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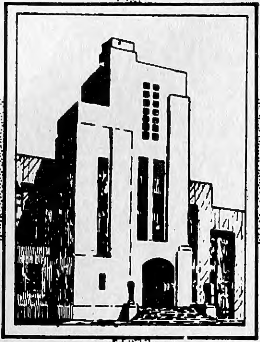

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SEADAC

THE TAYLOR MODEL BASIN SEAKEEPING DATA ANALYSIS CENTER

by

Wilbur Marks and Paul E. Strausser

HYDROMECHANICS LABORATORY

RESEARCH AND DEVELOPMENT REPORT

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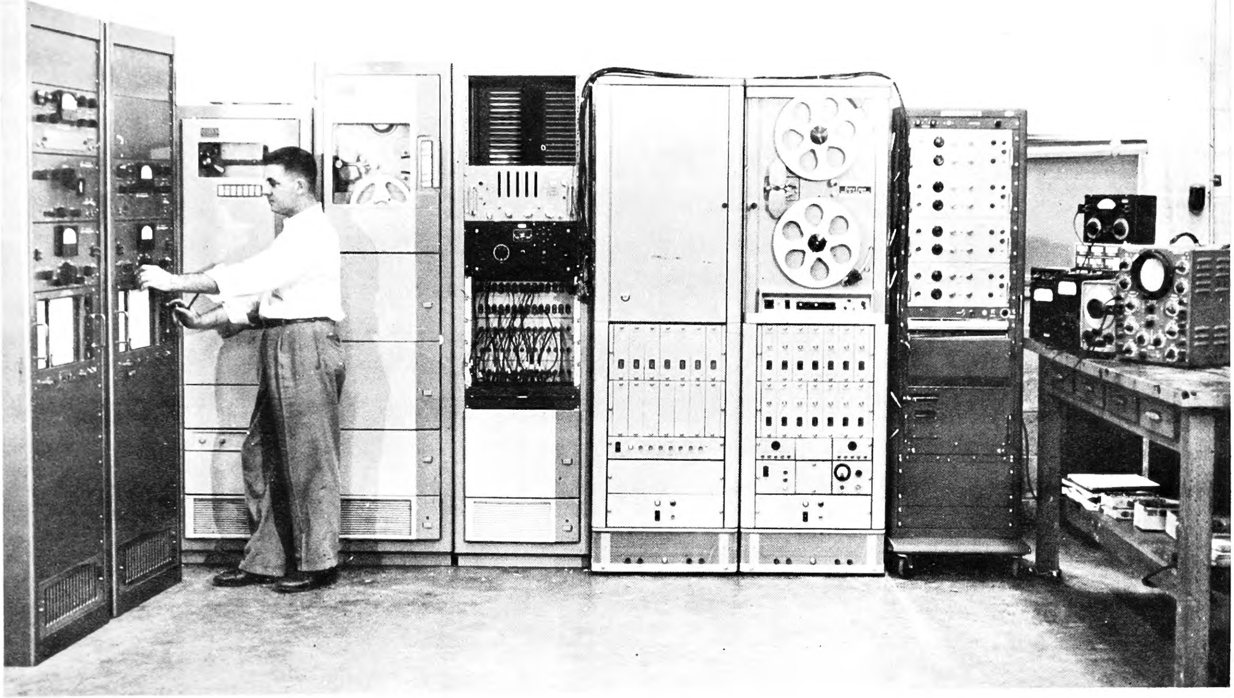
NOTATION

A	Area under SEADAC calibration curve
A_c	Amplitude of carrier signal
A_m	Amplitude of modulating signal
a	Instantaneous value of modulated signal
a_c	Instantaneous value of carrier signal
a_m	Instantaneous value of modulating signal
C_T	Transducer calibration
f	Number of degrees of freedom $(=2T\Delta f_a)$
f_a	Analysis frequency
f_t	True frequency
k	Ratio of any analysis frequency band to its length on the abscissa scale of the X-Y plot
k_a	Proportionality factor
L	Height of calibration curve
L_1	Maximum height of cumulative energy distribution
L_2	Maximum height of cumulative energy distribution calibration
m_a	Modulation index
S	Frequency multiplication factor
s_r	Recording speed
s_p	Playback speed
T	Length of time required for tape loop to make one complete passage in the loop recorder
T_e	Period of encounter
t	Time

V_{ms}	Mean square voltage
V_{rms}	Root-mean-square voltage
V_p	Peak voltage
Δf	Bandwidth of filter, cycles/sec
Δf_a	Effective bandwidth of filter
Φ	Mean total energy in spectrum
$\Phi(\omega_e)$	Spectral density
ω_c	Frequency of carrier signal
ω_m	Frequency of modulating signal
ω_e	Frequency of encounter, radians/sec



SEADAC

ABSTRACT

The Taylor Model Basin Seakeeping Data Analysis Center (SEADAC) is described. The methods for preparation, analysis, and storage of data are outlined. Confidence in the system is demonstrated by comparison of SEADAC computation of the spectral density of certain seakeeping events with numerical calculation of the same data. The limitations of the SEADAC are listed and changes that will improve the system's efficiency and extend its capabilities are suggested.

INTRODUCTION

In recent years there has been a trend toward the collection of large amounts of seakeeping data on full-scale trials. Two more sources of exceptionally large data supplies will soon appear at the Taylor Model Basin. The first is a system of automatic seakeeping instrumentation for TMB which will permit unattended quasi-continuous recording of full-scale seakeeping events for months at a time; the second is the new seakeeping facility (nearing completion) wherein much testing in irregular waves is anticipated.

Until recently, all detailed analyses of seakeeping data have been carried out by the Applied Mathematics Laboratory, on the UNIVAC I and II, and on the IBM 704. On the whole, these services have been satisfactory.

Certain deficiencies in our earlier methods of data handling became apparent, as the volume of data increased. The most obvious of these was (and still is) the expensive and time-consuming job of data preparation for input to the general purpose digital computer. The original data are displayed on chart paper from which semi-automatic readings are taken at equally spaced record intervals and transcribed onto punch cards. This information is then sent to the Applied Mathematics Laboratory where it is transferred to a digital tape for input to the general purpose digital computer. In addition to being time consuming, errors occur in reading, card punching, and computation which are often not discovered until the results are returned to the project manager. Furthermore, there is often a delay of several days in gaining access to the computer. Data preparation may be streamlined by analog to digital converters (if the original data is on analog tape), but this is an expensive undertaking and does not solve all the problems mentioned.

A more serious deficiency of the general purpose computer is that it is physically remote from the project manager. This eliminates all subjectivity in analysis. The project manager must decide, a priori, how the analysis will be made, i.e., resolution and confidence. There is no opportunity to "play" with the analyzer, to learn whether certain information (such as the occurrence of slamming), which can only be extracted from the data by changing the analysis constants during the analysis, really exists. A more direct example of the disadvantage of physical apartness of the computer and the project manager can be seen in the seakeeping facility. Model test programs often require alteration; that is, results may indicate that data are over-abundant in some areas and sparse in others. Test programs can be altered profitably, only if the results are available while the experiment is being conducted, not the next week or even the next day.

In certain operational problems, a knowledge of past history of ship motions is used to predict future behavior. This prediction is based on statistical evaluation of the time history of the event and must be made "on the spot". A special purpose computer is valuable in this regard.

It may be said that a special purpose computer has the following advantages:

1. Permits monitoring of all analysis results by the project manager.
2. Permits change of computational program, even during an analysis.
3. Assists in modifying test programs.
4. May be used aboard ship.

The special purpose computer, in this case the analog energy spectrum analyzer, is the heart of the SEADAC; the other components (tape recorder and plotter) are auxiliary equipment necessary to its performance.

This paper describes the SEADAC and is intended to be an operational guide to project managers who can only derive the maximum benefit from the SEADAC through an understanding of its philosophy and mechanics. The SEADAC is only a data handling and computational tool, and is not responsible for the quality of the results. Problems such as sampling variability, confidence bands, and stationarity of data must be resolved by the project engineer. The design of the data analysis procedure is also the responsibility of the project engineer; the material in this report will assist in formulating certain subjective decisions in this regard.

A photograph of the SEADAC appears as the frontispiece.

DESCRIPTION OF THE SEADAC

1. GENERAL

The SEADAC is associated with one specific aspect of seakeeping data reduction, that of converting time histories of random variables into some form of spectral density presentation. The basic functions of the system are summarized as follows:

1. Preparation.
2. Analysis.
3. Storage.

To get a clear general picture of the operation of the system, see Figure 1. The raw data are transmitted from the transducers (T) to the tape recorder in the field and are brought to the laboratory on reels of magnetic tape. Each reel may contain the data from many runs (experiments) and each run may comprise as many as 14 channels of information on the tape. These data are usually recorded at 1-7/8 ips (inches per second). The first operation involves playing the data back, on a reel recorder, at a speed 32 times greater than the original recorded speed (that is, 60 ips)and re-recording the sped-up signal on the loop recorder at 1-7/8 ips. At the same time, the signals on eight of the channels are recorded on 8-channel chart paper at 5 mm/sec. A second chart paper recording will be required if more than eight channels of information were recorded originally. The original data are coded so that runs are easily separated. The paper records are divided into separate runs, labeled properly for indentification, and put into a binder in the form of a book. Figure 2 shows a typical page from such a book.

After the original tape is speeded-up and re-recorded, it is divided into individual runs and each run is spliced into a loop. One loop may be inserted into the loop recorder (Figure 1) and played into the analyzer at 30 ips, a speed-up of 16 times that of the original recording of the loop. Two of the possible 14 signals are sent to the "A" and "B" analyzers, and then to their respective analog computers and X-Y plotters. The resulting graphs (amplitude density, energy density, total energy) refer to a frequency scale 512 (32 x 16) times the true frequencies in the signals. Calibration signals are put on each plot, and the graphs are given to the project engineer for statistical evaluation. The process may be repeated for each of the signals on each of the loops.

After all the data have been analyzed, the loops are placed in plastic capsules, labeled, and filed. The "book" is filed when the project engineer no longer requires visual checks.

Figure 1 illustrates some of the shortcomings of the SEADAC as it was originally assembled. When the data are being re-recorded onto the loop recorder, the analyzer is inactive; when the analyzer is active, data cannot be re-recorded. This seriously affects the time economics involved in volume data analysis. More important is the inability of the SEADAC to treat cross-spectrum analysis. A great deal of potential information is available in the simultaneous recording of seakeeping events which can only be extracted through cross-spectrum analysis. These and other improvements will be discussed in the section on the proposed extension of the SEADAC.

All SEADAC components are commercially available but the analyzer system* comprising 1) local oscillator, 2) filter networks, and 3) analog computers is relatively new and may not be well known.

2. DATA PREPARATION

The raw data are received from the transducer as an analog voltage, preamplified and frequency modulated (FM) onto 1-inch, 14-channel, 1.5-mil Mylar magnetic tape. Since the raw data will be subjected to a frequency decomposition in the filter network of the analyzer system (to be discussed), consideration must be given to the relationship between the range of frequencies in seakeeping events and electronically feasible filter networks. Seakeeping events seldom contain energy at frequencies outside the range 0.03 to 3.0 cps. Unfortunately, commercially available filters that are fairly sharply tuned are too wide to accommodate this frequency range. It is only since the recent advent of low-speed magnetic tape recording that the conventional "wave analyzer" has lent itself to use as a low-frequency analyzer. The principle is simply to bring the signal frequencies to the filter rather than the filter to the signal frequencies. This is accomplished by causing the filter to look at the time-history of the seakeeping event, not in true time, but in a highly condensed time scale. If a 20-minute record is speeded-up ten times, the record will pass through the filter system in one-tenth the recording time and the frequencies will appear to be ten times greater than they really are. Under such conditions, the "apparent" frequency range becomes

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*Instruction Booklet for TP-625 Wave Analyzer System, Technical Products Corp., Los Angeles, Calif.

0.3 to 30 cps. In practice, the speed-up is much greater. Records are made in the field at 1-7/8 ips. Through a process of playback (at 60 ips) and re-record (at 1-7/8 ips), a speed-up of 32 times is achieved. When this new signal is played through the analyzer at 30 ips, an additional speed-up of 16 times is realized. The total speed-up is 512 times true time and the apparent frequency scale of possible interest becomes 15.4 to 1540 cps. Lower recording speeds (less than 1-7/8 ips) are becoming commercially available, and it may soon be possible to do away with the re-record process in the SEADAC.

While the tape is being re-recorded on the loop recorder, it is simultaneously recorded (at 5 mm/sec) on an 8-channel Sanborn strip chart recorder (see Figure 1). This paper display (Figure 2) is not suitable for analysis but certainly illustrates what is on the tape. The information on the paper is completely described by writing in the experimental constant information, including calibrations, for each channel. In this form, the visual data may be used in deciding the proper analysis constants and will also serve as a check on analysis results, at least for orders of magnitude.

Each run constitutes a page in the "book" which is the recorded history of the experiment. A summary sheet describing the trial is attached to each book at the termination of the project, before it is filed.

The magnetic tape is likewise separated into runs and each run is spliced into a loop. A typical run which is 20 minutes in duration and 187.5 feet long (recorded at 1-7/8 ips) becomes a loop 5.86 feet long which takes 2.34 seconds (at 30 ips) to make one complete trip through the loop recorder.

It will be recalled that the probable frequency range for seakeeping data is 15.4 to 1540 cps at a speed-up of 512. Commercial filters from 2 to 20 cps are well suited for this range in terms of giving adequate resolution of the spectral density and have, as well, a fairly rectangular shape, which is desirable.

Tests in irregular waves in model tanks will often contain frequencies which are sufficiently high (depending on speed and relative heading of ship model) to obviate the necessity for re-recording. In such cases, the recorded signal is bound into a loop directly and played into the analyzer at 60 ips, providing a direct speed-up of 32.

3. DATA ANALYSIS

The data reduction portion of the SEADAC consists of two conventional linear-frequency, constant bandwidth wave analyzers specially modified to be driven by one stabilized local oscillator. One analyzer has four filters (2, 5, 10, and 20 cps) and the other analyzer has two filters (2 and 5 cps).

The oscillator is capable of sweeping three ranges:

1. 0-250 cps
2. 0-2500 cps
3. 0-25,000 cps

For most seakeeping events, the 0- to 250-cps range is adequate. It may be necessary to go to the 0- to 2500-cps range for slamming and vibration data.

The technique of separating the frequency components in the signal to be analyzed is based on amplitude modulation. The mathematics involved will not contribute to the continuity of the discussion and is given in the Appendix. However, a brief discussion of what amplitude modulation does will be helpful in understanding the analysis process.

The local oscillator generates a continuously changing "carrier" frequency which is 97,000 cps plus some frequency, let us say, in the 0- to 250-cps range. This frequency is modulated by (mixed with) all the frequency components in the random signal being analyzed. The result of this mixing is a new signal, which comprises all the signals which would result from separately amplitude-modulating the carrier by each frequency component of the random signal. Single component modulation produces a signal that contains the carrier frequency, the sum of the carrier frequency, and the particular modulating frequency as well as the difference of these two frequencies. The sum frequency is called the "upper sideband" and the difference frequency is called the "lower sideband." The amplitudes of these two waves are proportional to the amplitude of the modulating wave and is the quantity that must be measured.

The result of modulating a multifrequency signal then is a new signal which comprises the carrier frequency and all the upper (sum frequencies) and lower (difference frequencies) sidebands associated with the components of the signal to be analyzed.

The modulated signal is sent through a stationary band-pass filter centered at 97,000 cps. The carrier frequency component is rejected by the filter because it always generates signals with frequency greater than 97,000 cps. All upper sidebands are rejected because they contain sum frequencies which are always greater than 97,000 cps. The lower sidebands are also rejected, with the exception of that one lower sideband whose difference frequency is exactly 97,000 cps. The net result of the filter's activity is the passage of a pure sinusoid whose amplitude is proportional to the amplitude of that component of the modulating (random) signal which is at that moment specified by the local oscillator.

This discussion is idealized as well as somewhat over-simplified. The filter, in fact, is of finite width, let us say 5 cps. Consequently, it will pass all lower sideband components with frequencies between 96,997.5 and 97,002.5 cps. Under such circumstances, it is seen that the analyzer will sort out not individual frequencies in the spectrum but bands of frequencies, depending on the bandwidth of the filter employed.

Care must be exercised in the initial generation of carrier signals; they must always be of frequency greater than that of the upper side of the band-pass filter (in this case, greater than 97,002.5 cps).

Since the SEADAC has two analyzer systems (Figure 1), the carrier wave is modulated simultaneously (and separately) by two of the signals on the magnetic tape and everything that has just been discussed occurs independently and simultaneously, with respect to these two signals. For the sake of simplicity, the discussion will continue on the basis of one signal to be analyzed and one analysis system.

While the filter network, which is the wave analyzer, operates on the modulated carrier-input signal, through the entire frequency range generated by the oscillator, the passed components proceed to the analog computer portion of the SEADAC for further treatment. In the analog computer, one of the following operational modes may be programmed:

1. Average linear amplitude.
2. Mean square energy.
3. Integral of energy.

The average linear amplitude may be thought of as an estimate of the Fourier coefficients in a Fourier series analysis, where the amplitude assigned to a particular harmonic is the average amplitude of it and the neighboring harmonics within the bandwidth of the filter. As the width of the filter approaches zero, the Fourier representation of the seakeeping event is approached. This type of computer calculation is not desired at this time, and has consequently not been applied to any data.

The "mean square energy" operation is equivalent to computing energy spectral density. The amplitudes of the frequency components in the pass-band are continuously squared and averaged. This mode of operation is used most frequently.

Since the total energy in the spectrum is a measure of the "peak-to-peak" distribution of the record of the seakeeping event being studied, the "integral of energy" mode of operation is often used. Here the average square energy of the frequency components are added to provide a monotonic nondecreasing function (curve which never goes down) whose maximum (asymptotic) value is a measure of the total energy in the seakeeping record.

The output of the analog computer is applied to an X-Y plotter. The net result of analysis is a graphical display on 8½-in. X 10-in. paper of the output of one of the operational modes as ordinate, and frequency (magnified by speed-up ratio) as abscissa.

Figure 3 illustrates the most frequently used operational modes. Both the density function (spectrum) and the distribution function (integrated spectrum) relate to the same input data. It will be noted that the rate of change of the distribution function corresponds well with the ups and downs of the density function, as expected from the integration process involved. The maximum value of the cumulative distribution function is, as stated, a measure of the total energy and is therefore equivalent to the integral of the density function, or to the area it represents on the X-Y plotter.

Several analysis constants require discussion before the subject is closed. The width of the filter determines the resolution of the energy spectrum. A narrow filter provides fine detail but is a relatively poor estimate because fewer frequency components are averaged. Conversely, a wide filter provides good estimates but poor resolution. A priori knowledge of the shape of the spectrum is helpful in filter selection.

It is sometimes necessary to repeat analyses using different filters before the optimum one is found. Figure 4 shows the effect of different filters operating on the same input data.

The oscillator motor determines the time it takes the oscillator to scan the entire frequency range, which consequently determines the maximum analysis time. There are two choices: 11 minutes (fast scan) or 22 minutes (slow scan). Slow scan allows the filter to remain longer in its local frequency environment and permits better resolution. Fast scan may have a relative "smearing" effect because new frequencies are being scanned by the filter at a faster rate and corresponding new amplitudes are being squared and averaged at the same faster rate. The error or "smearing" thus introduced depends on the steepness of the spectrum. A flat spectrum is unaffected by fast scan. Figure 5 shows the same data subjected to slow and fast scan. In either case, it is important for the filter to scan the entire loop, before the frequency band it is examining moves very much, to get the benefit of all the available data. For this purpose the time (T) it takes the data to make one passage through the analyzer is important. A rule of thumb that suggests $T \Delta f \gg 1$ may be used as one guide in the selection of an appropriate filter bandwidth (Δf). A 20-minute record, for example, which is sped-up 512 times takes 2.34 seconds to pass through the analyzer once (loop time). A 5-cps filter would appear to be adequate in this case. Choice of both filter and scanning speed depends mostly on the shape of the spectrum. A flat spectrum can tolerate a wide filter and fast scan; a steep, rapidly changing spectrum requires a narrow filter and slow scan. Experience with the system has shown that most seakeeping analyses may be made at slow scan with a 5-cps filter. An exception to this is the usually narrow roll spectrum which suggests using a 2-cps filter with slow scan.

One further analysis constant to be considered is the averaging time constant. This is a memory medium that controls the length of time, in the past history of the excursion of the filter through the frequency range, that the analog computer will consider amplitudes in its averaging duties. The time constant is adjustable in the range of 0.1 to 100 seconds and should be at least as long as the loop time, to utilize all the data in the loop. The longer the time constant, however, the greater the range of amplitudes that will be averaged. A time constant of 3.5 seconds has been used successfully with seakeeping data.

The effect of creating a discontinuity in the record, where it is spliced into a loop, is to introduce spurious information in the signal that manifests itself as spikes in the energy spectrum. These spikes will appear at the fundamental of the new frequency created by the splice and at its harmonics. If the record is long and/or the filter wide and/or the time constant long, the splice effect will be reduced. There is no appreciable evidence of the splice effect in any of our analyses to date.

Since only about half the 0- to 250-cps oscillator frequency range contains energy, analyses usually take 5 or 10 minutes, depending on whether slow or fast scan is applied.

It should be obvious by now that the experimental setup for a particular analysis is highly subjective. The results depend on:

1. Loop time (length of record).
2. Filter bandwidth.
3. Scan rate.
4. Time constant.

Project engineers are encouraged to familiarize themselves with the operation of the equipment so that, with the cooperation of the SEADAC engineer, the most useful analysis can be made.

4. DATA STORAGE

After all the analyses are completed for a particular magnetic tape loop, the loop is stored in a small plastic cylinder and the cylinder is labeled with identification that relates its contents to a particular page in the "book" (Figure 2) wherein is contained all pertinent information on the trial.

Both the tapes and the book are filed for future reference.

COMPARISON OF SEADAC ANALYSIS WITH DIGITAL METHODS

The SEADAC is concerned primarily with the electronic determination of the spectral density function of a seakeeping event as represented by the observed time-history of that event. In a very general way, the spectral density function may be considered to be a display of the harmonic components contained in a signal such that the amplitude of each component is squared (ordinate) and assigned to its respective frequency (abscissa).

The particular process generated by the analyzer system of the SEADAC for realization of the spectral density function has been described. It should be noted, however, that certain errors, which arise in computation, may cast some doubt on the validity of results. These errors are not large but one is still obligated to establish confidence in such a new computing machine even if its principles are well-known and accepted. Some of the questionable features of this electronic analog computer are: (1) the creation of a discontinuity in the time history of the event being analyzed when it is joined to itself in a loop (splice effect), (2) the use of a nonideal filter (i.e., one which is not a perfect rectangle), and (3) the method of calculating running averages over the effective bandwidth of the filter as if the energy were constant over that bandwidth.

These deviations from an ideal method of analysis may be treated independently (as in the last section), to assess their individual effects on the outcome. It is, however, more profitable to examine the effect of the aggregate of all these errors; if the total error is sufficiently small, there is no reason to pursue the matter further. The best method for verification of SEADAC operation is a comparison of the output of the SEADAC with the known and understood results of a general purpose digital computer, wherein the numerical analysis is governed by an entirely different computational procedure than is the analog method. Instead of filtering, squaring, and averaging, the numerical method deals with a convolution of the original time history with itself, and then a Fourier transformation generates the spectral density function. The point is that the numerical technique is so different that a successful comparison of the two methods cannot be ascribed to like errors being propagated in the same way. The digital spectral densities computed for this comparison are considered to be representative of the data; it remains to be established that the analog analyzer of the SEADAC produces similar results.

For the sake of comparison, a set of data obtained on a Liberty ship full-scale trial was analyzed by both methods. The ship speed was approximately 15 knots in a head sea where the highest waves were about 8 - 10 feet.

The seakeeping events which were recorded and analyzed are listed below and appear as Figure 6:

1. Roll
2. Pitch
3. Heave Acceleration
4. Starboard Strain
5. Port Strain
6. Wave Height

Examination of the graphs in Figure 6 shows that the agreement is quite good so far as shape is concerned, and this is essentially all that may be required of the SEADAC. Where the curves do not superpose indentically, it is believed that instrumentation calibration is at fault. This is discussed in the next section. An unexplainable discrepancy occurs in Figure 6c, where the SEADAC shows a third peak in the spectrum that does not exist in the numerical calculations.

The analog analysis was repeated several times without any change. The original data will be re-submitted for numerical analysis. At this time, there is no explanation for the anomaly. Since the other five comparisons are good, there is probably little cause for concern.

It is reasonable to conclude that a SEADAC analysis is equivalent to a numerical analysis, made in an analogous way. It has been shown that different filter bandwidths, time constants, and scanning times affect the resultant spectrum. Consequently, the original data could have produced spectra that might look somewhat different from those in Figure 6, if the analysis constants were changed. The same, however, applies to the numerical analysis constants and equivalent results will only be obtained under analogous conditions. The SEADAC analyzer is therefore considered to produce good estimates of the spectral density function of a random signal.

PRESENTATION OF RESULTS

1. LABELING OF COORDINATE AXES

To derive meaning from the spectral density representation, it is necessary to label the coordinate axes; this assigns quantitative value to the graph. Certain basic information is required:

1. Frequency multiplication factor.
2. SEADAC calibration.
3. Effective filter bandwidth.
4. Instrument calibration.

The first step is to convert the frequency scale, which is given by the local oscillator, into true frequencies appropriate to the true recording time. Analyses will, in general, be made for the 0- to 250-cps scale or 0- to 2500-cps scale. If the 0- to 2500-cps scale is used, the oscillator frequencies are multiplied by 10 to give analysis frequencies.

The frequency multiplication factor (S) is that number by which the true frequencies (f_t) in the record have been multiplied, during data preparation and analysis, to yield the analysis frequencies (f_a),

$$f_t = \frac{f_a}{S} \qquad [1]$$

The frequency multiplication factor (S) is determined by the recording tape speed (s_r), and the playback tape speed (s_p) by the equation

$$S = \frac{s_p(1)}{s_r(1)} \times \frac{s_p(2)}{s_r(2)} \qquad [2]$$

where (1) and (2) in Equation [2] refer to first or second record and/or playback. From Equations [1] and [2] , the true frequencies are found to be

$$f_t = f_a \frac{s_r(1)\ s_r(2)}{s_p(1)\ s_p(2)} \qquad [3]$$

If, for example, a signal is recorded at 1-7/8 ips, played back at 30 ips, re-recorded at 3-3/4 ips, and played into the analyzer at 15 ips, then Equation [3] states that the analyzer frequencies must be divided by 64 to get the true frequencies.

It is sometimes desirable to display the abscissa scale in terms of the circular frequency of encounter (ω_e). This is given by

$$\omega_e = 2\pi f_t \qquad [4]$$

or directly by multiplying Equation [3] by 2π.

The ordinate scale of the spectrum representation requires attention next. Where the local oscillator scale was used to represent the analysis frequency scale, the peak voltage output of a pure sinusoid is used to represent one point on the analysis ordinate scale. This calibration factor is obtained by analyzing a pure sinusoid in the same way (same constants) as the particular seakeeping event being analyzed. Since the bandwidth of the filter is much greater than the frequency band of the calibration signal (zero), the result is a curve which represents the characteristics of the filter rather than the pure sinusoid. This is all right because only the peak value of this curve is important, at the moment. Figure 7 shows typical calibration curves for different filters. According to our analysis technique, the peak value of the calibration curve is the square of the amplitude of the pure sinusoid being analyzed. If this amplitude is characterized by its rms (root-mean-square) voltage input (V_{rms}), then the peak value of the resulting calibration curve (V_p^2) is

$$V_p^2 = (\sqrt{2}\, V_{rms})^2 = 2V_{ms}\,(\text{volts}^2) \qquad [5]$$

Figure 8 shows a spectral density analysis of a seakeeping variable made with a 5-cps filter. The calibration curve appears at the right. Since the rms input voltage is $V_{rms} \doteq 0.04$, the output peak value is by Equation [5], $V_p^2 = 0.0031$ volts^2. This is the height of the ordinate scale appropriate to the peak of the calibration. Since also, the base of the ordinate scale is zero, the ordinate scale will be completely defined, in terms of the analysis parameters, once the filter bandwidth is taken into account.

It should be noted that the application of different filters to the same random signal results in spectra of different apparent sizes (Figure 4), yet the peak values of the calibration will be the same (Figure 7). This results in the same scale for all the spectra in Figure 4, but is not paradoxical so long as it is remembered that the ordinates represent averaging over the filter bandwidth. That is, a 10-cps filter analysis should result in a spectrum which has twice the area of that resulting from a 5-cps filter analysis.

It has become the practice in the SEADAC to eliminate the confusion resulting from the averaging process by relating the spectral density to a unit frequency band. This is accomplished by dividing the ordinate scale by the "effective bandwidth" (Δf_a) defined as

$$\Delta f_a = \frac{A}{L} \times k \qquad [6]$$

where A is the area under the calibration curve (Figure 8) measured in square units of the graph paper, L is the height of the calibration curve measured in units of graph paper, and k is the ratio of any convenient frequency band on the analysis frequency scale to its length in units of graph paper. As an example, consider the area under a particular calibration curve, purporting to represent a 5-cps filter, to be 137 units^2. The height of the calibration curve is measured as 15.2 units and a frequency band of 10 cps is equivalent to 16 scale divisions on the analysis frequency scale. Equation [6] shows that the effective filter bandwidth is 5.63 cps and states that the effective filter bandwidth is equivalent to the width of a rectangle whose height is the height of the calibration curve and whose area is the area under the calibration curve. In principle, the effective bandwidth of each filter should be constant but variations of several percent indicate instability of the crystalline structure of the filter which, it is hoped, will be corrected with air conditioning of the space in which the system is installed.

To complete the universalized ordinate scale, in terms of the seakeeping event being studied, it is necessary to introduce the instrument calibration. The signal being analyzed is a fluctuating voltage which may represent heave, pitch, etc. Before each run, a calibration should be applied to the tape which relates particular voltage settings to particular transducer signals. The value of the calibration squared ($C_T{}^2$) is all that is required to complete the ordinate scale.

If the squared calibration is taken together with Equations [5] and [6], the resultant spectral density ordinate $\Phi(\omega_e)$ associated with the peak of the calibration curve is

$$\Phi(\omega_e) = \frac{C_T^2\, V_p^2}{\Delta f_a} = \frac{2C_T^2\, V_{ms} L}{Ak} \qquad [7]$$

which has the dimensions of seakeeping units (degrees, feet, etc.)

squared, times time.

A mode of operation called "bandwidth divisor," which has not been discussed, essentially divides the ordinate scale by a frequency bandwidth related to the effective bandwidth. This mode is being investigated with a view toward eliminating the necessity for manual division.

2. COMPUTATION OF MEAN TOTAL ENERGY

The total energy in the spectrum Φ , which yields important statistical information on the amplitude distribution of the event being studied, is defined by the area under the spectral density curve as

$$\Phi = \int_0^\infty \Phi(\omega_e)\, d\omega_e \qquad [8]$$

One obvious method of calculating Φ is by measuring the area bounded by $\Phi(\omega_e)$ and the abscissa scale. Another less troublesome, more accurate method was mentioned in the section DATA ANALYSIS (page 8) as"integral of energy" where the operation described in Equation [8] is performed in the analog computer of the SEADAC. Such an integration appears in Figure 9 where the integrated spectrum is superimposed on the spectral density curve derived from the same data. Examination of this cumulative representation of the spectrum shows that it is steep when the spectral density curve is steep (upward), has inflection points where the spectral density curve has peaks, and becomes asymptotic to a constant as the spectral density function goes to zero.

The value Φ is the highest value assumed by the integrated curve. To find this value, a calibration is made of a pure sinusoid for the "integral of energy" mode of operation. This appears in the lower right-hand corner of Figure 9. The maximum value of the calibration curve is given by Equation [5] . The maximum value of the cumulative curve is given by

$$\Phi = \frac{L_1}{L_2} V_p^2 C_T^2 \qquad [9]$$

where L_1/L_2 is the ratio of the height of the seakeeping cumulative curve to the height of the calibration curve. Φ is given in seakeeping units squared.

3. CONFIDENCE BANDS

The presentation of the energy spectrum of a seakeeping event would not be complete without some measure of confidence. This confidence is usually expressed by a pair of curves which flank the spectral density curve in such a way that it may be said: "The true spectrum is expected to lie between the two curves with a probability of x."

The confidence bands are determined from the chi-squared distribution with f degrees of freedom where

$$f = 2T \Delta f_a \qquad [11]$$

T is the time it takes the magnetic tape loop to make one traverse through the analyzer.

The number of degrees of freedom is entered into Figure 10 to obtain the numbers by which the spectral ordinates must be multiplied to gain any desired percentage of confidence.* For example, consider the energy spectrum in Figure 11. This graph resulted from an analysis with a filter whose effective bandwidth was 5.63 cps; the record length was T = 2.81 seconds. From Equation [10] it is seen that f = 31.64. The 90-percent confidence bands are found by entering 31.64 on the abscissa scale of Figure 10 and reading off the multiplying factor from the projections on the ordinate scale of the intersections of f = 31.64 with the 5-percent and 95-percent curves. Figure 11 shows the energy spectrum of that seakeeping event with its associated 90-percent confidence bands.

PROPOSED EXTENSION OF THE SEADAC

Even while the SEADAC is relatively new, some additional components are being considered which will: (1) increase its efficiency through saving of computational time, (2) extend its usefulness through new operations, and (3) prepare magnetic tape for re-use in the field.

Figure 12 is a block diagram showing the SEADAC, with the proposed additions (dotted lines). The magnetic-tape recording brought from the field to the laboratory will be reproduced at 60 ips on a reel recorder, as before. Instead of re-recording, at 1-7/8 ips, on the loop recorder, this operation is now performed on another reel recorder. The benefits derived from the addition of a reel recorder are two-fold: (1) all the information on the reel may be transcribed on one re-recording and (2) the loop recorder is always free to play data into the analyzer. No time will

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*Figure 10 was constructed from tables of the chi-square distribution found in most textbooks on statistics.

be lost in the re-record process. A magnetic-tape signal eraser will be incorporated to remove the signals from the original tape after it is transcribed onto the other reel. The original tape will then be sent back into the field for re-use. The transcribed tape is then 1/32 of its original length and after being converted to loop form (appropriate to each run), it is ready for analysis. During the re-record period, the information will be simultaneously transcribed onto graphic chart paper, as at present, and a book of the experiment will be prepared and filed. After the loops are played through the analyzer, they will also be stored, as at present.

Two changes are planned for the analyzer; one is simple and direct, and the other requires some careful electronic engineering. As mentioned in the preceding section, the two most popular modes of SEADAC operation are computation of the spectral density function and computation of the total energy in the signal. In the present system, each calculation can be made either successively on one analyzer or simultaneously on both analyzers. If each analyzer can be made to perform both operations simultaneously, analysis time will be cut in half. The way to accomplish this is to incorporate an additional power integrator and recorder into each analyzer. This was done experimentally with the existing equipment and the result appears in Figure 13. The spectral density curve and integrated curve marked "A" represent successive analyses on a single analyzer, whereas the curves marked "A + B" represent simultaneous analyses of the same data on the same analyzer with the addition of the power integrator and recorder of the other analyzer. The small differences are attributed to the different gains of the two systems and are corrected by the calibrations. The good agreement of the curves seems to justify the extension of the analyzer system in this direction.

Computation of cross spectra is not yet available as commercial analog electronic equipment, so this matter must be pursued at the users' level. Some cross-spectrum analyzers have been built in the laboratory, and at least one is known to be successful.

There are two known methods of performing cross-spectrum analysis that are amenable to incorporation in the SEADAC:

1. Single-filter, and
2. Matched filters.

The first method requires the combination of two simultaneous records by addition and by differentiation and addition. The record which results from these operations is treated like an ordinary record and its spectrum is analyzed accordingly. The result played out on the X-Y recorder is operated upon, in certain ways, to extract the co- and quadrature-spectra (the desired components of the cross spectrum).

The second method involves the simultaneous modulation and filtering of the two records. The outputs of the matched filters are multiplied together, once directly, and once after one signal is phase-shifted 90 degrees

The results, after integrating and averaging, are played out on the X-Y recorders as the co- and quadrature-spectra.

To accommodate both types of cross-spectrum analysis in the SEADAC (which is our intent), the following operations must be incorporated into the analog computer:

1. Addition of signals,
2. Differentiation,
3. Multiplication, and
4. Phase shifting.

After completion of the SEADAC, as described, there will be two alternative methods of treating data (Figure 12):

1. Auto-Spectra
    a. The energy spectrum of each of two signals.
    b. The total energy in each of two signals.
2. Cross-Spectra
    a. The energy spectrum of each of two signals.
    b. The co-spectrum (in-phase) of the two signals.
    c. The quad-spectrum (90° out-of-phase) of the two signals.

In the prospective form discussed in this section, the data-processing method employed by the SEADAC may be considered to be comprised of three separate operations, as shown in Figure 12:

1. Data collection.
2. Data preparation.
3. Data analysis.

The sole interdependence of these operations is in the necessity for each operation to provide work for the succeeding operation. As long as each operation has data on which to operate, it is completely independent of the others.

It is possible that the system as outlined here will sometimes suffer from an imbalance because of the piling-up of data in one operation and a dearth of data in another. The frequency and magnitude of such occurrences are difficult to predict in such a dynamic environment, and problems of this sort will have to be treated as they arise. It is believed that the system design is capable of handling the present and near future workloads of the Model Basin, insofar as they can now be determined.

APPENDIX

AMPLITUDE MODULATION APPLIED TO THE SEADAC

The analyzer system of the SEADAC is essentially a beat frequency analyzer commonly encountered in the field of acoustics; that is, a pure carrier frequency is mixed in a certain way with the random signal (sea-keeping event) being studied. The process of mixing the carrier with the random signal, to assign amplitudes to the frequency components in the random signal, is called amplitude modulation. The carrier frequency is called the modulated frequency, and the frequencies in the random signal are called the modulating frequencies.

In the SEADAC, the oscillator produces a range of frequencies between 97,000 cps and 122,000 cps. This generation of frequencies by the oscillator occurs in a continuous fashion so that the resulting modulated signal is always changing.

For the sake of simplicity, we shall deal with the modulation process which occurs at any particular instant of time and a modulating signal which is a single frequency; we will then generalize for the random signal containing many frequencies.

Consider the unmodulated carrier signal to be

$$a_c = A_c \cos \omega_c t \qquad [A-1]$$

where c means carrier and ω is the frequency. The modulating signal combining with the carrier is

$$a_m = A_m \cos \omega_m t \qquad [A-2]$$

where m refers to the modulating signal and $\omega_c \gg \omega_m$ for reasons not of interest here. The process of modulation results in a combination of Equations [A-1] and [A-2] into the form

$$a = A_c \cos \omega_c t + k_a A_m \cos \omega_m t \cos \omega_c t \qquad [A-3]$$

$$= [A_c + k_a A_m \cos \omega_m t] \cos \omega_c t$$

where k_a is a proportionality factor which determines the maximum variation in amplitude for a given modulating signal a_m. The term $[A_c + k_a A_m \cos \omega_m t]$ is the envelope of the modulated carrier frequency in Equation [A-3].

A trigonometric expansion of Equation [A-3] results in the component separation of the modulated carrier frequency

$$a = A_c \cos \omega_c t + \frac{m_a A_c}{2} \cos [\omega_c + \omega_m]t + \frac{m_a A_c}{2} \cos [\omega_c - \omega_m]t \qquad [A-4]$$

where $m_a = k_a A_m / A_c$ is called the modulation index and determines the degree or nature of the modulation as dictated by A_m and A_c. A sample of a modulated carrier wave given by Equation [A-3] appears in Figure 14. The graph of Equation [A-4] is shown in Figure 15 as a frequency spectrum of the relative amplitudes of the component waves in the modulated signal. Equation [A-4] and Figure 15 show that the frequencies of the resultant modulation are the carrier frequency and the sum and difference of the carrier and modulating signal.

Consider now an example where a carrier signal of 97,100 cps is mixed with a modulating signal of 100 cps. The resulting frequencies in Figure 15 will be, from left to right; 97,000 cps, 97,100 cps, and 97,200 cps. If then a filter designed to pass only 97,000 cps receives the modulated signal, only that component which is the lower sideband (difference frequency) may pass through the filter.

Examination of the term representing the difference frequency in Equation [A-4] shows that the amplitude of the lower sideband is proportional to the amplitude of the modulating signal (A_m) because $m_a A_c = k_a A_m$. To generalize to the random signal, consider that a given carrier frequency will mix with all the components in the random signal, but only that component which produces a lower sideband (difference frequency) of 97,000 cps will pass through the filter.

It should be noted that filters are not as narrow as suggested here so that a 5-cps filter, for example, will be centered at 97,000 cps but will permit all difference frequencies between 96,997.5 cps and 97,002.5 cps to pass. The analog computer squares and averages all these frequencies and assigns this estimate of the spectral density to the appropriate ω_m designated by the oscillator which generates the carrier frequency. As long as the spectrum is relatively flat in this area, the estimate is good.

To summarize then, the random signal modulates a particular carrier signal in such a way that only the resulting difference frequencies pass through a narrow band fixed filter. The amplitudes of the passed components are proportional to the amplitudes of the modulating components and the frequencies are related to the carrier wave. If the carrier wave frequency is constantly increased, all the frequencies in the random signal may be identified. After a component is passed through the filter, it is sent to an analog computer where it is squared, and then to an X-Y plotter where the squared amplitude-voltage is displayed against frequency. Adjustment of the ordinate and abscissa scale to account for transducer and analyzer calibrations results in a plot of spectral density versus frequency.

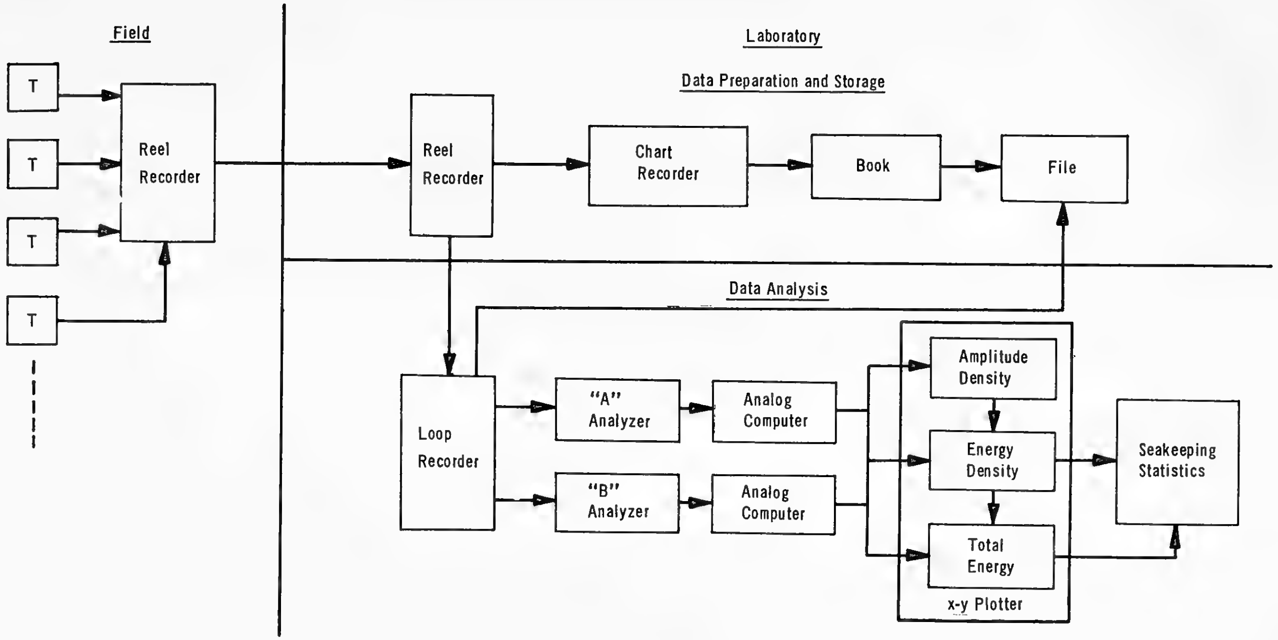
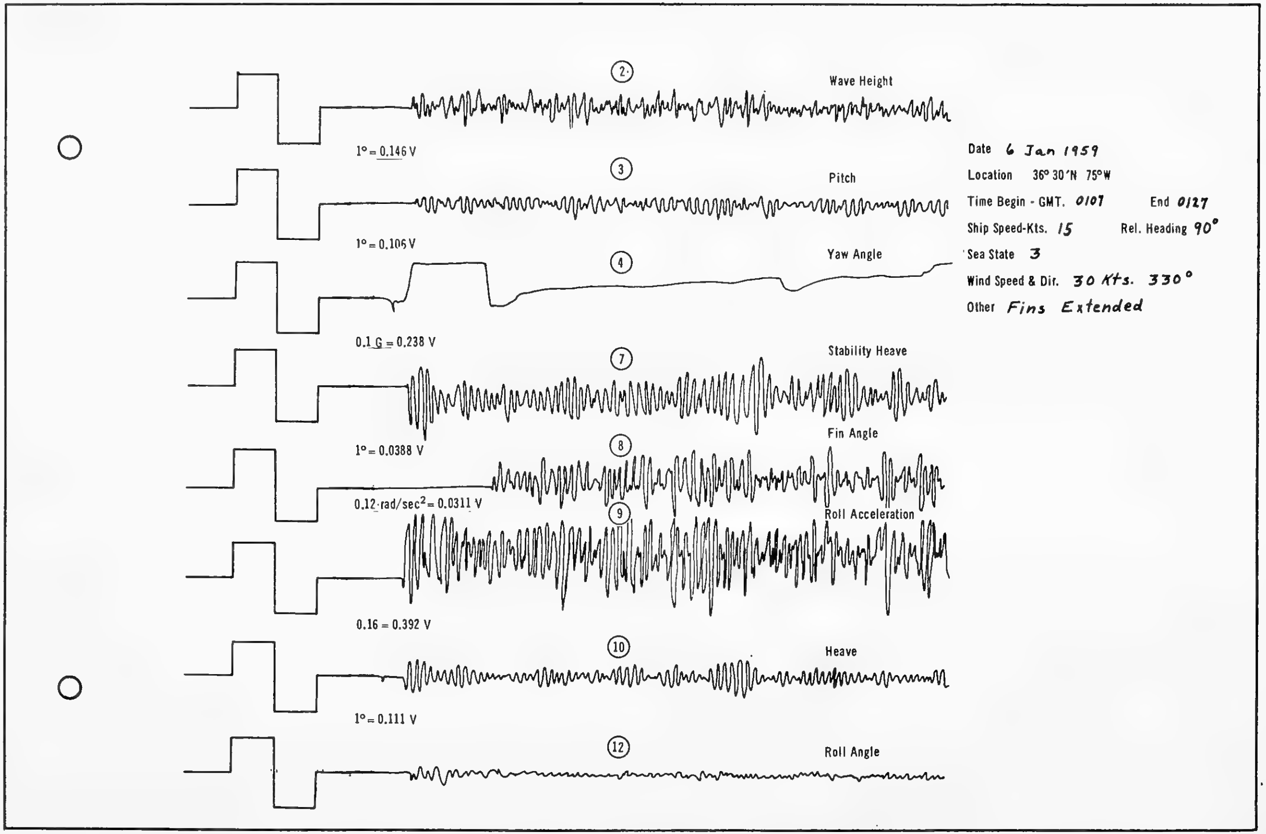


Figure 1 – Block Diagram of the SEADAC



Date 6 Jan 1959
Location 36° 30'N 75°W
Time Begin - GMT. 0107 End 0127
Ship Speed-Kts. 15 Rel. Heading 90°
Sea State 3
Wind Speed & Dir. 30 Kts. 330°
Other Fins Extended

Figure 2 – Page of a "Book" Showing Records of Seakeeping Events Recorded on Magnetic Tape

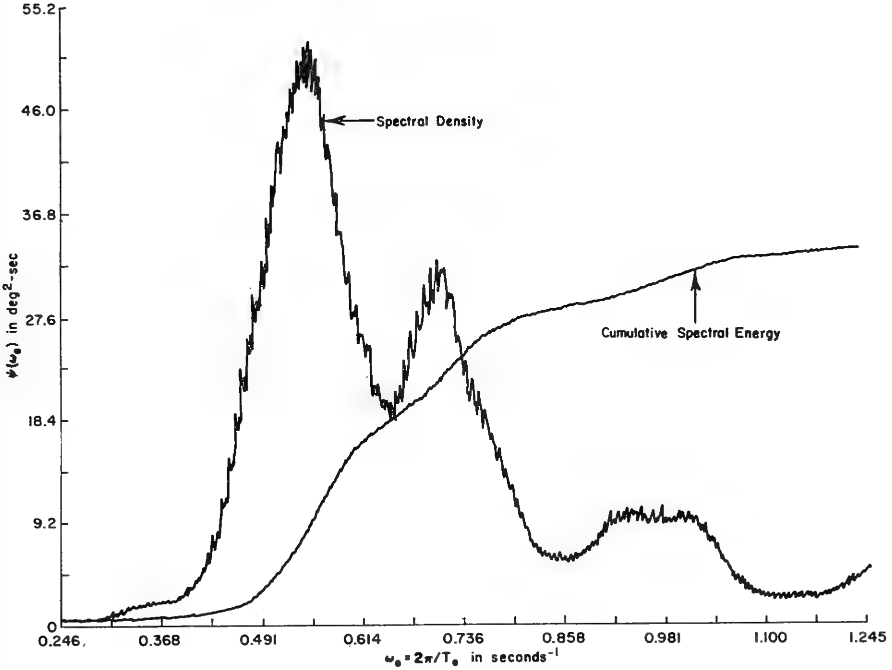


Figure 3 – The Integrated Spectrum of a Pitch Record Superposed on the Energy Spectrum of the Same Record

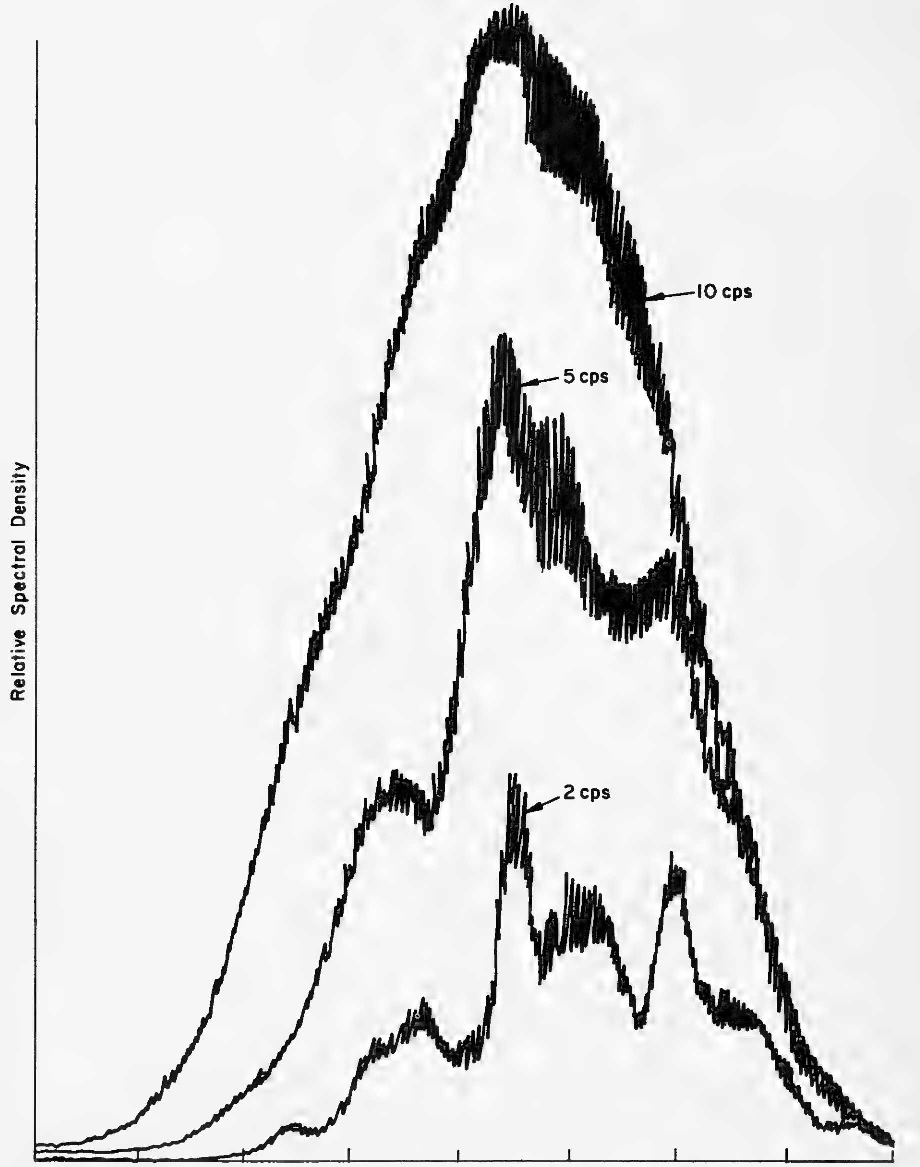


Figure 4 – SEADAC Analysis of a Pitch Record Using 2-, 5-, and 10-CPS Filters

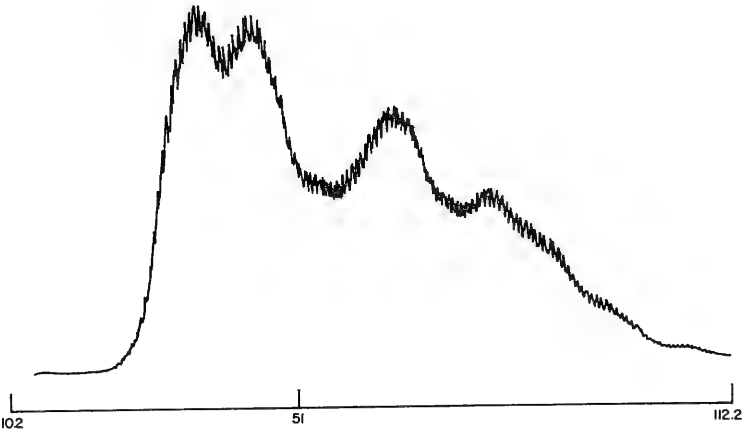


Figure 5a – Slow Scan

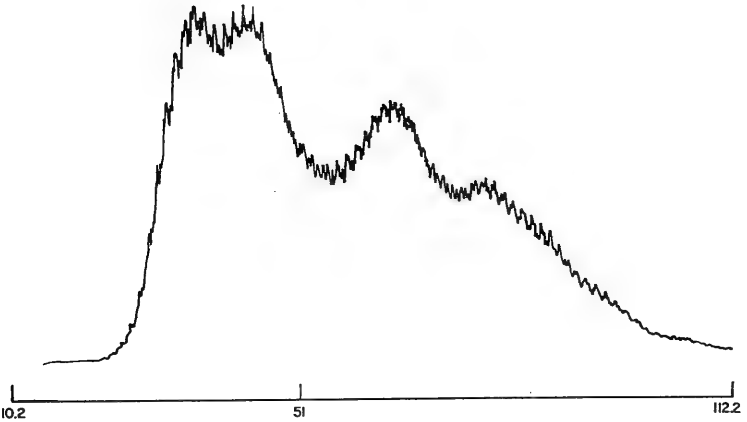


Figure 5b – Fast Scan

Figure 5 – Spectral Density Functions Computed from Same Seakeeping Record for Slow Scan and Fast Scan

Figure 6 – Energy Spectra of Several Seakeeping Events Analyzed by the SEADAC with the Numerically Computed Energy Spectra Superposed

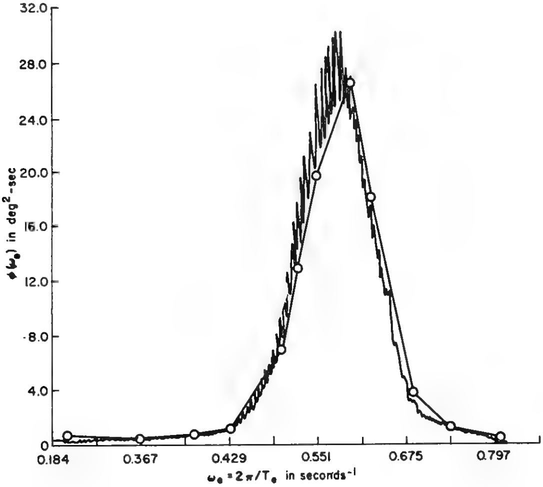


Figure 6a – Roll

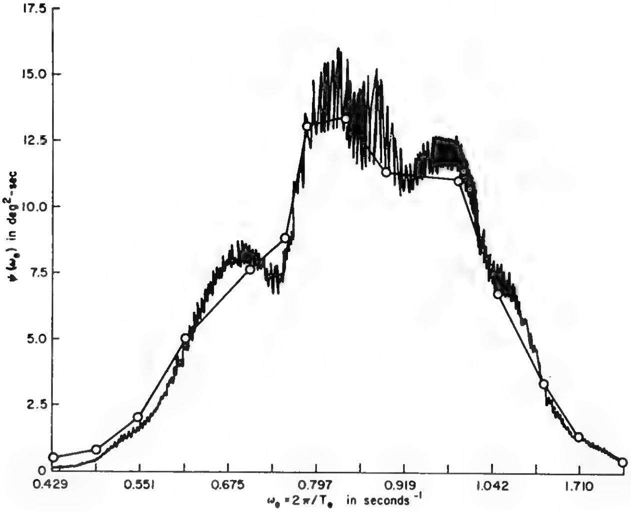


Figure 6b – Pitch

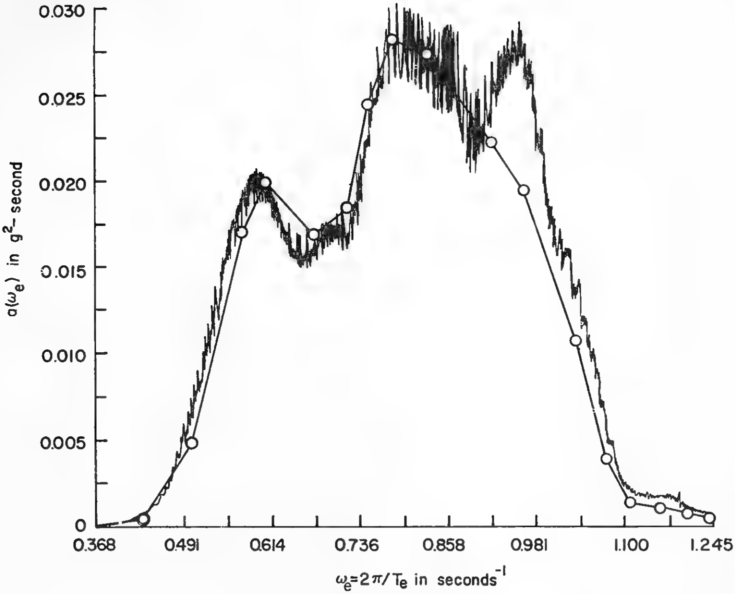


Figure 6c – Heave Acceleration

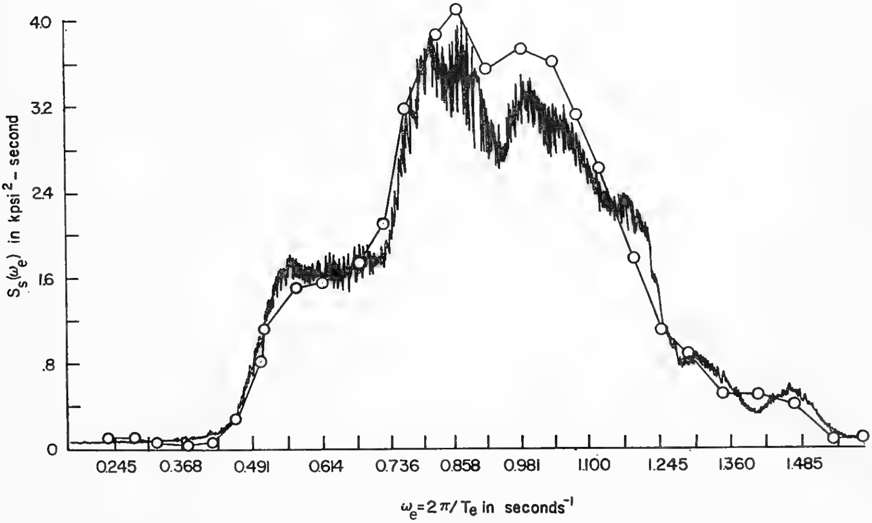


Figure 6d – Starboard Strain

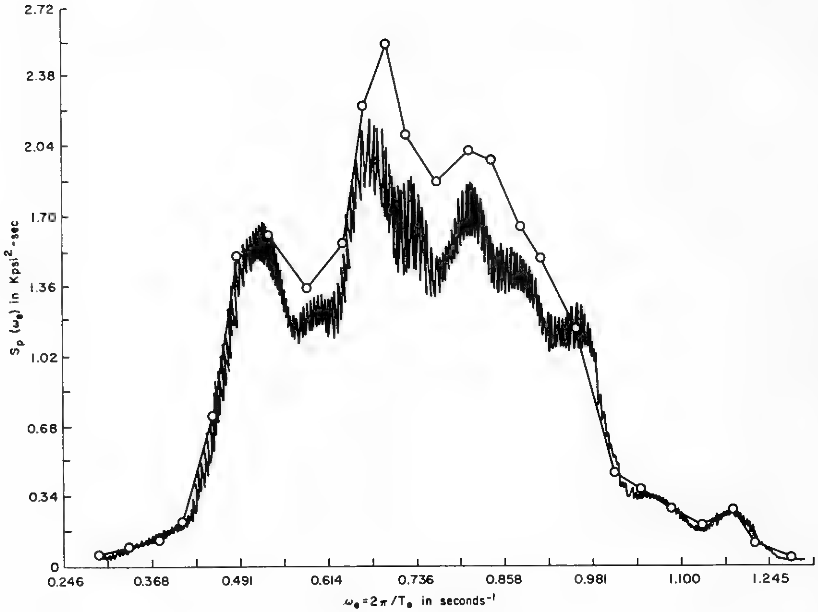


Figure 6e — Port Strain

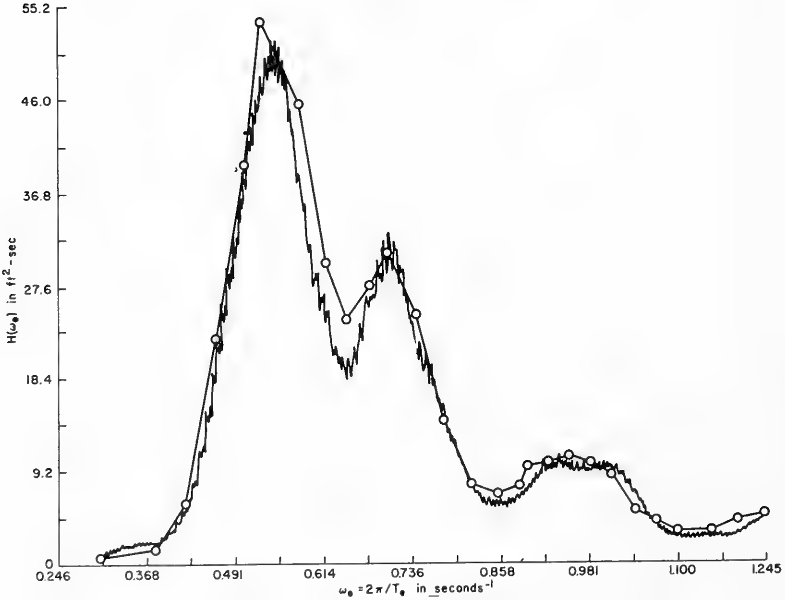


Figure 6f — Wave Height

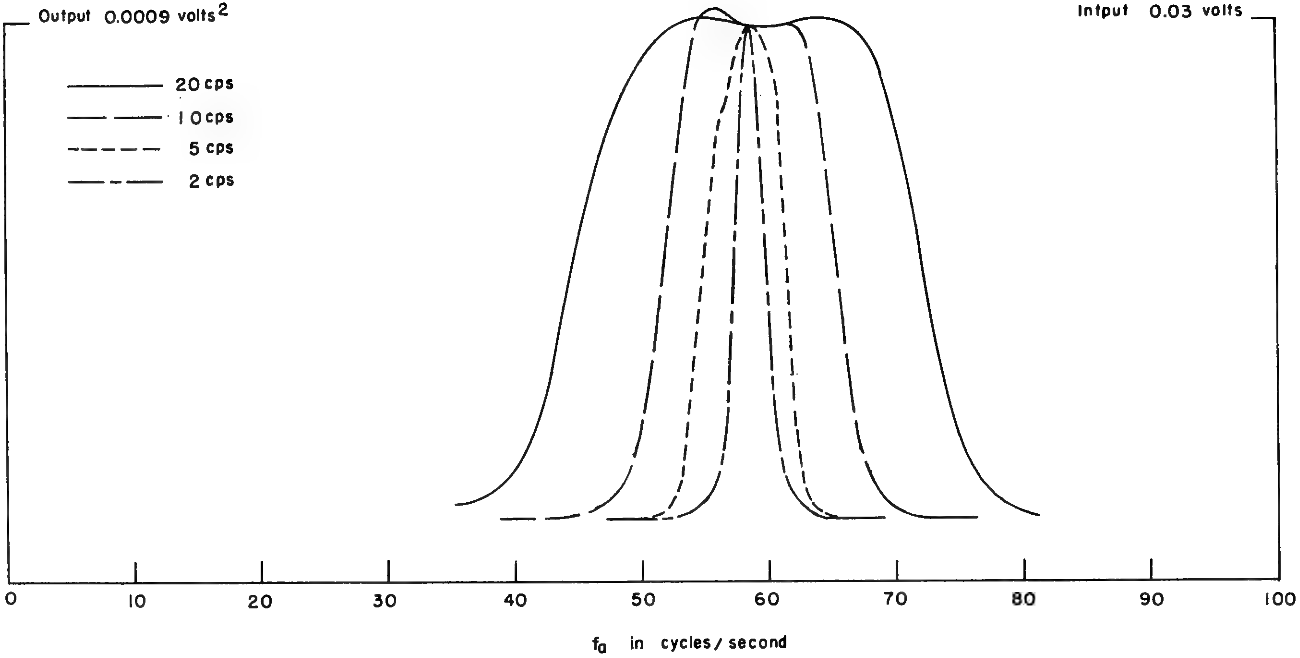


Figure 7 – Calibration Curves for 2-, 5-, 10-, and 20-CPS Filters

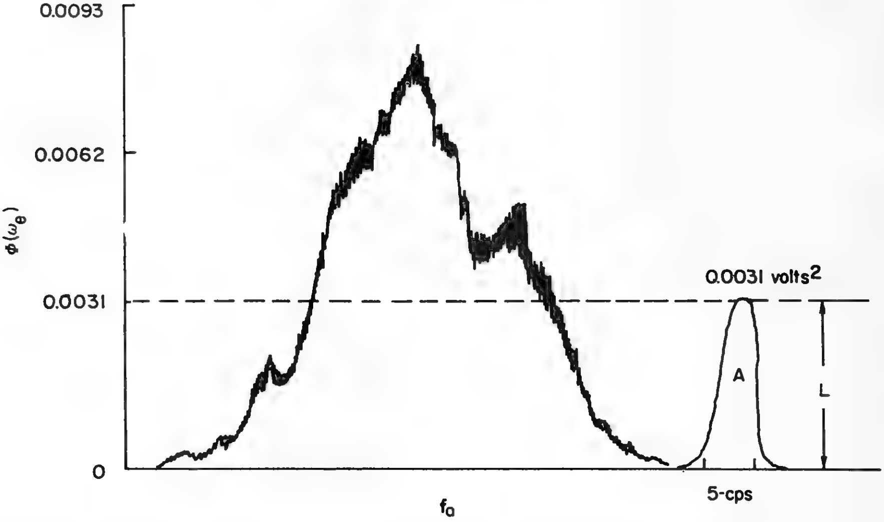


Figure 8 – Analog Spectral Density of a Seakeeping Event with Appropriate Calibration Curve

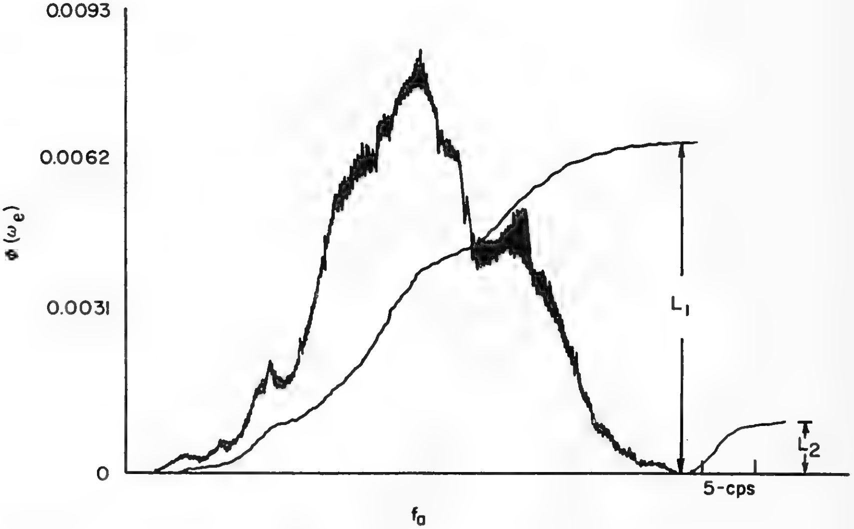


Figure 9 – Analog Spectral Density of a Seakeeping Event with Cumulative Energy Distribution Function Superimposed

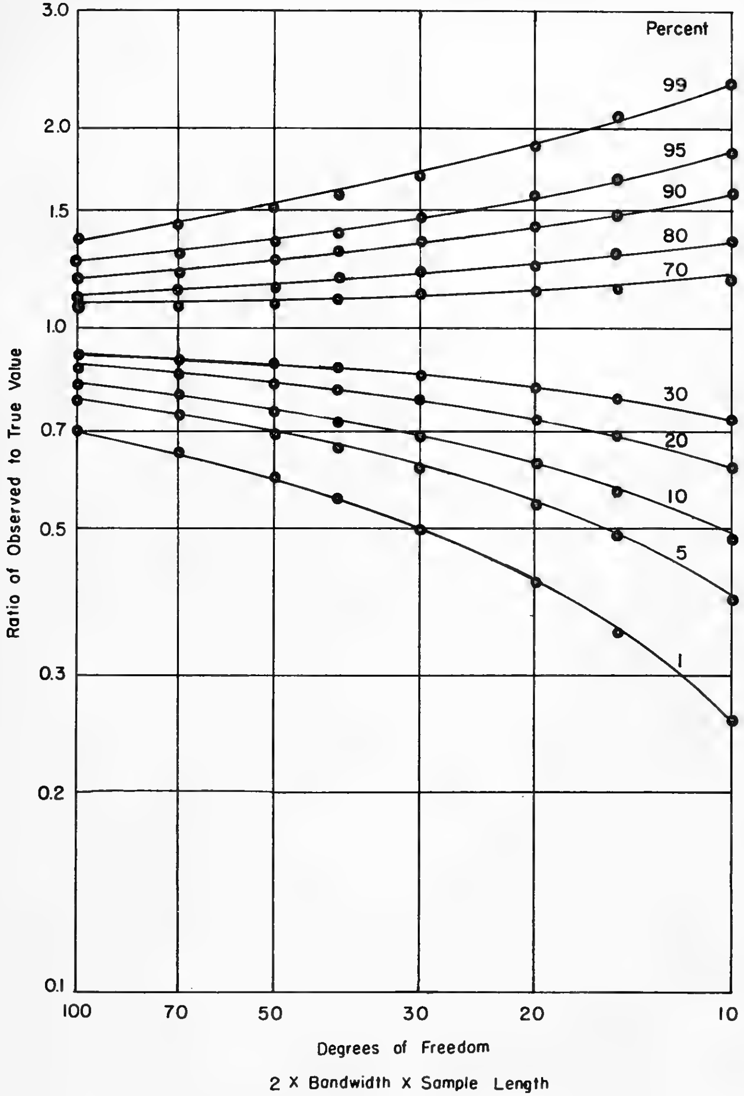


Figure 10 – Reliability of Spectral Density Estimates

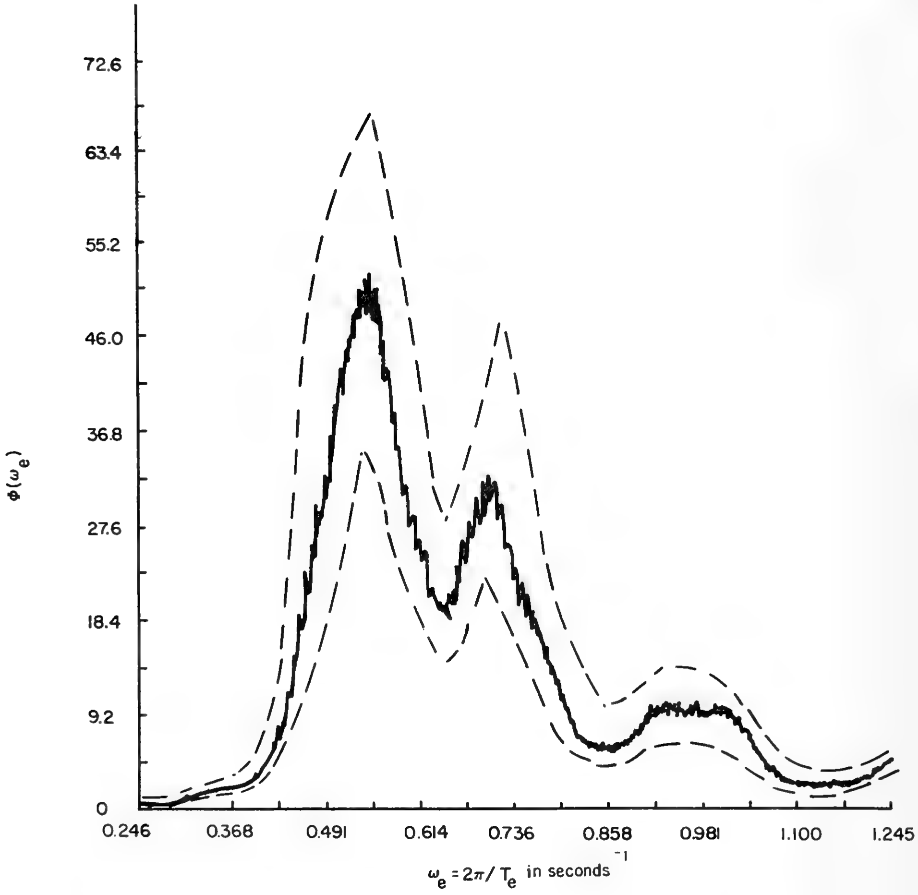


Figure 11 – 90-Percent Confidence Bands (Dashed Lines) Applied to a Spectrum with 31.64 Degrees of Freedom

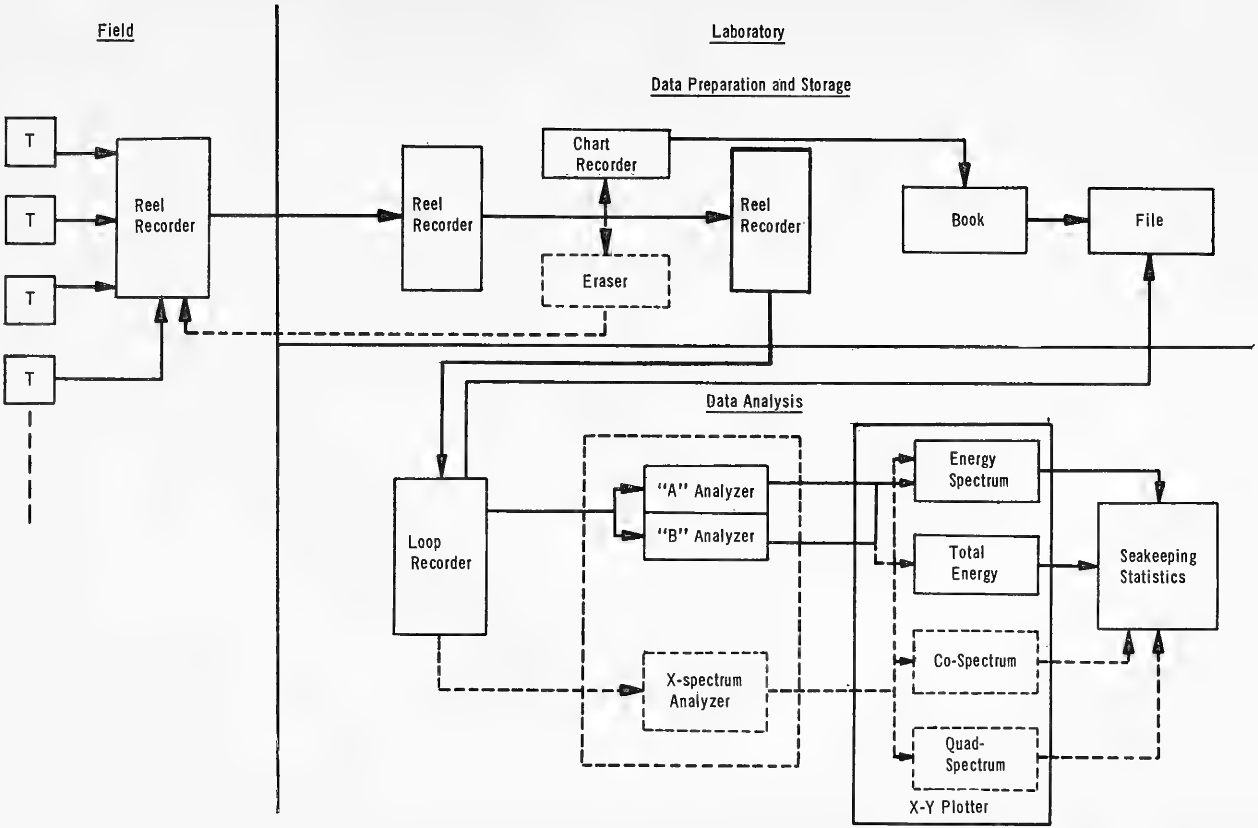


Figure 12 – Block Diagram of Proposed Extensions to the SEADAC

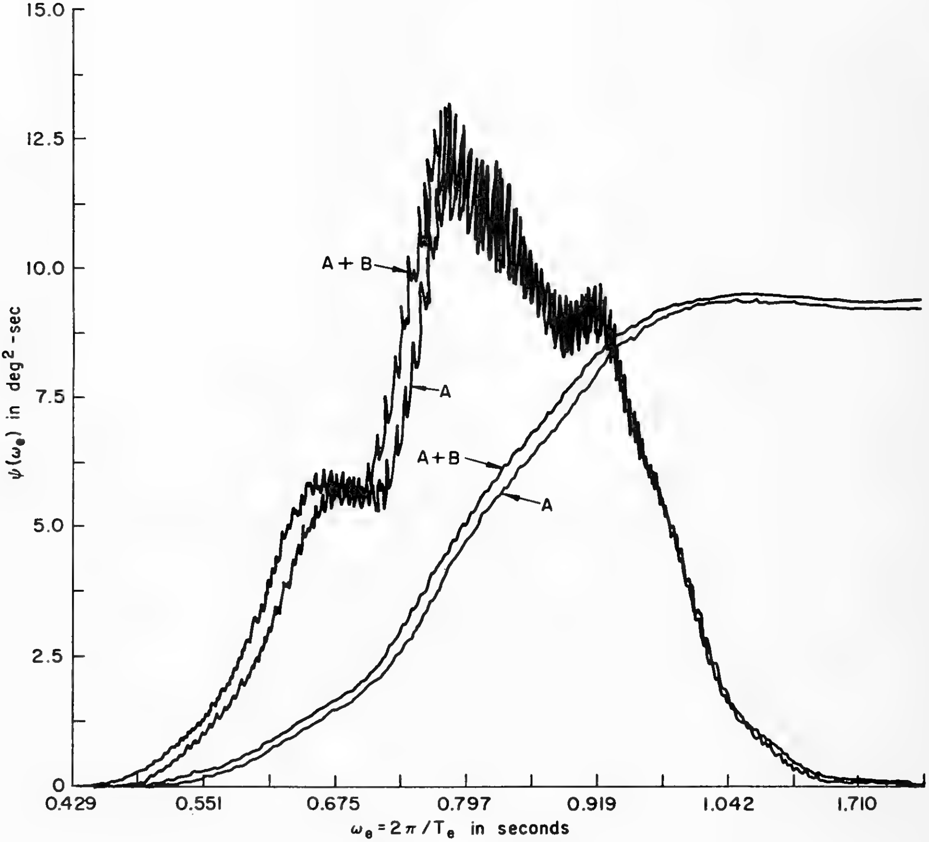


Figure 13 – Computation of Spectral Density and Total Energy by: 1) Successive Steps in One Analyzer, and 2) Simultaneous Calculation in the Same Analyzer with the Addition of Another Power Integrator and X-Y Recorder

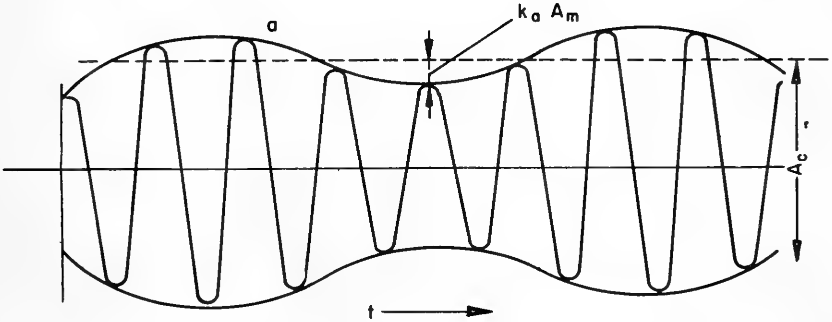


Figure 14 – An Example of a Modulated Carrier Wave

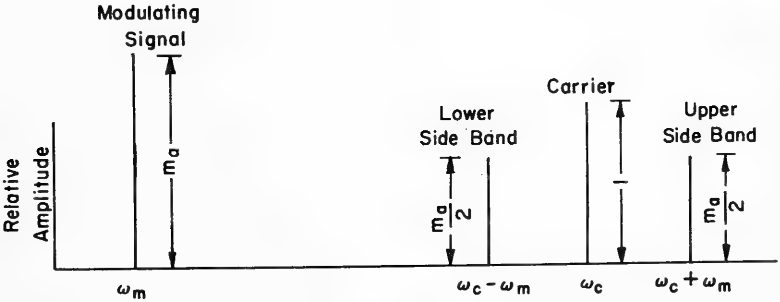


Figure 15 – The Spectrum of the Relative Amplitudes of the Components of a Modulated Wave as a Function of the Frequency of Those Components

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David Taylor Model Basin. Report 1353.
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2. Analog computers – SEADAC
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II. Strausser, Paul

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