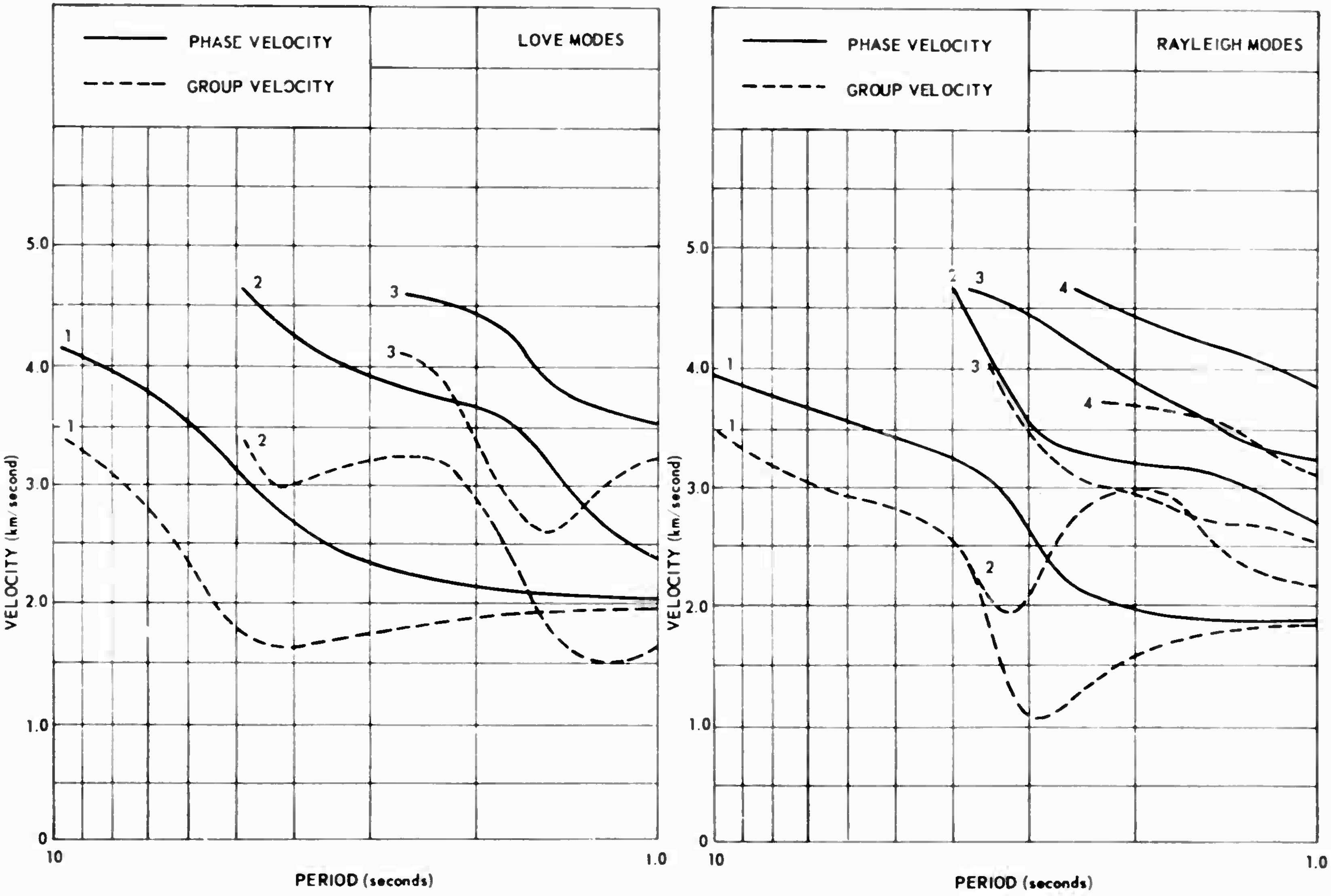
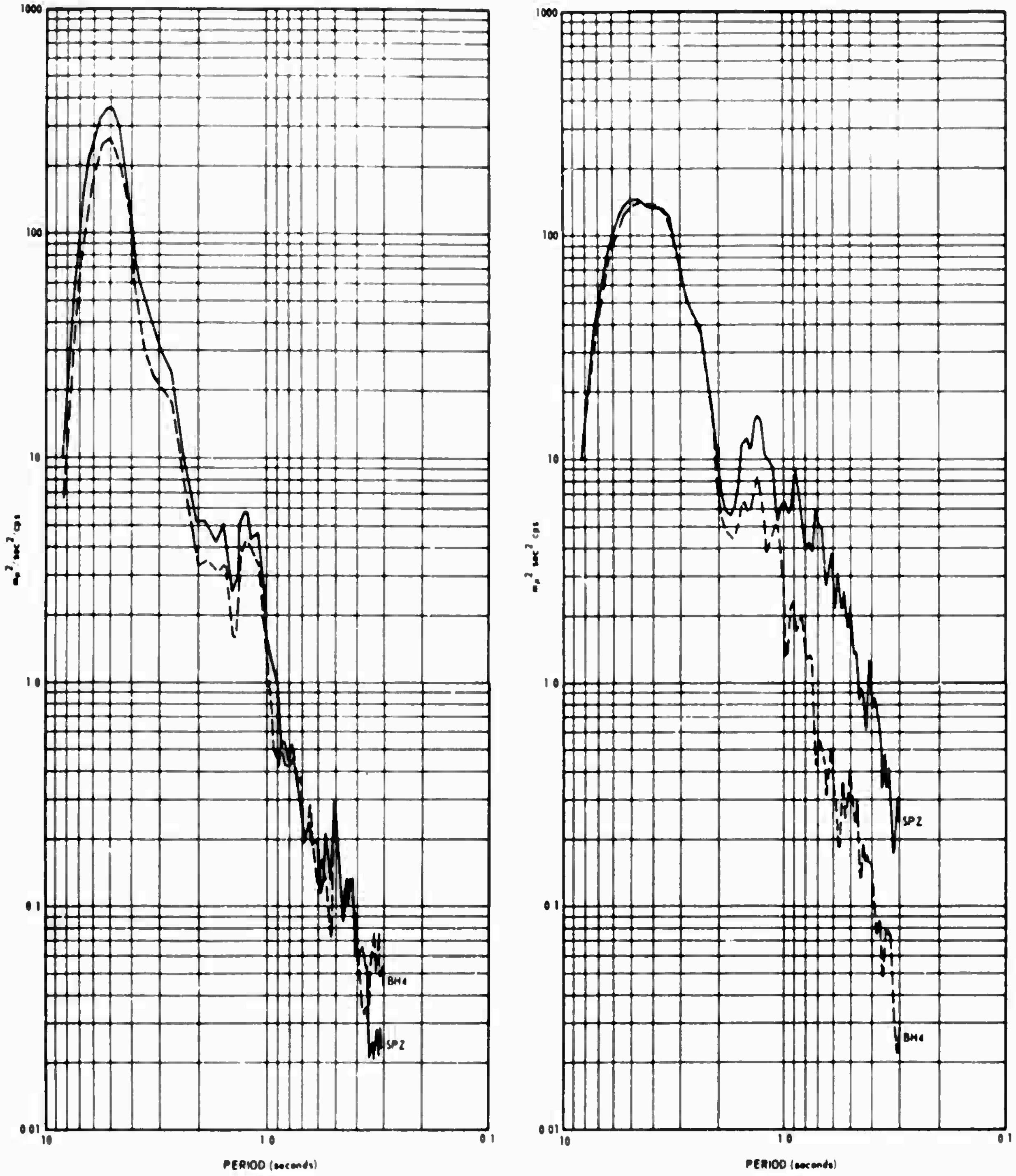


Figure 11 Phase and group velocities of Rayleigh and Love waves. Station Inge Lehmann. Ice thickness assumed to be 2.8 km. Number identifies order of mode starting with 1 for the fundamental



(a) (b)

Figure 12 Velocity spectra of the noise at Station Inge Lehmann on (a) wind 0-10 km/hr, 8 December 1966 (b) wind 40-60 km/hr 5 December 1966

## Coherences

Several sets of spectra and cross-spectra were computed for the noise recorded by the array. Figures 13 (summer) and 14 (winter) show the coherences obtained in this fashion. The coherence used here is defined as:

$$\text{Coh} = \frac{\left|\,\text{cospectrum} + \text{quadspectrum}\,\right|^2}{(\text{spectrum 1} \,.\, \text{spectrum 2})}$$

For the length of sample and time window used, the expected coherence (if the actual coherence is zero), is 0.08; values less than this number have not been plotted. For both of the distances between seismometers (2.7 and 4.7 km) in the array, the coherence is negligible for periods less than approximately 1.5 sec. For greater periods, the coherence increased rapidly to high values. It must be noted that there is little or no difference in the coherences between summer (figure 13) and winter months (figure 14). This feature would suggest that the sources are the same but only the intensity changes.

On comparing these results with the spectra shown in figure 10, it is apparent that the coherence becomes small at the same period where the slopes from the long periods flatten out. This behavior indicates that the two period ranges (greater and less than 1.5 sec) are fundamentally of different wave types and possibly from different source mechanisms.

The results shown in figures 13 and 14 are of interest in array design; they indicate that the noise is uncorrelated between seismometers for periods of greatest interest in detection. Because this fact is of importance and because it is possible to obtain low coherences from interference effects, it was decided to check this conclusion. Whether the low coherence is actually caused by interference of different wave types from a number of different directions can in theory be resolved by the use of multiple coherences (Bendat, 1966). The multiple coherence function between $x_i(t)$, one of the seismographs of the array, and the other seismographs $x_1(t)$ through $x_n(t)$ of the array, is defined as:

$$\gamma_{ix}(f) = 1 - \left[C_i(f) \,.\, C^i(f)\right]^{-1}$$

where $C^i(f)$ denotes the ith diagonal of the inverse of the spectral matrix. The multiple coherence is a measure of the linear relationship of the time series at one point, and the time series at the other points. Essentially, it is a measure of how well a set of linear filters can predict the noise at one seismograph of the array when applied to the outputs of the other seismographs. Figure 15 shows the results obtained. For the period range below 2.0 sec, the multiple coherence is low, indicating that for the seismometer separation used here, optimum filtering techniques will not be effective. In order to test the improvement in signal-to-noise ratio possible if a simple time-delay and sum, beam-steering process was used at this site, it was decided to obtain the spectrum of the direct sum of the seismographs. For the periods where the noise is uncorrelated between seismometers, the power should increase by a factor of 4. Figure 16 shows the results; the value obtained (4.0 $m\mu^2$/cps) is slightly higher than the theoretical expected factor of 4, indicating a small (< 10 percent) amount of correlated noise. The coherences shown in figure 13 in all cases, except BH3 to BH4, show a dip in the coherences at 3.5 sec period. The only reasonable explanation for this behavior is that the two peaks in the spectrum at 2.9 and 3.5 sec (figure 10) are either the same wave type from two different directions or different wave types from the same direction, or both. However, this explanation does not appear to agree with the phase angles between instruments.

## Velocities of the Noise

Several attempts were made to obtain phase velocities of the noise traveling across the array. The phase angles shown in figures 17 and 18, for summer and winter, respectively, indicate clearly that the noise cannot be explained by a wave traveling across the array from a single direction.

A number of frequency-wave number plots for the noise at different frequencies were computed. These results were inconclusive; the results indicate that the apparent velocity is higher (>6.0 km/sec) than possible for surface waves (even for the 6.0 sec period waves which are generally assumed to be fundamental mode surface waves). It is, of course, possible that body waves predominate in the noise, but this cannot be proven because interference effects between surface waves arriving from a number of directions can give the same results. The main problem encountered in the calculation of f-k spectra was that the resolution in k-space from a four-element array is very poor; this is clearly shown in figure 32, which gives the wave-number response of the present array.

## Wind Noise

At this site in the middle of the Greenland Ice Sheet, extreme wind velocities are not as common as close to the coast where temperature differences between ocean and land cause the wind to blow. However, high wind velocities do occur quite regularly.

When the wind is blowing less than 20 km/h, there is little or no difference between the surface instrument located in a chamber excavated

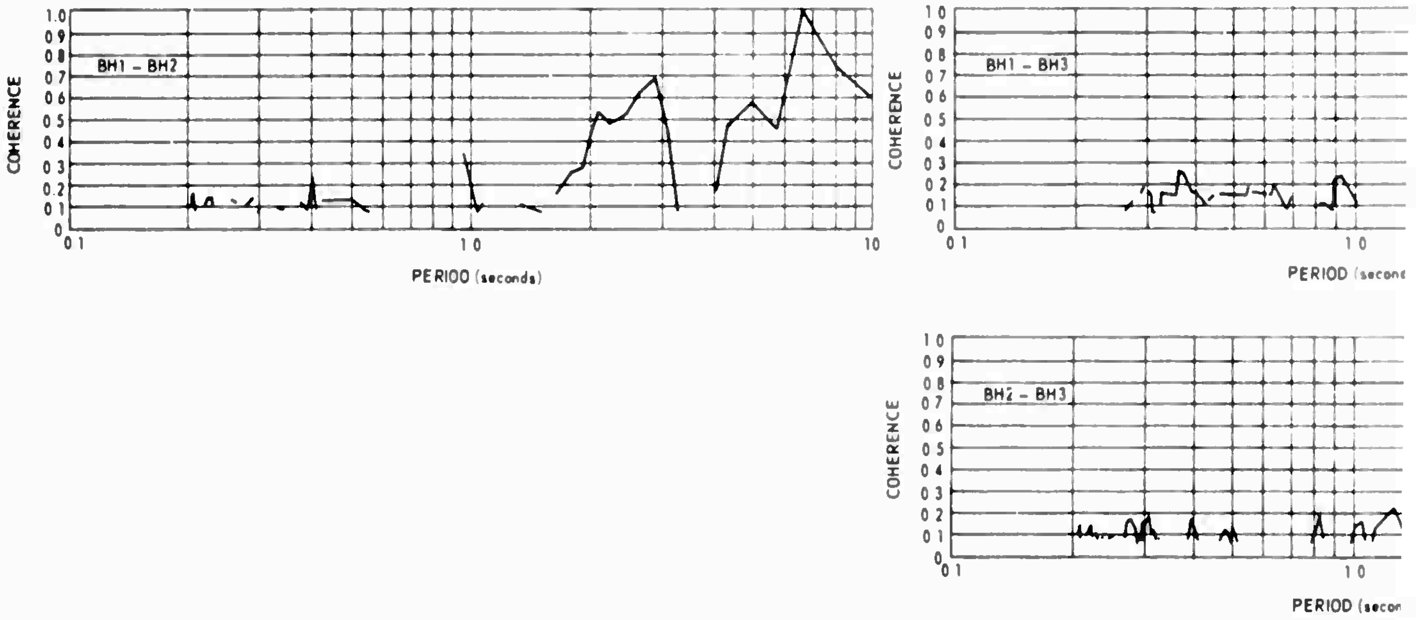
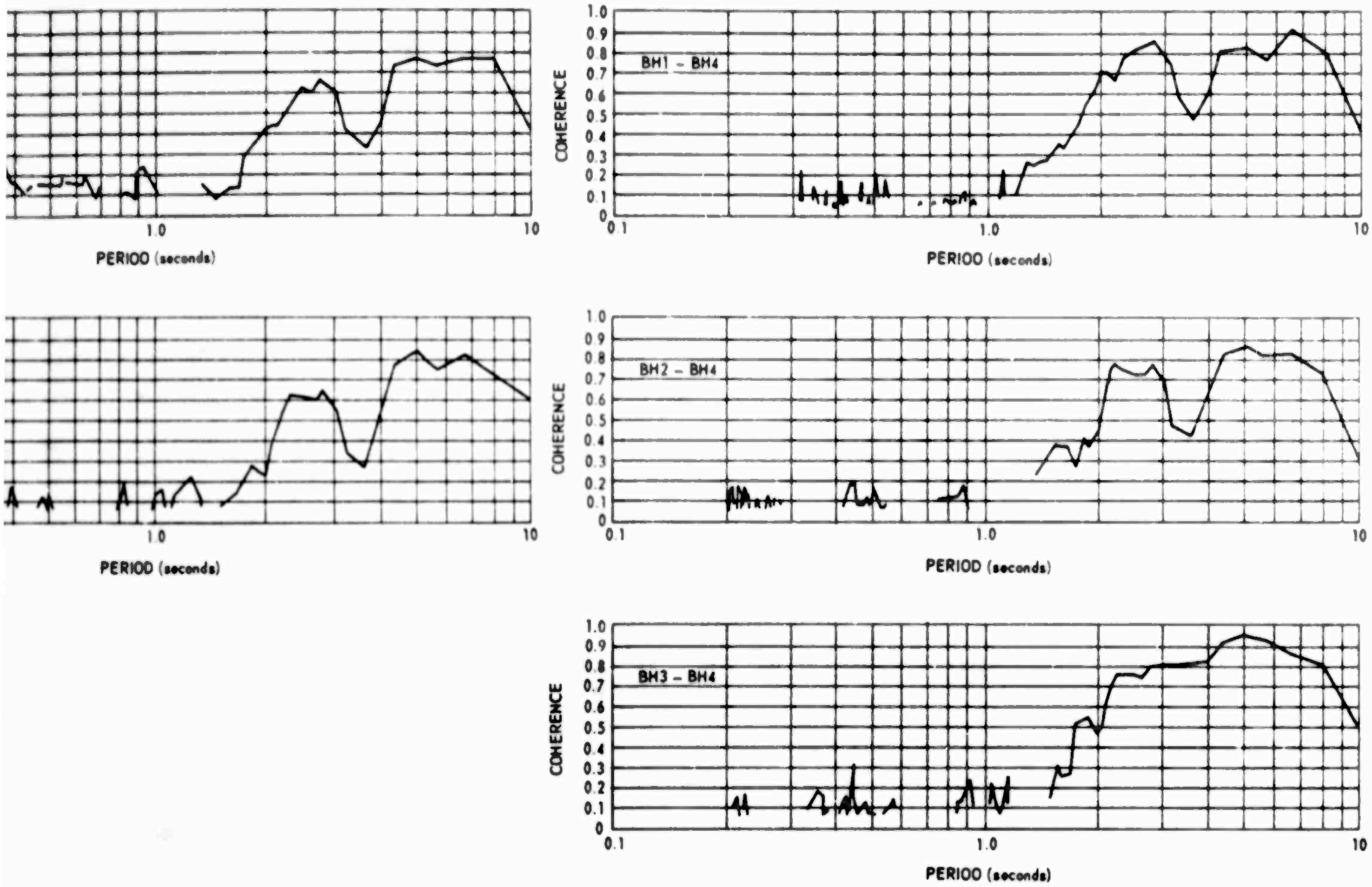


Figure 13 Coherences from spectral analysis of the Inge Lehma
coherence (0.08) are not plotted. Data taken from records made

A



lysis of the Inge Lehmann array. The coherences below the expected 0
aken from records made in the summer of 1966

B

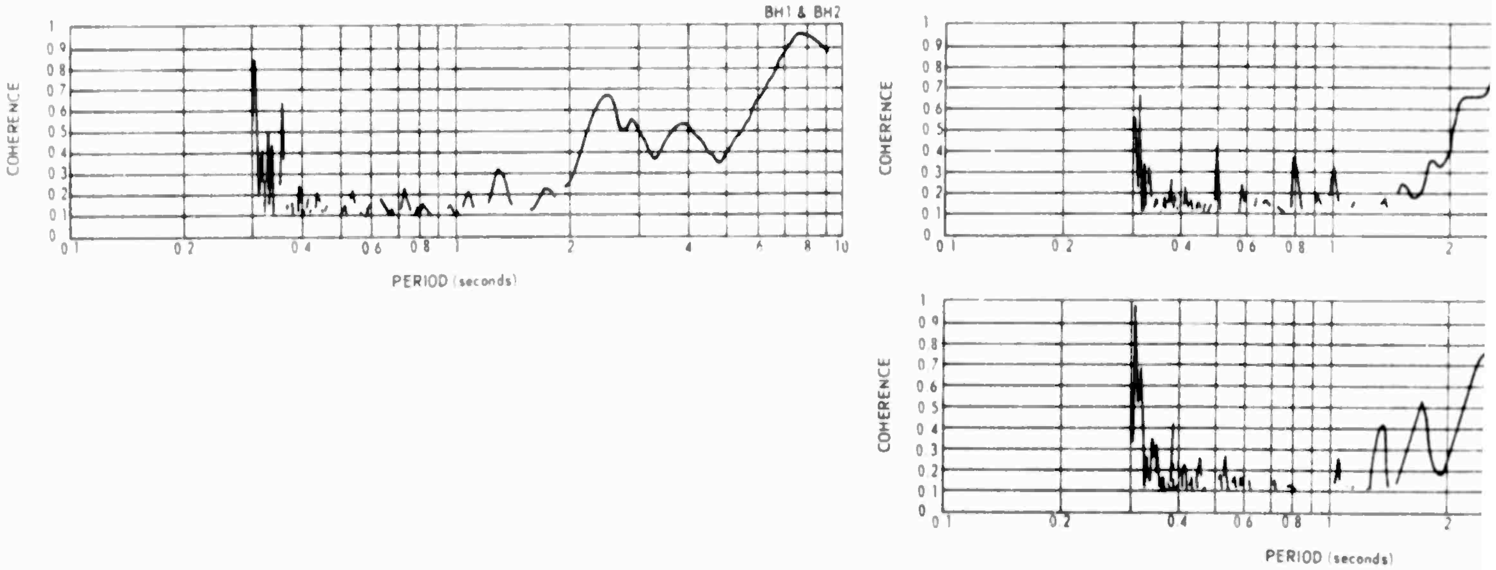
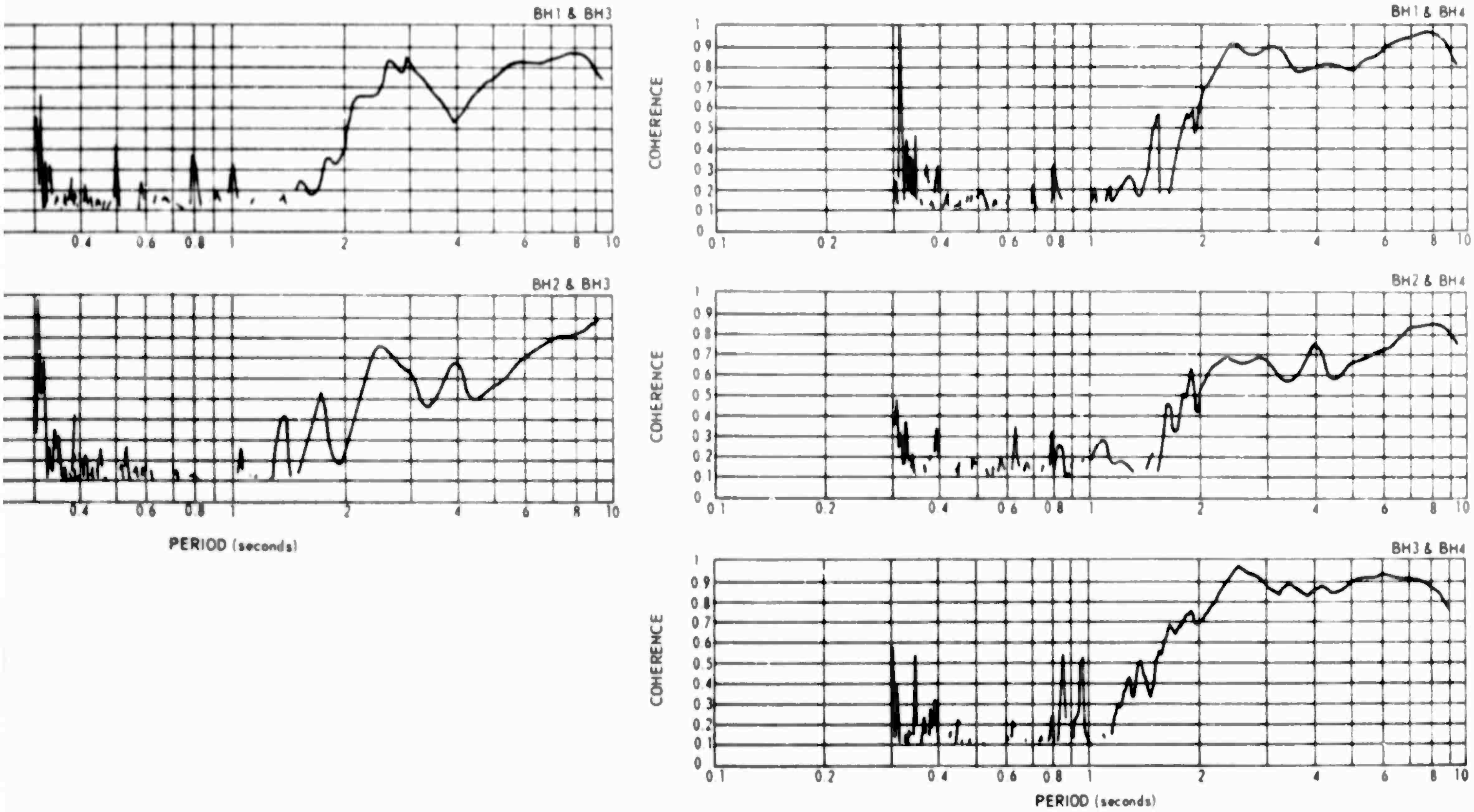


Figure 14 Coherences from spectral analysis of the Inge Le



es from spectral analysis of the Inge Lehmann array

B

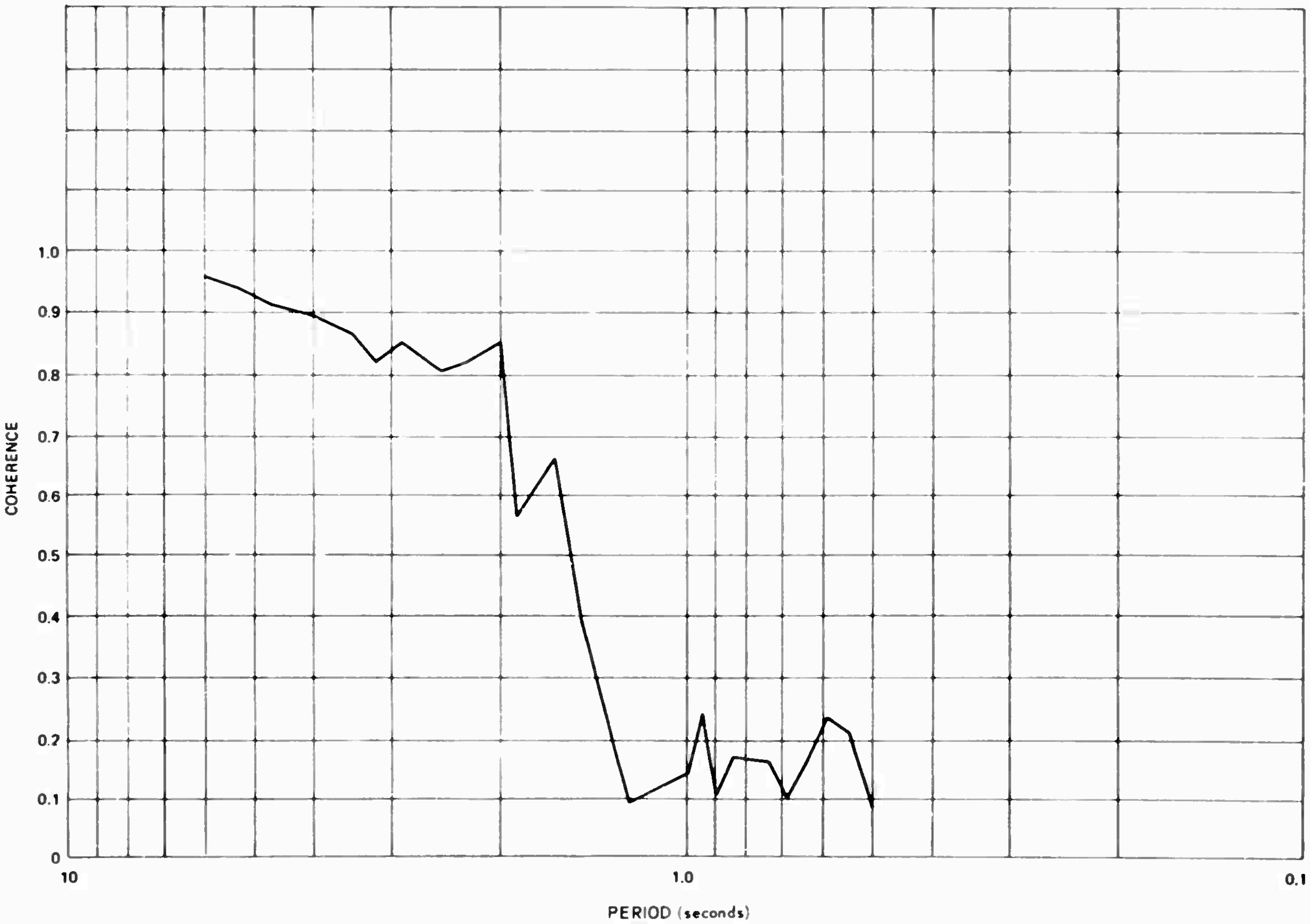


Figure 15 Multiple coherence between the seismographs DH-4 used as output

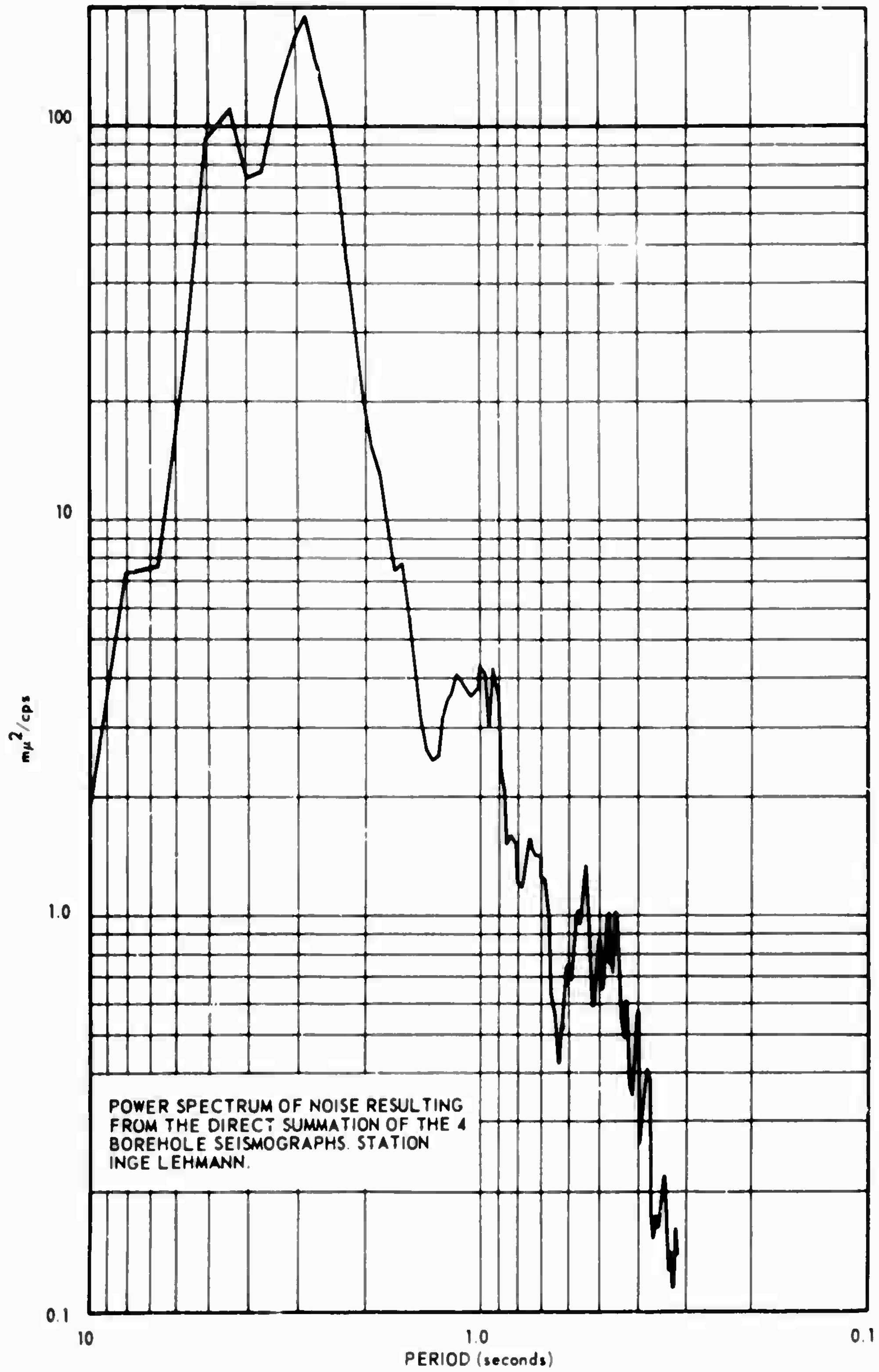


**Figure 16** Power spectrum of noise resulting from the direct summation of the four borehole seismographs. Station Inge Lehmann

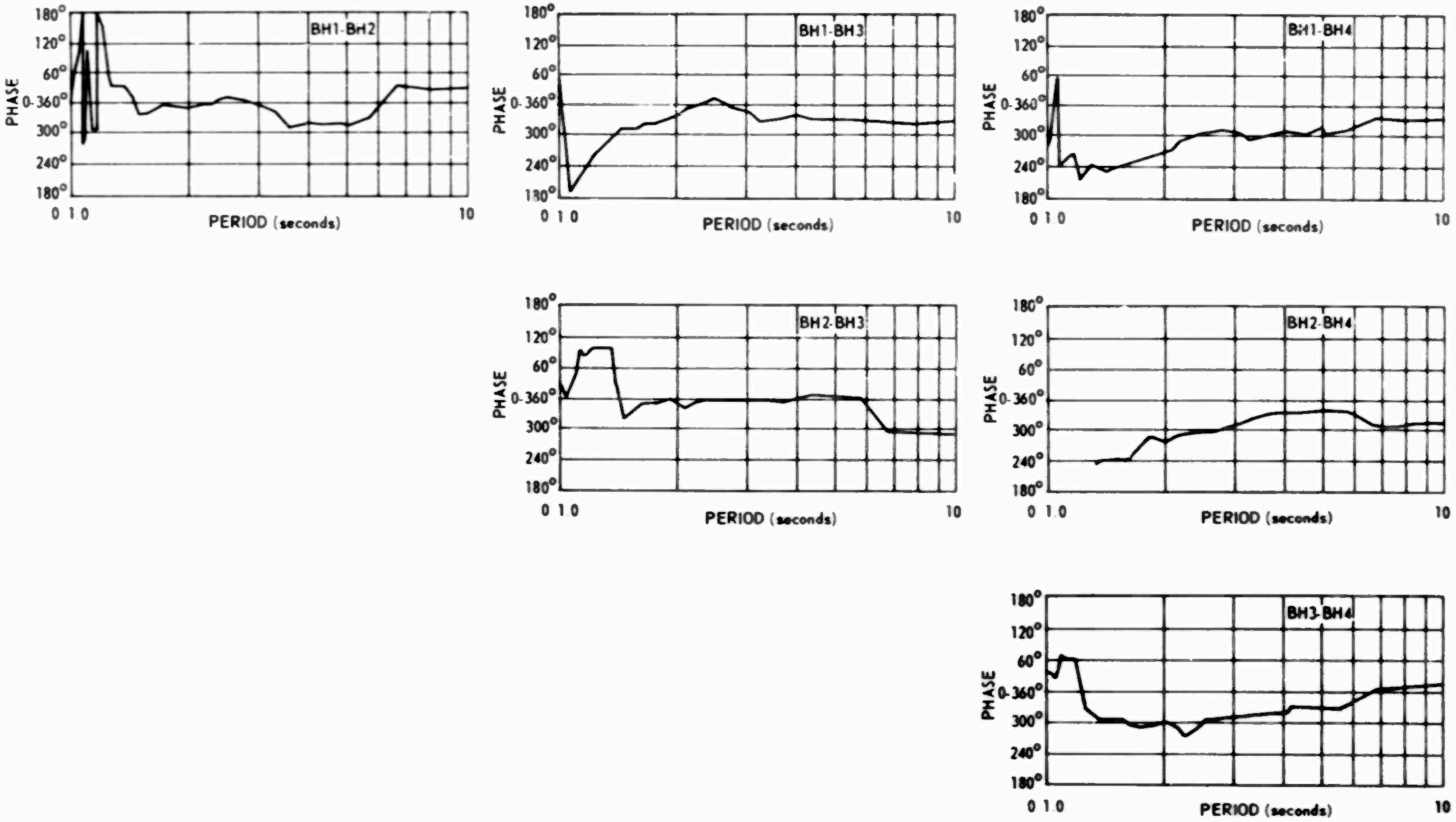


Figure 17 Phase angles between seismographs from spectral analyses of the noise. Station Inge Lehmann, Greenland. Data from recordings made in the summer

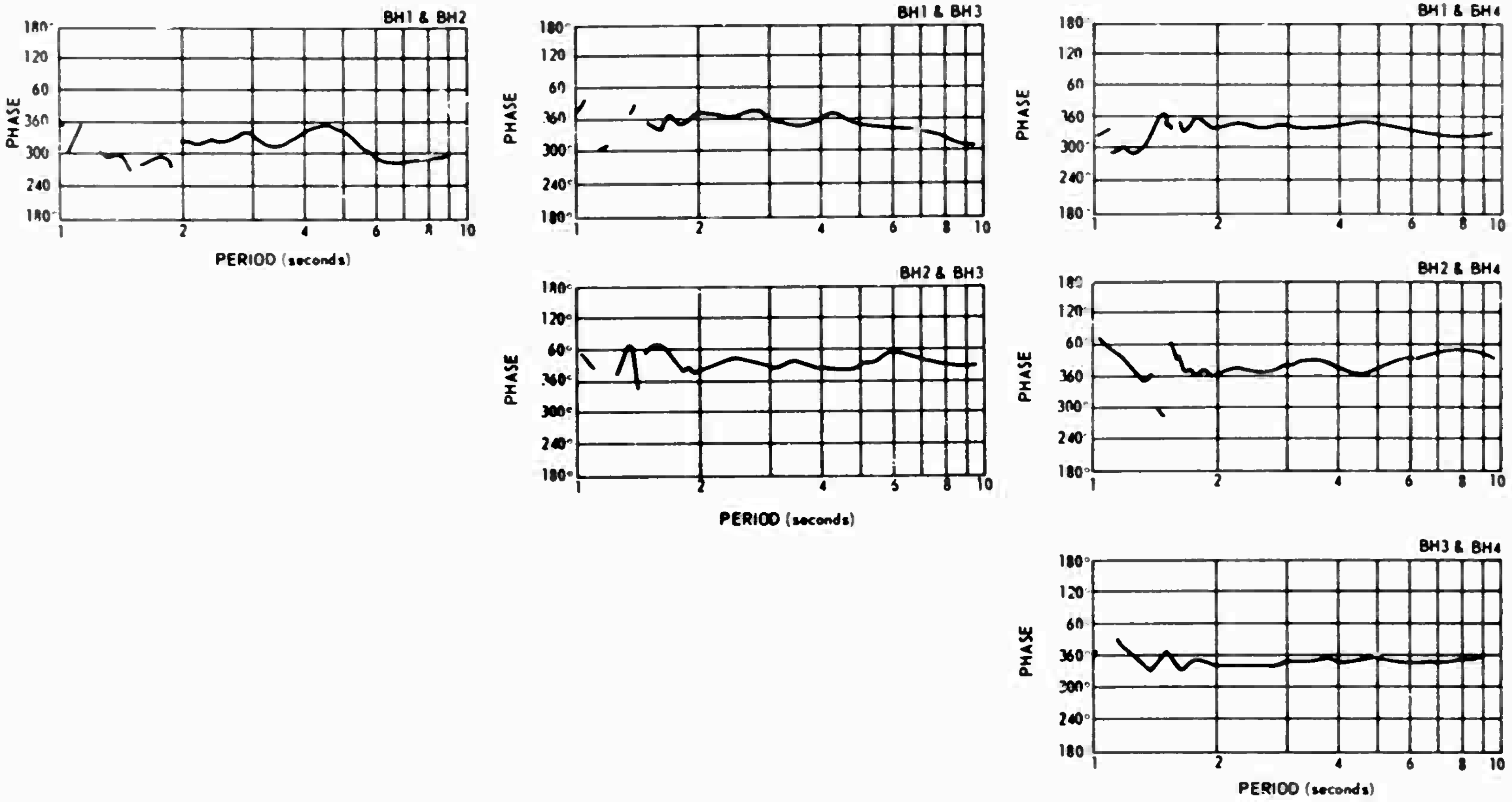


Figure 18 Phase angles between seismographs from spectral analyses of the noise. Station Inge Lehmann, Greenland Winter, 1966-67.

in the ice and BH4 located nearby (see figure 5) at 50 m depth. Figure 12 illustrates this point; the small differences in the spectra are within the errors expected from calibrations. The spectra shown are from recordings 3 days apart. On the same figure 12, the spectra of the surface seismograph and BH4 show that for periods greater than 2.0 sec no differences in the noise level between the two seismographs were recorded. This is in agreement with results obtained in shallow holes at sites in both soft and hard rocks (Douze, 1964).

Figure 12 also shows the spectra of the noise several days earlier when the wind was blowing 40-60 km/h. For periods less than 2.0 sec period, appreciable wind noise is recorded by the surface seismograph while the shallow-hole seismograph noise level is close to the same for both windy and quiet days. There is a slight increase in noise level on BH4 on the windy day; however, the increase is within the limits of variability of the changes for quiet days; thus, no significance can be attached to it. It must be noted that the increase in the noise level obtained during windy days at the surface is less than that which would take place for a normal tank vault on the continent at a quiet site. This phenomenon is almost certainly caused by the very flat relief which does not result in turbulence being generated. Previous studies have shown that turbulent flow over obstacles is a major contribution to wind noise. Winds on the ice sheet do not generate traveling wave motion at periods above 2.0 sec; figure 12 shows that the long-period noise is larger on the quiet day than the windy day. A visual examination of the records show no relation between the longer periods (>2.0 sec) and the wind. This fact is in general agreement with the well-established hypothesis that noise at these periods originates in large bodies of water, mainly the oceans.

## Short-period Signals

Signals recorded at Station Inge Lehmann were analyzed to obtain a detection threshold and to obtain an estimate of the ice thickness. In general, the signal coherences (from visual examination) are high across the array, at least for the first 3 or 4 cycles. Later cycles often show larger moveouts than expected for teleseisms probably because of signal generated noise. Figure 19 shows an example of an event recorded by the station at a distance of 49 degrees. Figure 20 shows events received from distances of 49 and 58 degrees.

Reverberations will be present at this site because of the large change in impedance at the ice-basement interface. The result will be an increase in the complexity of the signal. It is quite simple to design digital filters to eliminate the reverberations; however, better information than presently available on ice thickness and basement velocities will be necessary. If a digital processor is to be used later in the program with an ex-

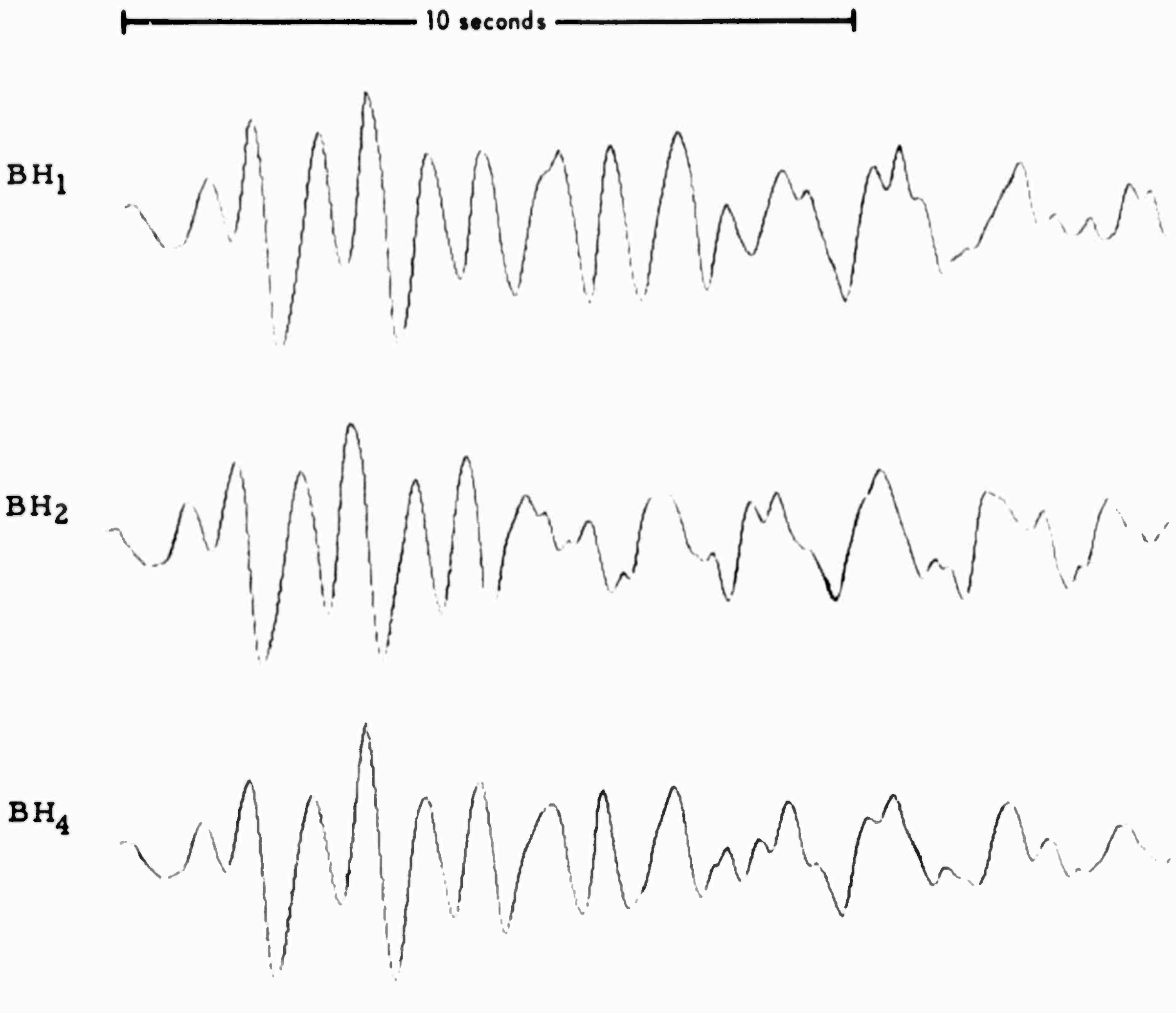


Figure 19 Teleseism recorded from Greece, distance 49 degrees, magnitude 5.3

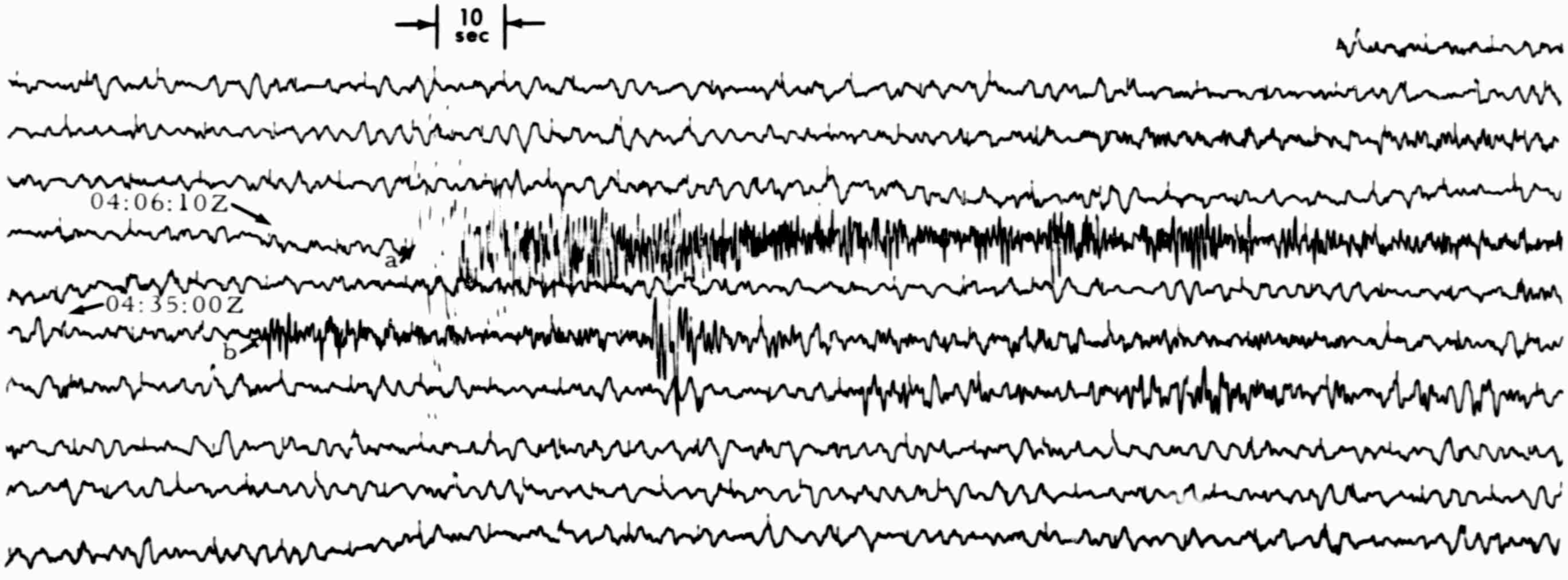


Figure 20 Reproduction of Helicorder record of shallow-hole (180 ft) seismometer showing the following two events: a. 5.7 magnitude in eastern Kazakh, SSR, 49.9N, 78.0E, distance = 49 degrees; b. 4.3 magnitude in Hokkaido, Japan, 44.5N, 141.0E, distance 58 degrees. Magnification 460K

panded array, these filters could be incorporated into the processor.

## Ice Thickness

Several methods have been employed by seismologists to determine the thickness of a low-velocity layer. Of these methods, the measurement of phase velocities of surface waves is probably the most common; however, no surface waves adequate for this purpose were recorded.

Another method consists of measuring the spectra of body waves. If these spectra could be normalized by the actual spectra of the waves below the ice layer, this method would be quite effective. However, the spectra of the incoming wave are unknown and it is only possible to search the measured spectra for low values which may be caused by interference effects, as a result of energy returning to the surface after reflecting from the ice-basement boundary. Figure 21 shows the expected theoretical spectra for a white signal output, an angle of incidence of 20 degrees, and an ice thickness of 2.8 km. Also shown are the spectra for a signal arriving at this angle of incidence. There is reasonable agreement between the two curves in the location of the highs and lows, indicating that the assumed depth of 2.8 km is approximately correct. A number of teleseisms were examined in this fashion; the average depth to basement found is 2.7 km. It must be noted that the ice thickness determined in this fashion assumes that no low-velocity material exists between ice and basement. The presence of low-velocity material below the ice cannot be determined by the information available.

## Detection Threshold

Figure 22 shows the number of events detected from teleseismic distances between 40 degrees and 90 degrees plotted against the magnitude. The curve indicates that all events of magnitude 5.0 were detected, but only approximately 50 percent of the events of magnitude 4.3 were detected. The plot contains all the events recorded from August 1966 to June 1967. The USC&GS preliminary epicenter cards were used to locate the events and to obtain the magnitudes. Less than half the events recorded at the site were identified by this procedure.

Note that the line drawn through the points is not of unity slope, but the best fit line drawn through the points.

There are several reasons to believe that the actual detection capability of the site is better than indicated by the results given in figure 22. According to Green and Wood (1966), the detection capability of the USC&GS world wide network is such that 50 to 75 percent of events above magnitude 4.3 to 4.5 are located.

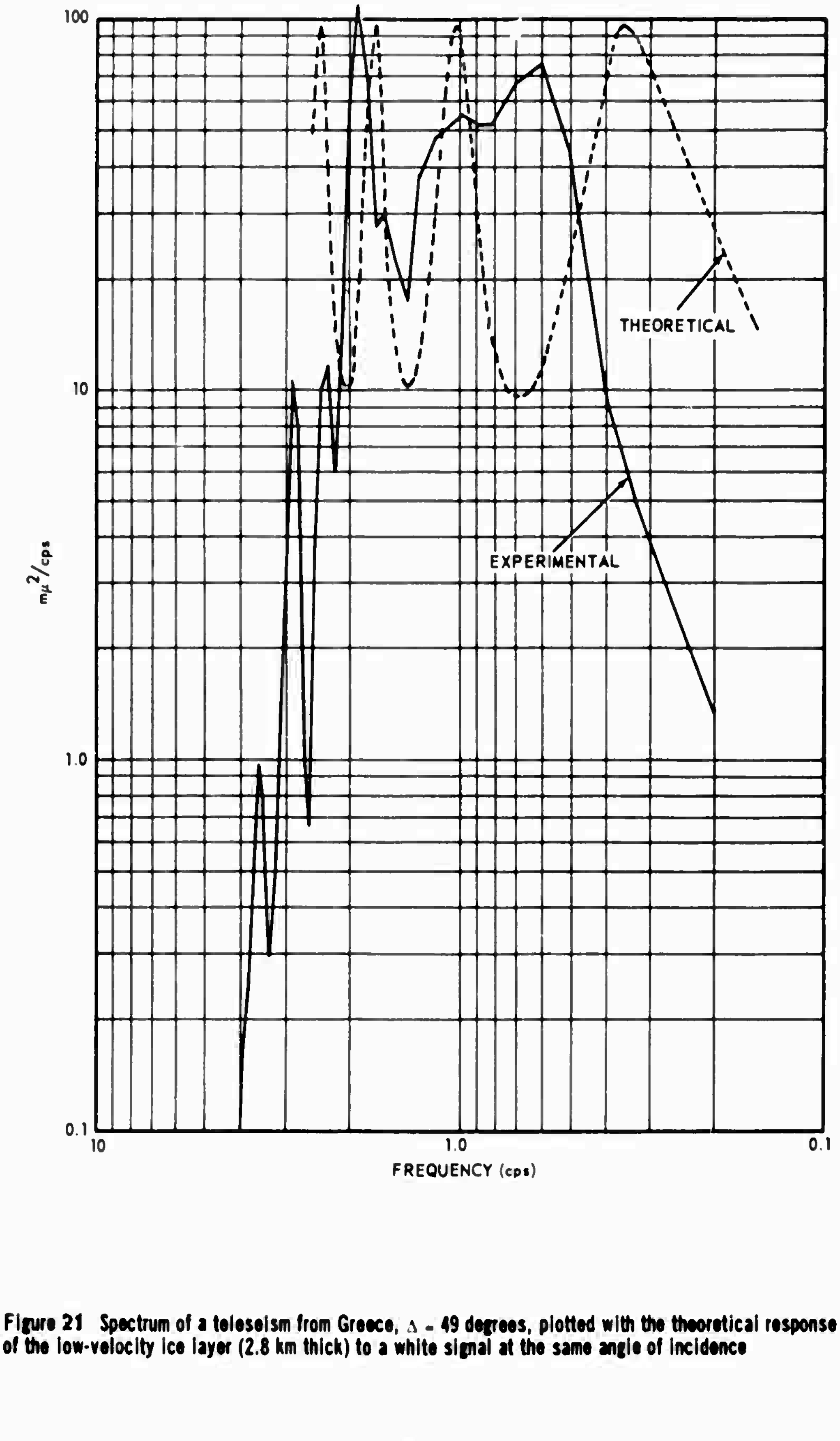


Figure 21 Spectrum of a teleseism from Greece, Δ = 49 degrees, plotted with the theoretical response of the low-velocity ice layer (2.8 km thick) to a white signal at the same angle of incidence

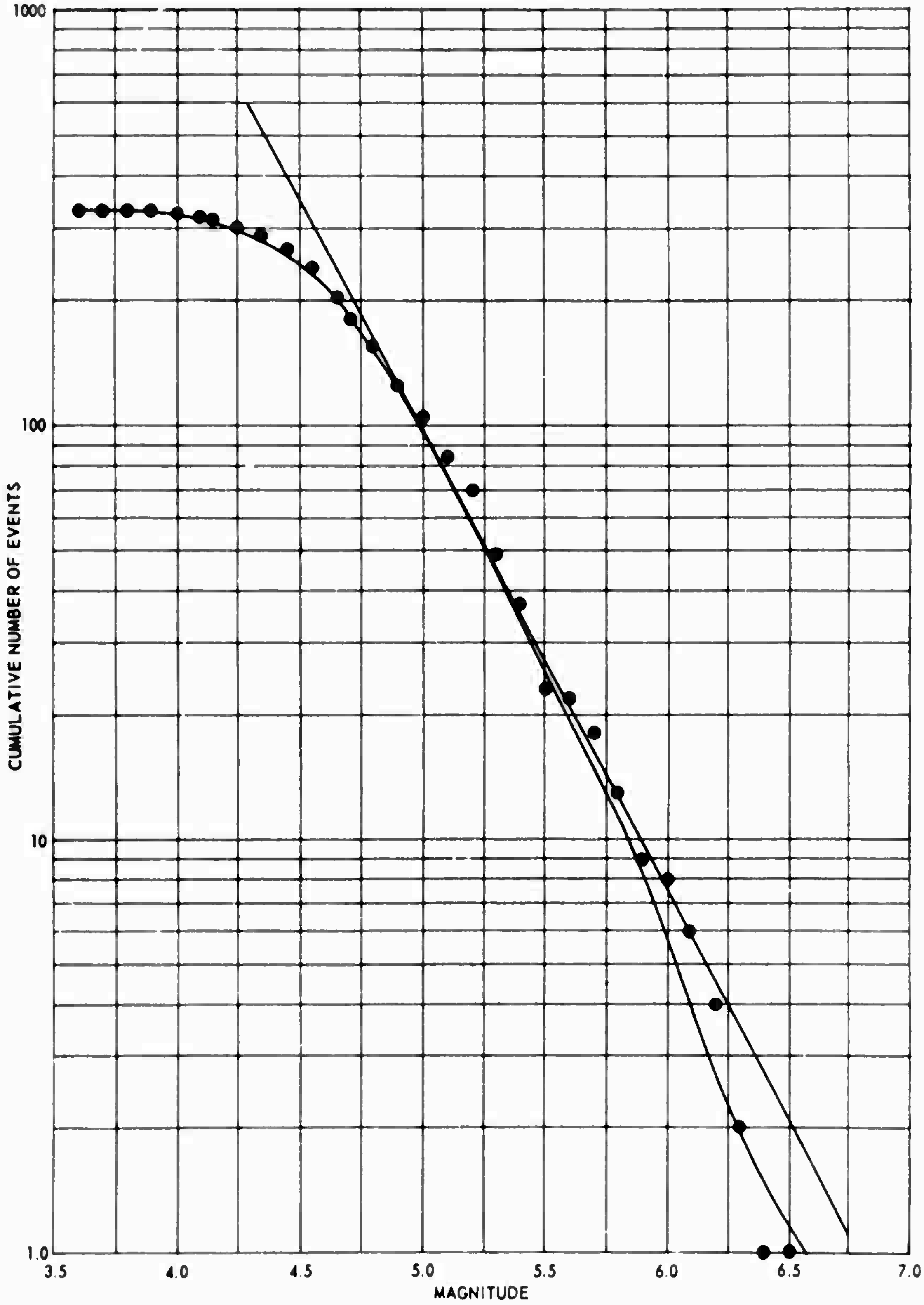


Figure 22 Cumulative probability of detection curve for Station Inge Lehmann, Greenland

The results shown in the probability of detection curve are essentially identical to that which would be obtained if a probability of detection curve were drawn for the USC&GS network. Therefore, the curve shown in figure 22 indicates only that the detection capability of the site is at least 4.3 at the 50 percent level and could be appreciably better.

No certain way around this problem has been found because of the absence of a better reference.

An attempt to obtain a better detection capability was made by using small earthquakes from Nevada. The data points scattered so badly that no conclusion could be reached; this result may be connected with the problem of obtaining meaningful magnitudes at close ranges (Evernden, 1967).

One comparison which indicates that the station detection capability is better than indicated in figure 22 can be obtained from the Kurile Islands Experiment. A series of small explosions (only the 5-ton explosions are discussed here) were detonated close to the Kuriles in November and December 1966. Table III shows a comparison between the number of signals recorded at the Tonto Forest Seismological Observatory (TFSO), by Station Inge Lehmann, and by Lincoln Laboratory (1967). The distances to the sites are approximately the same. The number of explosions recorded by Inge Lehmann is considerably larger than that recorded by TFSO. It must be kept in mind that TFSO is generally considered to be the best VELA array station in the Continental United States and LASA reports a detection capability of magnitude 3.7. While this experiment is not conclusive, because either source or receivers could be affected by directional phenomena, the results certainly suggest that the probability of detection curve underestimates the capability of the site. Figures 23 through 25 show examples of two clear events: a debatable arrival, and a time where no arrival could be picked. Note the time-delayed summation in figure 23.

Examination of the location of the 5.2-ton shots shows no relationship with features such as depth of water that would explain the large differences in amplitudes recorded at Inge Lehmann.

## Long-period Seismograph Analysis

An installation of long-period vertical (Geotech 8700C) and horizontal (Geotech 7505A) seismographs was installed at Station Inge Lehmann. Installation was completed on April 29, 1967.

The long-period seismographs were installed approximately 20 m from the short-period vault. The seismographs were located at a depth of 6.9 m in a chamber excavated in the ice. The steel plates on which the seismometers were placed were heated so that the ice would melt and on freezing would pro-

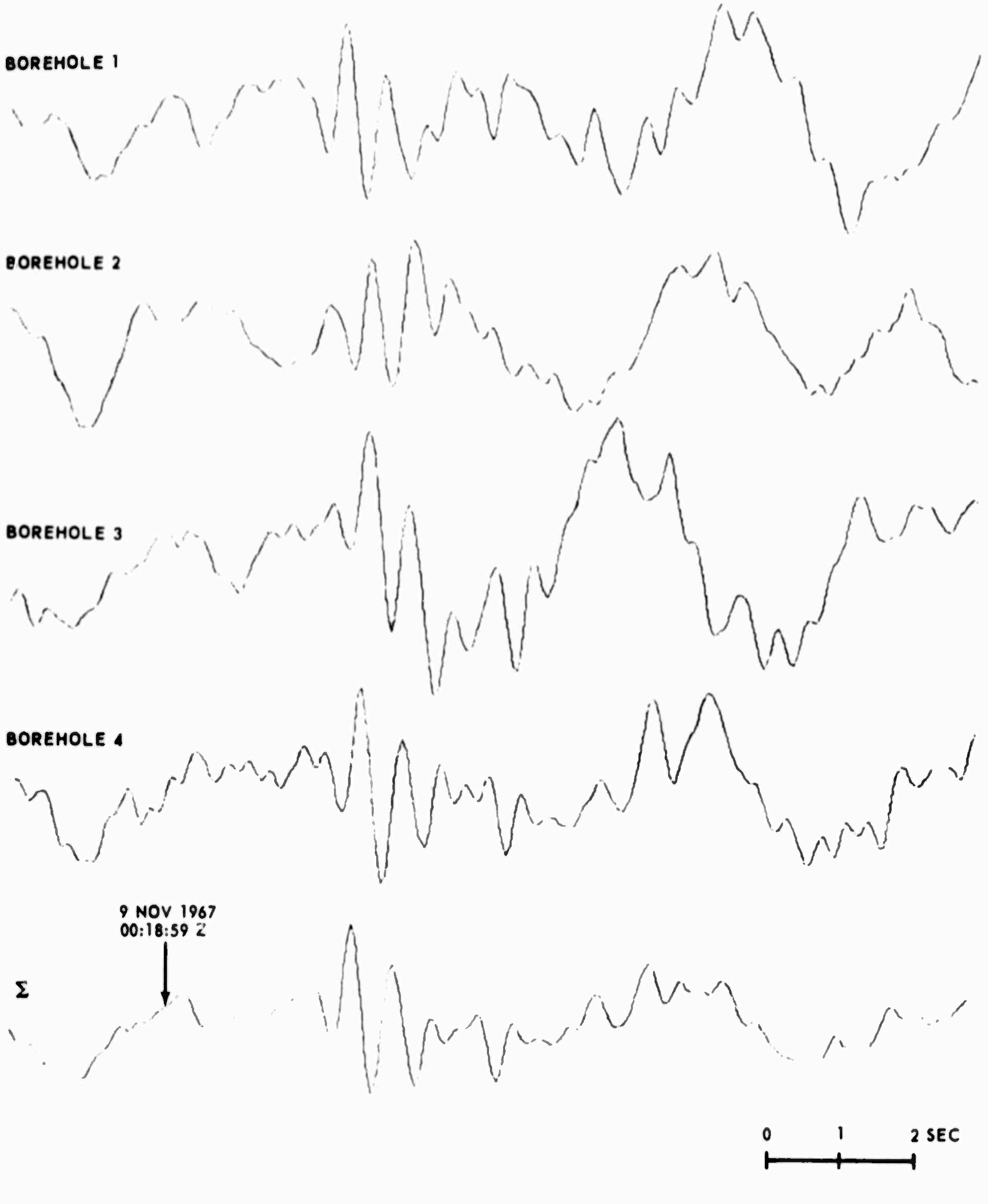


Figure 23 Event recorded by the Inge Lehmann array in Greenland from a 5.2-ton explosion; epicenter, 44° 31′N, 151° 12′E, Kurile Islands. The bottom trace is a time-delayed summation

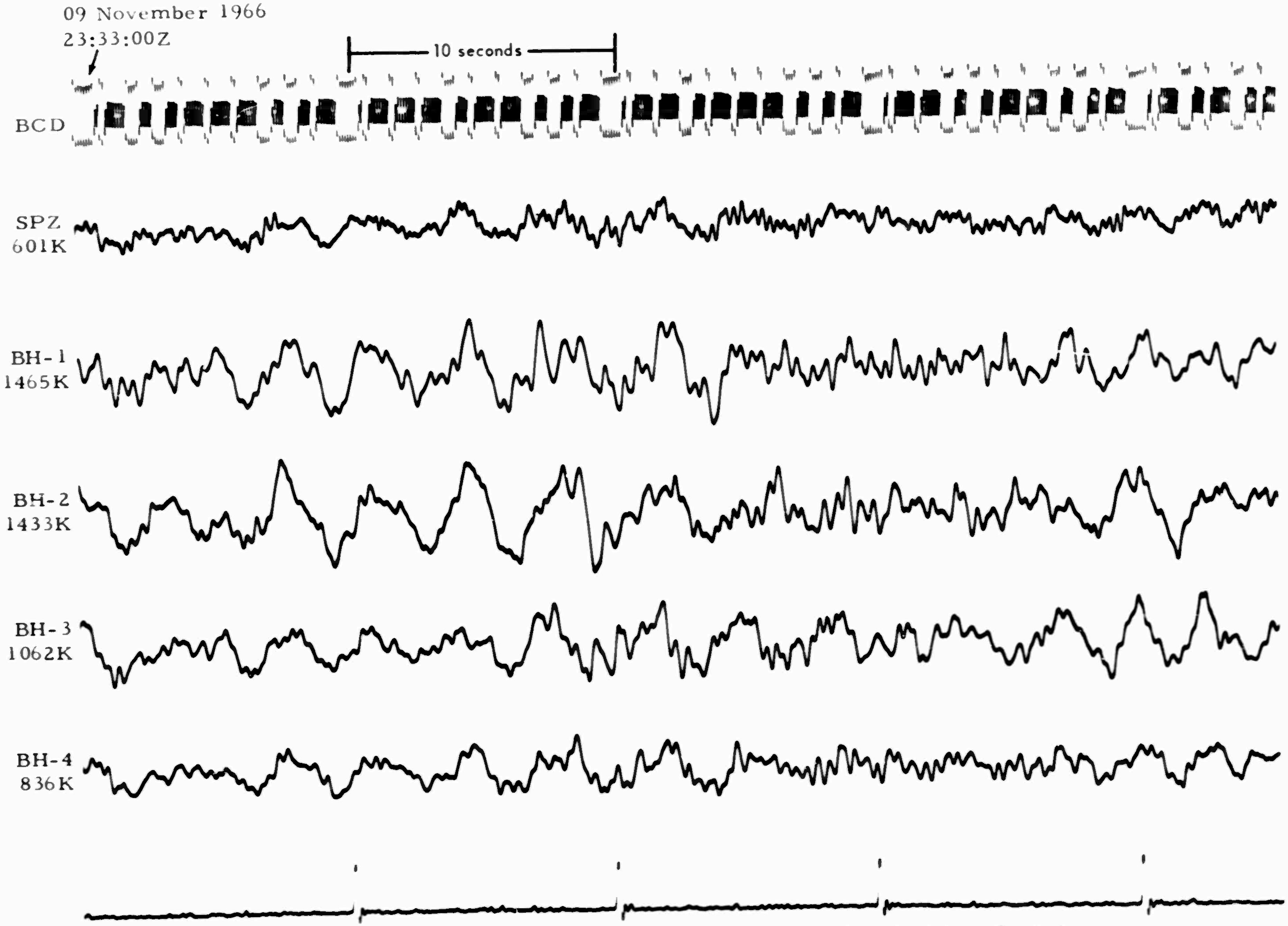


Figure **24** Recording of explosion from the Kurile Islands recorded by the shallow bore-hole array at Station Inge Lehmann, Greenland.
Shot - E-4, Size - 5.2 tons, Δ 6288.0 km

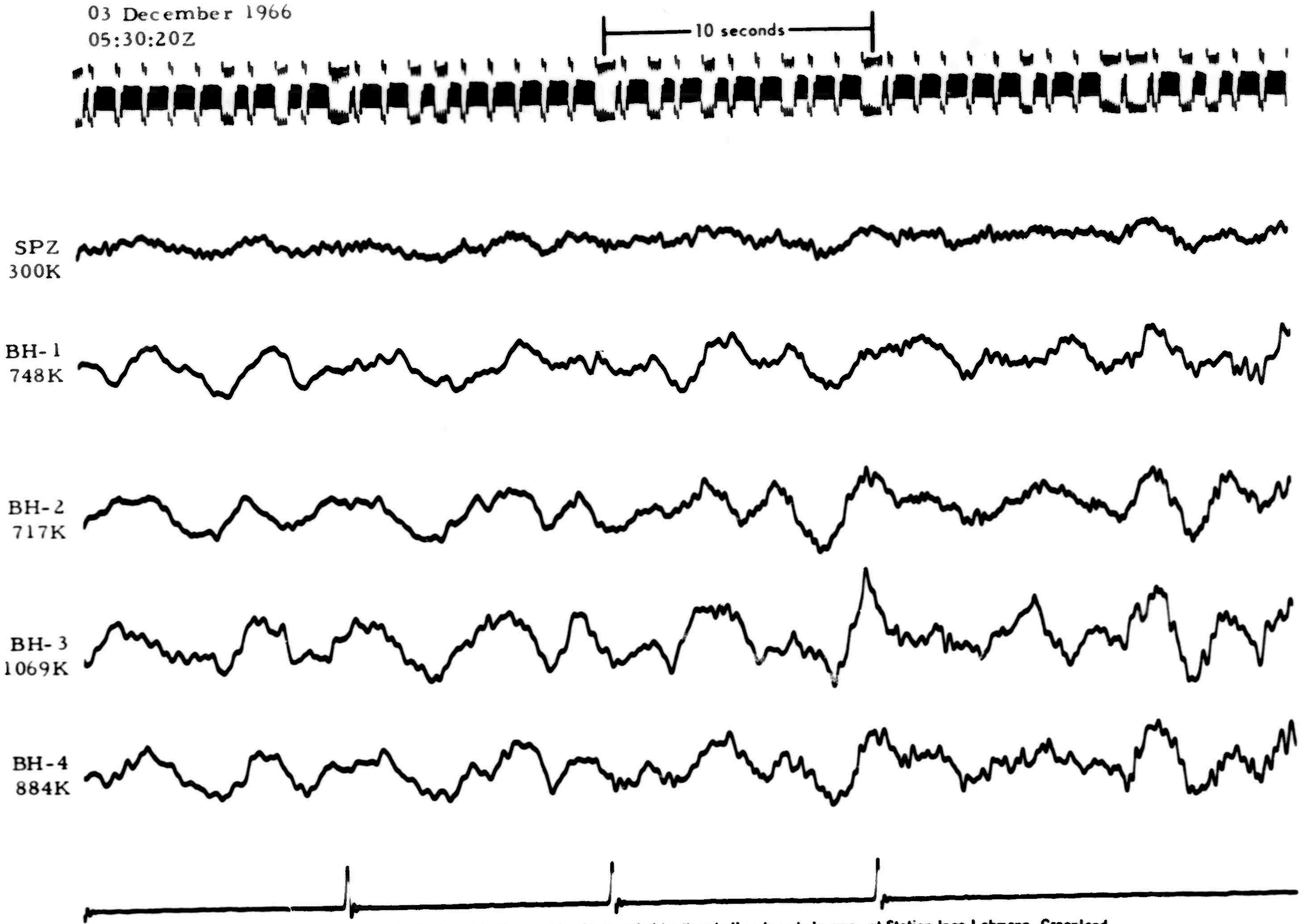


Figure 2.5 Recording of explosion from the Kurile Islands recorded by the shallow bore-hole array at Station Inge Lehmann, Greenland.
Shot - E-13, size - 5.2 tons, $\Delta = 6509.0$ km

Table III. Comparison between number of signals recorded

| Position No. | Date | Size (tons) | Detected by<br>LASA | <br>Inge Lehmann | <br>TFSO |
|---|---|---|---|---|---|
| E-8 | Nov 8 | 5.2 | No | Yes | Yes |
| E-5 | Nov 9 | 5.2 | No | Yes | Yes |
| E-6 | Nov 9 | 5.2 | No | No | No |
| E-4 | Nov 9 | 5.2 | Yes | ? | No |
| E-2A | Nov 12 | 5.2 | No | Yes | No |
| E-1 | Nov 13 | 5.2 | No | Yes | No |
| E-12 | Dec 2 | 5.2 | Yes | No | No |
| E-13 | Dec 3 | 5.2 | Yes | No | No |
| E-7A | Dec 3 | 5.2 | Yes | No record | No |
| E-14 | Dec 4 | 5.2 | Yes | Yes | No |

vide a good bond. The velocity response of the long-period vertical system is shown in figure 26. The horizontal seismograph responses are practically identical. The spectra of the noise from several samples are shown in figures 26 through 28. The vertical noise amplitudes are similar to those recorded by seismographs at stations in the continents. The peaks at approximately 8.0 and 18.0 sec are at the same periods where high amplitudes are normally recorded at continental stations. Long-period noise consists of surface waves from the oceans and propagates efficiently over long distances. As discussed in the section on short-period noise, the low noise amplitudes recorded are probably caused by high attenuation of waves traveling in the ice layer. The long-period waves are not controlled by the ice layer but by deeper layers with more normal attenuation factors. Therefore, there is no reason to expect low amplitudes for the noise at the longer periods. Figures 27 and 28 show the spectra obtained from the horizontal seismographs. One of the most obvious features is the large amount of energy present at periods greater than 20.0 sec despite the fact that the response is dropping rapidly. It is almost certain that these high values are not true ground motion. Horizontal seismographs are also excellent tilt meters. As pointed out previously, the ice below the station must be deforming plastically. Under these circumstances it is probable that an appreciable amount of tilting occurs and that this is the cause of the high noise at the longer periods. This hypothesis is reinforced by the fact that the seismometers had to be recentered every 2 days because they drifted to the stops.

Figures 29 and 30 show examples of long-period signals. The long-period seismographs were not operated for a sufficient length of time to obtain an estimate of their detection capabilities.

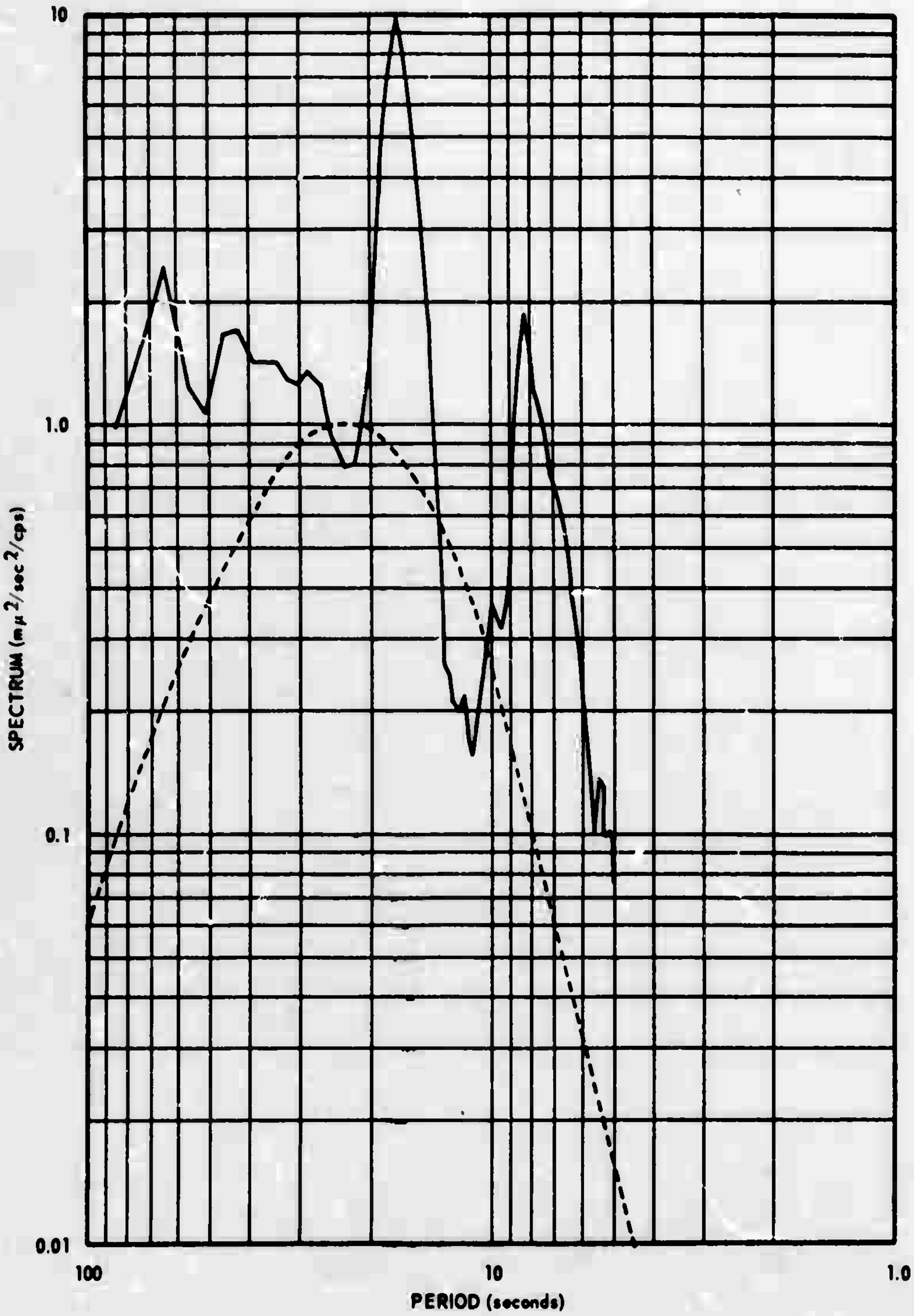


Figure 26 Velocity spectrum of the vertical long-period noise at Station Inge Lehmann. Dashed curve is the velocity response of the seismograph

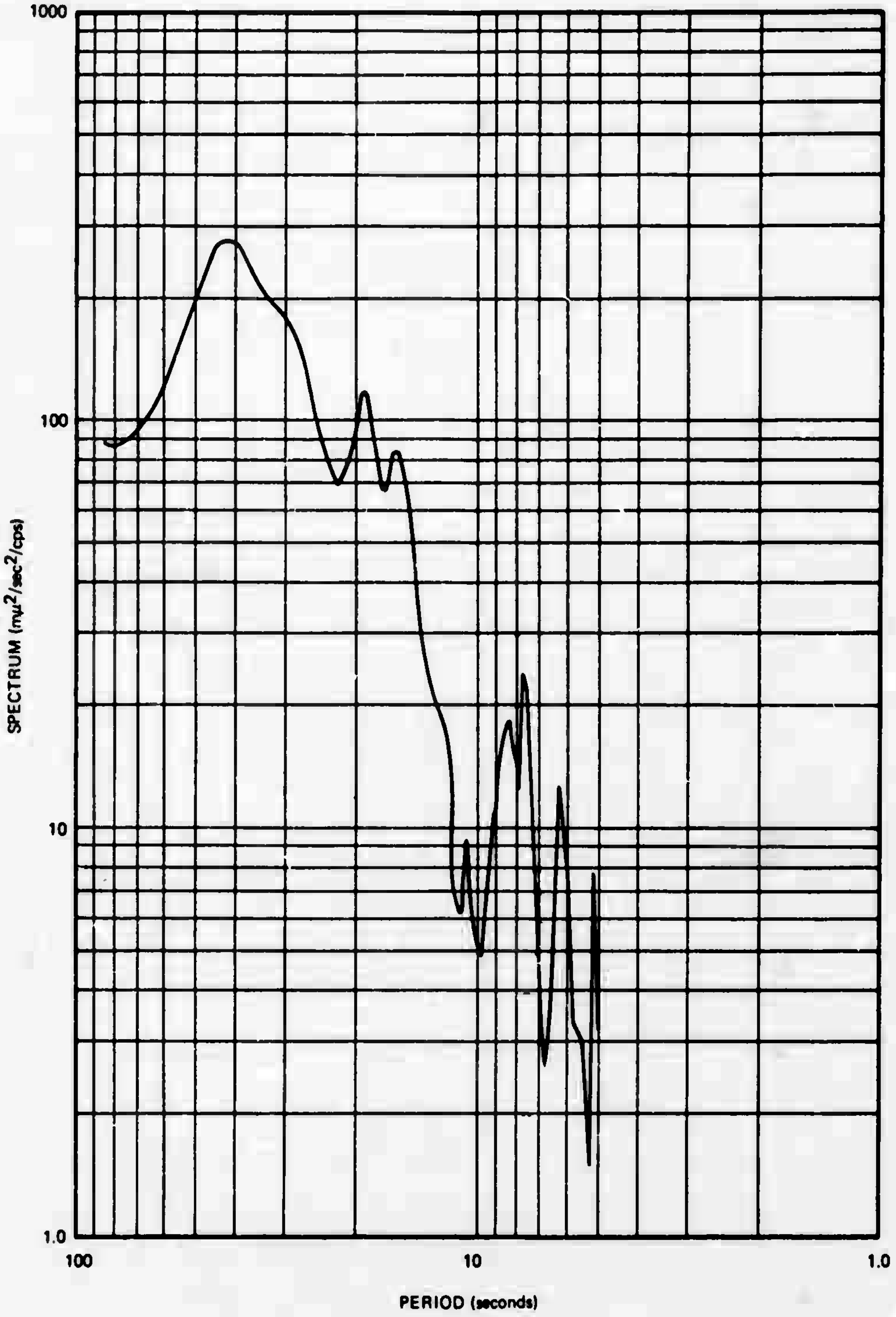


Figure 27 Velocity spectrum of the horizontal (north) component of the long-period noise

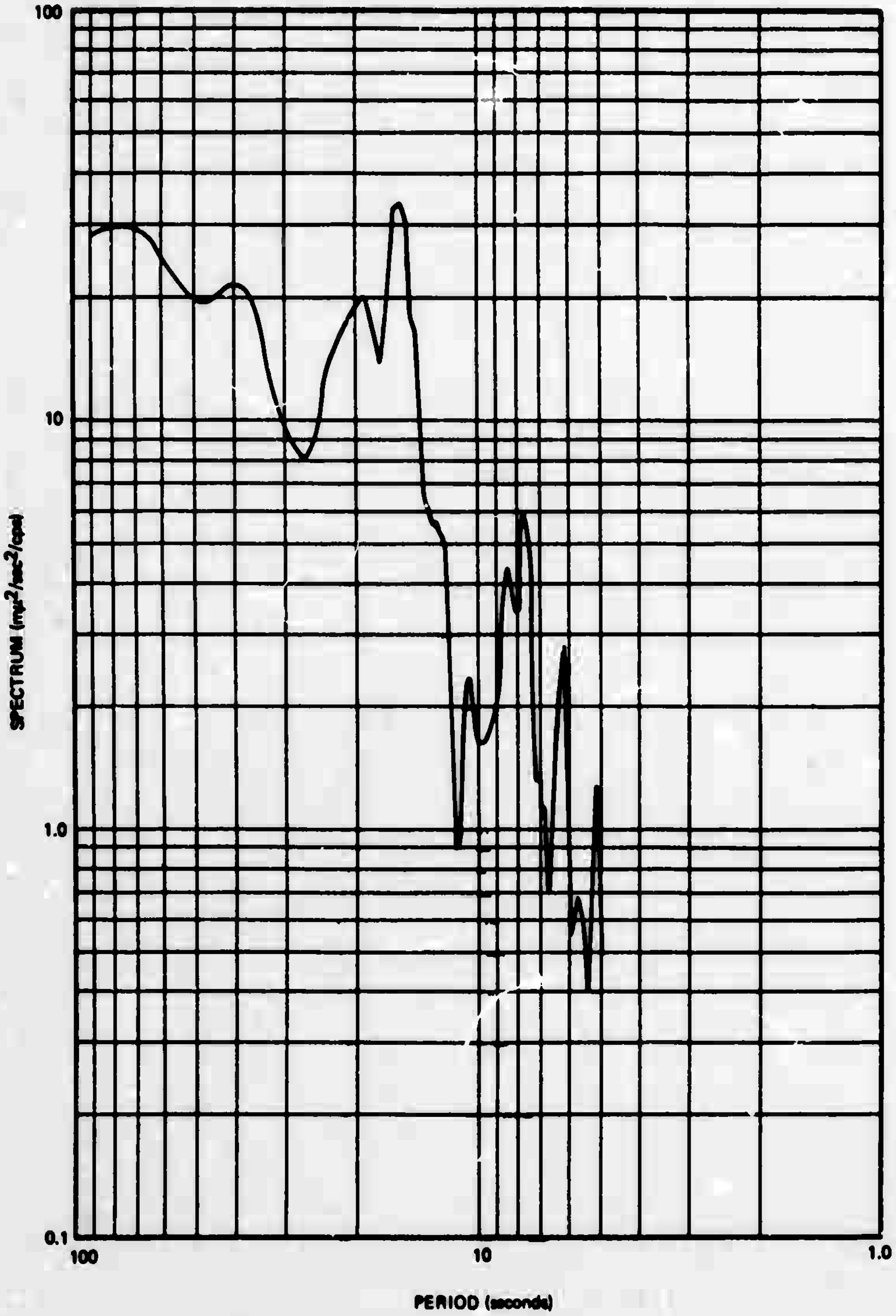


Figure 28 Velocity spectrum of the horizontal (east) component of the long-period noise

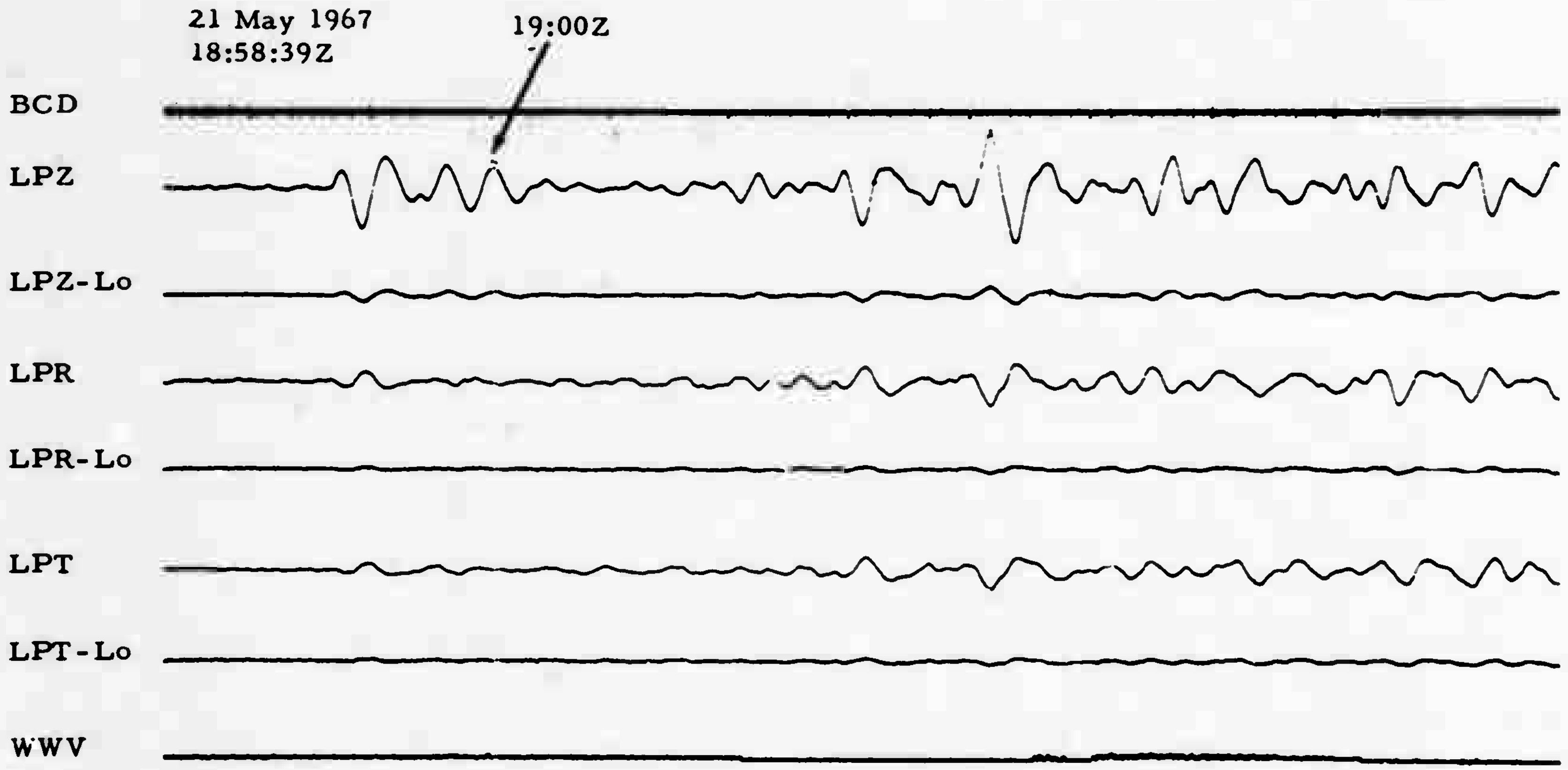


Figure 29 Recording of event from South Sumatra by LP instruments at Inge Lehmann, Greenland
$\Delta$ = 99° Mag - 6.3 P - Phase

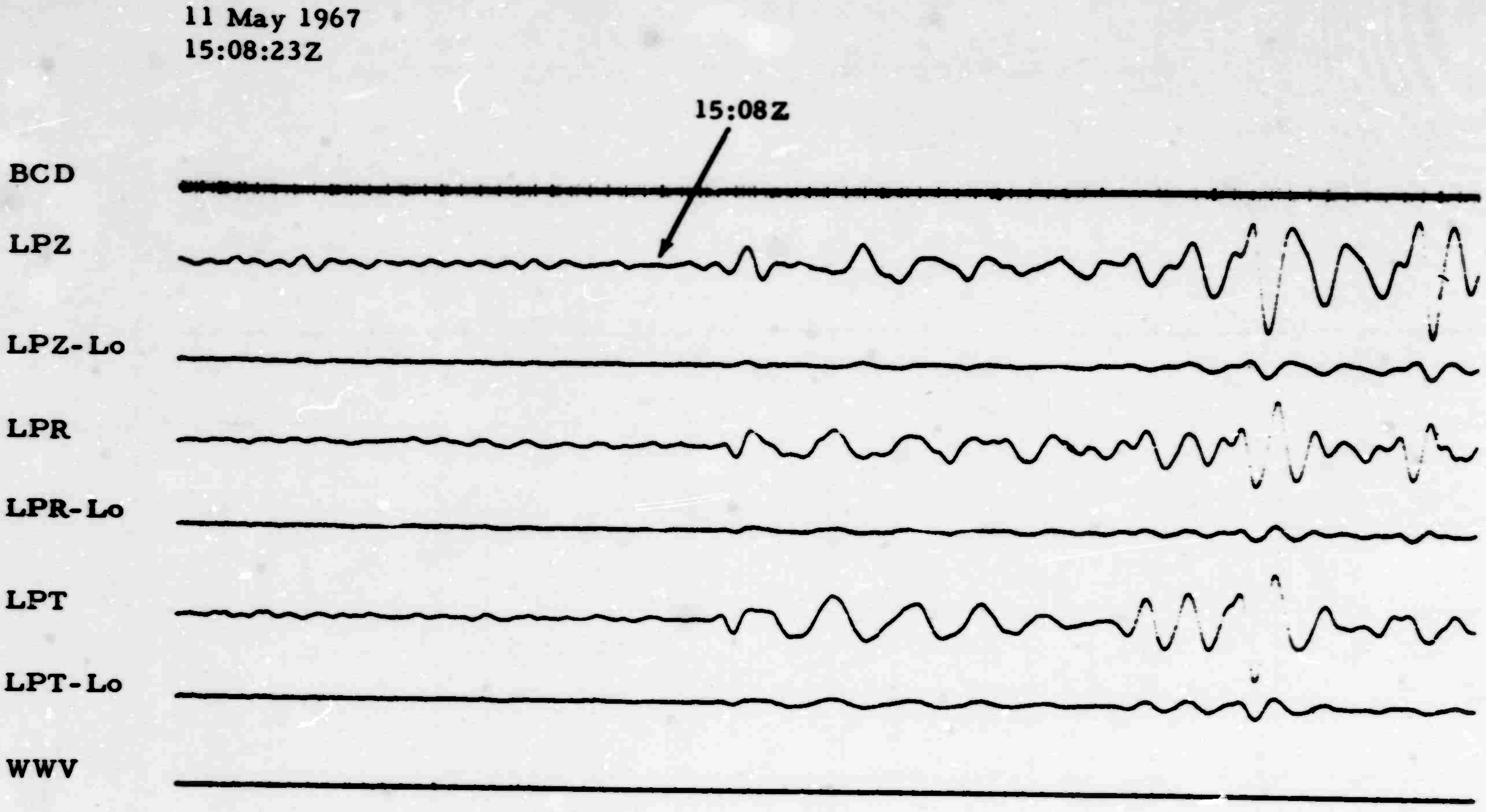


Figure 30 Recording of event from Tadzhik-Sinkiang Border Region by LP instruments at Inge Lehmann, Greenland
Δ = 55 Mag - 5.6 S - Phase

## Recommendations for Expanded Array

For the seismometer spacings used in the experimental array, the noise in the period range of greatest signal detection (1.4 to 0.3 sec) is close to incoherent between seismographs. Therefore, an array with similar or larger spacing using a time-delay and sum processor can be expected to result in an improvement in the signal-to-noise ratio of close to the square root of the number of seismometers. This is the philosophy of approach recommended here. Arrays with smaller spacings between seismometers could possibly result in appreciable coherences between seismographs and could therefore make use of optimum filtering techniques. However, past experience at quiet sites has generally shown that this approach is not effective because of high-velocity noise. It must be noted that optimum processing techniques are not effective if the noise is incoherent between seismographs. With the approach suggested here, the improvement that will be obtained depends on the number of seismometers that are installed. Increasing the spacing from that used presently will not improve the detection capability in the main band of interest and will increase the cost of installation, maintenance, and processing.

For periods greater than 1.5 sec, the coherences obtained are high and can be expected to remain appreciable at even larger separations. It would be desirable to design the array in such a way as to minimize the energy in the period range of 2.0 to 3.0 sec (close to the period range of principal interest). Unfortunately, the velocities of these waves, which must be known in order to design against them, have not been determined. It is possible that the design considerations will change when the velocities are determined.

Optimum filtering techniques will be effective if these longer periods are to be reduced. However, it is doubtful that the added complexity of the processor is worth an improvement outside of the period range of greatest interest. Also, these longer waves are not time stationary and the optimum filters would have to be re-calculated at regular intervals.

Considering the factors discussed above, the array shown in figure 31 is recommended. It consists of 19 seismometers, with two rings of seismometers at the same seismometer spacings used in the present array. For periods less than 1.5 sec, this array should increase the detection capability by a factor of approximately 4. It is not expected that the square root of the number of seismometers will be obtained because of the small signal variations across the array. The detection threshold would be lowered so that essentially all events of magnitude 4.5 and 50 percent of the events above magnitude 3.9 will be detected. If the present detection capability is actually better than indicated by figure 22, the threshold for the array will be correspondingly lower. The proposed array can always be further im-

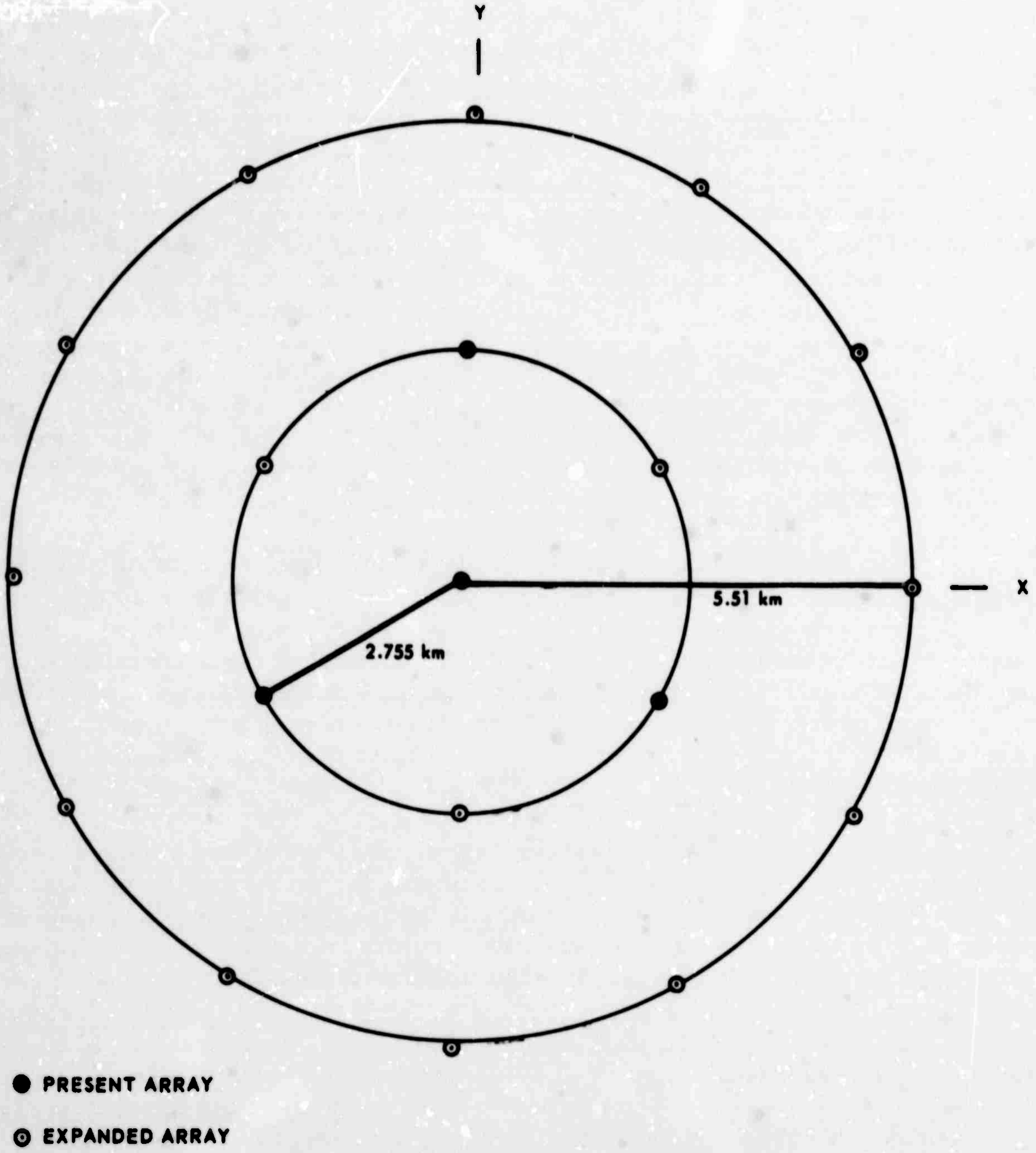


Figure 31 Expanded array at Station Inge Lehmann, Greenland

proved by adding another ring of seismometers. However, considering the hostile environment of the site, it appears desirable to keep the array as small as possible.

Figures 32 and 33 show the k-space response of the array that is recommended and the response for the present array.

Figure 34 shows the surface radiation pattern of the proposed array at periods of 1.0 sec and 0.5 sec for a phase velocity of 10 km/sec. It is apparent that the reasonably small size of the array results in a broad beam; therefore, formation of fewer beams (than on a larger array) will be necessary. To obtain an estimate of an actual degradation obtained by using one beam for a number of velocities, an actual signal from one seismometer was used in an off-line time-delay and sum program. The results are shown in figure 35; the array was tuned to a velocity of 1 6 km/sec, and an apparent velocity range of 10 to 20 km/sec was simulated. The results indicate that for this small array the signal degradation is not significant. A signal with an impulsive start will of course be degraded more rapidly in the first break than the signal shown here.

From the array size and the apparent velocities, it can easily be calculated that if a time-delay and sum processor is used, a maximum of 18 directions and 2 velocities will be needed if all directions are of equal interest. This results in a total output of 36 beams. These beams would cover all directions and apparent velocities between 8 and 25 km/sec (distances of 16 and 100 degrees) with only a slight degradation of signal quality for errors in azimuth and direction. Almost any small digital computer on the market is capable of forming, in real time, the number of beams discussed here.

## Conclusions

It was not possible to obtain a value measure of the detection capability of the site on the Greenland Ice Sheet. However, at the 50 percent probability level, the detection capability is at least 4.3 and is probably considerably better.

The noise levels are very low and compare favorably with some of the best stations in the Continental United States.

Emplacement of the seismometers in shallow holes is completely effective in attenuating wind noise.

For the spacings used in this experiment, the most effective array processor would be time-delay and sum beam steering. The coherences indicate that optimum processors will not be effective in suppressing the noise.

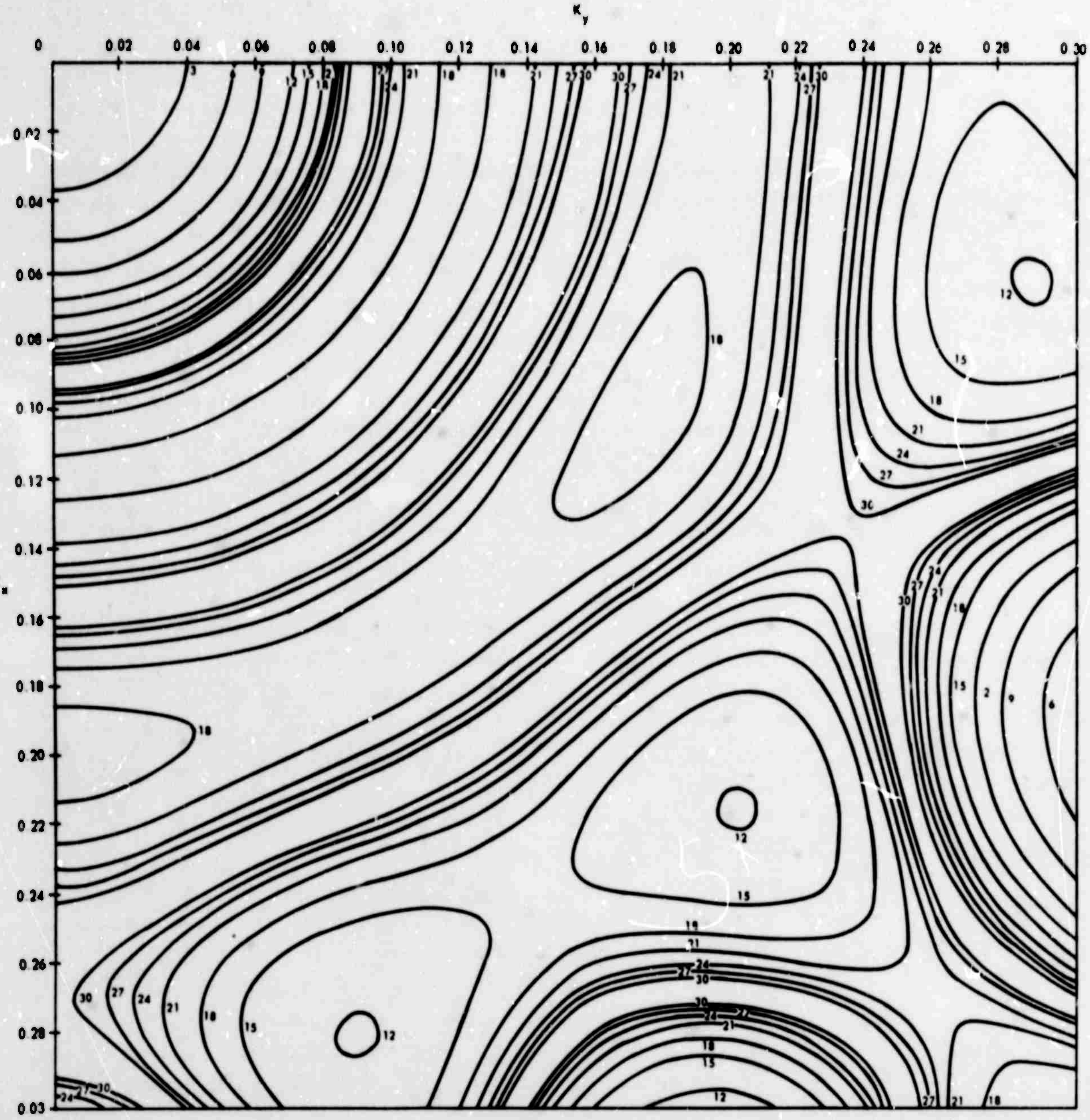


Figure 32 K plane response of the proposed 19 element array at Station Inge Lehmann, Greenland. Contours in decibels. Only one quarter shown because of symmetry

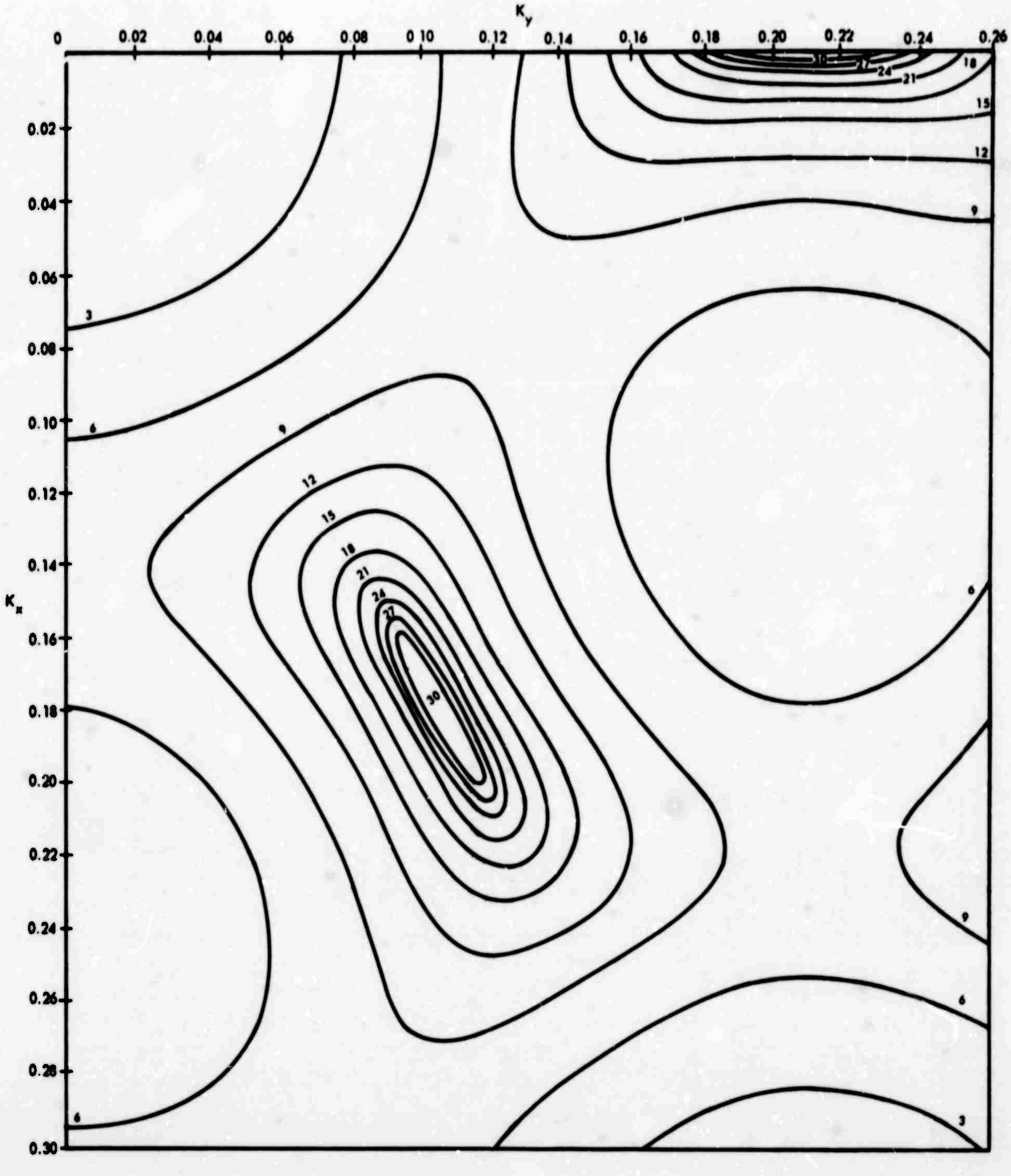


Figure 33 K plane response of the four-element array at Station Inge Lehmann, Greenland. Contours in decibels. Only one quarter is shown because of symmetry

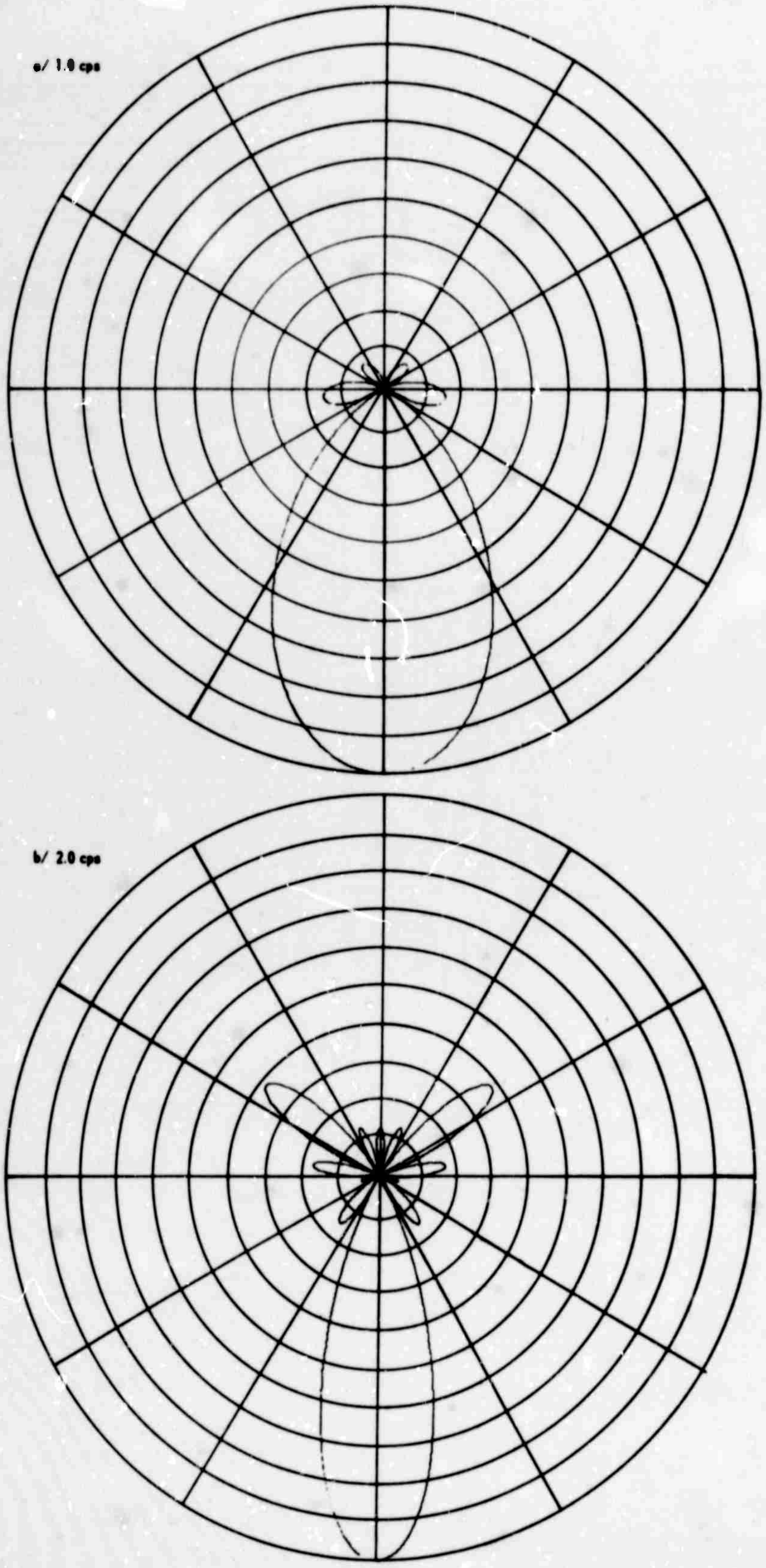


Figure 34 Radiation pattern of the proposed array for 1.0 cps and 2.0 cps and 10 km/sec

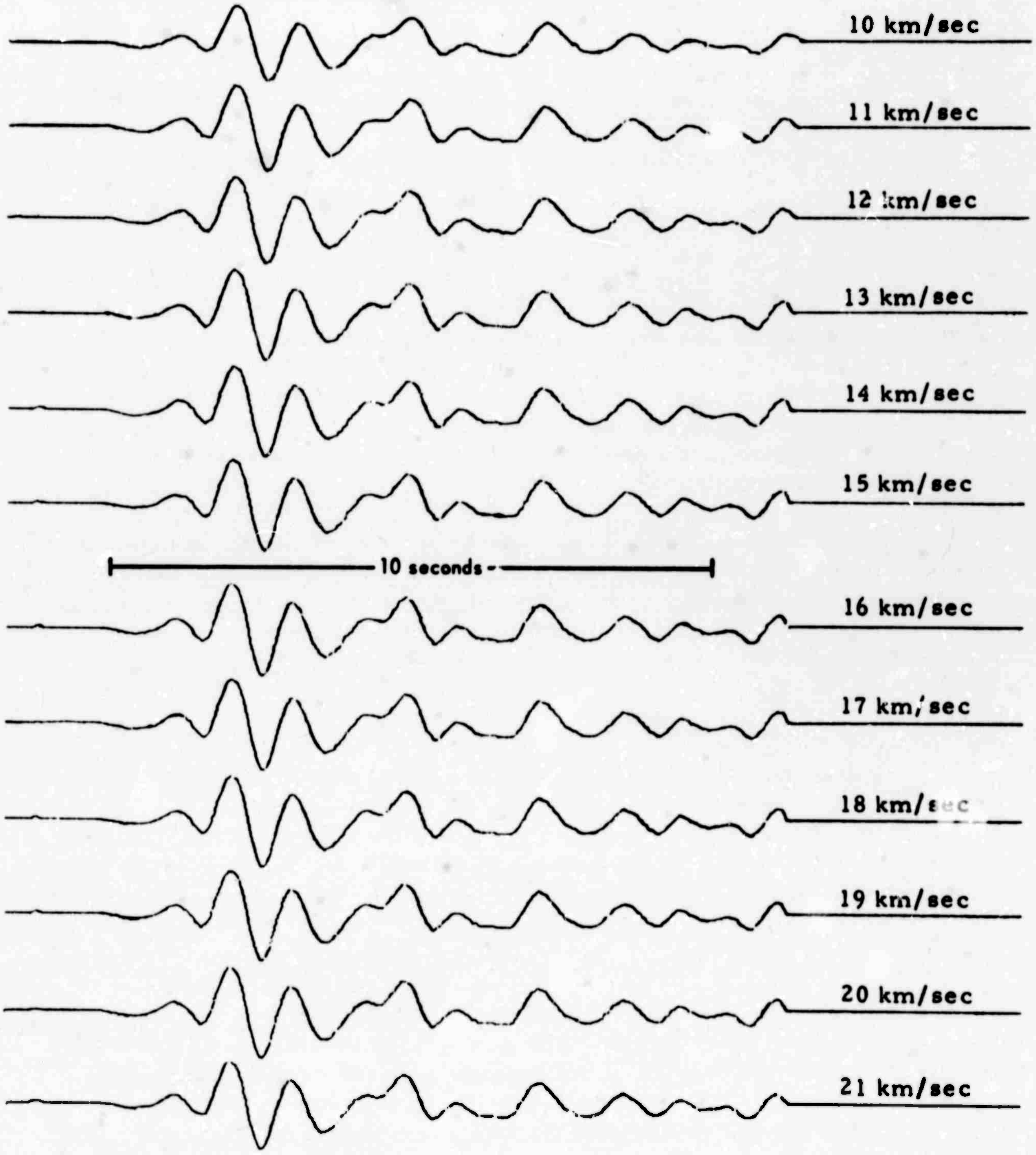


Figure 35 Signal degradation resulting from signal traveling across array at different velocities. Array tuned to 16 km/sec

## 2.5 GEOMAGNETIC OBSERVATIONS MADE AT INGE LEHMANN STATION

### Introduction

The existing network of magnetic observatories operated in the inner polar region of the northern hemisphere was supplemented during summer, 1966 by the establishment of two temporary magnetic stations in Greenland. One of these was located at Inge Lehmann Station, the other at Station Nord.

The main objective of this experiment was to obtain magnetograms for further investigations of the magnetic activity in the region inside the auroral zone. Particular emphasis was to be placed on a study of the bay-type magnetic variations, i.e., variations with periods of 1-4 hours. It can be seen from a map that the two temporary stations together with the six permanent observatories Mould Bay, Baker Lake, Resolute Bay and Alert in the Canadian Arctic and Thule and Godhavn in Greenland provide a useful array for this purpose.

The experiment was carried out by the Geophysical Section of the Danish Meteorological Institute under direction of Dr. K. Lassen in co-operation with the Arctic Institute of North America. The magnetic station was planned and established by J. Wilhjelm, who also undertook the operation of the station until September 3, 1966.

### Instruments and Observations

At Inge Lehmann Station the geomagnetic field was recorded by a magnetograph consisting of the following three la Cour type variometers: D-variometer D133, H-variometer H142 and Z-variometer Z154. The records were obtained photographically on a clock driven drum operated at 15 mm/hr. Time marks were superposed on the records every 10 minutes. The first magnetogram was obtained July 8, 1966.

Scale values were determined by means of a Helmholtz-Gaugain coil, yielding the following values: D 4.04'/mm, H 13.5 $\gamma$/mm and Z 15.6 $\gamma$/mm. These values were later checked through a series of absolute measurements performed during an interval of magnetic bay-disturbances. The same series of measurements was also used to determine any possible influence of H on the D-variometer and of D on the H-variometer. Both these correction terms were found to be negligible.

Absolute measurements were carried out regularly during July and August (2-3 measurements per week). Determinations of the horizontal components D and H were made with the quartz fiber instruments QHM 631 and QHM 633. The vertical component was measured by BMZ 280.

Azimuth of fix points in the horizon was determined from sun observations.

## Description of Magnetic Station

The distance from the magnetic station to the camp was sufficient to ensure that no artificial disturbance of the magnetic field would influence the measurements. Figure 36 shows the situation plan.

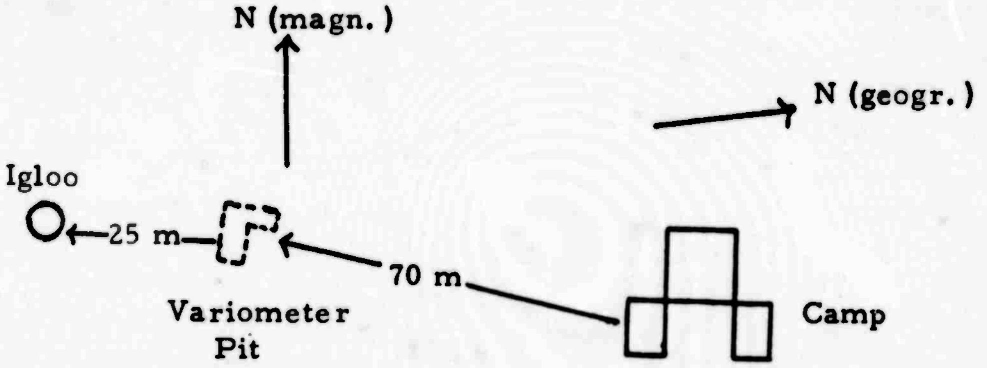


Fig. 36 Situation Plan of the Magnetic Station

The variometers were installed in a pit hollowed out two meters below the surface of the snow. The absolute measurements were carried out in a snowhut (igloo) placed near the pit. A six volt battery and a chronometer (providing the time marks) were installed in the camp and connected with the pit by two cables.

Figure 37 shows the magnetograph installed in the pit. The variometers were mounted on a wooden platform, which had been stabilized by pouring a mixture of snow and water around each of its six supporting posts, as shown in Figure 37.

A cover of black plastic foil suspended on a bamboo framework served to light-proof the pit.

## General Remarks

Several advantages were obtained by placing the magnetograph below the snow surface: it was easy to avoid any magnetic materials in the "construction," the temperature was very nearly constant, and the variometer pier could be made sufficiently stable. No baseline changes have occurred which could be traced to movements of the pier.

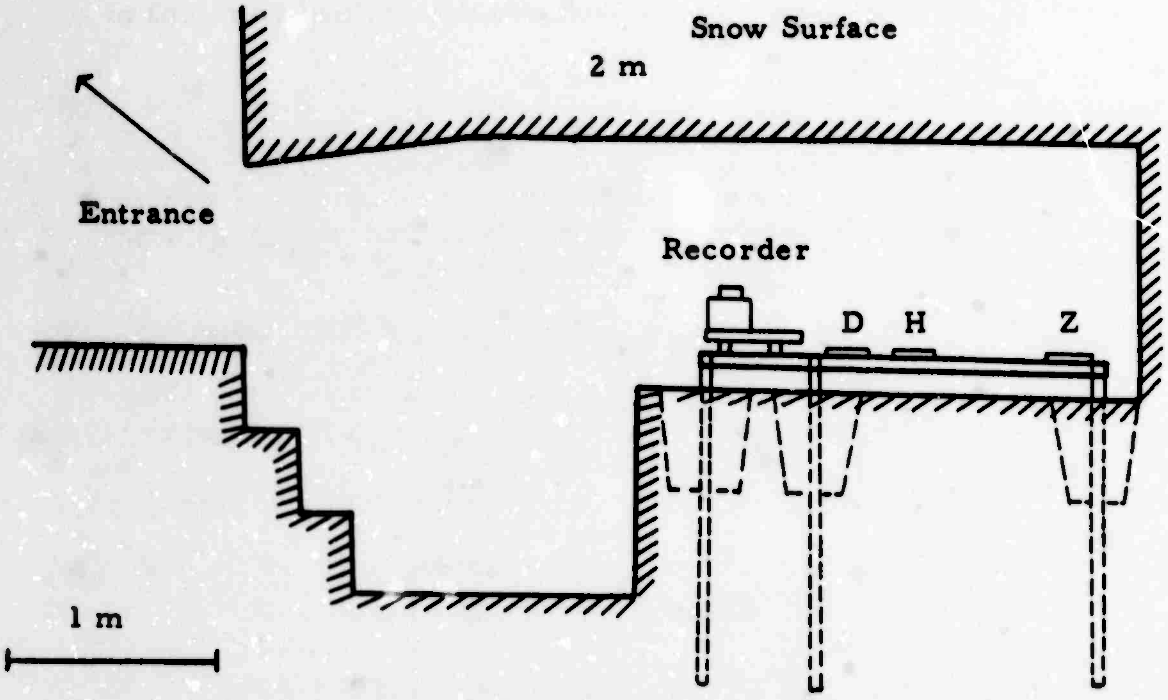


Fig. 37. Magnetograph Installation

The diurnal variation of the temperature in the pit was less than 1°C. Furthermore, the variometers were temperature compensated. The influence of temperature variations on the magnetograms can therefore be considered negligible.

During July and August a constant temperature of -25°C was recorded at the variometers. This low temperature created a serious problem of ice formation on prisms and lenses during paper changes and particularly during the installation of the instruments. The problem was reduced by use of face masks and moisture absorbing bags.

As the variometer pit was planned for use only during a period of two months, the floor space was reduced to a minimum; it measured 4 x 1 1/2 $m^2$. However, a dimension of 4 x 2 1/2 $m^2$ would have been more appropriate.

Supplementary Measurements

By means of the BMZ a profile of the geomagnetic field was measured along a 10 km line in direction S-N (magn.) and along a 25 km line in direction W-E (magn.).

Magnetic recordings were continued through the winter until the closing of the station in September, 1967.

All magnetograms were despatched by air to the Danish Meteorological Institute, Copenhagen where the analysis of the magnetic observations is being conducted.

## 2.6 OTHER SCIENTIFIC ACTIVITIES

Because of the unique location of Inge Lehmann Station, other scientists with experiments which would add significantly to the knowledge of the area were sponsored.

Two experiments were primarily by-products of the drilling program. The first was the preparation and shipping of selected ice cores taken from the boreholes to the U. S. Army Cold Regions Research and Engineering Laboratories, Hanover, New Hampshire for crystallographic studies.

The second concerned the measurement of the specific activity of $Si^{32}$, a cosmic produced radio nuclide, which required the selection of samples from the boreholes in addition to one ton of ice collected from below the six meter level (from the pre-hydrogen bomb testing era prior to 1953). This was flown to Thule AFB for analysis by scientists from the University of Copenhagen. The purpose of this experiment was to check whether or not the fallout of naturally produced $Si^{32}$ is influenced by a continental effect for the possible use of $Si^{32}$ for dating of ice. Comparison with a similar sample collected at Camp Century 500 km west of Inge Lehmann Station should give the answer to this question.

Two other programs were conducted by investigators visiting Inge Lehmann Station. In July, 1966, Dr. Wilford F. Weeks and Mr. Steven J. Mock of U. S. Army CRREL conducted ten meter snow temperature studies and small party traverse techniques in the area.

In July, 1967, Drs. E. Robinson and R. C. Robbins of Stanford Research Institute collected samples for their study of the carbon monoxide content of glacial ice and the natural atmosphere.

The results of these experiments will be published by the investigators after completion of the field studies and analyses.

# 3. OPERATION BLUE TREK

## 3.1 GENERAL DESCRIPTION

Operation Blue Trek was planned as a small mobile scientific party whose objective was to make observations of the seismic noise field along a line between Inge Lehmann Station and Thule to determine how close to Thule a seismic observatory could be placed and still remain as seismically noise free as the Inge Lehmann Station. Six temporary stations were occupied as shown in figure 38. In addition to the principal objective, magnetic and gravity measurements were recorded at five nautical mile intervals, and standard synoptic weather observations were made and relayed to Thule.

The group consisted of six men as follows:

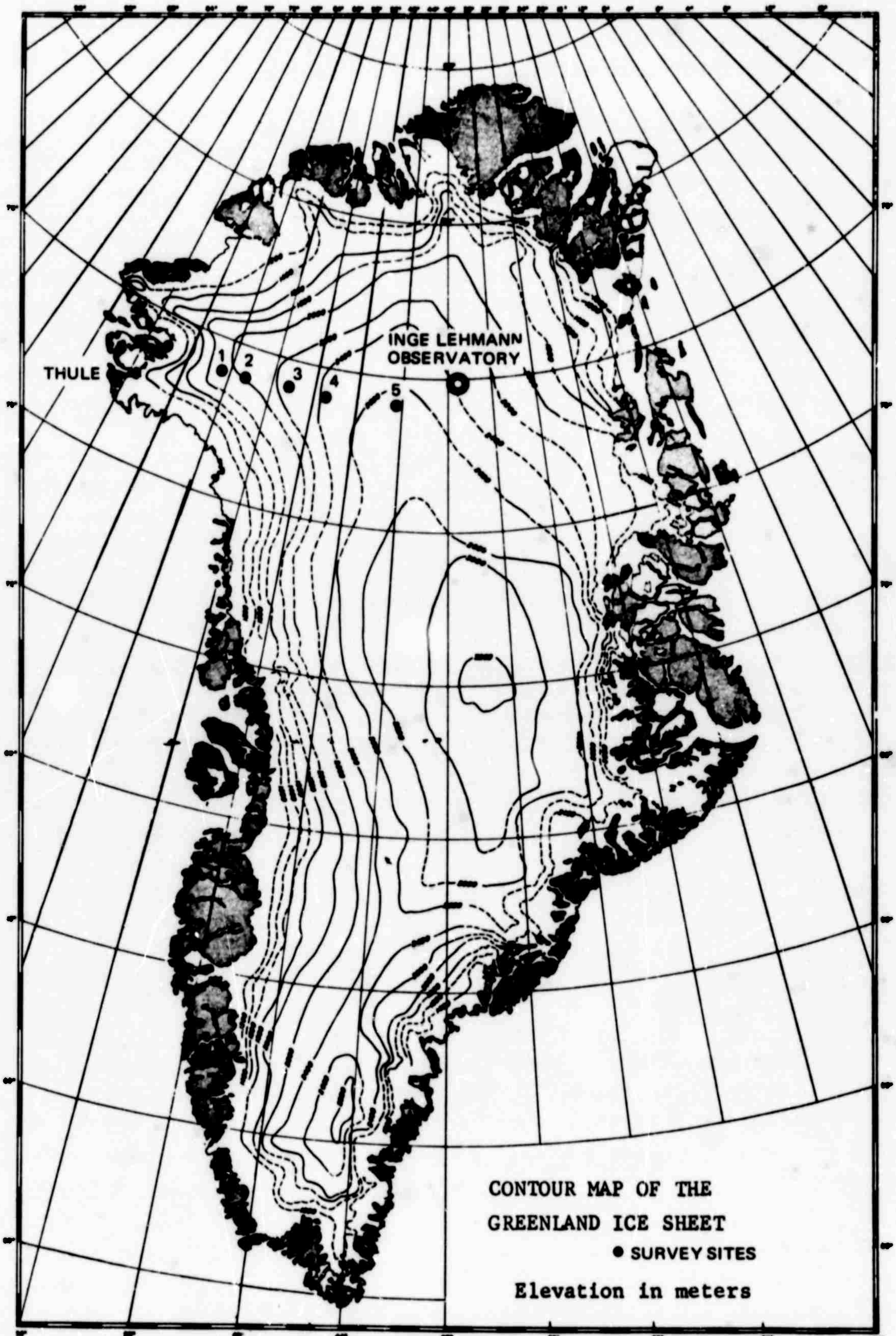
| | | |
|---|---|---|
| Ralph A. Lenton | Leader | Arctic Institute of North America (AINA) |
| Erik Hjortenberg | Seismologist/ Magnetics | Geodetic Institute, Denmark |
| O. Layne Churchman | Seismic Technician | Geotech, Garland, Texas |
| Gerald W. Johnson | Surveyor | AINA |
| Freidrich Belzer | Mechanic | AINA |
| Michael Davis | Arctic Technician | AINA |

In addition, Major D. D. Young, Air Force Office of Scientific Research, joined the group at site 4 to accompany the party the remainder of the journey to Inge Lehmann Station.

### Trail Equipment

The major items of equipment and supplies essential to travel and living on the ice sheet were as follows:

1 Snocat model 443
1 Snow Toboggan, Polaris Cruiser model
1 Snow Toboggan, Arctic Cat model 460D
2 Cargo sleds, one ton U. S. Army type
3 Nansen sleds



SOURCE: COLD REGIONS RESEARCH AND ENGINEERING LABORATORY RESEARCH REPORT 170.

Figure 38 Location of BLUE TREK survey sites

3 Hexagonal Arctic Tents
Fuel, lubricants and spare parts for vehicles
Rations
Communications equipment
Navigation equipment
Portable Gasoline Generator 2500 w
Arctic clothing and individual mess gear

In addition to the above equipment, approximately 1000 pounds of scientific equipment were carried including portable seismic unit, magnetic instruments, gravity meter, portable met station and drilling kit.

## Snocat Model 443

The Snocat built in 1956 for the U. S. Army at Camp Tuto was transferred to Operation Blue Trek as our primary hauler. After many hours spent freeing rusting tracks and checking the engine, transmission and differentials, the traverse mechanic declared it serviceable. The interior was fitted with racks to accommodate the radio equipment and delicate scientific instruments. Personnel clothing and sleeping bags were also carried in this compartment.

The vehicle performed well throughout the traverse, towing two cargo sleds and one nansen sled with loads composed of POL, generator, spare parts, bamboo poles and drill kit totalling approximately two tons. This load decreased as fuel and trail markers were used. Gasoline consumption for the journey averaged two miles per gallon. Regular maintenance was performed on the vehicle and the major repairs were on the tracks, where 14 rollers, 4 cross links, and 3 track bars were replaced. At the completion of the project, the vehicle was parked outside at Inge Lehmann with all systems drained. If required for further use, the tracks, 6 v battery and front and rear springs should be replaced.

## Arctic Cat Model 460D

The Arctic Cat was purchased because of its suitability for hauling and was used as the lead vehicle, towing one nansen sled loaded with approximately 800 pounds of equipment and rations. Fitted with a 12 hp, 4 cycle Kohler engine it averaged 5 miles per gallon throughout the trek. Regular maintenance was performed and no repairs were required. It is stored in the garage at Inge Lehmann.

## Polaris Cruiser

The Polaris snow toboggan was one of two purchased at the commencement of the project and already had one year at Inge Lehmann. It was completely checked in Thule, where new tracks and a new engine of the same type as in the Arctic Cat were fitted. Towing one nansen with a 700 pound load, it averaged 5 miles per gallon. A break in the keyway of the drive-shaft of the track system occurred and was temporarily repaired, but after a second break, the vehicle was cached at the borehole marker at site 5, 75 miles from Inge Lehmann. It was unfortunate that no spares of this part were carried.

## Logistics

Support of the Blue Trek party was performed by the C130 aircraft of the 17th TCS. The traverse began at Camp Century and the initial flight of men and equipment was flown in on July 17th. Due to the difficulty of take-off from Century, it was decided that all support flights would be flown with a second aircraft acting as cover during unprepared surface landings. The plan was to resupply the party at site 4 but difficulties with the recording equipment necessitated two additional missions, one landing and one air-drop, for essential parts. The much needed resupply of fuel and rations was delivered at site 4 on August 17th. Evacuation of the party was made from Inge Lehmann on September 1st.

## Navigation

A well-marked trail for possible future use provided us with a simple means of navigation between sites. Once the course had been set, navigation continued by rear sighting along the trail of flagged bamboo poles which were positioned approximately every third of a mile, with closer spacing when visibility conditions deteriorated. Marking the trail and recording the scientific observations at five mile intervals resulted in travel periods averaging one hour twenty minutes per five miles. A total of sixty stations were occupied.

## Rations

Blue Trek was provided with more than adequate rations. The major portion of the dehydrated foods, frozen and dried meats, dried fruit and concentrated fruit juices used were purchased directly from the commissary and base exchange at Thule. This supplied each man with a well-balanced diet of approximately 4000 calories daily, supplemented by fresh fruit, milk and baked goods delivered by plane. For emergency use a ten-day pack of concentrated trail rations was carried.

## Surface Meteorological Data

Limited surface weather data were obtained during the traverse at three-hour intervals, with the information then relayed to Thule for the use of the Air Weather Service. The observations followed a general format for mobile stations, and included cloud cover, wind speed and azimuth, barometric pressure and temperature. A sling psychrometer, a Wallace and Tiernan altimeter and a portable meteorological station model AN/PMQ-7 on loan from the Air Weather Service, USAF were the instrumentation used. The AN/PMQ-7 pressure sensor was not used as it was limited to elevations below 5000 feet. It is recommended that this component of the unit be extended to cover high elevations.

The daily observations of temperature, wind speed and wind direction are plotted in figure 39. Temperature range varied from day to day, gradually cooling as the traverse proceeded inland, coupled with the rise in elevation. The lowest temperature recorded was -33°F on August 24th. Prevailing winds on this part of the ice sheet are from the southeast and south; after the traverse passed its highest elevation, there was a noticeable change to westerly winds. The wind was fairly persistent throughout the traverse, but actually only two days were lost due to storm and blowing snow.

Cloud cover averaged approximately 47 percent daily, with a predominance of high cloud. Visibility for the most part was excellent, averaging above 20 miles. During the latter part of the journey, ground fog and associated whiteout conditions were prevalent during the early mornings and late afternoons. These fog whiteouts occur when warm maritime air moves over the cold snow surface, and impose restriction on air and surface transportation. The traverse was fortunate in that the occurrences of fog whiteouts did not coincide with the travelling periods to the extent of bringing the party to a complete stop.

<u>Blue Trek Traverse Log</u>

| | |
|---|---|
| 26 July | Left Camp Century. Arrived at site 2, 35 n.m. from Century. |
| 28 July | Decision made to call for support plane due to equipment problems (seismometer). |
| 30 July | Support plane arrives and returns to Thule with equipment to be repaired. |
| 1 August | Plane returns to site 2 with equipment and accompanying personnel. |
| 4 August | Left site 2, arrived at site 3 after 50 n.m. travel. |
| 9 August | Plane flown in from Thule to drop parts for equipment repairs. |

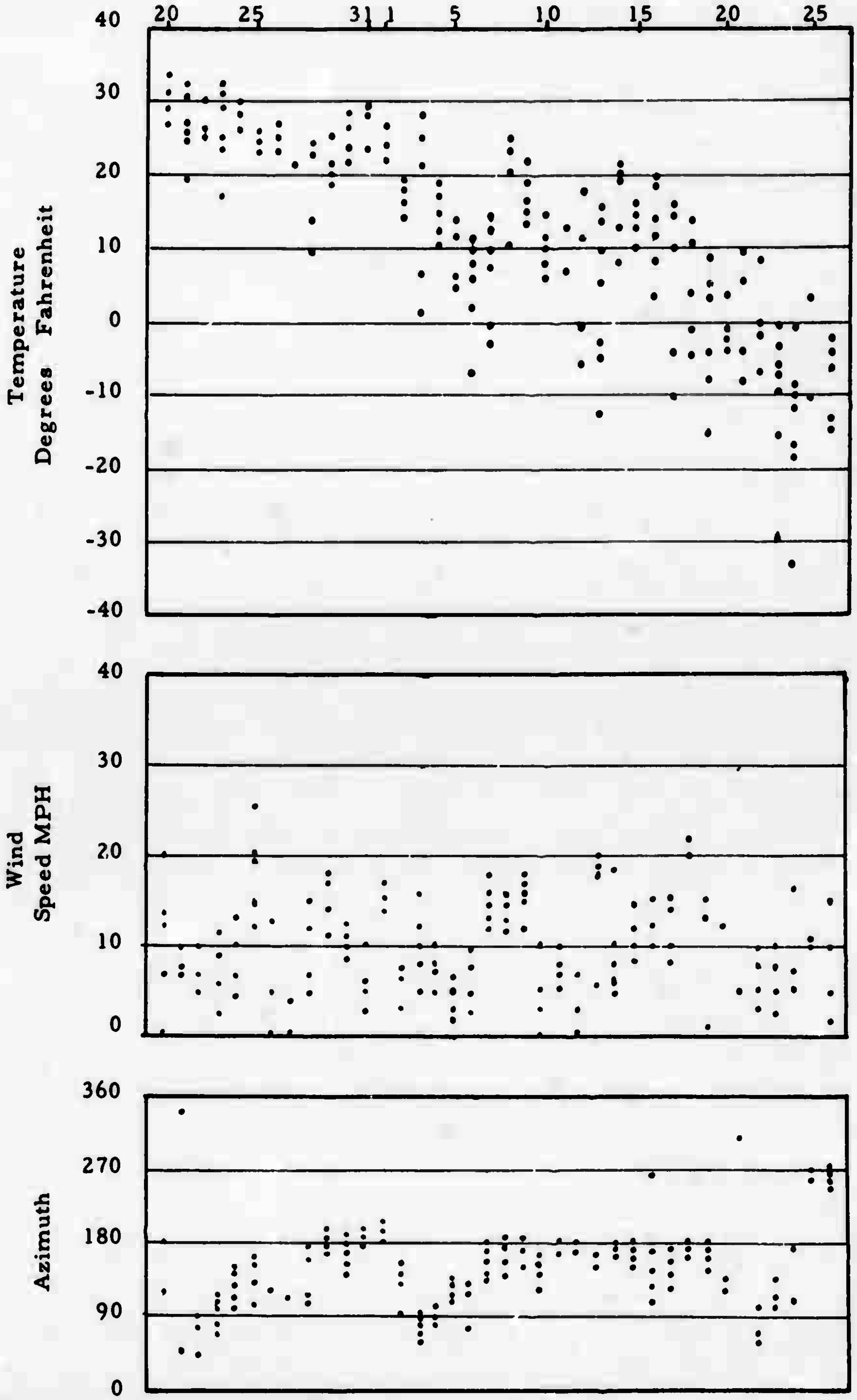


Fig. 39. Temperature, Wind Speed and Azimuth Readings, Operation Blue Trek.

| | |
|---|---|
| 11 August | Left site 3, arrived at site 4 at 2:30 a. m. after 50 n. m. travel. |
| 17 August | Plane arrived with supplies and spare parts; Major D. D. Young joined the party for the remainder of the journey. |
| 19 August | Left site 4, made camp after 40 n. m. |
| 20 August | Fog and whiteout conditions slowed travel, so that site 5 was made after 30 n. m. |
| 24 August | Left site 5 after caching Polaris vehicle which could not be repaired. Made camp after 25 n. m. since travel was slowed by cold and fog. |
| 26 August | Left camp on last leg of journey and arrived at Inge Lehmann Station at 10:30 p. m. local time. |
| 1 September | Party evacuated from Inge Lehmann Station. |

## 3. 2 OPERATION BLUE TREK SEISMIC NOISE ANALYSIS

The following chapter summarizes the results of the analysis of the seismic data recorded during the Blue Trek survey. Observations of the seismic noise field were taken at six temporary stations along a line from Inge Lehmann to Thule and at the Inge Lehmann Observatory site. The locations of these stations are shown in figure 38 and computed positions in Table IV, page

### Data Acquisition

The sensor used in the survey was a shallow-hole seismometer, model 20171. The data were amplified and recorded on a helicorder at a chart speed of 1.5 mm/sec. The frequency response of the system is shown in figure 40. In order to isolate the detector from wind noise, it was seated at the bottom of a 17 meter borehole. Observations were made over a period of two to three days at each site. During each recording period, the system was calibrated daily and routine weather observations were recorded.

According to the field information, the survey system was operated at magnifications of 327K and 652K. A direct comparison of the amplitudes of teleseismic signals recorded by the survey and standard equipment at the Inge Lehmann site and at site 5, however, indicates that the actual survey magnifications never changed from 327K. Figures 41 and 42 show teleseismic signals recorded by the survey and permanent systems which support this finding. To minimize any possible errors arising from un-

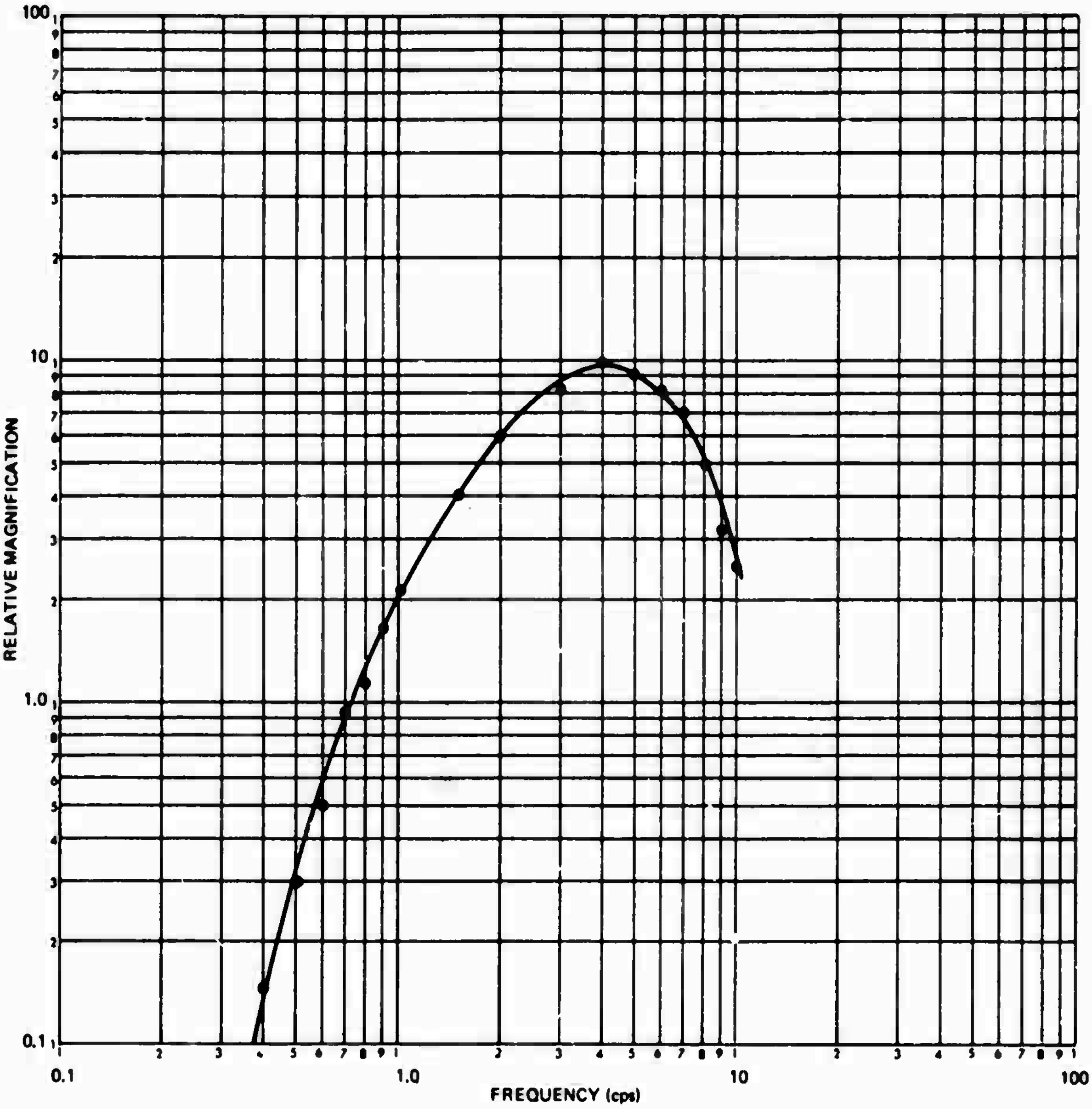


Figure 40 Frequency response of 20171 seismometer

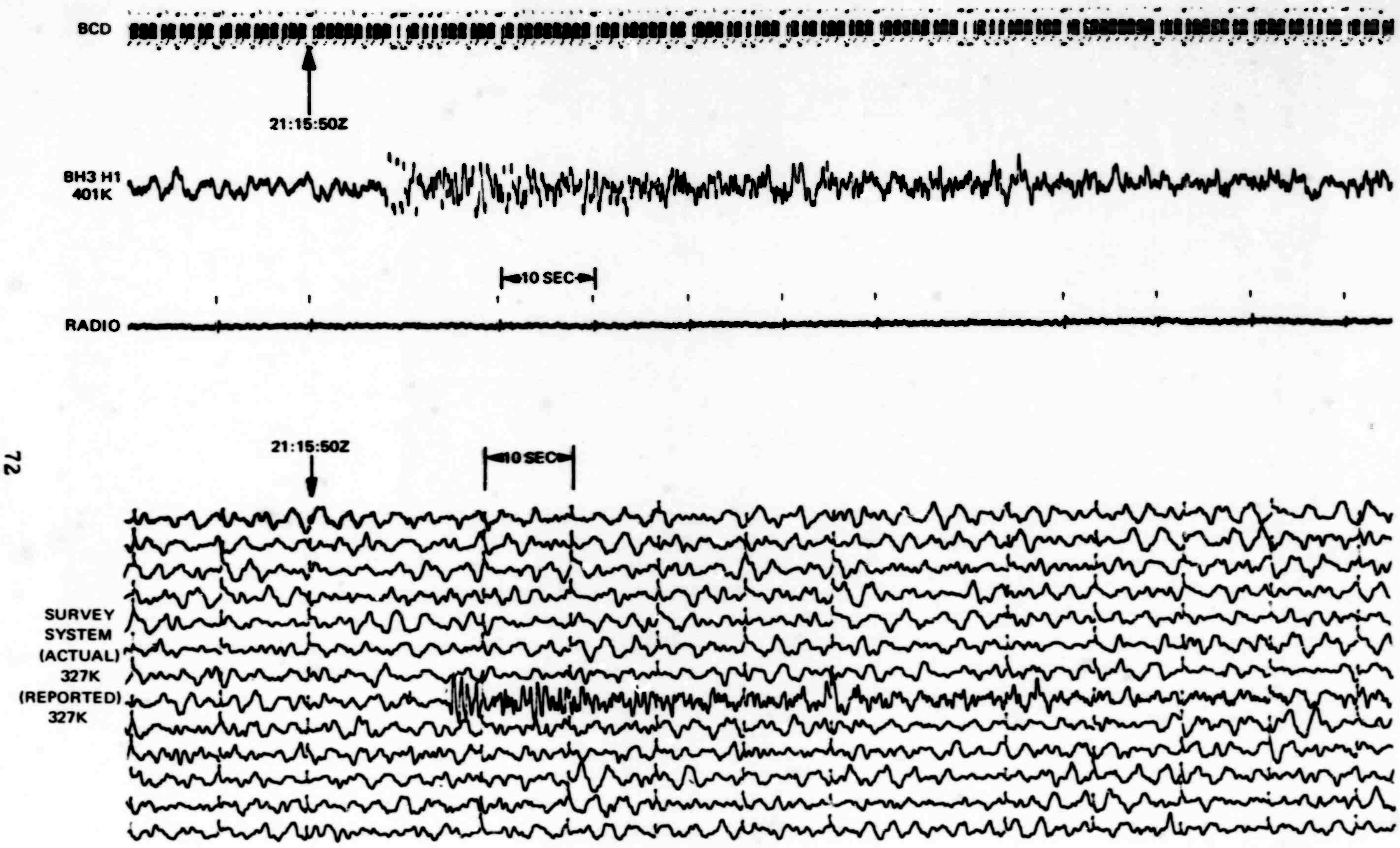


Figure 41 Comparison of teleseismic event recorded by permanent and survey systems at the Inge Lehmann site

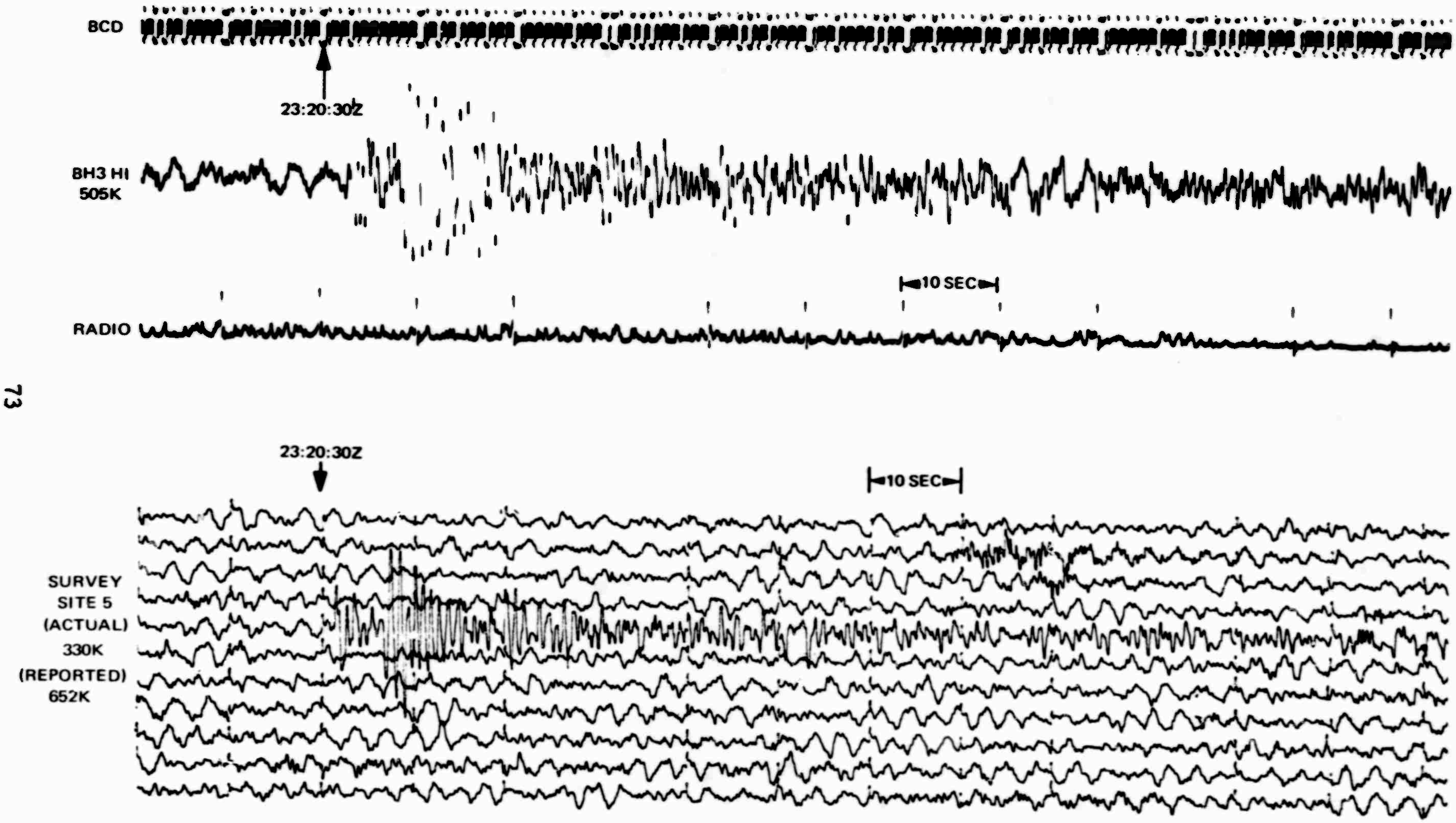


Figure 42 Comparison of teleseismic event recorded at site 5 by survey system and at the Inge Lehmann site by the permanent system

certainties in magnification, the data analyzed were restricted to those recordings with a magnification reported by the survey field team of 320 to 330K. By this procedure, it was possible to establish relative noise levels at Inge Lehmann and the various sites occupied during the survey.

## Data Analysis

Of the six survey sites where recordings were made, suitable data were obtained at sites 2 through 6. Qualitatively, the records obtained by the survey can be readily separated into two classes. The records obtained at sites 2 and 3 are characterized by frequent bursts of relatively high frequency noise. These noise bursts are substantially reduced both in amplitude and duration on records obtained at sites 4, 5, and the Inge Lehmann Station. This sharp break in character is shown quantitatively by the power density spectra of noise samples recorded at each site shown in figures 43 through 47. These spectra were estimated from noise samples 100 seconds in length and hand digitized at the rate of 5 samples /sec. The samples taken from the sites 2 and 3 records were carefully chosen to avoid large bursts of the short-period noise. Thus, they represent the "best" background possible at these sites. The samples at the other sites were chosen randomly. A comparison of the spectra reveals that the noise power is roughly equivalent at each site at periods greater than about 1.2 seconds allowing for day-to-day fluctuations. At the shorter periods, however, the noise power at sites 2 and 3 is considerably higher than at sites 4 through 6, even though a special effort was made to select samples at these sites during a period of relatively low short-period background activity.

In figure 48, the total power in the bandwidth $0.4 \leq T \leq 1.0$ sec recorded at each site relative to the total power in the same bandwidth at site 6 (Inge Lehmann) is plotted versus distance. Because of the low sampling rate, this is a more meaningful test for equivalence than a period by period comparison. Note that for all practical purposes, the noise power in this bandwidth recorded at sites 4 and 5 is equivalent to the noise power at Inge Lehmann. At sites 2 and 3, the noise power is roughly a factor of 5 higher.

The time domain analysis yields additional evidence for relative differences in the ambient noise fields at the different survey points. During this phase of the investigation, the peak-to-peak amplitudes of the largest wavelet occurring in the band-pass of 0.5 - 2.0 sec in one minute intervals were measured. Two hundred such observations were made for each day's records obtained from sites 2 and 3. One hundred observations were made for each day at the remainder of the sites. The mean amplitudes were computed for each site and normalized by dividing each by the mean value obtained at the Inge Lehmann site. The resultant normalized means which are plotted in figure 49 show the same general trend of increasing amplitude as the coast line is approached. It appears quite likely that the high fre-

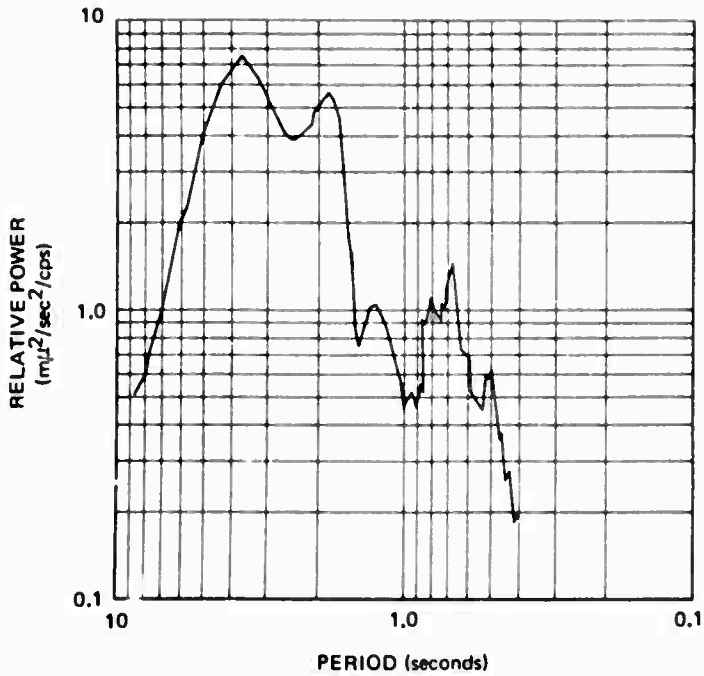


Figure 43 Project BLUE TREK site 2 power spectrum
03 August 1967

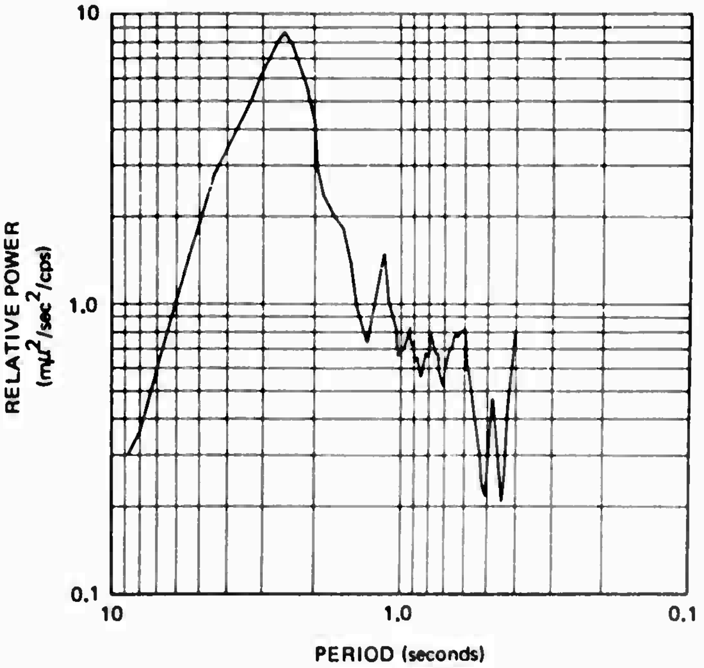


Figure 44 Project BLUE TREK site 3 power spectrum
08 August 1967

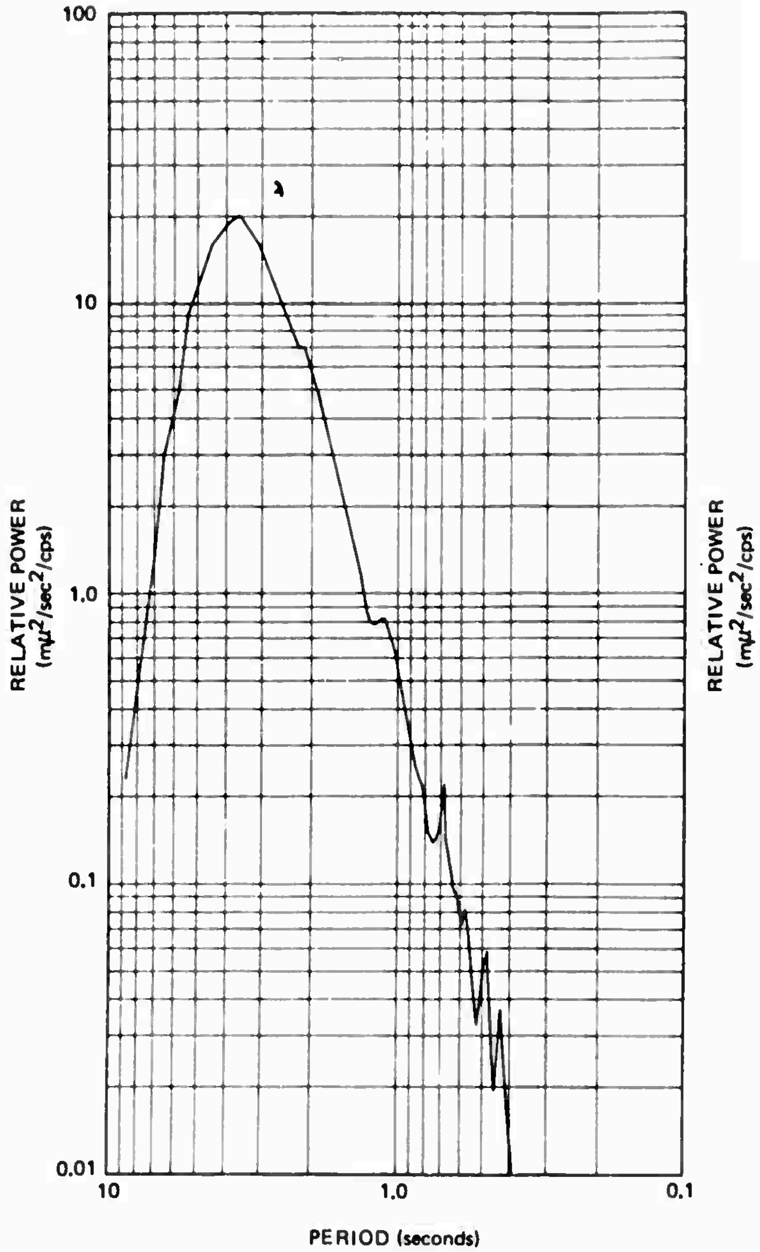
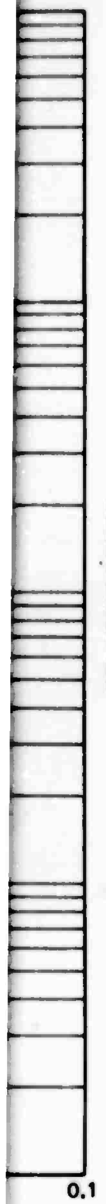


Figure 45 Project BLUE TREK site 4 power spectrum
17 August 1967



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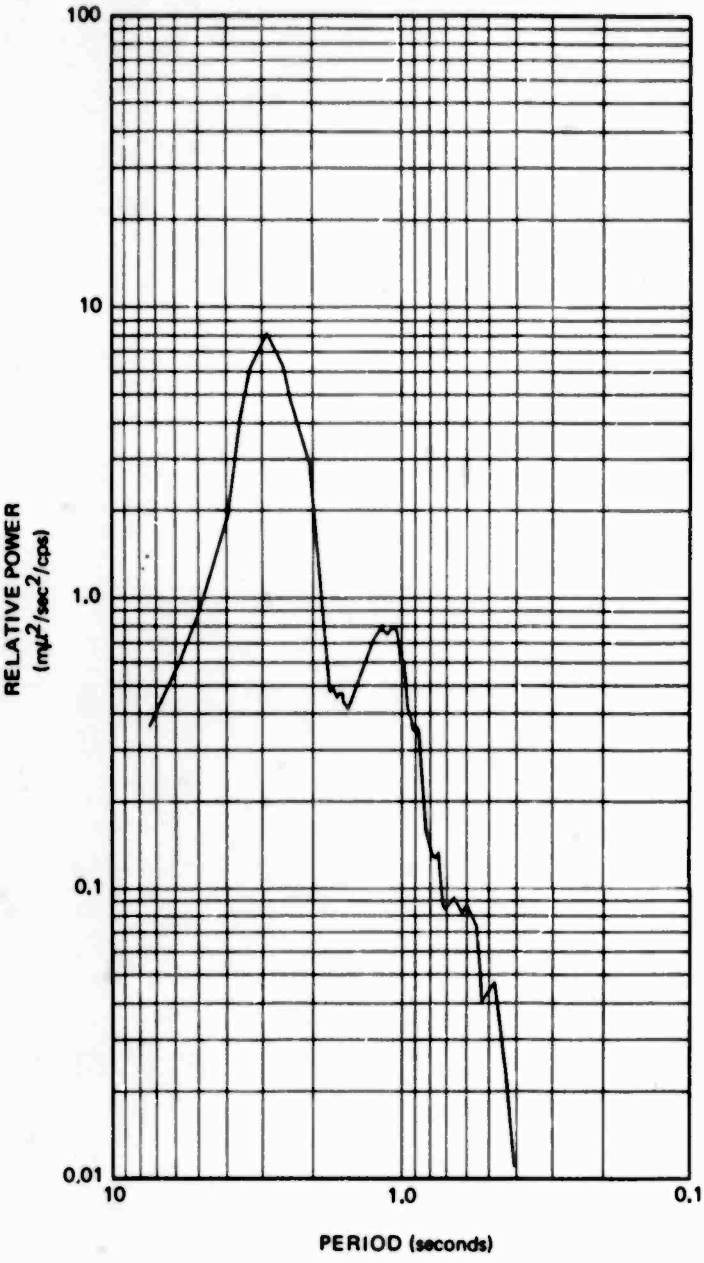

Figure 46 Project BLUE TREK site 5 power spectrum 22 August 1967

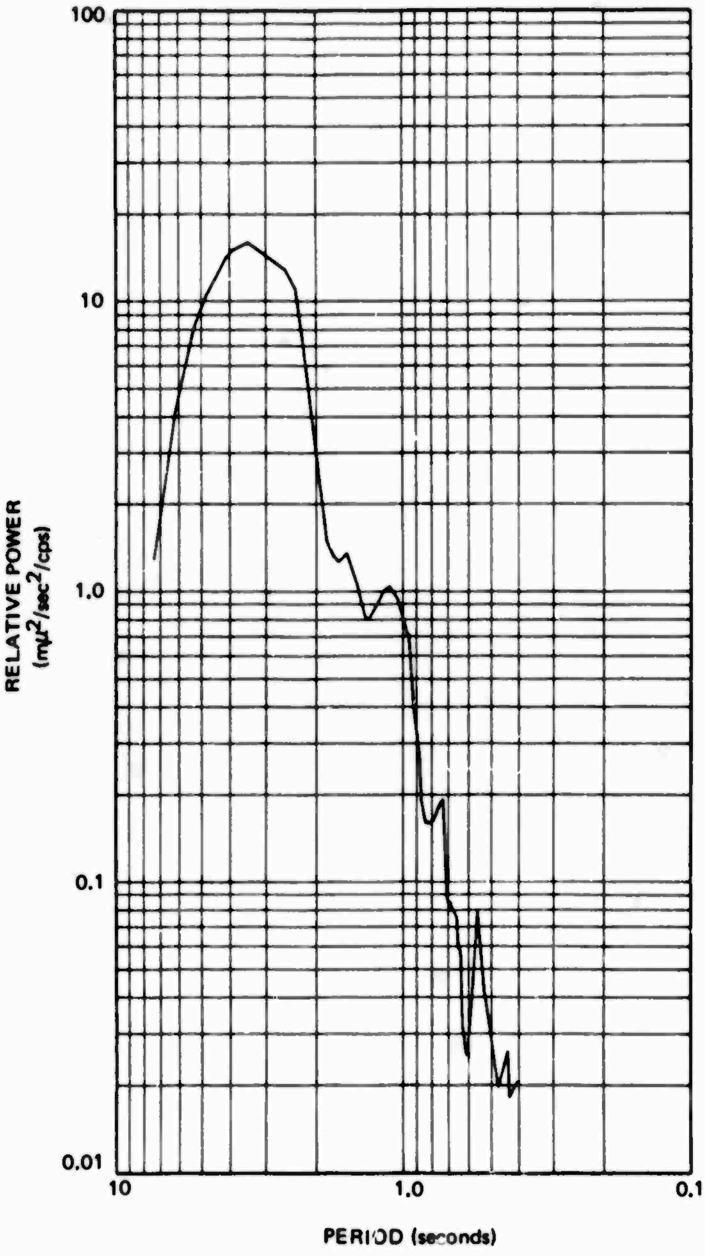

Figure 47 Project BLUE TREK Inge Lehmann site 168 ft borehole power spectrum 30 August 1967

B

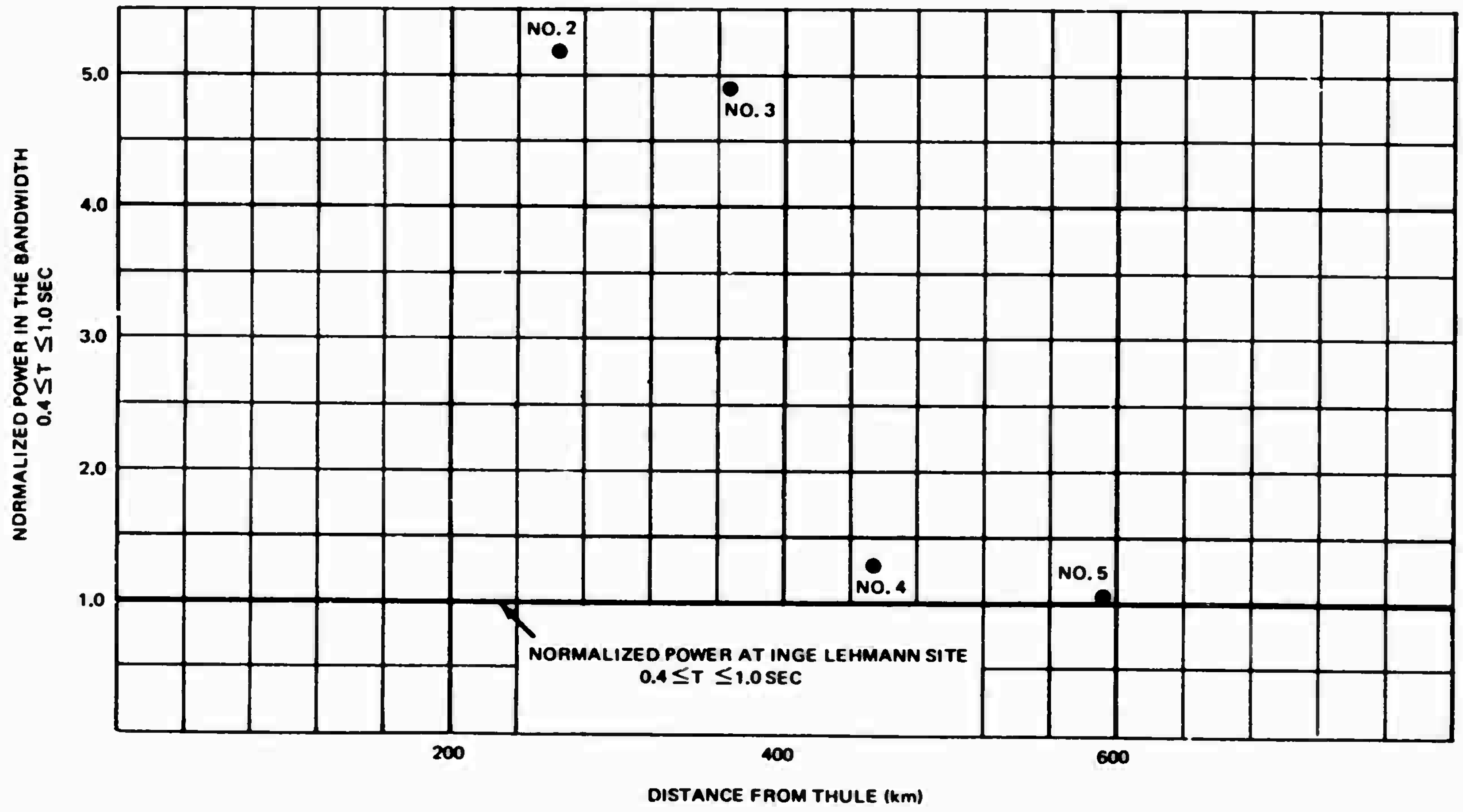

Figure 48 Relative power in bandwidth $0.4 \leq T \leq 1.0$ sec at the various survey points normalized with respect to power at Inge Lehmann site

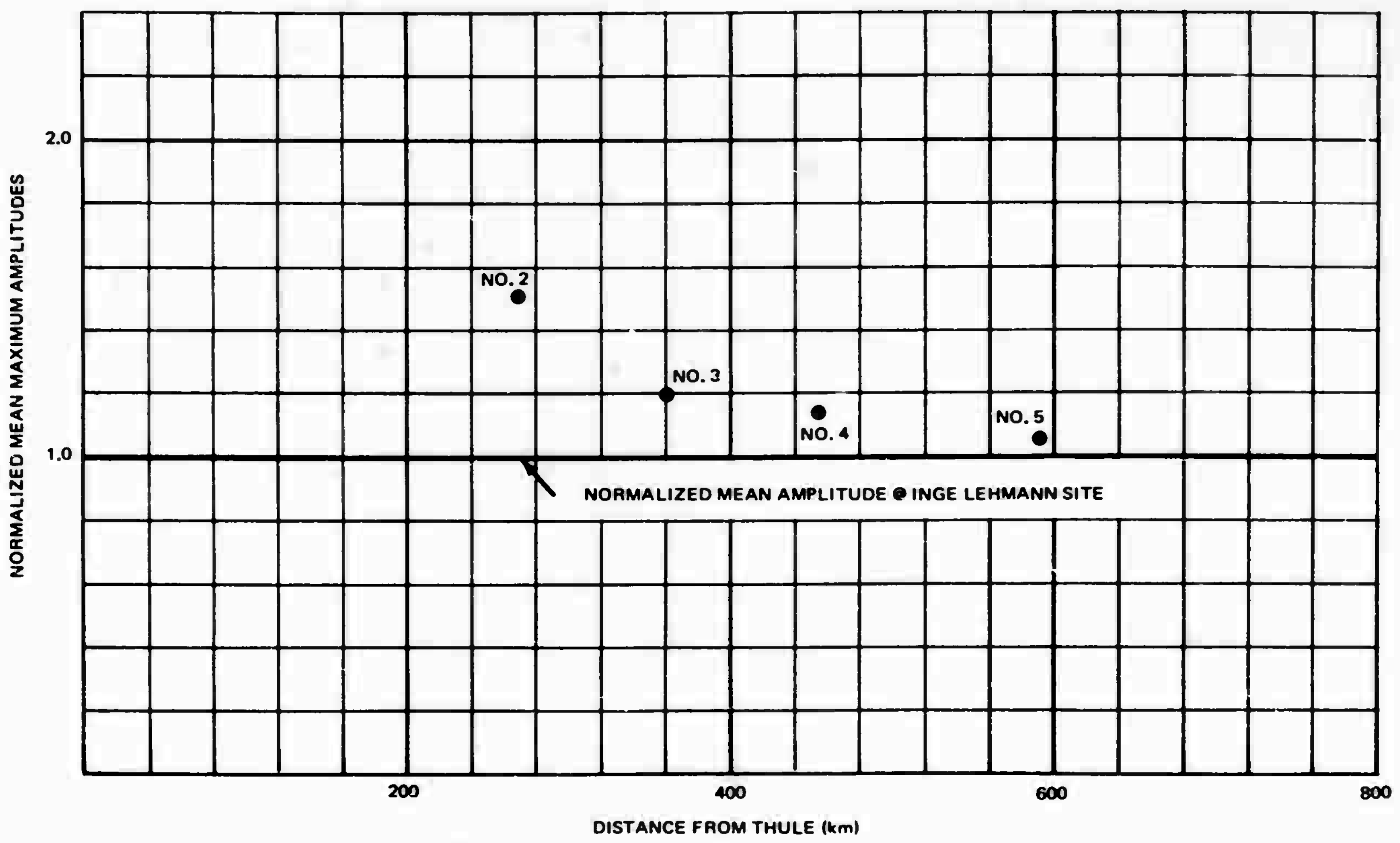

Figure 49 Normalized mean maximum amplitude at various survey points

quency noise bursts at sites 2 and 3 are connected with the ice breaking as it moves toward the coast. Between sites 3 and 4, the behavior changes and the ice deforms plastically.

### Summary of Results

The results suggest the following generalizations:

a. At periods greater than about 1 second, the ambient noise field is probably the same at all survey stations.

b. At periods less than 1 second, the ambient noise field appears to be sharply attenuated between sites 3 and 4. Sites 2 and 3 are characterized by similar short-period noise levels which are approximately a factor of 5 higher in power than the short-period noise at the other survey points.

These results indicate that the noise levels are quite similar at points between site 4 and the Inge Lehmann Station.

## 3.3 MAGNETIC MEASUREMENTS

The magnetic program of Operation Blue Trek had two objectives: first, to record the daily variation of the earth's magnetic field vector at the high geomagnetic latitudes traversed by the expedition, and second, to measure a profile of the vertical component of the earth's magnetic field.

Dr. K. Lassen of the Danish Meteorological Institute was responsible for the research program. The field work was done by Dr. E. Hjortenberg of the Danish Geodetic Institute.

The equipment for recording the daily variation is shown schematically in figure 50. The sensor, power supply and electronics were built by F. Primdahl, civ. ing., of the Danish Meteorological Institute.

Recordings were obtained from the stations 1, 2, 3, 4, and 5. At each site the sensor was installed in an igloo to protect it from the wind. The sensor was placed on any hard layer of snow encountered a few feet below the snow surface, and the igloo was built so that it was possible to re-level the sensor during the recording period. It was found, however, that only minor adjustments were necessary to keep it level.

The recording equipment was installed in a tent, which was unheated apart from the 200 watts generated by the electronics. The low temperatures during the last part of the trek did not create any instrumental problems.

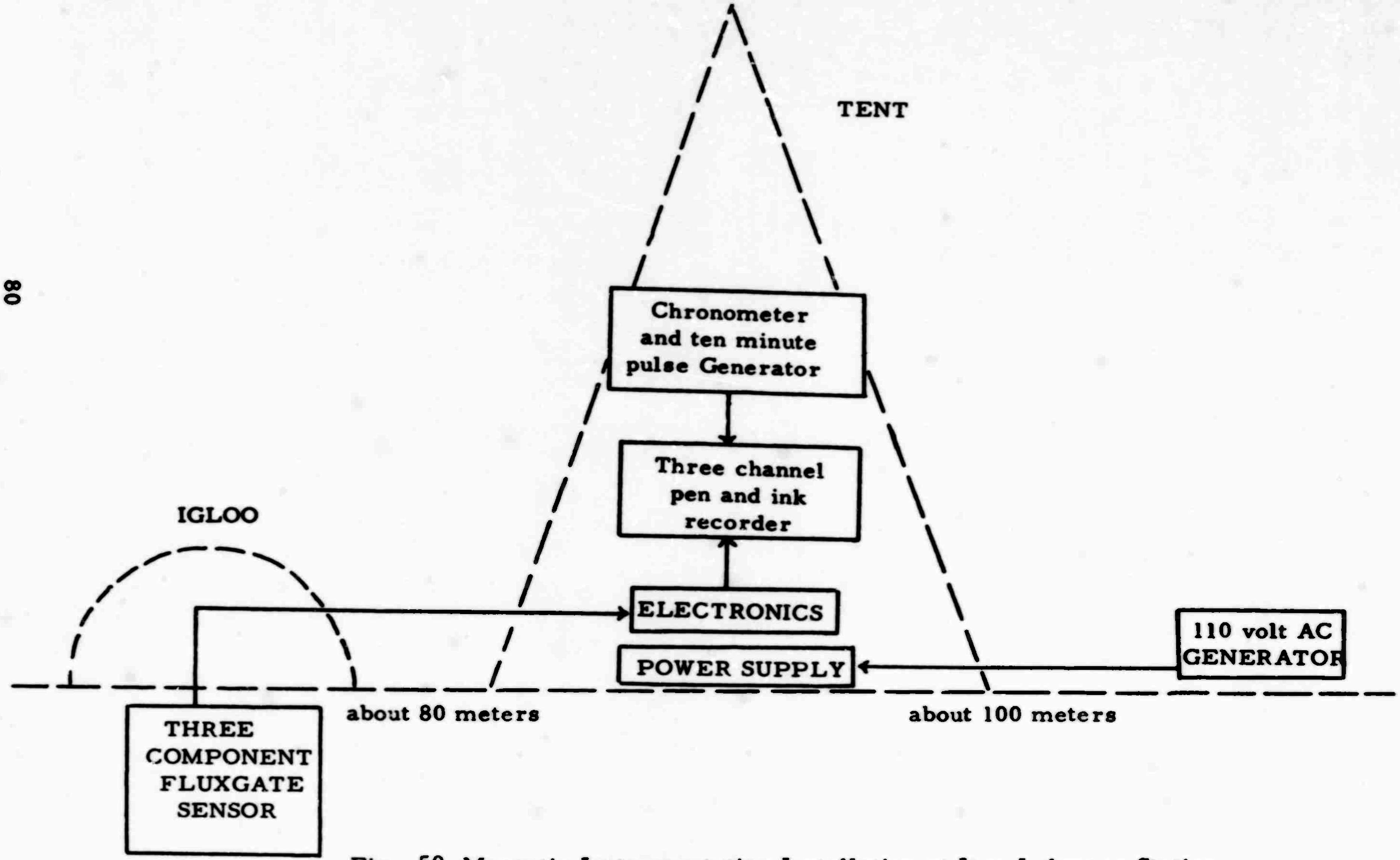

Fig. 50 Magnetic Instrumentation Installation at Inge Lehmann Station

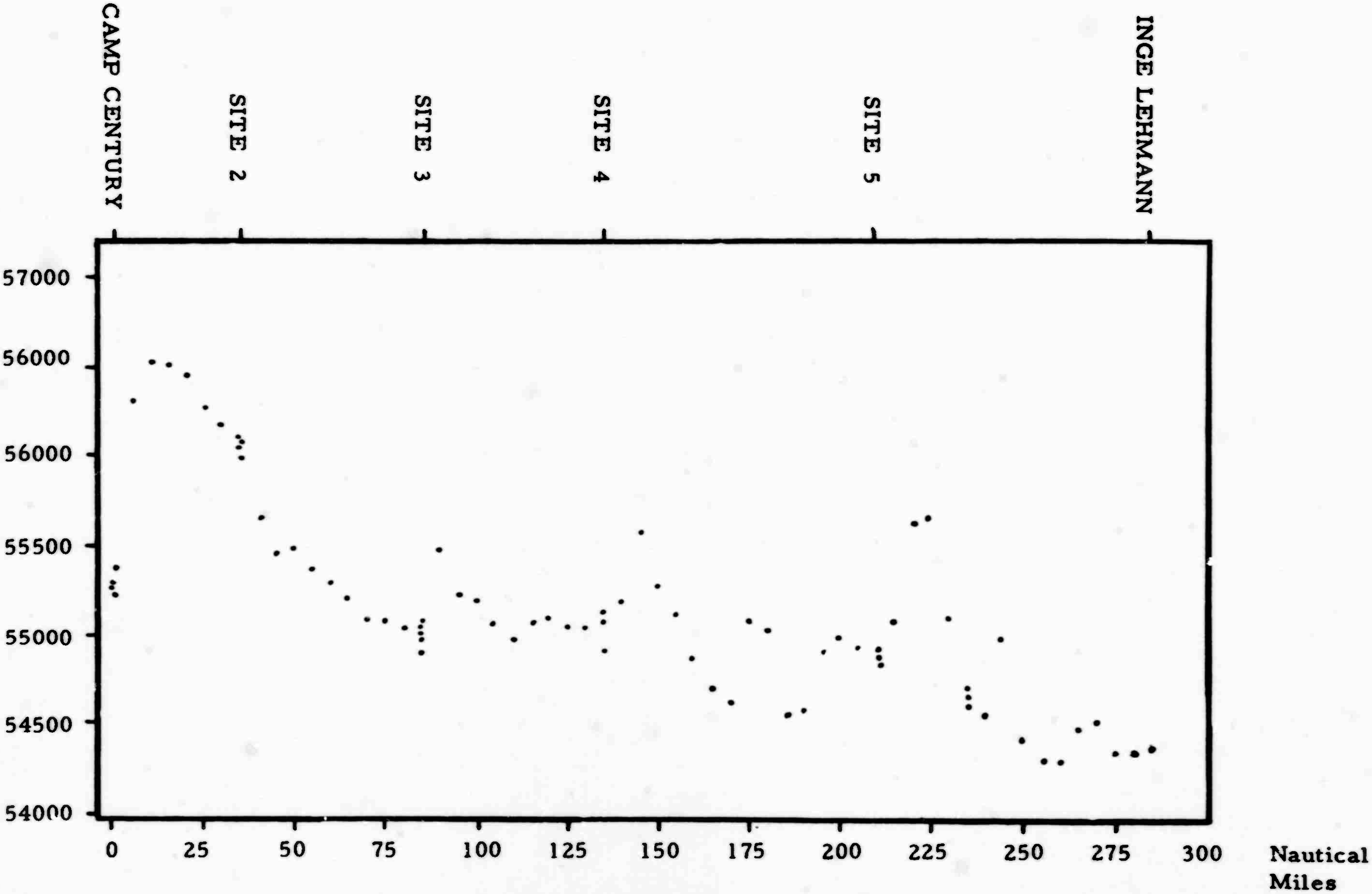

Fig. 51 Vertical Component of the Magnetic Field between Camp Century and Inge Lehmann

Several absolute measurements of the magnetic field were made at each station. The instruments used were the la Cour BMZ and QHM (Inst. Meteor. Danois, Comm. Magn. 15 and 19, Copenhagen 1936 and 1942). These measurements provided a check on the recording instruments. The checks were satisfactory except for that at Camp Century, where the abandoned installations below the surface may have created slightly different fields at the position of the BMZ instrument and at the position of the recording instrument.

The profile of the vertical component of the earth's magnetic field was obtained by using the BMZ instruments at the recording sites and along the trail at five nautical mile intervals. The profile runs from Camp Century to Inge Lehmann Station. The calculations necessary to reduce the measured data were performed by K. Frellesvig, mag. scient., using the GIER computer at the University of Copenhagen. The results are shown in figure 51. The most prominent feature is an anomaly in the Camp Century area. This anomaly is large enough also to affect the flight level measurements done earlier by Serson (private communication).

## 3.4 SURVEYING

The surveying required to support the Blue Trek traverse can be divided into two categories: (1) the field techniques used for day-to-day navigation on the traverse, and (2) the data reduction methods used for determining the geographical location of all points occupied by the trek.

Surveying equipment consisted of a Wild T2 Theodolite equipped with a Roelofs Solar Prism, a chronometer, a stop watch, a portable radio for receiving time signals, and a 50 meter steel tape. Thermometers and barometers were also available for obtaining the required meteorological data.

### Traverse Navigation

Traverse navigation was carried out using modified celestial navigation procedures. Although several day-light star and planet observations were made, observations of the sun were used almost exclusively for obtaining field positions. There were two reasons for this: first, the operational schedule of the trek (one or two days traversing and several days at a site) permitted observations of the sun at any desired azimuth, and second, it was not always possible to observe a star or planet at a desired time or position.

Observations for position were generally made at four hours before local noon, local noon, and four hours after local noon. Although, at the time of year and latitudes at which the traverse took place, the sun was above the horizon twenty-four hours a day, observations taken at these times gave a strong line-of-position triangle while avoiding as much as possible the uncertainties of atmospheric refraction encountered at low elevations.

Observations were made in sets of three or four, and two of these observations were initially reduced. If the initial two were in close agreement, no further reductions from the set were made. If there was a large discrepancy, additional observations were reduced, and the erroneous observation was eliminated before the line-of-position was plotted. The refraction correction was calculated from a standard formula taking into account surface temperature and pressure. All field reductions were accomplished with the aid of The Nautical Almanac and H. O. Publication 214, Tables of Computed Altitude and Azimuth, Volume VIII.

At each site a reference mark was established, and once the latitude and longitude were determined, the azimuth of the reference line (observing station to the reference mark) was determined. From this reference line the initial course to the next site was sighted, and the first two or three trail markers for the course were set.

The Snocat odometer was used for ascertaining the distance between stops and the travel distance to the next site. It was initially calibrated at Camp Century, and it was recalibrated at Sites 2 and 3 based on the distances between these sites. The calibrations had a variation of about 3 percent which was attributed to differences in surface conditions and loading, deviations of the vehicle from a straight line track, and errors in the odometer itself.

## Data Reduction

In order to eliminate the effects of atmospheric refraction, which cannot always be reliably computed for the elevations encountered, the final site positions (see Table IV) were computed by the azimuth method rather than by the line-of-position method. Basically this method is based on the movement of celestial bodies in azimuth, and the horizontal angle from a reference point rather than the elevation angle above the horizon is measured. Because the latitude and longitude must be determined simultaneously from three or more observations, the method does not lend itself to field reduction and is generally practical only when an electronic computer is available.

The horizontal angles required for this method were usually obtained simultaneously with the elevation angles required for the line-of-position method. This necessitated aligning both the horizontal and vertical crosshairs of the theodolite on the body at the same instant and resulted in the loss of a certain amount of accuracy. The observations were carried out simultaneously for two reasons: first, it shortened the time required for any given set of observations, and at many of the temperatures encountered

## TABLE IV.
## OPERATION BLUE TREK, STATION POSITIONS WITH COMPUTED GRAVITY AND ELEVATION READINGS

| SITE | MILE (N.) | LATITUDE -N | LONGITUDE -W | OBSERVED GRAVITY * | CORRECTED ELEVATION (FT.) |
|---|---|---|---|---|---|
| Camp Century | 0 | 77°10'24" | 61°05'01" | 982,452.8 | 6054 |
|  | 5 | 77°11.2' | 60°43.0' | 433.4 | 6253 |
|  | 10 | 77°12.1' | 60°21.2' | 433.6 | 6257 |
|  | 15 | 77°12.8' | 59°59.3' | 433.5 | 6263 |
|  | 20 | 77°13.6' | 59°37.3' | 426.1 | 6347 |
|  | 25 | 77°14.3' | 59°15.3' | 423.1 | 6384 |
|  | 30 | 77°15.0' | 58°52.9' | 421.4 | 6407 |
| Site 2 | 34 | 77°15'32" | 58°34'59" | 412.0 | 6481 |
|  | 38 | 77°16.9' | 58°13.7' | 404.1 | 6604 |
|  | 43 | 77°18.3' | 57°52.2' | 397.7 | 6681 |
|  | 48 | 77°19.6' | 57°30.8' | 425.9 | 6390 |
|  | 53 | 77°20.8' | 57°09.5' | 391.5 | 6764 |
|  | 58 | 77°22.1' | 56°47.6' | 380.5 | 6890 |
|  | 63 | 77°23.3' | 56°26.0' | 375.2 | 6955 |
|  | 68 | 77°24.5' | 56°04.3' | 363.3 | 7090 |
|  | 73 | 77°25.7' | 55°42.4' | 357.3 | 7162 |
| Site 3 | 83 | 77°28'08" | 54°55'15" | 352.0 | 7257 |
|  | 88 | 77°29.7' | 54°32.9' | 334.2 | 7434 |
|  | 93 | 77°31.1' | 54°12.6' | 330.1 | 7487 |
|  | 98 | 77°32.5' | 53°51.2' | 323.0 | 7572 |
|  | 103 | 77°34.0' | 53°29.4' | 317.6 | 7640 |
|  | 108 | 77°35.3' | 53°08.1' | 314.9 | 7677 |
|  | 112 | 77°36.7' | 52°47.0' | 314.3 | 7693 |
|  | 117 | 77°38.1' | 52°23.7' | 310.1 | 7747 |
|  | 122 | 77°39.4' | 52°02.0' | 305.0 | 7810 |
|  | 127 | 77°40.6' | 51°40.1' | 303.9 | 7830 |
| Site 4 | 133 | 77°42'11" | 51°12'24" | 296.6 | 7918 |

## TABLE IV. (cont.)

| SITE | MILE (N.) | LATITUDE -N | LONGITUDE -W | OBSERVED GRAVITY * | CORRECTED ELEVATION (FT.) |
|---|---|---|---|---|---|
| | 138 | 77°43.1' | 50°49.2' | 290.6 | 7988 |
| | 143 | 77°44.0' | 50°25.3' | 287.3 | 8029 |
| | 149 | 77°44.9' | 50°01.3' | 284.1 | 8069 |
| | 154 | 77°45.8' | 49°37.2' | 281.5 | 8103 |
| | 159 | 77°46.6' | 49°13.7' | 277.1 | 8155 |
| | 164 | 77°47.4' | 48°49.0' | 278.1 | 8149 |
| | 176 | 77°49.1' | 47°53.9' | 272.7 | 8218 |
| | 181 | 77°49.7' | 47°29.3' | 271.8 | 8232 |
| | 186 | 77°50.4' | 47°04.9' | 269.1 | 8265 |
| | 191 | 77°51.0' | 46°40.4' | 268.4 | 8276 |
| | 195 | 77°51.4' | 46°21.4' | 265.8 | 8307 |
| | 201 | 77°52.0' | 45°57.3' | 262.5 | 8346 |
| Site 5 | 206 | 77°52'29" | 45°31'29" | 263.5 | 8371 |
| | 211 | 77°52.9' | 45°07.4' | 257.5 | 8405 |
| | 216 | 77°53.3' | 44°43.3' | 255.5 | 8429 |
| | 221 | 77°53.7' | 44°18.5' | 256.2 | 8424 |
| | 226 | 77°54.0' | 43°55.2' | 257.1 | 8416 |
| | 231 | 77°54.3' | 43°31.1' | 259.7 | 8391 |
| | 236 | 77°54.6' | 43°07.0' | 263.4 | 8353 |
| | 241 | 77°54.8' | 42°42.8' | 267.2 | 8314 |
| | 247 | 77°55.0' | 42°18.6' | 272.1 | 8263 |
| | 252 | 77°55.2' | 41°54.4' | 274.3 | 8241 |
| | 257 | 77°55.3' | 41°30.0' | 279.4 | 8188 |
| | 262 | 77°55.4' | 41°04.2' | 284.1 | 8139 |
| | 267 | 77°55.4' | 40°41.2' | 288.9 | 8088 |
| | 272 | 77°55.5' | 40°17.7' | 293.3 | 8042 |
| | 277 | 77°55.4' | 39°53.3' | 297.5 | 7996 |
| | 282 | 77°55.4' | 39°29.2' | 307.2 | 7893 |
| Inge Lehmann | 285 | 77°55'20" | 39°13'58" | 313.5 | 7788 |

* All gravity values based USAF value for Thule J (982,928.6 mgal) and measured interval Thule J to Camp Century -475.8 mgal. Probable error in station positions: at sites, latitude ± 12", longitude ±45"; at stops, latitude ± 0.5', longitude ± 2.5'.

it would have been impossible for the observer to take a second set. Second, weather conditions did not permit observations at all times, and in the interest of obtaining both required sets, it was decided that a small loss of accuracy would be acceptable.

The number of observations per site ranged from twelve to twenty-four, depending on weather conditions and the length of time the site was occupied. Each observation was the combination of a direct and reverse sighting with the theodolite. Thus twenty-four observations represented forty-eight sightings. The final positions of the individual sites were based on nine to sixteen observations, the others having been eliminated because of apparent errors.

Observations for the same site were often taken on different days, and because of this timing errors were not always of the same magnitude. As the trek moved inland from Camp Century, it became harder and harder to obtain a chronometer check at any given time. For this reason the chronometer error applied to many observations had to be taken as the average of the last time check and of the next check that could be obtained. Systematic timing errors of up to one second were possible under these circumstances.

The intermediate stops between sites have been designated by their nominal milage (nautical) from Camp Century. The spacing of these stops was intended to be approximately five miles, but for many reasons, it was not always possible to maintain this spacing. The latitude and longitude of the stops (see Table IV) was determined by proportioning the odometer distances along a calculated direct course between the sites.

Weather did not permit a complete set of observations at North Ice, and the published position of that site has been used in this report.

The probable error of the site latitudes varied from ±3" to ±12", and the probable error of the longitudes varied from ±15" (±3" expressed in the prime vertical) to ±45" (±9"). The sites with the greatest number of observations generally had the lowest probable error. In the interest of uniformity a probable error of ±12" in latitude and ±45" in longitude has been assigned to all sites. Because of the uncertainty as to how close the actual track followed a direct course between sites, a probable error of ±0.5' has been estimated for the intermediate stops.

## 3.5 GRAVITY AND ALTITUDE MEASUREMENTS

### Gravity Measurements

Through the courtesy of the U. S. Army Map Service in providing the LaCoste and Romberg Gravimeter No. 46, observations of the gravity field were recorded throughout the traverse.

The observed gravity values listed in Table IV are based on the USAF value for Thule J (982, 928.6 mgal) and the measured interval Thule J to Camp Century -475.8 mgal. Thule J is one of a net of stations in the USAF world gravity reference system.

The data is subject to misinterpretation and error, since information was collected only along a single line and there was a ten milligal failure to close upon return to Thule. It is hoped that Inge Lehmann Station can be reoccupied at sometime in the future to confirm the readings observed on Blue Trek.

The data has been deposited with the Gravity Division of the U. S. Army Map Service.

### Altitude Measurements

In addition to the gravity observations, the geometric altitudes of the points along the traverse at which gravimeter readings were made were calculated and are also listed in Table IV. Data available for use in the calculations included Wallace & Tiernan Altimeter readings made simultaneously with the gravimeter readings on the traverse, surface pressure data from Inge Lehmann Station, and surface pressure and radiosonde data from Thule and Nord Stations. The altitudes of three points along the traverse, Inge Lehmann, Century, and North Ice, are also known quite accurately.

The traverse altimeter readings were first converted into pressure. Then, since the pressure vs. altitude distribution at Nord and Thule and the surface pressure and altitude at Inge Lehmann Station are known, the interpolation necessary to arrive at the actual altitude along the traverse could be performed. This approach relies on the rather tenuous assumption that the pressure vs. altitude distribution is well correlated over much of the Greenland ice sheet. To check this assumption, the surface pressures at Thule and Nord, the surface pressure at Inge Lehmann, and the geometric altitudes at which a pressure of 850 mb was observed at Thule and Nord were plotted. It is evident that there is good correlation between the plots for all three stations except between August 26 (1800 Z) and August 28 (1200 Z). In this interval, the plot for Thule exhibits a marked decrease in pressure which is not followed at the other stations. Except for this interval, the assumption of a well correlated pressure vs. altitude distribution over much of the Greenland ice sheet appears to be valid.

## Theoretical Background

The ideal gas law states that

$$PV = nkT \qquad (1)$$

where $P$ = pressure

$V$ = volume

$k$ = constant

$T$ = absolute gas temperature

$n$ = number of moles of gas present

If we examine an elementary volume of gas with unit cross section and small height $\Delta h$

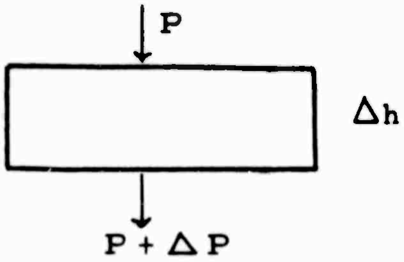

Figure 52.

we see that

$$\Delta P = -pg\Delta h \qquad (2)$$

where $p$ = gas density

$g$ = acceleration due to gravity

$\Delta h$ = height of the elementary volume

From (1) we get

$$n = \frac{PV}{kT} \qquad (3)$$

and we know by definition that

$$n = \frac{pV}{M} \qquad (4)$$

where $M$ = molecular weight of the gas

By equating (3) and (4), we get

$$p = \frac{PM}{kT} \qquad (5)$$

from (2) and (5), we get

$$\Delta P = \frac{-PM}{kT} g \Delta h$$

$$\text{or} \quad \Delta h = \frac{-kT}{Mg} \frac{\Delta P}{P} \qquad (6)$$

From (6) we can calculate the distance $\Delta h$ between a known pressure level and a level whose pressure differs from it by $\Delta P$.

If we take T in $^{o}$K, P and $\Delta P$ in millibars, and assume the presence of dry air, (6) becomes

$$\Delta h \text{ (feet)} = 96.1 (T) \left(\frac{\Delta P}{P}\right) \qquad (7)$$

Analysis

The altimeter readings taken at Inge Lehmann Station and on the traverse were corrected for instrument errors and converted to pressure measurements using U. S. Standard Atmosphere tables. The altitudes at Thule at which the pressures observed on the traverse were measured ("traverse pressure" altitude) were taken from radiosonde data. The "traverse pressure" altitudes at Inge Lehmann were computed using equation (7) above. The $\Delta$h computed from (7) was added or subtracted as appropriate to the station's known altitude of 7895 feet. Once the "traverse pressure" altitudes at Thule and Inge Lehmann were found, they were averaged as follows to give a corrected altitude for the traverse observation point.

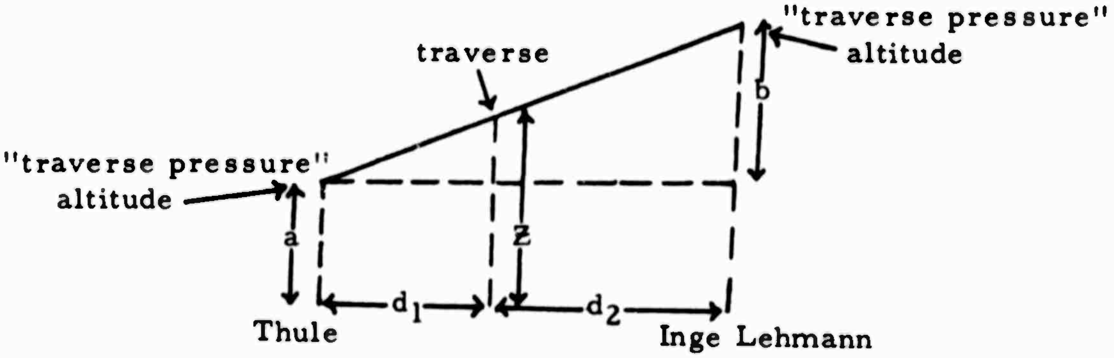

Figure 53.

The distances $d_1$ and $d_2$ were known for each point on the traverse. If "b" is the difference between the "traverse pressure" altitude at Thule and Inge Lehmann, and "a" is the "traverse pressure" altitude at Thule, then the traverse altitude "Z" is given by

$$Z = (a + b)\left(\frac{d_1}{d_1+d_2}\right) \qquad (8)$$

The averaging was performed upon measurements taken only at Thule and Inge Lehmann because the distance to Nord rendered the correction introduced by the measurement taken at that station negligible. However, the good correlation between trends of pressure variation at all three stations substantiates the method used here to determine the traverse altitudes.

For the data taken between August 26 (1245 Z) and August 31 no averaging with the Thule data was performed. The corrected altitude was taken as the "traverse pressure" altitude measured at Inge Lehmann for the following reasons:

1) The anomalous behavior of the pressures at Thule for some of the dates concerned leads to the inference that its behavior is not correlated too well with the traverse data for those dates, which at that point was being taken relatively close to Inge Lehmann.

2) The extreme proximity of the traverse to Inge Lehmann caused the Inge Lehmann reading to "swamp" the averaging with the Thule readings on the days which showed no anomalous behavior.

An indication of the accuracy obtained by the above method is given by a comparison between the known altitudes of North Ice and Century (7708 and 6035 ft respectively), and the altitudes calculated for these points in this study (7712 ±5 and 6054 ±13 ft respectively).

# APPENDIX --

## Photographs of Inge Lehmann Station

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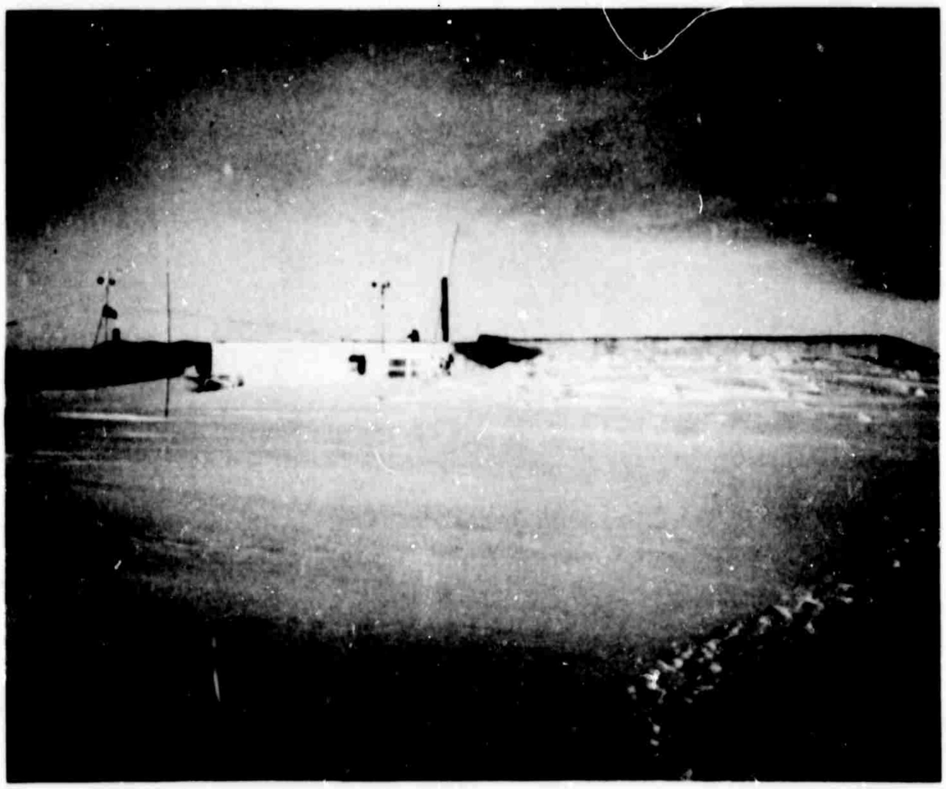
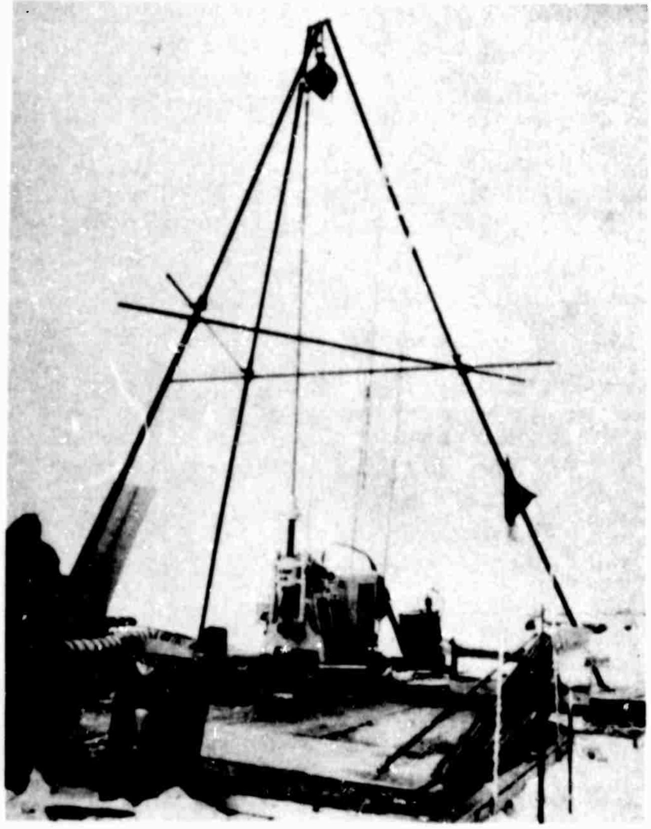
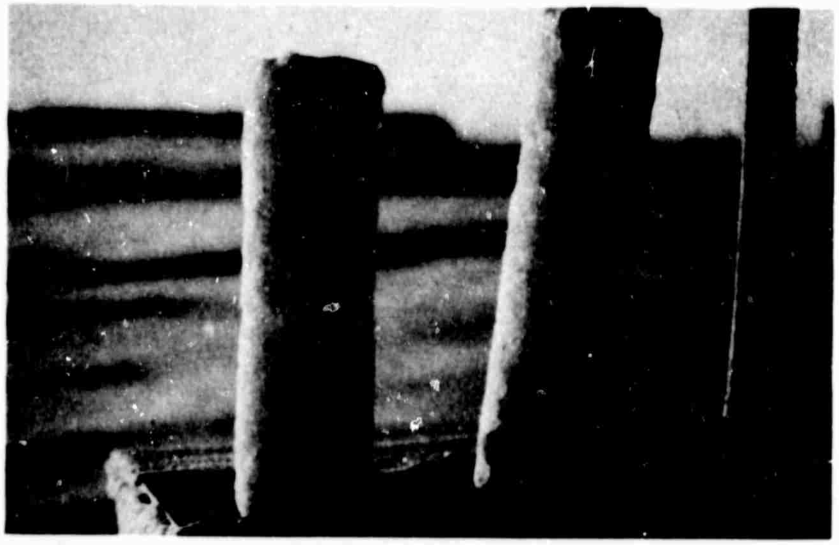
Ski equipped C130 of the 17th Troop Carrier Squadron arrives with supplies. Snow toboggan used for lightweight transportation in foreground.



Inge Lehmann Station, October, 1966 during construction and preparations for winter.

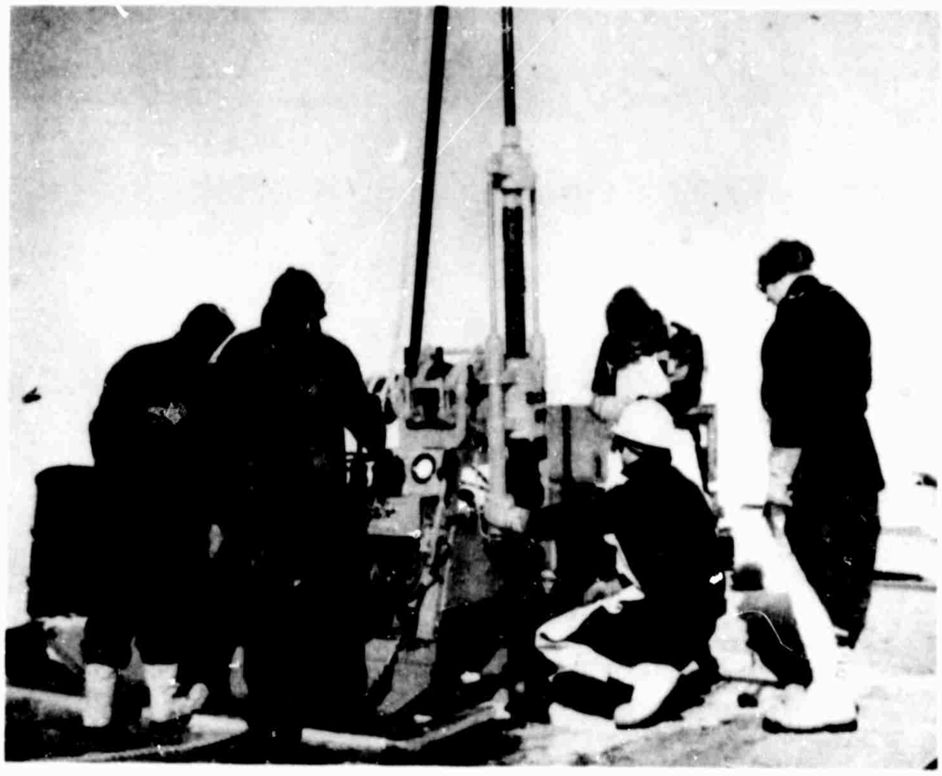


Drilling platform, rig, and tripod

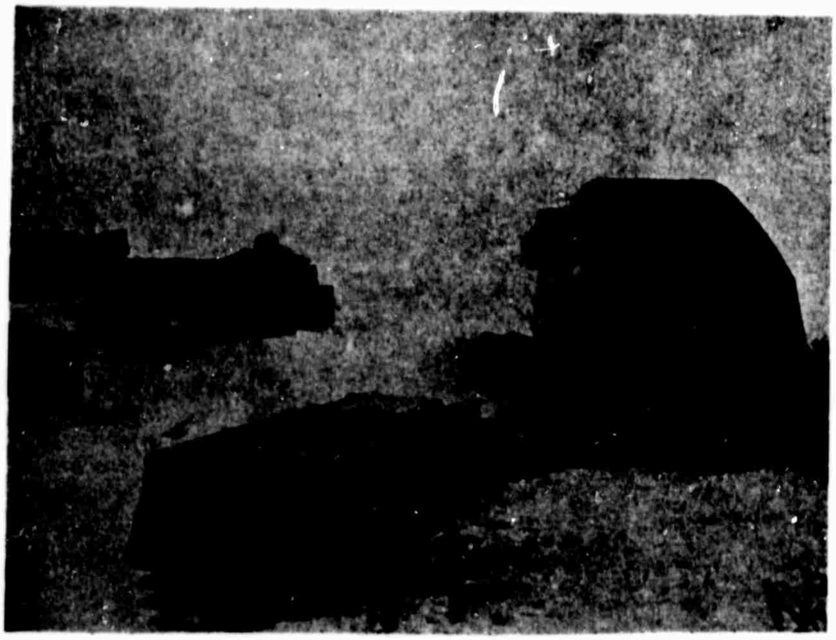


Sample of ice cores taken from one of the shallow holes

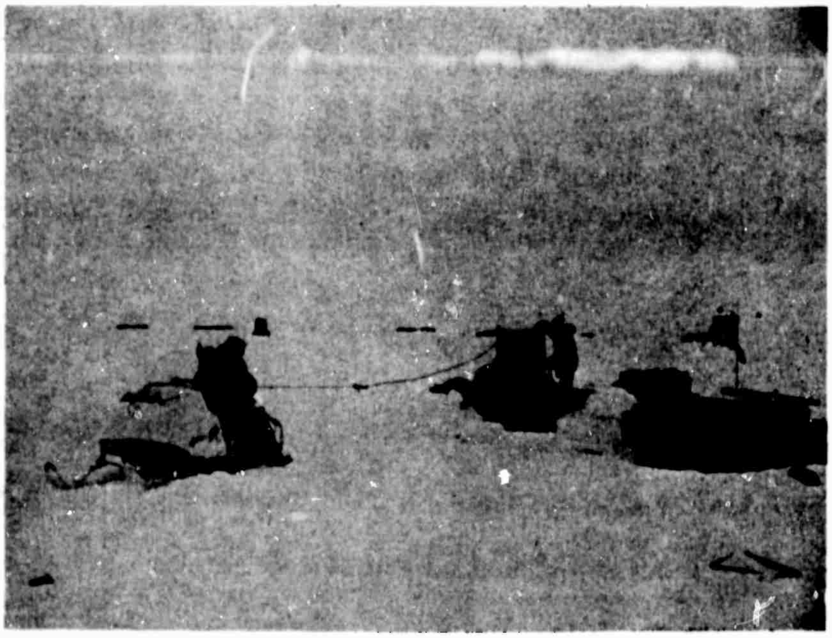
Lowering model 20171 seismometer into completed borehole.



Drill rig showing large diameter coring auger in use.

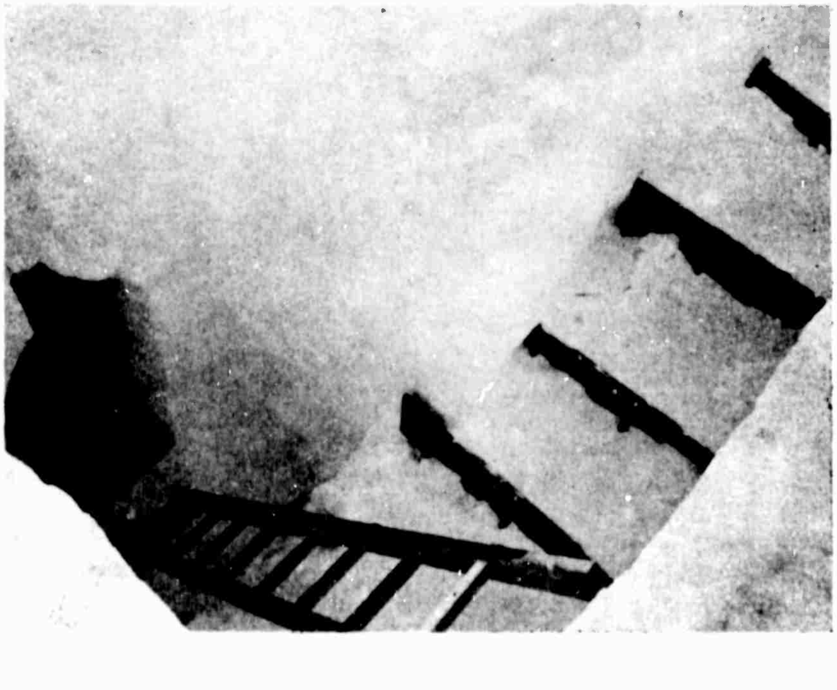


Cable is being heated before being drawn out to outlying array seismometer.

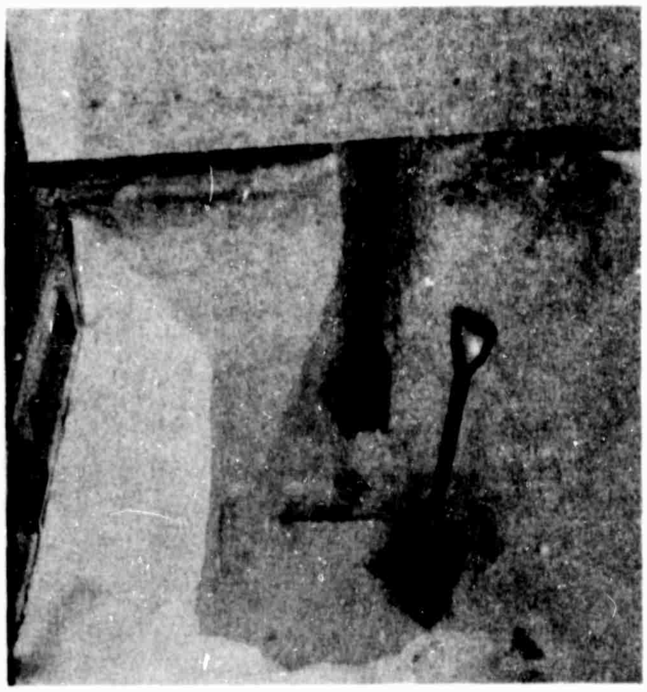


Cable being drawn out by snow vehicle to outlying array seismometer.

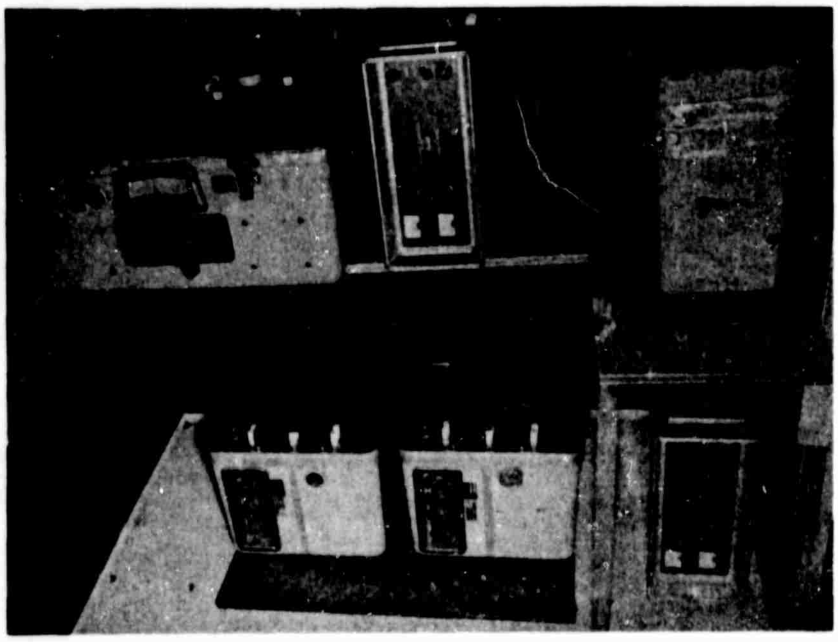
View inside of bunker and shelf cut in snow for the short-period 18300 seismometers



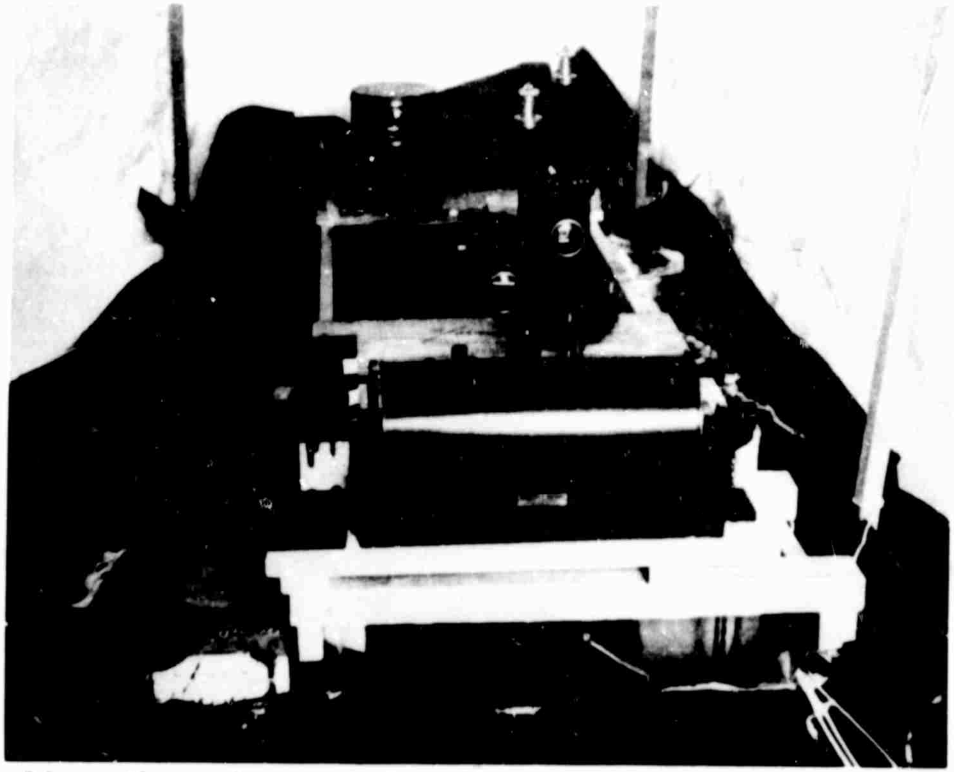
View of entrance to short-period 18300 seismometer bunker.



3-1/2 inch pipe on which platform for photocell amplifier was fixed.

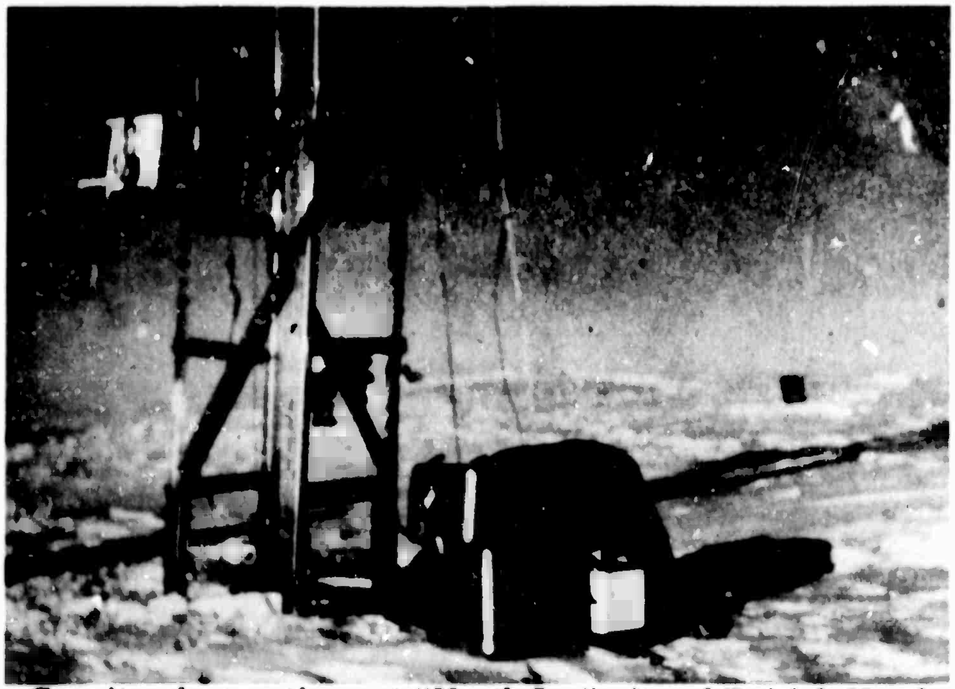


Interior view, instrument trailer. Photocell amplifiers at bottom rest upon isolated plate fixed to 3-1/2 inch pipe shown above.



Magnetic variometers installation, Inge Lehmann Station.

Magnetic Observations. Dr. Erik Hjortenberg making absolute measurements during Blue Trek traverse.



Gravity observations at "North Ice" site of British North Greenland Expedition 1952-54.

Portable AN/PMQ-7 instrument used for meteorological observations during Blue Trek traverse. Snocat Model 443 in background.

Unclassified
Security Classification

## DOCUMENT CONTROL DATA - R&D

*(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)*

1 ORIGINATING ACTIVITY *(Corporate author)*
The Arctic Institute of North America
1619 New Hampshire Avenue, N. W.
Washington, D. C. 20009

2a REPORT SECURITY CLASSIFICATION
Unclassified

2b GROUP

3 REPORT TITLE
Greenland Ice Cap Noise Studies
Project Blue Ice

4 DESCRIPTIVE NOTES *(Type of report and inclusive dates)*
Scientific Final

5 AUTHOR(S) *(Last name, first name, initial)*
R. A. Lenton

6 REPORT DATE
June, 1968

7a TOTAL NO. OF PAGES
iv, 89

7b NO. OF REFS

8a CONTRACT OR GRANT NO.
AF49(638)-1722

b. PROJECT NO.
8652

c.

d. 6250601R

9a ORIGINATOR'S REPORT NUMBER(S)

9b OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*
AFOSR 68-1940

10 AVAILABILITY/LIMITATION NOTICES
1. This document has been approved for public release and sale; its distribution is unlimited.

11 SUPPLEMENTARY NOTES
Tech, Other

12 SPONSORING MILITARY ACTIVITY
Air Force Office of Scientific Research
Directorate of Physical Sciences (SRPG)
Arlington, Virginia 22209

13 ABSTRACT

Seismic noise studies on the Greenland ice sheet were conducted as part of the VELA Uniform Basic Research Program under the code name Project Blue Ice.

The station on the Ice Cap showed low-noise levels and low coherences between seismographs indicating that a larger array would be an effective tool in detection. Emplacement of the seismometers in shallow holes eliminated the noise associated with high wind velocities. At the 50-percent probability of detection level, a single seismometer at the station has a detection capability of at least magnitude 4.3. The long-period noise levels were comparable with average sites on the continents.

In addition to the major experiment, other scientific programs were conducted in the fields of glaciology, magnetics, gravity and air pollution.

DD FORM 1 JAN 64 1473

Unclassified
Security Classification

| 14. KEY WORDS | LINK A | | LINK B | | LINK C | |
|---|---|---|---|---|---|---|
| | ROLE | WT | ROLE | WT | ROLE | WT |
| Greenland | | | | | | |
| Seismic array | | | | | | |
| Signal | | | | | | |
| Noise | | | | | | |

## INSTRUCTIONS

1. **ORIGINATING ACTIVITY:** Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization *(corporate author)* issuing the report.

2*a*. **REPORT SECURITY CLASSIFICATION:** Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

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4. **DESCRIPTIVE NOTES:** If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. **AUTHOR(S):** Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. **REPORT DATE:** Enter the date of the report as day, month, year; or month, year. If more than one date appears on the report, use date of publication.

7*a*. **TOTAL NUMBER OF PAGES:** The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

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