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PROFILES IN SCIENCE

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Allyn Vine is the Senior Scientist at the Woods Hole Oceanographic Institute. For many years his work has been supported by the Office of Naval Research especially in the fields of underwater acoustics, oceanographic research ships and deep submersibles, and specialized instruments to broaden our at-sea measurement capability.

Mr. Vine is renowned for improving the basic vehicles and techniques which will make the ocean more accessible to oceanographers. He has been prominent in designing and procuring the research submarines ALUMINAUT and ALVIN and the research ships ATLATIS II and FLIP.

Some Underwater Applications of Nonlinear Acoustics*

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Introduction

Over the past decade, nonlinear acoustics has experienced an unprecedented expansion in theory, experiment, and application. This vigorous activity has its roots in Westervelt's theoretical discovery of the parametric acoustic array (1960). This type of transducer utilizes the nonlinear properties of the water itself to produce a low frequency, superdirective radiation from the parametric interaction of two high frequency generating waves. The superdirective radiation so created is a wide band entity having no spatial diffraction lobes. Several practical applications of parametric arrays are now emerging; these include bathymetric profiling, the location of artifacts in marine archeology, ultrasonic imaging and biomedical diagnostics, and measurements on waveguide propagation in shallow water. Much of this research has been conducted and is continuing under the support of the Office of Naval Research.

The engineering interest in the parametric array derives from its great directivity, specifically its narrow beamwidth and the absence of minor lobes in its radiation patterns. The narrow beamwidth is a result of the shape of the zone of modulation. By analogy to the ordinary end-fired array, it can be easily seen that the longer the zone of modulation, the smaller is the beamwidth of the parametric array. Since the zone of modulation is usually very long in comparison to its width, the parametric array produces a radiation much narrower than that which would be produced by the source transducer were it operating linearly at the difference frequency. The parametric array is shaded by virtue of the naturally smooth decay in the conversion of carrier frequency sound to difference frequency sound with increasing distance from the electroacoustic source. This inherent form of array shading, which is due to the absorption of the carrier waves and to diffraction within the zone of interaction, gives rise to an angular response that

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decays monotonically with increasing angle from the acoustic axis. In other words, the beam pattern of the parametric array contains none of the undesirable minor lobe structures that are common in conventional piston type transducers. Parametric arrays are capable of great frequency agility, which can be used to advantage in wide band system applications.

In 1968, the author and J. E. Blue were privileged to do some full-scale measurements on parametric arrays in a fresh water lake (1). The purpose was to tie all of the previous measurements together in some experiments that would not be limited by model tank constraints. A handy experimental test was developed to identify difficulties arising from nonacoustic modulation phenomena. The main measurements used a 2 in. × 2 in. piston projector at 0.981 and 1.124 MHz to produce a 1.70° difference frequency beam at 143 kHz. Its axial propagation, angular response, frequency dependence, and amplitude response were measured at ranges out to several hundred yards. The data agreed well with Westervelt's theory and this seemed to help alleviate some of the lingering suspicions about parametric arrays.

Applications

The practical utilization of nonlinear acoustics in underwater sound owes much to the superdirective capabilities of parametric arrays. It has been found that parametric systems are competitive with their linear counterparts when the transducer size of the latter becomes prohibitively large. Some interesting civil applications are emerging and these will be summarized here.

Bathymetric Sounding

The applicability of the parametric acoustic transmitting array to bottom and subbottom profiling was first recognized (1) in 1968 to be a feasible approach to high resolution bathymetry. The parametric transmitter offered all of the desirable features for bottom and subbottom profiling, i.e., a narrow beam at a low operating frequency, with a small projector that could be used from small oceanographic vessels. The only significant disadvantage was the inefficiency of the parametric process; however, this difficulty did not turn out to be prohibitive for echo sounding, because the ocean bottom affords an excellent target with good echo return. It was clear from the onset that deficiencies in the parametric signal-to-noise ratio could be remedied by use of any of a number of wide band signal processors. This is especially true in subbottom profiling, where signal processing is essential to good sediment penetration.

A block diagram of one of the earlier depth sounder designs is shown in Figure 1. This system is sufficiently similar to those fabricated and tested in this country and abroad to serve as an example

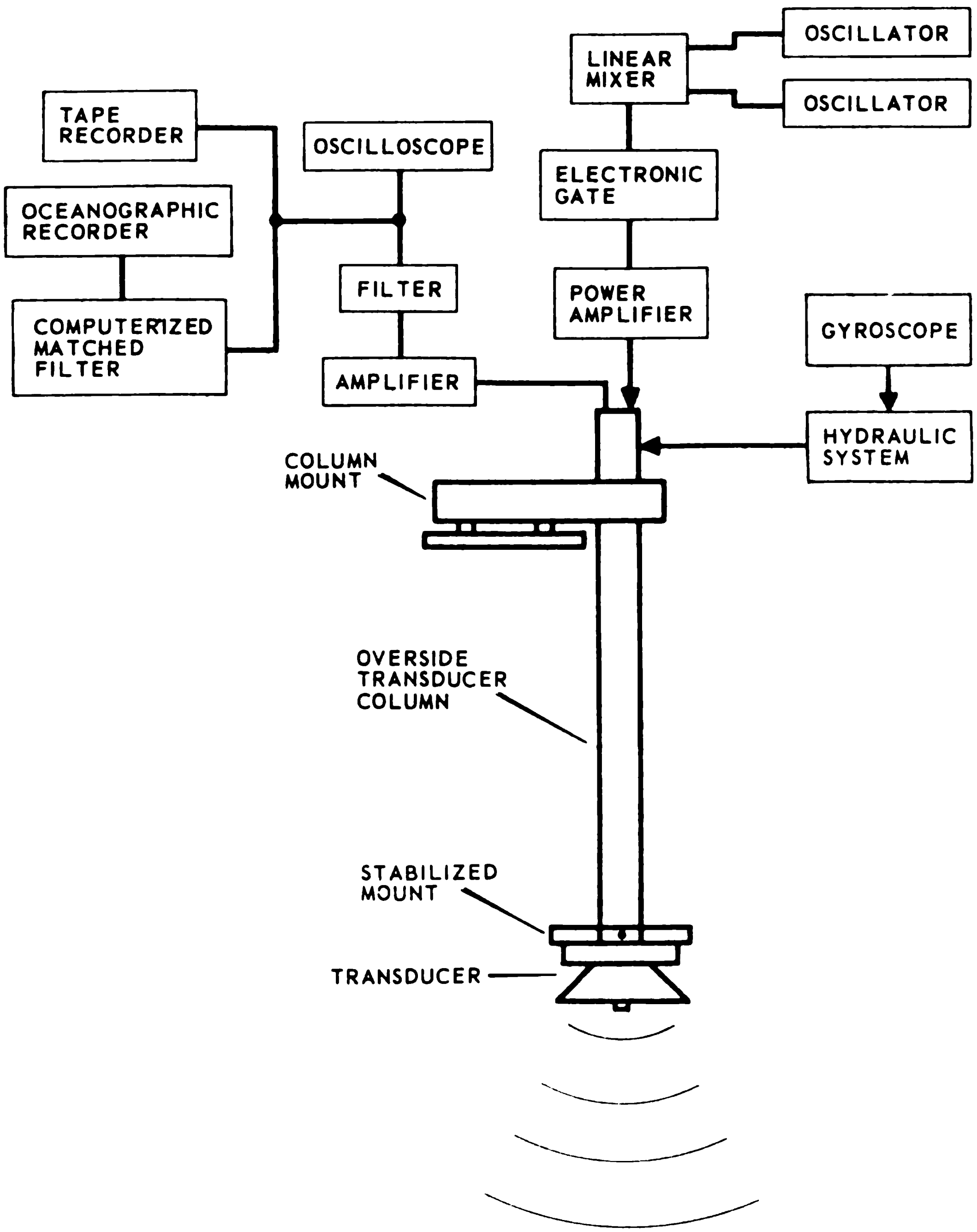

Figure 1 – Block diagram of parametric depth sounder

for discussion. The outputs of two FM oscillators are summed, gated into a dual FM pulse, amplified, and applied to a single high frequency projector.

Difference frequency sound generated in the water reflects from the ocean bottom and returns to a low frequency hydrophone located in the same housing as the high frequency source. The received signal is amplified, filtered, and processed by means of a correlator.

The usual components for bathymetric measurements and research are also shown in the sample block diagram, namely an oceanographic recorder and a tape recorder. One method of mechanical mounting of the system transducer is also indicated. This method is applicable to extremely narrow beam systems that may require a stabilized soundhead.

The first at-sea tests of a parametric echo sounder were reported by G. Walsh (2) of the Raytheon Company. The system tested differed from that of Figure 1, primarily in that the soundheads were towed in a VDS fish to avoid the mechanical stabilization problem. This system, dubbed "FADS" for Finite-Amplitude Depth Sounder, used a mean primary frequency of 200 kHz and a mean difference frequency of 12 kHz, in a 60 msec FM pulse having a bandwidth of 2 kHz. The primaries were transmitted from a 9 in. aperture at a source level of 125 dB re 1 μbar at 1 yd. A difference frequency source level of 88 dB re 1 μbar at 1 yd was produced in a 3° beam.

A side-by-side comparison of this system with a conventional 12 kHz echo sounder, both operating in Narragansett Bay, is shown in Figure 2. Oceanographic recorder data for the parametric system is shown on the left side of Figure 2, with the conventional system data presented on the right. The superiority of the parametric system is clearly evident in three major features. First, the fish shoals appear as distinct targets in the parametric case, in contrast to their appearance as hyperbolic traces in the data acquired by the conventional system. The hyperbolic traces are obtained because the conventional system beamwidth is so broad as to receive echoes from these targets long before, during, as well as after, the survey vessel passes over the target area. The location and extent of the fish shoals are much more clearly defined with the parametric system. Secondly, the bottom appears as a distinct boundary in the parametric case, with some lateral discontinuities that are not evident in the data for the convention system. This is due to a substantial amount of averaging within the wide beam of the conventional system that "washes out" many of the important details that are recorded by the narrow beam parametric system. Finally, the remarkable fine structure in the subbottom layering for the parametric data

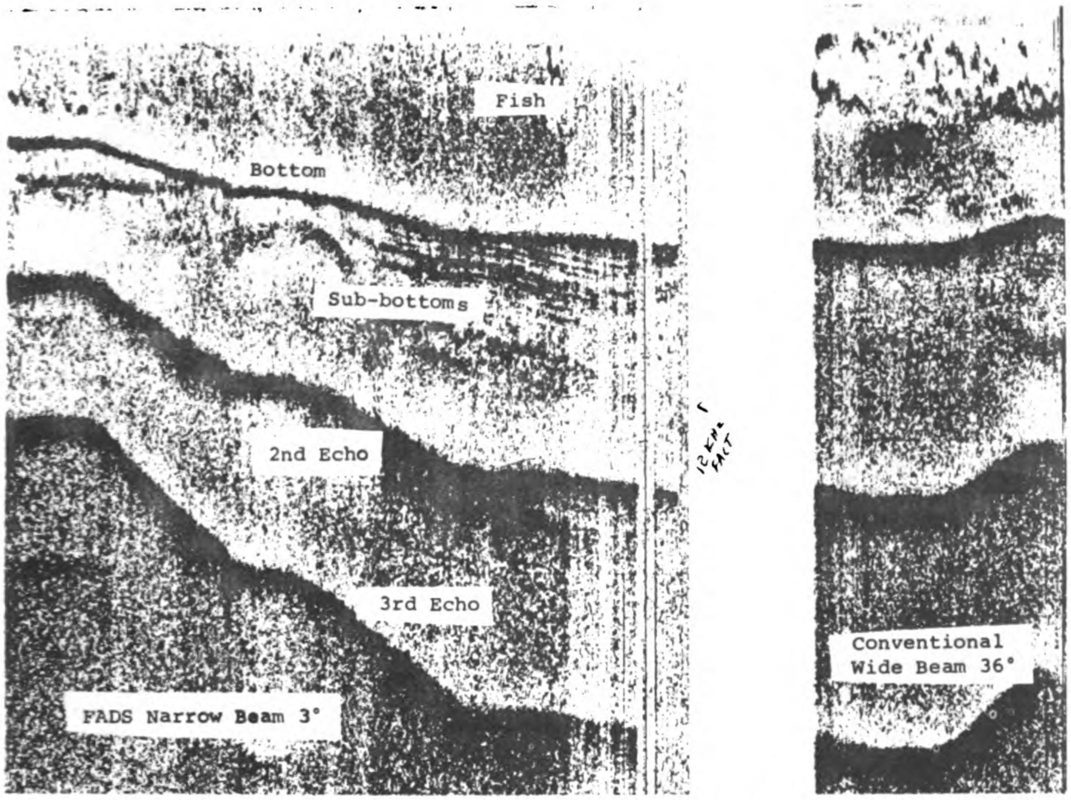

Figure 2–Fads/conventional comparison at 12 kHz

is far superior to that of the conventional system, also due primarily to the latter's large-scale beam averaging.

Considering the fact that both of these systems have radiating apertures of identical size on the survey vessel, and that the increased complexity of the parametric system is purely electronic (and therefore relatively easy to accommodate), one is drawn to the obvious conclusion that a significant advance in echo sounding has been achieved.

Recent work in the bathymetric sounding area has been carried out with the "TOPS" system (Towed Parametric Sonar) at the Naval Underwater Systems Center (3). A photo of its primary sound source is shown in Figure 3. This is one of the largest parametric systems to date. The soundhead is 78.5 in. long by 21 in. wide. It operates at a mean primary frequency of 23 kHz, with variable difference frequencies in the 50 to 5000 Hz band. A source level of 247 dB re 1 μPa at 1 m is achieved at each primary frequency with an input power of 80 kW. Difference frequency source levels range from 164 to 228 dB between 50 and 5000 Hz. Half-power beamwidths for the difference frequency radiation range from 10.4° to 1.8° over the same band.

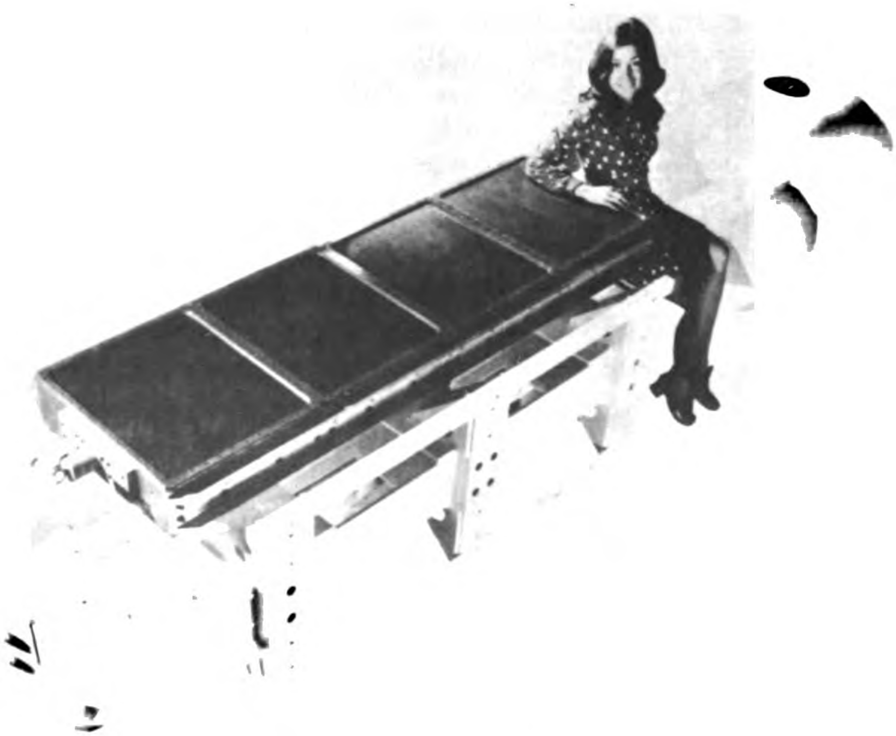

Figure 3 – The "tops" array

Bottom profiling has been achieved with this system to sediment depths of 250 ft in waters as deep as 3600 ft. The TOPS array is also being used in a wide variety of underwater sound experiments.

Detection of Buried Artifacts in Marine Archeology

The utilization of parametric sonar for search, discovery, and site delineation in marine archeology has been recognized (4,5) as a unique application of nonlinear acoustics. Archeologists usually locate a potential site by some combination of (a) extensive historical research, (b) "tips" from amateur treasure hunters, and (c) accident. These methods of location are inexact by modern technological standards because of the rather large margins of error associated with ancient navigational records.

In recent years, magnetometers and conventional subbottom sonars have been used in conjunction with improved navigational techniques. Although modern navigational aids are adequate, the sensors now used for artifact detection are limited by poor resolution. Once on site, the recovery of artifacts from the sediments is an expensive, time consuming process, due simply to the fact that the excavators have considerable difficulty in determining exactly where to dig. Acoustic sensors have high resolution beams with frequencies low enough for good sediment penetration are therefore of great practical interest in this field.

This interest, coupled with the success of the echo sounder in penetrating subbottom layers, prompted some field experiments (5) on the detection of buried artifacts. It was decided to study the parametric echo return from a small metal sphere at oblique angles of incidence to determine the feasibility of a subbottom sonar having a relatively wide searched sector. An aluminum sphere, 5 in. in diameter and not unlike an ancient cannon ball, was buried in a dense sand sediment in the Corpus Christi ship channel. The sediment was classified as a fine, well-sorted sand with a specific gravity of 1.89, an acoustic attenuation of 1 dB/period, and a sound speed 12% higher than that of the water column. After burial, approximately 6 in. of sand covered the target.

These conditions of burial make for a difficult sonar problem because (a) the sand was very absorptive, (b) the proximity of the water-sediment interface provided background reverberation capable of masking target echoes, and (c) the target strength of the small sphere was relatively low.

A parametric array generated by the nonlinear interaction of 190 and 210 kHz primaries emitted by a 17 in. diameter line-in-cone projector was used to develop a 20 kHz difference frequency radiation having a half-power beamwidth of 2.4° and a pulse length of 230 μsec. This device was used to obtain echoes from the sediment and the target, before and after burial.

Some results are shown in Figure 4, which presents A-scan echo data in both the primary and difference frequency bands. Here, the

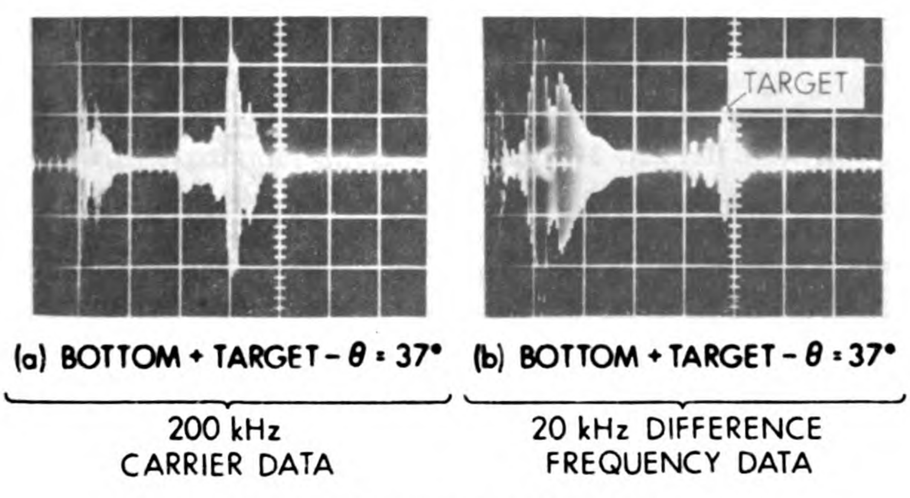

Figure 4–Parametric sonar detection of buried target

target was located at a slant range of 11 ft., where it subtended projector grazing angles in the neighborhood of 35°. As can be seen, only the difference frequency radiation produced a target echo, which was subsequently verified by excavation. This is due to the prohibitively high attenuation of the 200 kHz primaries in the sediment. The detection of this small target in these measurements was therefore encouraging as regards the eventual feasibility of parametric subbottom sonars for use in marine archeology.

Although several sonar configurations are undoubtedly good candidates for practical implementation, the one shown in Figure 5 is especially adaptable to the small "vessels of opportunity" usually employed by marine archeologists. Such a system has been fabricated at Applied Research Laboratories and is now undergoing tests.

This instrument employs acoustic parameters similar to those of the previous experiment. The soundhead is towed in a spherical fish to minimize the effects of the vessel's pitch and roll as well as the noise from its engines and propeller. Sequential formation of a large number of parametric beams has been achieved by mechanical rotation of two liquid filled acoustic prisms. Although sequential beam formation and processing lead to low sonar search rates, this approach greatly simplifies system design because it requires only a single channel sonar. A small VDS hoist, an oceanographic recorder, and a modest amount of electronic hardware for this simple sonar completes the configurational description. It is anticipated that instruments of this type will be a significant asset, both in locating artifacts

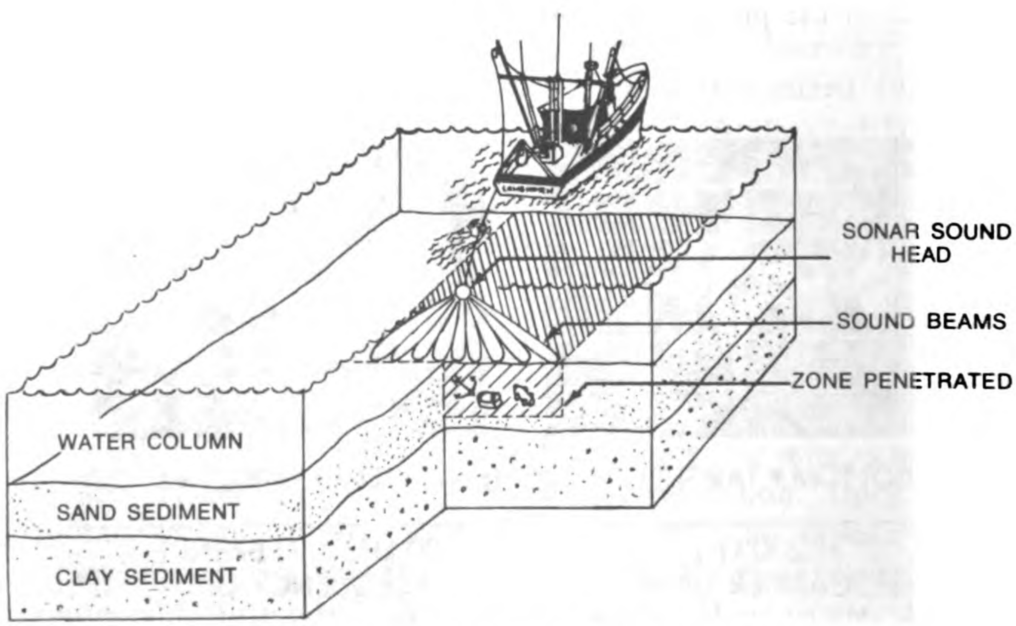

Figure 5–Concept sketch of an archeology sonar

of historical importance and in reducing archeological survey time and expense.

Ultrasonic Imaging and Biomedical Diagnostics

Some of the most important applications of acoustics involve the use of high frequency sound for nondestructive tests and inspections. The question frequently arises as to whether or not parametric arrays may be as useful in this technology as they are in ocean acoustics. Although this question has not been adequately investigated, some important points of comparison should be made.

First, the economics of Naval architecture impose a severe limit on the size of transducers needed for the low frequency sonars used in ocean acoustics. This limitation is not so important for ultrasonic imaging in the laboratory, where we see relatively large, linear transducers and lenses employed to develop fractional degree beamwidths.

Second, fractional degree beamwidths are only achieved with parametric arrays when the difference frequency is relatively close to the primary frequencies. Since the parametric beamwidth is never much smaller than the beamwidth of the primary transducer, the use of closely spaced primary and difference frequencies leads to very modest reductions in transducer size. It should be remarked that this description applies to parametric arrays with fractional degree beamwidths only, and it is not applicable to arrays with beamwidths on the order of 1° to 2°. On the other hand, it can be argued that parametric arrays have a much greater depth of field than focused arrays, and that possible assets for imaging work might also lie in their frequency agility and bandwidth features.

These possibilities prompted some developmental research (6) on a rudimentary parametric imaging device operating at megahertz frequencies. The intent was not to solve any crucial problems in either industrial testing or biomedical diagnostics, but merely to gain some experience with a parametric echo scanner. It was felt that this experience would also be valuable because the experimental system would serve as a model for larger systems of future importance in underwater sound.

A sketch of the experimental system is shown in Figure 6. Three ceramic transducers are used: a piston 0.64 cm in diameter that operates at a primary frequency of 10 MHz, a 1.1 cm annulus that produces a 7 MHz primary, and a 1.43 cm annulus to receive echoes at the 3 MHz difference frequency. The primaries are transmitted as cw pulses of a few microseconds duration at peak pulse powers of a

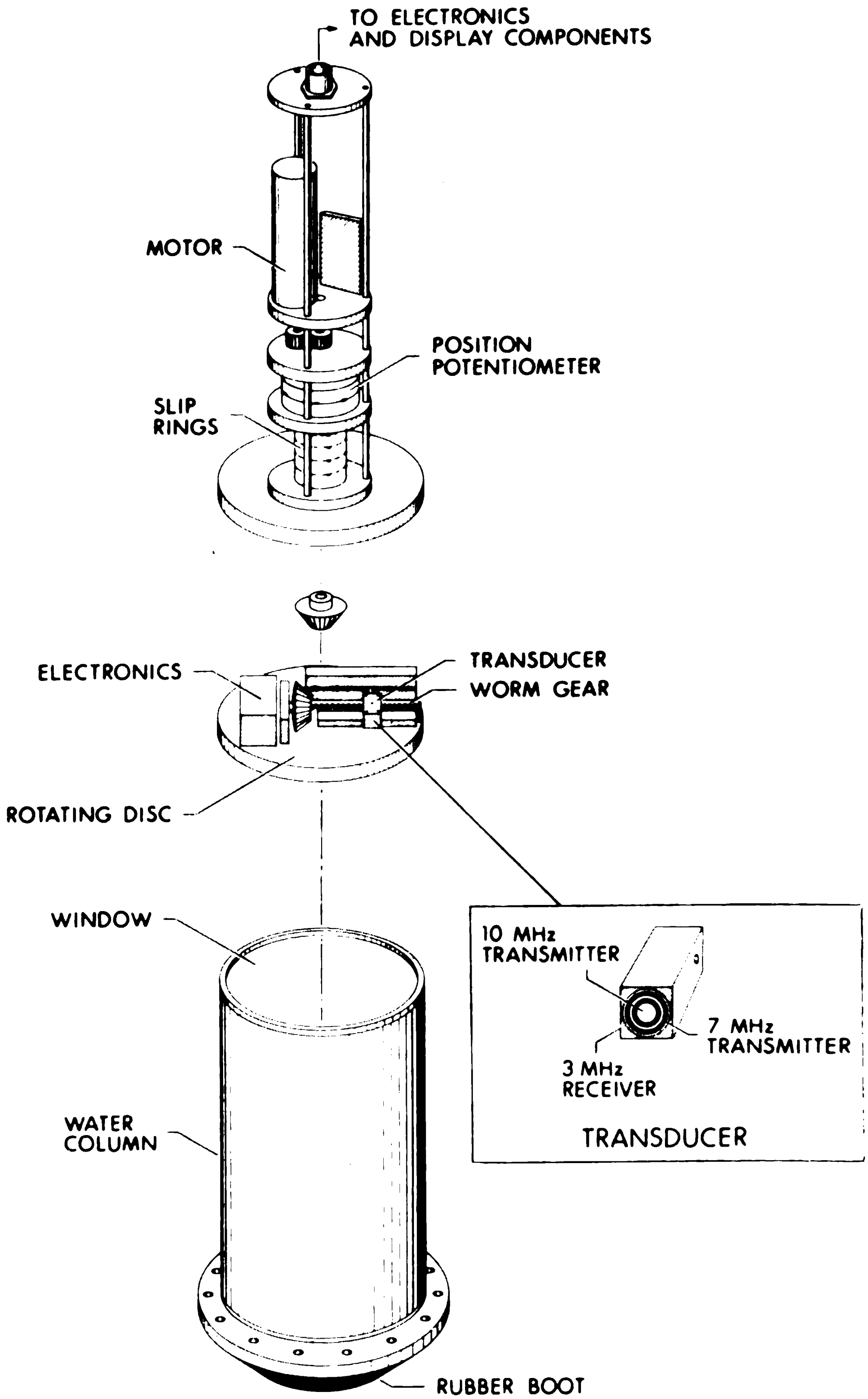

Figure 6—Parametric echo scanner

few watts. Difference frequency sound pressure levels in the range of 35 to 55 dB re 1 μbar are produced at distances of 5 to 100 cm from the soundhead.

The transducers are mounted on a rotating disc containing a worm gear for radial movement. The combined angular and radial motion causes the transducers to sweep out a helical path, thereby scanning a circular surface. This surface is connected to the area to be examined by means of a cylindrical water column, wherein the nonlinear interaction and beam formation occurs. A rubber boot at the bottom of the water column couples the scanner to the medium to be imaged. This boot also acts as a low pass filter in removing the high intensity primary radiations. The transmitters and potentiometers are located on the scanning device. The display and most of the receiver are located in separate housings. An intensity modulated electron beam presents the detected echoes from time gated sagittal sections on a memory type, cathode ray tube display.

The system was first used to image a few metal targets at a range of about 20 cm in water, and the results are shown in Figure 7. The half-power width of the parametric beam at this range was approximately 0.5 cm and this was also found to be the effective angular resolution of the system, provided the video circuitry was kept below saturation. It was also found that the excellent minor lobe suppression of the parametric beam reduced the imaging of false targets over a broad range of video gain settings.

Unfortunately, the measurements of Figure 7 represent the sum total of our experience with parametric imaging to date. The frequency agility and bandwidth features have not yet been investigated for possible applications to this problem. Although it is hoped that these and other aspects can be examined in the near future, it should

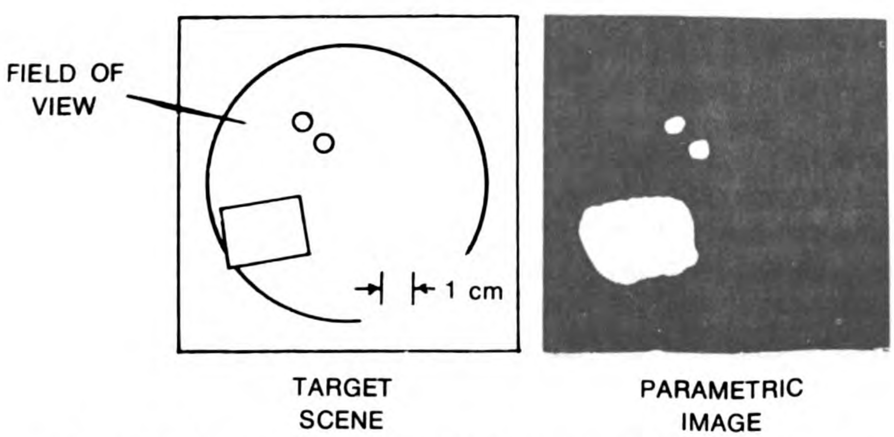

Figure 7–Ultrasonic imaging with the parametric echo scanner

be pointed out that the parametric array technology is almost totally confined to the sonar community, where research in sonic imaging is of minimal importance due to the poor prospects of applying it to long range detection.

In passing, it should be remarked that acoustic lens beamforming can also be applied to parametric arrays, (7) just as acoustic prisms can be used in beam deflection and scanning (see previous application). Lenses have also been useful in focusing the primary radiations for studies of special parametric interaction phenomena (8). Although focusing the primaries within the zone of interaction has not led to significant improvements in the end-fired directivity, (9) the use of lenses in focusing reasonably well developed difference frequency beams appears to be a good way to improve the angular resolution for imaging applications.

Shallow Water Propagation

The transmission of low frequency sound in shallow water is governed by classical waveguide physics, somewhat modified to account for several environmental effects, including a thermodynamic stratification in the acoustic velocity that arises from solar heating. The shallow seas are thought of as two-dimensional waveguides, driven by acoustic transmissions from a wide variety of sound sources.

The problem is illustrated in Figure 8, where we see the situation for conventional low frequency transmission sketched in the upper portion. Most conventional projectors radiate a continuum of rays in a broad beam with, at best, a shaded distribution of minor lobes. The

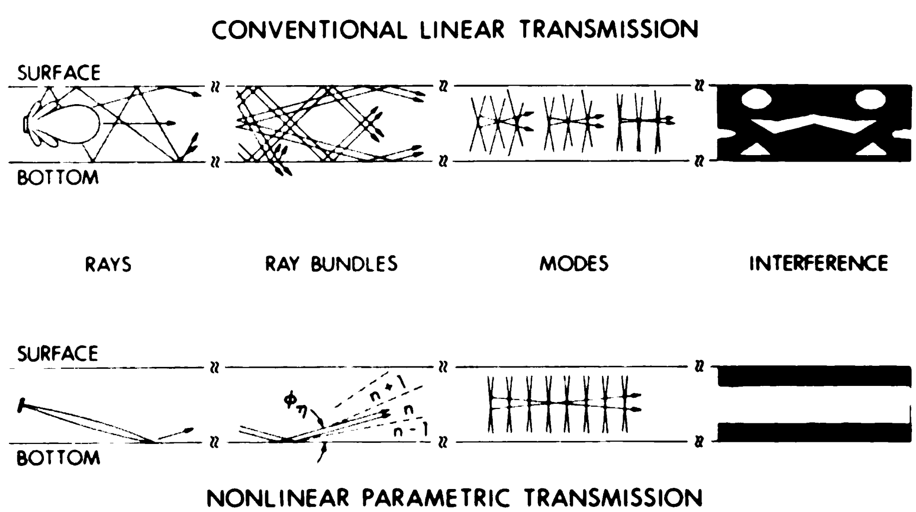

Figure 8—Mode formation in isothermal shallow water

reflection of these rays from the boundaries leads to considerable multipath interference which destroys the coherence of the radiated beam. The medium eventually selects those rays grouped about preferred ray bundles, in accordance with the spatial resonance phenomena of waveguide propagation. Allowed ray bundles then develop into a series of up going and down going wave sets, at discrete grazing angles. The self-interference of each wave set characterizes a particular mode of propagation. Since the modes follow different angular paths in the vertical plane, their horizontal velocities down the waveguide are different. This difference leads to quasiperiodic interference between the modes that further destroys the coherence of the transmission, giving rise to "hot spots" and "dead spots" in the insonification of the water column.

This rather confusing picture has been extremely difficult to unravel in both scientific and system applications of shallow water acoustics. One method of alleviating the complexity of this problem has been to employ a vertical string of hydrophones stretched from surface to bottom, such that the transmission is selectively matched to a given mode of propagation (10).

Another method is to employ a narrow beam parametric array, (11) directed at the eigenray angle appropriate for the excitation of a discrete mode, as is illustrated in the lower part of Figure 8. Here, one can maximize the energy coupled, say to mode n, at the expense of that coupled to the other modes. The end result reduces the intermodal interference, leaving a more uniform band of insonification down the waveguide. Although this technique is less efficient than the vertical string, it does provide good horizontal directivity. (The string is omnidirectional in the horizontal plane.)

Model tank experiments (11) on the use of parametric arrays in shallow water appear to support the interpretation of Figure 9. These studies were done in a 4.5 in. water column overlying an aluminum bottom, 25 ft. long. A piston projector, 1.3 in. in diameter, radiated primary frequencies at 1.53 and 1.73 MHz, producing a 200 kHz difference frequency radiation with a half-power beamwidth of 2°. At this frequency, the water column was 15 wavelengths deep and the eigenrays of the modes were separated by 2° in the vertical plane.

Pulse arrival data presented in Figure 9 show the difference between conventional and parametric excitation of the water column. These data were taken with a delayed time base oscilloscope so as to expand the detail about the arrival times. In each case shown in the figure, a 200 μsec pulse was transmitted horizontally into the shallow water at mid-depth. The hydrophone was also located at mid-depth at a range

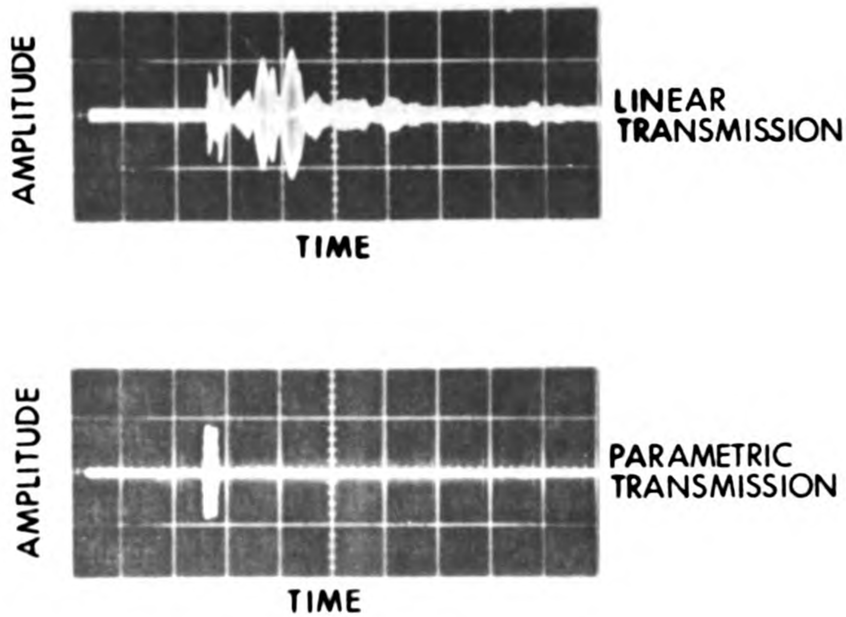

Figure 9–Pulse arrival data

of 15 ft. The projector had a horizontal orientation, which was very near the eigenray of the first mode.

In the linear case, considerable interference and smearing in the pulse arrival can be seen. The early arrivals show interference resulting from multipath reflections in the intermediate ray/mode regime. This interference is visible in the "dip" or "notch" appearing in the first of the linear pulses. Most of the later arrivals arose from relatively wide-angle scatterers in the tank, i.e., the bottom suspension wires, the tank sides, etc.

The data for the parametric case show practically no interference or smearing. In fact, clean pulses of this type were obtained at ranges out of 500 ft.* despite the fact that the water column was only 4.5 in. in depth. No significant reflections from unwanted scatterers in the tank are obtained. This illustrates the model tank advantages of the narrow beam parametric system, with its side lobe-free radiation field.

Applications to systems operating in other reverberant environments are also worthy of consideration.

Measurements on the amplitude of the peak pulse arrivals for both linear and parametric operation are shown plotted in Figure 10 as a function of range. These are simply propagation curves with amplitude plotted in the decibel format and range plotted on a linear scale.

*Data were obtained at ranges longer than the length of the tank by use of titanium reflectors at each end. This allowed a "folded" model sea of greater versatility.

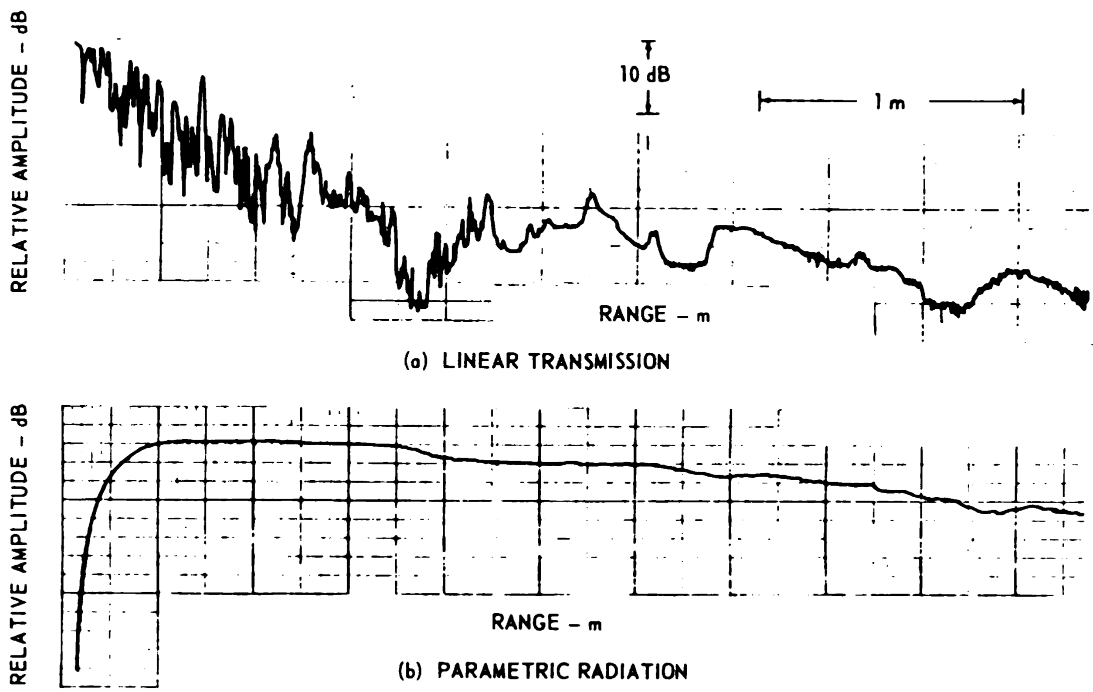

Figure 10–Model tank propagation curves

The data for linear operation of the system were acquired with a time-gated receiver adjusted to reject most of the unwanted reflections from scatterers in the tank. The resulting propagation curves are therefore fairly representative of the fluctuations brought about by modal interference. The propagation characteristics are quite complicated, illustrating the general difficulties of shallow water work.

It was not necessary to gate-reject unwanted echoes in the acquisition of the parametric data shown in Figure 10, because there were no unwanted echoes. The parametric propagation curve is very smooth and well behaved. Note that the amplitude of the difference frequency radiation is essentially zero at zero range and then grows rapidly, reaching a maximum at a range of about 1/2 m. This behavior illustrates the phenomenon of nonlinear sound generation in the water itself. The behavior of the remainder of the propagation curve illustrates the immunity of the difference frequency radiation to the acute modal interference phenomena associated with the linear system. If modal interference exists at all in this parametric data, it must not only play a minor role but also must be one with minimal excursion.

Future model tank work on the application of parametric arrays to propagation in shallow seas will be addressed to the effects of induced thermal structures, and rough and sloping bottoms. Full scale tests at sea are also being considered.

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Smoke from Polymeric Material Fires Carries Toxic Gases

Experiments by a team of Naval Research Laboratory chemists have revealed that the soot and water particles generated in fires with chlorinated polymeric materials transport potentially toxic amounts of hydrogen chloride (HCl) gas.

Shipboard fires below deck have long harassed the Navy. But more recently, man-made polymeric materials have added another degree of complexity to the problems such fires cause.

Chlorinated polymeric materials are used on ships as deck coverings, paints, and electrical insulation, and are also widely used in industry. They reported that, although these polymeric materials have attractive properties that include fire retardance, when such polymers are involved in fires, they release HCl which can be transported on the smoke, as well as in the water used to fight the fire.

The scientists say that normally, moderate concentrations of HCl gas would be removed by an individual's upper respiratory tract, and would not penetrate the lungs.

However, if the HCl gas is deposited on minute soot and water particles (less than 3 micrometers), the hydrogen chloride could get past the defense of the upper respiratory tract and could be deposited in the lungs.

Desorbing from the particles, the gas then invades the delicate tissue of the lungs and could cause pulmonary edema. The scientists suggest that this could be the cause of deaths that sometimes occur up to 48 or even 72 hours after exposures to certain fire situations.

An important factor in this research, the scientists feel, is that those using chlorinated polymeric materials, especially on ships, be made award of the additional factor of danger, so that when fire breaks out, masks or other methods may be used to avoid harmful breathing conditions.

Room Temperature Inorganic Lithium Cells

Adam Heller*
GTE Laboratories

Lithium cells have been the target of many years of DOD and industry sponsored research. The interest of both the DOD and industry in lithium cells resulted from the weight and volume reduction sought for mobile electronic and electrical equipment. The need for such a reduction became evident after transistors replaced the heavy and bulky electron tubes, and particularly after integrated circuits were introduced. At this point the battery became the heaviest and largest single component of mobile military equipment used in many communications, detection, timing and data acquisition systems and also in non-military products such as pocket calculators, wristwatches, hearing aids, pacemakers, radios, cassette recorders, and, of course, also flashlights.

The idea of weight and size reduction in batteries by using lithium anodes has been known to electrochemists since the metal was first electrodeposited in the beginning of this century. Lithium is both the lightest metal, its atomic weight is 7, and is the most strongly reducing one in both aqueous and in many non-aqueous solutions. At 25°C its potential (versus a standard hydrogen electrode) is –3.045 V as compared to the –0.763 V potential of zinc, the most commonly used battery anode material. Since lithium metal reacts with water on contact, it cannot be used in cells with aqueous electrolytic solutions. Consequently, a substantial part of the lithium battery research of the past twenty years consisted of studies of electrochemical reactions in non-aqueous solvents.

Until the beginning of our work at GTE Laboratories two major groups of non-aqueous solvents were investigated – molten salts, such as molten lithium chloride and organic liquids ("organic electrolytes") of which propylene carbonate is an example. The primary lithium cells made with molten salts offered exceptionally high power or rate capabilities and high energy densities. However they required preheating to high temperatures. Their activiation and deactivation was much too difficult to allow their incorporation in any of the mobile electronic systems mentioned, or in flashlights. The molten salt cells

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also had materials problems, because of accelerated corrosion at high temperatures.

The "organic electrolyte" lithium cells were sufficiently advanced by 1970 to allow their consideration in selected military applications such as sensors. The specific objective of the DOD effort was to develop batteries capable of operating at temperatures as low as -40°F, having an energy density of 100 Whr/lb.* Achievement of these goals was to result in a downward extension of the operating temperature range of aqueous cells, and in halving the weight of the then state-of-the-art mobile electrical power sources.

If one were to judge the significance of a technological objective from the number of corporations, universities and research institutes striving for its realization, primary lithium batteries were an important target. The list of organizations doing lithium battery research included, in addition to the battery manufacturing companies, most of the electronics, chemicals, automotive and aerospace companies, major research institutions and a number of universities. One of the exceptions was GTE Labs.

At GTE Labs we had no intention of entering the race for lithium batteries. We were swept into it by a series of discoveries, many of which were made in pioneering research projects that we could start because of the faith and vision of the Office of Naval Research. In retrospect, it seems that part of our strength was in the fact that we were not battery experts. On the one hand we did miss credentials to do battery work. But, on the other hand, we were free of the biases of the well-established field of batteries.

The sequence of events which led to the development of our battery can be traced to GTE's interest in liquid lasers.

In 1966 we were studying the cause for the lack of laser action in liquid solutions and neodymium salts. At that time, laser action had been known both in solid crystalline and solid glass solutions of Nd^{3+} ions, but no laser action could be achieved in liquid Nd^{3+}. We traced the cause for the lack of laser action in liquids to transfer of energy from the excited Nd^{3+} ions to vibrations of solvent molecules in the

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The energy density measures the quantity of deliverable electrical energy stored in a battery of standard weight or standard volume. Energy density per unit weight is usually expressed in watt-hours per pound. A battery weighing 1 lb and delivering 1 watt hour (Wh) of electrical energy is defined to have an energy density of 1 Wh/lb. Energy density per unit volume is usually expressed in watt-hours per cubic inch. A battery having a volume of 1 in^3 and delivering 1 watt-hour of electrical energy is defined to have an energy density of 1 Wh/in^3. A fresh flashlight battery ("dry" or "Leclanche" cell) has energy densities of 30 Wh/lb and of 2 Wh/in^3. A 100 Wh/lb battery is 3.3 times lighter than a flashlight battery of equal operational life or lasts 3.3 times longer if its weight equals that of a flashlight battery.

vicinity of the ions. The rate of this transfer was found to depend on the frequencies of vibration of the solvent molecules, which in turn depended on the mass of the atoms constituting the solvents. For heavy atom solvents, the vibrational frequencies were usually small relative to the frequencies of electronic transitions of the Nd^{3+} ion. For this reason the coupling was weak, and the rate of loss of energy from the ion was low. In solvents with light atoms, and particularly in solvents containing hydrogen atoms, the vibrational frequencies were much higher and approached the electronic transition frequencies of the Nd^{3+} ion. In the resulting near-resonance case, the ion excitation rate (by energy flow to vibrations) was very rapid. Thus our objective became the forming of Nd^{3+} ion solutions in hydrogen (and deuterium) free solvents. The first solutions that we successfully prepared and in which we observed the expected laser action, were Nd^{3+} solutions in selenium oxychloride.

After learning how to prevent radiationless energy losses from the excited neodymium, we, as well as other groups in many parts of the world, extended our studies to other luminescent ions and to other solvents. By 1968 we knew how to assure efficient luminescence in liquid solutions of many luminescent ions, and proceeded to ask a seemingly simple question. Why does one not observe the emission of light from electrodes immersed in solutions of ions when a dc current is passed? Obviously, if the electrode processes are sufficiently energetic to strip electrons from ions or to add electrons to these, they must be energetic enough also to excite the ions, and light emission should result if the ions are luminescent, i.e., they do not lose all their energy by a non-radiative process. We argued that such light emission should be observed if non-radiative loss is prevented by the use of heavy atom solvents. Using rare earth ion solutions in phosphorus oxychloride, Kenneth French, Paul Haugsjaa, and I, did, indeed, observe the expected low voltage dc electroluminescence at cathodes. By introducing the appropriate ions we could actually observe light emission in the ultraviolet, visible and infrared spectral regions. Our study of this new phenomenon revealed that the emission of light is taking place at the cathode-liquid interface, and is due to the injection of electrons from the cathode into the interface, where the density of cations is high. If the cations are luminescent, some of the injected electrons collide with the cations, excite the ions to their luminescent states and emission of light is observed. The phenomenon that we observed was, in its essence, the liquid analog of the emission of light in the negative glow region of a gaseous glow discharge. However, the emission of light was an inefficient process.

Tracing the cause for the inefficiency we found that collisions of rare earth cations with electrons resulted not only in excitation, but also in trapping of the electrons, or simply in the electrochemical reduction and electrodeposition of the luminescent rare-earth cations. Another cause for the observed inefficiency was the production of chlorine in the anodic process. This chlorine diffused to the cathode and trapped electrons to form chloride anions. What our experiments had shown was that we made the first room temperature rare earth metal-chlorine cells. Indeed, when we measured the potential across the electrodes following an electroluminescence experiment we found it to be 3.4 V, as expected from thermodynamic calculations. The rare earths are among the most strongly reducing metals, and chlorine is one of the most strongly oxidizing elements. Thus, we discovered that by using the oxyhalide solvents we could make high energy density cells of exceptionally high potentials: the cells had potentials well above those at which both water and non-aqueous organic solvents decompose. Subsequent studies revealed that we could realize such cells for two reasons: some of the oxyhalides (such as sulfuryl chloride) are stable to oxidation by strong oxidizers, including chlorine and bromine; and many of the most reactive metals are protected from attack by the oxyhalides by an extremely thin layer of insoluble metal halide which is formed on their surface when immersed in the oxyhalide solutions.

Lithium and sodium were found to be among the reactive metals that did not corrode on prolonged boiling in some of the oxyhalide solutions. Using lithium tetrachloroaluminate as our electrolyte, Kenneth French and I made the first room temperature lithium/chlorine cells. These cells had the expected high potential, 4.0 V for lithium/chlorine cells and 3.9 V for the sodium/chlorine cell. Our solvent, in these first experiments, was phosphorus oxychloride and we used carbon and metals as cathodes. In later experiments we replaced the chlorine by a variety of solid oxidizing (positive) electrode materials. James Auborn, who joined us in 1971 and who led the subsequent phases of the work, made, at this point, one of the key observations on which the cells now in production are based. He noted that lithium cells show, with respect to the positive electrode, coulombic efficiencies exceeding the theoretical efficiency based on the amount of cathode oxidant introduced into the cells. This could be explained only by the electrocatalytic reduction of the solvents on the cathode; we discovered that we can use the solvent itself as our active cathode component. After reducing all of the active cathode material, the cells continued to provide electrical power and lithium chloride was still forming in the cell reactions!

In the next series of experiments we replaced the solvent by thionyl chloride and by sulfuryl chloride, and concentrated on cells with carbon cathodes. The reason for switching to thionyl chloride and to sulfuryl chloride was the desirable liquid range of these solvents, -157°F to 185°F in the case of thionyl chloride, and -66°F to 158°F in the case of sulfuryl chloride. The stability of lithium to attack was also improved in both solvents; boiling for six months had no effect on the metal.

The use of the solvent itself as the oxidizing cell component has given our cell a dramatic energy density advantage and has also allowed us to obtain a cell in which the cell potential remains constant when the cell is discharged (Figure 1) or stored. The reaction taking place

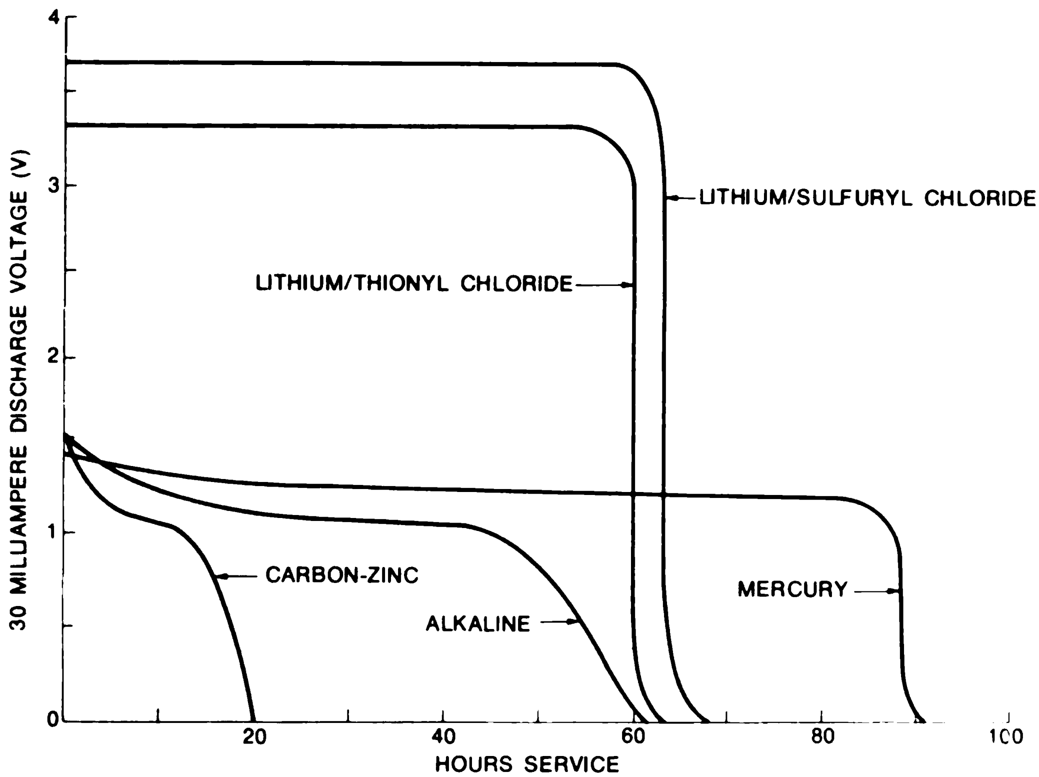

Figure 1–Electrical energy content and voltage stability of various "AA" ("penlight") size cells. The vertical coordinate represents the voltage of the cells when discharged at a 30 mA rate. The horizontal coordinate shows the number of elapsed hours of operation. The integrated areas under the curves measure the energy (number of watt-hours) stored in each of the cells. The carbon-zinc cell is the ordinary dry (zinc-manganese dioxide) cell used in flashlights, toys, etc. The alkaline cell is the highly advertised alkaline version of the zinc-manganese dioxide cell. The mercury (zinc-mercuric oxide) cell is an expensive premium cell used in sensors, hearing aids, pacemakers, etc. The two new cells based on the lithium/thionyl chloride and on the lithium sulfuryl chloride systems combine exceptional features of energy content, high voltage and voltage stability.

in the thionyl chloride containing cells can be approximated by the formula:

$$8\,Li + 3\,SOCl_2 \rightarrow 6\,LiCl + 2\,S + Li_2SO_3 \qquad (1)$$

Analytical results proved the presence of all of the three reaction products and the 3.65 V open circuit potential agrees with the potential calculated for reaction (1).

The reaction taking place in the sulfuryl chloride cell can probably be approximated by the formula:

$$Li + 3\,SO_2Cl_2 \rightarrow 6\,LiCl + 2\,Li_2SO_3 + S \qquad (2)$$

for which a cell potential of 3.9 V is calculated and measured.

Following the completion of the basic phase of our cell studies we defined the parameters for our prototype cells. These design parameters defined performance characteristics that exceeded with respect to size reduction (energy density per unit volume), to weight reduction (energy density per unit weight), to operating temperature range, to voltage stability and to shelf life, any other primary battery system, including lithium based battery systems with "organic electrolytes." By appropriate cell design, we could also reach exceptionally high power densities or discharge rates: for example, in an experiment aimed at demonstrating the feasibility of discharge rates encountered in torpedoes (where the energy stored in the cell must be delivered in a ten minute period) it was not only shown that such rates are realizable, but also that the new battery could give the Navy a smaller and lighter torpedo power source at a greatly reduced cost. Table 1 compares the performance characteristics of various commercial cells and of a typical "organic electrolyte" lithium cell with those of our lithium/thionyl chloride cell. The weight and volume reduction achieved are seen in Figures 2 and 3. Beyond its technical performance advantages, our cell has also a materials cost advantage relative to many of common primary cells.

The cost of electrode materials, solvents and electrolytes that are used in making various cells that have naval applications has been calculated. The materials cost of one watt-hour delivered by the least expensive flashlight (zinc-manganese dioxide) cells is of about 0.2¢/Wh; the better alkaline zinc-manganese dioxide cells have a materials cost of about 0.4¢/Wh. The cost of materials in mercury (mercuric oxide-zinc) cells used in communication systems, mines and a variety of electronic applications is 7¢/Wh. The materials cost of the silver (oxide)-zinc torpedo battery is near 30¢/Wh. The materials cost of our Li/$SOCl_2$ cell is of 0.23¢/Wh.

MAJOR NONRECHARGEABLE TYPES OF BATTERIES

	LECLANCHÉ [a]	ALKALINE [b]	MERCURY [c]	MAGNESIUM [d]	Organic Electrolyte Li/SO_2-PC-AN/C [e]	GTE Li/$SOCl_2$/ CATALYST [f]
NEGATIVE ELECTRODE	Zn	Zn	Zn	Mg	Li	Li
POSITIVE ELECTRODE	MnO_2	MnO_2	HgO	MnO_2	SO_2/C	$SOCl_2$/CAT.
ELECTROLYTE	NH_4Cl/H_2O	KOH/H_2O	KOH/H_2O	$MgCl_2/H_2O$	SO_2-PC-AN/LiBr	$LiAlCl_4/SOCl_2$
ENERGY DENSITY (Wh/lb)	30	35	45	65	150	250
ENERGY DENSITY (Wh/cu in)	2	3	7	4	8	15
OPEN CIRCUIT VOLTAGE (V)	1.5	1.5	1.35	1.7	2.9	3.7
VOLTAGE STABILITY (0-90%)	1.5-0.7	1.5-0.8	1.3-1.1	1.7-0.9	2.7-2.0	3.6-3.2
POWER DENSITY (W/lb)	25	30	5	40	50	250
POWER DENSITY (W/cu in)	1.5	1.5	0.7	3	2.7	5
TEMPERATURE RANGE (°F)	20-130	-20-160	-20-160	40-160	-40-165	-70-165
OPERATING VOLTAGE (V) AT 1 mA/cm^2	1.3	1.3	1.2	1.7	2.7	3.6
SHELF LIFE (YEARS) AT 70°F	1	2	> 2	2	> 2	> 2

(a) The Leclanché cell is the common dry cell used in flashlights, toys, radios, etc.

(b) The alkaline cell is the premium version of the zinc-manganese dioxide cell, used where higher power (faster discharge) is required.

(c) The mercury cell is a premium cell used in electronic devices which must be compact and require stable voltage. Hearing aids, sensors, pacemakers and transceivers are examples of applications.

(d) The magnesium cell has been used in military transceivers and in premium flashlights.

(e) The Li/SO_2-PC-AN/C cell is an example of a state-of-the-art "organic electrolyte" lithium cell. (PC stands for propylene carbonate and AN for acetonitrile.) The cell contains gaseous sulfur dioxide under pressure. It is used in military sensors, mines and communication systems.

(f) The catalyst in this cell is usually carbon black. By using sulfuryl chloride (SO_2Cl_2) instead of thionyl chloride ($SOCl_2$) the energy density is increased by an additional 10% and the cell voltage is raised to 3.9V. The cell out-performs all the others in its energy density, in its operating temperature range, in its voltage and voltage stability and in its shelf life.

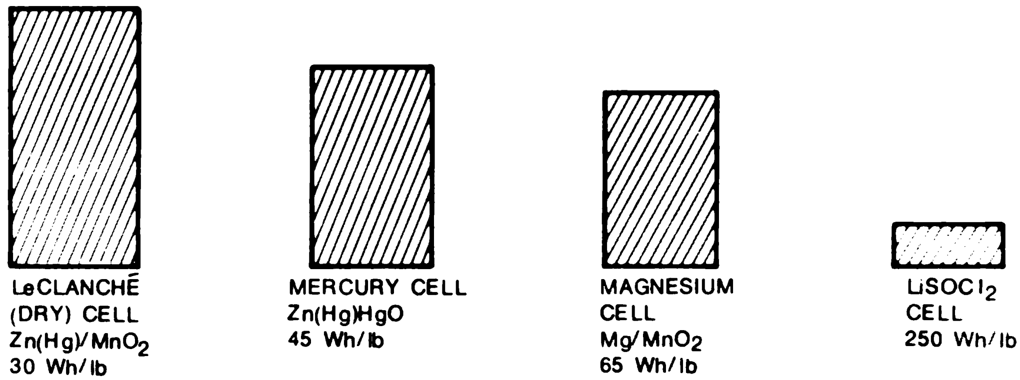

Figure 2 – The areas of the blocks represent the relative weight of cells of equal electrical energy content. A two ounce Lo/$SOCl_2$ cell contains as much energy as a one pound dry cell, a ten ounce mercury cell or an eight ounce magnesium cell.

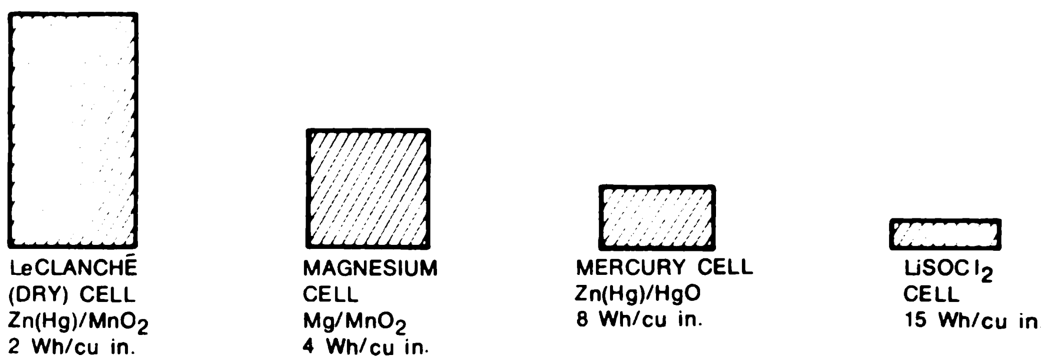

Figure 3 – The areas of the blocks represent the relative sizes of cells of equal electrical energy content. A Li/$SOCl_2$ cell having a volume of 4.3 fluid ounces contains as much energy as a half pint mercury cell, a one pint magnesium cell or a quart size common dry cell.

Following the identification of materials in which inert cell components (such as seals, cans, electrode supports and separators) could be made, we built a task force to manufacture the first several hundred prototype cells. These cells not only met but exceeded the projected performance criteria of Table 1, and led to the establishment of our present development and production operation. In its development and production stage the performance of the cells was further improved, particularly with respect to low temperature performance, rate capability and energy density. Cells of various common and uncommon configurations are now being manufactured.

Eight years after our entry into inorganic liquid lasers, we are producing a revolutionary battery. With it, we have made a flashlight that delivers twenty times more light (lumen-hours) than delivered by flashlights with conventional batteries (even after prolonged storage); portable radios that retain their sound quality and do not require battery replacement for years; and several medical and consumer electronic products. We are indeed grateful to the Office of Naval Research for the partial support in the work that helped lead to this development.

Successful Growing of Liver Tissues May Lead to Hepatitis Vaccine

Under a study sponsored by the Office of Naval Research, new techniques for growing liver tissue in the laboratory have been developed. Aimed at providing an appropriate medium in which to cultivate hepatitis-causing viruses, these techniques represent an important step toward the eventual development of a vaccine against hepatitis.

The work has been done by scientists at the University of California, Los Angeles, under the direction of Professor G. L. Gitnick.

Hepatitis is a highly infectious disease which infects the liver and is often transmitted by blood transfusions, by contaminated food or water, or by poorly sterilized syringe needles, stylets and even dentist's drills. The spread of the disease is facilitated by such conditions as poor sanitation, overcrowding and malnutrition. The incidence of hepatitis is on the increase in several countries including the United States.

Young people are especially susceptible to this disease which often results in chronic liver damage and in its most severe cases is fatal. It represents a serious health hazard to military personnel.

Presently there is no practical means of significantly reducing the frequency of hepatitis and its eradication may not be possible until a vaccine is developed.

The ONR-funded research is aimed at finding leads toward the development of a safe, live vaccine using less virulent strains of hepatitis viruses. Toward this end, Professor Gitnick has been attempting to grow the appropriate hepatocytes—types of liver cells—on which to cultivate the hepatitis-causing virus.

Until recently, however, these efforts have been frustrated by the fact that although hepatocytes would grow, other cells would soon develop in the culture to inhibit the further growth of hepatocytes. The hepatitis virus may only grow on hepatocytes. Professor Gitnick has now developed new methods which keep the hepatocytes growing for extended periods of time without overgrowth by other cells.

Future work will involve attempts to grow hepatitis viruses on these tissues by infecting them with diseased cells taken from liver biopsies of hepatitis patients.

FLIP Aids Fleet Training

Charles B. Bishop and F. H. Fisher*
Scripps Institution of Oceanography

Tactical development and evaluation (TACD&E) is receiving increased emphasis in the Navy as commanders strive to attain the capabilities needed to accomplish their mission at sea. TACD&E is a significant part of major exercises, providing a means for evaluating new tactical ideas and new Fleet equipment in realistic environments, under actual Fleet operating conditions. The importance of environmental effects on these evaluations has been recognized at high levels in the Navy, and by special study groups such as the recent Morse-Andrews-Munk study for the Naval Research Advisory Council (NRAC). Indeed, sizeable Navy efforts have been applied to this problem for many years, resulting in large quantities of environmental data, and the development of procedures and organizations to apply the data to Fleet problems. There remains, however, considerable room for increasing the understanding and use of environmental information at the operating levels of the Fleet.

Years of research and development have been devoted to the advancement of the capabilities of antisubmarine warfare (ASW) equipment in order to exploit our increased knowledge of the environment. Modern underwater acoustic systems are capable of using various propagation paths, and can be adjusted to optimize signal-to-noise ratios and recognition differentials under different environmental conditions. The key to the successful use of these new capabilities lies in the Fleet operators' recognition of these conditions, and understanding of how to get the best performance from ASW systems as they change.

In the field of underwater acoustics, the Marine Physical Laboratory (MPL) is seeking ways to contribute to these efforts. The key to effective interaction is first-hand contact between operational and scientific personnel in order to acquaint each other with their particular insights as well as problems. Since Fleet operations are now limited by force reduction, fuel costs, and personnel and material readiness requirements, the opportunities for scientific involvement

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on a "supercargo" basis are few indeed. However, the concept of direct participation in the achievement of Fleet exercise objectives is much more likely to be acceptable to Fleet personnel and provide the desired interaction between the operational and scientific communities.

To test this concept and assess prospects for greater interaction in the future, MPL offered the services of FLIP (Figure 1) in conjunction with an equipment checkout operation to RADM Myers, Commander, Cruiser Destroyer Group 3 for a June 1974 Pacific Fleet exercise.

FLIP (1,2,3) is an unusual vessel developed under the sponsorship of the U. S. Navy's Office of Naval Research to fulfill a need for an extremely stable and yet mobile platform from which accurate acoustical measurements could be made at sea.

FLIP, which has an overall length of 355 feet, is towed in the horizontal position to the area where scientific operations are to be carried out. Upon arrival on station, the tow line is cast off and ballast tanks distributed throughout the aft 255 feet of the vessel are

Figure 1 – FLIP showing the aft 225 feet of the vessel where the ballast tanks are distributed

flooded. In about 20 minutes the vessel is completely vertical with approximately 55 feet of prow pointed skyward and the remaining 300 feet of vessel under water.

The diameter of the hull, which is 20 feet between 300- to 150-foot depth, tapers down to 12-1/2 feet at the 60-foot depth. This change in diameter gives FLIP a natural period of 27 seconds for vertical motion compared to an 18-second period for a cylinder of the same depth. The longer period reduces FLIP's response to wave motion since wave energy in the ocean usually occurs at periods below 18 seconds; for a 30-foot wave, FLIP's vertical motion is less than 3 feet.

FLIP's stability, 300-foot draft, and low acoustic noise level have made it uniquely suitable for a wide variety of research experiments: hydrophones can be positioned at a variety of depths for listening to acoustic signals; the same applies for other instrumentation such as pressure sensors for measuring wave heights, tilt and depth of FLIP, or temperature sensors for measuring thermal structure in the ocean. In order to study the horizontal extent of thermal variations in the ocean, three booms can be extended so that temperature sensors can be lowered simultaneously at known distances from one another. Meteorological instruments mounted on a vertical mast that can move up and down at the end of a boom make it possible to make measurements immediately above the sea surface. Its deep sea winch can lower instrumentation packages to a depth of 4000 meters. Booms below the waterline can also be mounted on the hull for obtaining horizontal separation of sensors. In the vertical position FLIP either drifts freely or is held in position by using up to a 3-point moor in any depth.

Liaison with COMCRUDESGRU THREE developed the following objectives for FLIP's participation:

a) A submerged target in deep water to train sonar operators in all modes of operation.

b) A sound source in deep water environment to enhance passive training for sonar operators.

c) A sound source in deep water environment to train Light Airborne Multi-Purpose System (LAMPS) and Ship Towed Underwater Detector (STUD) teams in classifying and localizing underwater sound sources.

d) A navigational aid to assist in reconstruction of exercises.

The operations with FLIP covered two days of the Fleet Exercise and involved three hull mounted sonar ships, two with the LAMPS system, and one with the STUD passive array. FLIP was positioned in 2000 fathom water, 150 miles west of San Diego in a drifting mode. Her position plot was maintained to a high degree of accuracy using satellite navigation as she drifted at 0.3–0.7 knot in 20–25 knot winds.

Training was conducted in all phases of long range sonar operations. Firm sonar contact was established in each mode of sonar operations, providing several hours of training in each of the modes.

FLIP lowered a transducer and transmitted a variety of taped submarine radiated noise signals as requested by the destroyers (DE's), This permitted training of sonar operators on the LAMPS sonobuoy system, and the towed array in both detection and classification of sounds from different submarines. Ships' ASW officers and sonar supervisors were able to evaluate their operators' performances in a realistic, at-sea situation, using their own sonar equipment.

In addition, the entire LAMPS system, including command and control, was exercised in a multi-ship, multi-helo situation, with real operating conditions in a deep-ocean environment. This type of training is essential to the development of LAMPS tactics, and the molding of LAMPS into a coordinated part of the DE's ASW attack team.

Since FLIP projects 55 feet above the sea surface when in the vertical position, she provided an excellent visual and radar target, particularly for the helos. This eliminated the problem of target location, and contributed significantly to the long hours of contact time.

The satellite navigation data acquired by FLIP provided a highly accurate track of her position while drifting on station. This capability of acting essentially as a "mid-ocean lighthouse" offers considerable promise for exercises in which positional reconstruction is important to the analysis of tactics and their results.

The success of this initial Fleet training operation with FLIP is measured not only by the valuable sonar and ASW system training received by the participants, but also by the interest and involvement of ship and helo crews and commanders, Flag officers and their staff officers in the problems associated with optimizing the performance of their ASW equipment in the real ocean environment.

Wherever and whenever the Navy's R&D community can help the Fleet advance its readiness to perform its missions, the opportunity should not be missed. In particular, stimulating the thinking of Fleet personnel on the most effective use of the highly capable ASW equipment which past R&D efforts have provided is not only productive but enjoyable. This can be done best by personal involvement in the continuing tactical and training evolutions of Fleet units. FLIP provides one valuable tool to achieve this purpose. Other research platforms and vessels may offer other useful approaches.

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Simultaneous Two-Wavelength Operation in Infrared Lasers

Scientists at the Naval Research Laboratory (NRL) have developed a laser system which provides simultaneous operation of any two laser transitions occurring in an infrared laser.

A chemically active element in combination with a germanium flat polarizes and spatially separates the two laser beams so that their polarizations are perpendicular to each other, and directs the laser beams to separate gratings.

Each grating is rotated to select and reflect a laser beam of a particular wavelength back through the system so that two particular beams are directed from the output.

New Class of Resinous Materials as High-Temperature Adhesives

Naval Research Laboratory chemists have developed a new and improved class of resinous materials which can be used as strong adhesives where temperatures exceed 200 degrees centigrade.

Epoxy resins are broadly useful as adhesives and matrix plastics for fiber-reinforced composites. However, the high-temperature continuous service limit for epoxies of any type is about 200°C, because of the intrinsic characteristics of their molecular structure. Consequently, there has been a requirement in high-temperature epoxy applications for resins capable of performing at temperatures above 200°C.

The new improved class of resinous materials is called "polyphthalocyanine resins," because of the significance of the phthalocyanine nucleus to their high-temperature performance capabilities.

Research Notes

Chemical System to Break Water Emulsions in Fuel Oils

A Naval Research Laboratory chemist has developed a new chemical demulsifier system which promises to have high potential in the separation of oils and water from stubborn emulsions.

Laboratory tests on emulsions of water in Navy special fuel oils with the new system show it to be considerably more effective than many commercially-available agents.

The researcher explained that it is really a two-part system comprising an effective wetting agent, sodium di-octyl sulfosuccinate, and a high molecular weight polymer, polyethylene oxide.

The new demulsiffer is so effective that even stiff buttery emulsions can be thinned and broken at temperature as low as 50°F. Most commercial demulsifiers, on the other hand, require heating of the emulsion well above 100°F to realize their full effectiveness.

The new demulsifier remains quite effective even in emulsions containing large amounts of dirt, rust and other particulate matter which can often make significant contributions to emulsion stability. The wetting agent displaces the emulsion stabilizer from the oil-water interface and the water-soluble polymer assists in the coagulation of any stabilizing particulate matter.

Sensitive Instruments Measure Weak Magnetic Fields

The world's most sensitive instruments for measuring the very weak magnetic fields that abound in nature are producing vital new facts about matter and energy in such diverse fields as medical diagnosis, scientific research, and prospecting for oil, other minerals and sunken ships.

This was disclosed today by physicists James Mercereau and Harris A. Notarys, who did much of the pioneering development of these instruments at the California Institute of Technology under the sponsorship of the Office of Naval Research.

The instruments, which are just now coming into commercial use, are capable of measuring the magnetic field of a single atom in a biological molecule. They can detect a field as weak as one ten-billionth that of the earth's overall field of less than half a gauss (a unit of measuring magnetic fields).

This enormous sensitivity is made possible by incorporating a superconducting phenomenon known as the Josephson effect into the instruments, which are magnetometers. The effect, named after Brian Josephson who was awarded the Nobel Prize for discovering it, only occurs in superconducting materials. The system is being used to make the first measurements ever done of the magnetic fields of metal atoms in protein molecules. In this work it was determined how oxygen becomes bound to a blood protein, hemerythrin.

The system is also being used to map the large-scale polarity reversals of the earth's magnetic field over the centuries as recorded in the Grand Canyon region rocks. The system's sensitivity has greatly expanded the range of rock samples that can be read.

The instrument is beginning to be used for measuring blood flow and muscle motion, for magnetocardiograms (for diagnosing heart conditions), and for monitoring the magnetic field of the brain (a new diagnostic tool).

The new cryogenic magnetometers are 1,000 times more sensitive than the non-cryogenic magnetometers that have been used for some time in geological prospecting. The new instruments are expected to provide more elaborate information about the probable locations of oil fields and other mineral deposits by revealing more details concerning faults and other geologic features that cause subtle changes in the earth's magnetic field.

The magnetometers are maintained at a temperature of minus 269 degrees centigrade (452 degrees below zero Fahrenheit), which is only four degrees centigrade (7 1/2 Fahrenheit) above the coldest temperature known. This extremely cold temperature enables certain metals and alloys to acquire the ability to carry an electric current virtually forever without loss of power and without resistance.

Not only does superconductivity greatly magnify the sensitivity of the magnetometer, it also suppresses the instrument's own magnetic "noise." The material whose magnetic field is being measured, however, may be at room temperature.

The instruments themselves are modest in size, the actual probe that measures magnetism being smaller than a little finger. Much of the instruments' bulk is the equipment necessary to keep them very cold. This includes Dewar flasks containing liquid helium.

The probe mechanism consists of a small cylinder of two superconducting metals–niobium and tantalum–vaporized onto a glass cylinder a little more than three millimeters (an eighth of an inch) in diameter. The superconducting metal cylinder is about three millimeters in length. A very thin slot is cut down the cylinder, a few microns wide. A micron is one 25-thousandth of an inch. A very small bit of the two metals, but in different proportions than in the rest of the cylinder, is fitted into the central part of the slot, the rest of it being left open.

Around the outside of the cylinder–but not touching it–are wrapped two or three coils of wire of a superconducting metal. The ends of the wire are attached to a voltmeter. The sample whose magnetic field is to be measured is placed in the cylinder. The magnetic field in the sample, no matter how small, will generate a very small electric current in the cylinder and coil. The cylinder and coil represent a miniature transformer. The amount of the magnetic field determines how much current can cross the slot in the cylinder.

This is the Josephson effect, and the current, perhaps only one millionth of a volt, has been calibrated so that the strength of the magnetic field can be calculated. The magnetic field acts much like a valve to control the flow of electron pairs around the superconducting cylinder. However, because of the unique properties of superconductivity, the valving action is quantized in much the same manner as though the cylindrical super currents represented giant atomic orbits

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for the electrons. The magnetic flux is also quantized (separated into little pieces); the magnetometer can measure as little as ten-millionth of a single quantum of magnetism.

The Josephson effect that gives the magnetometer its extreme sensitivity involves a prediction by Josephson that when two superconductors are placed near each other (within a few angstroms. One angstrom is one 254-millionth of an inch), pairs of electrons would cross the space from one superconductor to the other.

According to cryogenic theory, in superconducting metals electrons always travel in pairs. They don't fly around randomly, sometimes striking the metal lattice and bouncing off each other, always losing energy in the process, as they do at warmer temperatures.

Instead of two superconductors, the Caltech physicists use the single cylindrical one with the slot down one side of it. The amount of magnetic field that is being measured determines the rate at which pairs of electrons can find their way across the little bridge of different superconducting metals. And that, of course, represents the amount of current flowing. The current is measured and from it the strength of the magnetic field can be determined.

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Cover Caption

FLIP on working site with 55 feet of prow pointed upward and the remaining 300 feet of vessel underwater. See page 26.

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DoD-316

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