Sonar Transducers: A History

World War II Prompted Incredible Accomplishments—Aided by Eliminating 'Red Tape', Rapid Advances in Production Engineering

By Frank Massa
Massa Products Corp.

Preface: *Our only available ASW sonar systems in 1940 were inadequate to prevent the very high rate of sinkings of U.S. merchant supply ships by the German submarine navy in the north Atlantic. The urgent solution to this problem was assigned the highest national priority and an all-out effort to solve it was undertaken under the civilian direction of the National Defense Research Council by enlisting every available engineering and scientific resource in the country.*

Some interesting personal recollections are presented in this article of how the removal of "red tape" and the elimination of the need to prepare written technical proposals sped the development and production of numerous transducers for use in various new ASW applications.

A very important personnel asset during the 1940s was the availability of experienced production engineers and mechanical designers. I had the tremendous advantage of having been trained with the best of them during the late 1920s and the following decade when mass production techniques and high reliability product design reached its zenith.

In addition to a highly condensed presentation of my own 50-year experience in sonar transducer development and production, I make two personal "editorial comments" in this article. I credit great advances in transducer development during 1940-45 to:

- *Early development of an underwater sound pressure measurement standard that quantified the actual performance characteristics of the many transducers being developed*
- *Early scrapping of unstable Rochelle salt crystals and the substitution of stable ammonium dihydrogen phosphate (ADP) crystals for all major transducer developments during the period.*

It is also my strong opinion that this country needs to restore the teaching of production engineering and reliable product design in our technical schools. This turnabout will, I am convinced, reverse the national trend toward the deterioration of product reliability due primarily to complicated, expensive structural designs. I am certain—as explained in the accompanying "sidebar"—that this lack in education is one of the fundamental reasons why we have lost our world leadership in product design and mass production capability.

This message applies as well to defense materials production, appliance manufacturers, and the automobile industry—where mass production was invented and brought to perfection and world recognition during the 1930s. Now the latter too seems to have forgotten the production engineering strength of its predecessors and joined the others in the easy downhill slide during the past few years.—Author

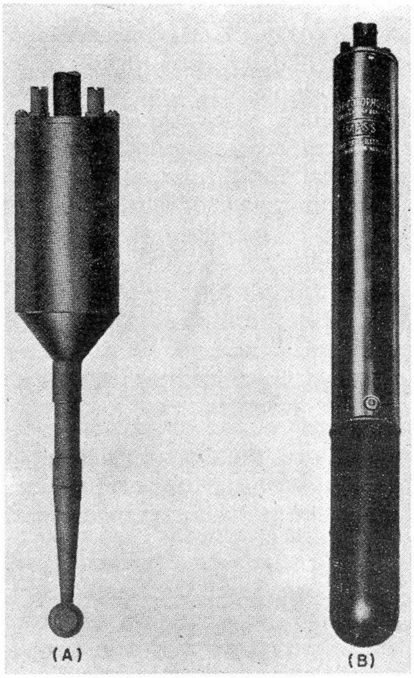

Submarine installation included passive sonar arrays inside the three fin-shaped sonar domes using length of the vessel as baseline for the complete receiving array.

Little progress was made in sonar transducer development during the period 1915-1940. The 1940 U.S. Navy sonar used a 24 kHz magnetostriction transducer comprising an array of nickel tubes driving a 1-foot-diameter steel plate mounted back to back with a Rochelle salt transducer inside a spherical housing. The latter was attached to a pipe that penetrated the ship's hull. During operation, the pipe was manually rotated and a pulse of sound was initiated at various selected bearings. If a submarine was nearby, a reflected echo would show up as a flash on a circular neon tube to indicate the range. The Rochelle salt transducer had a lower Q. But it was less reliable than the mangnetostriction unit, which was used as a substitute to maintain sonar operation during frequent periods of failure of the Rochelle salt.

Decade of Progress

The success of German submarines in sinking U.S. supply ships while moving in slow convoys during early World War II became intolerable. To prevent a national disaster, a high priority ASW effort was undertaken under the civilian direction of the National Defense Research Council by enlisting every available scientific and engineering resource in the country. The Navy's underwater Laboratory in New London, Connecticut, was rapidly expanded and undertook the development of magnetostriction transducers.

An underwater laboratory was established at Harvard University to investigate magnetostrictive materials to evaluate their use in transducer design. A Navy laboratory in San Diego was assigned to investigate Rochelle salt for the purpose of improving its reliability.



Early model of sound pressure measurement hydrophones (A) used Rochelle salt. Later model (B) used ADP crystals

During this period of increased activity, I joined Brush Development Co. as director of electroacoustic research. At the same time, a former associate at RCA-Victor was called into naval service as commanding officer of the Naval Gun Factory, which later became the Naval Ordnance Laboratory.

One of his first projects was to pretect individual slow moving ships from torpedo attack. His plan was to tow a streamer along each side of the ship with a small charge of TNT explosive at fixed spacings along its length. He asked for my help in developing a hydrophone to be placed at each TNT location to pick up noise from the approaching torpedo and automatically fire the charge nearest the hydrophone over which the torpedo passed before reaching the ship. Using the only available piezoelectric material at Brush, a Rochelle salt hydrophone was designed to solve the problem.

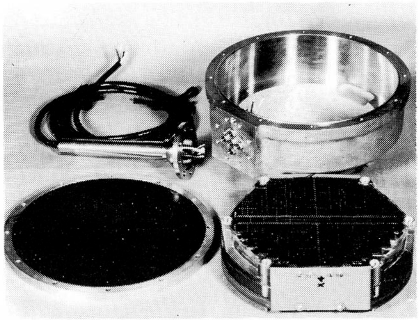
Following the success of the towed array, a contract was negotiated with the Navy to engage the full-time services of my small engineering group, which launched the writer and Brush into the relatively unknown field of underwater transducer design.

Under the services contract, a liaison officer from the Naval Gun Factory bypassed all the time-consuming formalities. These were usually required in preparing elaborate engineering proposals for each new development to repeatedly re-establish your already proven capability to fulfill the procurement requirements. Instead, the transducer specification for a new ASW application was sometimes communicated by telephone, and the development was initiated immediately without wasting valuable engineering time in generating voluminous paper proposals.

Under this efficient environment, a veritable stream of new transducers were developed and put into production by the writer, usually within a month or two of each new request. A very important factor that contributed to this rapid progress was the development of a measurement hydrophone for accurately calibrating transducers.

The inherent limitations of Rochelle salt were soon overcome by substituting ammonium dihydrogen phosphate (ADP) crystals that led to the greatly improved Model M-115B measurement standard.

The M-115B was widely adopted by the U.S. Navy laboratories and others and was successfully used as a stable reference standard for many decades.

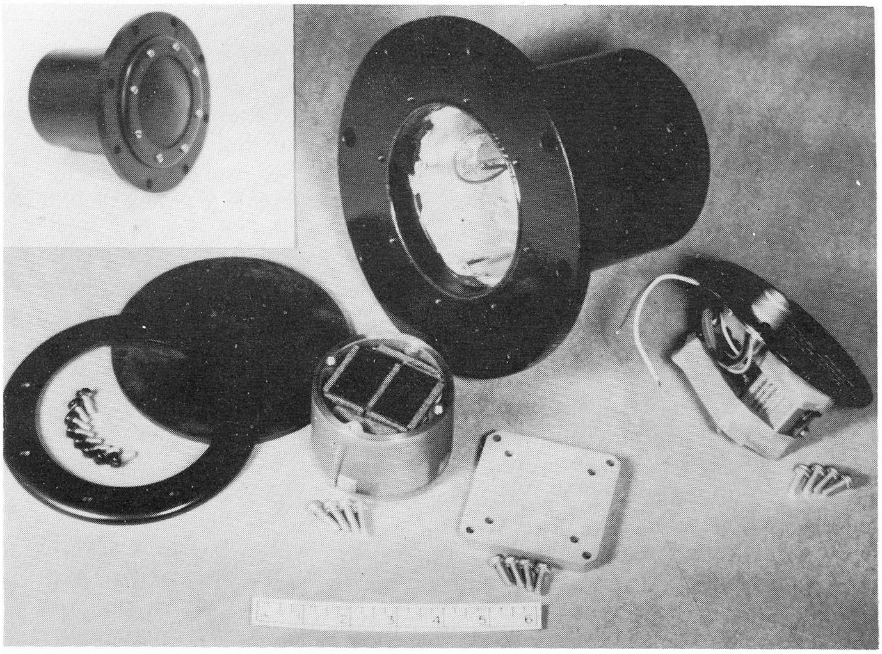


The first ADP transducer was designed as a replacement for the 24 kHz Rochelle salt device. Crystal assembly shown in foreground is mounted inside housing: a sound-transparent rubber disk molded to metal rim seals the opening. Assembly was vacuum filled with degassed castor oil.

ADP Replaces Rochelle Salt

It was soon apparent that Rochelle salt was a very unreliable material for sonar transducer applications. A search for something better indicated that ADP had the desired stability. A transducer was developed using experimentally grown ADP, and tests showed it to be far superior in power handling capacity and reliability. The Navy recognized the tremendous advantages of ADP over Rochelle salt and immediately provided funds for Brush to build a facility for growing large quantities of ADP.

Within nine months, Rochelle salt became virtually obsolete. Many tons of ADP crystal were used in the manufacture of tens of thousands of the many new transducers that were



Earliest application of ADP crystals was in an acoustically activated mine hydrophone.

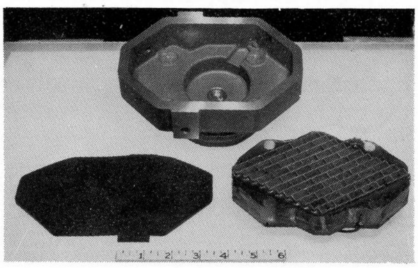
developed for use in new applications created by the rapidly advancing sonar system developments to meet the country's urgent ASW efforts.

The rapid progress in ADP transducer development required an expanded manufacturing facility from a few dozen personnel in early 1940 to several thousand by 1942. The production engineering experience acquired by the writer during the 1930s in the design and mass production of sound motion picture equipment and U.S. battleship communication equipment proved a valuable asset for creating numerous ADP transducer designs that were extremely rugged and low in manufacturing cost.

Acoustic Mine Hydrophones. One of the earliest applications of ADP was in a hydrophone design for use in acoustically activated mines. The hydrophone specifications included flat response in the low audio and subsonic frequency region; a low-frequency cutoff below 5 Hertz; ability to withstand water entry shock when air launched from 10,000 feet; and ability to withstand shock from neighboring mine explosions. Most important was a uniform sensitivity requirement within one-half decibel of a reference standard, which was easily met because ADP has zero aging characteristics and remains stable during many years of storage.

Acoustic Torpedo Transducers. The earliest acoustically guided torpedoes made use of passive sonar. Four identical high-frequency directional hydrophones were located symmetrically on the nose of the torpedo; one pair was located in the horizontal plane with their axes inclined at equal angles to the left and right of the torpedo axis, and the second pair was similarly located in the vertical plane. At the cross-over point of the beam patterns along the axis of the torpedo, the sensitivities of the hydrophones are equal; therefore, if the acoustic noise generated by the submarine indicates the same output level on each of the four receiving channels, the axis of the torpedo is aligned with the target. If the target is not aligned with the torpedo axis, the relative levels of the detected signals in the hydrophones will change and the course correction is automatically adjusted until the signal levels in both pairs of hydrophone channels are equal. This simple acoustic homing system worked well until a countermeasure neutralized its effectiveness. The target submarine discharged an effervescent chemical and abruptly changed course where it remained undetected while the torpedo pursued the fizzing decoy.

However, the countermeasure was neutralized by converting the torpedo homing system to active sonar. A small transducer mounted in the nose of the torpedo transmitted periodic tone bursts, and the target echoes were received by the torpedo hydrophones and used for making the course correction in the same way as in the original passive system.



Ultrasonic ADP transducer for acoustically guided torpedoes uses low-cost shading for secondary lobe reduction.

The diamond-shaped pattern of the crystal area reduces secondary lobes and also produces a narrower beam in the vertical plane than in the horizontal plane, which is preferable for the application. The use of identical rectangular crystal plates arranged in staggered rows (as indicated) achieved a much lower cost compared to the mathematical shading techniques that require each element in the array to be different in sensitivity.

Passive Long-Range Submarine Sonar. It is obvious that a submarine cannot use active sonar during combat because it would be suicidal to reveal its position. The high reliability and uniformity of ADP crystal made possible the development of a passive submarine sonar system for indicating the bearing of submerged or surface vessels at very long ranges. Several ADP crystal assemblies were precisely mounted inside a steel tube to form a high precision line hydrophone. A rubber boot and mounting flanges completed the hydrophone assemblies, after which they were vacuum filled with castor oil and mounted in parallel arrays.

To take full advantage of the extreme uniformity and stability of ADP crystal, the mechanical structures were designed to hold the parallelism of the acoustic axes of the hydrophones within 0.006 inch; otherwise, the phase shift of the received signal at the high frequency end of the audible range due to misalignment would limit the maximum detection range.

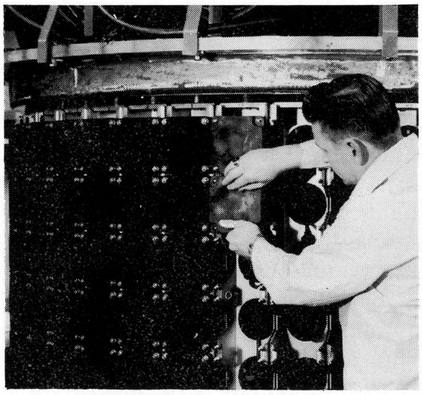
Polarized Ceramics Developments

At the end of World War II, the standard U.S. Navy scanning sonar transducer used an array of ADP crystals operating at 18 kHz. With increased knowledge of sound propagation in the sea, it became evident that lower frequencies would improve the range of detection. The practical size limitation of ADP crystals prevented their use at lower frequencies; therefore, magnetostriction and barium titanate ceramic designs were developed during the early 1950s for low-frequency use. Both these materials had limitations that prevented achieving uniform impedance characteristics among the separate stave assemblies, which in turn deteriorated the beam pattern during the operation of the sonar. Barium titanate was eventually replaced by more stable lead zirconate titanate and the scanning sonar frequency was progressively lowered from 19 to 5 kHz, which became the standard AN/SQS-23 sonar in widespread use for several decades throughout the U.S. fleet.

The magnetostriction transducer designed for the SQS-23 sonar used several tons of nickel, which was expensive and consumed enormous quantities of what was considered a critical material. The magnetostriction design was eventually replaced by a lead zirconate titanate ceramic design.

During the first decade of use of the SQS-23 sonar, ceramic transducers were being produced by several sonar system manufacturers, each using a different design. All designs developed serious problems in the fleet and required frequent transducer replacements due to various mechanical and electrical failures. It was also impossible to meet the required performance specifications because of the variations in the piezoelectric characteristics among the ceramic elements.

The inability to control the uniformity and reliability of the ceramic transducer was accepted by the Navy as being "beyond the state of the art." Also, deterioration in the mechanical integrity of the transducer soon after installation intensified serious Navy concern to find an acceptable solution to the problems—or find a replacement design.



Massa technician installs one of 432 TR-208A elements in the Navy's SQS-23 scanning sonar transducer system.

During the mid-1950s, Massa Products Corp. developed a proprietary ceramic transducer design for use on the SQS-23 sonar. The transducer met all the "beyond the state-of-the-art" specifications and its price and weight were approximately one-half that of the non-conforming previous designs.

More Reliability, Lower Cost

It is not generally recognized that transducer designs can be greatly improved by simply utilizing the specialized skills of competent production engineers who have had long experience in the manufacture of competitive commercial electromechanical products. A greater effort to enlist these production engineering talents—generally outside the interest or capabilities of physicists and other scientific personnel—would lead to greatly improved transducer designs. Elimination of unnecessary structural components would result in higher reliability and lower cost. The use of production control techniques would achieve a high degree of uniformity during the production of large quantities of the transducers.

The scanning sonar transducers developed during the late stages of World War II operated at relatively high frequencies, which meant that the transducer assembly was rather small, consisting of an array of ADP crystal staves attached to the perimeter of a tubular frame. A single rubber boot enclosed the assembled structure. With the progressive lowering of sonar frequencies, transducer dimensions became larger, and it became necessary to fabricate the transducer as a large structural array employing hundreds of modular transducer element assemblies. The use of a modular design in the transducer configuration imposed severe requirements in uniformity and reliability among the individual transducer element assemblies that were non-existent in the earlier high frequency sonar systems.

Expendable Modular Design

It had been a long established Navy policy that transducers should be designed to permit making repairs at Navy yard transducer maintenance facilities. To achieve this objective, the general practice was for the housing assembly to be held together by bolts, and that removable gaskets be provided for sealing the separable sections to prevent the seepage of water into the transducer. This type of construction was a reasonable requirement for the earlier types of sonar transducers in which the complete assembly was contained in a single housing.

However, as the transducers became larger and required arrays of many hundreds of separate transducer elements, this policy became self-defeating.

In the first place, if the transducer module is designed to permit disassembly, the seals and associated hardware required to hold the separable parts together becomes a significant source of mechanical failure, which reduces the reliability of the element. The added parts and extra machining required adds materially to the manufacturing cost of the structure. Another significant increase in cost results from the necessity of providing spare parts for all the individual structural components, which must be very specially and expensively packed to prevent deterioration in storage. Finally, much highly skilled labor is consumed at the maintenance depots for disassembling failed transducer elements and rebuilding them with replacement spare parts.

The combination of all these factors adds very materially to the actual cost of the transducer and also defeats the basic design objectives set forth in MIL-E-16400F(Navy), which states:

> "The basic design objectives are that the equipment will meet the needs of the Naval service and that the final product will reflect the utmost in simplicity, have maximum reliability and minimum weight consistent with the state of the art, and be easy to install and maintain."

To overcome the objections asso-

Production Engineering—Still a Basic Need

It is an unfortunate fact that the design of many transducers now being procured for diversified operational needs could be greatly improved. The key is to apply the specialized skills of competent production engineers who have had successful production design and manufacturing experience in industries engaged in the manufacture of competitive electromechanical products.

In some instances, manufacturing drawings included in transducer procurement specifications indicate a lack of production engineering experience on the part of the scientific team that created the design. Occasionally, the production design represents little more than a computer-derived mathematical model that includes mechanical configurations that are not only responsible for *increased* costs but actually serve to *decrease* the reliability and ruggedness of the transducer. It is unreasonable to expect that good production designs should originate from physicists or scientists whose primary interests and skills lie in the theoretical analysis of vibrating systems.

Qualifications for a good production engineer must include a basic knowledge of efficient manufacturing methods and production control procedures, together with long personal experience in the successful production design of competitive industrial products. Equipped with these skills, the production engineer can convert a developmental model into a structure that can be manufactured reliably and repetitively at low cost. That product will also assure a high degree of uniformity in performance characteristics among large production quantities.—**Frank Massa** ciated with the repairable modular construction and at the same time better meet the Navy reliability objectives, Massa designed a replacement transducer for the SQS-23 sonar as a hermetically sealed, low-cost assembly. If a module fails, it is simply replaced by an identical spare. Advantages of such a design include the elimination of extra costs associated with a repairable structure. By eliminating the extra mechanical parts and seals not required in the expendable design, a major source of mechanical failure and corrosion is also eliminated. In the sealed modular design, it is possible to simplify the assembly and reduce the number of parts.

The expendable modular design permits the use of a sealed, low-cost, non-corrosive protective covering that eliminates the need for expensive stainless steel housings and fittings generally required for conventional designs.

The expendable module eliminates the need for field repairs and only replacement modules are needed for spare parts. Because the module is a complete waterproof operating unit, expensive packing is not necessary. Since the spare module is built with precision production tools, it will be identical in operating characteristics to the module which it replaces.

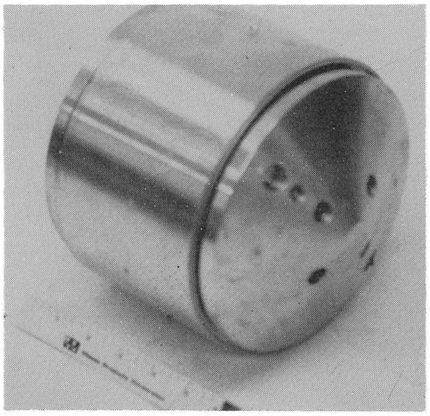
Ultra-Long-Range Sonar Needs

During the past two or three decades, considerable effort has been expended in the development of high-power transducers for use in the low audible frequency region to meet the requirements of future ultra-long-range sonar systems not yet fully defined. Some examples:

Magnetostrictive Ring Transducer. A large-diameter ring comprising a cemented multiple layer scroll of nickel strip (over which is wound a toroidal coil of insulated wire) will vibrate in the radial resonance mode when an AC current is superimposed on a DC biasing current supplied to the winding. It is extremely difficult to provide a uniform film of high strength cement over the entire surface of the continuous nickel strip while it is being wound; thus, there is a high risk of delaminating the nickel scroll by failure of the cement during high-power operation.

Ceramic Ring Transducer. Large-diameter ceramic rings fabricated from wedge-shaped ceramic sections cemented together to form the ring have also been built for use as high-power low-frequency sound generators. However, they are subject to high risk of structural failure when operated at high-power levels. Another disadvantage of the ring design is that it cannot be used conveniently in planar arrays to form high-power directional beams.

Megawatt Low-Frequency Electromagnetic Transducer Array. Electromagnetic transducers that operate by electromagnetic forces have shown the most success. The forces are generated in an air gap between the magnetic laminations attached to the vibratile structure and the magnetic laminations attached to the massive inertial non-radiating structure. The world's largest transducer array—a 300,000-pound array, 1500 square feet in area—was designed and manufactured by Massa for the Office of Naval Research as a replacement for a magnetostriction scroll array that failed while operating at high-power levels. The electromagnetic structure operated successfully during its use in a five-year research program to make very-long-range sonar propagation studies to determine the possibilities of designing a distant early warning submarine detection sonar. The large array operated at a measured 60% efficiency and could be driven with up to 1 megawatt of audio power in the 400 to 500 Hz frequency band.



Lightweight (10 pound) transducer module delivers 3 kilowatts in the 3-kHz frequency region.

High-power Electromagnetic Transducer for Very Great Depths. A spherical low-frequency transducer element assembly approximately 2 feet in diameter, is driven electromagnetically, push-pull, from opposite sides of a circular disk that lies in the equatorial plane of the sphere. The spherical shell oscillates as a dipole. When rho-c loaded, it delivers from 2 to 4 kilowatts of sound with a Q between 3 and 4 depending on the frequency range of operation and the thickness of the spherical housing, which in turn depends on whether the depth of operation is 20,000 or 2,000 feet. An underwater horn was designed for increasing the radiation resistance on one face of the spherical dipole by more than an order of magnitude over the loading on the rear face of the sphere, thus eliminating the need for a pressure release baffle.

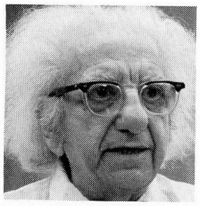
Electromagnetic Transducer for High-power Low-frequency Arrays. A very recent development is an inertial mass-loaded electromagnetically driven vibrating piston. The vibrating piston is a rigid 17-inch-diameter plate spring mounted to the inertial mass portion of the vibrating structure. The heavy copper coils and E-laminations which comprise part of the magnetic circuit are bonded to the massive steel plate and contribute to the total inertial mass. The lighter I-laminations that complete the magnetic circuit are bonded to the inner surface of the vibratile plate. A circumferential row of springs separate the vibrating plate from the inertial mass and the spring stiffness determines the resonance frequency of the transducer. The transducer design achieves a low Q of less than unity for a rho-c loaded array. Each transducer element can deliver 2-3 kilowatts of sound at approximately 50% efficiency over an octave bandwidth within the low-frequency region below 1 kHz.

Lightweight Sonar Systems

The continued lowering of sonar frequencies for achieving greater range has resulted in very massive sonar transducer arrays weighing many tons. A conventional scanning sonar transducer for operating in the 3-4 kHz region weighs approximately 20,000 pounds. A novel modular high-power transducer we developed weighs only 10 pounds and generates 3 kilowatts of sound in the 3 kHz region when used in an array for a radically new sonar system.

Two conically tapered pistons are driven at opposite ends of a lead zirconate titanate ceramic stack. Both pistons move in phase and a stationary node is established at the center of the stack, equivalent to an inertial loading for each piston of infinite mass but zero weight. The tapered pistons form a radial underwater horn at the junction of each pair of modules when a number of modules are aligned along the vertical axis of a tubular housing. The increased resistance loading due to the circular horn structure results in a Q of 2 which achieves 1/2 octave broadband response. A line array 9 inches in diameter by 50 inches long weighs 125 pounds and generates 20 kilowatts of sound in an omnidirectional horizontal beam with a vertical beam angle of 25°

An engineering prototype of a portable long-range sonar system includes the new lightweight transducer mounted axially within a 9-inch-diameter housing. The unit also contains the power supply and a very high precision nine-element line hydrophone receiving array that achieves a target bearing accuracy of 2°. The complete underwater portion of the Model M-1002 long-range 3 kHz portable sonar system weighs 250 pounds. The new portable sonar system has a range of 20,000 meters and a bearing accuracy of 2°. Preliminary tests conducted in Massachusetts Bay have located targets at ranges of 5 to 10 miles. /st/



Frank Massa is considered by most the "father" of modern sonar transducer development. His career began at Victor Talking Machine Co. (later RCA Victor) in Camden, New Jersey, where he pioneered in electro-acoustics and basic development of early microphones and speakers. At Brush Development Co. (Cleveland), Massa turned the corner to sonar. In 1945, he established his own firm in Cleveland and is now chairman and executive consultant for the firm, now located in Hingham, Massachusetts. Massa has completed four textbooks and more than 60 technical papers; he also holds more than 140 patents.