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Woods Hole Oceanographic Institution

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Technical Report

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1 Scientific Motivation

By examining the details of the propagation of a pulse of sound sent from a source to a receiver some distance away, it is possible to learn about the medium through which the sound propagated. Use of sound pulses to study the structure of the water column is generally called "acoustic tomography", a technique which has been developed by a number of researchers over the past fifteen years. Mid frequency (50 to 1000 Hz) studies of the top kilometer of the ocean bottom are often referred to as "bottom acoustics".

For both civilian and naval purposes, the study of the water column and bottom in shallow water coastal regions ($H \leq 500m$) has become increasingly important. It has long been known that, in looking at the details of the acoustic field from 50 to 1000 Hz in shallow water environments, an acoustic normal mode representation is more useful than a ray representation (Figure 1). The modal representation is not only exact mathematically, but it is also efficient, i.e. one needs only a few normal modes to represent the acoustic field in shallow water whereas one would need many rays. (The opposite is true in deep water.) In studying the ocean bottom or the water column using pulses of sound (broadband signals), it has been common practice to look at multi-path arrivals, be they rays or modes, which are cleanly separated in arrival time (Figure 2). This is relatively easy to do at long ranges, where small differences in the group velocities separate the arrivals in time. The equation

$$\Delta T_{n,n\pm1} = R/\Delta v^G_{n,n\pm1}, \tag{1}$$

where ΔT, Δv^G and R are the arrival time difference, the group velocity difference, and the range separation respectively, shows the simple proportionality to distance. However, at the short ranges to which one is generally limited in shallow water due to the high propagation loss incurred by boundary reflections, time separation of different modal arrivals can become impossible. Since the modal arrival times are basic data for bottom and water column inverses, one often needs to resort to spatial array processing methods to separate the modes. Both vertical and horizontal acoustic arrays can be used to filter modes in shallow water. However, in terms of mode filtration efficiency per unit length of array, vertical arrays are preferred. Moreover, one is able (to a first approximation) to separate as many normal modes as there are hydrophones in the array.

1.1 The Barents Sea Polar Front Experiment

A vertical line array (VLA), played a vital role in the Barents Sea Polar Front Experiment conducted in the coastal waters of Svalbard in August 1992. In this experiment, a combination of CTD hydrography, moored oceanographic sensors, broadband acoustic bottom measurements, and acoustic tomography were employed to study the structure and dynamics of the Polar Front. Participants in the experiment included R. Bourke, C.S. Chiu, J. Miller and M. Stone from NPS, R. Muench from SAIC, J. Bouthillette, J. Kemp, S. Liberatore, J. Lynch, A. Newhall, R. Pawlowicz, K. von der Heydt, and N. Witzell from WHOI.

This report is focused on the technical aspects of the development and use for the Barents Sea Polar Front Experiment of a VLA coupled to a buoy using a new radio telemetry technique to acquire data in realtime aboard a nearby ship. Scientific results of the experiment will be reported in pending journal articles by a subset of the above mentioned personnel collectively referred to as the Barents Sea Polar Front Group.

The Polar Front is formed by the confluence of cold, fresh Arctic water and warmer, saltier North Atlantic water and is bound topographically to the 200m isobath. The topography of the experiment area is found in Figure 3a, along with the three tomographic paths along which we transmitted. It is seen that the eastern half of our experiment region (which actually extended 10 km further east), was a rather simple E-W shelf, whereas the western half had a significant valley (called Fingerdjupet) which could make the oceanography more complicated, e.g. by creating eddies which propagate up the valley and mix waters across the shelf. A topview of the front is seen in Figure 3b, which displays the water temperature at 70m, just below the mixed layer. One sees the first order adherence of the front to the bathymetry, including the valley. A side view of the front in terms of temperature is shown in Figure 3c. Many interesting features are evident. At about 75m depth, one most clearly sees the cold Arctic water on the right and the warmer Atlantic water on the left. Protrusions of Atlantic water into the Arctic water are also seen from 50-100m depth. These are thought to be significant in frontal mixing. The surface layer is clearly seen from zero to 35m depth, and interestingly enough, does not show a distinct front in temperature (though it does in salinity). A flow of colder Arctic water underneath the Atlantic water is seen near the bottom.

The temperature component of the experiment was included to look at the temporal and spatial structure which is aliased by the CTD survey and moored sensors. For instance, the front can move 5-10 km over a 12 hour tidal cycle, which is the order of time it takes to complete a north-south CTD transect. By sampling every five minutes, tomography can avoid aliasing this frontal movement, which also may account for some of the E-W corregations seen in Figure 3b. The baroclinic tilting mode of the front, the time evolution of the interleaving structure, the internal waves and internal tides are also of interest and should be observable by tomography.

2 Technical Backround

Initially our experimental plan was for the USNS Bartlett to remain on station tethered to the array so that data could be acquired on board to verify operation of the VLA system and to process data in real time to adapt the experiment to unforseen environmental changes. Our main concerns with this scheme were twofold: i) that noise radiated form the ship could occlude the acoustic signatures that we hoped to record, and ii) that it would be impractical to tether an affordable array to the Bartlett which offered no facilities for multi-point mooring.

Ship noise has been a chief concern with attempts to record low SNR data from tethered vertical arrays and is the reason for extraordinary efforts towards noise abatement in the design of ships such as the R/V Alliance operated by the SACLANT center in La Spezia, Italy. Also, experiments have demonstrated that it is no small feat to remain successfully connected to a bottom founded array for days, even with much smaller and more maneuverable craft than the Bartlett. These two issues have always been strong motivation to entirely decouple vertical arrays from a ship by using a buoy equipped with the means either to store data for retrieval when the system is recovered, transmit data to the ship in realtime or some combination of the two. Our design had to address these issues.

Though efforts are underway at WHOI to design hydrophone arrays employing very high resolution analog-to-digital conversion at sensor sites and digital transmission of data on a minimum of conductors up the cable, the Barents Sea project enjoyed neither the time nor the resources to pursue that goal. It was clear at the outset that we had to utilize an existing array architecture to minimize risk and cost.

The ocean acoustics community has assembled arrays of hydrophones in many different configurations with a wide variety of objectives. Our requirements were for a system that included an array that could be deployed vertically, with emphasis on the near bottom region in 200-300m of water with a minimum "watch circle" of lateral motion, as well as the means to record digitized signals aboard the ship. To separate the roughly 20 acoustic normal modes which we expected from our primary cross-front tomographic track, a 16 channel hydrophone array was considered a minimum configuration.

The acoustics component of the science plan called for use of tomographic acoustic sources operating at center frequencies of 224 and 400 Hz, the latter with up to 100 Hz of bandwidth. In addition, SUS charges were to be dropped from both the USNS Bartlett and a plane which would clearly inject energy at frequencies beyond 400 Hz; however it would have been too difficult to monitor the position of array sensors with sufficient accuracy to permit coherent processing of data beyond 500 Hz. Tomographic signals in previous experiments have typically been sampled at a convenient multiple of 4 times the center frequency which eases the quadrature demodulation process that is usually the first step in processing such data. A sampling rate of 1600 Hz was chosen since 2 of the 3 sources were to be centered at 400 Hz with 100 Hz bandwidth, allowing anti-alias filtering at 500 Hz. Data at the 224 Hz center frequency is thus interpolated and resampled prior to processing.

We were also keen on recording the data aboard ship rather than with a self-contained system internal to the buoy, both to be confident of data quality in realtime and because we had no suitable autonomous system. Various broadband FM transmission systems have been invented or adapted to multiplex individual channels from acoustic arrays for transmission to distant receiving platforms. The dynamic range, overall data quality and reliability of these systems has been variable and often in the field, some or all of these characteristics have been less than ideal. Though such systems have been used successfully, we were not in a position to quickly borrow or buy and adapt one for our needs. Similarly, digital transmission using broadband FM links, such as those available from Aydin-Vector, to send serial bit streams at megabit/sec rates can and have been configured. These systems require a receiver and transmitter at both ends to achieve a bidirectional link, as well as signal conditioners, bit synchronizers and forward error correction hardware/software to achieve these rates with reliable reception of data. Despite the high quality of these products, a large amount of time and money can be spent developing protocols that are able to detect errors and request retransmission of lost or erroneous data. It became clear that for our purposes, this method was risky and simply too expensive.

During the summer of 1991, we had begun to experiment with wireless Local Area Networks (LAN's), which are now becoming available with raw rates up to 5 megabits/sec. These are radio or infrared linked systems that are designed primarily for use in office spaces, warehouses and in some cases between buildings where cables are expensive to run or change. The data transport layer of the radio based systems is designed for shorter range and lower bit rate but otherwise similar to microwave links used to transmit digital data over long distances for telephone traffic and dedicated network connections between distant sites. These new products are typically spread spectrum, operate in the ISM bands, (though at least one is licensed at 18 GHz) and offer true LAN topologies in that they provide multi-node network capability without cables.

When we first became interested, the NCR WaveLAN had just become available. The WaveLAN hardware is a board that plugs into a PC, (16 bit ISA bus), and achieves an Ethernet connection to additional PC's each with WaveLAN boards, using spread spectrum techniques in the 902 - 928 MHz radio band rather than coaxial or twisted pair cable. WaveLAN is advertised as having a maximum range of 5 miles using 20 dB of antenna gain and a power level of 24dBm. For applications such as ours, the compelling feature of these systems is that they allow use of software that over the years has been developed and refined for the LAN world to assure reliable data transmission between systems connected on the world-wide Internet network, through use of Transmission Control Protocol (TCP). Though this software protocol has been designed for use over cables in a Collision Sense Multiple Access, (CSMA) environment, they are equally effective over radio links. It matters not to the TCP protocol whether transmitted data is lost due to radio link fades, interference or "nobody home". The nature of TCP guarantees that if the data is delivered, there is a very high probability that it is 100% correct.

Our early field tests over water not only confirmed that we could use the same Ethernet applications such as "ftp" for reliable file transfer over the WaveLAN hardware (as we are accustomed with cabled networks), but that with antennas of modest gain, the system was indeed useful over water at line-of-sight ranges of at least a 1 km. These were very promising results that encouraged our application of this emerging technology to remote acquisistion of data from a buoy to which instrumentation was attached. Data rates using "ftp" between 2 mid-speed 286 and 386 PC's were typically 30 to 40 kbytes/sec to/from slow disk drives and twice that to/from memory.

Some months later after funding for the VLA portion of the Barents Sea experiment had been obtained, further testing was done. From FTP, a network software vender in Cambridge MA, we acquired their software package PC/TCP, for developing Ethernet TCP applications for PC's. This, along with the Network Data Interface Standard (NDIS) driver that NCR was supplying with the WaveLAN hardware, allowed us to write code that directly accessed TCP functionality. We were able to demonstrate that with our software, the WaveLAN hardware was capable of as much as 150 kbytes/sec over a TCP stream connection. This was quite acceptable for a link rated at a maximum of 2 megabits/sec and comfortably greater than the 50 kbytes/sec we estimated was necessary to continuously acquire the data from a 16 channel VLA during the Barents Sea experiment.

3 System Design

3.1 Array

Fabrication of the array cable with 16 breakouts for hydrophones was contracted to Neptune Technologies in Picayune MS. Although hydrophones could have been purchased as well, we chose to manufacture our own as we have done for other projects. The cable was 1.5 km in length, contained 39 individually insulated, stranded #26 copper conductors, (of which 32 were used), layed up in 3 concentric layers. The conductors were covered with a layer of Kevlar with a nominal 12000 lb breaking strength, covered by a polyester sheath interwoven with a hairy fairing for strum suppression. The finished, relaxed outer diameter is about 5/8". The basic cable was made by Yale Cordage. Figure 4 is a plot of showing stretch and yield strength of the Kevlar component of the cable.

Neptune installed 16 breakouts at 10 m spacing starting from the outboard end of the cable, leaving a 2 pin connector and aluminum tube protective cover for a hydrophone at each site. The pair of wires to any given sensor is disconnected from the remaining length of that pair beyond the breakout. Table 1 details the conductor numbering and colors, the channel spacing, sensor numbering and connector pinout cross references.

A current mode preamplifier was used with each sensor such that a single independent pair of wires carries power to and signal from each hydrophone. Voltage driven designs can result in fewer wires; however, they are less desirable as breakage of conductors can affect more than one sensor. The preamps, housed internal to the cylindrical sensor elements, draw approximately 3.6 ma from a power supply that must be at least 10 volts, but can range up to about 30 volts DC. The nominal sensitivity of the hydrophones is -160 dBV referenced to 1 μPascal. The equivalent sound pressure noise (ESPN) of the preamp in dB re 1 μPa is 34 @ 100 Hz, and approximately 27 @ 1000 Hz. The -3db point of the sensors was set at 50 Hz to minimize signal levels from array and sea surface motion. Figure 5 is a power spectral density (PSD) plot of the preamp self noise level referred to the input (for sensor 15), relating ESPN to frequency.

The sensor consists of two PZT4 ceramic cylinders in series with stainless steel endcaps .25" thick. The cylinders and endcaps were assembled with isocyanurate glue. The power/signal lead was brought through a tight hole in one endcap and the ground lead was simply connected with a screw on each side of that endcap. A Brantner MAW-2 connector (to mate with the array breakout), was then attached. The assembly was dipped in urethane for a thin insulating coating and allowed to cure. It was then dipped in a nickel based compound (Acheson Electrodag 550) to provide a complete electrostatic shield connected to ground. Finally, the shielded assembly was inserted into a mold for an outer layer of urethane. The finished size of the sensor was approximately 4" long with a 1.5" diameter and fit snugly into the protective aluminum housings attached at each array breakout.

Despite the modest bandwidth (500 Hz) of signals to be transmitted up 1.5 km wire pairs, we were concerned about crosstalk, particularly between adjacent conductor pairs. This led us to specify conductor assignments such that physically distant sensors used correspondingly separated wire pairs in the cable. It is our experience that it is difficult to model crosstalk as a function of frequency whether a cable contains twisted or untwisted conductor pairs. We did some simple tests of this cable in air as well as a 300 m piece in both air and sea water. The following measurements were made in air using the 1500 m Barents Sea cable with the signal injected from the sensor site at the end of the cable (CH 0) and channels 1 through 15 terminated at the receiveing end. Similar measurements taken with the 300 m length in air and sea water suggest that crosstalk is generally lower by 15 to 20 dB in sea water.

IN AIR --->	FREQUENCY (Hz)	CH 1 (dB)	CH 15 (dB)
	50	-50.6	-51.2
	100	-44.6	-45.6
	200	-38.6	-39.5
	500	-30.3	-31.0
	1000	-22.2	-22.0

We estimate that signal coupling from one channel to any other, while the array is deployed, would be attenuated by 45 to 50 dB at 500 Hz. As one might expect, crosstalk increases with cable length and frequency with approximately a "20 log" relationship. After observing the crosstalk levels on a number of channels, it would appear that there is little difference with respect to physical proximity of one pair of conductors to another in the cable bundle.

3.2 Mooring

The U-shaped mooring system as shown in Figure 6 was designed for a short term deployment of the VLA. This design took advantage of previous sub-surface and "S-tether" technology developed at WHOI to accommodate a limited budget and a compressed schedule. Emphasis was placed on minimizing strain applied to the cable during deployment and on maximizing the distance between the array and the telemetry buoy. The array cable between the vertical active array section and the telemetry buoy was continuous to eliminate the risk and expense of using underwater connectors. Mechanical attachment points for anchors and instrumentation were fashioned using Kevlar grips.

The section of the mooring containing the 16 element hydrophone array was modeled using the NOYFB software developed at WHOI. It was designed to maintain inclinations from the vertical of less than 3 degrees in a linear current profile of 25 cm/sec, (0.5 knot).

An acoustic navigator was installed in-line at the array top and used to track the mooring motion by interrogating 3 bottom mounted transponders. Each of the 3 expendable transponders, operating in the 10 kHz region, were surveyed from the ship using a combination of GPS and acoustic traveltime measurements to obtain estimates of their absolute positions. Two-way travel times, recorded within the navigator at 10 minute intervals throughout the experiment, were later processed to estimate the "watch circle" motion of the array.

The surface leg of the mooring between the second bottom anchor and the buoy was designed as a low-forcing "S-tether" with a scope of 1.5. WHOI's SURFMOOR design program was used to evaluate the mooring performance. This design in which a slack tether mechanically decouples buoy motion from the anchor, reduces the dynamic loading on the array cable. In addition, a flexible chain-in-urethane section was used directly beneath the buoy to reduce cable fatigue due to surface induced motion. The 39 conductor array cable was simply attached to the lower end of the chain section with a grip and passed upward around the outside of the buoy with chaffing protection.

3.3 Buoy

The Telemetry Surface Buoy, for which the cross section is shown in Figure 7, was originally designed as a coastal radio/marker buoy. The hull is a rolled Surlyn foam flotation collar made by Gilman Corp. The foam collar is sandwiched between a removable galvanized steel upper structure and the lower ballast stand using 1/2" threaded rod. A 12 inch diameter, steel pipe instrument well extends centrally through the foam collar. A removable aluminum tube mast with supports provided mounts for the antenna, light and radar reflector approximately 10 feet off the water. The buoy specifications are as follows:

- Air weight, 906 lbs
- Reserve buoyancy, 1870 lbs
- Overall height, 14 ft
- Maximum diameter, 62 in
- Well inside depth, 70 in
- Well inside diameter, 12 in

Referring again to Figure 7, the central 12" diameter tube of the buoy housed alkaline batteries for 10 days operation, an accurate self contained timebase and realtime clock, a 6 slot, 16 bit ISA backplane within a chassis containing a 16 channel amplifier and filter, a DC to DC converter, and 4 plug-in cards: i) a 16 channel ADC board, ii) an interface to the external clock, iii) the WaveLAN board, and iv) a single board 'C286 based DOS PC. Figure 8 is a block diagram of the acquisition and telemetry system contained within the buoy. The array signals were connected via a 37 pin waterproof *Impulse M/N MSAM-37-BCR,CCP* connector mounted on the cover of the buoy tube. A ten foot mast supported a radar reflector, flasher and the antenna for the WaveLAN radio link.

The dynamic range requirements of sampling a combination of nearby explosively generated signals and ambient level signals would normally lead us to use an auto-ranging or floating point amplifier/digitizing system that was developed at WHOI for other projects. This was impractical for this application as that system is bulky and would have used far too much battery power. The radio LAN link is bidirectional so a simple front end was designed that allows "manual" gain changes to accommodate the dramatically different signal level requirements of shots and the low SNR tomographic signals. Signal conditioning for each channel consisted of a differential input current mode receiver with software programmable gain selections of 0, 20, 40, & 60 dB, followed by an 8 pole Butterworth low pass filter at 500 Hz. Figure 9 is the schematic of the current mode, differential input, programmable gain recevier and low pass filter applied to each channel. Figure 10 is a plot showing the shape of the broadband response of the amplifier and filter. Sixteen channels were configured using 2 identical 8 channel printed circuit boards designed to fit into the cover (with shielding), of the 6-slot ISA bus chassis.

With a fixed gain system, a 16 bit sample word was desirable. An 8 bit PC bus ADC board (Datel PC411) that multiplexes the 16 VLA channels through a single converter to achieve the 1600 Hz sample rate was used. The Datel board was upgraded from 14 to 16 bits by changing the A to D converter part after tests of the board indicated that the increased resolution would be meaningful. The First In First Out memory (FIFO) on the ADC board was upgraded from 1 to 8 kbytes to decrease the software overhead of data transfers to system memory. Our concern was that the high rate of interrupts from continuous network transactions and ADC data transfers would be a significant software overhead that might become the limiting factor for speed rather than the WaveLAN link itself.

A 1 MHz timebase and IRIG-B timecode was supplied from a self-contained unit that was borrowed from another project. This package has internal batteries but was used with an external battery as well. The timebase source uses an Austron 1115 crystal which drifted approximately 10 microsecond per hour over the period of the experiment. Stability and predictable drift of the timebase are crucial to accurate estimation of travel times of tomographic signals, which in turn determines how well the oceanographic parameters can be inferred. The IRIG-B code was used to supply a realtime sync anytime the buoy system was restarted either due to cycling of the power, a reset or by command over the LAN link. The operation of this clock unit was independent of the PC system in the buoy.

Within the ISA chassis was a board, designed for another project and for which software existed, having a clock with microsecond resolution that could be synchronized through software to the IRIG-B timecode from the external timebase unit. This clock was regularly read by the acquisition program with microsecond resolution for the current time value that was placed in data records transmitted to the shipboard system. In this way, there was never any doubt regarding the precise time associated with the data stream.

The WaveLAN board is full length and has an inconvenient F-type, 75 ohm connector at the edge for an antenna feed cable. The antenna provided by NCR is omnidirectional with no gain and suitable for mounting on a wall near a desktop computer. On the buoy, an F to BNC adapter was used to connect the antenna with about 12 feet of RG58 cable. The antenna and cable has a 50 ohm characteristic impedance; however, the mismatch had no discernable effect. The RG58 cable was made as short as possible to minimize attenuation which at 900 MHz is about 14 dB/100 ft. When coupled with the losses through connectors, the total attenuation was nearly equal to the 3 dB gain of the buoy antenna, which was a 5/8 over 1/4 wavelength ungrounded whip. It was necessary to electrically isolate the antenna from the buoy or the radiated power would be very much diminished.

The implementation of a DOS PC was easily achieved using a single board computer (SBC), that included a 16 MHz 80C286, 2 MB of memory, a PROMDISK, standard interfaces for keyboard, parallel & serial ports, floppy and IDE disk drives. Program development was done using all the on-board facilities with disks and a separate video adapter; however, during operation in the buoy, no peripherals were connected to the CPU board and the video adapter was removed. The SBC was configured to boot as well as execute the acquisition program from the PROMDISK. The SBC was purchased from Micro Computer Specialists, Inc. and performed adequately. A later, faster version using a 386SX processor would have been more convenient and may permit faster transmissions with the WaveLAN, though at the expense of at least another watt of power dissipation. 26 A commercially available DC/DC converter was mounted within the chassis to supply power to all plug-in cards. The efficiency of the conversion was about 82%, leading to a total power dissipation for the buoy system of about 28 watts as summarized below. The amplifier/filter section and the hydrophone preamps were supplied from a separate battery without regulation. The system ground was isolated from the buoy. The battery was a 11.75 inch diameter "puck" of 60 "D" alkaline cells configured as ±12VDC. The main battery powering the DC/DC converter consisted of 5 - 11.75 inch diameter "pucks", each made of 120 alkaline "D" cells, stood 25 inches high and represented about 6kw hours at zero degrees C. This battery was designed to be adequate for 9 days of continuous operation. Figure 11 shows the cell arrangement in one of the D-cell pucks.

The total power dissipation while transmitting at 50 kbytes/sec is summarized below:

- Array nominally 18VDC, 12V minimum @ 56ma, approx. 1 watt
- 16 CH Differential amp & filter, nominally ± 12VDC @ 100ma, approx 2.4 watt
- Timecode/timebase interface board, 0.5 watt
- 16 channel ADC board, 3.7 watts
- WaveLAN board, 10 watts on average
- MCSI 'C286 computer board, 5.5 watts
- Timebase package, approx 0.5 watts

3.4 The Shipboard System

The shipboard system is diagrammed in Figure 12. It consisted of a PC with a second WaveLAN board, a SCSI host adapter, and an 8mm EXABYTE tape drive. A conventional Ethernet interface adapter was used to enable data transfers to a Sun SPARC for processing and display of acoustic receptions. The PC was a relatively fast 486 to allow simultaneous storage to the Exabyte and the disk, to perform some basic quality checks on the data as they arrived, and to make sure that the shipboard end of the WaveLAN link would not be the limiting factor on link throughput.

The WaveLAN board was connected via about 65 feet of RG8 coax cable (attenuation of 8dB per 100 ft), to an omnidirectional antenna with 4 dB of gain covering the 900 to 950 MHz band. The antenna was mounted about 21m off the water, the highest point on the ship. The modest gain was chosen rather than something higher because we were unsure just how tight an antenna pattern could be used given the constant motion of both the ship and the buoy. Despite being in the swept beam of a 50kW, 10 GHz radar, only about 15 meters away on the forward mast, interference neither caused damage nor noticable data interruption.

3.5 Acquisition Software

All programming in support of data acquistion for both the buoy and shipboard systems was done using "C" in the DOS environment. Although the PC/TCP libraries from FTP were meant to be linked with code compiled with Microsoft C, the Borland C++ 2.0 package was used with a few minor changes to the FTP code. Our work required only 2 of the FTP libraries, "pclib" and "netlib". It seems that if routines return nothing but integer or character variables it is possible to get the Borland linker to handle Microsoft compiled code with exception only where there is no one-to-one correspondence of routines in both name and exact function.

Enough cannot be said of the ability to develop the acquisition portion of the program and call as needed functions from a package such as ftp's PC/TCP to provide reliable data transmission without having to pay attention to error detection, correction or retransmission requests at either end. The TCP protocol accomplishes this in a wholly transparent manner, given that the radio link is maintained for an adequate part of the time on average.

The buoy was equipped with 1 Mbyte of FLASH PROM disk which was enough storage for DOS 5.0, the WaveLAN network drivers and the executable acquisition program so that upon reset, the system simply went through a normal boot process as if it was doing so with a fast hard disk.

4 Operation

4.1 Deployment and Recovery

Like most prototype mooring systems, the VLA imposed some unique deployment concerns. The danger in deploying any U-shaped mooring system is the risk of dragging either of the mooring anchors during launch, resulting in damage to the system. Our plan for the Barents array was to lower both anchors on separate 3/4" plaited nylon lines, eliminating the need to fairlead hydrophones, connectors and associated hardware through blocks while under tension. This also gave us the flexibility of using either the ship's capstans or the WHOI mooring winch to lower either anchor.

The array cable was "figure eighted" into two separate coils amidship on the afterdeck. The first coil contained the vertical hydrophone cable between the subsurface buoy and the acoustic release. The second coil contained the balance of the cable between the release and the surface telemetry buoy. This allowed us to make all electrical and mechanical connections to the entire mooring system prior to deployment, thus reducing the possibility of stoppages during installation. Figure 13 is a picture showing the arrangment described just prior to deployment from the USNS Bartlett.

Once the Bartlett was on station, the first step in the deployment was to hang the surface buoy from the ship's crane in a launching position on the outboard side of the port rail. The buoy was held snug against the rail by maintaining an inboard crane angle as well as tension on 2 slip lines. The bitter end of the array cable was faired around the outboard side of the stern A-frame and connected to the bottom end of the buoy. Although the telemetry buoy was the last piece to be launched, having it in position as described enabled us to quickly release it a sufficient distance outboard. Both 600 ft lowering lines were reaved through separate blocks on the A-frame. One lowering line was connected to the flounder plate above the acoustic release and tension was taken using the ships capstan to suspend the release vertically over its anchor at which time all connections were made. The second line which would lower the surface buoy anchor was wound on the mooring winch and connected to its anchor.

On completion of prelaunch preparations, the Bartlett was requested to steam at 1/2 kt upwind towards the deployment site so operations could begin. The 48 inch diameter syntactic sphere and WHOI acoustic navigators were deployed first using the ship's stern A-frame and capstan. The vertical hydrophone section was then easily run out by hand as the buoy drifted slowly astern. The load was then transferred to the flounder plate and the first anchor was lowered to the bottom using the capstan. The ground cable was run out maintaining as much tension as possible by hand. Since the cable was almost neutrally buoyant, this was easily done. Once it was determined that the anchor was on the bottom by noting decreased tension, the lowering line was removed from the capstan, the end weighted and jetisoned. Once the ground portion of the array was run out, the load was transferred to the second bottom anchor which was then lowered to the bottom similarly to the first. Having previously attached "Panther" sphere floats and depressor chain to the S-tether section it was a simple matter of keeping tension on the cable as it was manually deployed. With approximately 30m of cable remaining on deck, the telemetry buoy was slung outboard on the crane, lowered and released. As the buoy drifted astern, the remainging few meters of cable were released. As the ship continued to move ahead, the remainder of the second anchor line was run out, weighted and dropped. The total deployment time was an hour and a half.

Upon completion of the experiment the subsurface float anchor was acoustically released. The foam sphere was hooked from the side of the ship and recovered first. Once the float was aboard and disconnected, the array cable was hauled using the mooring winch. The cable was fair-led through a 28 inch sheave suspended from the stern A-frame to avoid any damage. Moderate tension ($< 1000lbs$) was encountered as the surface buoy anchor was lifted from the bottom. All instrumentation and hardware were disconnected on the outboard side of the A-frame block as the cable was hauled aboard. The telemetry buoy was recovered last, using the A-frame and capstan. All hydrophones were found to be working, indicating that the cable was intact.

4.2 Acquisition and Telemetry

At reset or power-on, the buoy system attempts, until successful, to establish a TCP stream connection with the shipboard system. The GMT timecode is then read from the timebase package, and the hardware clock set to the millisecond. Time is then transmitted at the second mark and subsequently displayed at the ship screen as an indication that the buoy system is nominally functional. If acquisition had been gracefully terminated at the ship, the buoy system simply waits to re-establish the connection and skips the timecode sync step.

To initiate data collection, the ship board system offers a selection of options to set parameters at the buoy: amplifier gain, sampling rate, channels in use, S/H settling time, buffer size, data record size, and the compilation of an error log. Typically, these were left unchanged from appropriate defaults.

Data were transmitted as sequences of 16-channel scans with each scan consisting of a sequence of 2 byte samples, one from each channel. The available memory buffer space in the buoy system was broken up into 15 - 48 kByte sub-buffers which was about 14 seconds of data. Thirty of these buffers comprised a data record. Prior to transmitting each data record, a record header of 1024 bytes was transmitted that among other parameters, included the start time of the data record with microsecond resolution, the record number and the current system gain.

The 15 memory buffers were circularly filled by incoming data via an interrupt routine and similarly readout and transmitted over the wireless Ethernet link. Error checks were made to assure knowledge of outgoing data that was prematurely overwritten by incoming data. The only source of such an occurance was an occasional increase in the separation between the ship and the buoy to a range that was insufficient for the required data rate. In fact, at about 2 to 3 km, depending on sea state (antenna pointing problems, as well as propagation losses) the link would quickly degrade to where it could not keep up with the 50 kB/s rate. Normally, the 14 seconds worth of buffer space was enough "elasticity" to prevent loss of data from TCP overhead due to radio dropout for whatever reason.

The shipboard system received buffers and checked at 30 buffer intervals for key information in record headers. It is important to realize that the TCP connection has no explicit knowledge of boundaries in the data stream, i.e. it is incumbent on the programmer to install checks as to what is in the data stream at any given time. TCP "only" guarantees that whatever is *received* is what was *sent*. The shipboard software keeps track of record boundaries as a check on the integrity of the data, as well as to be able to report on the screen information as to buoy time, record number and gain. The program would also report basic statistics of the data such as minimum and maximum values and the current buffer being received. Typically, all data were stored on an 8mm Exabyte tape drive though for quick look purposes, using MATLAB, data was stored to disk as well.

The WaveLAN bandwidth is about 22 MHz centered about 915 MHz. With the stock 0 dB gain antennas and the attached 6 ft cables, the link is advertised as having a maximum range of 800 feet, line-of-sight. It is difficult to estimate the maximum range since propagation loss is going to be a function of antenna clearances and in our case, since the antennas were in constant motion, they will view each other only part of the time as a function of sea state. We were hopeful that a range of 1 km could be achieved and in fact the system routinely transferred data at 50 kB/s at a range of 2.5 km in sea state 2 - 3.

The RF link power budget was estimated as shown.

Transmitted power	24.0dBm
Buoy antenna gain	3.0dB
Ship antenna gain	4.0dB
Buoy cable losses	-1.7dB
Ship cable losses	-5.2dB
Connector losses, . 5dB/connection	-3.0dB
Free space loss at 2 km	-98 dB
Additional loss due to low buoy antenna	-24 dB
Estimated RF level at receiving system	-101 dBm

5 Results

5.1 Mooring Performance

Although a short term deployment, the VLA mooring was very successful. Upon recovery, there were no visable signs of damage to the cable. The technique can provide reliable performance certainly for periods less than a month in water less than 500 m. After further evaluation of equipment and data from this experiment, longer term deployments might be attempted with more attention given to the historically difficult area of the cable connection to the surface buoy. Clearly, a U-shaped system would benefit from a second release just above the telemetry buoy anchor by reducing tension during recovery.

5.2 Telemetry Performance

Seventy hours of data were collected in 2 episodes. Upon the first deployment, the system worked flawlessly. The sea state was 2 to 3 and it was quickly apparent as the ship departed from the buoy that 50 kByte/sec was easily achieved. There was little fluctuation in the arrival rate of data buffers, an indication that the link was continuously of adequate quality. We were then confident of an approximately 60 dB reduction of the Bartlett's radiated noise level received at the array. (Though a Russian surveillance ship was in the area, it too generally remained at least 1 km from the array site.) After 15 hours of operation, and numerous acoustic sequence receptions, it was apparent that the gain could be increased from 20 to 40 dB as the signal level readout showed a minimim to maximum signal swing of only 2.5% of the ADC input range. (The sensor sensitivity was -160 dB re 1V/μPa and gain selections of 0, 20, 40, & 60 dB were available). Data acquisition was terminated normally in order to increase the gain to 40 dB; however, the buoy failed to restart properly. Although the Ethernet link responded to "pinging" (a program commonly used on Ethernet networks to establish the existence of a specified machine on the net), the acquisition program would not establish the TCP connection. The hardware "deadman" timer on the CPU board apparently was being reset by the program as it should have been, otherwise the buoy system would have rebooted.

Though the sea state was moderate, we were not permitted to take a small boat to the buoy to either manually reset the system or recover the electronics. The entire mooring system, array and buoy were recovered without damage in approximately 3 hours. Shortly after recovery, the weather deteriorated and 2 days passed before the system could be redeployed.

Upon testing, the buoy system restarted and functioned properly. We surmised that a software error was responsible for the "hung" state. Though much of the available time prior to a second deployment was spent in an attempt to establish and fix the software, we were unable to do so. Continued operation was made possible by using a timer output from the timebase along with a quickly patched together bit of hardware to enforce a power off/on cycle precisely on the hour. This actually turned out to be convenient as the shipboard system software was then modified to anticipate the hourly shutdown, close the data file, and restart after the buoy system was back on-line. The hourly data file size was a more manageable 175 Mbytes in length.

Shortly after redeployment, the gain applied to the array hydrophones was set at 1 and we began to deploy SUS charges from the Bartlett to be sure of a minimum shot data set. When an abrupt sluggishness in data reception was soon observed, it was realized that in the flurry to collect shot data, which had to be done while underway at 7 knots, the ship had gotten over 3 km from the buoy. Upon reversing course, reliable telemetry was again established at about 2.5 km. This proved to be about the maximum useful range although later, with calmer seas, slightly greater range could probably have been maintained.

The system ran continuously for another 50 hours except for short hourly breaks. Eight Exabyte tapes were filled with data for a total of about 17 gigabytes of data.

Figure 14 is a printout from a navigation program that was used during station keeping operations in the vicinity of the VLA to show the position of the ship with respect to the array. It depicts our proceedure of maintaining a range of from 1 to 2 km from the telemetry buoy at site D, the triangle, by alternately driving the ship up-current from, and drifting back towards the buoy. Site R1 marks the location of the array and sites R2, R3, and S mark the locations of bottom mounted acoustic transponders used to navigate the top of the array. The positions shown are from GPS.

5.3 Scientific Results

To the scientist, technology is the means to an end, that end being the collection of high quality, experimentally valuable data. The data collected in the course of this work in the Barents Sea were of 3 types: i) broadband tomography data at 224 and 400 Hz, ii) narrowband (CW) data at 224 Hz, and iii) broadband shot generated (SUS) data. All data sets required the 16 channel array to separate the normal modes. Preliminary results of the mode separation for the 224 Hz broadband tomography data are shown in Figure 15. Low noise, high gain, and low array sensor motion were needed for both the broadband and narrowband tomography data. Using this array design with telemetry, high SNR's were achieved, despite the USNS Bartlett's noise level measured to be about 134 and 130 dB in the 200 and 400 Hz regions respectively. (A Russian intelligence ship, CCB-512, was also in the area with a similarly high radiated noise.) The shot data, on the other hand, needed far less gain. By remote adjustment of the system gain, we obtained pulses which optimally used the available dynamic range of the system without clipping (Figure 16a,16b). The final result as far as science is concerned is that a wide range of useful data for probing the environment has been collected with a single, very flexible instrument.

6 Future Plans

Having built, tested and field deployed a prototype system, we now have the experience base needed to see where the technology can and should go. We present here a brief list of system improvements that we hope to implement in a "next" effort.

- Mooring designs can be altered for use both in deep and shallow environments.
- A combination of bottom mounted horizontal and vertically suspended array channels could be used to achieve both vertical and azimuthal directivity.
- Radio links and acquisition electronics can be upgraded for higher bit rates allowing higher frequency data and/or more channels.
- Internal storage (~ 5 Gbytes) can be included allowing ship to leave array site for up to a day for other tasks, returning to "dump" data from the previous day as well as current data.
- Higher power radio LAN links will become possible. We expect that with greater power and higher gain antennas, the range between buoy to ship could be extended to 5 miles and to an elevated land site up to about 20 miles.
- Real-time sensor navigation can be added by telemetering vertical array tilt and heading data and/or acoustic transponder data to receiving platform.
- Buoy lifetime can be extended with photovoltaic augmented battery systems for longer data collection periods.
- Raw data compression (allowing up to 100% improvement in bit rate) or signal processing could be done in the buoy system to reduce transmission or storage requirements.
- Software can be improved to enable "fine tuning" of the Ethernet connection and hardware.
- Array signals can be digitized at the sensor for optimal signal quality.
- Wireless LAN based capability can be improved for use with any data source where similarly high continiuous data rates are required from an untethered system. We think of the current system as an evolutionary step towards "desktop" network access to "wet" instrumentation.

It is clear that radio linked LAN connectivity now offers, for certain applications requiring modest range, an ease and reliability that has been difficult to achieve. This is an emerging technology that will improve, allowing greater data rates, use of a variety of data compression schemes and for oceanographic purposes, puts us one step closer to realtime "desktop" access to data from sea-going instrumentation.

7 Acknowledgments

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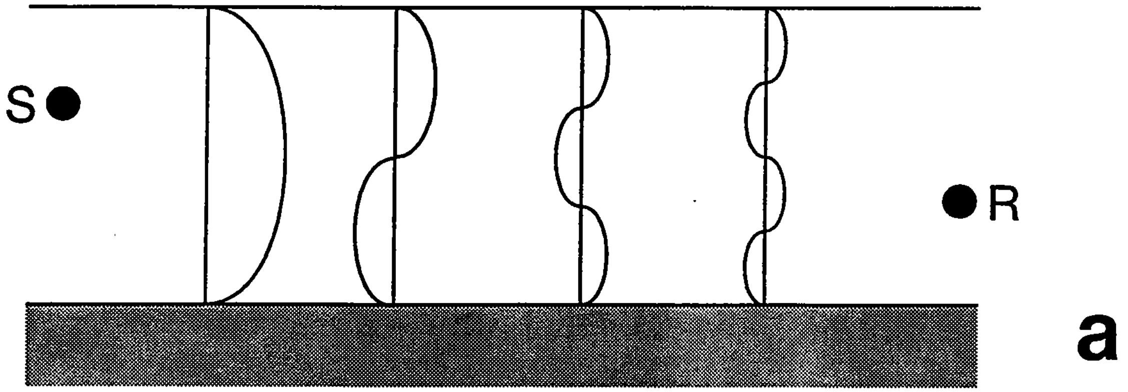
The authors wish to recognize the efforts of members of the scientific party and crew aboard the USNS Bartlett during the Barents Sea experiment for their assistance during the VLA deployment, especially J. Bouthillette and S. Liberatore as well as the following individuals who contributed to design and technical preparations at WHOI related to the VLA, D. Koelsch, G. Stanbrough, K. Wannop, and P. Boutin.

8 Figures



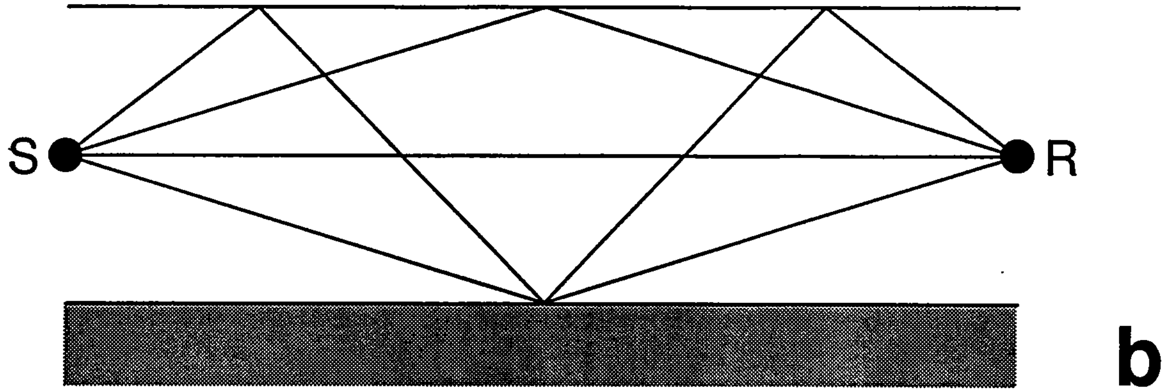


Figure 1a. In normal mode picture, arrivals seen at receiver from acoustic source are a sum of standing waves. Modes shown above are for iso-velocity water, a pressure release surface and bottom, and are similar to standing waves on a string with fixed end points. Only a relatively few modes specify the field in shallow water.

Figure 1b. Eigenrays connecting source and receiver. Many of these rays are needed to specify the field in shallow water.

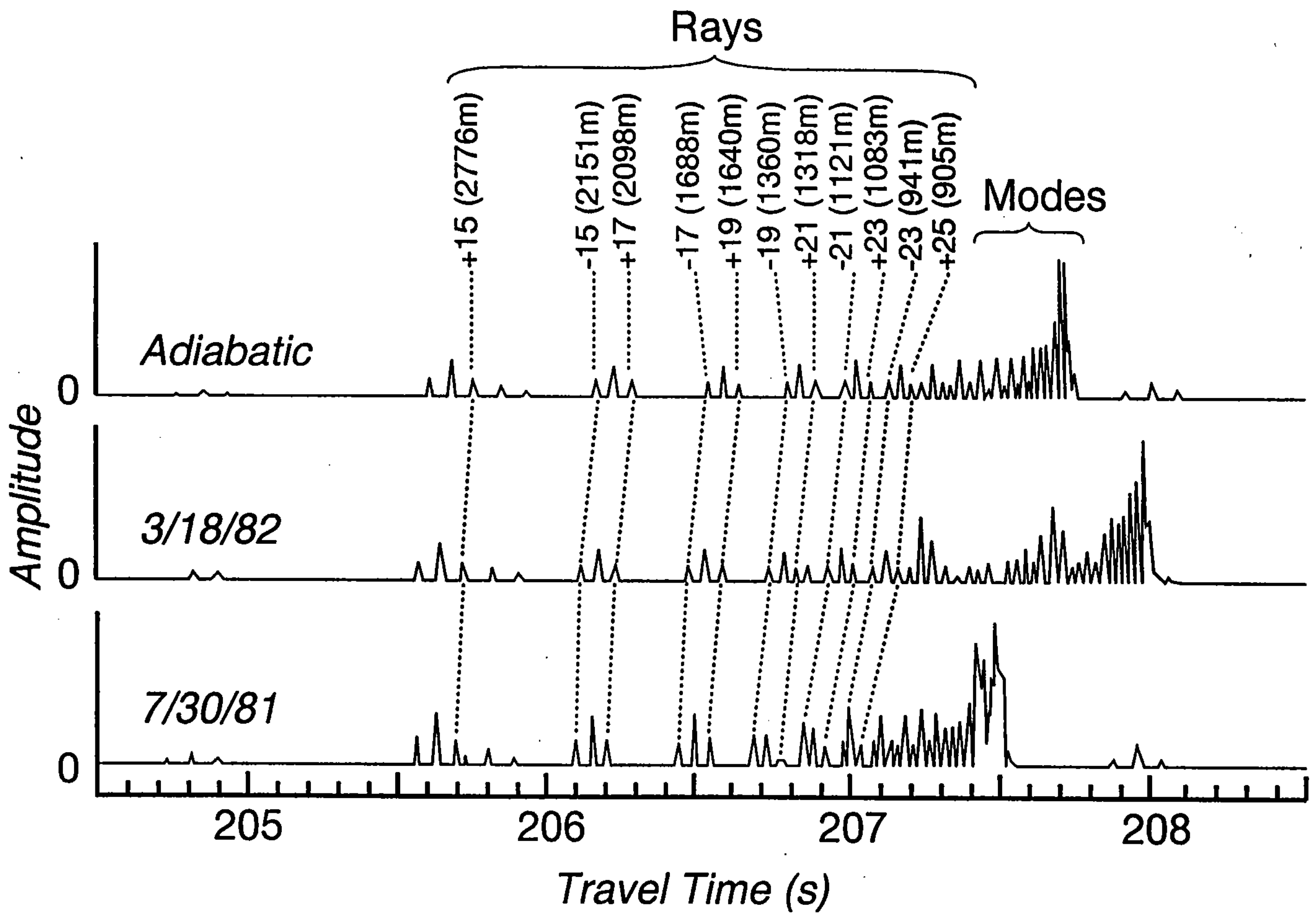


Figure 2. Simulated arrival structure for a typical deep ocean tomography experiment (the 1988-89 Greenland Sea Experiment). The early arrivals are clearly distinguished as rays in this experiment while the later arrivals are better described as modes. In the Barents Sea, we saw the opposite, i.e. modal arrivals first followed by the ray arrivals.

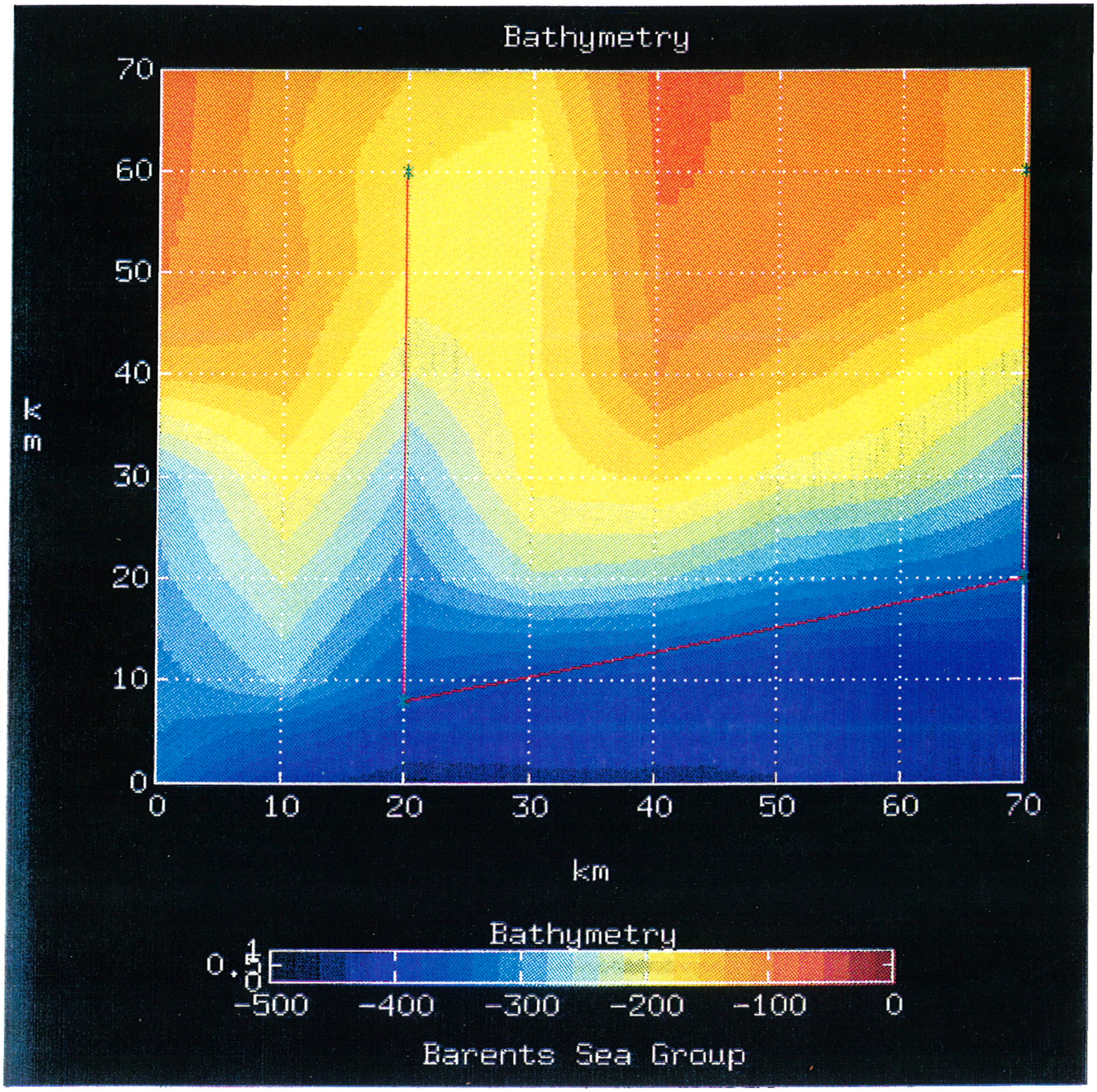


Figure 3a. Bathymetry in the Barents Sea Polar Front experimental area. The telemetered array was in the SE corner, the 224 Hz source in the NE corner, and the two 400 Hz transceivers were in the Fingerdjupet valley.

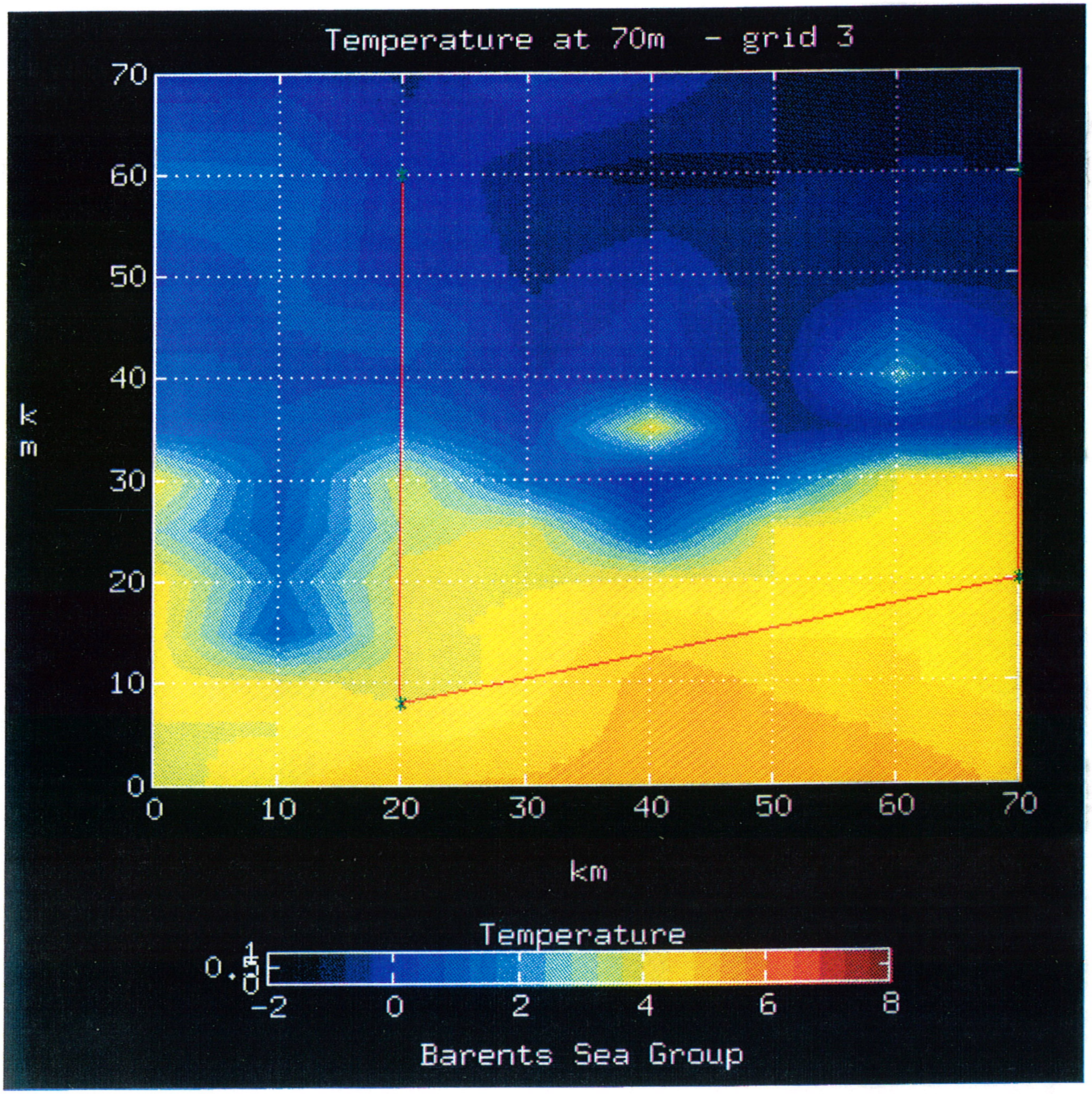


Figure 3b. Temperature at 70m depth in the Barents Sea Polar Front experimental area. The Front adheres (roughly) to the 250m bathymetry contour.

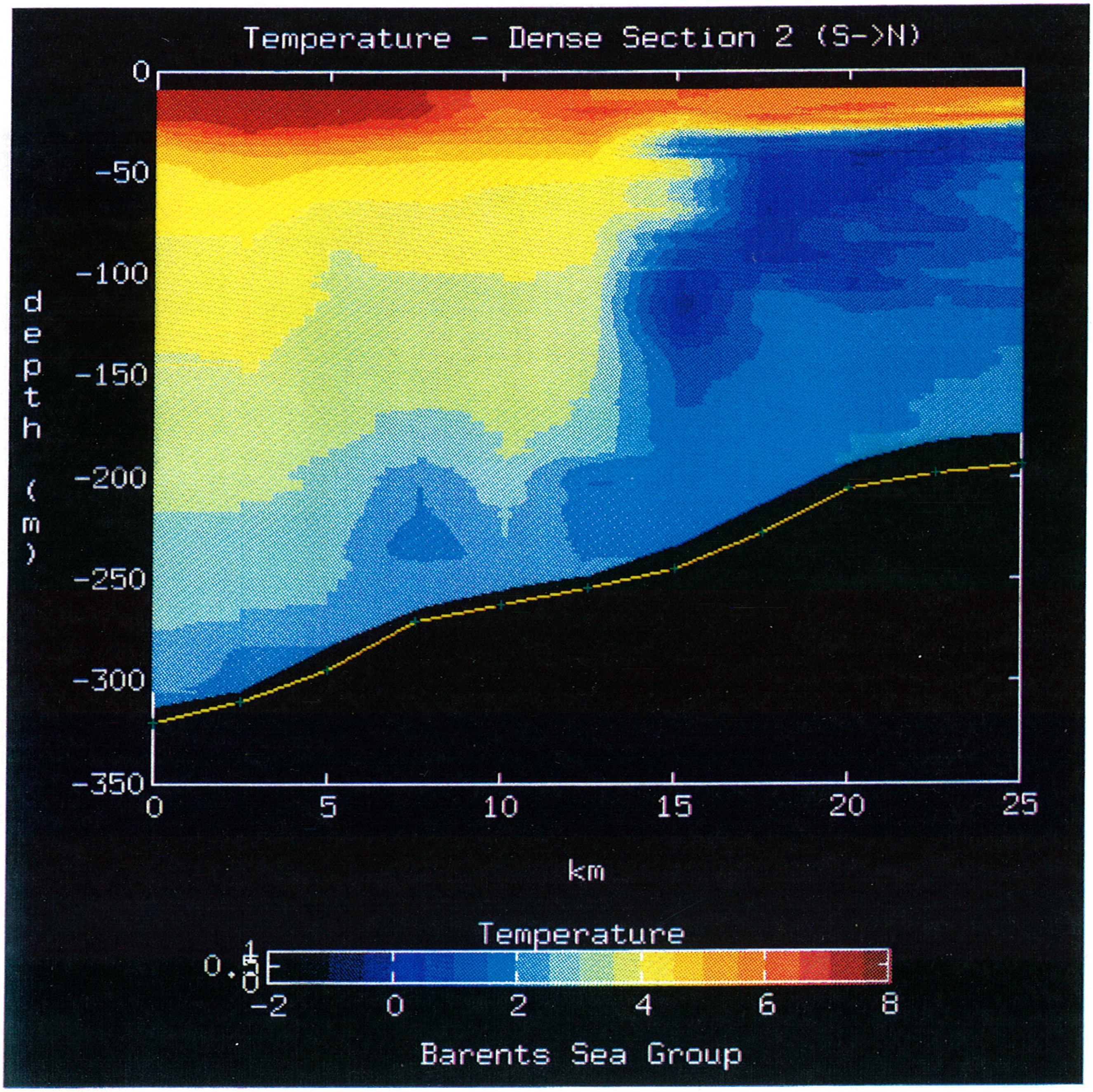


Figure 3c. Side view of the Barents Sea Polar Front, using a well sampled grid.

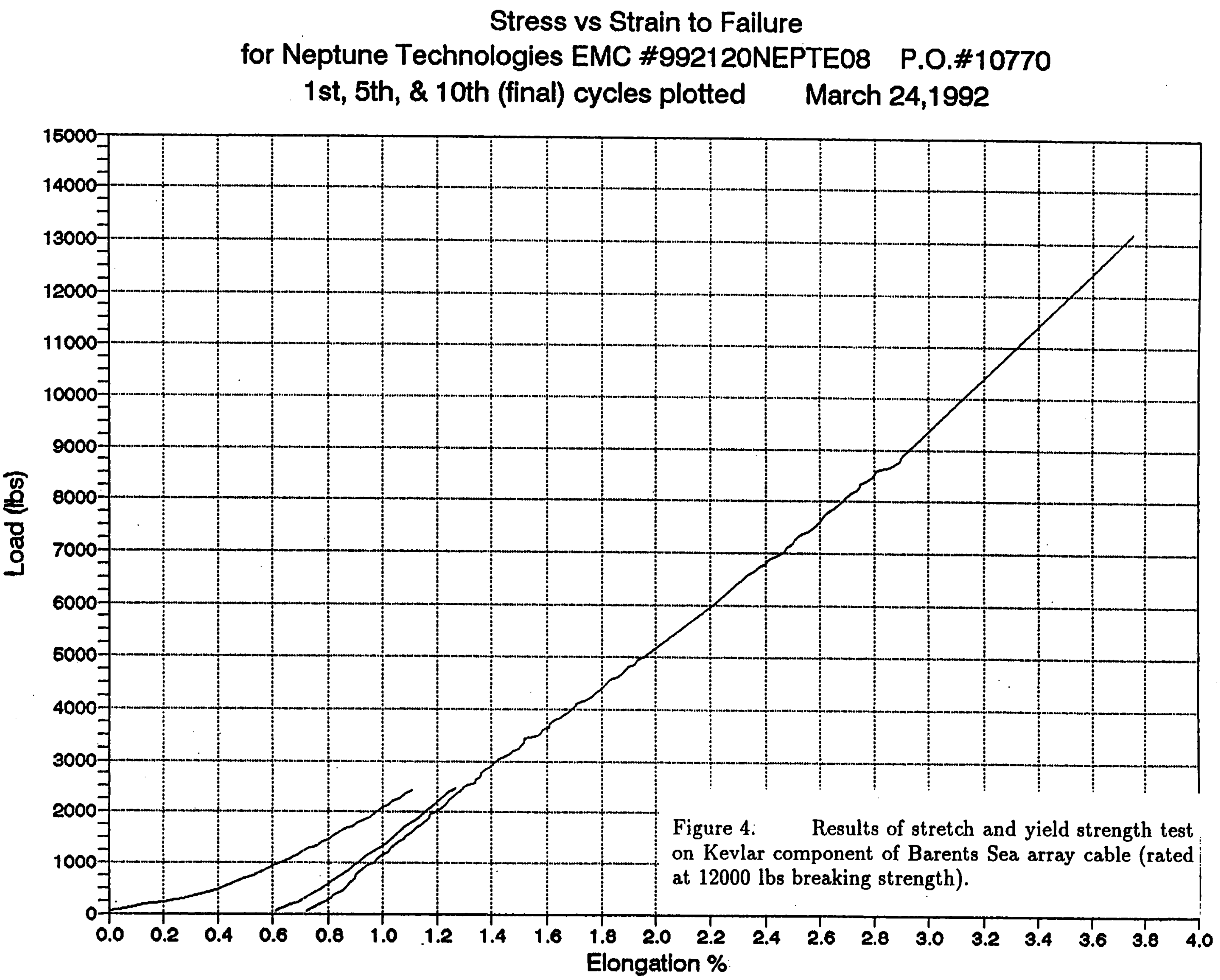


Figure 4: Results of stretch and yield strength test on Kevlar component of Barents Sea array cable (rated at 12000 lbs breaking strength).

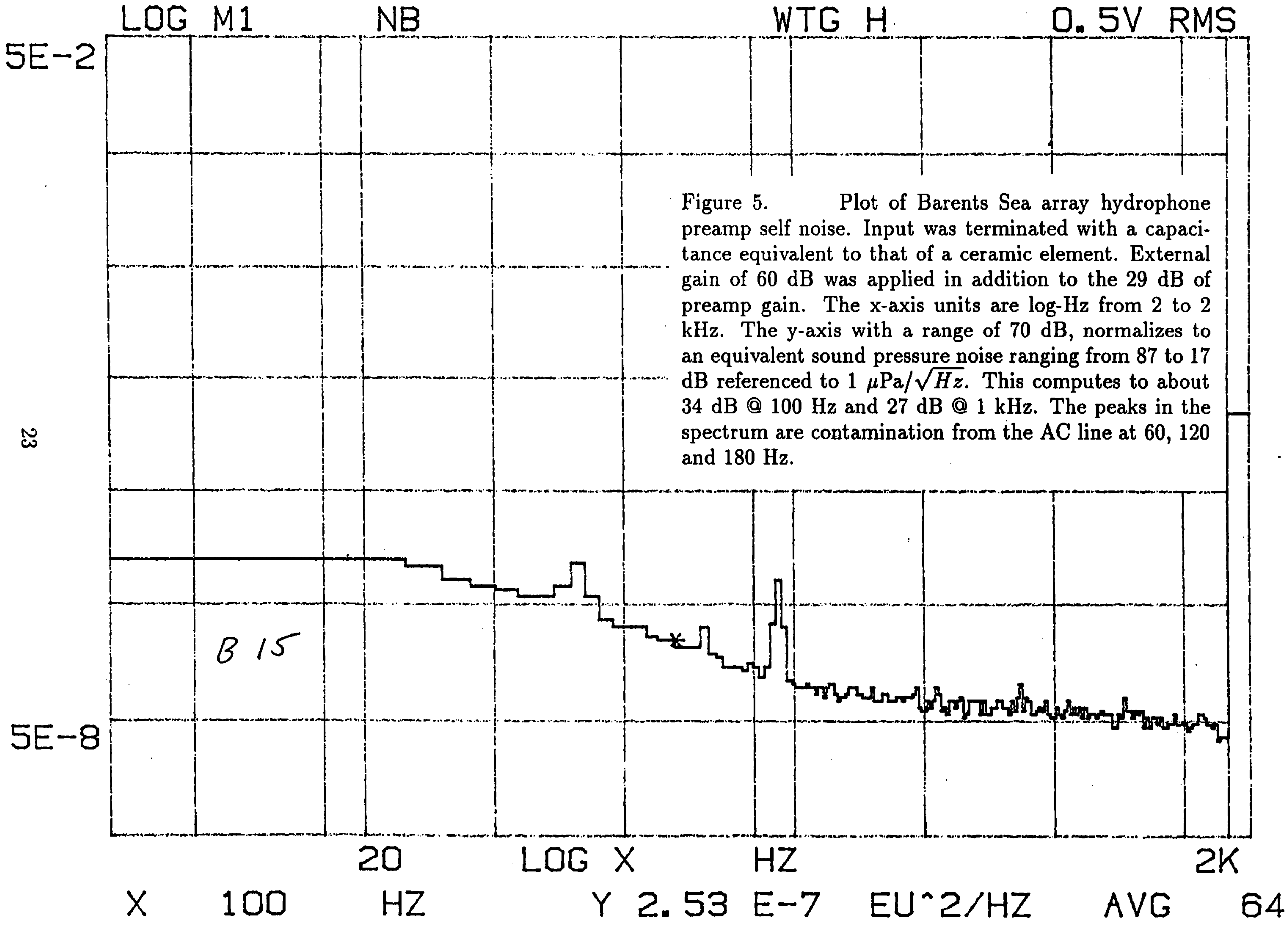


Figure 5. Plot of Barents Sea array hydrophone preamp self noise. Input was terminated with a capacitance equivalent to that of a ceramic element. External gain of 60 dB was applied in addition to the 29 dB of preamp gain. The x-axis units are log-Hz from 2 to 2 kHz. The y-axis with a range of 70 dB, normalizes to an equivalent sound pressure noise ranging from 87 to 17 dB referenced to 1 $\mu Pa/\sqrt{Hz}$. This computes to about 34 dB @ 100 Hz and 27 dB @ 1 kHz. The peaks in the spectrum are contamination from the AC line at 60, 120 and 180 Hz.

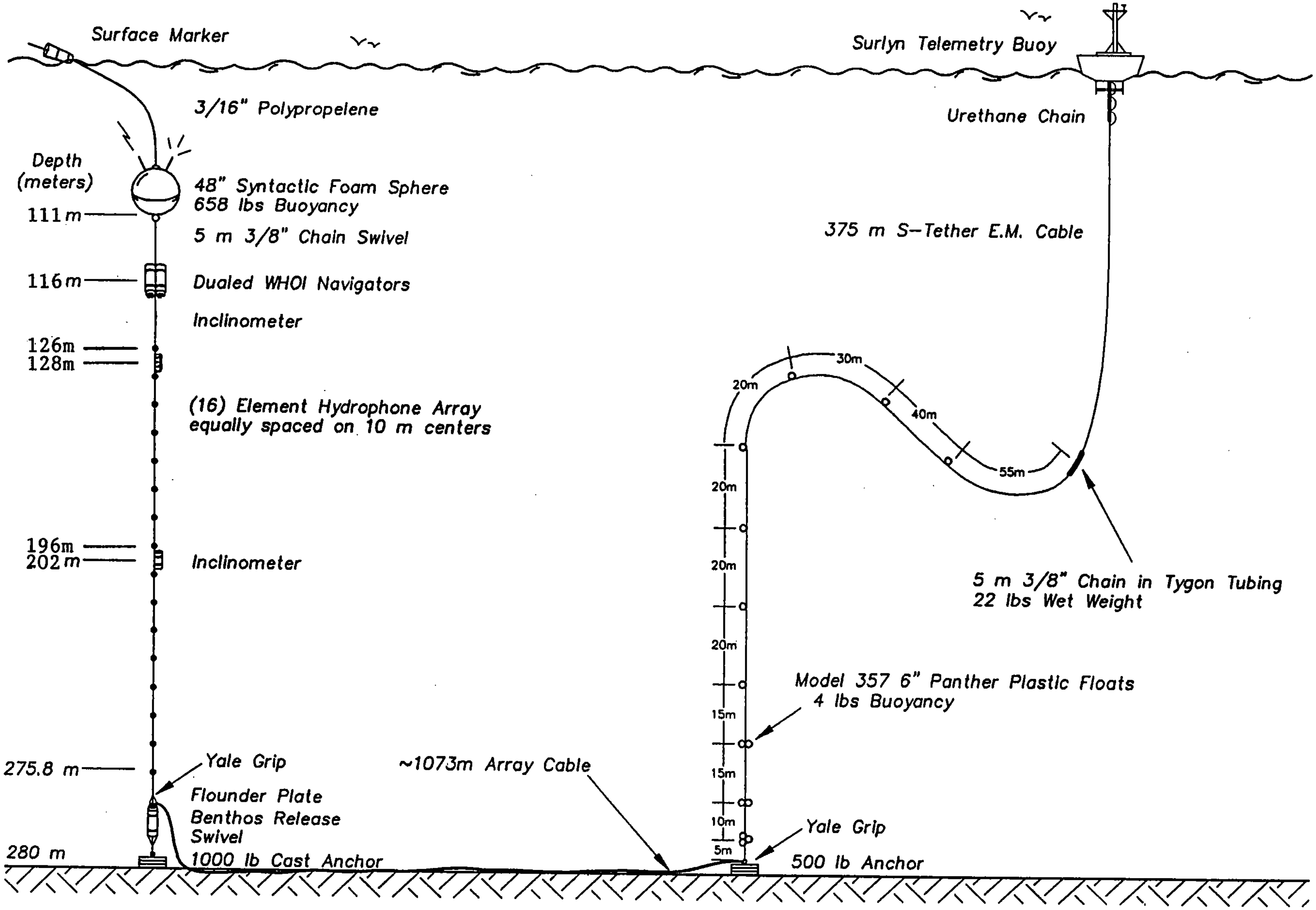


Figure 6. Barents Sea VLA mooring with telemetry buoy. The objective was to decouple the array from surface motion and maintain a minimum distance of 1 km from the USNS Bartlett. The 39 conductor electrical cable was continuous between the array and the buoy.

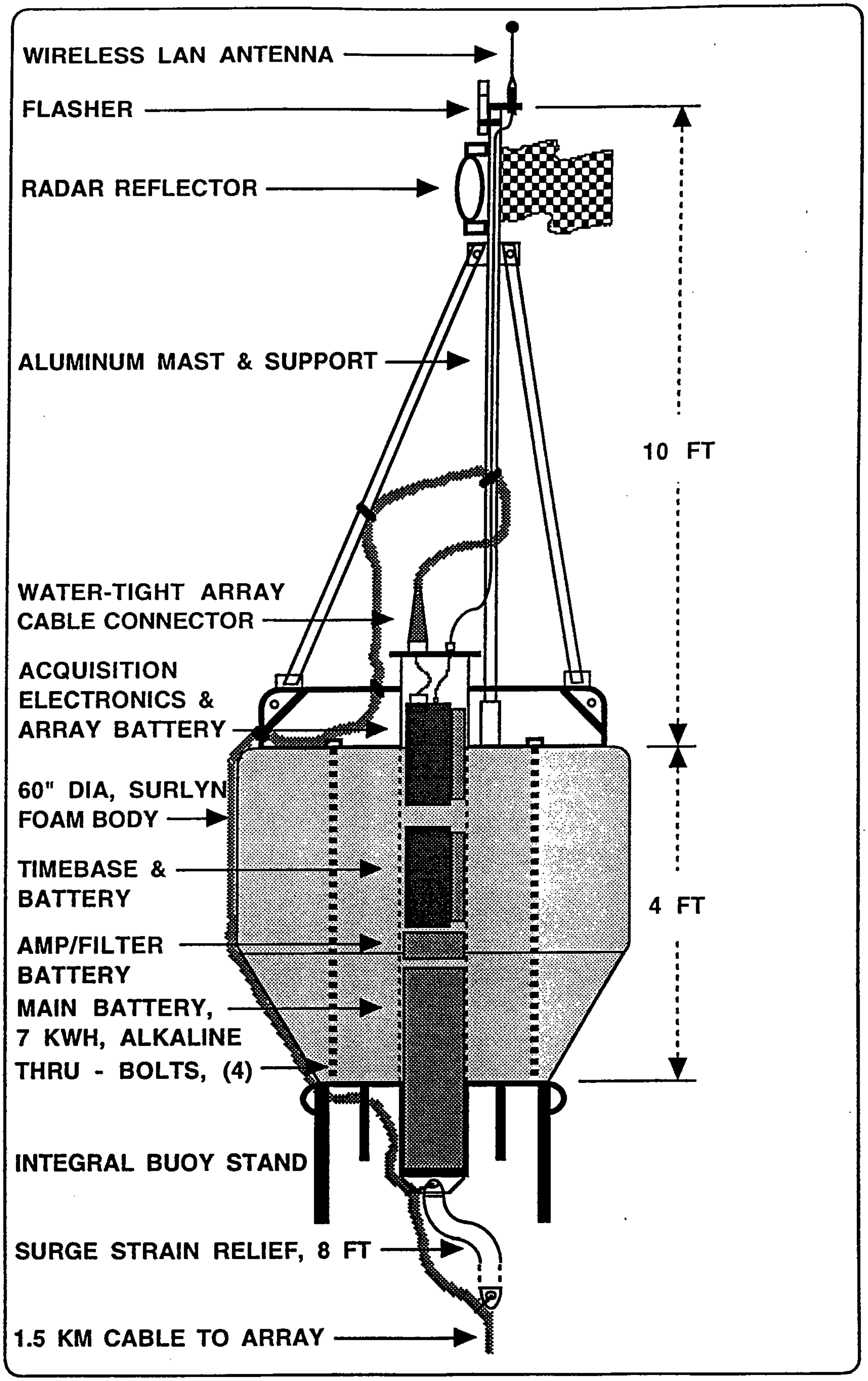


Figure 7. Cross section view of the Barents Sea telemetry buoy. The array cable was attached to the strain relief and brought up around the side of the buoy to a connector at the top of the central instrumentation tube.

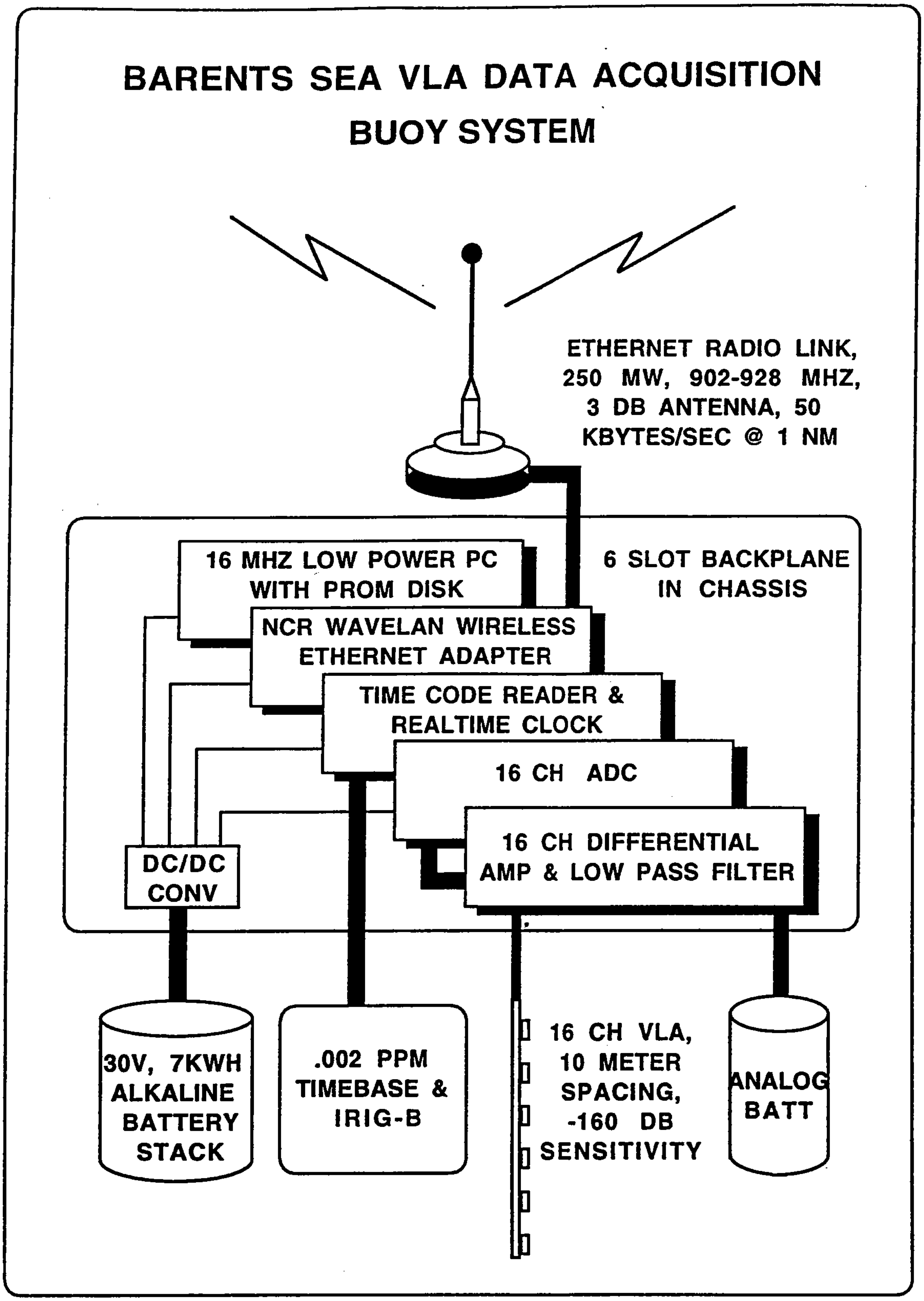
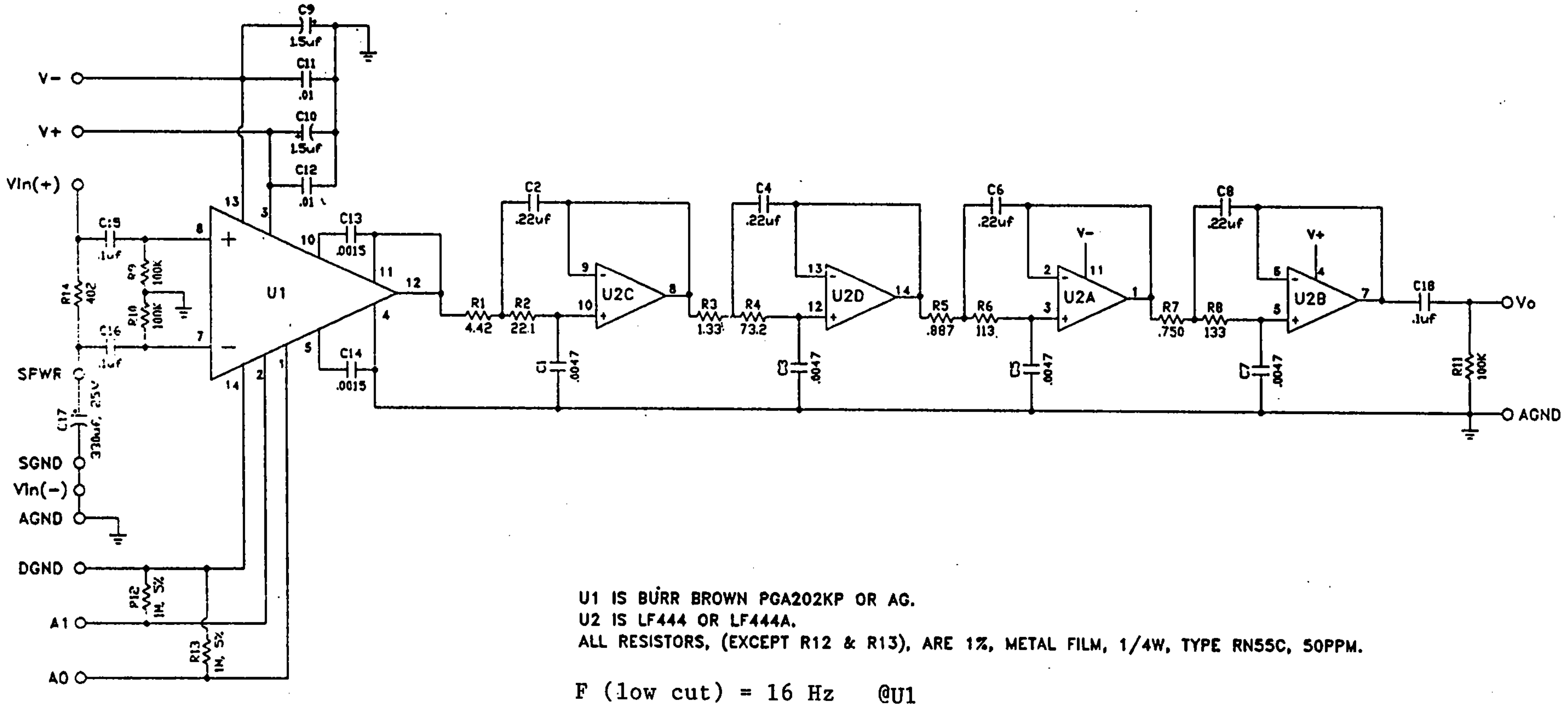


Figure 8. Barents Sea VLA data acquisition; buoy system block diagram



A1	A0	GAIN
0	0	1
0	1	10
1	0	100
1	1	1000

1=HI

U1 IS BURR BROWN PGA202KP OR AG.
U2 IS LF444 OR LF444A.
ALL RESISTORS, (EXCEPT R12 & R13), ARE 1%, METAL FILM, 1/4W, TYPE RN55C, 50PPM.

F (low cut) = 16 Hz @U1
F (hi cut) = 3500 Hz @U1

8 POLE BUTTERWORTH LOW PASS @ 500Hz

Figure 9. Barents Sea VLA data acquisition; differential receiver and lowpass filter.

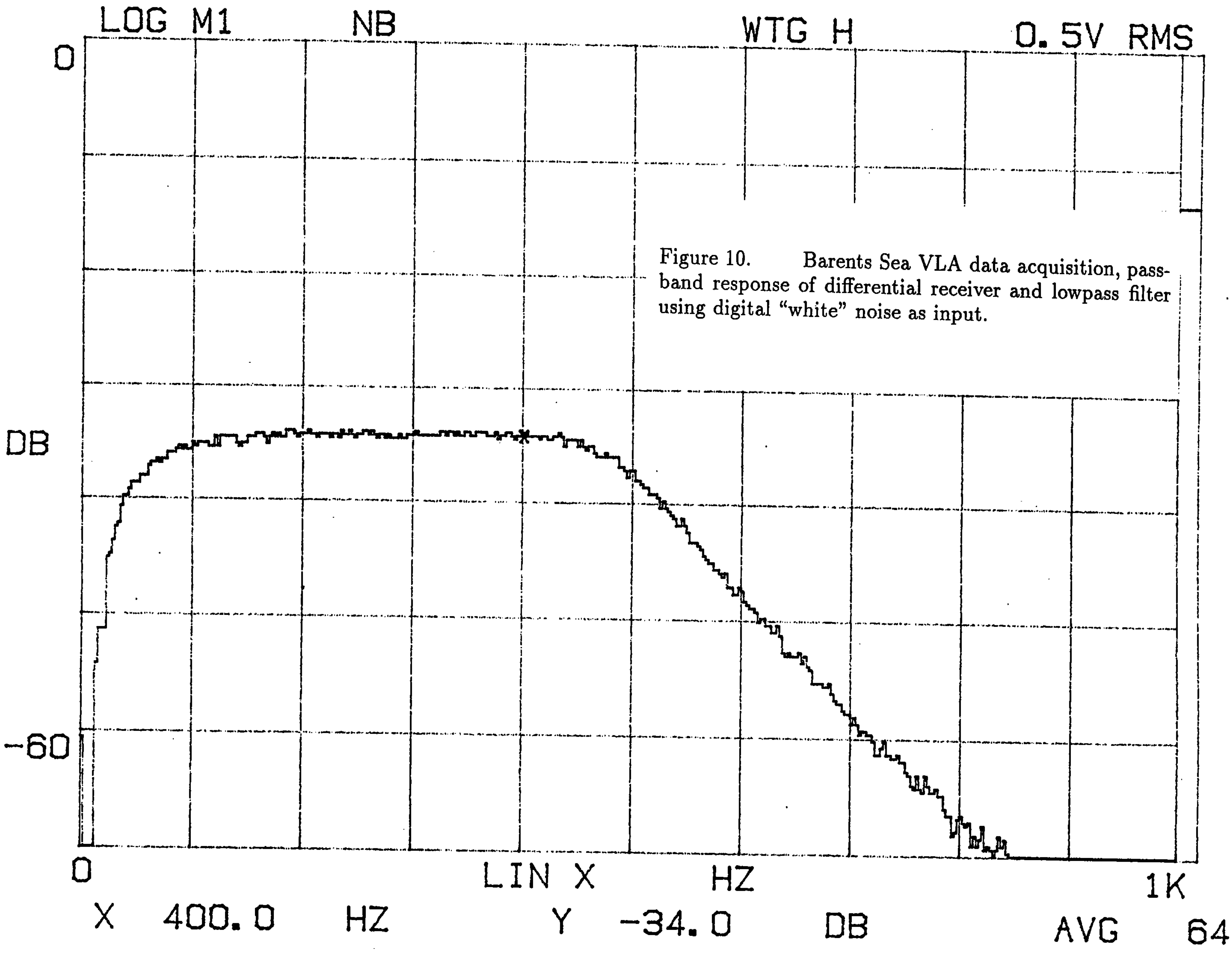


Figure 10. Barents Sea VLA data acquisition, passband response of differential receiver and lowpass filter using digital "white" noise as input.

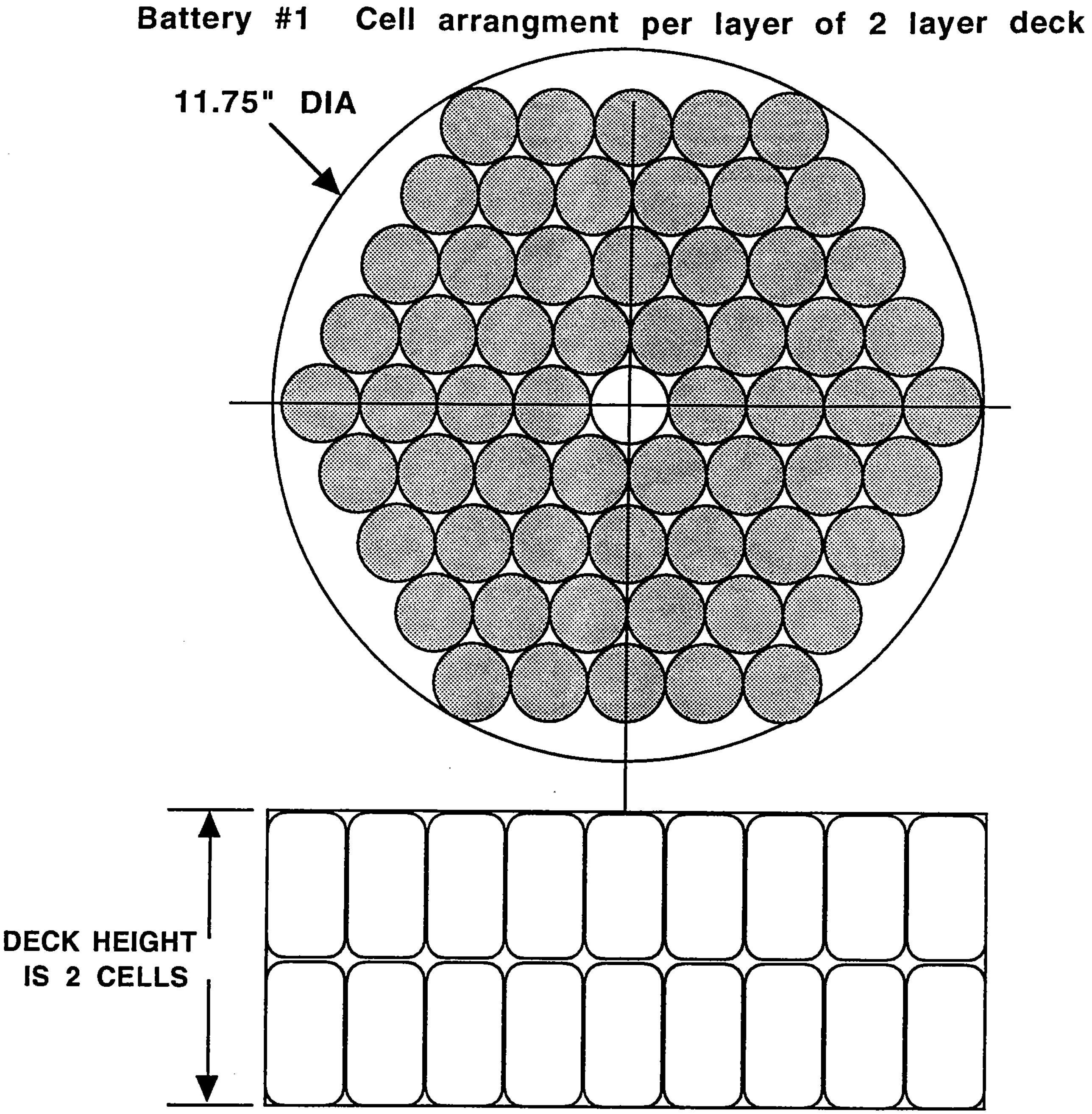


Figure 11. Barents Sea VLA data acquisition; main battery pack configuration for buoy system power. The pack consisted of 5 "decks", each consisting of 2 layers of alkaline "D" cells connected as 6 parallel stacks of 20 cells each. Each stack was isolated with a 1N5822 Schottky diode to minimize losses. The design current drain was 1.5A at 0° C at a nominal 30V (approximately 6kwh). The five 120 cell layers were separated with 1" of soft foam and the pack was bound under its own weight with duct tape and a plywood disk as a base. It was about 25" high, just under 12" diameter and weighed about 150 lbs. A 6th single tier puck was configured as ±15 VDC to supply the analog power required by the differential amplifiers and lowpass filters.

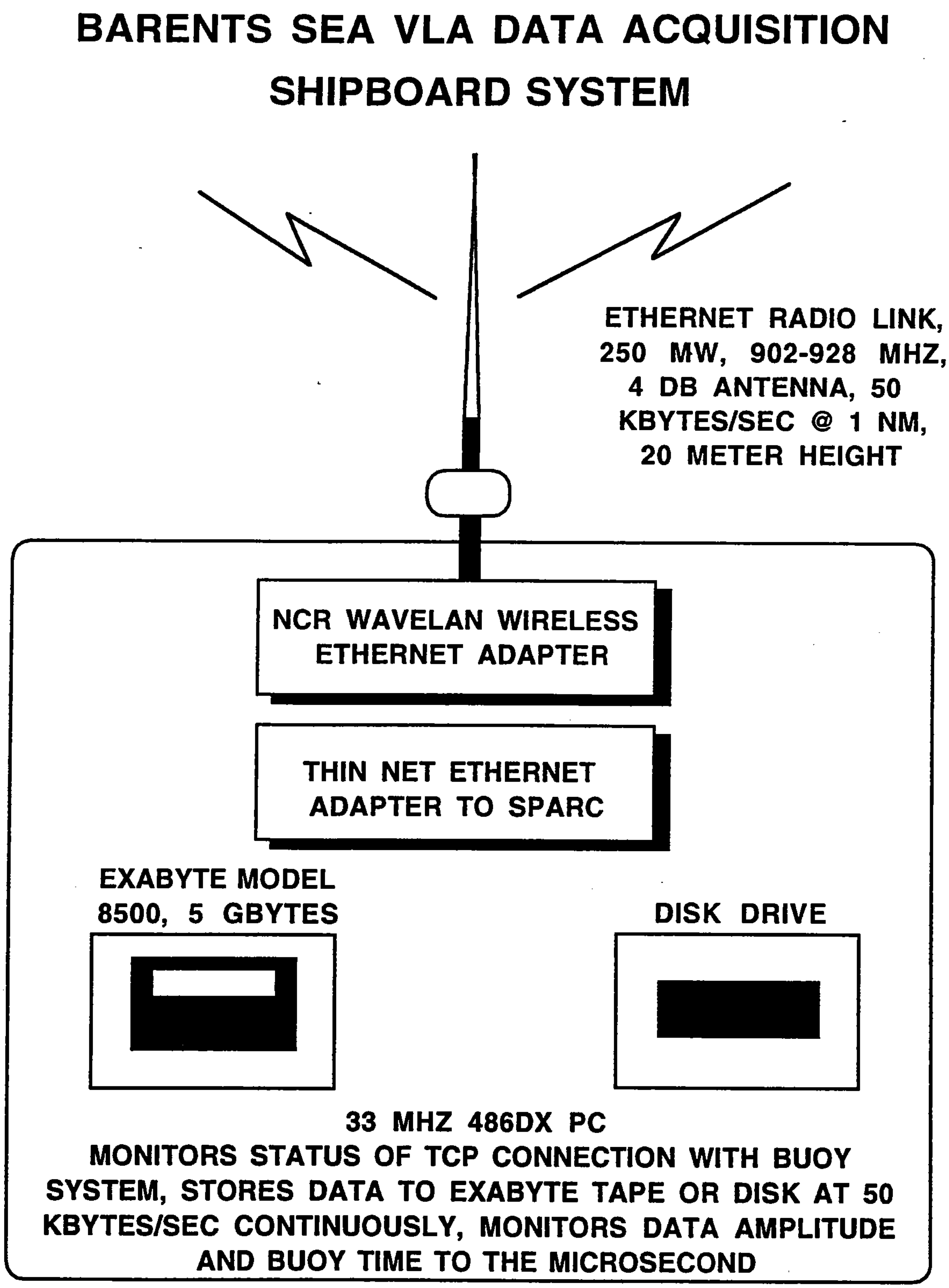


Figure 12. Barents Sea VLA data acquisition; shipboard system block diagram.

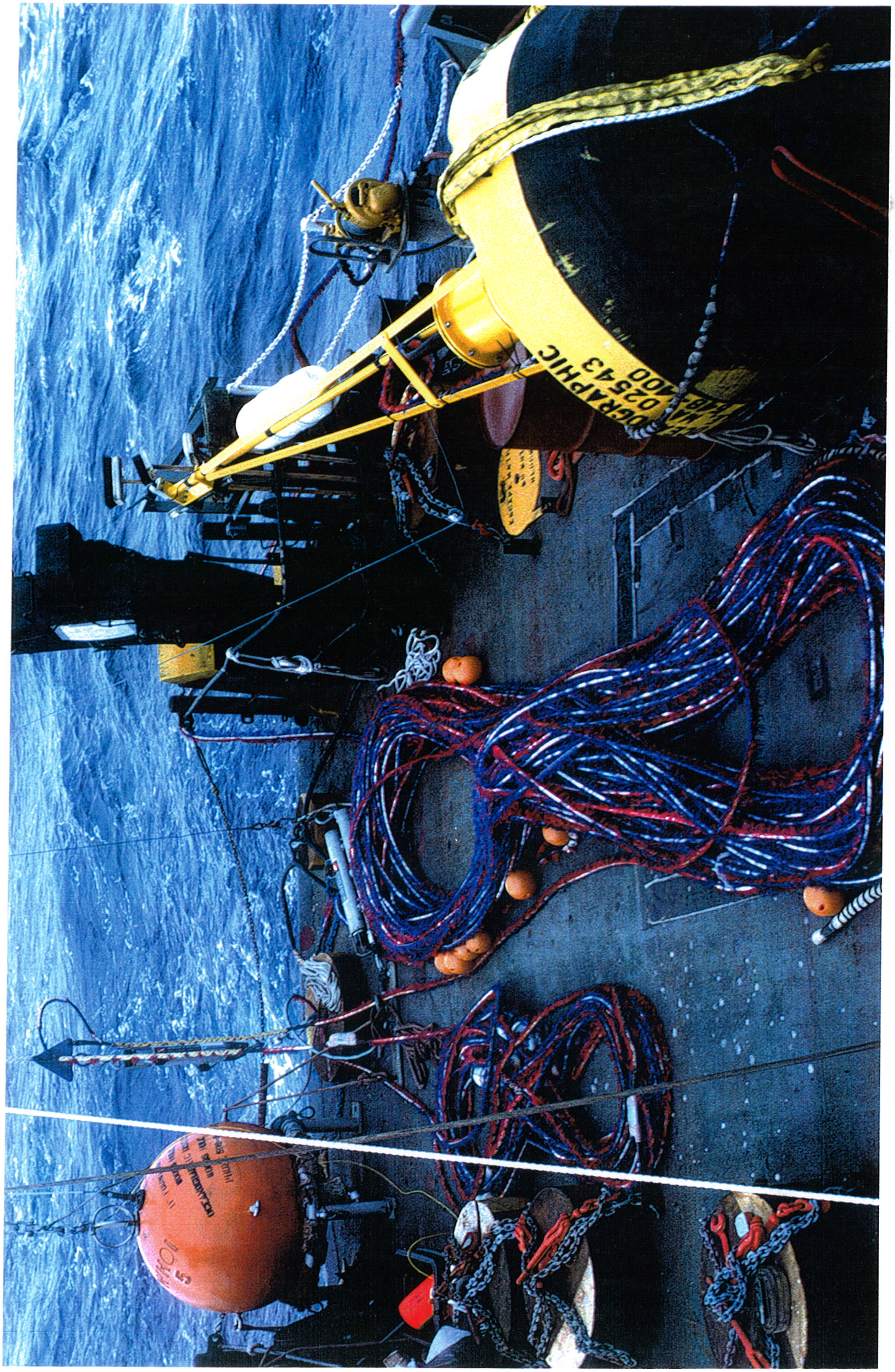


Figure 13. Photograph showing fantail of USNS Bartlett with Barents Sea array, telemetry buoy, flotation and mooring tackle prepared for deployment.

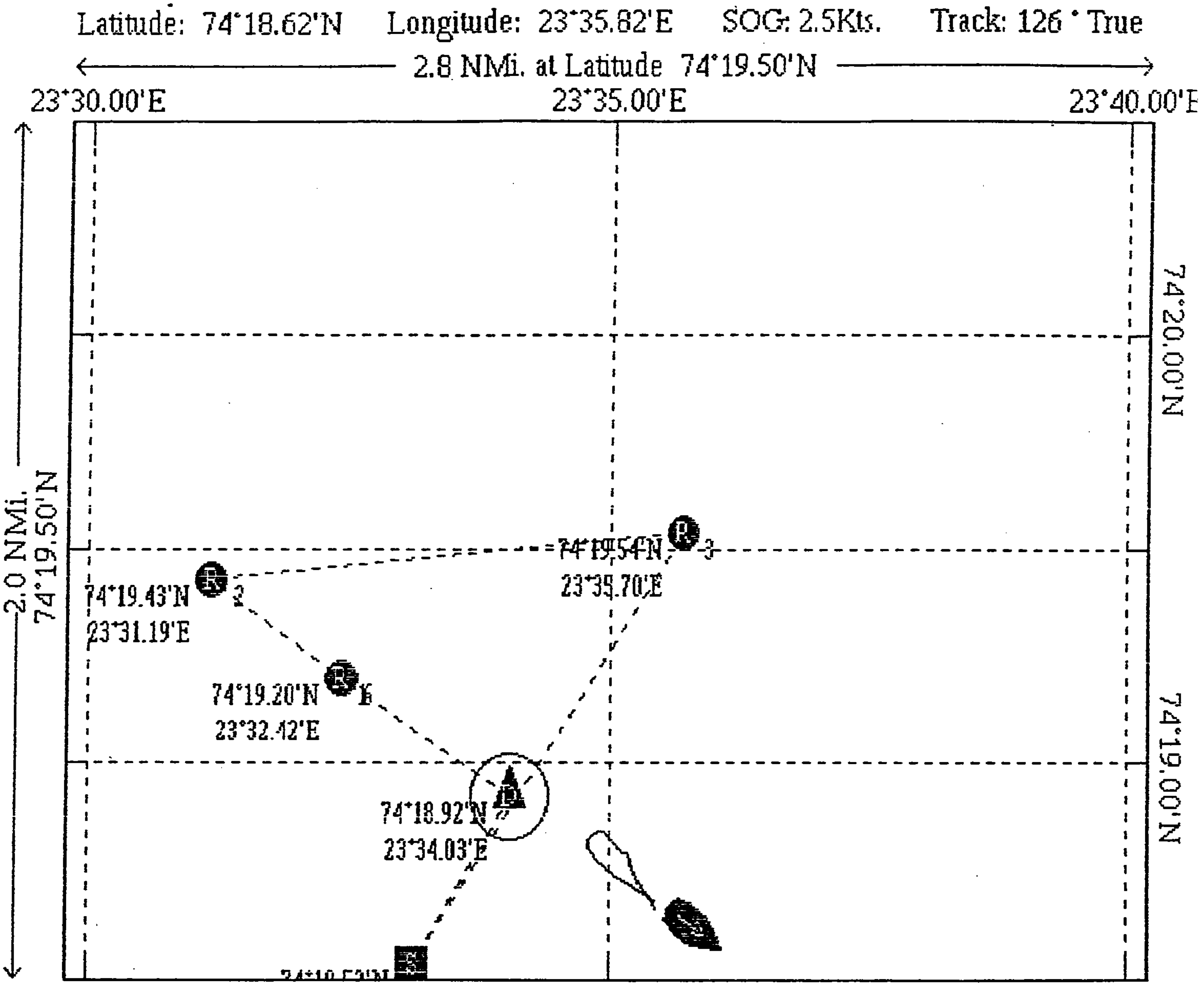


Figure 14. Sample navigation plot produced during VLA operation during the Barents Sea experiment. Site R1 is the array, site D is the location of the telemetry buoy, sites R2, R3 and S are bottom mounted acoustic navigation transponders. The ship position and track is shown bottom center which demonstrates the pattern of steaming to the southeast followed by a period of drifting towards the buoy. The wireless LAN link typically performed well until the range between the boat and the buoy spread beyond about 2.5 km. Approximate distance shown between ship and array is 2 km. Both the lab and ships personnel on the bridge had this information in realtime to enable maneuvering to keep the ship within range of the buoy.

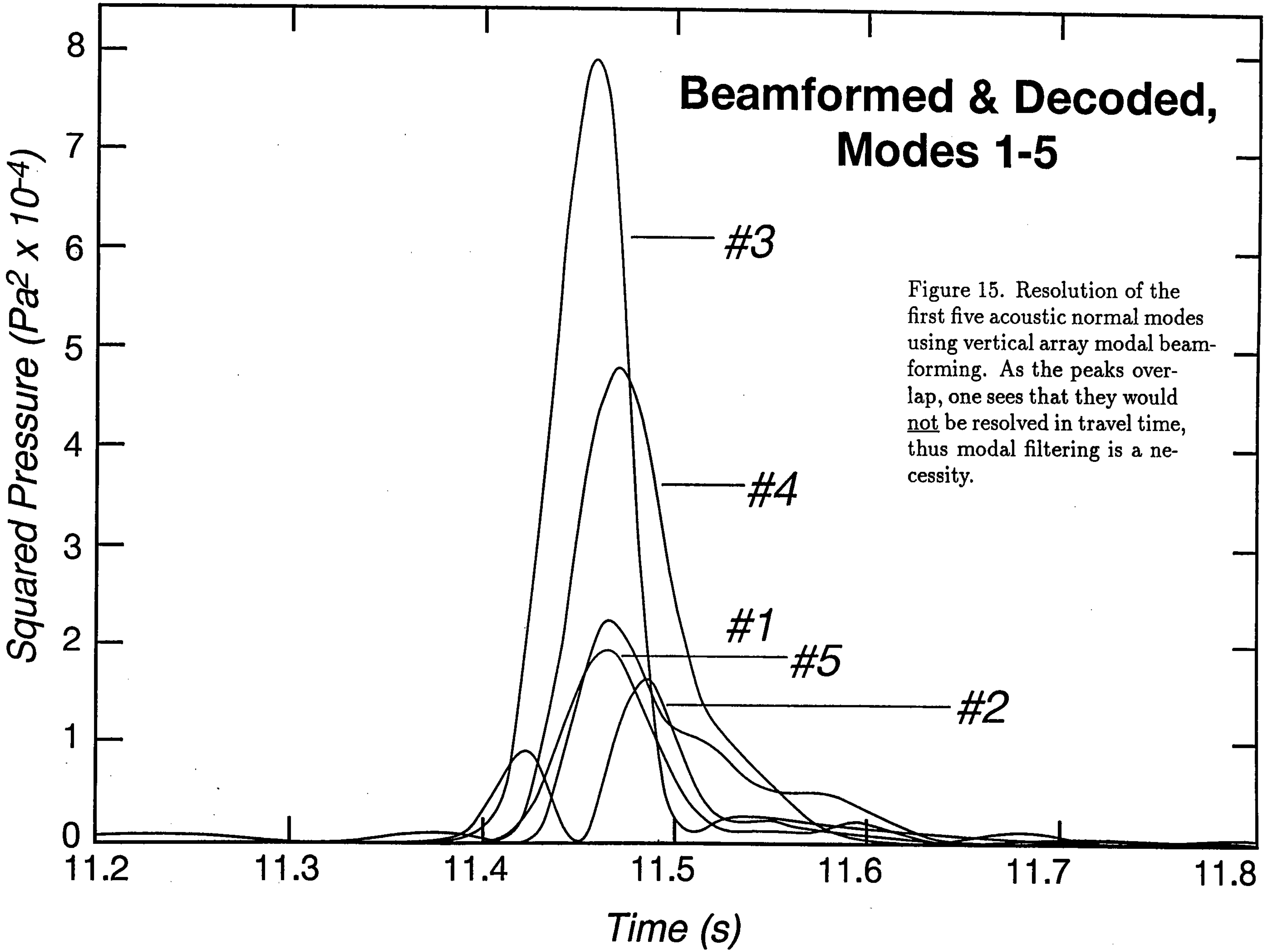
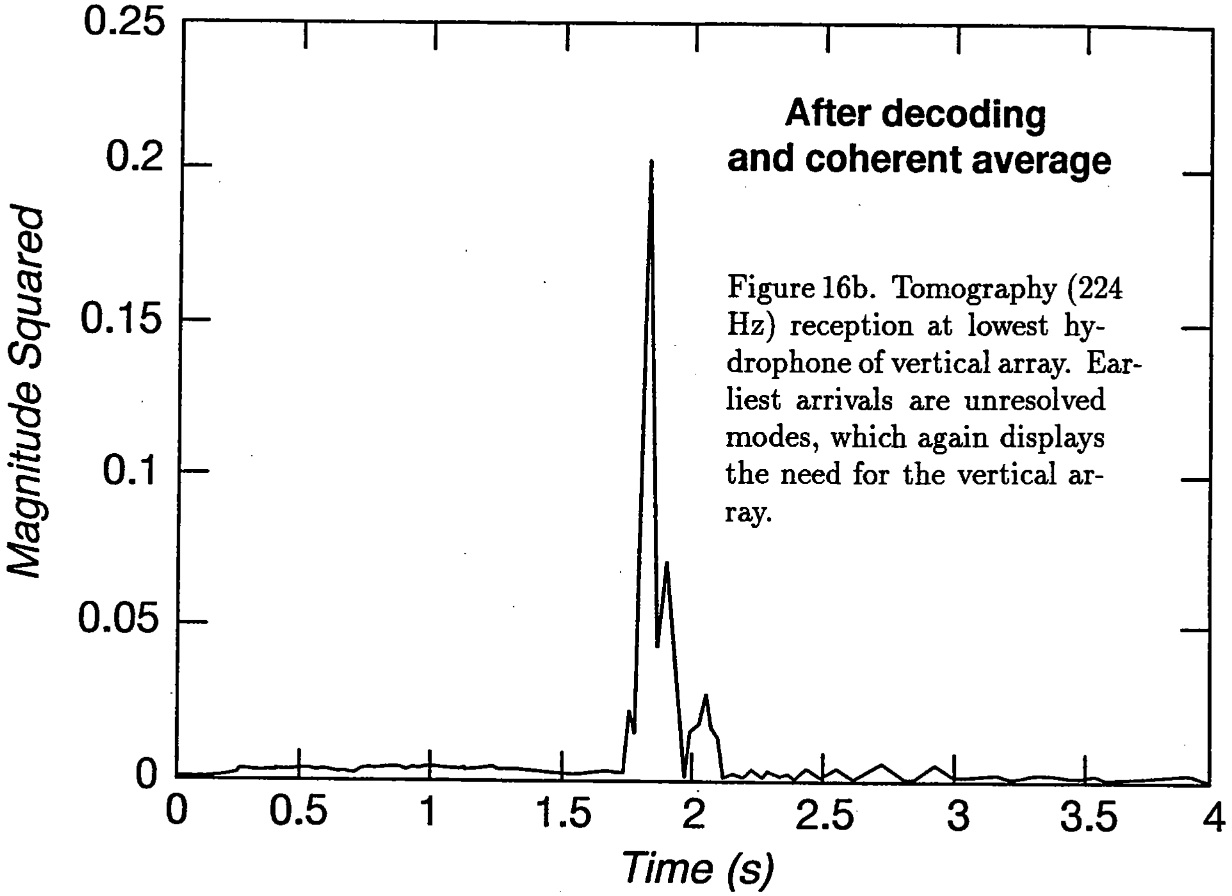
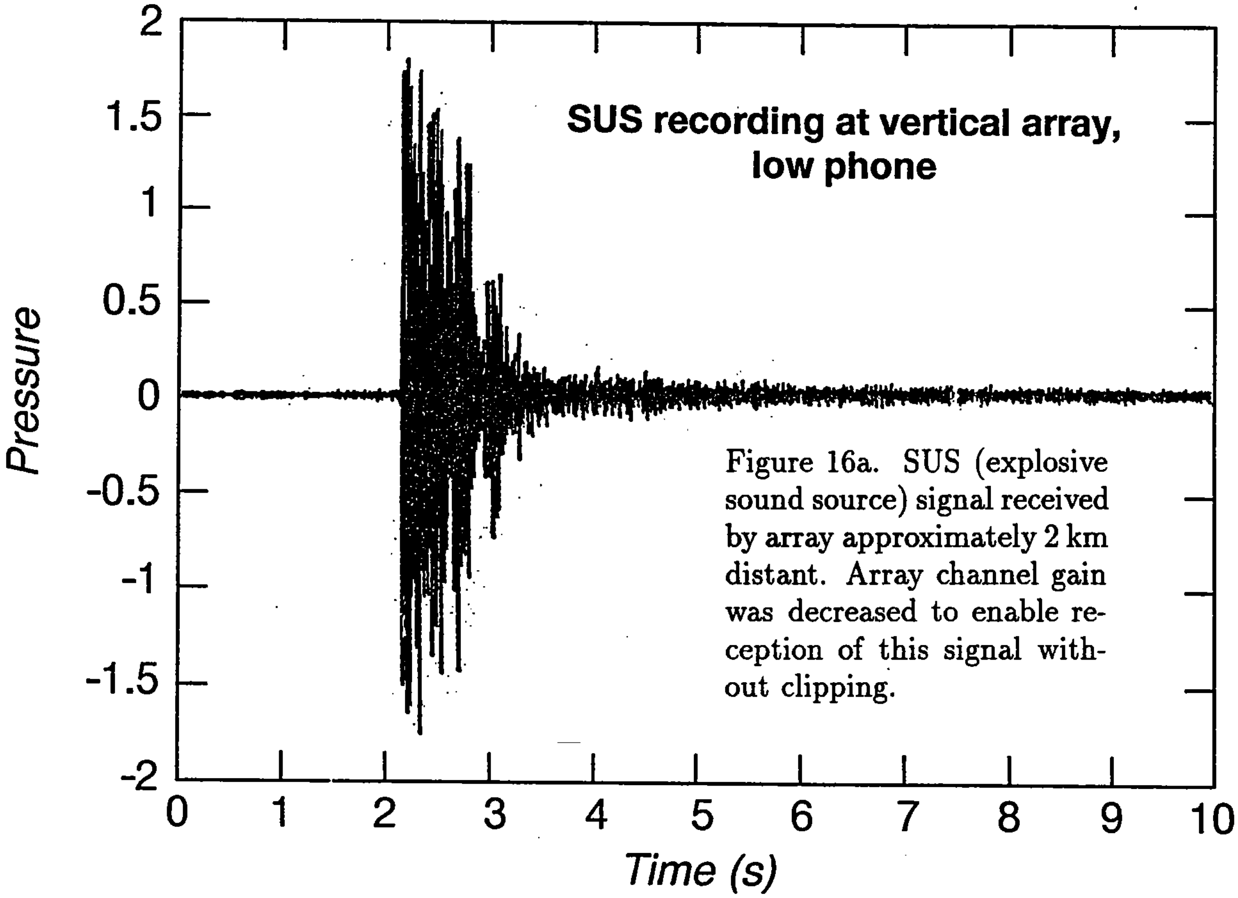


Figure 15. Resolution of the first five acoustic normal modes using vertical array modal beamforming. As the peaks overlap, one sees that they would not be resolved in travel time, thus modal filtering is a necessity.



After decoding and coherent average

Figure 16b. Tomography (224 Hz) reception at lowest hydrophone of vertical array. Earliest arrivals are unresolved modes, which again displays the need for the vertical array.



SUS recording at vertical array, low phone

Figure 16a. SUS (explosive sound source) signal received by array approximately 2 km distant. Array channel gain was decreased to enable reception of this signal without clipping.

Table 1
Barents Sea Vertical Hydrophone Array Connections

ARRAY CH#	ARRAY SENSOR#	ARRAY COND#	ARRAY COLOR	ARRAY FUNCTION	DISTANCE FROM END	IMPULSE PIN#	DB37S PIN#	DB25P PIN#	ARRAY CH#
0	1	3	orange	POS/SIG	10m	1	1	24	0
		2	red	NEG/GND		2	2		
1	2	1	brown	P	20m	3	3	10	1
		7	violet	N		4	4		
2	3	4	yellow	P	30m	9	9	21	2
		5	green	N		8	8		
3	4	18	green	P	40m	7	7	7	3
		17	black	N		6	6		
4	5	16	yellow	P	50m	5	5	18	4
		15	black	N		10	10		
5	6	14	orange	P	60m	11	11	4	5
		13	black	N		12	12		
6	7	12	red	P	70m	13	13	15	6
		11	black	N		14	14		
7	7	10	brown	P	80m	15	15	1	7
		9	black	N		22	22		
8	8	39	black	P	90m	21	21	12	8
		38	white	N		20	20		
9	9	37	gray	P	100m	19	19	23	9
		36	white	N		18	18		
10	10	35	violet	P	110m	17	17	9	10
		34	white	N		16	16		
11	11	33	blue	P	120m	23	23	20	11
		32	white	N		24	24		
12	12*	31	green	P	130m	25	25	6	12
		30	white	N		26	26		
13	13	29	yellow	P	140m	27	27	17	13
		28	white	N		28	28		
14	15*	27	orange	P	150m	33	33	3	14
		26	white	N		32	32		
15	17	25	red	P	160m	31	31	14	15
		24	white	N		30	30		
		20				29			
		8				34			
		21				35			
		22				36			
		23				37			

- Wire size is #26, nominally 42 ohms/1000 ft. The measured resistance of one conductor of the CH 0 pair the entire length (4887 ft) is 200 ohms.
- The cable contains 39 identical conductors, layed up (untwisted) in 3 concentric lays with a twist to the entire bundle estimated to be about 2 feet.
- Breakouts start 10m from the outboard end with CH 0, 1 breakout per 10m and a total of 16 using 32 conductors.
- The pin on the breakout connectors is the GROUND side of the connection. The socket of the connector is the POWER/SIGNAL connection.
- (*) CH 12 is unshielded, CH 15 breakout was fixed

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15. Supplementary Notes

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16. Abstract (Limit: 200 words)

This report describes the application of a new technique of digital radio telemetry, based on a recently available wireless Local Area Network Ethernet adapter, to the need for realtime transmission of data from a vertical line array (VLA) of hydrophones to a nearby ship. The report is technical in nature and discusses the design and performance of the system as used during the Barents Sea Polar Front Experiment in August 1992. A key feature of the use of LAN technology in a "telemetry" application is the availability of Transmission Control Protocol (TCP) software for Ethernet hardware that greatly eases the task of achieving error free digital data over a radio link prone to dropouts.

17. Document Analysis a. Descriptors

1. digital radio telemetry
2. shallow water tomography
3. vertical hydrophone array

b. Identifiers/Open-Ended Terms

c. COSATI Field/Group

18. Availability Statement

Approved for publication; distribution unlimited.

19. Security Class (This Report)

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20. Security Class (This Page)

21. No. of Pages

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22. Price

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