Theoretical and Computational Acoustics
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What Theory Doesn't Tell You About Array Design: The Environmental Factors

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Ocean acoustic arrays have long been used to measure ambient noise and estimate environmental parameters. At specific experiment locations, environmental factors such as water currents, tidal energy, surface waves, ambient noise and reverberation characteristics affect optimum array design. Innovations in the size and cost of array systems for ocean acoustic applications have emerged in response to declining research dollars and large spatial and temporal scale experiments, such as the acoustic monitoring of temperature. The low-cost aspect of these systems, however, is predicated on keeping changes to existing designs to a minimum, and designing systems which are easily modified. A case study is used to describe such an array system and the modifications driven by the intended environment as well as by the recording system interface.

1. Introduction

The paucity of long-term ocean acoustic measurements can be attributed, in part, to the prohibitive costs associated with instrumenting the world's oceans. Recent developments, however, have led to pilot studies and experiments involving large spatial separations and many acoustic sources/receivers for extended periods of time, such as for the acoustic monitoring of temperature [1,2]. Additionally, innovations in the size and cost of array systems for more conventional ocean acoustic applications have emerged in response to declining research dollars. For real-time data over large spatial and temporal scales, system cost is driven by mundane technical issues including recording/retrieval methods, and system deployment and longevity concerns. To address these issues and still contain system costs, a light-weight, low-power array system has been developed and tested in the Arctic [1,3]. This array system is also low-cost provided modifications are minimal. This paper addresses such modifications in system components effected by environmental and recording constraints for a particular case study.

Costs for array systems required to obtain these measurements, however, can be prohibitive and are driven by technical issues including number of arrays, deployment methods, power/battery requirements, and data recording/retrieval methods. To address these issues, a light-weight, low-power array system has been developed and tested. During 1995, designs were implemented to increase the bandwidth of the Arctic system by nearly an order of magnitude from 60 Hz to 500 Hz. The Arctic system had been originally designed to facilitate changes to the number of sensors, bandwidth and aperture. The anti-aliasing filters of the 60 Hz system had been designed to this effect, such that a change in bandwidth required only replacing 5 capacitors in the 5-pole elliptical filter. The electro-optic node contained the timing and array interface parameters in a programmable logic device (PLD) which need only be reprogrammed.

With the flexibility built into the array system, and the planned increase in system bandwidth to meet the specifications of 100 m aperture, 16 element, 500 Hz HLAs for the Arctic project, other applications were easily within reach. In specifying array parameters for future systems, however, care must be taken to consider the effect of the experimental objectives and the environmental parameters of the experiment location on the specific array design. A case study is used to examine this concern, commencing with a brief description of the original arctic system, the new application to measure acoustic effects of internal waves, a discussion of the modifications required to adjust system parameters to the current, surface wave and ambient noise environment of the new location, the interface with an existing recording system, although not the recording system itself, and the final array system description.

2. Arctic System

The Arctic system was designed for multiple apertures which could easily be configured in a distributed configuration. The general system idea was to interface the time-division analog hydrophone signals to a single-board electro-optic node which digitized the signals and interleaved bit streams arriving optically from other nodes. The single system bit stream is sent to the ice, or could be sent optically long distances to a terminus on shore, for recording.

The array is designed such that all sensor outputs, whether they respond to acoustic pressure, environmental parameters such as temperature, or generate known signals for testing, interface identically to the node on a single analog line. This facilitates the node design and provides an extremely flexible array configuration as any sensor may be placed anywhere along the array cable.

The four-wire array cable consists of a common ground, an analog data line, and a differential clock signal generated by the node. All sensors have identical multiplexer circuits which monitor the clock signal and respond with an analog voltage by closing a switch during the time corresponding to their address. All sensors on a subarray have a unique address, identified simply by counting clock pulses after the reset pulse. Each clock period corresponds to data from a different sensor, sampled sequentially by the node as time-division analog multiplexed signals.

The Arctic hydrophone elements have a response of -196 dB//mPA/$\sqrt{Hz}$, 40 dB of fixed gain, a variable gain stage with four 6-dB steps (0-18 dB), and a 5th-order low-pass elliptical filter. Each element contains local batteries which can operate the sensor for up to 5 years. The multiplexer decodes command signals which are embedded in the array clock signal. The commands instruct the acoustic sensors to change gains, and control specific engineering/environmental sensors. If the electro-optic node does not send the clock signal, the array goes into a sleep state, drawing 7.5 mW, extending the system life.

The engineering sensors include an array element localization (AEL) subsystem for array shape estimations [4]. The subsystem consists of AEL receivers distributed along the VLA, a controller which sends signals to the transponders, and several (usually four) autonomous transponders which receive the controller signal and respond with an AEL receiver signal. The flight time from the controller to the transponders and back to the array can be translated into slant ranges and inverted for x,y,z positions. The initial timing and AEL command sequence is generated on the ice or shore and decoded by the node and sent to the arrays.

The node receives the downlink clock and command signals over the same single fiber trunk cable used to send the data. From the downlink clock a higher frequency master clock is generated and the embedded commands are decoded and sent to the arrays. Each node is configured for two subarrays; the analog section contains two 16-bit analog to digital converters (ADC). The node is designed to be powered by an external battery pack for extended periods of time (months to years).

2.1. SWARM 95 Application

The SWARM 95 experiment scheduled for August 1995 in about 50 m of water off the coast of New Jersey, was planned jointly by Woods Hole Oceanographic Institute (WHOI) and Naval Research Laboratory (NRL) to investigate the acoustic effects of internal waves. During preliminary discussions with WHOI, it appeared that only minimal modifications were required to accommodate preliminary specifications of a 45 m aperture, 16 element, 500 Hz system to support this experiment, given that modifications to meet the 500 Hz bandwidth specifications of the Arctic system were already underway. This liaison would provide a synergistic opportunity to test the new HF arctic sensor design while providing an inexpensive measurement array for WHOI during the experiment. Anticipated surface currents would require a working tension of 90 kg, which could easily be attained by increasing the kevlar strength member. The interface for the array system would require a simple rerouting of the Manchester encoder output to the WHOI recording system rather than the normal conversion to optical signal. These small modifications accumulated however, as the intended environment was investigated and the interface between the array system and the recording system was examined and discussed. The modifications required to meet experimental objectives in the specified location and to interface with existing recording system design criteria are described. A system description for the SWARM experiment WHOI/NRaD array is also provided.

2.2. SWARM Array Modifications for Environment and Experiment Objectives

The only environmental measurements available for assessment of the expected environment were from the winter rather than the summer season and were viewed with some skepticism. Water motion was described as approximately 25 cm/sec currents (probably tidal), and a 5-sec dominant wave period with a significant wave height of approximately one meter, hence the rationale for increasing the array breaking strength to 454 kg. Nominal ambient noise levels in the 50-100 Hz band were reported at 90-100 dB// μPa/$\sqrt{Hz}$, much higher than the 80 dB//μPa/$\sqrt{Hz}$ Arctic levels. Narrowband source levels of 125-130 dB//μPa/$\sqrt{Hz}$ were expected at the array. These parameters effected a number of modifications in the array.

The water motion affected array tensions, strum characteristics, and low frequency acoustic input levels. To accommodate the required increase in array tension, the breaking strength of the kevlar was increased by a factor of four and the anchor and float terminations were modified. The expected water currents and increased array tension were used to determine new fairing characteristics to mitigate array strum. The benefits of array strum reduction were weighed against the modeled predictions of array tilt due to increased drag and the required adjustments in fabrication methods to accommodate the increase in fairing hair density. The sensor shape was also evaluated in light of the expected water motion. The fin-shaped sensors were designed to align themselves into the flow to reduce potential strum and water flow (vortex shedding) noise. Alignment with the nominal Arctic currents of 6-8 cm/s toward the east and a 10 cm/s 25 hour tidal component, produced a slow insignificant wave in the mechanical sensor response. Aligning with the 5-second swell expected off of New Jersey however, had the unsettling potential of causing the array to twist itself up in a knot if each of the 7000/day swell-induced oscillations caused a full revolution of the sensor. Without actual current profiles and time-series, an accurate estimate of the array motion was not possible and a 3-element backup array with cylindrical sensors was fabricated and tested.

The preamp gain was lowered and the high-pass filter cut-off frequency was increased to insure the pressure signal from the 5-sec swell would not overload the first stage of the sensor. Assuming a 1 m worst case wave height, the signal seen by a phone just below the surface would be over 195 dB//μPa. Circuit time-domain, transient and frequency responses were modeled to evaluate system impact and optimize the time required to implement the changes on existing boards. Nevertheless, the preamp modifications introduced an unacceptable dc-bias, which was removed by capacitively coupling the signal to the next stage. The affect of the additional capacitor on circuit stability and high-pass filter characteristics had to be accounted for in the overall circuit response.

The preamp modifications also increased the system noise levels. The Arctic array sensors are built with a total of 4 hydrophones wired 2 in series to increase the sensitivity (-196 dBV/μPa) and 2 in parallel to lower the input preamp noise. The SWARM array was built with only 2 hydrophones in series (-190 dBV/μPa) since the extra capacitance provided by the series phones was not required due to the high ambient noise and the reduction in components saved time in fabrication.

The downward refracting sound speed profiles, the expected ambient noise levels, and the smaller array aperture can affect the acoustic element localization (AEL) subsystem. Simulations were run to investigate an appropriate transponder geometry and depth for the acoustic propagation environment. The gains of the AEL receivers along the array and the transponder receive gains were reduced by approximately 12 dB, and the transponder delays were increased to accommodate the ambient noise predictions, the high reverberation environment and the peculiarities of the WHOI surface navigation system.

3. Recording System Interface

Additional modifications to the node were implemented to accommodate the interface to the WHOI recording system. The original system design for the Arctic was built to accommodate two subarrays and multiple nodes for a distributed array aperture. The SWARM system required a single vertical array; there was no need for the second array input. In previous tests with single VLAs, the second array input was simply recorded as zeros and only the valid data was processed. Because the WHOI recording package was autonomous, additional constraints were placed on acceptable power and memory capacity requirements.

To minimize node power, all components for a second subarray input were removed, as was the Manchester encoder chip which interfaced to the optical data transfer subsystem. In its place, a daughter board with an RS422 driver circuit containing a new low power crystal oscillator circuit was installed. Although originally an optical isolator was discussed to minimize subsystem interference, the 1.6 Mb/sec data rate was too high for available off-the-shelf components and the RS422 standard was selected instead.

To maximize memory efficiency, the most effective modification was to provide a gated "valid data clock" from the node, which the recording system could use to initiate storage. This reduced the amount of recorded data by nearly half but required software modifications to the node PLD. Other PLD changes were implemented to provide available information to assist in data reduction such as the number of words per frame, and a sync select which is used for frame synchronization. All signals were transmitted to the recording system via RS422.

The data format changes imposed by implementing the gated clock and modifying the number of sensors/scan necessitated updates to the system checkout and validation equipment, including the node simulator, array simulator and lab integration test and recording system.

The system commands in the original arctic design originated from an operator console. Because the WHOI recording system was autonomous, commands either had to be disabled (sensor calibration clock), implemented by jumpers (variable gain), or generated automatically by the node. The flexibility of the microprocessor and was utilized in generating commands to the acoustic element localization (AEL) subsystem. Node command select jumpers were modified to perform selectable AEL functions such as setting the time between AEL commands to either a 5 or 30 minute interval to accommodate the high reverberation environment, and setting the desired array gain in four 6-db steps. The AEL command sequence to activate the controller and turn on/off the AEL receivers was generated by the node microprocessor in a series of 19 steps.

The final interface was in the physical packaging for deployment, insuring proper connectors and interface cables between the array, node, AEL controller, battery pack and a node isolation box for installation within the WHOI deployment package.

4. WHOI/NRaD Array System Description

The array system consists of the time-division analog multiplexed array, the electronics node, and the AEL subsystem. The array is 45 m in aperture with 20 data channels (Figure 1) described as: 16 acoustic channels, two engineering channels, a command/status channel and a sub-muxed channel. The two engineering channels are a mid-amplitude sinusoid for channel-to-channel crosstalk evaluation, and a hydrophone-simulated channel which has a capacitor rather than a hydrophone for system noise measurements. The sub-muxed channel has signals from 3 AEL receivers and 3 DC signals (+max, -max, gnd) sampled at the low rate (defined below), and an accelerometer sampled at the medium rate (defined below). The pre-amp gain is set to 15 dB to accommodate the expected acoustic levels, with 4 different gain settings which can be changed with jumpers on the node board, as shown in the system gain block diagram in Figure 2.

The system calibration parameters are derived from measurements taken at Transdec, a local acoustic calibration facility, where working standards are traceable to the USRD facility in Orlando, FL. The complete array of 16 hydrophone channels was calibrated at two frequencies using the actual node amplifier and ADC. Sensitivity corrections as a function of pressure and temperature were not measured for these sensors, but are expected to be negligible based on test results of past, similar units and the shallow water environment. If S(f) is the overall system sensitivity as a function of frequency for a given acoustic channel and gain setting (dbV/μPa), S1 is the measured overall system sensitivity (dBV/μPa) measured at Transdec at 224 Hz, 5.5 m depth and 23.1 degrees C, and S2 is the sensitivity correction as a function of frequency for any acoustic channel, at any gain, relative to that at 224 Hz, then the channel sensitivity is S(f) = S1 + S2, where S1 and S2 are tabulated in Tables 1 and 2 below. The hydrophone sensor directivity pattern was also measured at Transdec for 224 Hz, 400 Hz and 500 Hz and showed less than 1/4 dB variation with azimuth at all gains.

The hydrophone channels are sampled at 2.0 KHz, four times over sampling for a high frequency 3-dB cut-off at 500 Hz, and a low frequency 3-dB cut-off at 15 Hz. The measured frequency response of a representative hydrophone channel is shown in Figure 3. With the variable gain set to 2 (6 dB), the equivalent broadband noise that a hydrophone channel can measure without overloading is shown in Figure 4a. Also shown in this figure is the expected ambient noise level at the experiment location and the measured pre-amp noise levels as referenced to an equivalent acoustic input as a function of frequency. The equivalent tonal system levels, which can be measured by this array without system overload are shown in Figure 4b, along with the signal level of a 1-m surface wave and the source levels scheduled for the SWARM 95 experiment.

The AEL system consists of 3 receivers listening at 32 KHz for pings from the 4 autonomous transponders who listen for pings at 24.7 Khz from the controller which is initiated by the node. AEL sequence repetition rate is set to 5 minutes (or 30 minutes also jumper selectable), and since the experiment location is a high reverberation area, the unique transponder delays were anticipated to be set at over 4 seconds each. The actual transponder delays at 32KHz of 4, 12, 20 and 28 seconds were specified to accommodate the WHOI surface navigation system. Source level at the controller (the pinger activated by the node which sends the 24.7 KHz pulse) and for the transponder replies are set at 186 dB// μPa, to be deployed at a nominal horizontal distance of 100 m.

The node creates the data bit stream format and transmits the signals (power, gated data, sync-select and gated clock) to the recording system via an RS422 interface. The sensor locations physically (on the array) and within the bit stream are shown in Table 1. The data words are 16 bits in NRZ format (rather than the usual 20 bits from the Manchester chip). A data frame consists of 64 scans of all 20 channels (assuming a gated clock) plus one sync word (16 bits each) per frame. The high bandwidth (i.e. hydrophones) sample rate is 2.0 KHz resulting in a 25 msec slot width for each of the 20 channels. Channel 19 contains the sub-multiplexed data: the medium bandwidth sub-muxed sample rate is 125 Hz (accelerometer), the low bandwidth sub-muxed sample rate is 31.25 Hz. The frame period is 32 ms, there will be 20 16-bit samples per scan, 64 scans per frame plus the sync word. This amounts to 1281 words per frame or 640K bit/sec gated transfer rate to the recording system. Since the node clock was originally configured for two arrays, it is clocking at 1.6 Mhz.

5. Discussion

Although an array system with no modifications is by far the least expensive, to produce the most effective measurement tool, the environment of the experiment must be assessed. The water motion parameters including a current profile, tidal energy estimations, and surface wave characteristics require array system modifications for good array performance. Specifically, increased water motion requires an increase in the breaking strength of mechanical linkages. Water motion past the sensors will produce vortex shedding and flow noise past the array cable will increase array drag and strum, requiring an increase in fairing hair density. The increased hair density will also increase the array drag characteristics which causes vertical array tilt. Large surface waves create low frequency pressure fluctuations which affect the pre-amp gains and the high-pass filter cut-off frequency. Sensor shapes which mitigate vortex shedding noise (fin shape) could cause the array cable to twist if subjected to swell-induced revolutions.

Ambient noise levels, sound speed profiles and expected reverberation will affect the acoustic element localization subsystem. The AEL transponder delay and sequence times were increased to accommodate the increased reverberation. The AEL transponder locations are optimized based on the array aperture and configuration and local sound speed profiles. The horizontal distance of the transponders and the ambient noise levels are used to determine AEL source levels and gain settings. Ambient noise levels will also affect the system gain settings and hydrophone sensitivity specifications.

The remainder of the array system modifications were to accommodate the recording system interface, power and memory constraints, and deployment package which are to be expected for any joint system design. The WHOI/NRaD array was configured and fabricated for a joint test to demonstrate the 500 Hz arctic sensors and provide measurements during the SWARM experiment. The cost to duplicate this particular array system (acoustic array, node, AEL subsystem with NO modifications) would be around $25K. Although the modifications were numerous, many of them were simple and did not require much labor and will substantially enhance the array performance in the specified environment. The majority of the cost in the modifications were to provide a suitable interface with the recording system.

6. Acknowledgements

Tom Curtin of the Office of Naval Research provided the initiative in arranging the liaison between NRaD and WHOI. A great working relationship with Jim Lynch, Keith von der Heydt and particularly Cal Eck of WHOI was maintained throughout and appreciated. The support and assistance of Mike Zika of Polar Associates in fabricating and testing the array and of Sandra Hall of ORINCON Corp. in preparing this manuscript was invaluable. This work was supported by the Office of Naval Research.

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Table 1. WHOI/NRaD array system bit stream slot assignments and physical locations on array.

Bit-stream Sensor Slot	Sensor	Physical Location (m from bottom eye)
0	Acoustic	2
1	Acoustic	5
2	Acoustic	8
3	Acoustic	11
4	Acoustic	14
5	Acoustic	17
6	Acoustic	20
7	Acoustic	23
8	Acoustic	26
9	Acoustic	29
10	Acoustic	32
11	Acoustic	35
12	Acoustic	38
13	Acoustic	41
14	Acoustic	44
15	Acoustic	47
16	Capacitive Short	36.6
17	Sine Wave	30.5
18	See below	-
19	Sub-muxed	See below

Slot 18 - Recorded Data

Scan Number	Word Number	Description
0	18	Status Word
1 through 57	-	Empty
58	1178	Frame Count Wd1
59	1198	Frame Count Wd2
60 through 62	-	Empty
63	1279	Last Command

Slot 19

Scan Number	Repetition Rate	Sensor	Physical Location (m) from bottom eye)
0	32 times per frame (every 4 scans)	Accelerometer	24.5
3	Once per frame	AEL #1	3.5
7	Once per frame	DC Pos Cal	42.5
11	Once per frame	DC Neg Cal	6.5
15	Once per frame	DC Gnd Cal	21.5
19	Once per frame	AEL #2	18.5
23	Once per frame	AEL #3	45.5

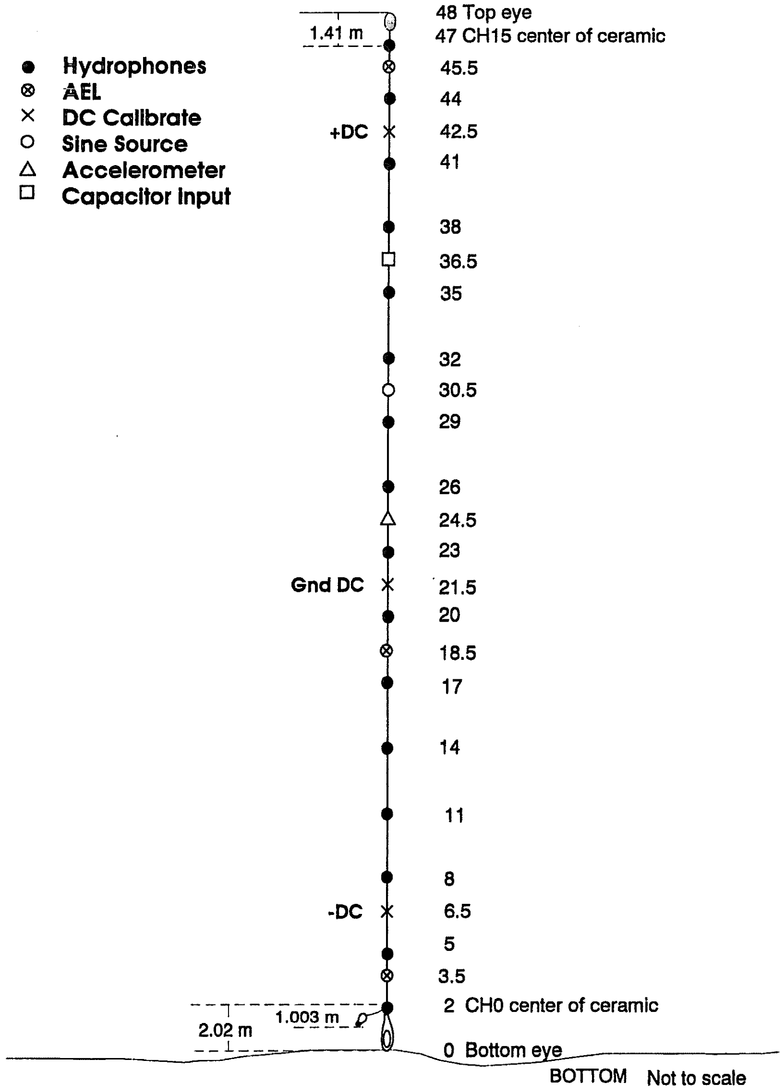

Figure 1. WHOI/NRaD SWARM '95 Array. The figure shows the location of each sensor in meters on the right.

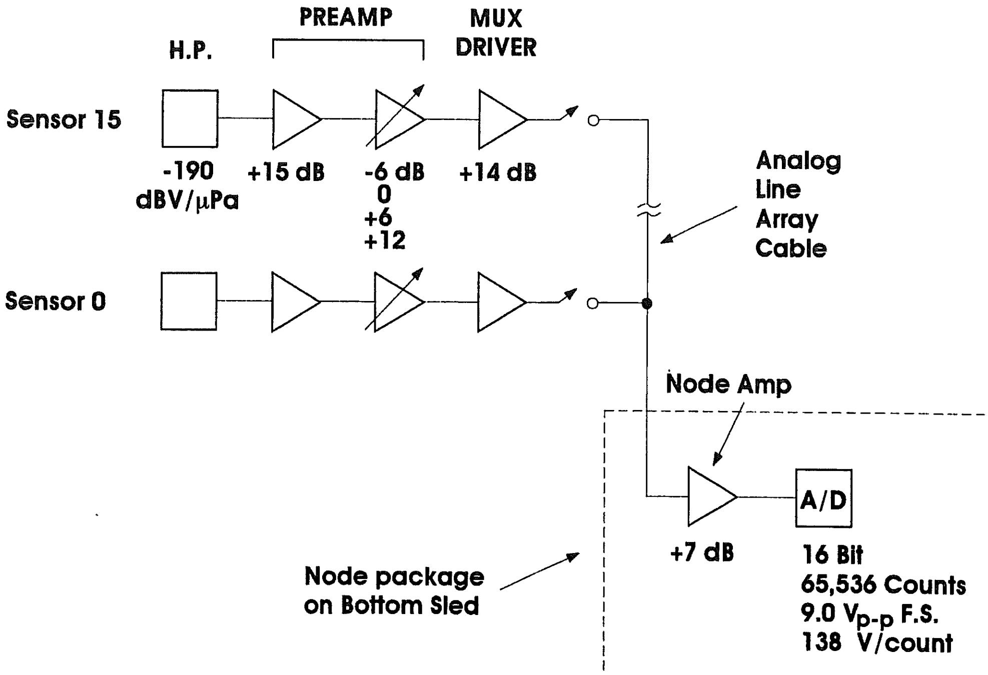

Figure 2. System gain block diagram.

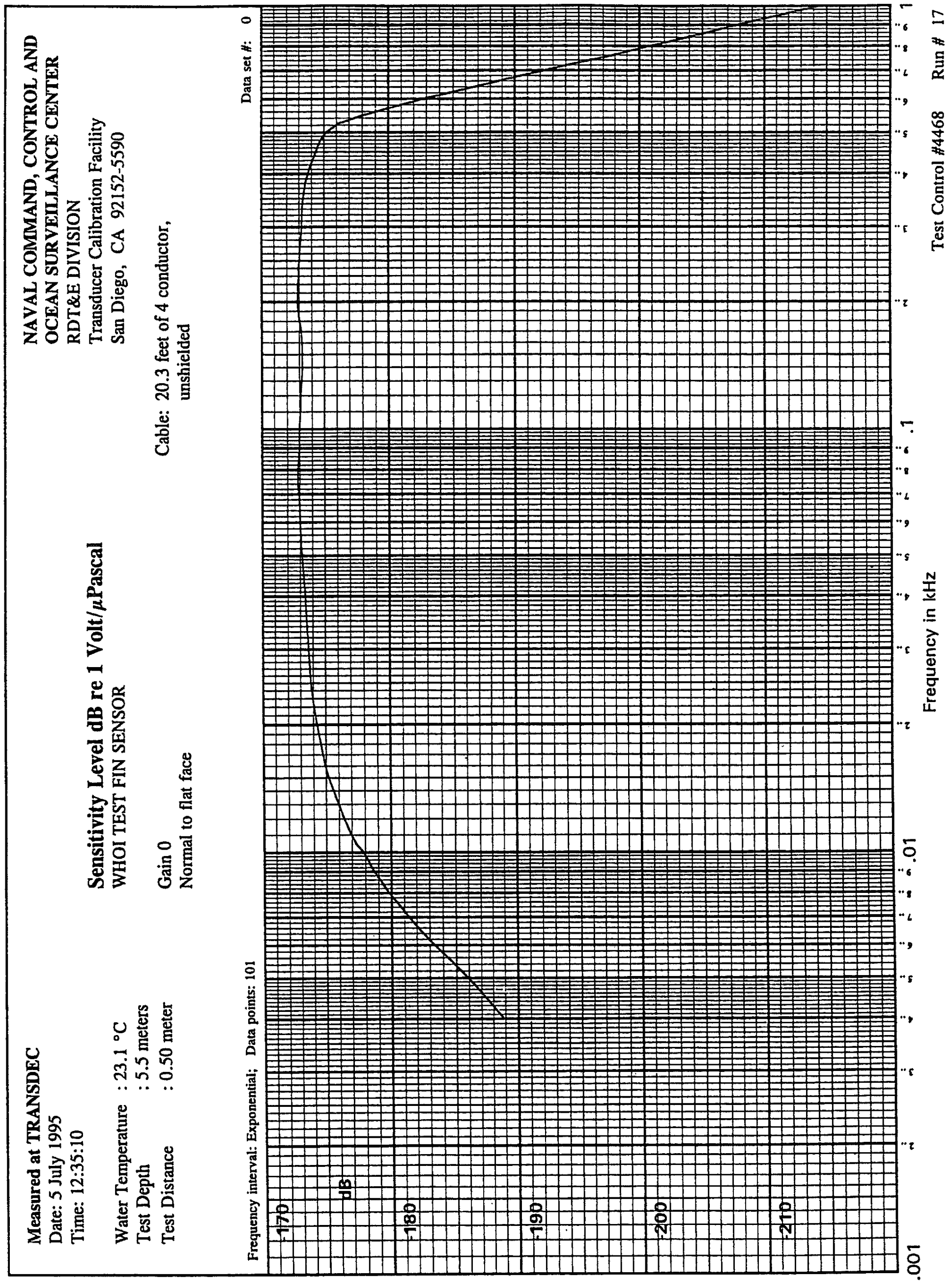

Figure 3. Measured frequency response for representative hydrophone.

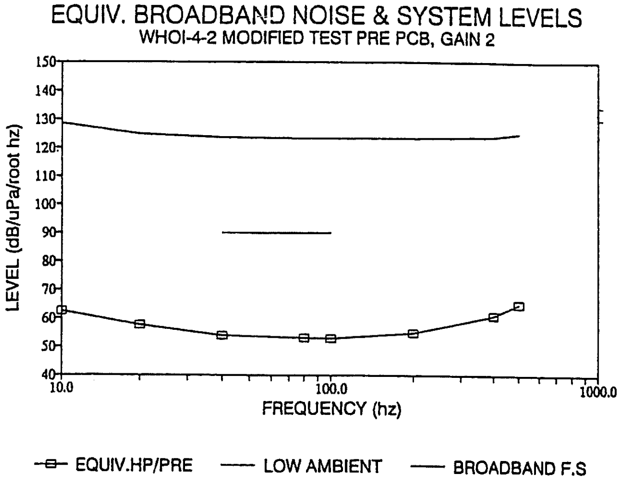

Figure 4. Equivalent input and system levels. a) equivalent maximum broadbandd noise, expected ambient noise and pre-amp self-noise

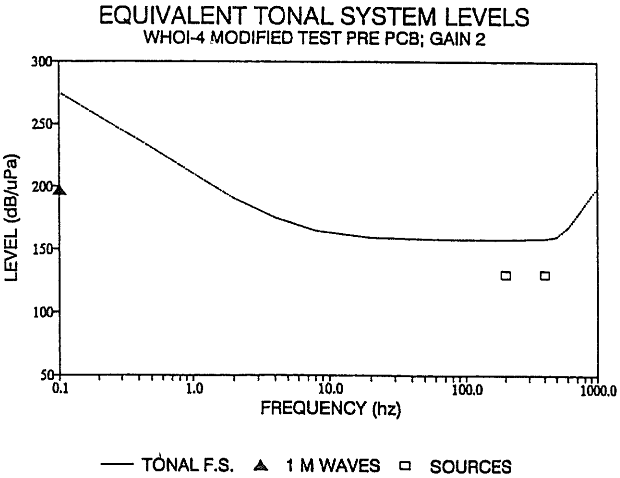

Figure 4. b) equivalent maximum tonal levels, expected source levels and surface wave impact