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The Cylindrical Transducer at the Underwater Sound Laboratory

Presented at the 93rd Meeting of the Acoustical
Society of America 6-10 June 1977

H. E. Nash
(Consultant)
Office of the Associate
Technical Director for Technology

6 October 1980

NUSC

Naval Underwater Systems Center
Newport, Rhode Island • New London, Connecticut

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Preface

This document presents a paper given by H. E. Nash at the 93rd meeting of the Acoustical Society of America, 6-10 June 1977, Pennsylvania State University, University Park, Pennsylvania. The document was prepared under NUSCIR&IED number 710W11.L10.

Reviewed and Approved: 6 October 1980



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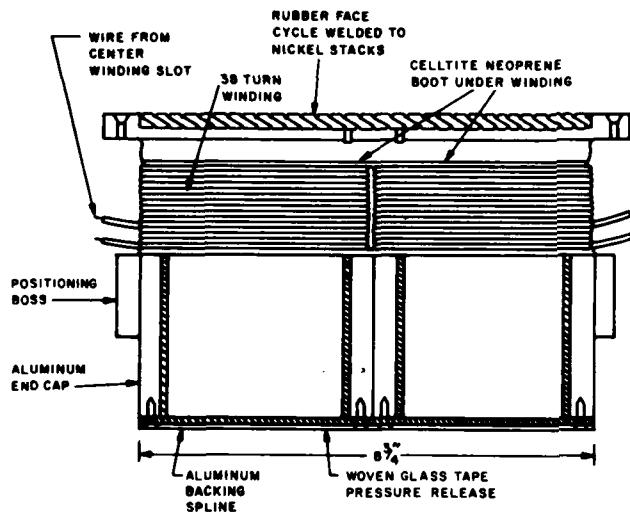
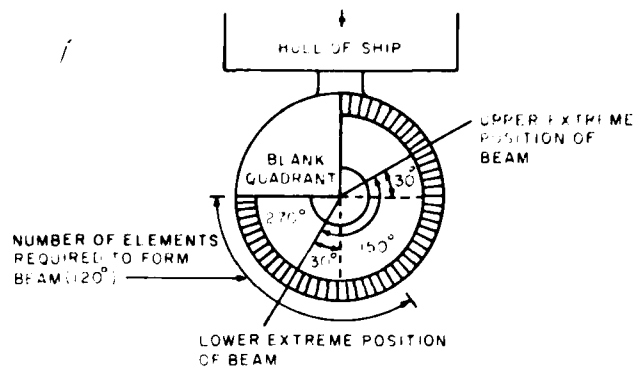
THE CYLINDRICAL TRANSDUCER AT THE UNDERWATER SOUND LABORATORY

INTRODUCTION

↓

This presentation describes two major projects in the field of scanning sonar. These projects were initiated at the Harvard Underwater Sound Laboratory and completed at the New London Underwater Sound Laboratory, following transfer in July 1945. The first of these developments involved the exploitation of the scanning sonar principle in a vertical scanning system for target depth determination. This was designed as part of a complete search/attack system known as the Type B Integrated Sonar. The second major development was an electronically rotated scanning system intended for use by submarines. This system, known as the XQKA, employed a rotation rate of 300 Hz and thus permitted the use of short pulses -- a desirable attribute for a submarine sonar. This presentation describes these two projects, and then discusses some of the work of the Underwater Sound Laboratory that led to the cylindrical and spherical arrays now employed on Navy ships and submarines. It concludes with a brief discussion of the impact of modern sonars on ship design.

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Slide 1

The Type B Integrated Sonar was designed to employ scanning in the horizontal plane for search, and scanning in the vertical plane for depth determination and complete target localization and tracking. At the upper left of slide 1 is the first experimental transducer, which employed 48 magnetostrictive staves mounted over an angle of 270° . Each staff consisted of two elements cemented to a rubber face strip, as shown by the sketch at the lower left, so that the transducer could be electrically split vertically into left and right halves for precise bearing determination. In the lower right is a complete transducer assembly, as eventually installed

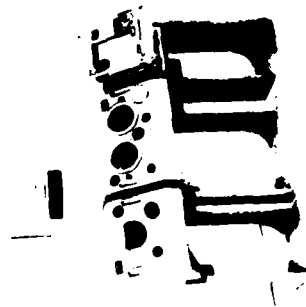
in USS MALOY. This assembly contains a 38-kHz depth scanning transducer mounted beneath as an azimuth scanning unit on a shaft, which was trained to keep the depth unit on target. This active assembly had to pass through a 19-inch gate valve so that it could be housed in a standard sea chest. The geometry of the depth scanning unit is shown at the upper right. 120° of the cylinder is used for beam formation through the associated capacitive commutators; the total 270° occupied by elements permits centering the beam from 0° to 90°, with an additional 30° for stabilization.

ELEMENTS OF TYPE B INTEGRATED SONAR

- **AZIMUTH SCANNING**
- **DEPTH SCANNING**
- **TWO AXIS STABILIZATION**
- **BEARING DEVIATION INDICATOR (BDI)**
- **RANGE AND DEPTH COMPUTER (OKA)**
- **DEPTH RECORDER**
- **ATTACK DIRECTOR**

Slide 2

The major elements of the system shown in slide 2 were an Azimuth Scanning Unit, a Depth Scanning Unit, a trunnion tilt corrector for two-axis stabilization which provided azimuth training signals for mechanical training of the transducer shaft and electrical signals for stabilization of the sweep on the Elevation Position Indicator, a BDI (Bearing Deviation Indicator) to provide accurate bearings, a computer which used bathythermograph data, a sound range and elevation angle to compute horizontal range and depth to the target, a range recorder, a depth recorder, and finally, an attack director to control the ordnance and aid the conning officer in making the attack.

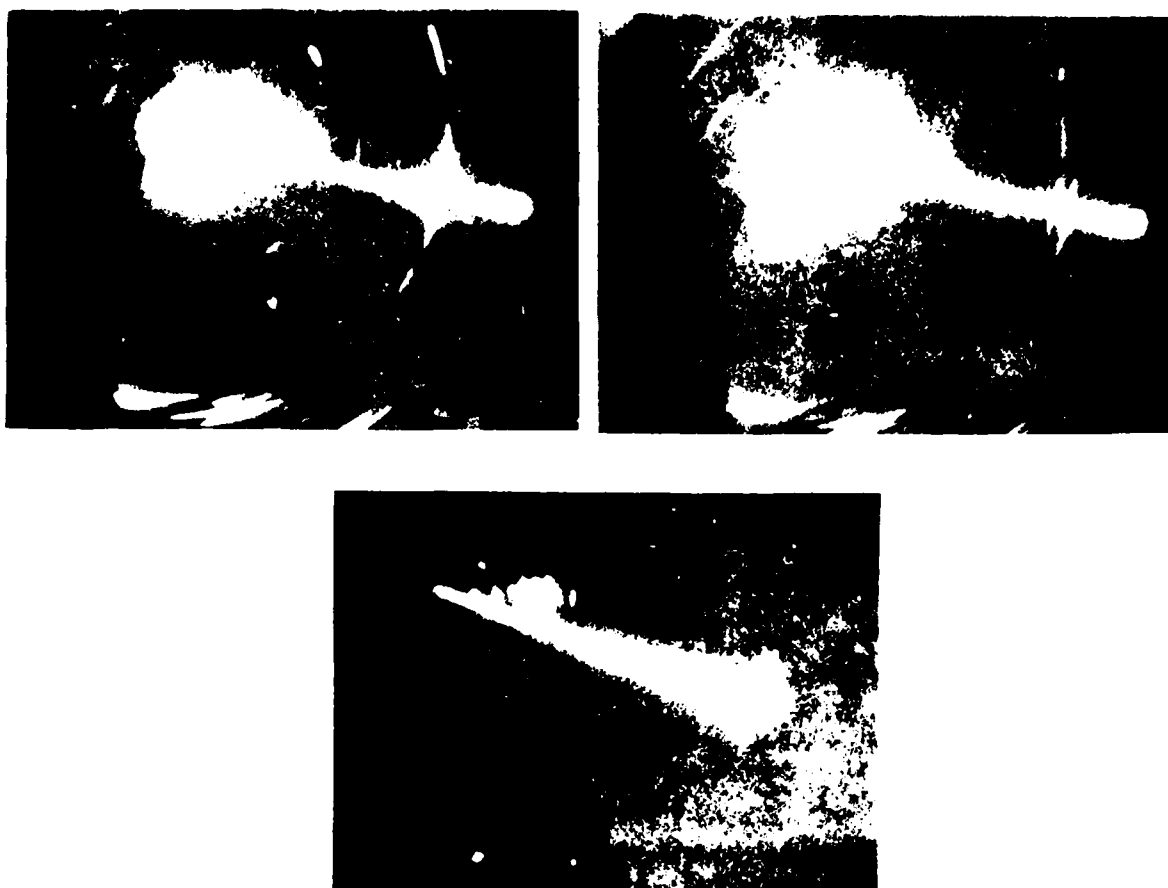


Slide 3

The Azimuth Console, seen in the center of slide 3, has both a PPI and a Bearing Deviation. The BDI could be driven either from the Azimuth Scanning Unit or the vertically split depth scanning unit. On the left is the EPI (Elevation Position Indicator), and on the right is the depth recorder, also installed in this compartment.

While four operators and a sonar officer were required for the system during an attack, during search only one was needed. Upon target detection and confirmation, the attack system operators were alerted and the attack system activated as soon as the target closed to 1000 yards.

The basic system design was done at Harvard in 1944 and 1945, and the practicality of depth scanning demonstrated in the spring of 1945. The construction of the complete system took place at the Underwater Sound Laboratory in 1945 and 1946. It was then installed in USS MALOY and extensively tested at sea against both real submarines and triplane targets. One problem encountered involved multiple bottom reflections in shallow water; the solution required transmitting on a directional beam with the depth scanning transducers. A second major problem was interference by surface reflections at shallow angles.

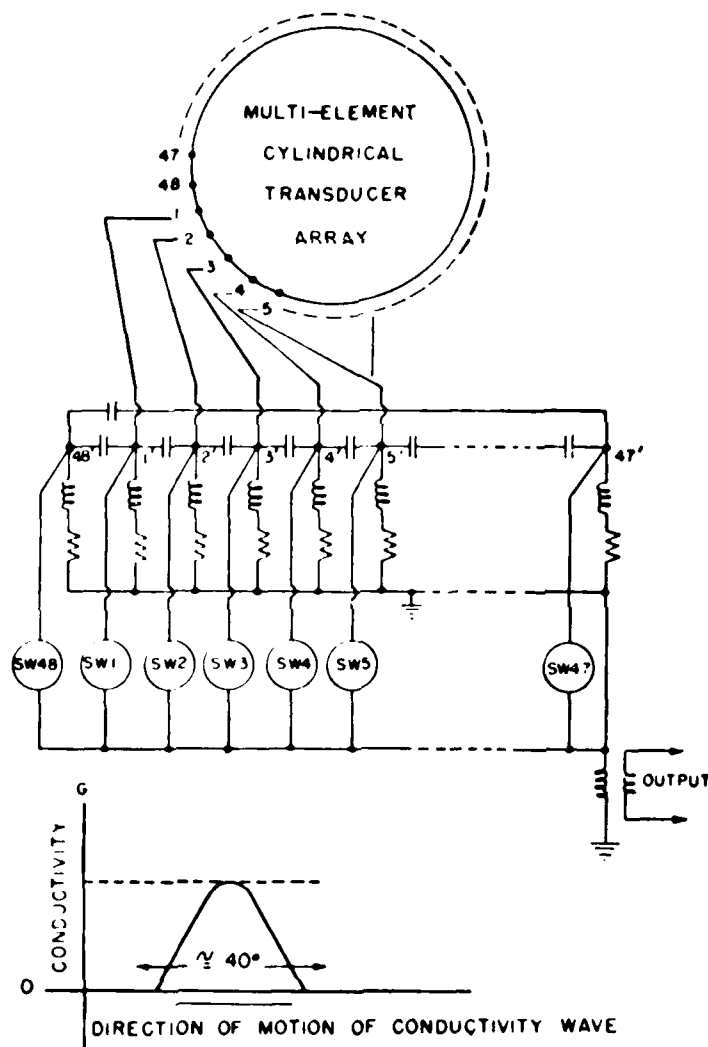


Slide 4

On the upper left of slide 4 is a target at a range of 1000 yards and a depth of 200 feet; on the upper right is the same target with a strong surface reflection distorting the picture. At the bottom is the target at 600 yards. At this range and depth, there is no problem with surface reflections.

In retrospect, the Type B Integrated Sonar was shown to be a competent attack system for targets at 100 yards and a depth of 210 feet in controlled tests.

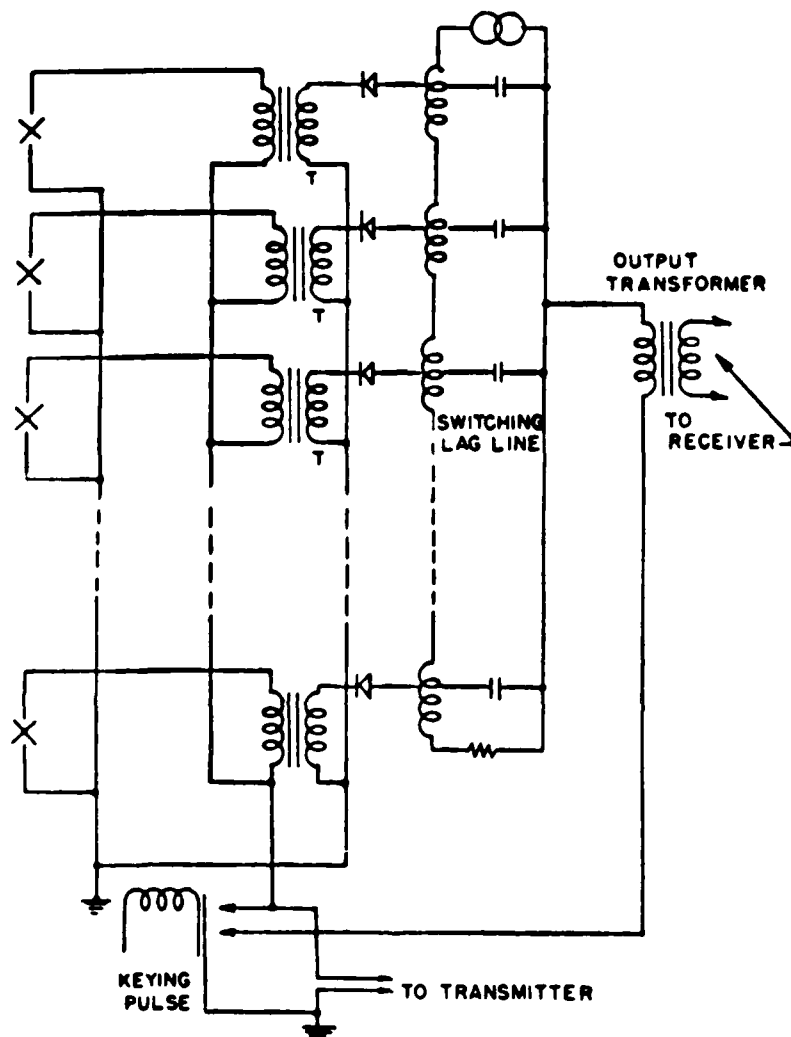
In semi-operational free play tests firing dummy hedgehogs at real submarines, a reasonably high success ratio was achieved. The project was concluded in 1949 with the preparation of specifications to guide procurement of a search attack system of this type.



Slide 5

The second unfinished development bequeathed by Harvard to USNUSL was an electronically rotated scanning sonar, designed for submarine use, and employing a simple symmetrical phasing network, or lead line, for beam formation.

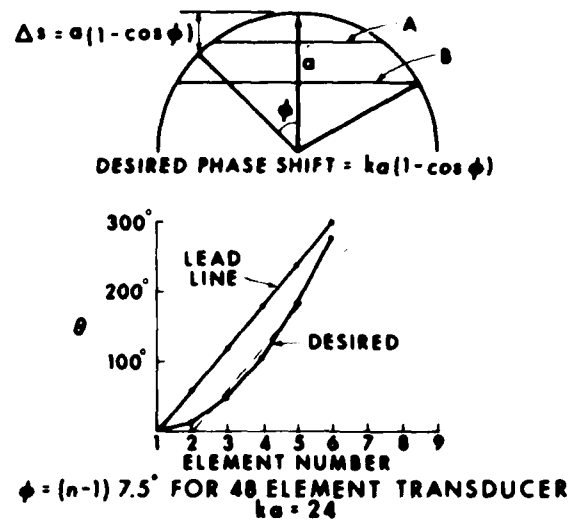
At the top of slide 5 is a multi-element cylindrical transducer with each element coupled to a lead line consisting of capacitors as series elements, and inductors and resistances as shunt elements. Note that the lead line is lossy and is terminated on itself. Scanning and interpolation is provided by a switching pulse (indicated at the bottom of the slide) which was tailored to turn on the switches in a desired pattern.



Slide 6

Note the delay line at the right in slide 6.

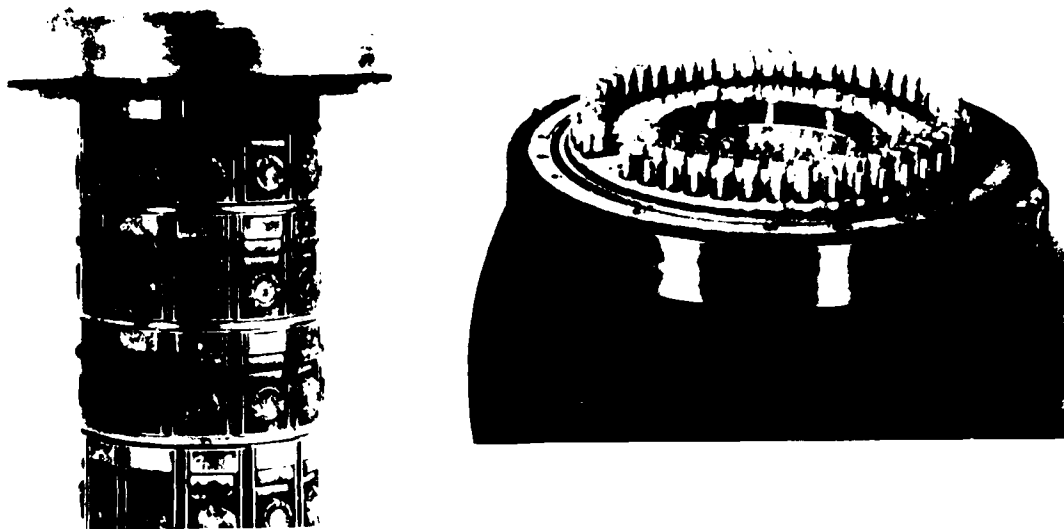
In practice, the tip of a sine wave derived from a tapped delay line 360° long at the scanning frequency was used, and three to five switches were wholly or partially conducting at any instant. In the final development at New London, the switching functions were chosen to flatten the phase characteristic of the lead line about the beam axis. The reason for this is shown in the next slide.



Slide 7

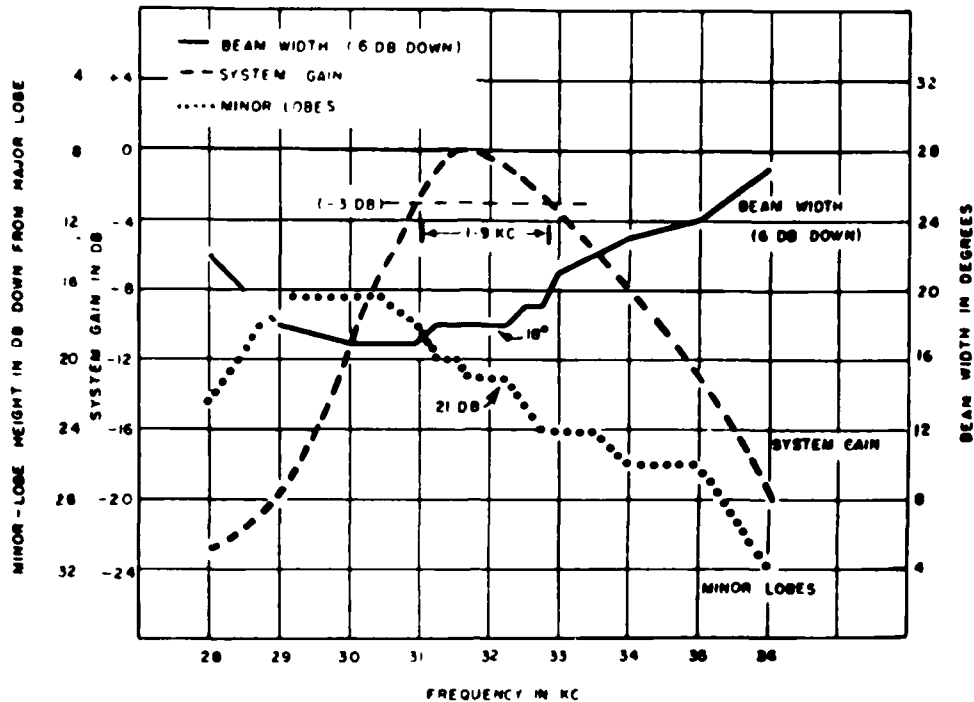
At the top of slide 7 is the geometry for a plane wave arrival at a cylindrical transducer of radius a . At the bottom, the curved solid line shows desired phase shift, plotted against element numbers on the abscissa. The straight solid line is the phase shift on the lead line for the case of a $60^\circ/\text{section}$ design; the dashed line is the phase shift resulting from reducing the relative phase between elements 1 and 2 right and 1 and 2 left to zero, by means of the switching pulse. In this example, nine elements -- four either side of the center -- are within 15° of the desired phase.

While the lead line is a simple structure and the available parameters are quite limited, the complete pattern is so complicated a function of these parameters that the problem of optimizing it analytically was not solved, and only limited parametric studies were possible with the computational facilities available there.



Slide 8

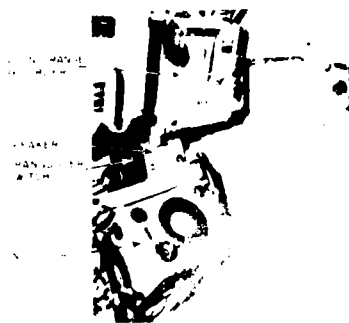
The development of electronically rotated scanning systems began at Harvard in 1943, and culminated with the design of a submarine system, the XQKA, being tested at New London in the spring of 1945. The left half of slide 8 shows the electronic rotor, which was designed initially to be installed in the transducer, shown on the right. The development continued at New London after the war, and resulted in a prototype submarine scanning sonar system with a rotation rate of 300 Hz, permitting a transmitting pulse length of 3.3 ms, and having characteristics shown in slide 9.



Slide 9

The abscissa is frequency from 28 to 36 kHz. With a nominal center frequency of 32 kHz, the -3 dB system bandwidth was 1.9 kHz. The minor lobe level is shown by the dotted line and is more than 21 dB down at 32 kHz. The solid line plots beam width, which was 18° at 32 kHz. This is 50 percent greater than can be achieved with a transducer of this type and a properly designed delay line or precise phasing system. The merit of the XQKA resided in its simplicity and the ability to achieve a high rotation rate and thus permit the use of a short pulse with a scanning sonar.

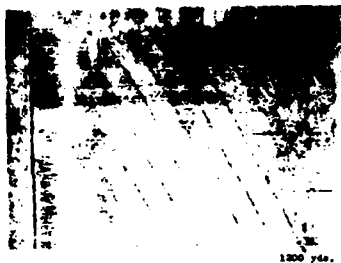
The system was designed for small object detection, single ping echo ranging, navigation in harbors and channels, and passive detection of noise sources such as ships and torpedoes.



Slide 10

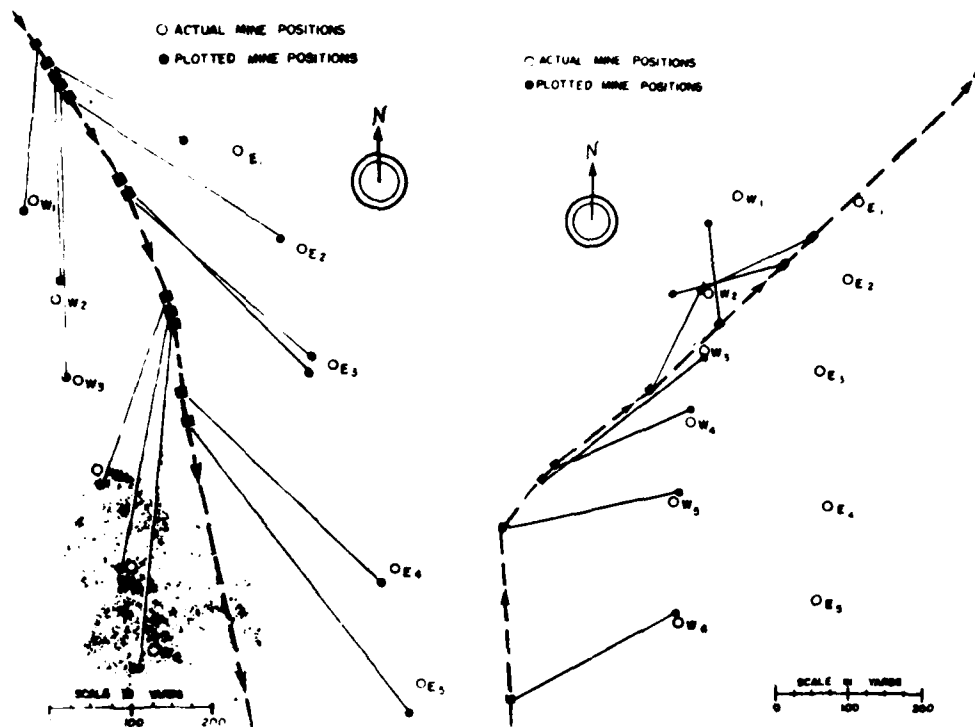
The final prototype was installed in USS SARDA in January of 1947. Slide 10 shows the conning tower installation in SARDA. Both bottomside and topside transducers were employed. Since a prime purpose of the XQKA was minefield navigation, the skipper wanted to see for himself whatever was on the scope, and conned the submarine from that information.

The controls on the PPI at the lower left of the slide were extremely simple; the handwheel at the lower right positioned the bearing cursor on the desired target and controlled the bearing of the listening commutator. The handwheel on the lower left positioned the range cursor, and range was read from a dial immediately above. There was a range switch at the upper left, and a gain control at the upper right. There were only two switches: an on-off switch and a switch to ping automatically or emit a single ping. While all functions were satisfactorily evaluated at New London, this presentation describes only a few results from the practice mine field runs.



Slide 11

At the top of slide 11 are range recorder traces from a mine field. Maximum range in the trace at the left is 2500 yards and at the right, 1200 yards. At the bottom are two PPI pictures showing mines 100 yards apart on the 600-yard range scale.



Slide 12

Shown in slide 12 are two plots made on a submerged run through the mine field. The open circles are the supposed actual mine positions and the black dots are the plotted positions from the XQKA. The transit on the left was made under good sonar conditions. On the right is a submerged run under poor sonar conditions, 20° temperature gradient in 40 feet. Clearly, a mine field transient under such poor sonar conditions would be extremely hazardous.

SCANNING SONAR- CYLINDRICAL TRANSDUCER

1. ACTIVE SEARCH-360°
2. PASSIVE DETECTION OF NOISE SOURCES-360°
3. DIRECTIONAL LISTENING-CLASSIFICATION
4. ACTIVE ATTACK-VERTICAL SCAN
5. SMALL OBJECT DETECTION-360°
6. STEERABLE HORIZONTAL DIRECTIONAL
TRANSMISSION AND RECEPTION
7. STEERABLE VERTICAL DIRECTIONAL
TRANSMISSION AND RECEPTION
8. MULTIPLE BEAM AURAL SEARCH
9. NAVIGATION
10. DIRECTIONAL COMMUNICATION

Slide 13

As in the case of the Type B Integrated Sonar, XQKA development concluded in 1949 with the development of specifications to guide the procurement of a submarine scanning sonar system.

The introduction of scanning sonar into the fleet following the war proceeded rapidly, with the Sangamo Electric Company being the principal designer and manufacturer. The Underwater Sound Laboratory participated as an advisor to the Bureau of Ships, as the Bureau's agent for technical evaluations and in the development of new concepts in relation to scanning systems and the more effective utilization of their cylindrical transducers.

The most attractive feature of the cylindrical array shown in slide 13 is its symmetry about a vertical axis. In general, whatever can be done on one bearing can be extended by relatively simple means to all bearings.

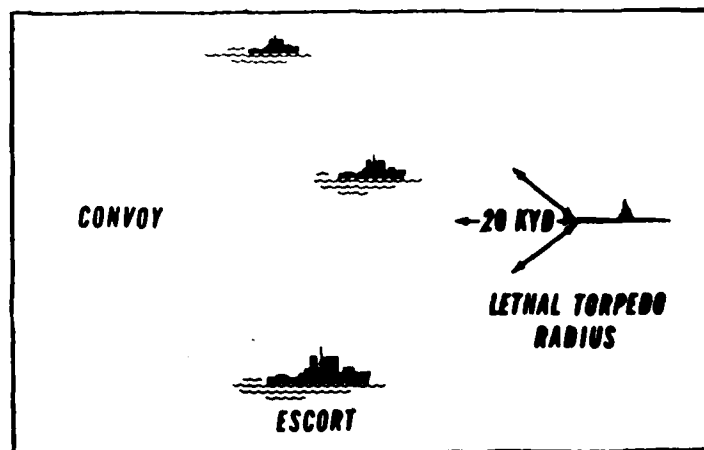
The first three items on the slide, 360° active search, passive detection of noise sources, and directional listening to evaluate either active or passive contacts, were common features in all scanning systems. While the feature of 360° active search with the PPI improved the search rate under good sonar conditions, it did very little to extend the range on below-layer targets. Consequently, under adverse sonar conditions, the first warning of the presence of a submarine was often the noise spoken on the PPI caused by a torpedo. Thus, countering torpedoes became a high priority item, and a Torpedo Bearing Indicator was developed as an add-on to scanning systems to improve their torpedo detection and tracking characteristics. This equipment involved a split commutator feeding a cross-correlation system and a bearing recorder. Once detected, the chosen target could be automatically tracked with bearing and bearing rate information provided for evasive maneuvering of the ship. This development was followed with an active torpedo detection adjunct, which employed a steerable directional transmitting beam that could be brought to the bearing of the torpedo so that

complete localization and tracking of the torpedo was possible. The directional transmitting beam, because of its increased directivity index, raised the system source level by 16 dB over the level of the 360° transmission, thus making possible the active detection of torpedoes with target strengths of the order of -15 dB at useful ranges.

This was followed by development of an accelerated active search adjunct called tribeam, which used the concept of directional transmission and a three-beam listening system called MASE (Multiple Aural Scanning Equipment) to increase the search rate of the listening channels by a factor of three. This development led to the RDT (Rotational Directional Transmitting) technique incorporated in many scanning systems.

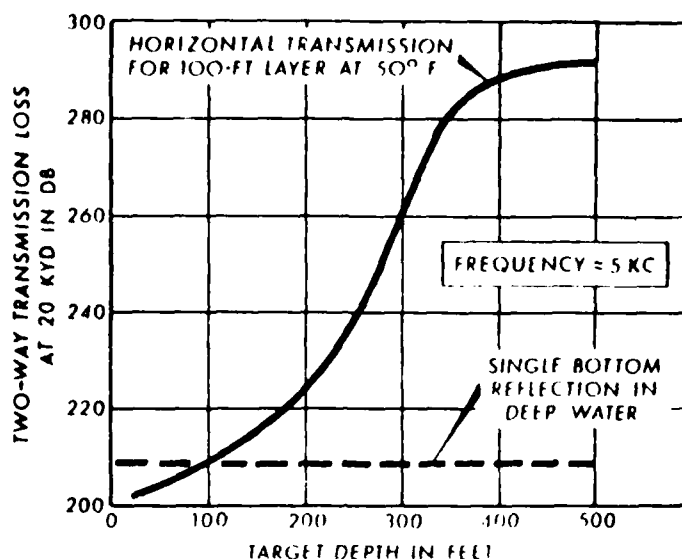
Finally, the techniques for steerable directional transmitting and receiving were extended to steering in the vertical plane, thus permitting the use of bottom bounce paths for long-range detection.

While many refinements of techniques were developed in the late 1940's and early 1950's, it became obvious that sonars designed under the constraint of a 19-inch gate valve were not going to solve the submarine detection problem. Thus, the decision was made to attach the transducer to the hull, and drydock the ship when necessary to change or repair the transducer. The QHB family had the 19-inch constraint, and operated over the frequency range of 30 to 30 kHz. The first stage in the lower frequency family was the SQS-4 and related sonars operating in the range of 8 to 14 kHz. By 1955, the Underwater Sound Laboratory had completed the Acoustic Meteorological and Oceanographic Survey (jointly with the Naval Hydrographic Office), and had expanded the knowledge of acoustic propagation and its relation to environmental factors tremendously. This information, coupled with that developed by other laboratories such as NRL, Naval Electronics Lab, and the Woods Hole Oceanographic Institute, formed the basis for a reexamination of the submarine detection problem.



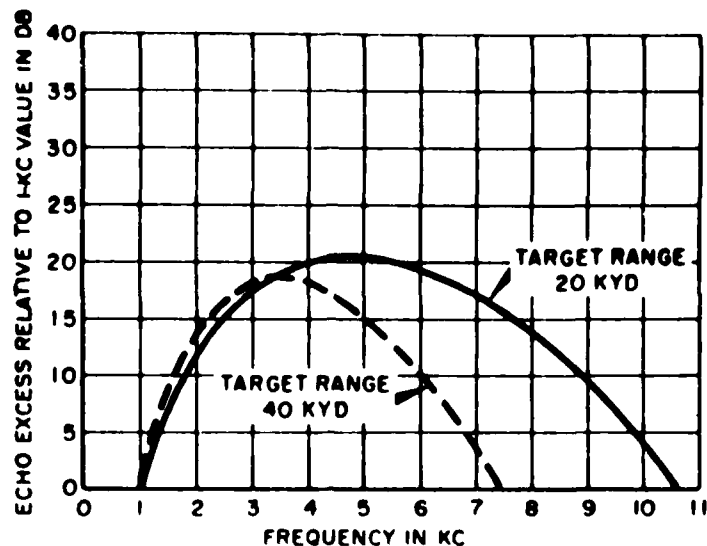
Slide 14

In a 1956 report, the Underwater Sound Laboratory considered the question: "What is next in sonar for convoy escort vessels?" The problem foreseen at that time is indicated in slide 14. This picture was based upon the anticipation that torpedoes effective at ranges from 10 to 20 kiloyards would become available within a few years, and also that an antisubmarine weapon effective at similar ranges would be developed; thus, the goal was established to develop an escort sonar with a reliable detection and tracking range of 20 kiloyards.



Slide 15

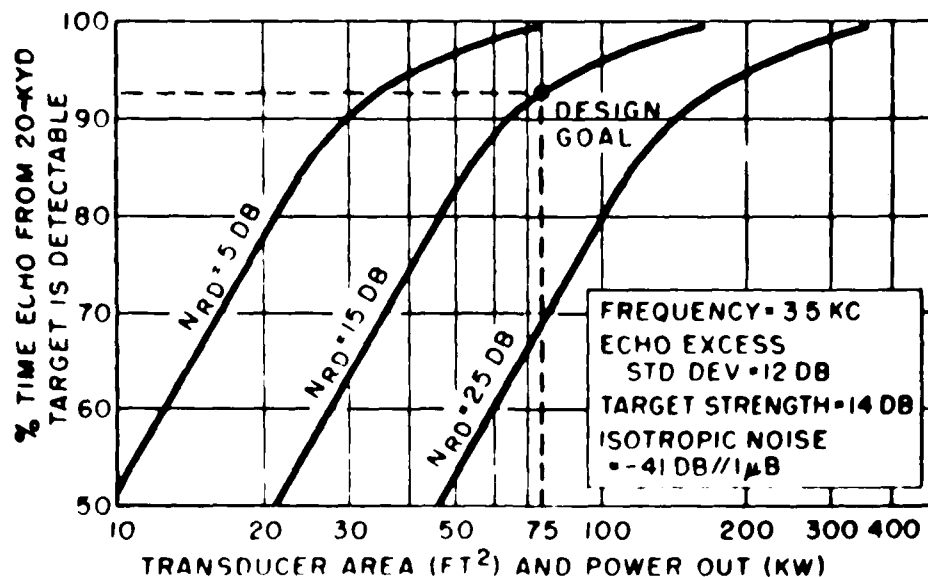
Slide 15 is a plot of two-way transmission loss at 20 kiloyards against target depth in feet for a frequency of 5 kHz. The solid curve is for direct transmission without the influence of the bottom. The dashed line is the two-way propagation loss for the signal travelling by way of a single bottom reflection. While the direct path has the least loss for depths less than the layer depth, the bottom reflection path is superior (and independent of depth) for all depths below the layer. For a target at 500 feet, the two-way propagation loss is some 80 dB less for the single bottom reflection path than for the direct path. The message was clear: If a sonar with adequate figure of merit to overcome the two-way propagation loss could be developed, a reliable long-range escort sonar was possible.



Slide 16

The next step was the consideration of optimum frequency. Slide 16 plots in dB on the ordinate, echo excess relative to the 1 kHz valve against frequency for a target range of 20 kiloyards in the solid curve, and a 40-kiloyard target in the dashed curve.

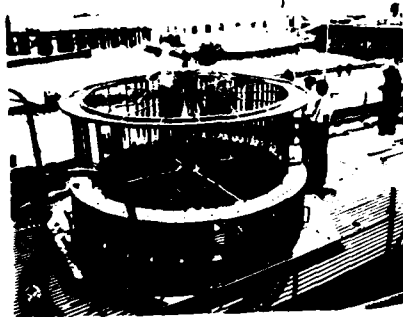
Note that optimum frequency does not depend on size nor power output of the equipment; it does depend upon the desired target range. Of course, the echo excess at the optimum frequency does depend upon equipment size and power level -- if it is not sufficiently large and powerful, the figure of merit will not permit detection of the target at any frequency. However, the shape of each curve is dependent solely on the rate of change of propagation loss with frequency and the rates of change of directivity index and noise level with frequency.



Slide 17

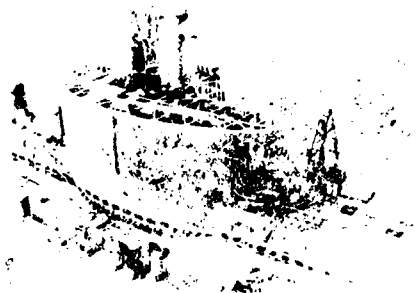
Slide 17 shows the design goal which was set forth in 1956 for the development of an experimental model of a sonar intended to exploit the bottom bounce path to provide a reliable long-range escort sonar. Many assumptions are included in this slide. It was assumed that a power level of 1 kw/sq ft of transducer face area would be achieved; it was also assumed that the recognition differential would be 15 dB and that the equivalent isotropic noise level would be -41 dB relative to a microbar.

An experimental program to achieve the goals outlined was undertaken and eventually lead to the development of various models of the SQS-26, which is a multimode sonar employing a large cylindrical array capable of exploiting all available propagation paths -- direct path, bottom bounce, and convergence zone. Steerable directional transmission in both vertical and horizontal planes is provided. While the scanning sonar PPI is still employed for all around alertness, high-performance digital signal processing techniques and sector search have largely supplanted the PPI for long-range search.



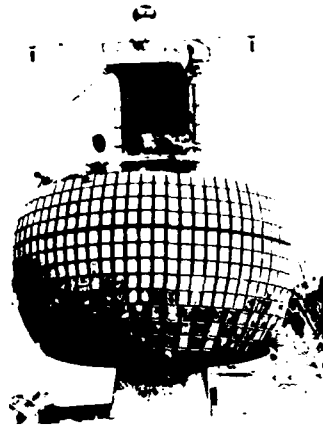
Slide 18

At the same time that USL was developing sonar systems based on cylindrical arrays for antisubmarine escorts, the laboratory was also exploring the use of large passive arrays for passive detection systems in submarines. Slide 18 shows such an experimental array. Electrically steered conformal arrays for passive detection had been extensively used by German and Japanese submarines during the war. The Underwater Sound Laboratory adopted their method of electrical steering but developed a means of splitting the array so cross-correlation techniques could be employed for detection, along with a bearing recorder for signal storage.



Slide 19

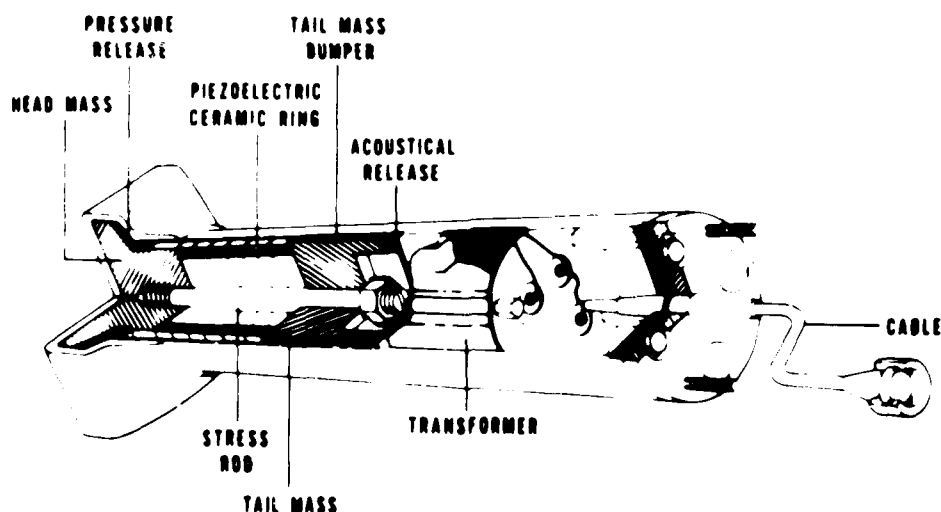
The largest such array developed at the New London Laboratory in the early 1950's was an elliptical array installed in USS FLYING FISH, shown in slide 19. This unit was 48 feet by 24 feet by 10 feet, and represented the first large-scale use of barium titanate hydrophones. These hydrophones were each 10 feet long, placed like a picket fence around the large ellipse. This experimental model was a precursor of the BQR-4 sonar. The performance of this equipment was outstanding when the self noise was controlled by having the submarine sit on the bottom and secure all machinery and people. Self noise in submarine sonars is a very serious problem, and is a principal reason for choice of the bow for location of modern submarine sonars.



Slide 20

At the same time that the laboratory was considering the large experimental bottom bounce sonar for escort ships, a program was initiated to develop a large spherical array for submarines. This was designed as a passive search equipment steerable in both the vertical and horizontal so that the predominant propagation path could be chosen; it was also designed for active directional transmission to obtain an accurate range before firing a weapon. Slide 20 shows a test fixture and a portion of this array.

When this system was first proposed, a number of critical technical questions existed, and the laboratory initiated efforts to develop at least one solution. Two of these problems were: 1) how to provide a smooth steering mechanism for the spherical array which would permit training to any horizontal or vertical angle and, 2) a transducer element was needed which could be produced with adequate tolerances, not change unduly with depth of submergence, and which would also handle the high power desired for the echo ranging function. Solutions for both of these problems were developed. The first involved the invention of a mechanically trainable spherical compensator, and the second, the development of a prototype transducer element employing PZT.



Slide 21

While slide 21 does not show the specific element, it is similar to the units employed in such arrays.

In about the same time frame that the initial experimental model of the SQS-26 became available, the precursor of the modern submarine sonars also entered the fleet.

CONCLUSION

The conclusion of this paper presents a review of the changing physical constraints on sonar systems, particularly, surface ships. In the 1940's, sonar design was constrained by the desire to bring the transducer inboard, using the currently available 19-inch gate valve. In the early 1950's that concept was abandoned in an effort to increase detection range; sonar size increased and frequency was lowered to the 8 to 14 kHz region. By 1955, in considering the design of a new class of escorts, the constraint placed on transducer size was set at 8 feet by 6 1/2 feet, which resulted in the SQS-23 operating at 5 kHz. Because of decreasing attenuation with frequency, maximum ranges of detection increased as size and power increased and frequency was lowered. But in this process, the short range of detection for below-layer targets changed very little. Some improvement in detection of below-layer targets resulted from development of variable depth sonars, but the real possibility of obtaining detection ranges beyond a few thousand yards required another change in the constraint on transducer dimensions. Systems designed to take advantage of reliable long-range propagation paths needed to be of the order of 15 feet in diameter, with operating frequency in the region of 3 to 5 kHz. That change was made with the introduction of the SQS-26. We have now come to the point where the size and weight and manning requirements of sonar systems have a major impact on the design of the ships and submarines which carry them. A recent article by LCDR Clark Graham, in

the Naval Engineers Journal for December 1975, addresses this matter. LCDR Graham shows that for a typical design, 60 tons of equipment directly associated for the sonar results in a total impact of ship displacement of 600 tons. His message is that equipment developers and ship designers need to work closely together to minimize the impact (and thus the total cost) of a given system. So long as the submarine threat is considered serious, it seems likely that the sonar-related displacement costs of a significant percentage of total displacement will be considered acceptable for at least major ASW ships. While sonars may not get much larger, neither will they get much smaller.

