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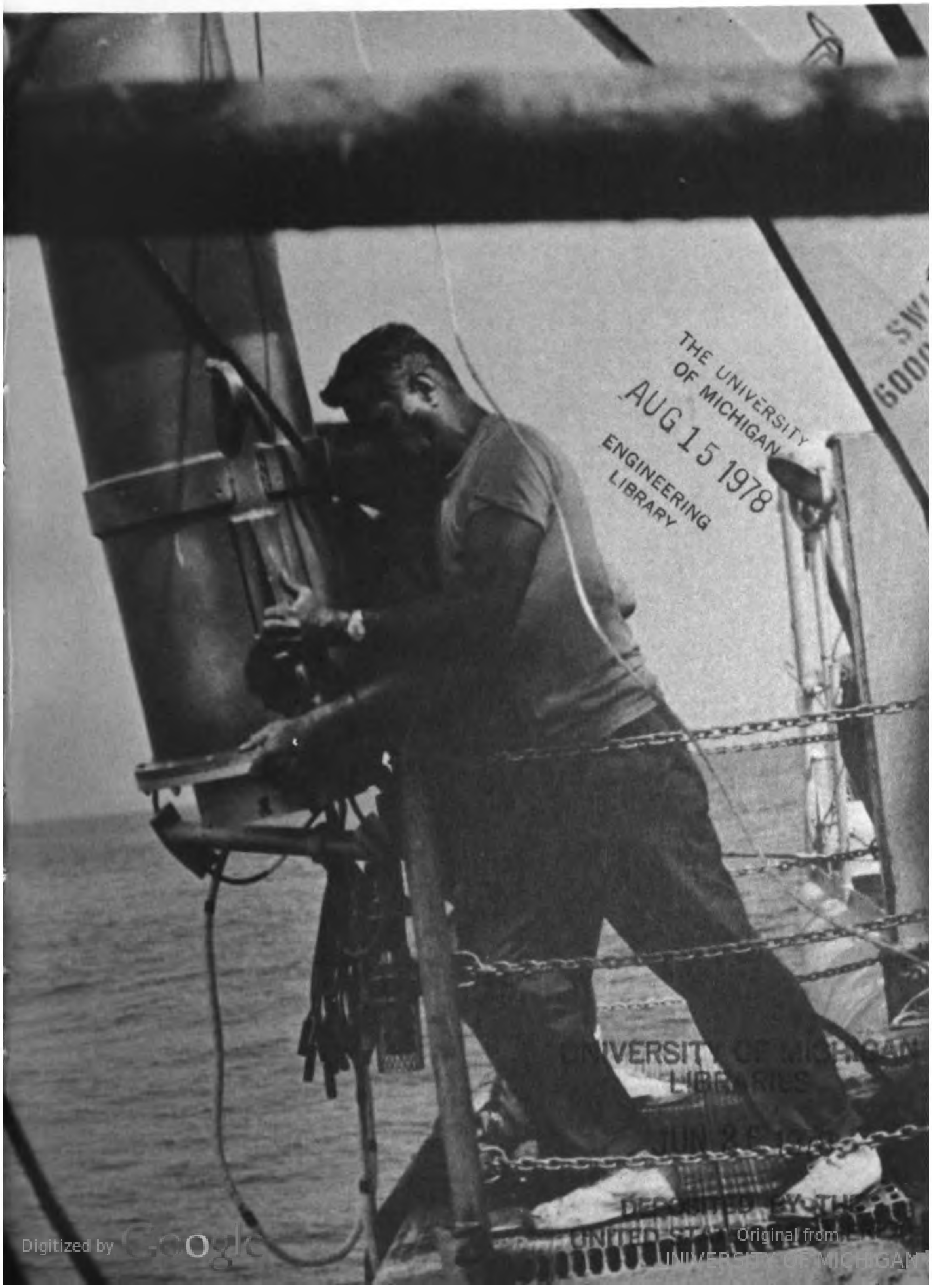

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PROFILES IN SCIENCE

Dr. Karl Herzfeld

Dr. Karl Herzfeld, who is Professor Emeritus at the Catholic University of America, is world renowned for his contributions to theoretical physics. Herzfeld and H. G. Grimm first proposed that energy relations decide which compounds exist in the crystalline state and that the refractive index could be used to decide whether a crystal would be metallically conducting. Collaborating with F. O. Rice, Professor Herzfeld developed the equations relating sound absorption to the "relaxation time" of energy transfer. Later Herzfeld showed that the reflection coefficient of high frequency sound waves may be considerably decreased by heat conduction to the reflector. In the field of liquids he developed in 1958 a general theory of viscosity and bulk viscosity.

For the past fifty years Professor Herzfeld has been doing important work in the fields of ultrasonics, electronic structure of molecules, solid state theory, thermodynamics, kinetic theory of gases, reaction velocities, semiconductors, and interior ballistics. Herzfeld was a coauthor for "Dispersion and Absorption of Ultrasonic Waves," which is the classic text in the field.

He has made many contributions to the Navy through his research supported by the Office of Naval Research and his leadership on the Mine Advisory Committee sponsored by the National Academy of Sciences. Professor Herzfeld's influence has guided many of his students to prominent careers in naval research.

His achievements have been recognized by five honorary degrees and many awards. He is a member of the National Academy of Science and a fellow of the American Physical Society.

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Sound Propagation in Shallow Ocean Water

F. Ingenito*
Naval Research Laboratory

Introduction

Shallow water is often defined as those areas of the ocean overlying the continental shelves (Figure 1). A roughly equivalent definition denotes shallow water as those areas having depths less than a hundred fathoms. Both these definitions are unsatisfactory from a scientific point of view but they do delimit the geographic extent of shallow water and, by implication, suggest its importance.

All of the continental land masses are surrounded to a greater or lesser extent by shallow water. Therefore all shipping and naval units

Figure 1 — The shaded areas show the continental shelves surrounding North America. Note the extensive shallow water off the East Coast.

*Dr. Ingenito is a member of the Applied Ocean Acoustics Branch of NRL. His major field of research is shallow water acoustics.

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entering or leaving port or transiting straits and passages must pass through shallow water. The resulting high density of shipping makes shallow water a likely major scene of submarine operations, and it is essential for the Navy to have anti-submarine warfare (ASW) capability there.

Most sonar systems have been designed with deep-water applications in mind and have proved to be of limited usefulness in shallow water. It is clear that the designer of sonar systems for shallow water use must confront the unique problems presented by that environment. These problems become evident when we consider the physical features of shallow water and how they affect its acoustical characteristics.

From the acoustical point of view, water is shallow when a sound wave propagating through it interacts strongly with the boundaries (the surface and bottom). This occurs when the ratio of the water depth to the wavelength of the sound is relatively small. At sufficiently low frequencies (long wavelengths) even comparatively deep water can be considered shallow while the continental shelves appear "deep" at high frequencies. Sound propagating in deep water may travel long distances without interacting with the bottom or the surface while sound in shallow water will undergo many reflections from the surface and bottom over its propagation path. No simple deep water paths like convergence zone or bottom bounce are available in shallow water; a received signal will be the sum of sound waves which have traveled many different paths with resulting signal fluctuations and lack of coherence. It becomes difficult to think of the sound in terms of "rays" and it is often necessary to use the more complex wave theory methods in analysis.

Even the acoustical definition of shallow water does not suggest all of the differences between deep and shallow water. Greater interaction of sound with the boundaries means greater loss and a higher level of reverberation (sound returned to the receiver by scattering from the boundaries and from inhomogeneities present in the ocean). The variety of bottom materials encountered is much greater in shallow water. They may be mud, sand, gravel, rock, coral, and so on, while the deep water bottom is usually composed of mud and ooze. The proximity to land masses means variations in salinity due to fresh water runoff from the land, including large rivers. Shallow water areas also are subject to tidal currents and upwelling from the bottom and are the scene of greater biological activity.

These phenomena — and others not mentioned here — make shallow water a highly variable medium for the propagation of sound. In addition, detection of sound emitted by submarines is made more difficult by the presence of high noise levels from shipping concentrations and from sources such as industrial activity on shore, offshore oil operations, and biological sources. Sonar performance is further degraded by the greater density of false targets caused by wrecks, reefs, pinnacles, and fish schools.

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One of the aims of the Navy's research program in underwater acoustics is to develop models with which to predict the performance of sonar systems under realistic conditions. Such performance prediction models are composed of various submodels, including models for the signal field, the ambient noise field, and the reverberation field. In this article, the discussion has been focused on the propagation of sound which is basic to an understanding of ambient noise and reverberation.

Early Shallow Water Research

The study of sound propagation in shallow water and the recognition that it presented problems quite distinct from those in deep water, began in World War II. Worzel and Ewing, receiving signals at large distances from explosive sources in shallow water, observed that the different frequency components of the signal arrived at the receiver at different times, that is, the signal exhibited dispersion (1). They also noticed that some of the received sound traveled through the bottom. Both of these observations were contrary to experience in deep water and could not be explained by the then available theoretical models. They communicated their results to C.L. Pekeris who they knew had been working on similar problems. It turned out that Pekeris already had gone a long way toward the solution of their problem. Pekeris had developed the normal mode theory of propagation of sound in layered media which he proceeded to extend to the case of sound from explosive sources. He produced an elaborate report containing extensive calculations (without the aid of high-speed computers) which explained the findings of Worzel and Ewing (2). Pekeris' report is a classic in the field of underwater sound and the basis for later developments. His results are still quoted in books and articles published today, over thirty years later.

Rays and Normal Modes

In analyzing a medium as complicated as the ocean, it is necessary to make a number of simplifying assumptions. Later, some of these assumptions may be modified, or discarded entirely. Generally, we seek the simplest model which will provide predictions that agree with actual measurements. The major assumption we make in the study of sound propagation in the ocean is that the observable quantities such as acoustic pressure, density, and particle displacement satisfy the acoustic wave equation. Other assumptions about the surface and bottom will be discussed later. The solution of the wave equation, together with the initial and boundary conditions, gives the complete solution of the problem within the framework of the model.

Since solving the wave equation is often a difficult mathematical problem, an approximation called the "ray method" is commonly used.

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A ray describes the direction of propagation of a wave front and defines the direction of acoustic energy propagation. The path of a ray is determined by a set of equations derived from the wave equation by making the approximation, in effect, that the properties of the medium do not change appreciably over the distance of an acoustic wavelength. To calculate the sound field by the ray method, a number of rays are started from the source and their paths traced in accordance with the ray equations. The relative density of rays in a given region of space provides a measure of the sound intensity. The ray method is simple and powerful, and offers a physically-satisfying picture of the propagation of sound. It fails at long wavelengths (or low frequencies) and does not predict the correct sound intensity in regions of space where diffraction is important, as in shadow zones. In a practical sense, the ray method becomes very cumbersome when sound may arrive at the receiver by many different paths. This is precisely the case in shallow water, where the small ratio of water depth to range means that rays are reflected from the surface and bottom many times in traveling from source to receiver and neighboring rays may have entirely different histories. This is quite different from the deep water case in which rays usually make only a few surface and bottom reflections before they reach the receiver. Also, because ray theory is a high frequency approximation, it cannot (in its basic form) predict frequency effects such as the frequency dispersion in shallow water observed by Worzel and Ewing. It was for these reasons that Pekeris used the normal mode method to describe sound propagation in shallow water.

The normal mode method provides an exact solution to the wave equation. It therefore gives as complete a picture of sound propagation in shallow water as can be obtained from the idealized model. The method depends on the separability of the wave equation, which in turn depends on the separate dependence of the ocean environment on range and depth. Pekeris assumed that the ocean and bottom could be treated as a stratified medium; that is, that the sound, speed, and density depended only on depth, not on range. To solve the wave equation, we must also have boundary conditions, specified by the physical situation. For example, at the surface we assume that the acoustic pressure vanishes because the density and sound velocity of air are very small compared to water. The boundary conditions at the surface and at the bottom determine an infinite set of solutions to the wave equation and each individual solution is called a normal mode. The complete solution of a given problem then is given by a sum of normal modes.

The physical meaning of the normal mode is less obvious than that of the rays. When a source of sound is present, the surface and bottom boundaries act like the walls of a duct, trapping most of the sound energy. Sound is reflected from the boundaries many times and interference patterns are formed. Sound reflected from the boundaries at certain angles will interfere constructively and will be propagated along the

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duct as discrete waves with characteristic velocities. These are the normal modes of propagation. At the other angles, the reflected sound will interfere destructively and will not be propagated. The normal modes are so called because they are individual solutions of the wave equation, in analogy with the theory of vibrating systems, such as strings.

Sound can be propagated in the duct only as normal modes and each mode will have its own characteristic velocity of propagation and vertical pressure distribution. The properties of the normal modes, in particular their velocities, are functions of frequency. This is the reason for the frequency dispersion observed by Worzel and Ewing.

The Pekeris Model

In developing a theory of sound propagation in shallow water, the physical characteristics of the water, the bottom, and the boundaries must be modeled. Pekeris assumed that the water was a lossless fluid layer of constant thickness with constant sound velocity and density. He took the bottom to be a semi-infinite fluid layer of constant, but greater, sound velocity and density. The boundaries were perfectly smooth (Figure 2).

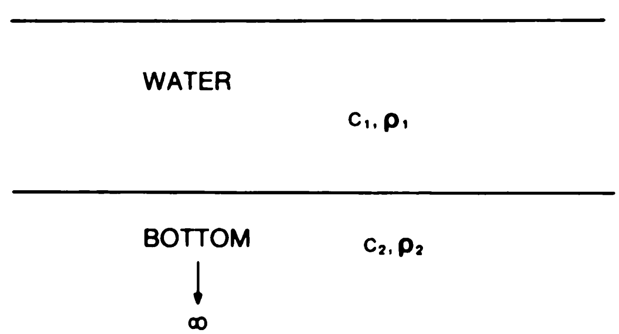

Figure 2 — The geometry of the Pekeris Model. The sound velocities of the water and bottom c_1 and c_2 and the densities ρ_1 and ρ_2 are constants. The water depth is constant and the boundaries are smooth.

Applying the normal mode method to this model, Pekeris was able to predict the propagation characteristics of a sound pulse emitted by an omnidirectional point source in the water layer. An explosive detonated underwater emits a pulse of sound containing a broad, continuous, band of frequencies. All of the frequencies are emitted by the source at the same time; but Pekeris was able to show that at a distant receiver, the first arrivals would be the low frequencies, which had traveled through the higher velocity bottom (the ground wave) followed by the high frequencies (the water wave) and then the other frequencies (Figure 3). This is in accord with the experimental observations of Worzel and Ewing.

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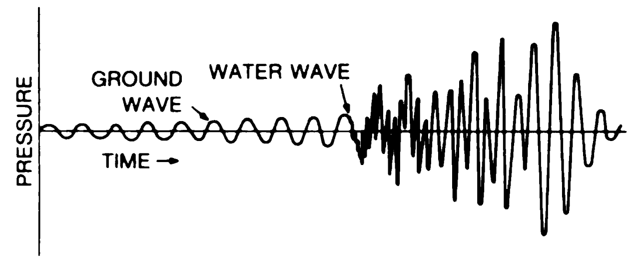

Figure 3 — Sketch (after Pekeris) of the contribution of the first mode to the signal produced by an explosive source at some distance. The first arrival is the low frequency ground wave followed by the high frequency water wave.

Laser Theoretical Developments

Pekeris' theory, successful as it was in explaining the results of the Worzel and Ewing experiments, left many questions unanswered. His model assumed a highly idealized picture of the ocean. For example, the sound velocity in the water is not constant but varies with depth and range. Although the sound velocity varies only by a few percent in a particular region of the ocean, it may have an important effect on a propagating acoustic signal, as demonstrated in deep water work.

Furthermore, in the design of sonar systems, it is essential to know the "propagation loss", the amount by which the strength of the sound signal diminishes in traveling from the source to the receiver. The propagation loss is a complicated function of range exhibiting a superposition of periodic oscillations caused by the interference of a number of modes arriving at the receiver (Figure 4). In deep water, propagation of this type is called multipath propagation, and it is the *rule* in shallow water. Often in sonar work it is sufficient to use the "incoherent" propagation loss, an average calculated by neglecting the phases of the modes.

The most important contributors to the propagation loss in shallow water are geometrical spreading as the sound wave radiates from the source, absorption of sound in the water and in the bottom, and scattering by the irregular surface and bottom boundaries. The Pekeris model includes only geometrical spreading as a loss mechanism.

Building on the Pekeris model, and with the aid of high-speed digital computers developed after the war, normal-mode models were developed which could accommodate a sound velocity in the water column which varied arbitrarily with depth (3,4). This is a relatively simple extension of the basic model although it is necessary to resort to numerical methods to calculate the normal modes.

The bottom is a much more complex problem. In shallow water at frequencies of less than a few thousand Hertz, absorption by the water

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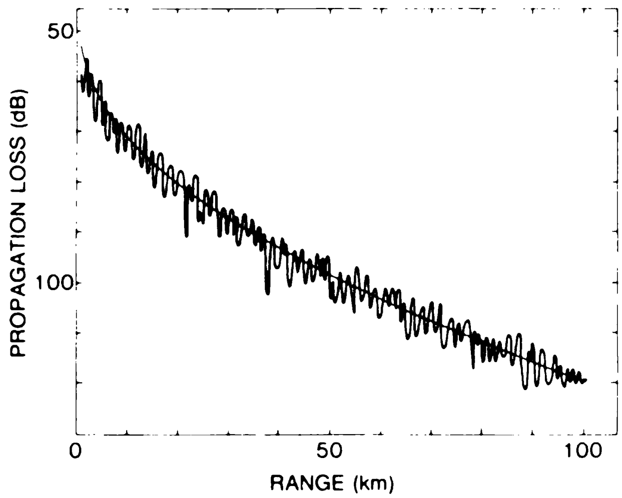

Figure 4 — An example of calculated propagation loss. The irregular line is the coherent propagation loss which shows the effect of multiple arrivals, with different phases, adding at the receiver. The smooth line is the incoherent propagation loss with phase neglected.

(which is comparatively well understood) is negligible and bottom absorption dominates. The bottom is difficult to treat for two reasons. First, it is a complex inhomogeneous substance consisting of sand particles of various sizes, shells, live organisms, water, gas bubbles and a variety of other things. Second, even if it were possible to treat such a medium theoretically, it is very difficult to determine experimentally the characteristics of more than the first meter or so of the bottom.

This situation has forced scientists to fall back on gross idealizations of the bottom. Pekeris himself generalized his model of the bottom, adding a fluid layer of constant thickness, sound velocity, and density overlying the original semi-infinite layer. Later workers generalized the model to include any number of distinct, homogeneous layers. Further generalizations have been made which replace the fluid layers by visco-elastic solid layers which are a bit closer to reality, since experimental evidence shows that bottom materials can support shear waves as well as compressional waves, and that both types of waves are absorbed (5).

A different approach to the inclusion of bottom effects in their models has been used by some theorists. They express the effect of the bottom on the waterborne signal by introducing the plane-wave reflection coefficient of sound waves at the water-bottom boundary (6). This approach has the advantage that detailed knowledge of bottom structure is unnecessary, and only the end effect of the bottom on the signal, expressed by the reflection coefficient, is needed. The reflection coefficients used in such models are usually obtained experimentally (theoretical reflection coefficients would require knowledge of the bottom structure) and obtaining them presents a major difficulty. Experi-

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mental reflection coefficients turn out to be functions of the experimental geometry, primarily because it is difficult to generate the plane waves required for the measurement.

The surface and bottom boundaries, which Pekeris assumed to be smooth, are, in fact, rough. The surface is disturbed by wind generated waves and by swells, both of which vary with time. The bottom boundary is also irregular, but is constant in time, at least over the period of a short experiment. Sound impinging on the boundaries is scattered by the irregularities and some of it is lost from the signal which effectively increases the propagation loss. Some progress in accounting for boundary roughness effects has been made by treating the boundaries as randomly rough, then calculating reflection coefficient and using them in a manner similar to the bottom loss case (7).

All these effects are also present in deep water, but their influence is more important in shallow water since a sound wave interacts with the surface and bottom much more strongly.

The normal-mode method, although most commonly used, is only one way of solving the wave equation. In recent years new methods of solution have been developed which, in some cases, offer computation advantages over the normal-mode method. The Fast Field Program (FFP) expresses the wave equation solution in integral form and uses the Fast Fourier Transform to compute the integral (8). Results obtained by the FFP method and the normal-mode method are equivalent; choice between them is made on grounds of computer storage requirements, speed, and personal taste. The Parabolic Equation (PE) method uses a fast, efficient algorithm to solve an approximate form of the wave equation. It has not been applied to shallow water problems to any great extent (9).

Experiments

Experimental work in shallow water has been of two general types: survey measurements and model validation. Survey measurements are made in a chosen area of the ocean in different seasons to determine the propagation characteristics of the region. Large quantities of data are collected, usually of propagation loss with supporting environmental data, and reduced to a form suitable for examination. Conclusions can then be drawn about how sound is propagated in that region. Survey data are of value to the designers of sonar systems because they are the results of actual measurements made in the area of interest; sometimes they are made with operational sonars. Their disadvantage is that conclusions drawn from them are not readily generalizable to another area.

Examples of this type of experiment are the COLOSSUS II Shallow-Water Propagation Studies done in the later 1950's (10). A great many data were taken and summarized in a semi-empirical model of sound propagation in shallow water (11). Other empirical models

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have been developed as the result of similar studies (12-14). Their basic appeal is simplicity, but as they represent averaged results or bits of experimental data, their predictions are less detailed than those of the theoretical models.

Model validation experiments are themselves of two types: scale-model laboratory studies and actual at-sea experiments. Scale-model laboratory studies are appealing because it is possible to control the environment and to isolate and study a desired mechanism and determine its effect on sound propagation. They are also much less expensive than at-sea experiments. Such studies have verified the basic validity of normal-mode theory (15-18).

At-sea validation experiments are much more difficult and expensive to perform but they are also more convincing. Many factors affect sound propagation in the ocean and they are all interdependent. The environment can be partially controlled by proper selection of area and weather conditions. Experiments have been performed in areas where considerable knowledge of the environment, especially the bottom, existed and where conditions were favorable for the experiments. Fixed shore instalations or off-shore towers have often been used for greater stability and the resulting data, carefully processed, have tended to agree with the predictions of normal-mode theory although with greater uncertainty, reflecting the variable character of the ocean as a medium for the propagation of sound (5,19).

Shallow Water Research at the Naval Research Laboratory

As discussed above, a sound wave propagating in shallow water is a superposition of normal modes, each of which has a characteristic propagation velocity and attenuation. Due to its complexity (Figure 4), it is very difficult to extract information about the physical processes taking place in the medium from measurements of the total signal. The situation is made even worse by the variability of the shallow water medium which causes relative variations in the phases of the normal modes resulting in a fluctuating total signal. In contrast, the individual normal modes behave more simply, and they are the basic components of any propagating signal.

The objective of the NRL Shallow Water research program is to develop validated models of sound propagation useful for sonar performance prediction. To this end, a normal-mode model was developed and refined, supported by experiments designed to validate features of the model and to provide inputs.

The model, in its current state, consists of a layer of water with depth-dependent sound velocity overlying a two-layer bottom (20). The upper layer of the bottom is assumed to behave as a fluid, with depth-dependent sound velocity while the second, semi-infinite bottom

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layer can be either a fluid or a solid with constant compressional and shear velocities (Figure 5). The densities of the three layers are assumed to be arbitrary constants. Absorption in the bottom can be included, as can the effects of roughness at the surface and bottom boundaries (21).

Model Geometry

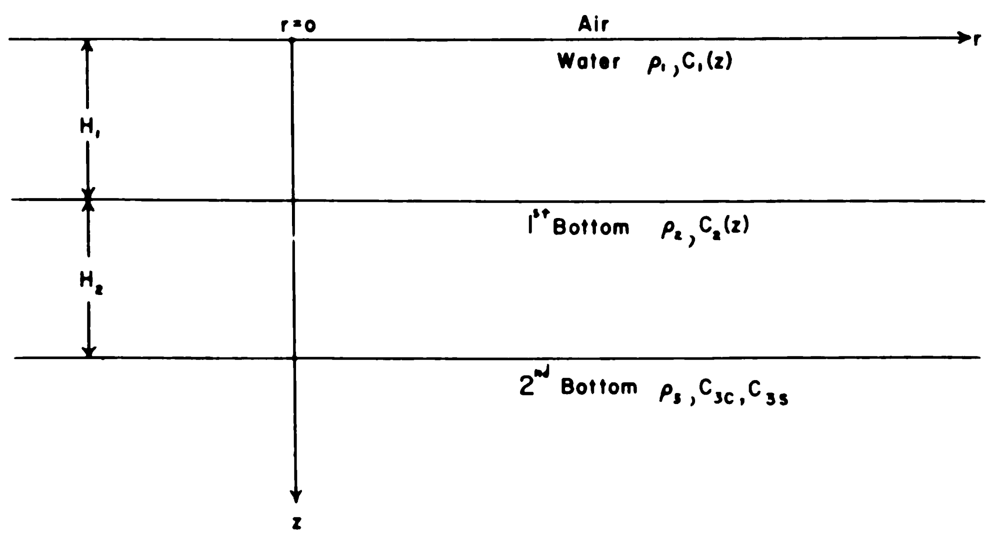

Figure 5 — The geometry of the NRL shallow water model. The sound velocities in the water layer c_1 and the first bottom layer c_2 can be functions of depth z. The compressional and shear velocities (c_{3c} and c_{3s}) of the semi-infinite second bottom are constants, as are the densities ρ_1, ρ_2, and ρ_3. Absorption in both bottom layers can be included as well as the effects of roughness of the boundaries.

The model calculates the mode amplitude functions, the attenuation of each mode, and the phase and group velocities of each mode. The group velocity is the velocity of a narrow band of frequencies and is the rate of energy transport in the medium. The propagation loss is calculated by summing the modes either coherently or incoherently. Figure 4 is an example of propagation loss calculation.

The propagation loss calculation allows the environment to vary gradually with range. The so called adiabatic approximation is used, which assumes that in a slowly varying medium there is no exchange of energy among the modes and that the characteristics of the modes at any range can be calculated using the properties of the environment at that range.

This model is necessarily a highly idealized one, so early experimental work attempted to verify the applicability of the detailed normal-mode picture to the real ocean. Individual normal modes had been studied previously in scale-model laboratory experiments and in other controlled situations, but never in the open ocean. To do this it

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was necessary to develop experimental techniques for isolating, identifying, and measuring individual normal modes.

Separation of the normal modes was achieved by taking advantage of their dispersive properties (22). Since the modes travel at different velocities, it is clear that at a sufficiently large distance from the source the modes will no longer overlap. If a very short initial pulse is used, the modes can be separated at a reasonable distance from the source. The modes can be identified by measuring the acoustic pressure as a function of depth. In the simple Pekeris model where the velocity of sound in the water is constant, the modal pressure amplitudes as functions of depth are simple sine functions with the first mode having no zeros except at the surface, the second mode one zero, and so on. When the velocity of sound is not constant, the modal pressure amplitudes are more complicated functions of depth; but they still retain the correspondence between zeros and mode numbers. Thus simply counting the number of zeros serves to identify the mode.

Clearly, the method requires that the acoustic pressure be measured as a function of depth over the entire water column. A remote sensor buoy was designed and built to serve as a sensor platform. Up to twelve hydrophones can be suspended from the buoy which contains a radio telemetry system which relays the received signals to the mother ship for recording and processing (Figure 6). The remote sensor buoy permits single ship experiments to be conducted in any shallow water area. An example of the received signals is shown in Figure 7.

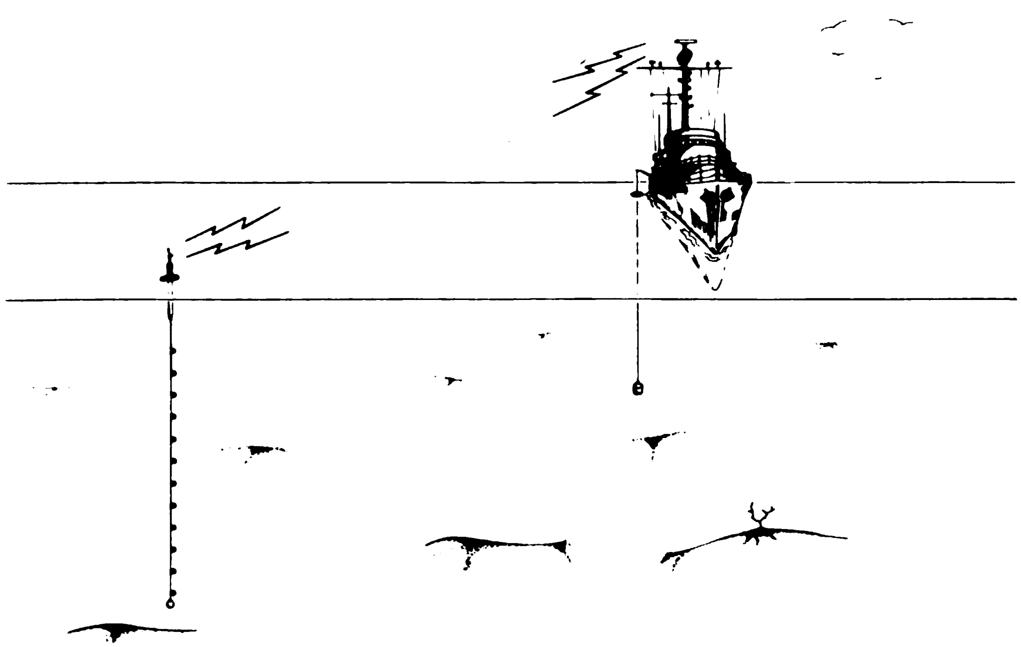

Figure 6 — Sketch of the experimental geometry, showing the remote sensor buoy with a string of hydrophones suspended below. A source, suspended from the ship, emits acoustic signals which are received by the hydrophones and relayed by radio back to the ship for recording and processing.

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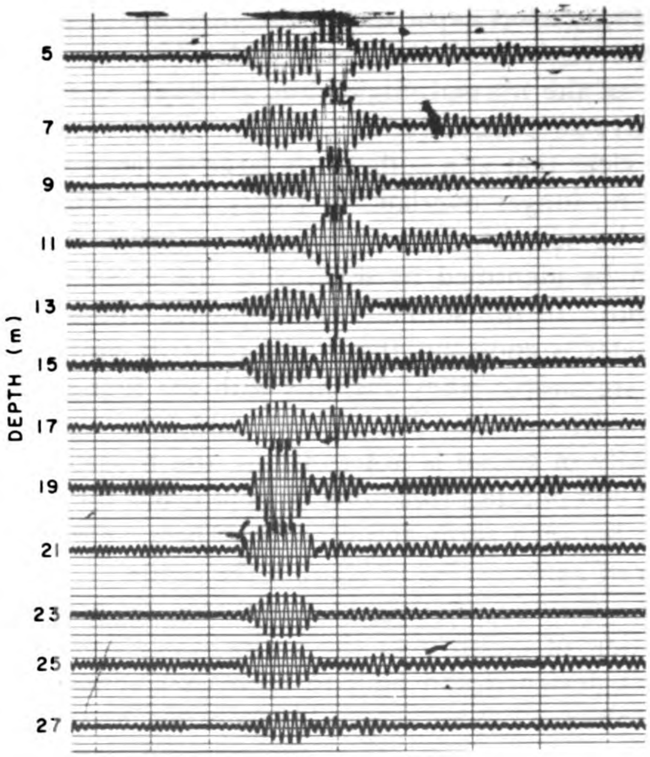

Figure 7 — An oscillographic recording of the outputs of twelve hydrophones vertically distributed in the water column. Time progresses from left to right. In this example, a phase change between the nine-meter hydrophone and the thirteen-meter hydrophone is clearly visible, indicating that this is the second mode. The first mode, which has no phase changes arrives second.

Three types of measurements were conducted with this system: modal pressure amplitude as a function of source depth, receiver depth, and modal attenuation. Experiments were conducted in several selected shallow water areas, each of which had a different bottom type: various sandy bottoms and consolidated limestone. Examples of the results obtained are shown in Figures 8, 9 and 10.

The results of these experiments show that, given the necessary environmental inputs, the normal-mode model can predict the signal field in shallow water of constant depth (22,23). Experiments have also been performed in an area of changing water depth and sound velocity profile with range (24). These measurements have tended to confirm the validity of the adiabatic approximation, at least when the environment does not change too rapidly.

Conclusion

Considerable progress has been made in the study of sound propagation in shallow water and in the development of propagation models.

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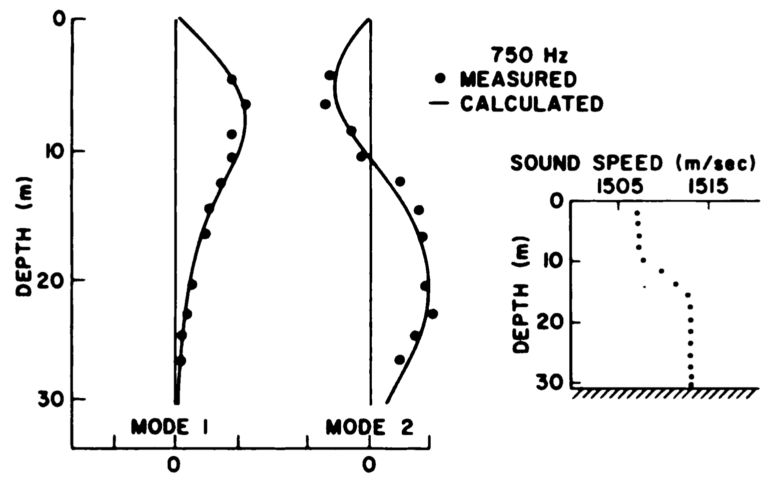

Figure 8 — Comparisons of measured and calculated mode amplitude functions as functions of receiver depth for the first and second modes. The prevailing sound-velocity profile is also shown.

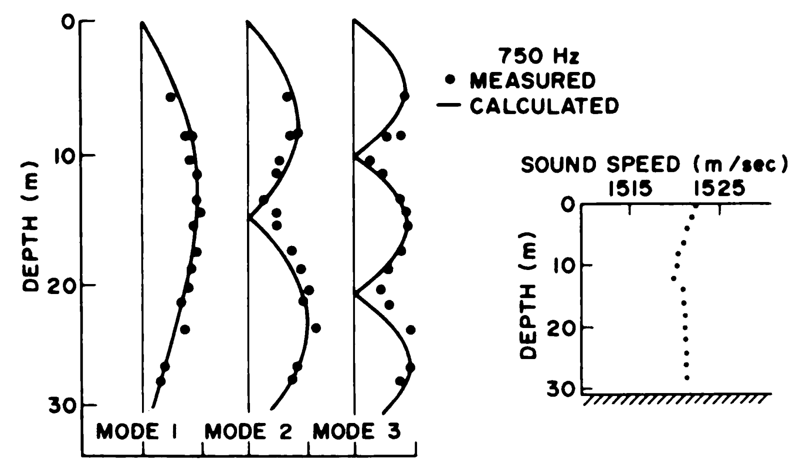

Figure 9 — Measured and calculated mode amplitude functions as functions of source depth for the first three modes. Since it was necessary to move the source to a new depth for each measurement, it was not possible to distinguish phase. The prevailing sound-velocity profile is also shown.

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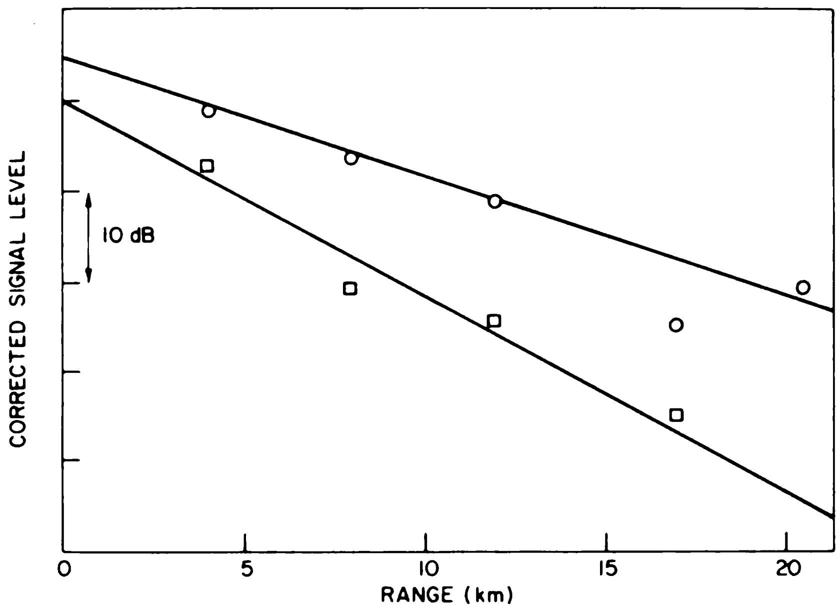

Figure 10 — An example of the results of a mode attenuation experiment. The signal levels of the first (circles) and second (squares) modes at 750 Hz vs. range are shown. The signal levels have been corrected for cylindrical spreading. The slopes of the straight lines, which have been fitted to the measured points, are the mode attenuation coefficients.

However, sound propagation is still less well understood in shallow water than it is in deep water, partly because it has received less research effort but also because it is a considerably more complex problem. Shallow water propagation models are well advanced and are capable of treating the environment with considerable sophistication. An exception is the important case of range dependent environments where better models are cleary needed. Aside from this, the models will accept environmental input of greater detail than is usually possible to obtain in the field. Along this line, the greatest deficiency, from the shallow water point of view, is the lack of knowledge about the bottom. Methods must be developed to determine actual bottom properties in sufficient detail to be used by the models. Another weakness is lack of knowledge of biological effects on the signal field. There is evidence that, in some cases, schools of fish can make an important contribution to the attenuation of the signal (25). Other aspects of propagation about which little is known are the coherence and fluctuations of the signal field. These are of great importance to the sonar designers.

Finally, this article has been concerned with propagation of an acoustic signal. Other aspects of the shallow water problem such as ambient noise and reverberation have not been discussed. Some work has been done on these problems but much work remains to be done and these are fertile fields for future research.

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The Physics and Operation of Transferred Electron Devices

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Introduction

Since the invention of the transistor there has been a continuing search for high frequency solid state sources. To some extent important requirements within the conventional microwave spectra, as well as portions of the millimeter wave spectra have been met by a group of devices known as transferred electron devices. These devices, often called Gunn diodes, entered the scene in 1963 when J.B. Gunn reported (1) that when the ends of a semiconducting gallium arsenide specimen were connected to the terminals of a sufficiently high voltage battery, microwave oscillations would appear. The oscillations appeared as a train of current spikes (Figure 1) with an oscillation period equal to the time it takes electrons to travel between the ends of the specimen (2). Typically, in the early experiments the oscillation frequencies were in the range of 0.5 to 6 GHz.

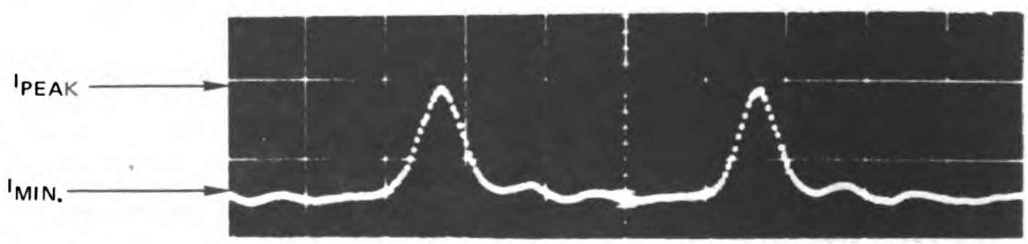

Figure 1 — One cycle of current versus time for a gallium arsenide device sustaining dipole oscillations. Nucleation and extinction of the dipole occurs during the 'spiked' portion of the oscillation. Dipole transit is associated with the flat portion of the oscillation.

During the fifteen years since Gunn's announcement the oscillation frequency has continually moved toward the 100 GHz mark. In addition a wide range of highly sophisticated devices, operating as local oscillators, amplifiers, and logic elements have been developed. Many

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of these devices are being designed as replacements for traveling wave electron tubes in military avionics, as well as for situations where low electric noise levels are important. The purpose of this paper is to provide some background into the physics underlying the phenomena observed by Gunn, and to discuss how the device is currently being used. Research of the type described in this paper is being sponsored by the Office of Naval Research.

Explanation of Gunn's Observation

Gunn's experiments demonstrated that the semiconductor gallium arsenide was capable of converting dc power to ac power. The explanation of this conversion, was given by H. Kroemer (3). He proposed that when the oscillations occured the electric field within the device became highly nonuniform. This nonuniformity would manifest itself in the appearance of regions of high electric field surrounded by regions of low electric field, as in Figure 2, and these high field regions, often called domains, would move toward one end of the specimen. The oscillation was then a consequence of the following sequence of events. First a domain would nucleate at one of the contacts (the cathode). At this point the current would drop, as in Figure 1. Then the domain would leave the cathode region and travel down the sample toward the second contact (the anode). Here, the current would be approximately constant. Finally, the domain would be extinguished at the anode contact and the current would rise. The oscillation period, T, was determined mainly by the time it took the domain to travel between the cathode and anode contacts, and this was determined by the speed, V, of the moving electrons. Thus $T = L/V$ where V is about 10^7 cm/sec and L is the length of the speciment. Note for $L - 10^{-2}$ cm, $T = 10^{-9}$ sec, and $1/T = 1.0$ GHz.

Kroemer's explanation of Gunn's experiments was a synthesis of earlier studies and relied on three key ingredients. *First* there was the presence of electron transfer (to be discussed below) and its conseqences. *Second* there was the concept of negative differential mobility and its consequences. And *third* there was a calculation relevant to the semiconductor gallium arsenide. With regard to electron transfer, B.K. Ridley and T.B. Watkins (4), in 1961 predicted that certain semiconductors would exhibit it, and that one important consequence of its presence might be that the semiconductor would exhibit a region of negative differential mobility. C. Hilsum (5), in 1962, showed by explicit calculation that gallium arsenide, through electron transfer, would exhibit negative differential mobility.

A material that exhibits negative differential mobility is one in which the electron velocity *decreases*, rather than increases, for a certain range of increasing electric field values (Figure 3). Its significance is that at sufficiently high voltage levels the material becomes electrically

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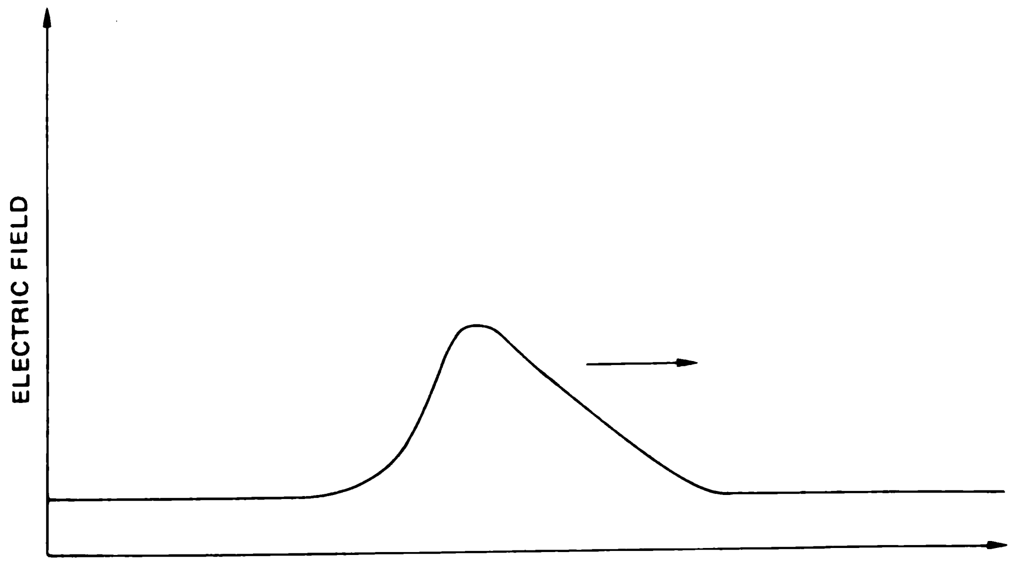

Figure 2 — Sketch of moving high electric field domain associated with the oscillation of Figure 1.

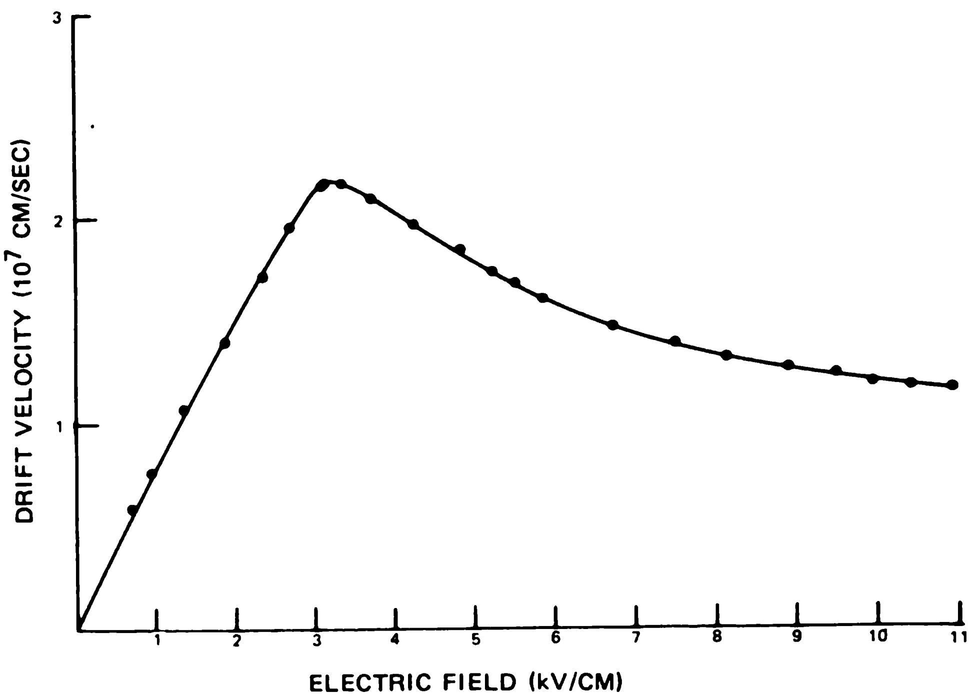

Figure 3 — Drift velocity versus electric field for electrons in gallium arsenide. Dots denote experimental points. Region of negative differential mobility begins at about 3.2 kilovolts/cm. From Ref. 6, with permission.

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unstable and the electric field becomes highly nonuniform. To understand this consider that there exists a small nonuniformity of field inside the specimen. Such a nonuniformity could be caused by ever-present fluctuations of charge within the solid. Suppose the fluctuations result in an increase in electric field. Ordinarily, this increased field would result in an increasing electron velocity and nothing particularly interesting happens. Rather the electrons move rapidly through the region of increased field which then proceeds to decrease in value. But a result of negative differential mobility the increased field leads to a decreasing electron velocity, which results in a tendency for the electrons to bunch together. This bunching then leads to a further increase in electric field. The situation tends to feed on itself until a high field domain forms.

While this situation was recognized by Ridley and Watkins in 1961, the subsequent development was not outlined until 1963. Then Ridley (7) showed that the domain was mobile, was composed of electrons, and would have a velocity equal to the average electron drift velocity. He noted that the domain would appear at some favored nucleation site, move down the sample and disappear at the anode. In Kroemer's explanation of Gunn's observations, the nucleation site was the cathode. Figure 4 displays a computer simulation (8) of the nucleation, propagation, extinction and renucleation of a high field domain for the smiconductor GaAs. The confirmation of the domain dependence of the gallium arsenide oscillation was demonstrated by Gunn in 1964 (9).

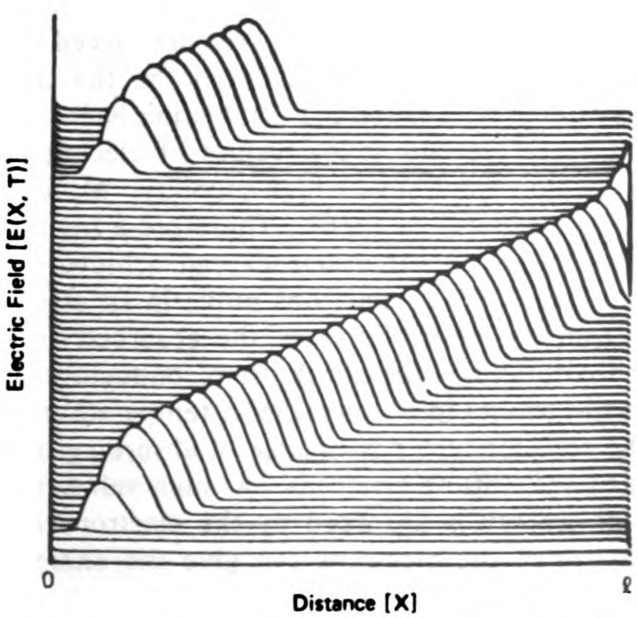

Figure 4 — Numerical simulation of the time-dependent behavior of a cathode nucleated domain. We show electric field versus distance at successive instants of time. From Ref. 8, with permission.

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The Transferred Electron Effect

The origin of the decrease in drift velocity with increasing electric field lies in the transferred electron effect. The transferred electron effect is a consequence of the fact the electrons in semiconductors are subject to the laws of quantum physics. In this sense they are subject to some of the same restrictions as electrons bound to an atom. Because electrons move throughout the entire semiconductor and are interacting with many atoms, the energy relation is more complicated than that associated with a single atom. One important difference is that instead of possessing discrete values of energy, as one normally finds when considering isolated atoms, the electron energy is smeared over a broader range or *band* of values. Like the situation of an electron and an isolated atom there are values of energy which the electron may not attain.

One of the principles of quantum physics is that a single energy state cannot be taken up by more than one electron. As a result of this it is possible that all available energy values within a certain band may be taken up by electrons. The laws of solid state physics teach that those bands that are either completely taken up by electrons or completely empty of electrons do not contribute to the current. Thus only partially occupied bands of energy allow for the flow of current. Crystalline pure gallium arsenide is a poor conductor at room temperature. There are very few electrons in the partially filled energy bands. In order to increase the number of electrons in these basically empty bands one normally introduces foreign atoms, often called impurities. In the case of gallium arsenide oscillators these impurities have an excess number of electrons and these electrons are placed into a basically empty energy band, where they may take part in the conduction process. This band of energy is called the conduction band.

At room temperature and at low values of electric field the electrons in the conduction band have a high mobility. Mobility is the ratio of drift velocity to electric field (v/E). Therefore a high mobiltiy semiconductor is one in which the electrons can achieve high velocities with small field values. When electrons move in an electric field, they absorb energy from the field. Some of the absorbed energy is given, via collisions with vibrating atoms in the semiconductor, to the material itself. This usually results in an increase in temperature of the device. At low fields the semiconductor is capable of absorbing most of the energy given to it by the drifting electrons. At high values of electric field the rate at which energy is absorbed by the electrons is much faster than the rate at which the electrons can give the energy back to the semiconductor. When this occurs a fraction of the electrons *transfer* to a region of the conduction band where their mobility is lower. As a result of this tranfer the overall mobility of the semiconductor decreases. This decrease in mobility does not in itself assure that the net

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velocity of the semiconductor will decrease. If the rate of transfer to the low mobility region is steep enough, negative differential mobility will occur. This is what happens in gallium arsenide. Figure 5 illustrates that at low values of electric field most of the electrons are in the high mobility part of the conduction band and their increase in velocity with increasing electric field is indicated by the top dashed curve. The net velocity of the semiconductor is indicated by the solid lines. As the electric field is increased an increasing fraction of electrons transfer and have reduced mobility (lower dashed curve) and the net velocity of the semiconductor reflects this reduction. Here the solid line is below the high mobility curve. At very high values of electric field the number of electrons with low mobility increases rapidly and the velocity undergoes a rapid reduction leading to negative differential mobility. The measured velocity electric field curve for gallium arsenide is displayed in Figure 3.

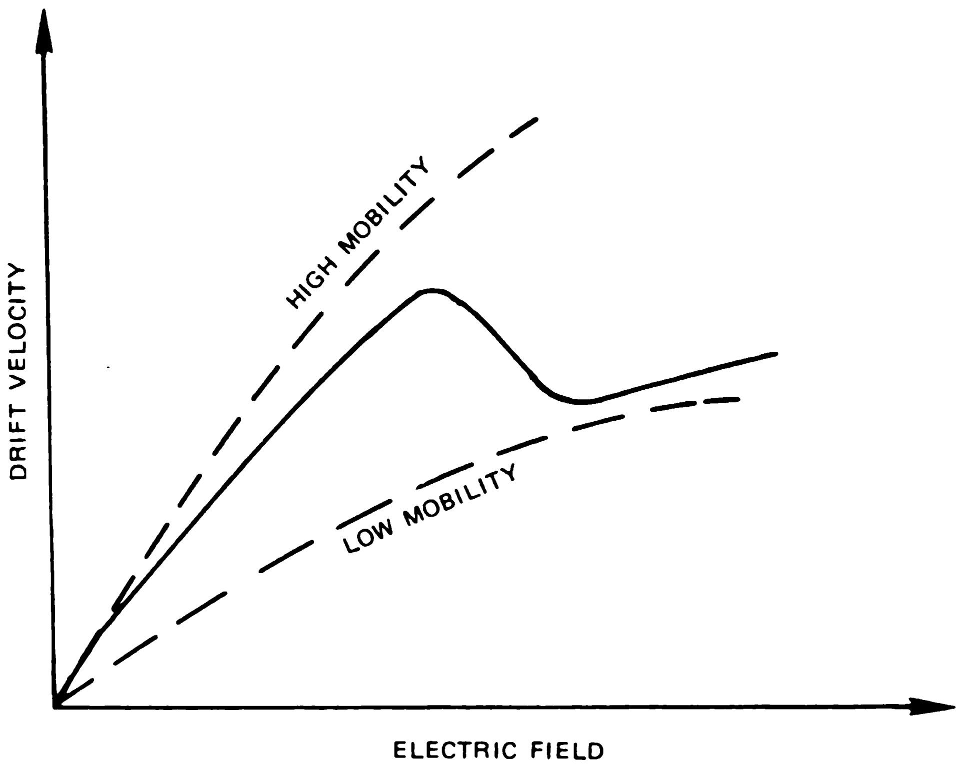

Figure 5 — Drift velocity of electrons with high values of mobility and with low values of mobility. Solid line denotes velocity electric field relation when electron transfer is operative.

Operation and Use of Transferred Electron Devices

Not withstanding Gunn's original observation and Kroemer's explanation of the phenomena, conceptually, the simplest kind of operation of a semiconductor with a region of negative differential mobility is

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one in which the electric field uniformly undergoes excursions into and out of this region. As it turns out this type of operation is, in a limited way, approximately possible. In 1966 J.A. Copeland (10) noted that since it takes a finite amount of time for a domain to grow, if the field across a gallium arsendie sample could be driven fast enough through the negative differential mobility region, domain growth could be reduced. Then if the field could be taken below the region of negative differential mobility for a length of time long enough to extinguish any incipient domains, the device would behave as a uniform electic field device. Figure 6 illustrates the type of resonant circuit for which approximate uniform field oscillations can occur (11,12). The capacitance required for oscillation is provided by the device. One importat advantage of this type of operation is that the circuit would control the oscillation frequency of the device. A.J. Shuskus and M.P. Shaw (13,14) reported, in 1965 and 1966, oscillations that apparently were of this type, although its significance was not recognized at that time.

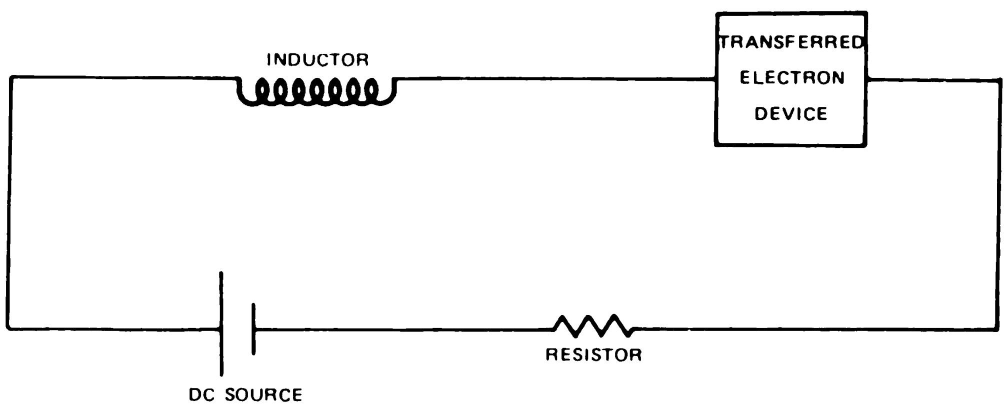

Figure 6 — Simple oscillator circuit for a transferred electron device in which domain transit-time oscillations may be suppressed.

Today with the exception of some logic devices many microwave transferred electron devices are designed with the uniform field concept in mind. This includes small signal amplifiers as well as the oscillators discussed above. The achievement of uniform fields for amplifiers requires, however, a different approach than that for oscillators. In the case of oscillators uniformity is approximately achieved by a suitable driving circuit. In the case of amplifiers special material fabrication design is necessary (15).

The continued interest in transferred electron devices since 1963 lies in the successful uses to which they have been put. As a fundamental source of oscillator power, the device may be placed in the circuit of Figure 6, but application designs are generally more detailed. Today the transferred electron device is the solid state device most frequently used as a local oscillator for radar applications (16). This includes marine, weather, portable battle field, aircraft and missile radars.

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In these applications the transferred electron device offers potential savings in weight and cost due to the elimination of high voltage power supplies associated with klystron local oscillators. Typical marine and weather radar utilize transferred electron oscillators which generate a few milliwatts of power in the frequency range of 9.3 to 9.5 GHz (16). Ku-band oscillators have also been developed for operation in the frequency range of 16.35 to 16.75 GHz with a minimum operating power of 40 milliwatts (17). In 1974 a survey of capabilities of transferred electron devices was published (18). Figure 7 summarizes the continuous wave power capabilities for a single transferred electron device as a function of frequency. We notice that the frequency range extends into the millimeter wave range. Here millimeter wave transferred electron device oscillators are also being used as local oscillators and as parametric amplifier pumps (16).

As amplifiers, gallium arsenide devices have demonstrated their utility as both narrow and broadband amplifiers in the microwave and millimeter wave range. They are attractive as solid state replacements for traveling wave tubes where low noise requirements must be met. Transferred electron amplifiers have been fabricated that yield noise figures (15) of 10 dB, very close to their theoretical minimum. Currently the transferred electron device amplifier has been used in communication systems. In one case (19) the frequency band was 10.7 to 11.7 GHz with 1 watt CW outpput at 30 dB gain. In a second example (20), the frequency band was 35.7 to 37.2 GHz with 100 milliwatts at 30 dB gain.

The amplifier and oscillator applications discussed above do not rely on the presence of traveling domain, although the conditions for domain motions determine the frequency limitation of oscullator application. Some logic devices using the transferred electron effect, however, make explicit use of the presence of mature traveling domains. To understand one particular application it is necessary to refer to Figure 1 and recall that when a device is operating as Gunn originally showed, the value of current is lowest when the domain is away from the cathod contact and is traveling toward the anode. (Flat portion of Figure 1). The current is highest when the dipole layer is being nucleated or extinguished (spikes of Figure 1). If we can imagine a situation where the battery voltage is just below that required to nucleate a domain then the current level in the device is approximately equal to the peak current associated with the spike of Figure 1. Then if a voltage pulse of finite time duration is applied to the anode contact, a domain would necleate and there would be a drop in current. The current would remain at the low value until it was extinguished at the anode contact at which time the current would rise to its original value. After domain transit and extinction the current remains constant at its high value until a new voltage pulse appears. The device acts as a "monostable multivibrator" (21).

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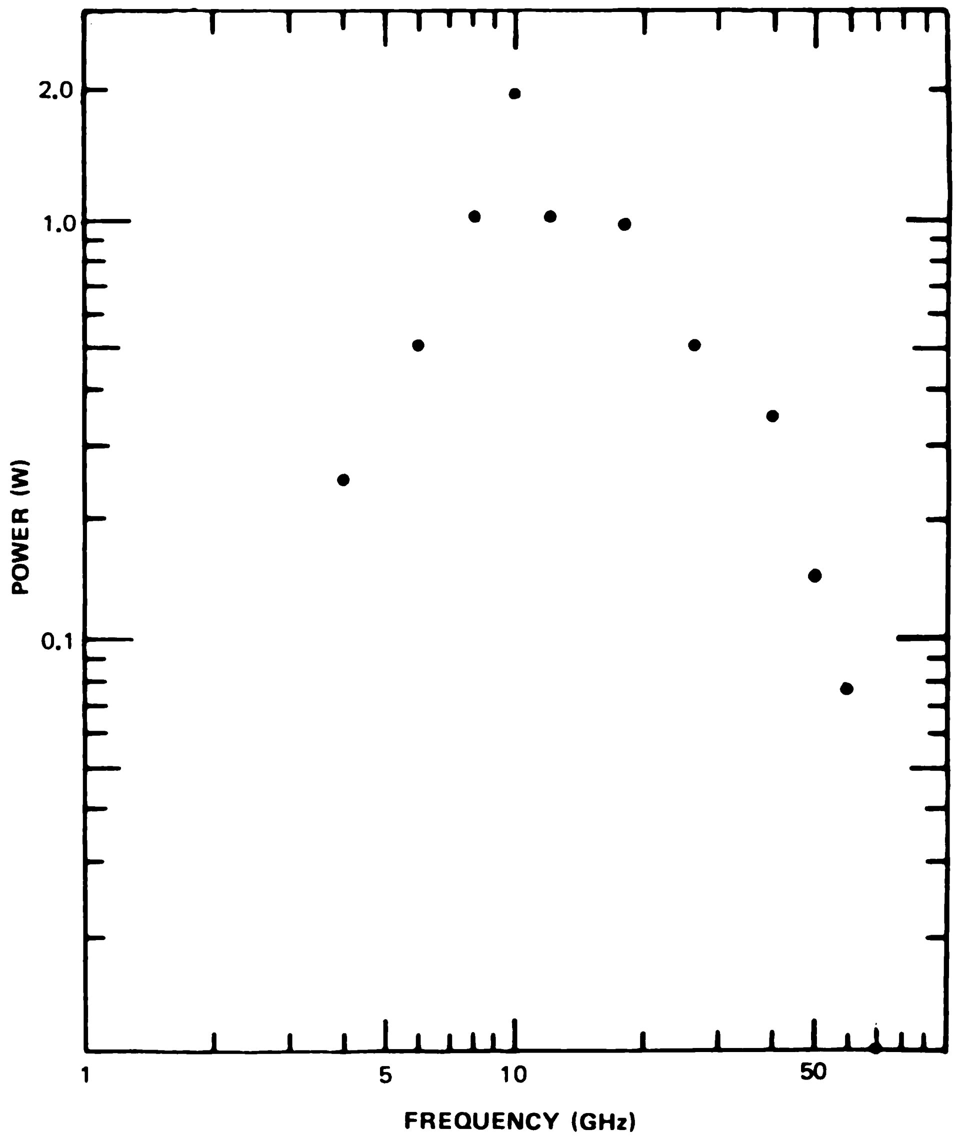

Figure 7 — Commercially available or state of the art power output continuous wave CW transferred electron device oscillators as of 1974. From Ref. 18, with permission. The diode manufactures are identified in Ref. 18.

The discussion above has concentrated on two-terminal transferred electron devices utilizing gallium arsenide. There are other two-terminal devices, avalanche devices, that make use of gallium arsenside as the principle semiconductor, but whose operation is not primarily dependent on the transferred electron effect. Three-terminal devices such as the field effect transistor sometimes use gallium arsenide, but they are also not dependent on the properties of the transferred electron effect for their operation.

While currently the semiconductor gallium arsenide is the material receiving the most attention, it is by no means the only material exhibiting electron transfer and negative differential mobility. Indium phosphide is another material, and its ability to convert dc to ac power was

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reported by Gunn in 1964 (9). Today indium phosphide is the second most actively studied transferred electron semiconductor. Other materials such as gallium-aluminum-arsenide and indium-gallium-arsenide-phosphide are also transferred electron semiconductors with microwave device potential, and are currently being studied. Each of these and other transferred electron semiconductors has a different and unique feature that makes one more suitable than another for a particular device application. One can envision a future capability where one can design a transferred electron semiconductor to meet the requirements of a particular microwave device application.

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Sun Tracking System

To operate solar refrigerators, air conditioners and cooking facilities of the future, effective concentrating collectors must be repositioned accurately and constantly throughout the day as they follow the sun and harness solar energy.

An integral component of such collecting systems is a tracking device which determines the sun's position and, in turn, repositions the collectors to maintain maximum solar exposure.

Currently used electrical tracking devices have not proven generally economical or practical. With those limitations in mind, the Civil Engineering Laboratory (CEL), Naval Construction Battalion Center, Port Hueneme, Calif., is developing a simple, solar-powered fluid mechanical tracking device that accurately tracks the sun to within one degree. The inexpensive and reliable system does not require electricity for power.

Dr. Carter Ward, CEL research mechanical engineer who invented the new concept, said such a tracker is needed to drive concentrating (rotating) collectors to heat fluids to temperatures significantly in excess of 200°F to operate solar refrigerators, air conditioners, and cooking facilities.

Flat plate collectors are commonly used for space heating and domestic hot water, but they are not capable of economically producing temperatures beyond the 160°-200°F range. Consequently, concentrating collectors (300°-600°F for residential use) are needed. These collectors have the added burden of accurately maintaining the reflective surface towards the sun to obtain the high temperature. Equally important, the CEL tracking device will be needed to drive large numbers of individual solar reflectors to power future solar electrical generating plants which require 600°-1,000°F temperatures.

Dr. Ward said electrical trackers are not durable nor reliable in an outdoor environment. Their delicate instrumentation simply falls victim to dust, rain, temperature extremes, humidity, and corrosion.

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Solar powered control systems do not require electrical power. They are expected to be trouble free and easy to maintain because the hardware is simple and all mechanical. Essentially, the sensor acts as a shade-seeking device, balancing its driving force (caused from an heliotropic fluid vapor pressure or a bimetallic expansion) against a spring or suspended weight.

To date, only one known solar tracking device has been tested. Although workable, several basic problems hinder operation of the mechanism. The device responds slowly to the morning sun. It also lags the sun's position in the morning hours and leads the sun's position in the afternoon hours. Excessive friction in the power cylinders and gear drive also hindered the device's positional accuracy. Average deviation is 4.86 degrees.

The CEL tracker will eliminate such problems. The drive mechanism consists of a four-bar linkage powered by an expansion bellows. The mechanism does not include gears or high-friction sliding devices. The fluid system is completely enclosed to protect the heliotropic fluid, Freon-II, from contamination. Instead of using opposing cylinders, a single drive mechanism is used to oppose a spring (bellows). This ensures that the tracking device is repositioned by the nighttime cooling, so as to face the east in the morning. The tracker will have a good response in the morning because little sunlight energy is required for early positioning. Only small displacements are needed to follow the sun's movement.

High accuracy is expected from the Laboratory tracking system. Filter plates are dimensioned (height vs. spacing) so that no direct sunlight is transmitted for angles greater than ± one half degree from the angle normal to the sun's rays. Angular position is controlled by the heliotropic fluid temperature. For sun ray angles less than desirable (relative to the tracker) the sun's rays are blocked totally from the heliotropic fluid collector surface and the fluid temperature will fall to ambient temperature. At 75°F, Freon-II vapor pressure is only 0.037 psi above atmosphere pressure. This will cause the bellows (spring) to rotate the tracking system in a direction toward the sun. The rotation will continue until the sun's rays pass through the filter and heat the fluid.

The system is configured so that only four minutes are required to heat the heliotropic fluid system from 75°F to 120°F. It takes four minutes for the sun's angle to change one degree. At 120°F there is more than enough vapor pressure to rotate the tracking system to its maximum western angle position.

When light friction or clouds are encountered, which tend to position the tracker behind the sun, the heliotropic fluid collector will become exposed totally to the sun through a side window, much as a flat plate collector. The solar heated Freon-II vapor pressure should be more than adequate to quickly reposition the sensor properly.

In addition to anticipated superb accuracy, the CEL tracker expects high torque capability for angular position control. The bellows selected will have a 23 inch effective pressure area with which to push. For a 20 psi vapor pressure, a rotational torque of 300 ft-lb will be available.

A half-scale mockup of the proposed tracking system has been constructed. Dr. Ward said a working full size experimental mode (16" × 6" × 8" and weighing 20 pounds) will be tested at CEL this summer to prove the concept's working principle and accuracy.

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Research Notes

Night Vision Systems

Logs floating in the water, unexpected reefs, large marine mammals and fish, buoys and various debris are often difficult to see in the dark and make night-time operations hazardous for fast ships, such as Navy hydrofoils, surface effect vehicles and planing craft.

Charles K. Borough of the Naval Ocean Systems Center, San Diego presented in a recent report some recommendations to improve night vision systems aboard Navy Hydrofoils. The improvements will make it possible for the helmsman to see night-time hazards that generally present very low constrast against the water, will permit a better tradeoff between field of view and resolution, will give better operator perspective of hazards in context with the ship's course during maneuvers, and at the same time will improve the cost/performance tradeoff.

Tests indicate that an active low-light-level television is the most promising viewing system for hazard avoidance. The recommended improvments are inexpensive and greatly reduce logistics problems that have been a shortcoming of more expensive and complex systems.

Active low-light-level television systems incorporate an illuminator to provide supplemental illumination. In the past, the more successful of these active systems have used laser illuminators with complex gating networks and requirements for extensive cryogenic cooling. Less successful systems have used continuous wave illuminators without gating and have incorporated horizontal or vertical separation of the camera and the illuminator, with both aimed to cover the same field of view. The new geometry has the illuminator mounted as low as possible and the camera as high as possible (vertical spatial separation), but the two are not aimed to cover the same field of view. Instead, the illuminator is aimed low, such that the top of its field of view intersects the water at the farthest target area of interest. The camera is aimed higher, such that the bottom of its field of view intersects the water at the nearest target area of interest. This results in the two fields of view intersecting only in the target area of interest, and backscatter is thereby greatly reduced. This geometry was tested at sea aboard USS Pegasus (PHM 1), first of the new class of patrol missile hydrofoils. Contrast was extremely high between the floating targets and the sea. Three illuminators have been fabricated at NOSC and will be used with a camera recently purchased for installation aboard USS Pegasus. The illuminators are filtered to pass only infrared illumination.

One of the improvements recommended in the report is a servo loop between the camera and the ship's helm, so that when the ship turns, the camera turns to more fully cover the path through which the ship will travel. This allows the use of a relatively narrow field of view lens (with its better resolution) while always covering the area of maximum importance.

It is often difficult to tell whether or not an obstacle is on a collision course, particularly when it is at some distance, and the ship is in a turn maneuver. The obstacle may appear on the right side of the television display and yet be far to the left of the path the ship will follow in the turn. It may also appear to be in a safe position and actually be directly on a collision course.

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It would be an advantage to have a representation on the display of the course the ship is steering, which would be understood as the "roadway" of the vessel. This could be accomplished by means of two lines on the display. The lines appear as an inverted "V", coming to a point at the horizon if the ship is steering straight ahead. The ship will travel directly between these two lines if it maintains a straight course. If a floating object appears between these two lines, it is on a collision course. The lines that form the roadway bend automatically in the direction and in proportion to the sharpness of turn maneuvers. There is always an outline of the water path ahead through which the ship is presently steering. The lines are electronically defined and generated and then added to the video information coming from the camera.

New Fiber Optic Sensing Device

Dr. Joseph A. Bucaro, principal investigator at the Naval Research Laboratory in the development of this new fiber optic device for sensing underwater sound, peers intently at the glowing assembly, which is powered by an argon laser.

This prototype of a fiber optic hydrophone, in which a light beam is modulated in an optical fiber by means of an acoustic field, was designed by Dr. Bucaro and Professor Edward Carome of John Carroll University, Cleveland, Ohio. Its primary element is composed of 50 turns of a fiber optic strand coiled to form the small loop.

NRL is now managing a joint Defense Advanced Research Projects Agency-Navy program to demonstrate the feasibility of a complete Fiber Optic Sonar System (FOSS) based on this technology.

Dr. Thomas G. Giallorenzi, whose Optical Techniques Branch at NRL furnished data for the development of the new hydrophone, says other sensors under consideration include fiber optic motion sensors or gyros, magnetic field detectors and covert intruder controls in surveillance systems. This project is partially funded by the Office of Naval Research.

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Editor: WILLIAM J. LESCURE NAVSO P-510

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Cover Caption

The launching of a remote sensor buoy with an array of hydrophones dangling from the bottom. Inside is an electronic package which telemeters the acoustic signals back to the ship for recording. (See page 11).

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