Development of a Multichannel Optical Correlation Detector for Sonar Signals

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The principle of operation and the theoretical fundamentals of the "Barber Pole" optical correlation detector are reviewed. This correlator, which may be classified as a noncoherent optical correlation detector of the stored reference type, performs real-time correlation of multiple delayed signals with a stored reference without requiring a prior knowledge of the signal delays. The use of real-time integration in the correlator makes it possible to avoid the usual step of recording received signals on film prior to correlation with the reference. The results obtained with the first model of this correlator are reviewed briefly. A description is then given of the new multichannel model that is being developed presently. The design features described are the optical layout for multichannel operation, the high-resolution transistorized vidicon system for scanning out the correlation function, and the modular nature of the equipment. Doppler compensation methods are discussed briefly. An example is given to show how the correlator can be used to simultaneously process the multiple preformed beam outputs of a sonar array. The paper is terminated with a list of potential ocean system applications.

Introduction and Review of Previous Work

THE optical correlation detector described here has been designed to correlate audio signals, of roughly 1-sec duration, with a noise-free, photographically stored reference signal. Correlation is carried out in real time without recording the received signal on film. When the correlator is used as an active sonar signal processor, its operations consist of providing an electrical version of the stored reference signal to the sonar transmitter and of correlating received acoustic echo signals having unknown multiple delays with the reference signal. An experimental version of the correlator has been built and operated in the laboratory. Results of this work are reported in Ref. 1. A brief review of previous work will be given here in order to provide background material needed for understanding the operation of the new development model correlator.

The principle of the correlator can be understood by referring to Fig. 1, which shows the basic elements. These consist of a moving photographic record, a light-beam intensity modulator (light valve), and vidicon tube. The reference signal recording is done in two dimensions to introduce a continuous range of reference signal delay. In Fig. 1 it is seen that the time-varying photographic transmission observed at a point on the y axis of the fixed coordinate system is the analog of the reference signal. At a different point on the y axis the same photographic transmission function is observed, but it is delayed in time because of the slant of the recording. At any point $y = gG\tau$ (where G is the record translational velocity and g is a dimensionless constant determined by the record slope), the time-varying record transmission can be represented by $a + S(t - \tau)$, where a is the photographic transmission bias $S(t)$ is the stored reference signal waveform, and τ represents the reference signal delay, which is a function of y. The reference function is converted to an electrical signal by focusing a pinpoint of light on the moving record at a given point y and by sensing the light transmitted through the record at this point with a photodetector. This readout signal is presented to the sonar transmitter for conversion to an acoustic signal. Echo signals, after being received, are used to drive the light valve. The light valve modulates the intensity of a fan-shaped light beam that illuminates the reference record along a narrow vertical line parallel to the y axis. The time-varying light intensity of the fan-shaped beam, when controlled by the amplitude of a received signal having delay α_1, can be represented by $b + K_1S(t - \alpha_1)$, where b is a light bias intensity and K_1 is an amplitude factor†. The intensity of the light transmitted at any point y along the illuminated line is the analog of the product of the reference signal (with delay corresponding to the location of the point y) and the received echo signal. The light transmitted by the moving reference record at each point y is imaged on the face of the vidicon tube. The vidicon tube serves the double purpose of integrating the light and of converting the integrated product signal into electrical form. There are four integrated product terms in the vidicon output because of the light bias and record transmission bias. The only important term is

$$R(y) = K_1 \int_{\rho y}^{\rho y + T} S(t)S[t - (\rho y - \alpha_1)]dt \qquad (1)$$

which is just the correlation function between the reference signal and echo signal. This function is represented in analog form on the vidicon tube face as exposure along a line image. The function peaks at a value of y corresponding to $\rho y = \alpha_1$, where $\rho = 1/gG$. The exposure function is converted to a time-varying electrical signal by scanning the vidicon electron beam along the line image.

The limits of integration of the product of the received and stored signals are controlled by the vidicon scanout timing. Integration proceeds for twice the reference signal duration. At the end of this time interval the correlation function (exposure function) is rapidly scanned out. The opaque portion of the record automatically adjusts the integration duration to be equal to reference signal duration at each point on the illuminated line. To provide for scanout of the correlation function without interrupting correlation of incoming signals, two fan-shaped beams are used. One is displaced along the reference record by a distance equal to the reference signal length from the other. With such an arrangement two line images are formed on the vidicon tube face. These are alter-

Submitted March 17, 1965; revision received October 21, 1965. This work was supported by the Lockheed Missiles & Space Company (LMSC) Independent Research and Development Programs. The author wishes to acknowledge the design work of W. J. Burgess and E. Cornish.

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† The signal waveform $S(t)$ is considered to remain unchanged during propagation in order to simplify the descripion of the correlator operation.

nately scanned out at times separated by the reference signal duration.

In the actual instrument the effect of the periodic reference record is obtained by wrapping one or more reference record periods around a transparent cylinder, which is caused to rotate at a constant rate. The appearance of the record cylinder has resulted in the name "Barber Pole" optical correlator. Echo signal delays are determined by noting the number of record periods which has elapsed since the signal was transmitted and by noting the locations of the correlation peaks along the y axis.

The performance characteristics of the optical correlator which are of primary interest are the signal-processing gain and the resolution of the correlation functions of two signals having a small relative delay. In the case of an ideal correlator using a reference signal having bandwidth W and duration T, the processing gain for detection of the signal is the presence of interfering noise having Gaussian statistics, and a uniform power spectral density is $2TW$. That is, the relationship between the input signal-to-noise power-ratio $(S/N)_{in}$ and the output peak signal-to-noise power-ratio $(S/N)_0$ is

$$(S/N)_0 = 2TW(S/N)_{in} \qquad (2)$$

The optical correlator cannot theoretically obtain the ideal processing gain because it is necessary to use light and photographic transmission biases in the optical operations, and because it is desirable to limit the received signal in order to keep the light bias value low.

The experimental work was done using a recording of a pseudonoise signal consisting of a binary-type optimal-length shift register sequence 511 bits in length. This signal has a triangular-shaped autocorrelation function having a base width 2 bits wide. The processing gain of the correlator (taking into account bias and limiting effects), when used with this pseudonoise signal, was theoretically determined to be 23 db. For the cylinder rotation rates used, the correlation function theoretical width was 1.5 msec.

Experimental tests were made using direct electrical connection of the reference readout signal to the receiver input where interfering noise was added. These tests showed the correlator processing gain to be 20 db as compared with the expected processing gain of 23 db. Resolution tests made with electrical delay lines showed the ability of the correlator to clearly resolve two signals of equal amplitude having a relative delay of 2 msec. Successful tests of the experimental correlator were also conducted in air over a one-way sound propagation path, although the performance was reduced because of inadequate transducer performance. The results obtained with the experimental model were encouraging enough to stimulate the development of a more versatile model. It is the purpose of this paper to describe the new model.

General Description of the New Correlator

The development work on the new model was undertaken with the goal of developing a multichannel correlator reliable enough to be taken to sea for sonar signal processing experiments. It is designed to incorporate a number of improvements over the first experimental model. These include multichannel operation, modular arrangement for increasing channel capacity, a new high-resolution vidicon tube, transistorized vidicon electronics, continuously variable cylinder rotation rate, and provision for later addition of a Doppler compensating unit. No attempt has been made to minimize the size of the equipment at this time.

The optical arrangement for multichannel operation is shown in Fig. 2. In this arrangement, a single fan-shaped beam of light intensity, modulated by the received signal, originates from an optical beam generating unit. This beam is split into two identical beams at a beam splitter. The two beams are incident on the rotating reference record at positions separated by one reference signal duration T. In the

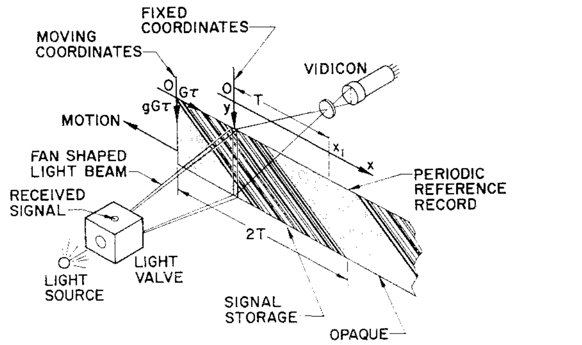

Fig. 1 Reference record and optical arrangement for correlating the received signal with the reference signal.

arrangement shown in Fig. 2, the reference record and opaque portion are each repeated four times around the cylinder. The two beams are incident on the record at locations angularly separated by 45°. The light transmitted through the rotating record is reflected by a mirror system, which causes it to pass out of the inside of the cylinder and back toward the vidicon tube. The two vertical lines of light appearing on the inside of the rotating cylinder are imaged on the vidicon tube face plate.

Additional fan-shaped light beams originating from other optical beam generating units are made to follow optical paths closely adjacent to the single channel paths shown in Fig. 2. These additional beams are made parallel by a group of narrow mirrors located near the center of the circle of optical beam generating units. These mirrors can be spaced closely at this point because the optical beams are thin here. Five beams are aligned in this manner. A sixth beam passes through the beam-aligning mirror group without reflection and goes directly to the beam splitter. The complete optical path of this beam is shown in Fig. 2. The optical paths of the other beams have been deleted beyond the beam splitter in order to avoid confusion in the drawing. The six-

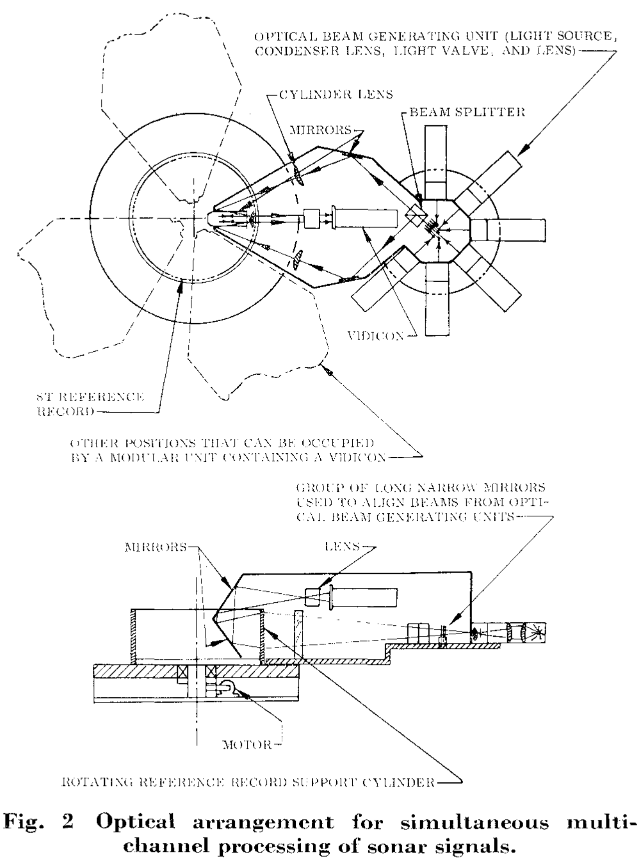

Fig. 2 Optical arrangement for simultaneous multichannel processing of sonar signals.

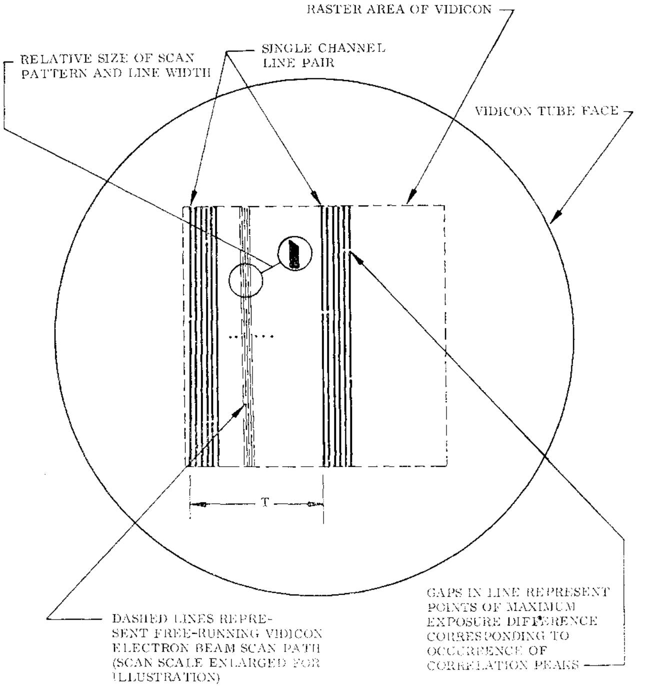

Fig. 3 Location of correlation function line pairs on vidicon tube face for multichannel operation; scan must progress from one line of a pair to the other in a time approximately equal to the signal duration *T*.

channel arrangement gives rise to the six closely spaced line pairs which are imaged on the vidicon tube face in the manner shown in Fig. 3.

The vidicon scanout pattern is chosen so that correlation function lines can be imaged anywhere in the raster area of the vidicon face and still be scanned out without synchronization and beam positioning adjustments. The scanning pattern is chosen to provide three longitudinal scans in the width of one correlation function line image. This insures that at least one complete longitudinal scan of each correlation function line will occur regardless of its location on the vidicon face. The transverse motion of the vidicon scan is synchronized with the record cylinder rotation period by means of a synchronizing pulse derived from the cylinder. Timing is not a critical factor, since a small percentage of the integration time can be lost without appreciably affecting the correlation function peak amplitude. The output signals resulting from scanout of the correlation functions corresponding to the different channel signals are filtered and put through a threshold device and are then displayed on a cathode ray oscilloscope tube face in intensity modulation form.

The multichannel correlator shown in Fig. 2 is modular in nature. Channel capacity of a basic unit can be increased from one channel to six by adding the desired number of beam generating units. (Actually, an additional layer of beam generating units could be added above the first layer, and their beams could be interleaved with the others by using additional mirrors.) When the channel capacity of one such basic unit is exhausted, other basic units can be added in the positions indicated by the dashed lines of Fig. 2.

Design Considerations and Component Selection

The important design considerations are the vidicon resolution, the vidicon illumination, the light modulator frequency response, the type of reference record, the record illumination, and the cylinder rotation rate stability. The vidicon resolution is the factor that, in practice, determines the upper limit of the correlator performance. This is because the number of points which can be resolved in scanning out the line image on the vidicon determines the useful time-bandwidth product of the reference signal, and thus the correlator processing gain. The correlation function scanout unit is designed to operate with either of two commercially available high-resolution vidicon tubes and its associated magnetic focus and deflection coils. The first tube is a $1\frac{1}{2}$-in. RCA-8521 vidicon, and the second tube is a 2-in. Machlett ML-2058G vidicon. The limiting resolution of these tubes is stated by their manufacturers to be respectively, "in excess of 1200 television lines," and "in excess of 2000 television lines." It is intended that the correlator performance will be checked using each of these tubes in turn.

The vidicon illumination in the region of the correlation peak on the line image must be large enough to satisfy the basic signal-to-noise limitation that arises from quantum fluctuations in the illuminating light. Using the signal-to-noise ratio expressions of Ref. 2 calculations indicates that the vidicon illumination should exceed 0.001 ft-candles in order to satisfy this limitation at a scanout frame rate corresponding to the maximum record cylinder rotation rate. This corresponds to a minimum vidicon exposure time of approximately 0.15 sec. The image illumination range is designed to be approximately 0.01–1.0 ft-candles. This illumination is less than that typically used in vidicon operations; however, less illumination is required because of operation at slower than normal scan rates.[3]

The light modulator bandwidth must be wide enough to pass the frequency components of the echo signal when the reference signal is transmitted with maximum bandwidth. This occurs when the reference signal is read out at maximum cylinder rotation rate. A commercially available light valve, having a frequency response from d.c. to more than 8 kc, is used for the light modulator. This light valve is a Westrex Model RA-1270, a type used for recording sound on film in the motion picture industry.

The signal stored on the reference record can be any one of a variety of types such as FM, noise, pseudonoise, or codes especially selected for their propagation properties. Previous experiments were conducted with pseudonoise signals because of their simple correlation functions.

The reference signal recording is done on Cronaflex CFM4 film. This film is a high-contrast contact film with a matte surface. Use of film with a matte surface causes the light transmitted through the film along an illuminated line to act as a secondary line source. This permits use of small diameter optical components for imaging the line on the vidicon tube. Film of this type must be illuminated and viewed at low angles of incidence because it approximates a Lambert-type light scattering surface. To insure uniform illumination along the line image, the maximum angles of record illumination and viewing are designed to be less than 6°.

The optical components need not be of especially high quality since the correlator is a noncoherent optical-type correlator. The optical components consist of one simple lens used to enlarge the beam of illumination leaving the light

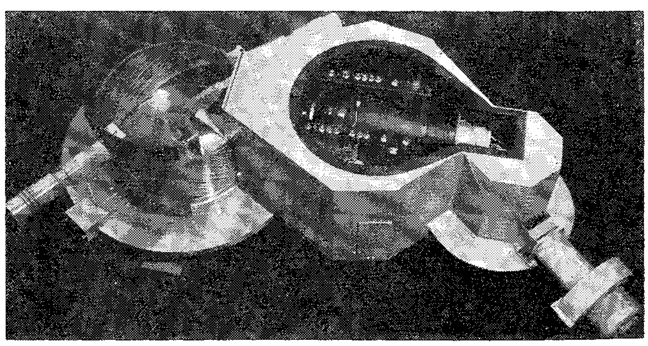

Fig. 4 Optical correlator with light-tight covers removed. Reference record cylinder (left), vidicon electronics (center), single beam generating unit (right).

valve, an inexpensive cylinder lens used to concentrate the record illumination along a sharply defined line, and an f:2, 105-mm lens used to image the secondary line sources onto the vidicon tube. For the last mentioned lens, a Komura telephoto lens was selected because it has a wide range of aperture control which is desirable for good control of the vidicon illumination.

The cylinder rotation rate stability requirement is determined by the time-bandwidth product of the signal that is stored. A variation of the cylinder rotation rate between time of signal transmission and time of echo signal reception tends to shrink or stretch the reference signal with respect to the transmitted signal. Since this is similar to a Doppler effect, the rotation rate stability requirement can be calculated using theoretical relationships between correlation function amplitude and target Doppler velocity.[4] Such calculations indicate that, with reference signal time-bandwidth products of 1000, the cylinder rotation rate should not vary more than 0.05% between time of signal transmission and signal reception in order to restrict the loss of correlation function amplitude to less than 0.6 db. This regulation requirement is in the order of the absolute regulation values found in many mechanical drives used in commercially available recording systems and poses no special problem.

Pictorial Description

Figure 4 shows the new correlator with the light-tight covers removed. The reference cylinder can be seen on the left side of the picture and part of the vidicon electronics can be seen in the center. The length of the housing is $3\frac{1}{2}$ ft. The two protruding parts on the left side of the picture are signal readout and timing optical assemblies. The protruding part on the right side of the picture is a light beam generating and modulating unit. Five additional such units can be attached against the five unoccupied flat sides of the housing, thus providing for six-channel operation. The main housing is angularly shaped so that three additional such units can be mounted around the single reference record cylinder, thus increasing the channel capacity to 24 channels.

Doppler Considerations

The effect of Doppler is to stretch or shrink the echo signal with respect to the reference signal. The Doppler effect shows up in the correlator as a movement of the instantaneous correlation peak along the correlation function line. This motion is seen easily by eye when viewing the light transmitted through the rotating reference record under conditions where the correlator input signal is derived from a tape recorder playing the transmitted signal back at a speed a little faster or slower than the recording speed. The motion of the correlation point smears the exposure along the line imaged on the vidicon tube. This causes a reduction in peak exposure and, hence, a reduction in peak electrical output signal associated with the correlation function maximum.

The exposure function appearing on the vidicon tube face can be written as

$$R(y, \alpha) = K \int_{\rho y}^{\rho y + T} S(t - \rho y) S(t - \alpha) dt \tag{3}$$

where three other terms consisting of a d.c. bias term and two self-noise terms have been neglected. A Doppler shift in the received signal caused by a relative motion between target and receiver can be introduced in expression (3) by letting the delay parameter α be a function of time. In particular, $\alpha(t)$ can be represented by

$$\alpha(t) = \alpha_0 \pm 2vt'/c \tag{4}$$

where v is target velocity, c signal propagation velocity, and t' the time measured from the start of the integration period. Then

$$R[y, \alpha(t)] = K \int_{\rho y}^{\rho y + T} S(t - \rho y) S\left(t - \alpha_0 \mp \frac{2vt'}{c}\right) dt \tag{5}$$

As t' increases from the initial matching time, the received and reference signals gradually get out of match. This effect can be compensated by making ρy vary with time so that it is always equal to $\alpha_0 \mp 2vt'/c$), in which case

$$R[y, \alpha(t)] = K \int_{\alpha_0}^{\alpha_0 \pm 2vT/c + T} S\left(t - \alpha_0 \mp \frac{2vt'}{c}\right) \times S\left(t - \alpha_0 \mp \frac{2vt'}{c}\right) dt \tag{6}$$

There are two ways of bringing this about: either ρ must vary with t', or y must vary with t'. The case requiring y to vary appears to be the easier of the two to implement in a multichannel correlator.

The variation of the observation point y with time can be accomplished in practice by introducing image motion compensation in the optical path between reference record and vidicon tube. For exact compensation, it is necessary for light leaving the moving instantaneous correlation point to be imaged at a fixed point on the vidicon tube face. This permits the exposure at the fixed point on the vidicon to grow to the maximum value that would be obtained with a stationary target and receiver. The image motion compensation has the effect of stretching or shrinking the reference record. This can be seen by referring to Fig. 5, which shows the integration paths along the reference record for zero Doppler and for positive and negative Doppler compensation. The reference record must be extended by $2vT/c\rho$ units in both the positive and negative y directions in order to insure that the compensated integration paths lie on the reference record for all possible locations of initial correlation points.

The required image motion could be imparted by placing a moving mirror in the optical path between the record and vidicon tube. This mirror would move during the integration time and would be reset at the end of each integration period. The amount of image motion compensation required is

$$\Delta y = 2gGvT/c \tag{7}$$

For a record slope $g = 1$, a record translational velocity $G = 2$ fps, a record duration $T = 0.5$ sec, a target velocity of 30 knots, and a line image magnification factor of 0.2, the motion of the line image required to stop the movement of the instantaneous correlation point would be 0.048 in.

Multiple Doppler compensation could be obtained by placing a group of mirrors, each moving at a different rate, in the optical path. In this way multiple Doppler bins (image motion compensated lines) could be simultaneously formed on the vidicon tube and scanned out as previously described The present model of the correlator does not have the Doppler compensating feature; however, it has been designed to allow easy access to the optical path between record and vidicon so that Doppler compensation experiments can be conducted at a future time.

Concept for Simultaneously Processing Preformed Multibeam Signals from Arrays

An example will be given here showing how the correlator could be used to simultaneously process the multiple preformed beam outputs of a sonar array. The reason for processing the array multiple outputs is to obtain target azimuth information. The active signal processing is considered to begin at the n-channel output of a sonar receiving array beam-forming circuit. The signals at the output of the beamformer are considered to be broadband signals, each of which represents an acoustic signal received in a narrow azimuthal increment associated with one of the n simul-

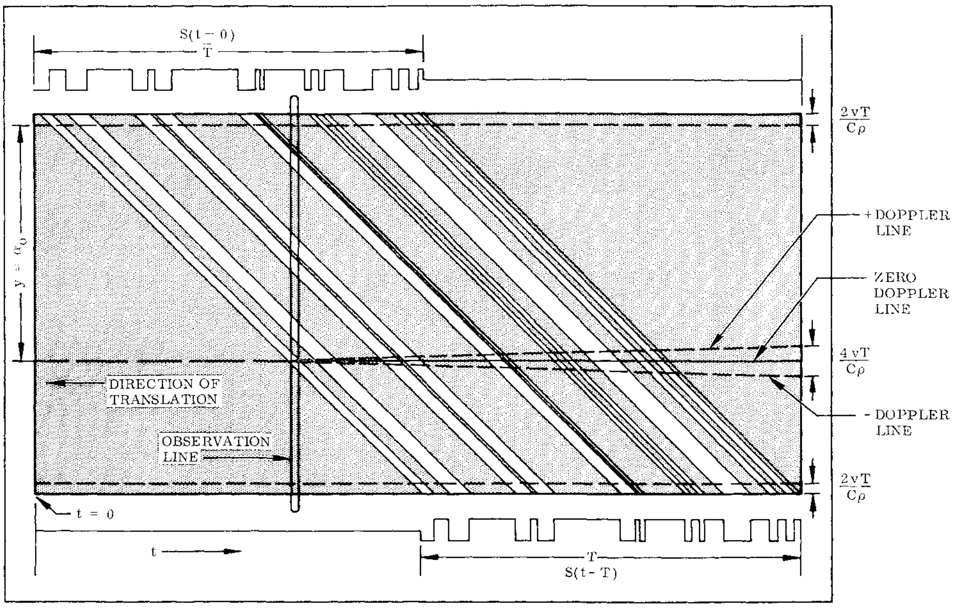

Fig. 5 Doppler compensated lines of integration along record.

taneously operating preformed beams of the array. Figure 6 is a block diagram of the receiving portion of a sonar system showing where the optical signal processing and signal presentation equipment would fit into the system. The multichannel correlation functions would be displayed in plan position indicator (P.P.I.) scan form after being scanned out by the vidicon electron beam. A P.P.I.-type presentation is indicated in Fig. 7. In this example the correlator is a 24-channel model made up of four basic units each containing six beam-generating units. The vidicon outputs after passing through a threshold circuit would be displayed as intensity modulation on a storage tube or conventional cathode ray tube. The radial sweep time of the display tube would be made equal to the time required for the vidicon beam to make one longitudinal sweep along a correlation function line. The azimuthal sweep of the display tube would operate at two different rates during the course of one 360° scan. The high rate azimuthal scan would start when the vidicon electron beam begins to scan the first line in the first group of six lines formed by the first six-channel unit. When these six lines have been scanned, the second basic-unit vidicon beam starts to scan the first line in its group of six. This process would continue until all 24 correlation-function lines in the first beam split paths have been scanned out and their information content has been displayed on the upper half of the display tube. At the end of this time interval, which might be 5% of the signal duration, the azimuthal scan rate of the display tube would be reduced to zero. After a rest period interval 5% shorter than the signal duration, the first basic-unit vidicon beam will have reached the first line in the second beam split group of six lines. At this time the azimuthal scan rate of the display tube would return to the former high rate and the information content of the second group of 24 lines would be displayed on the lower half of the display tube. The finite writing rate of display tubes makes it desirable to progressively increase the physical angular separation of the four basic units around the reference cylinder. This has the effect of equally spacing the times at which the 24 lines are successively scanned out by the four vidicon tubes. As a consequence, lines of constant range would take the form of spirals such as those shown in Fig. 7.

Results of Limited Testing at Sea

Sea tests of the new correlator were conducted at the U.S. Navy Underwater Sound Laboratory's Research Detachment (Trident facility) in Bermuda in April 1965. The experimental study had to be limited to an investigation of signal processing of narrow-band sonar signals because of the characteristics of available sonar equipment. In these tests the stored reference signal of the correlator was used to amplitude-modulate a carrier. The received signal was detected by a full-wave square law detector prior to being correlated with the stored reference signal. Successful signal processing tests were conducted on sound signals propagated one way from a bottomed projector to bottomed hydrophones located at distances of $\frac{1}{2}$ mile and 6 miles from the projector. The observed processing gains agreed with the theoretically predicted processing gains to within 3 db. Tests made over the 6-mile path showed good correlation detection for both the direct and surface-reflected propagation paths.

The tests were conducted using a single input channel. The multichannel capability of the system was in effect demonstrated by optically adjusting the position of the line images so that they were located at several different positions on the vidicon tube face during the time of the testing.

Potential Applications

The "Barber Pole" optical correlation detector has a number of general features which make it attractive for a variety of applications involving sonar signal processing. These features are as follows.

1) The signal format can be changed readily with only minor changes in the processing electronics.

2) The types of signals which can be stored as a reference signal are conventional AM pulse, FM, wideband noise, narrowband noise, and other signals of arbitrary waveform.‡

3) The correlator can be used with both base band and carrier modulated systems.

4) The parallel optical processing of signals in time has a rate advantage over serial processing of signals such as is carried out in systems using digital computers. The processing rate of the experimental single channel correlator is higher than that of a modern digital computer.

5) The optical correlator has fewer active components than has an electronic digital correlator. It is comparable in size

‡ It is also possible to make a reference record, which stores a multitude of filter impulse responses. Since the optical correlator performs a convolution operation between the input signal and the stored reference signal, the video output signal in this case represents a spectral analysis of the input signal. This feature has potential applications in passive sonar signal analysis.

now to an electronic correlator and can be made more compact in the future by using electroluminescent light modulators in place of the present light modulators, each of which contains a light valve, lamp, and optical train.

Some potential applications of the optical correlator in ocean systems are as follows.

1) Signal processor for sonobuoys: Use of correlation techniques in sonobuoy systems permits reduced average projected power while retaining high target range resolution (under conditions of fixed projected signal energy). The optical correlator is potentially capable of fulfilling the need for a simple and compact correlation detector of the type required for the processing of such signals in sonobuoys.

2) Underwater communication using waveform delay coding: Consider two optical correlators located at two stations of a communication link. Both cylinders rotate at the same rate and have the same stored reference signal. The signal can be read out photoelectrically at an arbitrary height on the transmitting cylinder, projected as a sound signal, and reconverted to an optical signal at the receiving correlator. The reception of the signal would result in a spike appearing in the video output of the receiving correlator. The polarity of the spike can be controlled by the polarity of the transmitted signal. Information can be transmitted by a combination of pulse position coding and pulse polarity coding. Synchronization of the two cylinders is not required since the information is sent in terms of pulse position and polarity and is not governed by the absolute time of signal correlation.

3) Sonar identification, friend or foe (IFF): This application is a variation on the underwater communication application. Special reference codes would be used for identifying friendly underwater vehicles.

4) Seismic signal processor for geophysical exploration of the ocean bottom: Correlation techniques are presently finding use in geophysical exploration.[5] The advantages of these techniques stem from the fact that the detectability of a reflected signal is governed by the total energy in the signal. The use of correlation detectors permits the replacement of high-power short pulse signals such as caused by explosions with low-power long duration acoustic signals. Geophysical system applications of the optical correlator are promising because its multichannel capability would be useful in handling multiple signals derived from arrays of geophones.

The optical correlator has potential applications as a research tool for experimentally investigating correlation aspects of sound propagation. Typical of the types of investigations in which it would be useful are the following.

1) Investigation of sonar target classification by correlation of reflected signals with the stored reference: A random noise sonar signal if reflected from a target will have its frequency components modified by the target shape. A long-duration signal of this type is not conveniently displayed on an oscilloscope and, if it is recorded by some means, it is difficult to interpret the information in the long spread out record. However, if the echo signal is cross-correlated with the reference signal, the resulting cross-correlation function is relatively short in duration and its shape is influenced by the spectral content of the reflected signal. An investigation of the target classification information contained in the shape of the cross-correlation function would appear to be worthwhile. The optical correlator would be a convenient experimental tool in such an investigation because the transmitted signal bandwidth and range resolution can be readily changed by varying the cylinder rotation rate.

2) Investigation of the effects of velocity dispersive sound propagation paths on correlation detection: The sea water medium by itself has negligible velocity dispersion in the range of sonar frequencies. However, when it is bounded, waveguide-like effects occur and the sound fields that propagate well (those that are compatible with the boundary conditions) tend to be velocity dispersive. It is of interest to investigate how correlation functions, appearing in the video output due to signals propagated via velocity dispersive paths, interfere with correlation functions occurring due to signals propagated over direct nondispersive propagation paths. Such information is of interest in determining the permissible interpulse spacing that can be used in correlation-type underwater communication systems.

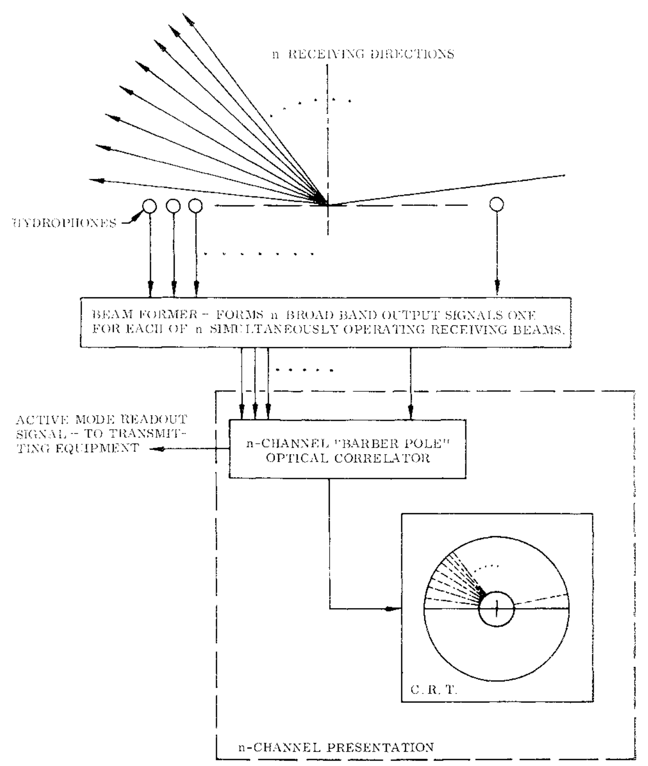

Fig. 6 Block diagram showing location of processing unit in receiving portion of sonar system.

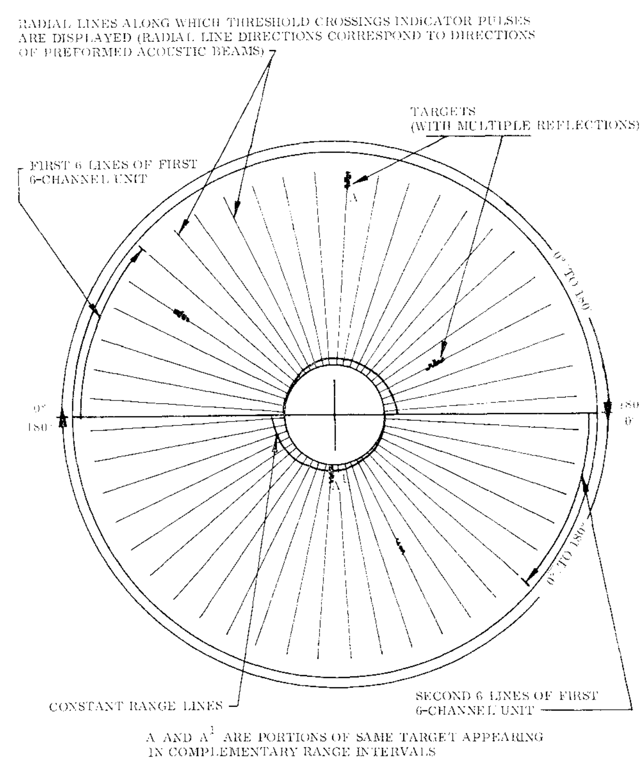

Fig. 7 P.P.I.-type presentation of multichannel optical correlator output. Maximum range on upper radial sweep coincides with minimum range on that lower radial sweep that is the extension of the upper (Doppler indication not shown).

The optical correlator would be a useful research tool in such studies.

The development work described here is still in the early stages. The eventual goal is to develop a compact simple sonar signal processing component that will be universal enough to find wide applications in marine systems of the future.

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MAY-JUNE 1966 J. AIRCRAFT VOL. 3, NO. 3

Dynamic Testing of the 80-Knot Hydrofoil Craft FRESH-1

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The FRESH-1 is a hydrofoil test craft designed to do high-speed hydrofoil research. It is thoroughly instrumented to sense and record craft motions, crew responses, engine performance, and foil force characteristics. Prior to a flight test, test maneuvers are performed on a six-degree-of-freedom analog computer simulation of FRESH-1. This allows the test time to be planned efficiently and provides predictions of the craft response for each test. All test data are recorded on an onboard magnetic tape recorder. In addition, certain critical channels of information are telemetered to a ground station where this data is displayed in the form of oscillographs and X-Y plots that can be interpreted readily by engineering specialists. A real time data reduction system allows the lift characteristics of a test foil to be presented instantaneously, as data describing the foil characteristics are obtained from testing. This system allows plots such as foil lift coefficient vs angle of attack at constant speed, foil depth, and flap angle to be displayed. Three methods of measuring the dynamic performance of hydrofoil craft have been evaluated in tests on FRESH-1: step response, frequency response by sinusoidal excitation, and frequency response by statistical correlation techniques. A comparison of the results of these methods is discussed.

Introduction

THE FRESH-1 is a hydrofoil research craft designed and built by The Boeing Company for the U. S. Navy Bureau of Ships under Contract NObs-4472. It provides a high-speed test facility for large-scale hydrofoil systems. The FRESH-1 not only measures foil hydrodynamic data, but also provides basic design information concerning the control system and operating procedures required by the test foils. An important part of the FRESH-1 test facility is an analog computer simulation of the craft, the test foils, and the control system. The simulation provides a means of predicting test craft responses and analyzing craft behavior. The purpose of this paper is to describe the FRESH-1 facility and its application to hydrofoil research and design.

Test Facilities

Craft

The FRESH-1 craft is shown in Fig. 1 during test operations on Puget Sound. The foils and struts are attached to lateral beams between the twin hulls. These beams may be positioned at several different longitudinal attachment points providing a great deal of freedom in the choice of the foil locations. Figure 1 shows the foils arranged in a conventional configuration with two foils forward and one aft. The FRESH-1 also has been operated in a "canard" configuration with one foil forward and two foils aft. Since the craft is powered by a turbofan jet, the propulsion system does not disturb the water flow around the test foils. Electrical and hydraulic power are furnished by a turbine-driven auxiliary power unit and by the main engine, respectively. Auxiliary power systems have been designed with sufficient capacity to accommodate a wide range of future hydrofoil systems. The onboard FRESH-1 data system records 84 continuous channels of information as well as 20 samples/sec of 82 other channels and 1 sample/sec of 176 pressure channels. With this large data recording capacity, a very complete record of the performance of all craft systems is maintained during all test operations. Foil performance is measured by a force balance located between the strut and the lateral beams providing a measure of the foil-strut assembly's lift, drag, and side forces. Pressure measurements also are made at critical points on the foil and strut. For a more complete description of the FRESH-1 craft, see Refs. 1–3.

Mobile Ground Station

The FRESH-1 has a crew of three and can carry one additional observer-passenger. A telemetry link between FRESH-1 and a mobile ground station allows test data to be

Presented as Preprint 65-452 at the AIAA Second Annual Meeting, San Francisco, Calif., July 26–29, 1965; submitted August 12, 1965; revision received January 10, 1966. The author wishes to acknowledge the contribution of technical material by the staff of the Advanced Marine Systems Organization, Aero-Space Division of The Boeing Company and the technical assistance of the U. S. Navy Bureau of Ships in the performance of this program.

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