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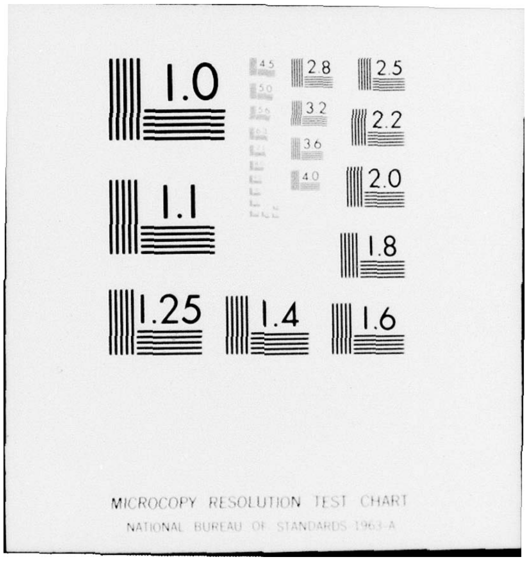
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SONAR SIGNAL PROCESSING

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SONAR SIGNAL PROCESSING*

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Introduction

15 Nonr-2216(05)

It is the intent of this paper to outline the philosophy which undergirds the field of signal processing as it relates to instrumentation in underwater acoustics and in particular to the most prevalent application of underwater acoustics, sonar. The term signal processing as used here refers to the real time transformations carried out in sonar equipments to maximize the performance of the equipment within the limitations imposed by the ocean and its boundaries. Emphasis is placed on the limitation of the ocean and the influence of these limitations on equipment design rather than on a detailed description of the signal processing instrumentation which has been developed over the past several years.

Sonar Compared to Radar

In order to emphasize some of the more important limiting factors of the ocean and its boundaries it is helpful to make a comparison with the companion field of radar. Although these two fields, at first thought, appear to be conceptually identical, the differences are important and introduce variations in the signal processing techniques of the two fields.

The primary common objective of both fields is that of echo-ranging. In the echo-ranging problem one is dealing with wave propagation in the medium and is concerned with the boundary value problem established by the physical relationship of the medium, the source and the target. For both cases the limitation in detection capability is the spurious background energy against which the target must be identified.

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Although this general statement of the problem is equally applicable to both sonar and radar, the differences in the detailed description of the problem have a greater or lesser influence on the signal processing of the two fields.

The electromagnetic field is a vector field as contrasted with the scalar acoustic field; however, this difference introduces only minor differences in signal processing techniques.

Transducers, converting acoustic energy to electrical energy, and vice versa, must be incorporated in sonar systems whereas antennas which couple electromagnetic energy directly into the medium may be used in radar. This difference again introduces only minor variations in signal processing techniques.

The most obvious difference in the wave propagation is the velocity of propagation where a difference of a factor of approximately 2×10^5 exists. This difference is reflected as a gross change in operating frequency and in travel time for an echo-ranging pulse.

The boundary conditions for the two cases are also appreciably different. In most radar work the atmosphere may be treated as a semi-infinite space with ground acting as an absorbing or scattering boundary. The ocean, on the other hand, must be considered as a layered space bounded by the surface and the bottom. The surface is a pressure release boundary which acts as a nearly plane perfect reflector, perturbed by surface wave action, while the bottom presents a physically complex boundary, the acoustical properties of which are difficult to predict in other than a statistical fashion.

A striking difference between the two fields occurs in the effect of the refractive index of the medium on the propagation paths. Traditionally the radar problem has ignored the refractive index of the atmosphere with perhaps the exception of extremely long-range equipment, whereas the field of sonar has always been plagued with strong refraction caused by the stratified thermal structure in the ocean and, as a matter of fact, in the majority of cases this refraction is the limiting factor in sonar performance.

The atmosphere and the ocean also differ in their power handling ability. The power limit of the two media in watts/sq cm are shown in Figure 1. In both cases, the power limit, which is established by the

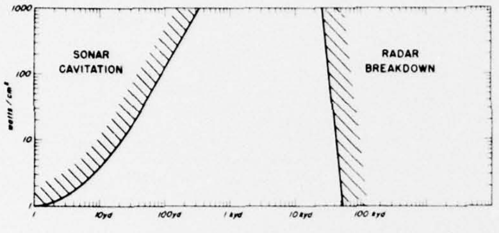

Figure 1.

electrical breakdown of the air for radar and the cavitation breakdown of the water for sonar, is dependent upon the distance from sea level. As can be seen, the power limitation of the earth's atmosphere is unimportant except for high altitudes in the case of radar. On the other hand, the cavitation threshold in the ocean imposes a severe limitation near the surface for sonar and is strongly dependent upon depth. The cavitation limit is one of the important factors which determines the size of an electroacoustic projecting transducer.

Two other factors of importance are frequency dependent, the attenuation of the medium and the background noise in which the system must operate. The interaction of the frequency dependent factors with the physical size of the transducer or antenna leads to the selection of an operating frequency. This selection is not a simple optimization process and thus a large variety of system configurations are in existence.

The practical selection of operating frequency for both radar and sonar operations is keyed to the physical size of the platform from which the equipment must operate. For portable equipment, carried by a man, the dimensions must be of the order of a foot. For vehicle-mounted equipment, such as a plane or ship, equipments may have a physical size of the order of magnitude of 1 to 10 feet. Moving into fixed land-based equipment, or large ship-mounted structures, the dimensions may increase to 10 to 100 feet, and finally, in systems designed to match the terrain, dimensions will be of the order of magnitude of 100 to 1000 feet. Of course, the physical dimensions by themselves are not sufficient to establish the operating frequency unless the required directional characteristics are brought into play. In general the beamwidths which are considered to be useful will range from 10 degrees to 0.1 degree, calling for a diameter-to-wavelength ratio falling between 5 and 500. The combination of the physical size and the required directional characteristics then fixes the wavelength region of interest as falling from 0.1 cm to 10^4 cm.

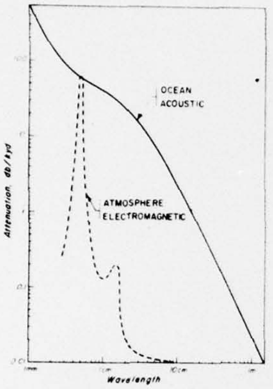

Figure 2.

Within these above limitations the attenuation and background noise combine to provide an optimization for the operating frequency. Attenuation in both radar and sonar is shown in Figure 2. Over most of the region of interest, from a few cm up in wavelength, the atmospheric attenuation for the electromagnetic case is essentially negligible in contrast to the very high attenuation for the acoustic energy in the ocean. In view of this, the influence of attenuation on the selection of frequency is considerably more important for the acoustic case than for the electromagnetic case.

The background against which the system must detect a signal is the masking, undesired, power appearing at the output of the receiver. This background is conventionally separated into three components: Receiver noise, or the random power output generated within the receiving system usually at the input stage, medium noise which is the amplified noise power appearing at the output of the receiving antenna or transducer in the absence of a radiated echo-ranging pulse, and reverberation or clutter, defined as the power appearing at the output of the receiving antenna or transducer which is dependent upon the energy of the radiated echo-ranging pulse.

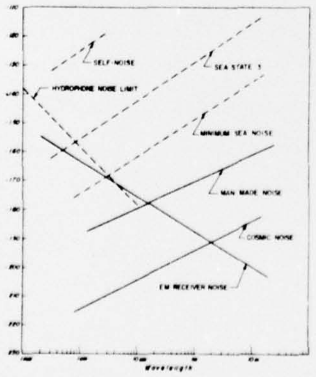

Figure 3.

The relation of receiver noise to frequency is illustrated by Figure 3. The electromagnetic and acoustic noise characteristics shown in this figure invoke some rather gross assumptions and must be taken as indicating general characteristics rather than basic equipment design data. In the region of a few centimeters the input noise of a receiver matched to a dipole exceeds the inherent electromagnetic background noise of the atmosphere whereas the input noise of a receiver matched to a hydrophone is less than the acoustic background noise of the ocean even for the minimum or "zero sea state" noise.

The reverberation background against which the system must operate is determined by the scattering coefficients of the medium or boundaries involved in the propagation path. The returned energy is dependent upon the pulse length of the transmission, the scattering cross-section and the area insonified which is a function of both the beamwidth of the transducer or antenna and the range at which the scattering occurs. Scattering from a surface will have a different range dependence than will scattering from a volume. Neglecting transmission anomalies such as attenuation and refraction, the energy returned from surface scattering falls off as $1/R^3$, the scattered return from volume scattering falls off at $1/R^2$ while the signal energy returned from a target of constant cross-section falls off at $1/R^4$. In general, the surface scattering is a near-in or short range effect compared to the volume scattering where it occurs. A comparison of volume scattering coefficients is given in Figure 4. The normal range of acoustic scattering coefficient in the upper 500 feet of the ocean is not strongly frequency dependent. Higher scattering coefficients are observed at the depth of the deep scattering layer. The electromagnetic scattering coefficient for heavy rain and light rain are shown for comparison. These fall off as $1/\lambda^4$ and for wavelengths much above 10 cm become unimportant in comparison to the equivalent scattering coefficient which would be associated with a 1 square meter target at 10 km, a beamwidth of 10° x 10° and a pulse length of 10 meters.

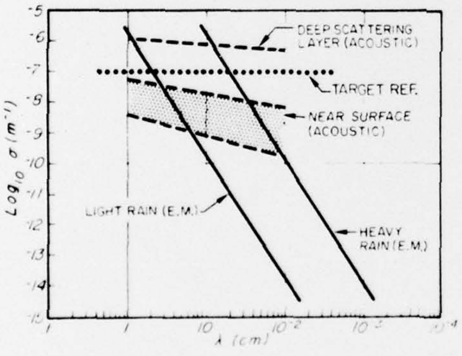

Figure 4.

In the electromagnetic case, with proper choice of wavelength, volume scattering is not a serious limitation in the performance of the radar, whereas the volume scattering coefficient for acoustic energy in the ocean is quite high and is a major limiting factor in the performance of sonar detection devices.

The important differences between sonar and radar which influence the approach to signal processing may be summarized as follows:

1. The acoustic velocity of propagation is much lower, introducing gross differences in travel time and in operating frequency.
2. The acoustic attenuation is higher and strongly frequency dependent.
3. The acoustic power limit of the ocean is relatively low.
4. Sonar is limited by the noise and reverberation associated with the medium rather than by the self-noise of the input stage of receiver electronics.

Methods of Sonar Signal Processing

There are two basic functions to be performed by the signal processing equipment of an echo-ranging system. These may be divided conveniently into spatial processing, or beamforming, and temporal, or time-series processing. For both of these, consideration must be given to the interaction of the spatial distribution of the transducers and target and the time-series associated with the transmitted pulse waveform.

At this point we find an interesting divergence of philosophy in the approach to the spatial signal processing of radar and sonar. In both cases, a directional receiver is required; however, in the radar case the power gain of a directional antenna is used to increase the signal level and thus provide an improvement over the circuit noise limitations of the system while in the case of sonar, either the medium noise or reverberation is invariably the limiting background of a properly designed system and thus the noise rejection of a directional receiver gives rise to a signal-to-noise improvement.

In order to achieve high power gain, an effective receiving radar antenna must be tightly coupled to the medium so as to extract maximum power from the incident electromagnetic wave, and therefore it will also serve as a good transmitting antenna. On the other hand, it is not necessary to tightly couple a hydrophone receiver to the medium inasmuch as the acoustic noise power of the medium is considerably higher than that required to overcome the amplifier noise of the receiving electronics. Therefore, it does not necessarily follow that a good sonar receiver is also a good sonar projector. As a matter of fact, in many instances, separate receiving and projecting transducers may be used to good advantage in sonar. The design of the projecting transducer is not commonly considered as a method of signal processing; rather, the operating frequency and bandwidth, the beam pattern, and the power handling capacity of the projector are introduced as limiting factors in the sonar design in the same light as the limitations of the medium.

The basic beamforming process as related to the receiver is concerned with the treatment of spatially separated samples of the acoustic field obtained from an array of transducer elements. In general, these samples must be treated by a process of time delay and summation. The time delays associated with beamforming lie in the millisecond region and the frequencies of the carriers involved are generally restricted to the region of a few kilocycles. The time delays required for beamforming will correspond to the dimensions of the array and will range from 5 to 500 wavelengths. This amount of time delay is small compared to the two-way travel time to the target. Neither the time delay nor the frequencies involved are limited to any extent by the component state of the art and thus one finds a remarkable flexibility in the techniques which can be used to carry out the beamforming process.

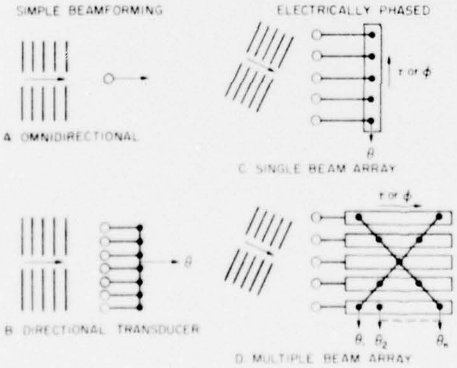

Figure 5.

The various beamforming methods may be listed in order of sophistication as shown in Figure 5. The basic omnidirectional transducer element, A, is devoid of any spatial signal processing, yeilding but a single spatial sample of the acoustic field. A number of these basic elements may be combined in a plane array. In this configuration no time delays are introduced in the element outputs, all elements are merely summed into a common electrical connection.

A further flexibility in the beamforming process is achieved by the introduction of a delay line for electrical time delay, as shown in C. The simplest configuration is one in which the individual signals from an array of elements are introduced into the appropriate taps of an electrical delay line so that the signals which arrive from a particular direction and are time delayed by their associated travel time across the aperture will be superimposed in phase at the output of the delay line. In this case the array elements are usually arranged in a regular geometric configuration in a plane so as to facilitate switching the time delay tap connections to permit steering of the electrically phased beam to different directions.

The beamforming process reaches its ultimate complexity when the number of delay lines is increased as shown in D and multiple electrically formed beams are simultaneously available. In this instance the arrays may take on arbitrary configurations in three dimensions and the preformed beams may cover both azimuth and elevation. The essential requirement of this last beamforming process is memory or time delay equipment which will provide a complete set of incremental time delays in a form suitable for combination in a beamforming matrix.

The temporal processing methods treat the waveform of the received signal and noise in order to provide maximum discrimination between the signal and the background. The various techniques of temporal processing may also be listed in order of increasing sophistication.

A. Spectrum or Energy Filtering
B. A + Post Detection Averaging
C. B + Multiple Sweep Energy Summation
D. A + Cross-correlation with a Reference Waveform
E. Multiple Sweep Energy Summation.

Although one could readily take exception to this list, it does implicity cover the range of methods used for temporal processing in sonar.

The first three are employed with simple "ping" sonars in which a single frequency carrier pulse is transmitted. When long, single frequency pulses are transmitted, the doppler shift caused by relative target motion can permit separation of the echo from a background of reverberation by simple narrow band spectrum filtering.

The latter two methods, B and E, pertain to the more recent member of the temporal processing fraternity, correlation or matched filtering. This is the most complex of the temporal processing methods and requires a memory in which that portion of the received waveform to be processed may be stored in such a manner that it may be compared with a reference waveform for all time delays within the range of interest. This time delay analysis of the correlation method is thus a convolution process and requires a considerably greater memory capacity and information rate than is called for in beamforming.

A variation of the correlation processing may be made with special waveforms such as a frequency modulated waveform which permits the transformation of time delay into the frequency domain where spectrum analysis may be used instead of the time delay analysis of true correlation. The FM processing predates true correlation processing by many years, having appeared in sonar equipment in World War II.

Medium and Methods

Having outlined the limitation of the medium and the methods of signal processing it now remains to discuss the influence of one on the other. The relatively slow velocity of propagation has been an important factor in the development of spatial processing techniques. With round-trip travel times which may be of the order of minutes for long range sonar systems it has become necessary to turn to the use of multiple beam processing so that a well resolved search in bearing may be carried out in a reasonable length of time. The high noise background in the ocean places a premium on the generation of large amounts of acoustics energy. In order to meet the requirement and still operate within the severe limitations on peak acoustic power imposed by the medium it has been necessary to employ the transmission of long peak-power limited pulses. Of course, the use of long pulses increases the zone of insonification so that reverberation becomes the limiting factor. In order to offset this increased reverberation energy it is necessary to retain a high degree of resolution in range by the use of broad band (0.25 to 0.5 octaves) waveforms in the transmitted pulse and the introduction of the correlation methods of signal processing. In this way both range and doppler resolution may be utilized to discriminate against the reverberation background while retaining the long pulse lengths required for maximum acoustic energy to overcome the noise background.

In general it can be stated that the sonar signal processing methods have been exploited to the maximum extent allowable by the limitation of coherence time in the ocean and the limitations of the technological state of the art. Nearly every known or conceivable memory device has been used or considered for use in sonar signal processing. The relatively low operating frequency of sonar equipment has permitted the use of memory equipment built with storage media such as electromagnetic delay lines, magnetic recording, dielectric recording, photographic film, digital computer components such as shift registers, magnetic core matrices, electrostatic storage tubes and ultrasonic delay line memories. The requirement for the use of long pulses having large time bandwidth products of the order of 10^3 or greater has justified the use of these later digital processing techniques which can operate effectively on clipped polarity samples of the acoustic waveforms and provide practical instrumentation for performing the involved transformations required for signal processing. The introduction of time compression techniques has shifted the kilocycle operating frequencies of sonar into the megacycle region so that full advantage may be taken of high speed computer logic in the signal processing equipment.

These various memory techniques have given rise to a myriad of instruments for both the spatial and temporal signal processing applications. The field of sonar signal processing has had a voracious appetite for the latest developments in component technology and it will continue to be a fertile field for the application of new component developments in years to come.