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## I. INTRODUCTION

A parametric acoustic receiving array (PARRAY) exploits the inherent nonlinearity in the pressure-density relationship of water to achieve directional reception of low frequency acoustic waves. It can be characterized as a volumetric, virtual array synthesized in the water column between two small, high frequency transducers called the pump and the hydrophone. The directional response characteristics of the PARRAY are very similar to those of a continuous end-fire array of length equivalent to the separation between the pump and hydrophone. The maximum response axis (MRA) of the synthesized array lies along the directed line segment from the hydrophone to the pump.

The work summarized in this report is a continuation of that begun under Contract N00039-76-C-0231. The reader interested in background material is directed to the final report under that contract, which also contains an extensive bibliography.<sup>1</sup> Although the contract period for Contract N00039-78-C-0121 officially began on 6 March 1978, work performed from mid-December 1977 through 5 March 1979 is summarized in this report. This procedure is followed to permit reporting work performed before the contract period but funded from this contract under an anticipatory cost agreement.

Work performed under this contract was divided between two major tasks. The first task was part of a program to investigate mobile sonar applications of the PARRAY, and was jointly supported by Defense Advanced Research Projects Agency (DARPA) and Naval Sea Systems Command (NAVSEA). Equipment and technology from the preceding long baseline PARRAY development (described in Ref. 1) were utilized to construct a short baseline PARRAY for installation and tests aboard the research submarine USS DOLPHIN (AGSS 555). Work on this task is summarized in Section II.

The second task was the design and construction of hardware for a large aperture, bottom mounted PARRAY to be tested at a sea site in a subsequent phase of the program, which will cover installation of the equipment, performance of the sea tests, and analysis of sea test data. This task was jointly supported by DARPA and Naval Electronic Systems Command (NAVELEX), Code 320.

Initial plans were to install and test the experimental long baseline PARRAY at a site near Bermuda. Technical and logistical problems associated with the planned test near Bermuda, as well as a renewal of interest in shallow water ASW, caused the sea test site to be changed to the Stage I facility of Naval Coastal Systems Center (NCSC), Panama City, Florida. Work performed in support of this task is described in Section III.

A number of papers and reports were produced throughout the course of the contract. Brief summaries of these papers and reports are given in Section IV.

A review and summary of this report are presented in Section V.

## II. MOBILE PARRAY EXPERIMENTS ABOARD USS DOLPHIN (AGSS 555)

The success of the PARRAY development program and the results of the interim lake tests of the 340 m PARRAY encouraged DARPA to consider other potential applications.<sup>1-7</sup> Therefore, in response to an ARL:UT proposal, the program was broadened to consider mobile sonar applications of the PARRAY. Tests and experiments were performed at LTTS to investigate the feasibility of using the PARRAY as a forward looking sonar on a submarine. These measurements included the effects of vibration, nearfield noise, and a reflecting plate on the operation of a PARRAY. These experiments demonstrated that the effects of vibration are understood and predictable, and that the PARRAY provides sufficient rejection of localized nearfield noise to make the PARRAY potentially useful for submarine sonar applications.<sup>8,9</sup>

To expedite investigation of the PARRAY for mobile sonar applications, ARL:UT designed and fabricated a short baseline PARRAY for installation and experiments aboard the research submarine USS DOLPHIN. To minimize the time and cost of these experiments, design parameters were not optimized for the short baseline PARRAY. Instead, some limitations on the experiments were accepted to enable equipment and technology from the long baseline PARRAY program to be exploited more directly. The goal of the USS DOLPHIN tests was to observe the effects of operating the PARRAY on a moving platform to assess the feasibility of using the PARRAY in mobile sonar applications.

A number of pieces of hardware were either designed and constructed or were modified for the tests aboard USS DOLPHIN, with the major effort devoted to design and construction of the transducers, domes and housings, and transducer mounting pylons. In addition, a new, smaller pump power amplifier and power supply were constructed as well as a new pump signal

source. The receiver electronics were basically the same band elimination receiver design employed in the earlier PARRAY work. The new receiver for the USS DOLPHIN tests was separated into two units, a band elimination amplifier and a sideband separator and demodulator.

A list of the PARRAY hardware designed and constructed for the experiments aboard USS DOLPHIN is given in Table I. An intensive effort by a number of engineers and technicians was required to design, construct, and test this equipment in a short time period to fit the schedule of USS DOLPHIN.

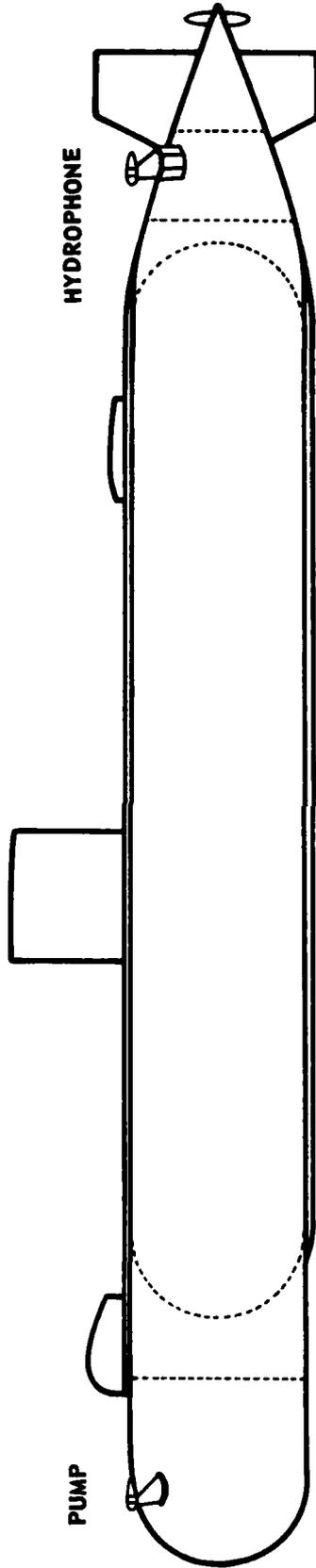
The hardware for the PARRAY tests aboard USS DOLPHIN was interfaced and integrated into an operating PARRAY. The new PARRAY was tested at LTTS to verify proper operation prior to installation and tests on USS DOLPHIN. All equipment to be installed outside the pressure hull of USS DOLPHIN was pressure tested to assure watertight integrity to approximately twice the maximum depth of planned experiments. The PARRAY hardware was packed and transported to San Diego by ARL:UT personnel, where the equipment was installed on USS DOLPHIN by ARL:UT and Naval Ocean Systems Center (NOSC) personnel.

For the measurements aboard USS DOLPHIN, two small transducers, enclosed in streamlined housings, were installed on pylons fore and aft on the port side of the boat, as shown in Fig. 1. These transducers operated at a pump frequency of 65 kHz and were approximately 0.15 m in diameter. The pump transducer was installed near the bow and approximately 1.5 m away from the hull. The PARRAY hydrophone was installed on a similar pylon located on the ballast tank aft of the pressure hull. This geometry provided a forward looking end-fire array with a 40 m aperture usable over the frequency range from approximately 100 to 3000 Hz.

Figure 2 is a photograph of USS DOLPHIN from the bow showing the external components of the mobile PARRAY hardware. Note that the foundation on which the aft (hydrophone) pylon is mounted is much larger and longer

TABLE I  
PARRAY HARDWARE CONSTRUCTED  
FOR EXPERIMENTS ABOARD USS DOLPHIN

PARRAY Pump  
PARRAY Hydrophone  
Transducer Domes and Housings  
Transducer Mounting Pylons  
Accelerometer Housings, Preamplifiers, and Buffers  
Accelerometer Receivers  
Pump Oscillator  
Pump Power Amplifier  
Power Amplifier Power Supply  
Power Amplifier Battery Charger  
Band Elimination Amplifier  
Receiver Processor  
Tape Recorder Calibration Unit  
Impedance Matching Network - Pump  
Impedance Matching Network - Hydrophone



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FIGURE 1  
PARRAY CONFIGURATION FOR TESTS ABOARD USS DOLPHIN (AGSS 555)

ARL:UT  
AS-78-2013  
TGC - GA  
1 - 3 - 79



FIGURE 2  
USS DOLPHIN SHOWING MOBILE PARRAY MOUNTING HARDWARE

than the foundation to which the forward (pump) pylon is attached. This is because the aft foundation had to be attached to the aft ballast tank which is in the tapered portion of the hull. Welding to the pressure hull was prohibited for safety reasons.

Accelerometers were mounted on the back of the PARRAY transducers so the vibration level of the transducers could be monitored and recorded on magnetic tape for later analysis. An omnidirectional reference hydrophone, Naval Research Laboratory, Underwater Sound Reference Division, NRL/USRD, Type F50, was mounted inside each pylon to provide a calibrated, independent measure of the ambient acoustic noise conditions at the pump and hydrophone locations. The outputs from these sensors were also recorded on magnetic tape for later analysis. This is indicated schematically in Fig. 3, which is a block diagram of the PARRAY system aboard USS DOLPHIN.

The experiments with the PARRAY aboard USS DOLPHIN were conducted in approximately 1800 m of water off San Diego, California, in March 1978. During the experiments, five dives, totaling approximately 30 h, were accomplished during which the experimental PARRAY operated without equipment failure. The outputs from the PARRAY and several auxiliary sensors were recorded on 1 in. analog magnetic tape using a 14-channel standard IRIG Wideband I tape recorder. Approximately 20 h of analog recordings were obtained with a bandwidth of 2.5 kHz on each of eleven FM channels. A reference tone was recorded on a direct record channel to permit compensation for wow and flutter of the tape recorder during analog-to-digital (A/D) conversion of the data at a later date. The twelve channels of data recorded on analog magnetic tape are identified in Table II.

These experiments are unique in that this is the first and only time a PARRAY has been operated on a mobile platform (submarine) underway at sea. The analog magnetic tape recordings of the outputs from the PARRAY and auxiliary sensors form a data bank that can be extremely valuable in assessing the potential usefulness of the PARRAY for mobile, and particularly submarine, sonar applications. Observations during testing and subsequent

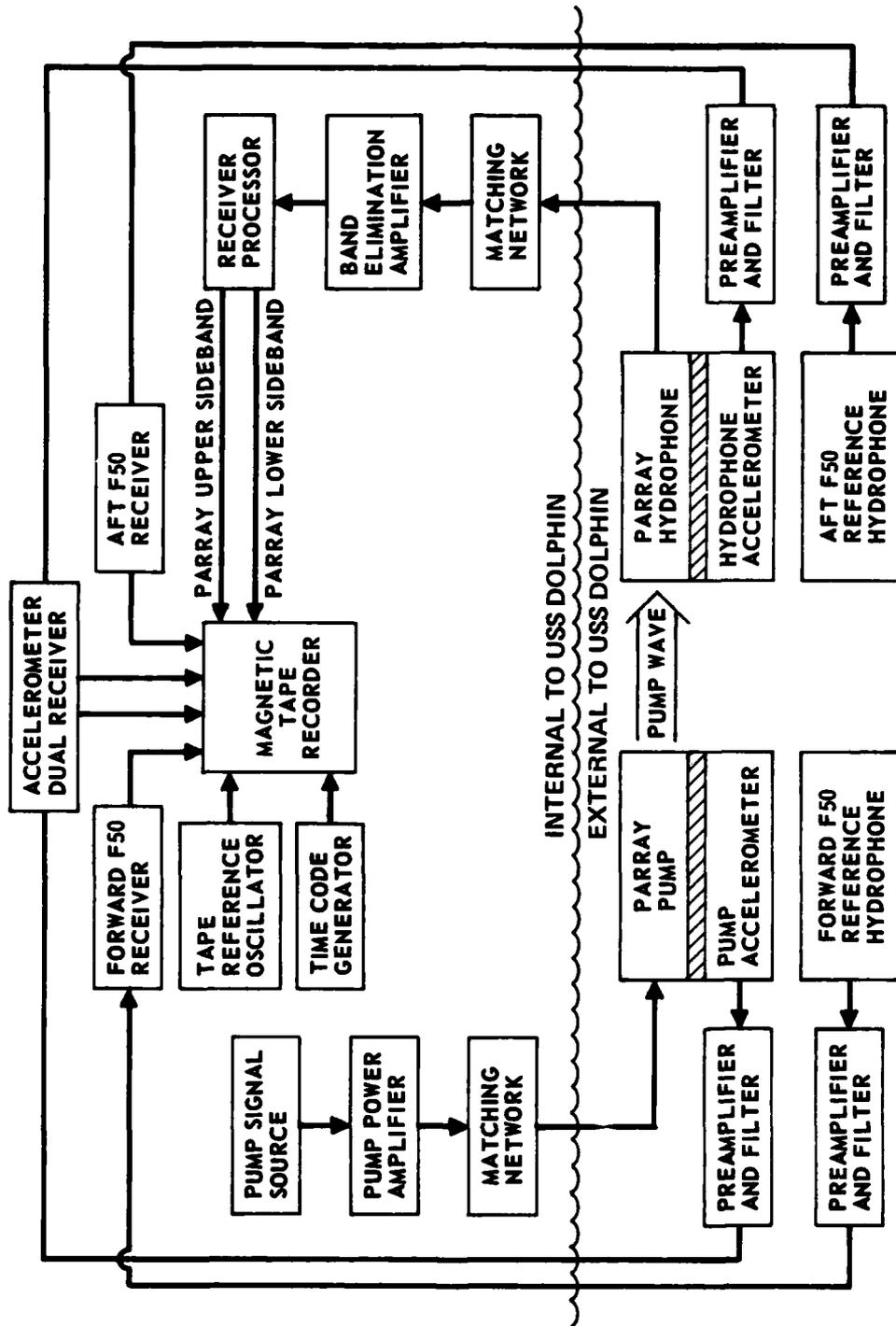


FIGURE 3  
SYSTEM BLOCK DIAGRAM FOR PARRY EXPERIMENTS  
ON USS DOLPHIN (AGSS 555)

TABLE II

SIGNALS RECORDED ON 1 in. ANALOG MAGNETIC TAPE  
DURING MOBILE PARRAY EXPERIMENTS ABOARD USS DOLPHIN

<u>Channel/Type</u>	<u>Signal</u>
2 FM	PARRAY Upper Sideband
3 FM	PARRAY Lower Sideband
4 FM	Forward F50
5 FM	Aft F50
6 FM	Forward (Pump) Accelerometer
7 FM	Rear (Hydrophone) Accelerometer
8 Direct	Reference Tone
9 FM	IRIG B Time Code
10 FM	AN/BQR-2 Audio Output
11 FM	Bow AN/BQA-8 Hydrophone
12 FM	Sail AN/BQA-8 Hydrophone
13 FM	Aft AN/BQA-8 Hydrophone

analysis of the recorded data show that the PARRAY operated as an acoustic sensor to receive acoustic signals transmitted from a distant source and that an array with processing gain was formed. Results of these experiments were reported in a paper presented at the 32nd U.S. Navy Symposium on Underwater Acoustics held at Naval Underwater Systems Center, (NLONLAB NUSC) New London, Connecticut on 14-16 November 1978. A copy of the paper was published in the proceedings of that symposium.<sup>10</sup> Additional information about the PARRAY tests aboard USS DOLPHIN is contained in Applied Research Laboratories Technical Report No. 80-8 (ARL-TR-80-8).<sup>11</sup>

### III. LARGE APERTURE FIXED PARRAY

#### A. Sea Test Site Selection

The search for a suitable site for the at-sea tests of the large aperture, bottom mounted PARRAY has been a continuing one since early in the PARRAY development program. At the beginning of this contract period, it was anticipated that such tests would be conducted at a site near Bermuda.

The Bermuda area was originally selected as the site for sea tests of the PARRAY because of the Tudor Hill Laboratory and its proximity to the deep ocean coupled with the anticipated availability of a multiple conductor sea cable at that location. At the time the plan was to install the PARRAY on bottom mounted tripods in water 500 to 1500 m deep and connected to the Tudor Hill Laboratory via the multiple conductor sea cable. However, a series of developments and compromises significantly altered these plans.

A high definition bottom survey would have been required to install the tripod mounted PARRAY on the ocean bottom. Unfortunately, a survey of the required resolution at the projected installation depths was beyond the resources eventually dedicated to the PARRAY program. The fallback position was to move to shallow water where a survey of the required resolution could easily be performed. The top of Plantagenet Bank seemed a logical choice since it is relatively flat and the PARRAY installation would be relatively easy. Furthermore, some benefits of the deep ocean site would be retained since the PARRAY could be oriented to provide an unobstructed field of view into the deep ocean basin.

As time neared for a decision on the sea test hardware configuration, it became apparent that the multiple conductor sea cable would not be available at the time required for the PARRAY sea test. The only sea

cable available at any site was a single wideband coaxial cable terminated in the Tudor Hill Laboratory and attached to an inoperative testbed array located a few miles off Bermuda. The testbed (TB) cable could be recovered and relaid to the top of Plantagenet Bank for use with the PARRAY. In response to these changes in support facilities, plans were made to design and develop a multiple channel telemetry system to operate over the wideband coaxial cable. It should be noted that although the telemetry system was not part of the PARRAY technology development, demonstration of the PARRAY technology at the Plantagenet Bank site would be critically dependent upon reliable operation of the telemetry system.

Because of uncertainties in regards to the Plantagenet Bank site, a survey of alternate test sites in the Gulf of Mexico was begun early in the contract period. Three major factors prompted the investigation. The TB coaxial cable was supposed to be recovered and relaid to the site atop Plantagenet Bank by PME 124-60 on a not-to-interfere basis. It was always understood that PME 124-60 would perform their operation and maintenance function first and that the TB cable would be moved only if time permitted. Cable relocation had been tentatively scheduled several times but each time it was deferred because of higher priority work. There was a definite possibility that PME 124-60 would not be able to move the TB cable before the PARRAY tests were scheduled. Furthermore, if the cable was moved, there was always the possibility that the cable might be damaged beyond use in recovering it and relaying it to the top of Plantagenet Bank.

Installation of the tripods and underwater portions of the PARRAY at Plantagenet Bank was to be accomplished by use of RV ERLINE, operated by the Tudor Hill Laboratory. Limited deck space and overboarding capability of the ERLINE placed severe limitations on design of the underwater portions of the PARRAY hardware.

The final area of uncertainty was the telemetry system. The telemetry system had always been one of the higher risk areas for the sea test,

but the loss of some key personnel exacerbated the problems and delayed development of the telemetry system.

It was in this context that a survey of possible alternate sea test sites was begun. For reasons of cost and logistics, the survey was limited to the Gulf of Mexico. Several oil companies, including Amoco, Exxon, and Shell, were contacted about the possibility of placing equipment and personnel aboard drilling or production platforms in the Gulf of Mexico. For various reasons none of these contacts appeared promising.

Naval Coastal Systems Center (NCSC), Panama City, Florida, was contacted about the possibility of conducting experiments from Stage I, a large Texas tower located in 34 m of water approximately 12 nmi from shore. The facilities at Stage I appeared adequate should a change in location of the sea test be required to eliminate the telemetry system or because the TB cable was not available.

About this time there also appeared to be some revival of interest in shallow water ASW. Since the PARRAY has vertical as well as horizontal directivity, it was believed that the PARRAY might be useful in shallow water ASW.

The final link in the chain of events leading to the change in sea test sites was the availability and condition of the TB cable itself. After numerous postponements and delays, the TB cable was recovered and relaid to the proposed test site atop Plantagenet Bank in October 1978. Mr. Rodney Lawrence of Western Electric, Greensboro, North Carolina, supervised the operation, which was performed from USNS AEOLUS (ARC 3). The following information was obtained in telephone conversations with Mr. Lawrence after the cable was moved.

1. A longer than expected cable run resulted because NUSC had laid another cable on top of the TB cable and Western Electric Company personnel, who laid out the new track for the TB cable, were not informed of that

fact until they were recovering the cable. As much of the TB cable as practicable was recovered and relaid to the Plantagenet Bank site. The length of the relaid cable was measured to be 38.8 nmi.

2. The TB cable was originally fabricated from many short, odd lengths of cable. The 38.8 nmi cable to the Plantagenet Bank site consisted of 15 pieces of cable varying in length from 0.033 to 7.812 nmi.

3. The cable segments from which the TB cable was fabricated were "nonconforming", i.e., the dielectric between the inner conductor and the shield varies in thickness. This variation causes the impedance of the cable to vary along its length and generates reflections of high frequency signals transmitted over the cable.

4. The length of the relaid cable was determined by measuring the transit time of a pulse. During this measurement, high levels of spurious echoes were observed. These spurious echoes were probably due to the impedance changes caused by the dielectric variations and the large number of splices in the cable.

When Mr. Donn Cobb of NUSC originally proposed the TB cable for use by ARL:UT in the PARRAY tests, it was expected that the cable run would be approximately 25 nmi. We requested that the length of the cable run be minimized because a repeater (amplifier) was not to be used. Considering the impact of cable length on the PARRAY system, a maximum cable run of 30 nmi was believed acceptable. Clearly, the 38.8 nmi cable run that resulted was substantially greater than what was believed to be the maximum acceptable cable length.

The telemetry system planned for the Bermuda experiment was described in the quarterly progress reports under the contract.<sup>12-14</sup> Considering the impedance variations and the number of splices in the cable, it appeared unlikely that the phase coded telemetry channels would function reliably with the TB cable.

As a result of the sea site investigations and the information summarized in the preceding paragraphs, it became clear that a more timely and cost effective sea test could be conducted at the Stage I facility of NCSC, Panama City, Florida, than at the Tudor Hill Laboratory, Bermuda. Sponsors at DARPA and NAVELEX were kept informed of these investigations and concurred in the decision to change the sea test site to Stage I, NCSC.

#### B. Hardware Development

The system hardware for a large aperture PARRAY developed by ARL:UT is to demonstrate that the PARRAY technology, as developed and demonstrated in a fresh water environment, is not degraded in an open ocean environment. Basic PARRAY technology developed previously under joint sponsorship of DARPA and NAVELEX<sup>1,3</sup> was used in the development of system hardware for a PARRAY sea test. As previously discussed, it was necessary to change the site for the large aperture PARRAY sea test, and hence significant changes had to be made in the system hardware to meet the requirements for a particular configuration.

The site off the coast of Bermuda entailed a long distance between laboratory space (used for data collection, power distribution, and system controls) and underwater hardware. This required a complex telemetry system to operate over a long coaxial cable in addition to the PARRAY system hardware. This arrangement also required much of the PARRAY hardware to be located in underwater canisters at the test site so that the data could be properly conditioned to meet the limitations imposed by the long data link.

With the change in test sites, as discussed in the preceding section, a revised system configuration for the Stage I site was developed. The Stage I site provided laboratory space very near the underwater hardware and thus did not require a telemetry system since short multiconductor cables could be used. Also, due to the very short cable runs, the entire

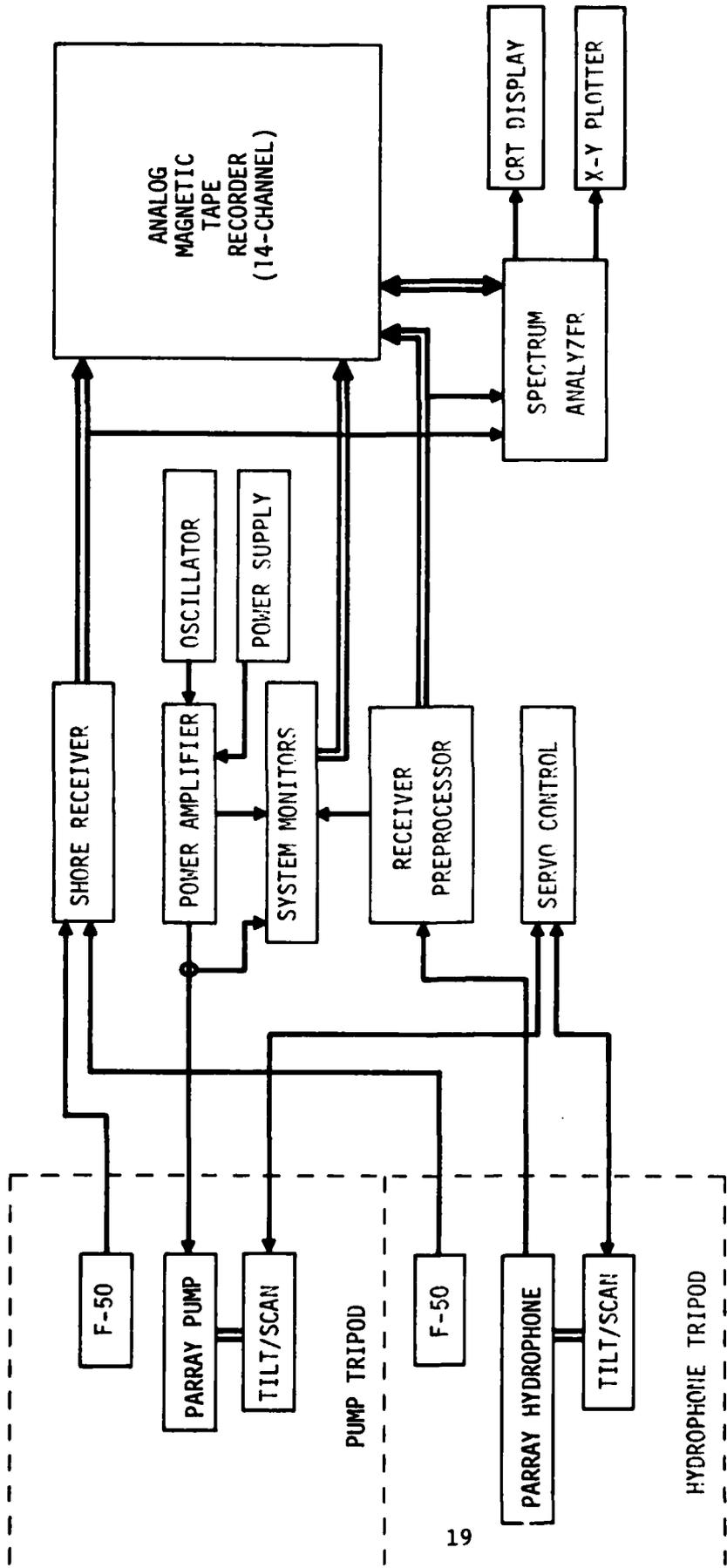
pump and receiver electronics could be located in the laboratory space, and this in turn provided a much simpler and more reliable system to operate and maintain during the sea test experiments.

Since the system configuration for the Stage I site differed considerably from that of the Bermuda site, some of the components originally developed for use at the Bermuda site, such as specific monitor and signal conditioning circuits and the telemetry system, will not be used. These subsystems had progressed to a breadboard stage but had not been fabricated in final form.<sup>12-14</sup> However, many circuits originally developed for use at the Bermuda site will be used in the Stage I system hardware. The major difference in the systems for the two sites is the data link and associated interface electronics.

The PARRAY system configuration for the Stage I site will use two bottom mounted tripods, each approximately 5 m on the side and separated by a distance of several hundred meters. The tripods will be placed approximately 30 m deep, 12 nmi off the coast of Panama City, Florida, in the vicinity of the Stage I platform. The transducers and positioning apparatus will be located on the tripods; data and control signals will be transmitted on multiconductor cables to and from laboratory space on Stage I for processing and recording. This procedure will minimize the inwater electronics and greatly increase the likelihood of a successful ocean demonstration of the PARRAY system.

A block diagram of the large aperture PARRAY is given in Fig. 4. The system will consist of four major units: the pump tripod, hydrophone tripod, Stage I PARRAY electronics, and data processing system.

The pump tripod installation will consist of the pump transducer, which projects the highly directional, spectrally pure pump signal, a tilt/scan mechanism for alignment of the pump transducer with the PARRAY hydrophone, and an ambient noise monitor (NRL/USRD hydrophone type F50) to measure the ambient noise levels during the experiments.



STAGE I INSTALLATION

FIGURE 4

PARRY SYSTEM BLOCK DIAGRAM

II:-WATER HARDWARE

The hydrophone tripod installation will consist of the PARRAY hydrophone, which will provide highly directional reception of the modulated pump signal, a tilt/scan mechanism to provide alignment between the two tripods and a noise monitor to provide another spatial sample of the ambient noise field. The signals to and from the tripods will be carried on several multiconductor cables.

The basic system parameter values for the PARRAY test at Stage I will be:

Pump Frequency	65 kHz
Power Amplifier Output	250 W
Pump Source Level	218 dB re $\mu$ Pa at 1 m
Transducer Directivity Index (Pump and Hydrophone)	30 dB
Pump-Hydrophone Separation	300 m

Data will be obtained in two ways: (1) realtime narrowband processing with an X-Y recorder output, and (2) recorded on analog multiple channel tape. The realtime data analyses will facilitate performing the experiments at sea. Additional analyses of the recorded data will be performed at ARL:UT using the PDP 11/34 data processing system developed under previous programs and used extensively.<sup>1</sup>

The system for the Stage I site required development of new hardware as well as modification of existing hardware to perform new functions.

The design of the band elimination receiver for the PARRAY system underwent significant changes to meet the requirements for the sea test. To properly evaluate system operation, monitors had to be incorporated in the receiver electronics. A carrier level monitor and carrier phase lock capability were added to allow the operator to properly interpret the carrier-to-sideband noise level and also to observe fluctuations, if any, in the carrier level. A fluctuating carrier level would contaminate

the data and possibly cause an erroneous conclusion as to system performance. A block diagram of the complete receiver is presented in Fig. 5.

The pump subsystem provides the high level pump signal for PARRAY operation. The pump signal source must satisfy stringent stability and spectral purity requirements and this purity must be preserved through all components of the pump subsystem. The design for a low noise oscillator previously developed at ARL:UT was used to build several new oscillators. Although only one oscillator is needed for the sea test hardware, the usual practice is to build several units and use the one with the lowest noise characteristics, a procedure found necessary because ARL:UT cannot screen all of the passive and active components used, and invariably some noisy components will be included in a unit. The spectrum level single sideband (SSB) noise of the unit selected was measured to be -165 dB referenced to the level of the 65 kHz primary frequency for frequencies a few hundred hertz away from the carrier. A schematic diagram of the low noise oscillator is given in Fig. 6.

A monitor was developed to permit continuous measurement of the spectral purity of the transmitted pump signal while the experiments are being performed. This is necessary to distinguish between noise components transmitted in the sidebands of the pump signal and components caused by intermodulation of signals in the water. It had been noted that power line transients and sudden mechanical shock to the pump signal source may cause undesired transients to be transmitted. These noise like signals are included in the acoustic signals received and are processed as well. The monitor consists essentially of another complete band elimination receiver with a different interface to monitor the output current of the power amplifier.

Hardware used in experiments at Lake Travis will be refurbished for use in the at-sea system. Complete system integration, lake testing, and sea testing of the PARRAY hardware will be accomplished under a subsequent contract.

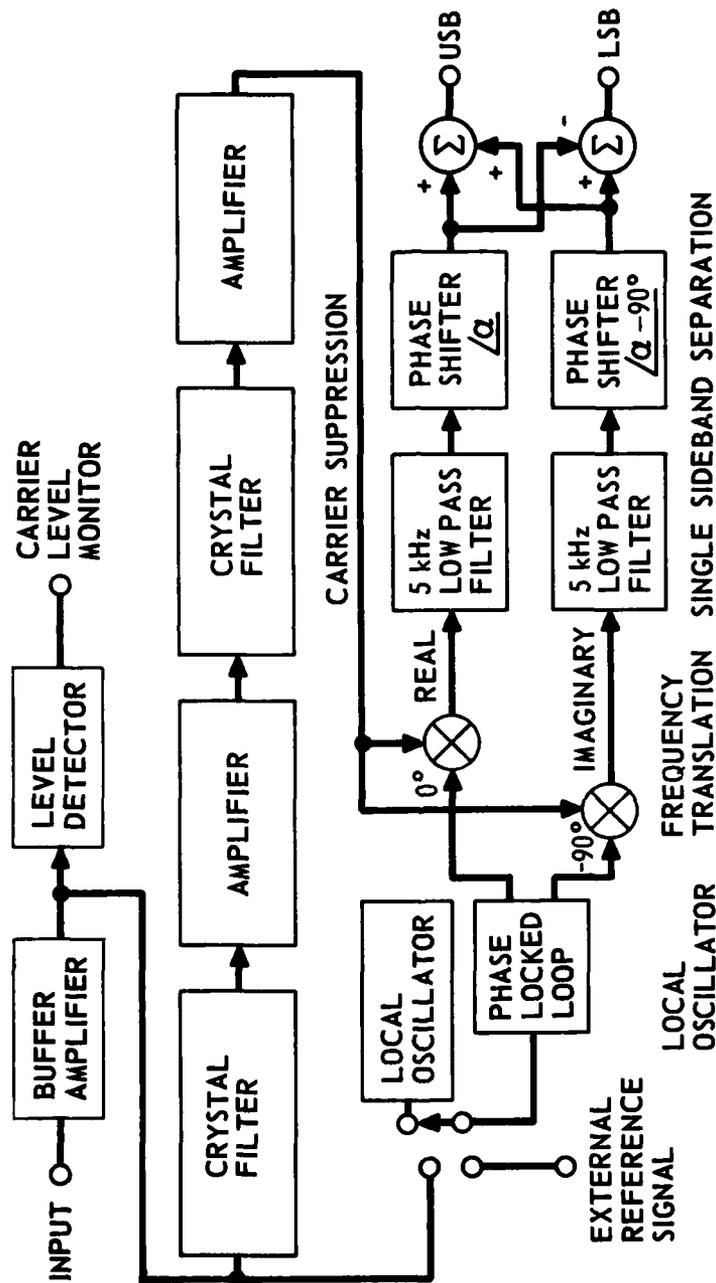


FIGURE 5  
RECEIVER FOR STAGE I EXPERIMENT

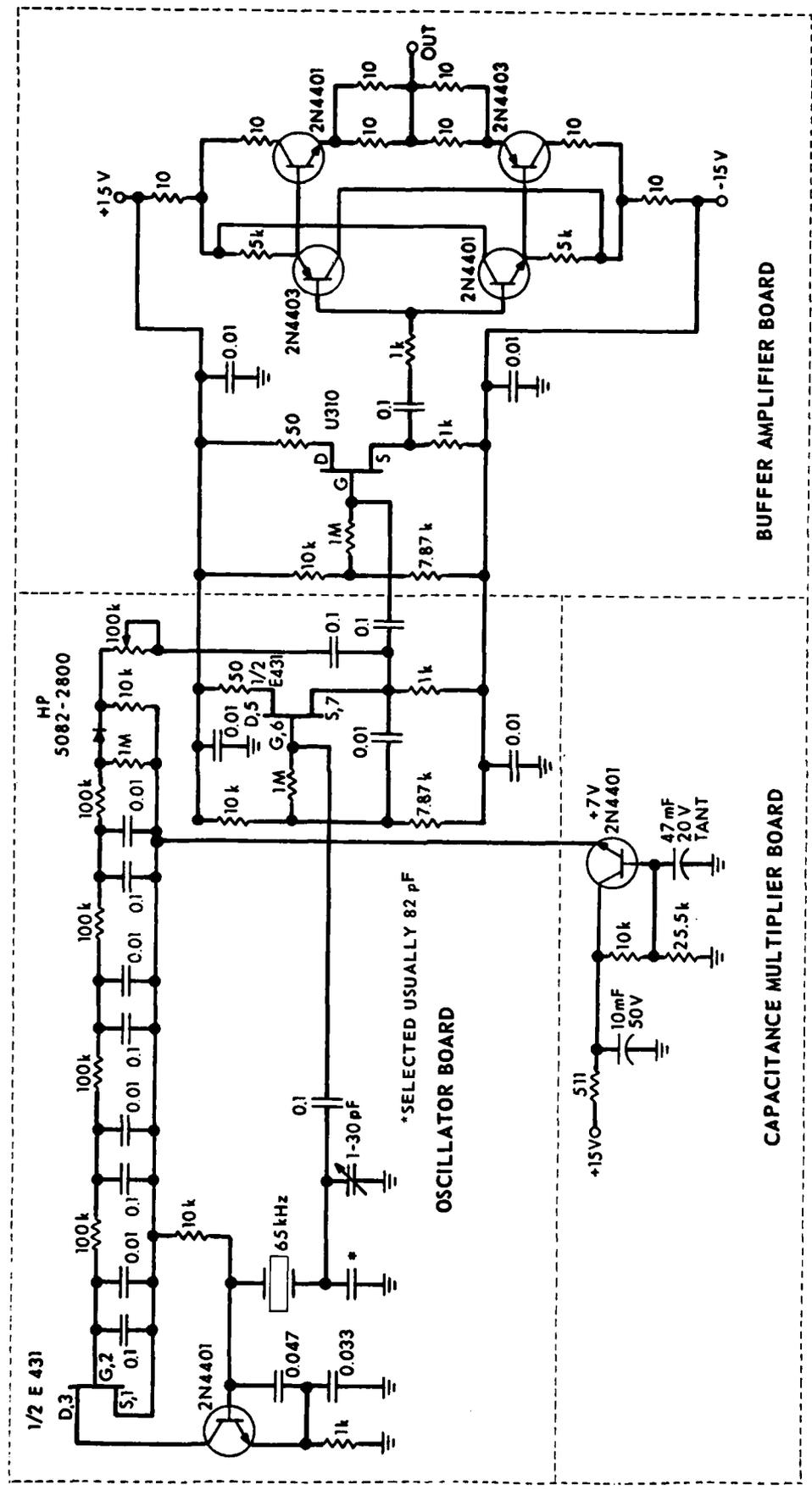


FIGURE 6  
PUMP SIGNAL SOURCE  
OSCILLATOR PACKAGE

ARL - UT  
AS-77-1071  
WSO - RFG  
9 - 20 - 77

#### IV. PUBLICATIONS, REPORTS, AND PRESENTATIONS AT SCIENTIFIC AND TECHNICAL MEETINGS

Several papers describing work on the PARRAY program were presented at scientific and technical meetings during the contract period. The texts of most of these papers were published in the proceedings of the conferences. In addition, several technical letters were written to sponsors to address requests for information on specific topics. One of these is discussed in the following material.

##### A. Surveillance Scenario Study

A study of surveillance applications of the PARRAY was performed under the preceding contract, N00039-76-C-0231. Results of that study were reported in Applied Research Laboratories Technical Report No. 77-61 (ARL-TR-77-61), distributed early in the current contract period.<sup>15</sup> The report describes a technique of using a PARRAY in conjunction with present day surveillance systems to improve overall system performance. A draft of the report was reviewed by Applied Hydro Acoustics Research, Inc. (AHAR), in a report entitled "Review and Discussion of Suggested Surveillance Applications of a Parametric Array." We replied to the AHAR critique in Applied Research Laboratories Technical Letter No. ST-78-2 (TL-ST-78-2), which is reproduced as Appendix A of this report.

##### B. IEEE International Conference on Acoustics, Speech, and Signal Processing

A paper entitled "Vibration Sensitivity of the Parametric Acoustic Receiving Array" was presented at the 1978 IEEE International Conference on Acoustics, Speech, and Signal Processing held in Tulsa, Oklahoma, 10-12 April 1978. The paper was published in the proceedings of that conference.<sup>16</sup> A copy of the paper is included as Appendix B of this report.

C. U.S. Navy Symposium on Underwater Acoustics

The 32nd U.S. Navy Symposium on Underwater Acoustics was held 14-16 November 1978 at New London Laboratory, Naval Underwater Systems Center, New London, Connecticut. Abstracts for three papers on the PARRAY were submitted to the technical program organizers; two of these papers were selected for lecture presentation, and the third was selected for presentation in a poster format.

Results of some tests and measurements with the 340 m PARRAY at Lake Travis Test Station (LTTS) were presented at the session on Large Aperture Acoustic Arrays. An unclassified abstract of that paper is included as Appendix C of this report. Text of the paper was published in the symposium proceedings.<sup>17</sup>

Experiments with a PARRAY aboard USS DOLPHIN were described, and data from these experiments were presented in Paper A5-2 of the session on Advanced ASW Sensors. The unclassified abstract of this paper is included as Appendix D. The paper was published in the symposium proceedings.<sup>10</sup>

A signal processing technique by which a PARRAY can be combined with a line array to produce an array system having more desirable characteristics than those of either individual array was presented in poster format. The abstract for this paper is not included in this report because it is classified; however, the abstract and text of the paper were published in the symposium proceedings.<sup>18</sup>

D. 96th Meeting of The Acoustical Society of America

The 96th Meeting of The Acoustical Society of America was held as a joint meeting with The Acoustical Society of Japan on 27 November - 1 December 1978 in Honolulu, Hawaii. A paper describing some of the results

of measurements with the 340 m PARRAY at LTTTS was presented at that meeting.<sup>19</sup> An abstract of the paper is included as Appendix E.

E. Mixer-Receiver Analysis

For some PARRAY applications a receiver employing a high performance diode mixer appears to have several advantages compared to a band elimination crystal filter receiver. The mixer-receiver has been analyzed and an expression for receiver performance in a PARRAY system has been derived. A technical report describing the results of this investigation was issued during this contract period.<sup>20</sup>

## V. SUMMARY

This report has briefly reviewed the work on the PARRAY under two major tasks: (1) design, construction, and installation of a short baseline PARRAY for experiments aboard the research submarine USS DOLPHIN, and (2) preparatory work and development of hardware in support of a long baseline, bottom mounted PARRAY for installation and tests at the Stage I facility of Naval Coastal Systems Center, Panama City, Florida. In addition, several publications, reports, and papers presented at scientific and technical meetings were reviewed and references to the complete papers and reports were given.

The first task, which was jointly supported by DARPA and NAVSEA, was part of a program to investigate the PARRAY for possible mobile sonar applications. Equipment and technology from the earlier, long baseline PARRAY development sponsored by DARPA were utilized to construct a 40 m PARRAY which was installed on USS DOLPHIN for experiments at sea. The experimental PARRAY operated without equipment failure during five dives totaling approximately 30 h. These experiments are unique in that this is the first and, so far, the only time that a PARRAY has been operated on a mobile platform underway at sea. The outputs from the PARRAY and several auxiliary sensors were recorded on analog magnetic tape. The approximately 20 h of magnetic tape recordings obtained during the experiments form an extremely valuable data bank for assessing the potential usefulness of the PARRAY for mobile sonar applications.

The second task involved preparatory work and development of hardware for tests of a long baseline, bottom mounted PARRAY for installation and tests at a sea site. As a result of the sea site investigation, including the hardware development schedule and the facilities at the prospective Bermuda site, it became clear that a more timely and cost effective sea test could be conducted at the Stage I facility of NCSC, Panama City, Florida, than at the Tudor Hill Laboratory, Bermuda. Development of hardware for

sea tests of the long baseline PARRAY was discussed, including the impact on the hardware development of conducting the tests at Stage I as opposed to Bermuda.

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APPENDIX A



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13 March 1978  
CRR:cag  
TL-STD-78-2

FROM: Sensor Technology Division

TO: Commander  
Naval Electronic Systems Command  
Department of the Navy  
Washington, DC 20362

ATTN: J. Bertrand, ELEX 320

SUBJ: Response to "Review and Discussion of Suggested Surveillance Applications of a Parametric Array"

This Technical Letter is written in response to the report "Review and Discussion of Suggested Surveillance Applications of a Parametric Array" by Applied Hydro-Acoustics Research, Inc., (AHA) in which AHA reviews an Applied Research Laboratories, The University of Texas at Austin (ARL:UT), proposed application for the Parametric Acoustic Receiving Array (PARRAY). The ARL:UT proposed PARRAY application is documented in the ARL:UT report "Surveillance Applications of the PARRAY as a Line Array Adjunct", (ARL-TR-77-61).

In the ARL:UT proposed system, the PARRAY is employed in conjunction with a conventional surveillance array to implement a surveillance system with certain desirable performance characteristics. The proposed system, shown in Fig. 1, is based on correlating the output of the PARRAY with the output of a conventional array beamformer. In the ARL:UT report, the performance of the correlation system is compared with the performance of a conventional system, a single line array with its associated beamformer and a spectrum analyzer. Comparison is made of the ability of each to detect narrowband signals in a noise field and also of the spatial selectivity of each system in an environment consisting of many narrowband signals. It is concluded that the performance of the correlation system shows some improvement over that of a conventional system in a broadband noise field. More significantly, however, the spatial selectivity, or clutter rejection, of the correlation system is very much greater than that of the conventional system in the case of many narrowband interfering signals.

The AHA report reviewing the ARL:UT system analysis and conclusions is generally supportive of the ARL:UT findings; however the AHA report expresses reservations and, in some instances, disagreement concerning the system analysis presented by ARL. We feel that these portions of the AHA report unjustifiably cast doubt on the validity of the correlation system concept and its proposed application. Moreover, we do not agree with the major criticisms expressed in the AHA report and wish to take this opportunity to reaffirm the original findings of the ARL:UT report. We will

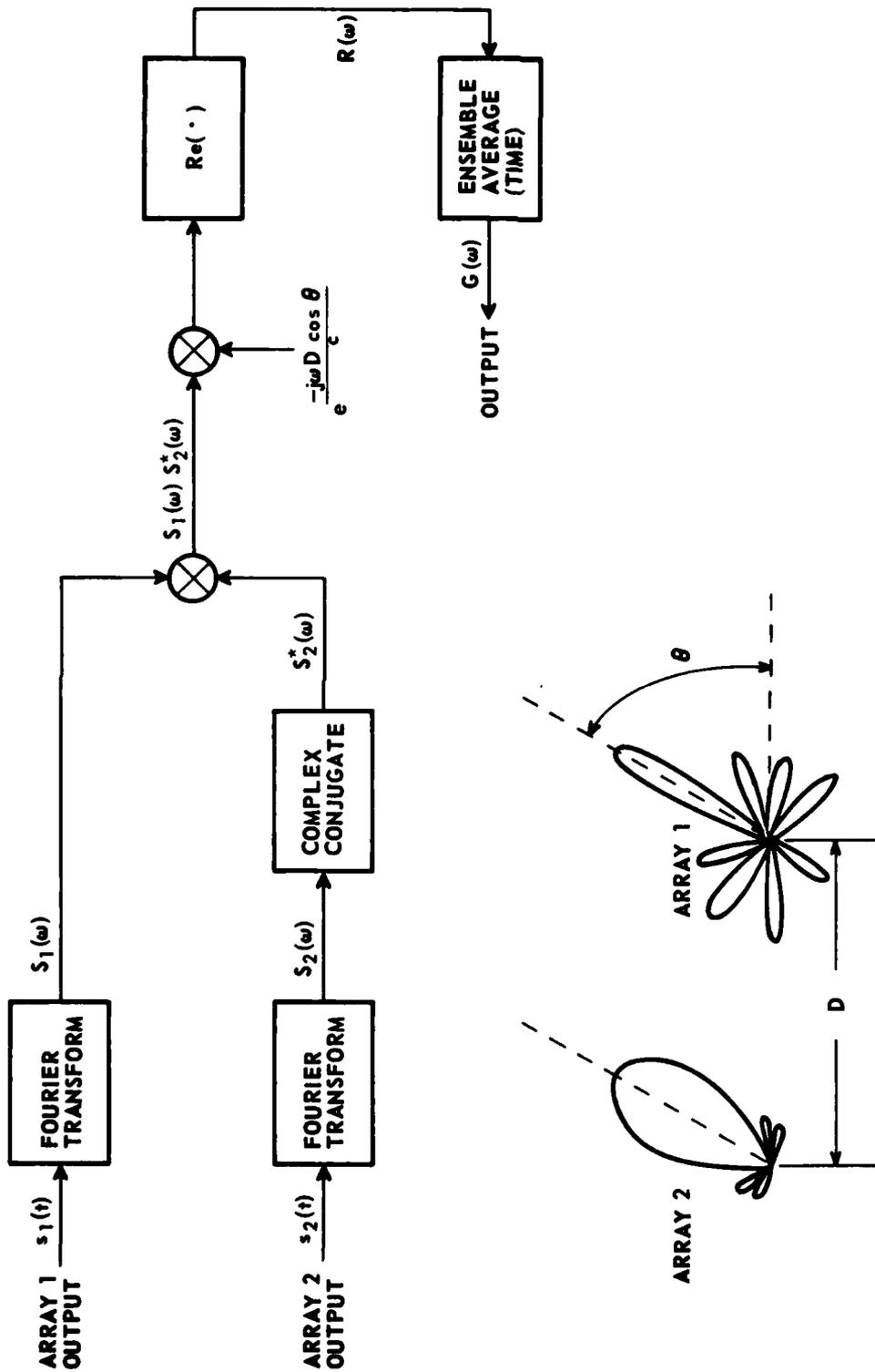


FIGURE 1  
CROSSCORRELATION OF OUTPUTS OF TWO ARRAYS

deal with the major points raised in the AHA report one at a time.

First, the AHA report expresses reservations about the validity of the ARL result showing that the beam pattern of the correlation system is equal to the geometric mean of the two individual array beam patterns. We contend that the ARL:UT result is correct when either or both of the following conditions are met:

- a) frequency exclusivity of all signals, or
- b) long averaging time.

We chose the first condition, frequency exclusivity, as a condition to simplify the analysis. As stated in the ARL:UT report, this is the condition under which beam patterns are customarily measured and so we do not consider it to be unrealistically restrictive. In addition, the work of Bucker [1] and, indeed, even the AHA report itself (equations II and III), show that the second condition, long averaging time, is sufficient by itself to validate the ARL:UT result; for the intended application of this system, this condition may often be met. The ARL report further states, by way of caution to the reader, that the spatial processing gain of the correlation system is not determined by the beam pattern, as it is for linear arrays; so in any event one should not attempt to use the correlation system beam pattern as a general measure of system performance.

Second, the AHA report states that obtaining frequency exclusivity, a supposedly required condition for the correlation system, by employing narrower band filters would improve the clutter rejection capability of an existing linear system. We are not able to agree with this because the clutter rejection ability of a linear array system is determined by the array beam pattern, which is not significantly affected by the system frequency resolution. The ARL:UT report shows that the response of the linear array to clutter is greater than the response of the correlation system to clutter over the angular sectors where there is a positive clutter rejection by the correlation system.

Third, the AHA report states that the ARL:UT model for the correlation system requires knowledge of the signal phase, a practically unobtainable requirement, and that this model is then compared in the ARL:UT report with a model for the linear array system in which the signal phase is unknown. The implication here is that such a comparison is unfair since knowledge of the signal phase, if available, could be used to greatly improve the linear array system performance. Furthermore, AHA is unable to reconcile their understanding of the models with the performance comparisons given by ARL:UT, saying that the difference in performance should have been even greater than that reported by ARL:UT. In fact, the ARL:UT model for the correlation system does not require knowledge of the signal phase, so it is quite fairly compared with the linear array model under conditions in which both systems perform incoherent detection. In the ARL:UT model development, a particular value was chosen for the signal phase to simplify the analysis. This is not the same as assuming knowledge of the signal phase. We acknowledge that this was not brought out as clearly as it might have been in the development, but the ARL:UT report stated that the several particular parameter values chosen to simplify the correlation model development did not affect the final results. It did not occur to

us that it would be thought we would make such an unfair system comparison; it was expected that the critical reader would understand the validity of the simplified development in the general case. That AHA misunderstood the model also explains the inability of AHA to reconcile their general system performance predictions with the ARL:UT reported results.

We wish to reiterate that the correlation system model presented in the ARL:UT report is quite fairly compared to the linear array model. The conditions of the comparison are those in which the linear array model, as pointed out in the AHA report, is optimum for processing the output of the single array. The fundamental reason why the correlation system outperforms the optimum single array system is that the correlation system has two arrays covering a larger acoustic aperture than the single array.

Fourth, the AHA report implies that the ARL:UT model for the single array system is in error because the statistical form of the ARL:UT model apparently does not agree with the well known statistics for the signals and noise. In fact, the ARL:UT model is quite accurate under the conditions in which it is employed. As stated in the ARL:UT report, the single array model was developed in its given form to make comparisons between the two system types more straightforward. A complete analysis of the single array system is given in DiFranco and Rubin [2], for example, but the comparison of the two system types using the complete model for the single array system is not as straightforward as the comparison given in the ARL:UT report. The models presented in the ARL:UT report for both the single array and correlation system are valid when the number of spectral averages is large.

Fifth, the AHA report faults the ARL:UT analysis for assuming that the in-phase and quadrature components of the noise output of the discrete Fourier transform (DFT) are independent. We are not able to understand their reservation on this point since it is well known that the stated condition is true under the assumption, also clearly stated, of white gaussian noise input to the DFT [3]. Moreover, this assumption is not restrictive but is quite reasonable for such an analytic development. Even in a practical example where the in-phase and quadrature noise components might not be completely independent, one would expect the correlation coefficient to be very small. Thus, any error in the practical application of this idealized model due to the assumption of independence would also be very small.

We feel that the ARL:UT findings are both valid and practical. The major points of disagreement between the ARL:UT and AHA reports have been discussed in the preceding paragraphs of this letter. The principal reason for this disagreement is a misunderstanding by the AHA reviewer of the correlation technique in the particular proposed application. If any significant areas of disagreement remain, we suggest that NAVELEX Code 320 host a meeting where the correlation system and its application can be discussed and any points of disagreement resolved.

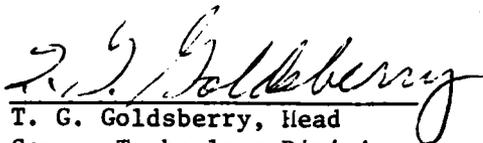
We also wish to take this opportunity to emphasize several of the many areas of accord between the ARL:UT and AHA reports. Both reports agree that the best current application of the correlation system may be found in situations where the clutter rejection capabilities of such a system may be used to advantage. Both reports also agree that the benefits of a correlation system may be highly variable and are strongly dependent upon the exact nature of the clutter and noise environment in which it is employed. Consequently, a detailed study on a case by case basis will be required to determine the best deployment sites and the specific benefits and costs for each site.

We feel that a detailed study of several specific sites where clutter is a recognized problem should be included in a continuing effort to more closely define and demonstrate the practical benefits of the correlation system to the Navy.



C. R. Reeves

APPROVED:

  
T. G. Goldsberry, Head  
Sensor Technology Division

13 March 1978  
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Page 6

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APPENDIX B

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## VIBRATION SENSITIVITY OF THE PARAMETRIC ACOUSTIC RECEIVING ARRAY

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### ABSTRACT

A parametric (nonlinear) receiving array exhibits sensitivity to motion of its transducers in a manner significantly different from that of conventional arrays. An understanding of this sensitivity is necessary for the proper evaluation of the benefits of parametric arrays in many applications of interest. In this paper a theory relating motion of the array transducers to the array output signal is developed, and predictions from the theory are compared with experimental observations on both 5 m and 340 m parametric arrays used for low frequency reception. Several methods of counteracting the detrimental effects of transducer motion are discussed.

### I. INTRODUCTION

The Parametric Acoustic Receiving Array (PARRAY) is a technique for obtaining directional reception of low frequency acoustic waves with only two relatively small high frequency transducers [1,2]. Recent development efforts have led to practical design procedures for PARRAY's which are significantly different from design procedures for conventional hydrophone arrays [3]. This paper addresses the response of the PARRAY to mechanical vibration of its transducers. It is shown that the response is predictable and not necessarily detrimental if the response is taken into account in the system design.

### II. THE PARRAY

A PARRAY functions as an acoustic sensor by taking advantage of the small nonlinearity involved in acoustic propagation through water. Because of the nonlinearity, multiple acoustic signals in water produce intermodulation products which are detected in the PARRAY. Figure 1 shows the basic elements of a PARRAY. A narrowband ultrasonic signal generated by the PARRAY pump constitutes one of the signals in the water. As this pump signal propagates toward the hydrophone, it mixes with ambient signals to produce products which, along with the pump signal, are received by the hydrophone. Conventional but state-of-the-art techniques recover the ambient acoustic signal by detecting the intermodulation products in the pump carrier sidebands.

The primary reason for receiving ambient acoustic signals by this method is that desirable directional response characteristics may be obtained. The amplitude of an intermodulation pro-

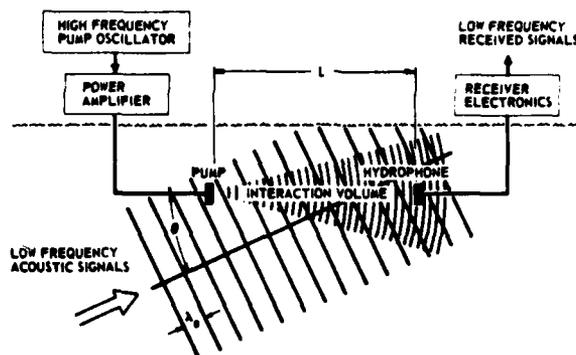


FIGURE 1. PARRAY FUNCTIONAL DIAGRAM

duct received by the hydrophone is dependent upon the angle between the direction of propagation of the ambient signal and the pump-hydrophone axis. This angular dependence is very similar to that of an end-fired array with length equal to the pump-hydrophone separation. Hence, the PARRAY is more than an acoustic sensor; it is a directional array.

The pump signal and intermodulation products appearing at the hydrophone can be expressed in closed form as a phase modulation of the pump carrier by the ambient acoustic signals [4]. Let the pump signal be a sinusoid  $C \cos \omega_0 t$ . Then the hydrophone signal can be expressed as

$$s(t) = C' \cos[\omega_0 t + \phi(t) + \psi] \quad (1)$$

where  $C'/C$  represents losses between the pump and hydrophone,  $\psi$  is a phase constant determined by the pump-hydrophone separation, and the phase modulation due to nonlinear interaction is given by

$$\phi(t) = \frac{\left(\frac{B}{2A} + \cos \theta\right) \omega_0 L \sin \left[\frac{\omega_1 L}{2c_0} (1 - \cos \theta)\right]}{\rho_0 c_0^3} p(t) \quad (2)$$

where

- $p(t)$  = ambient pressure signal at frequency  $\omega_1$
- $B/A$  = parameter of nonlinearity of water ( $\approx 5$ )
- $\theta$  = angle between direction of ambient signal propagation and pump-hydrophone axis
- $\rho_0$  = density of water
- $c_0$  = sound speed in water
- $L$  = pump-hydrophone separation distance

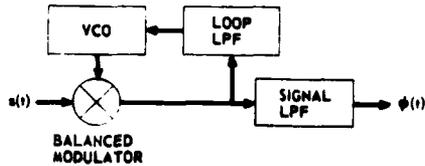


FIGURE 2. PARRY RECEIVER BLOCK DIAGRAM

For most values of  $\omega_1$ , the term with the form  $(\sin x)/x$  in Eq. 2 dominates the angular dependence of the phase modulation index and gives the PARRY its end-fired array directional characteristics.

### III. TRANSDUCER MOTION EFFECTS

The phase constant  $\psi$  in Eq. 1 represents the pump signal phase shift as it propagates from the pump to the hydrophone. For systems in which the pump and hydrophone are stationary, Eq. 1 is a sufficient model with  $\psi = \omega_0 L / c_0$ . However, when the pump and/or hydrophone are in motion there are additional phase shifts in the hydrophone signal due to Doppler effects. We consider first the effect of motion of the hydrophone only. The pump carrier signal as seen by the hydrophone will be phase shifted by

$$\phi_h(t) = -\omega_0 d_h(t) / c_0 = -\omega_0 \int \int a_h(t) dt^2 / c_0, \quad (3)$$

where  $d_h(t)$  is the displacement of the hydrophone along the pump-hydrophone axis in the direction away from the pump and  $a_h(t)$  is the corresponding acceleration. Transducer motion in directions other than along the pump-hydrophone axis causes no Doppler effect and therefore is not considered here or in the following development.

Motion of the pump transducer produces a similar effect on the signal at the hydrophone except that the propagation delay from pump to hydrophone must be taken into account. Here the phase shift is

$$\phi_p(t) = \omega_0 d_p(t - L/c_0) / c_0 = \omega_0 \int \int a_p(t - L/c_0) dt^2 / c_0. \quad (4)$$

The phase shifts due to pump and hydrophone motion are summed as

$$\phi_m(t) = \phi_h(t) + \phi_p(t) = \frac{\omega_0}{c_0} \left[ d_p \left( t - \frac{L}{c_0} \right) - d_h(t) \right]. \quad (5)$$

Then the pump signal and nonlinear interaction products received by the hydrophone are

$$s(t) = C' \cos[\omega_0 t + \phi(t) + \phi_m(t) + \psi], \quad (6)$$

and it is apparent that the phase modulation introduced by transducer motion,  $\phi_m(t)$ , is added to the desired signal,  $\phi(t)$ , and  $s_m^0$  cannot be easily disregarded. This expression may also be used to show the quantitative equivalence between acoustic sound pressure level (SPL) and vibration level in the PARRY. That is, the sensitivity of the PARRY to vibration can be expressed as an equivalent acoustic sensitivity by setting

$$\phi_m(t) = \phi(t) \quad (7)$$

and solving for the relationship between SPL and

vibration level. The general result is

$$p(t) = \frac{\left[ d_p \left( t - \frac{L}{c_0} \right) - d_h(t) \right] \rho_0 c_0^2 \left[ \frac{\omega_1 L}{2c_0} (1 - \cos \theta) \right]}{\left( \frac{B}{2A} + \cos \theta \right) L \sin \left[ \frac{\omega_1 L}{2c_0} (1 - \cos \theta) \right]} \quad (8)$$

which for on-axis arrival angle ( $\theta=0$ ) reduces to

$$p(t) = \frac{[d_p(t-L/c_0) - d_h(t)] \rho_0 c_0^2}{(B/2A+1)L} \quad (9)$$

This shows that the PARRY vibration sensitivity is independent of pump frequency and inversely proportional to array length.

A few computations indicate that the PARRY is sensitive to vibration at practical levels. For example, for a 5 m long PARRY in water, a sound pressure level of 100 dB re 1  $\mu$ Pa rms corresponds to a displacement of one transducer by  $7.58 \times 10^{-10}$  m rms. This displacement is equivalent to an acceleration level of 30 dB re 1  $\mu$ g at 100 Hz or 70 dB re 1  $\mu$ g at 1000 Hz.

### IV. PARRY SIGNAL PROCESSING

Since the modulation index of the phase modulation due to acoustic nonlinear interaction in water is ordinarily very small,  $10^{-4}$  to  $10^{-8}$  for SPL's typically encountered in underwater acoustics, the phase modulation process in the absence of vibration is for all practical purposes linear. Equation 1 may be rewritten

$$s(t) = C' \cos(\omega_0 t + \psi) \cos \phi(t) - C' \sin(\omega_0 t + \psi) \sin \phi(t), \quad (10)$$

which, for small  $\phi(t)$ , reduces to

$$s(t) = C' \cos(\omega_0 t + \psi) - C' \phi(t) \sin(\omega_0 t + \psi). \quad (11)$$

In this form it is apparent that the hydrophone signal consists of the pump carrier and a quadrature amplitude modulation component which carries the desired information  $\phi(t)$ .

The block diagram of a linear receiver for this signal is shown in Fig. 2. It consists principally of a phase locked loop which recovers the quadrature carrier. The bandwidth of this loop is made very small so that only the carrier and not the modulation sidebands are tracked by the loop. The sideband signals are demodulated by the loop mixer and  $\phi(t)$  remains after removal of double frequency components by the low pass filter.

In a similar manner, Eq. 6, which includes the effects of transducer motion, may be expressed as

$$s(t) = C' \cos[\omega_0 t + \phi_m(t) + \psi] - C' \phi(t) \sin[\omega_0 t + \phi_m(t) + \psi], \quad (12)$$

which equation is of the same form as Eq. 11 but includes transducer motion induced phase modulation in all the carrier terms. Equation 12 is the general model for the hydrophone signal in the presence of transducer motion. If  $\phi_m(t)$  is small, then Eq. 12 may be linearized as

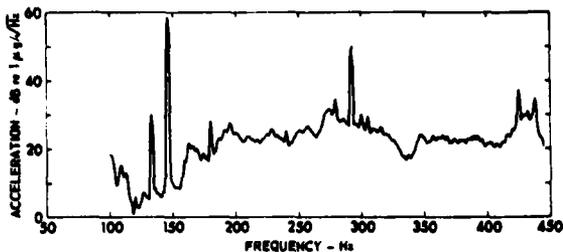


FIGURE 3. ACCELERATION SPECTRUM

$$s(t) = C' \cos(\omega_0 t + \psi) - C' [\phi(t) + \phi_m(t)] \sin(\omega_0 t + \psi) \quad (13)$$

This model is appropriate when transducer motion is very small.

When transducer motion is small the receiver configuration of Fig. 2 may be used with satisfactory results if the presence of  $\phi_m(t)$  in the output can be tolerated. The receiver output is  $\phi(t) + \phi_m(t)$  for this case.

It is informative to express the signal models of Eqs. 11, 12, and 13 in the frequency domain because all experimental data is presented in this form. For Eq. 11, the linear acoustic signal only model, the power spectrum of  $s(t)$  consists of the carrier at frequency  $\omega_0$  with symmetric upper and lower sidebands of the same form as the power spectrum of  $\phi(t)$ . The sideband power spectrum of  $s(t)$  is proportional to the power spectrum of  $\phi(t)$ :

$$|S(\omega + \omega_0)|^2 \propto |\phi(\omega)|^2 \quad (14)$$

Similarly, for the linear small vibration model of Eq. 13,

$$|S(\omega + \omega_0)|^2 \propto |\phi(\omega) + \phi_m(\omega)|^2 \quad (15)$$

However, when the vibration is of sufficient magnitude to warrant the use of the nonlinear model of Eq. 12 the power spectrum of  $s(t)$  is

$$|S(\omega)|^2 \propto |H(\omega) + j\phi(\omega) * H(\omega)|^2 \quad (16)$$

where  $H(\omega)$  is the spectrum of  $\cos[\omega_0 t + \phi_m(t) + \psi]$  and \* indicates convolution. The point to be noted here is that the spectral products in  $S(\omega)$  are not linearly related to  $\phi(\omega)$  and  $\phi_m(\omega)$ . This occurs both because  $H(\omega)$  is not linearly related to  $\phi_m(\omega)$  and because of the convolution with  $\phi(\omega)$ . In the linear models neither of these events occurred.

The equivalence between on-axis acoustic and vibration induced signals, Eq. 9, in the frequency domain is

$$\begin{aligned} |P(\omega)|^2 &= \frac{\rho_o^2 c_o^4}{(B/2A+1)^2 L^2} |D(\omega)|^2 \\ &= \frac{\rho_o^2 c_o^4}{(B/2A+1)^2 L^2 \omega^4} |A(\omega)|^2 \end{aligned} \quad (17)$$

where  $D(\omega)$  is the spectrum of  $d_p(t-L/c_o) - d_h(t)$ ,

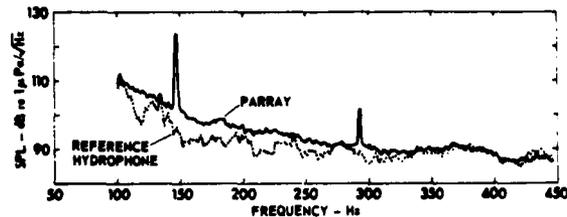


FIGURE 4. SOUND PRESSURE LEVEL SPECTRUM

the composite transducer displacement, and  $A(\omega)$  is the composite transducer acceleration.

#### V. EXPERIMENTAL VERIFICATION

Measurements to verify the theory were made at Applied Research Laboratories' Lake Travis Test Station using both 5 m and 340 m PARRAY's in fresh water. An accelerometer and shaker were mounted on the hydrophone of the 5 m PARRAY so that the motion of the hydrophone along the pump-hydrophone axis could be controlled and measured while the PARRAY electronic signal output was being measured simultaneously. For these tests, vibration levels were low enough that the linear model of Eqs. 13 and 15 held and an experimental receiver which detected only the upper sideband of the hydrophone signal was used rather than the receiver shown in Fig. 2. The PARRAY output was converted to its equivalent acoustic input signal for comparison with the accelerometer signal. This measured equivalence between acoustic and accelerometer signals was then compared with the theory using Eq. 17.

For the 5 m PARRAY, Eq. 17 may be expressed as

$$P_{dB}(\omega) = 150 - 40 \log_{10} f + G_{dB}(\omega) \quad (18)$$

where  $P_{dB}(\omega)$  is SPL in dB re 1  $\mu$ Pa and  $G_{dB}(\omega)$  is acceleration in dB re 1  $\mu$ g. Figure 3 is a plot of the hydrophone acceleration spectrum measured with the accelerometer while the hydrophone was being shaken at a fundamental frequency of 146 Hz and its 292 Hz harmonic. Figure 4 shows the simultaneously measured PARRAY equivalent on-axis SPL and the actual SPL measured with an independent omnidirectional reference hydrophone. The 146 and 292 Hz components seen in the PARRAY data are clearly due to the vibration since they do not appear in the reference hydrophone measurement. PARRAY background noise is apparently a combination of broadband acoustic noise and PARRAY receiver noise, which in this case is rather high because system parameters are not matched to the short length of this PARRAY. The equivalent SPL obtained by applying Eq. 18 to the acceleration data of Fig. 3 is shown in Fig. 5. Figures 4 and 5 exhibit agreement within expected experimental accuracy at both 146 and 292 Hz.

The same experiment was repeated several times at different vibration levels and frequencies. Differences between the theory and experimental results are shown in Fig. 6 for a number of vibration frequencies. These differences are believed to be due to inaccuracies in measuring the transducer acceleration.

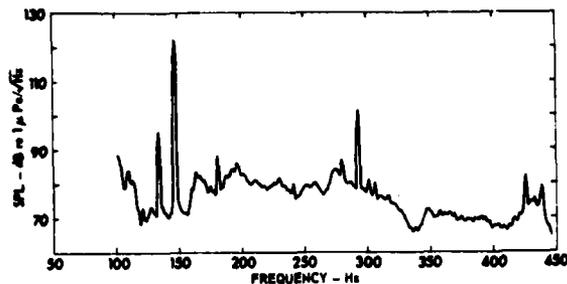


FIGURE 5. EQUIVALENT SOUND PRESSURE LEVEL SPECTRUM

For high amplitude vibration, the nonlinear model of Eqs. 12 and 16 must be used to relate the hydrophone sideband signal to the acoustic pressure and vibration. A single experiment to verify the form of this model was conducted using a 340 m PARRAY and the single sideband receiver used previously. In this experiment a diver rhythmically shook the PARRAY hydrophone while a 150 Hz acoustic signal was received by the PARRAY. For these conditions, Eq. 16 predicts spectral components deriving directly from vibration induced phase modulation of the carrier, and also deriving from the convolution of the modulated carrier spectrum with the 150 Hz acoustic signal spectrum. The receiver was not capable of receiving the carrier and its sidebands created by the vibration, but the spectral components resulting from the convolution were observed as shown in Fig. 7. Since the acoustic signal was very stable at 150 Hz, the carrier and its vibration-induced sidebands are reproduced exactly, but are centered at 150 Hz in this sideband spectrum. From these data one may deduce that the hydrophone was shaken at a frequency of 0.75 Hz with a displacement of  $4.9 \times 10^{-3}$  m rms which corresponds to an acceleration of 0.011 g rms. The phase modulation index of this process is 1.9. These derived parameters are in general agreement with observations made during the experiment.

#### VI. MINIMIZING THE EFFECTS OF VIBRATION

From a theoretical point of view, the effects of transducer vibration on PARRAY operation can be completely eliminated. This is so because the actual vibration of the transducers may be measured using, for instance, accelerometers, and the PARRAY signal output due to vibration can then be determined by using the models presented here. The vibration induced signal components can be subtracted from the PARRAY output, leaving only the acoustic signals. In practice, this technique will require extraordinary accuracy if it is to be effective.

If the vibration and acoustic signals occupy exclusive frequency bands, more easily implemented techniques may suffice. In the case of low level vibration where Eqs. 13 and 15 hold, the acoustic signals may be separated from vibration signals at the output of the receiver by filtering.

For high level vibration where the nonlinear model of Eqs. 12 and 16 hold, a straightforward

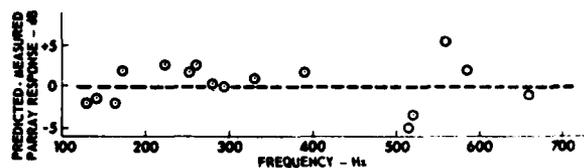


FIGURE 6. THEORETICAL - EXPERIMENTAL COMPARISON

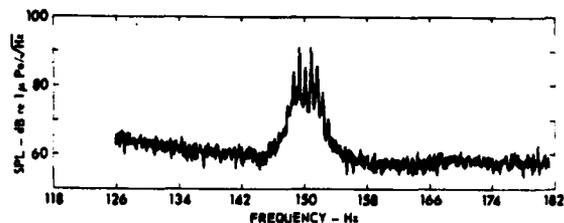


FIGURE 7. PARRAY SIDEBAND CONVOLUTION COMPONENTS FOR HIGH LEVEL VIBRATION

approach is to change the phase locked loop in the receiver, Fig. 2, so that the loop tracks the vibration induced phase modulation. The loop filter must pass the vibration frequencies. This linearizes the PARRAY response so that acoustic and vibration signals may be separated by filtering at the receiver output, as in the case of low level vibration.

#### VII. CONCLUSIONS

Models relating the response of a PARRAY to vibration of its transducers have been developed and predictions using the models have been shown to agree with experimental data. Electronic techniques for counteracting the effects of vibration are available and should be considered in PARRAY system design. [This research was supported by the Advanced Research Projects Agency of the Department of Defense and was monitored by the Naval Electronic Systems Command under Contract N00039-76-C-0231.]

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APPENDIX C

MEASUREMENTS WITH A LARGE APERTURE PARAMETRIC ACOUSTIC RECEIVING ARRAY (U)

## ABSTRACT

The parametric acoustic receiving array (PARRAY) exploits the inherent nonlinearity of the water to achieve directional reception of low frequency acoustic waves with two small high frequency transducers. It has been characterized as a continuous, virtual endfire array of length equal to the pump-hydrophone separation. Therefore, the directivity index (DI) of a PARRAY is approximately equal to  $10 \log (4L/\lambda)$  where  $L$  is the pump-hydrophone separation and  $\lambda$  is the wavelength of the acoustic signal to be detected. Recent development efforts have led to practical design procedures and hardware to make the PARRAY a useful acoustic sensor for surveillance applications. A PARRAY with a pump-hydrophone separation of 340 m has been installed in 45 m of water at the Lake Travis Test Station of Applied Research Laboratories, The University of Texas at Austin (ARL:UT). System self-noise has been reduced sufficiently to measure ambient noise equivalent to B shipping and sea state 2 over the frequency range from 40 to 800 Hz. Measurements over this frequency range have demonstrated array gain approximating the theoretical DI of the 340 m PARRAY. The geometry of the experiment is described and data obtained with the 340 m PARRAY is presented and discussed. Potential applications of the PARRAY in surveillance systems are discussed.

APPENDIX D

PARAMETRIC ACOUSTIC RECEIVING ARRAY EXPERIMENTS ABOARD USS DOLPHIN (U)

#### ABSTRACT

Unique experiments were performed with a parametric acoustic receiving array (PARRAY) aboard USS DOLPHIN (AGSS 555) in March 1978. These experiments represent the first time that a PARRAY has been operated on a mobile platform underway at sea. In a PARRAY, the inherent nonlinearity of the water is exploited to synthesize a volumetric, virtual end-fire array in the water column between two small high frequency transducers (pump and hydrophone). The pump and hydrophone transducers were installed on pylons fore and aft on the port side of the boat, to yield a forward looking PARRAY with a pump-hydrophone separation of 40 m. Measurements show that the PARRAY operated as an acoustic sensor to receive acoustic signals transmitted from a distant source and that an array with processing gain was formed. Platform noise rejection in excess of 30 dB was measured at frequencies as low as 200 Hz. Spatial processing gain approximating the directivity index was obtained in this same frequency region.

APPENDIX E

MEASUREMENTS WITH A LARGE APERTURE PARRAY

#### ABSTRACT

A parametric acoustic receiving array (PARRAY) is characterized as a continuous, virtual end-fire array of length equal to the separation between the pump and hydrophone. Therefore, the directivity index of a PARRAY is approximately equal to  $10 \log (4 L/\lambda)$  where  $L$  is the pump-hydrophone separation and  $\lambda$  is the wavelength of the acoustic signal. A PARRAY with a pump-hydrophone separation of 340 m has been installed in 45 m of water at the Lake Travis Test Station of Applied Research Laboratories, The University of Texas at Austin. Measurements over the frequency range from 40 to 800 Hz show spatial processing gains approximating the directivity index of the PARRAY. The geometry of the experiment will be described and data obtained with the 340 m PARRAY will be presented and discussed. [This research was supported by the Advanced Research Projects Agency of the Department of Defense and was monitored by the Naval Electronic Systems Command under Contract N00039-76-C-0231.]

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