A PROTOTYPE MAGNETIC CORRELATOR

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1949

Submitted to the faculty of the Graduate School of
the Oklahoma State University
in partial fulfillment of the requirements
for the degree of
MASTER OF SCIENCE
May, 1963

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PREFACE

The "VIBROSEIS" technique of seismic exploration has produced many equipment problems. One of these problems is obtaining the cross-correlation of the signals as required by the technique. This correlation, in the past, has been performed either electronically or optically. While both of these systems produced adequate results, a simpler, more direct system was needed. Seismograph Service Limited of London, England, a licensee of the "VIBROSEIS" technique, discovered that the correlation could be performed magnetically. The author was assigned the project of designing a prototype correlator using this magnetic correlation principle. This thesis describes the development of that correlator.

I would like to express my appreciation to Continental Oil Company for the opportunity to work on this project and for the release of this material. I especially thank Dr. H. L. Jones for his suggestions in the preparation of this thesis.

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CHAPTER I

INTRODUCTION

The advent of the "VIBROSEIS"[1] technique to seismic exploration has created a continuous search for the improvement and simplification of the equipment required for the fulfillment of this technique. The magnetic correlator is one example of the strides that have been made in this search. This thesis describes the development of a prototype magnetic correlator. Special emphasis is placed on that portion of the correlator which performs the correlation process.

To better understand the function of the magnetic correlator, it is necessary to know its role in the "VIBROSEIS" technique.

The "VIBROSEIS" Technique

Unlike conventional seismic methods, the "VIBROSEIS" technique employs the use of truck mounted servo-controlled vibrators for an energy source. The signal used to drive these vibrators is a nonrepeating linear sweep of frequencies of several seconds duration. This linear sweep, called the control sweep, is pre-recorded on a track of a magnetic tape. The control sweep is reproduced from this magnetic tape in the

[1]Trademark of Continental Oil Company

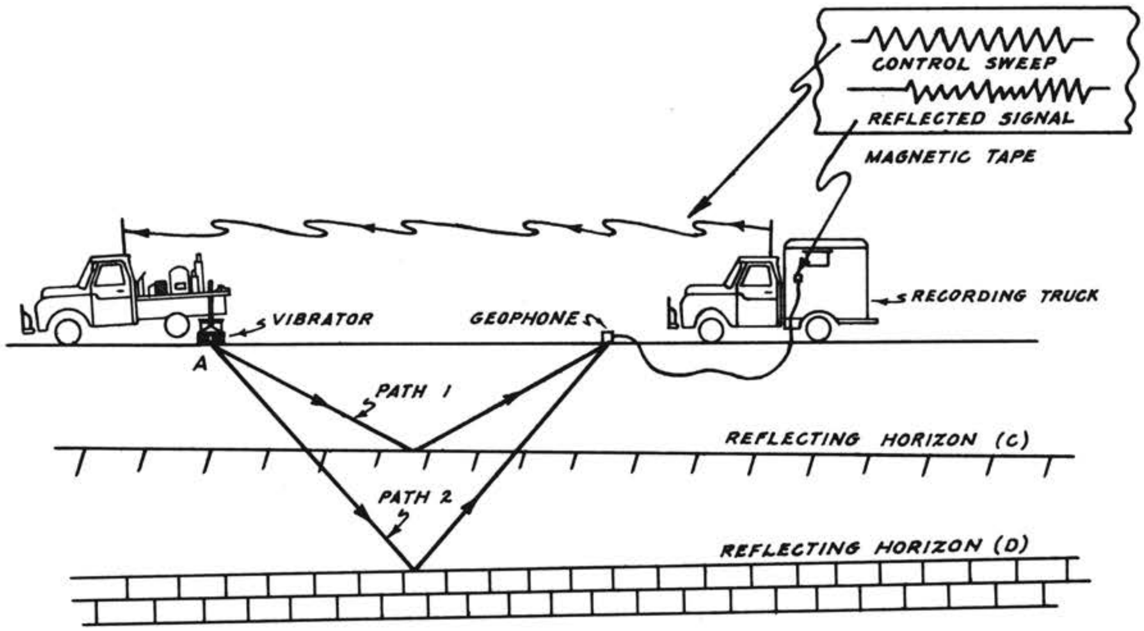

Figure 1. The "VIBROSEIS" recording process.

field recording truck and transmitted by radio to the input of the vibrators. The vibrators transmit into the earth a signal that varies exactly with the control sweep. These vibrations propagate through the earth as seismic wave trains and reflect from rock boundaries in the sub-surface. The reflections are picked up by geophone arrays and subsequently recorded on other tracks of the magnetic tape in the recording truck.

To better illustrate the recording process, consider the simple two path case as shown in Figure 1. For this ideal case it will be assumed that no noise or interference is present. The control sweep signal, transmitted into the earth at point A, is reflected from horizons C and D and the composite of these two signals is picked up by the geophone at point B.

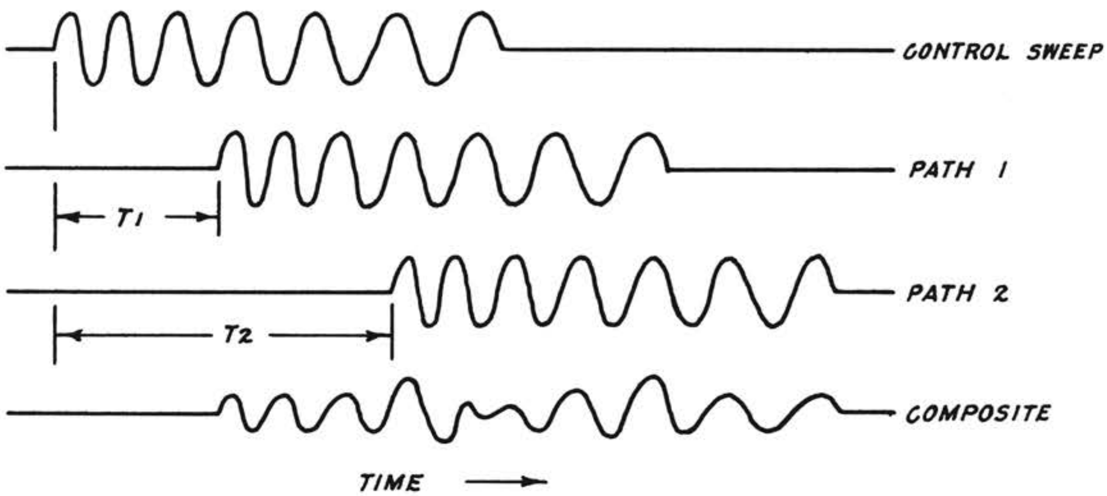

Figure 2. Relationship of signals for a two path case.

If the signals from paths 1 and 2 could be monitored individually, they would be as illustrated in Figure 2. Here it can be seen that the signal received from path 1 is identical to the control sweep except that it has been delayed by the travel time, T_1. Similarly, the signal received from path 2 is identical to the control sweep except that it has been delayed by the travel time, T_2. The composite of these two signals is also shown. The complexity of the composite signal eliminates a quick reconstruction of the initial conditions by ordinary means.

In order to obtain the information in more intelligible form, the technique of crosscorrelation is employed. By crosscorrelating the received composite signal with the known transmitted control sweep signal, proper times and amplitudes can be abscribed to the paths taken by the transmitted signal.

The crosscorrelation between these two functions can be defined as

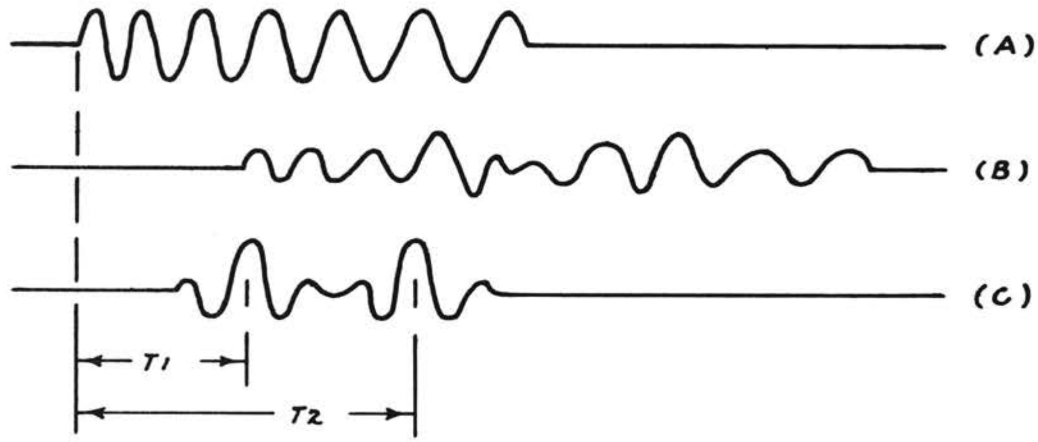

Figure 3. The correlation technique. (A) shows the generated signal, (B) the received composite signal, and (C) the crosscorrelation of (A) and (B).

$$\phi_{rg} = \frac{1}{T}\int_0^T r(t)\ g(t+\tau)\ dt \qquad (1)$$

where r(t) represents the received signal, g(t) represents the transmitted control sweep signal, and τ represents the incremental displacement between the two.

Performing the mathematical operation, as given in equation 1, on the example results in an output as shown in Figure 3C. In order to show the relationship between the correlated output and the original data, the transmitted control sweep signal and the received composite signal are shown in Figure 3C and 3D respectively.

As τ is varied incrementally and the multiplication and integration performed, ϕ_{rg} will reach its first maximum when $\tau = T_1$, where T_1 represents the travel time for path 1. ϕ_{rg} will reach another maximum at $\tau = T_2$, where T_2 represents the travel time for path 2. Therefore, the trace depicted in Figure 3C, very similar to that which would be obtained by other seismic methods, is in a form that can be readily interpreted.

In an actual case, the received information contains reflections from many subsurface interfaces as well as noise and interference. Consequently the correlation process is a must if intelligible results are to be obtained.

The equipment used to perform the correlation operation is called a correlator. Since the inception of the "VIBROSEIS" technique and before the advent of the magnetic correlator, two types of correlators have been used. In order to better appreciate some of the advantages of the magnetic correlator, a brief description of the first two types of correlators follows.

Electronic Correlator

The first type correlator used with the "VIBROSEIS" technique was classified as a multi-channel electronic correlator. At that time non-synchronous vibrators were in use, which made it mandatory that a sample of the base plate motion be recorded for each sweep. This sample became the control sweep. Consequently, the received reflected information had to be crosscorrelated with the control sweep that produced it.

The crosscorrelation operation was performed exactly as indicated by equation 1. The generated signal (control sweep) was taken from the field tape on the input drum assembly, amplified, and delayed in time, τ, by a delay drum. From there it was applied to one input of a multiplying circuit.

The received signal (signal picked up by the geophone arrays) was taken from the same field tape, amplified, and applied directly to the other input of the multiplying circuit. The output of the multiplier was integrated, by the use of an operational amplifier, over one complete revolution of the input drum. The output of the integrator, on completion of this drum revolution, was recorded as one point on a magnetic readout tape. This point then represented the crosscorrelation of the two signals when displaced in time by τ seconds. In order to describe signals as high as 100 cps, a sampling increment of three and one third milliseconds was used. Consequently the delay and readout drums were indexed in increments representing three and one third milliseconds and the correlation process repeated until the longest travel time of interest had been correlated. Therefore, each second of travel time required 300 separate index settings of the delay and readout drums.

The electronic correlator, as shown in Figure 4, had a capacity to correlate all forty channels of the input tape simultaneously, including as many as twelve control sweep channels. In addition, two sets of reproduce heads on the delay drum and two sets of record heads on the readout drum allowed correlation of two time zones simultaneously. Complete readout facilities were also included in the correlator equipment.

This type correlator is no longer in use. The advent of synchronous type vibrators paved the way for smaller and faster

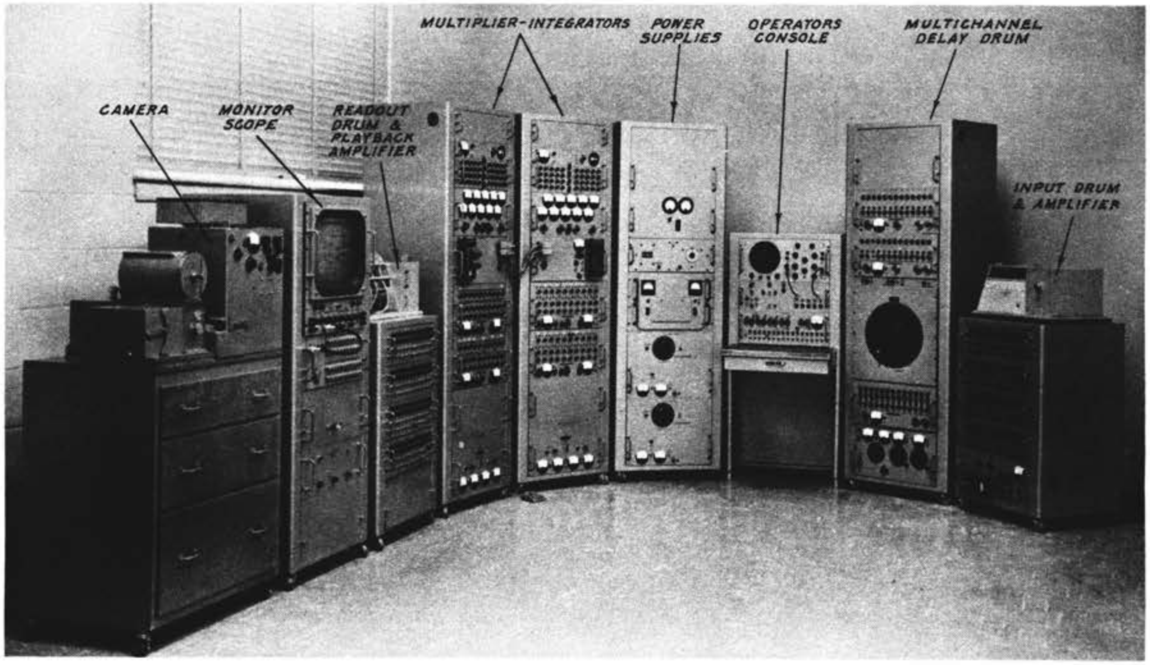

Figure 4. Electronic correlator

Figure 5. Optical correlator

correlators.

Optical Correlator

The second type correlator used with the "VIBROSEIS" technique is classified as an optical correlator. The optical correlator, which is presently in use on all of Conoco's "VIBROSEIS" field crews, is also a multichannel correlator.

Correlation on the optical correlator is accomplished as follows: The two signals to be crosscorrelated are each recorded as variable area traces on separate pieces of photographic film. The two pieces of film are placed in contact so that one variable area trace overlays the other. An extended light source is placed on one side of these films, and a continuous photo-voltaic cell, at least as long as the trace on the film, is placed on the other side. By sliding one film along the other, a varying amount of light is transmitted to the photo cell. The amount of light transmitted to the photo cell depends on the phase correspondence of the two signals at that particular displacement of the two films. Consequently by continuously adjusting the displacement between the signals, a function is described whose maxima correspond to points of considerable phase coincidence. This described signal is then recorded on a magnetic readout tape as a function of displacement between the two variable area records.

The optical correlator, as shown in Figure 5, has the capacity to correlate 12 channels simultaneously. Normally, ten of these represent received data channels, one the control sweep for determining zero time, and one the 100 cps signal for timing purposes. Readout facilities are also available for recording the final correlated record on film.

Since the crosscorrelation of two signals is obtained at all points simultaneously for any given phase displacement, the time required to correlate a record on the optical correlator is considerably less than that required by the electronic correlator.

The reasonable initial cost and size of the optical correlator allowed one to be placed on each field crew. The major disadvantage of the optical correlator is the cost of the great amounts of film required for routine correlation of a field recording crew's production. Some loss of time is incurred by the delay required for the variable area films to dry before the correlation process can be performed.

The magnetic correlator reduces both the initial cost and size, as well as eliminates the film cost associated with correlation. All further discussion will pertain to the prototype magnetic correlator.

CHAPTER II

THEORY OF MAGNETIC CORRELATION

Consider a magnetic tape, on which has been recorded a signal, whose recording current can be represented by the equation

$$i = kg(t) \qquad (2)$$

The value of remanent flux, ϕ_r, left in the tape is proportional to the magnetizing force applied at that point, which in turn, is proportional to the current that produced it, therefore

$$\phi_r = k_1 i = kk_1 g(t) \qquad (3)$$

The density of the flux, B_s, entering or leaving the surface of the tape varies with the changes in the remanent flux, ϕ_r, within the tape at that point. Therefore

$$B_s = k_2 \frac{d\phi_r}{dt} = k_3 \frac{d[g(t)]}{dt} \qquad (4)$$

Now consider a conductor that is placed tangent to the surface of the recorded magnetic track and perpendicular to its direction of motion during recording. If the tape is drawn past the conductor, a voltage, e, will be induced into the conductor which at any instant will be

$$e = k_4 B_s l v \qquad (5)$$

where B_s is the surface flux density at that instant, l is the effective length of the conductor cutting flux at right angles, and v is the relative velocity between the conductor and the tape.

Substituting equation 4 for B_s, equation 5 becomes

$$e = k_5 l v \frac{d[g(t)]}{dt} \qquad (6)$$

which states that the voltage induced in the conductor is proportional to the rate of change of the original function as well as to the effective length of the conductor cutting lines of flux.

Now consider a copper conductor that is shaped into a waveform that can be expressed by

$$y = k_6 g(t) \qquad (7)$$

where the maximum excursion of y does not exceed the width of the track recorded on magnetic tape. g(t) represents a function which is identical to that expressed in equation 2. For convenience, it is expressed as a function of time. Time being equal to s/v, where v is equal to the velocity of the tape in the previous recording and x is the distance along the conductor or tape. If the flux, as given in equation 3, were plotted against distance, x, along the tape it would be identical to the conductor waveform, given by equation 7, except perhaps for amplitude.

If this conductor is placed in contact with the recorded magnetic track as shown in Figure 6 and the magnetic tape drawn past the conductor, a voltage will be induced in the conductor that is proportional to the rate at which it cuts

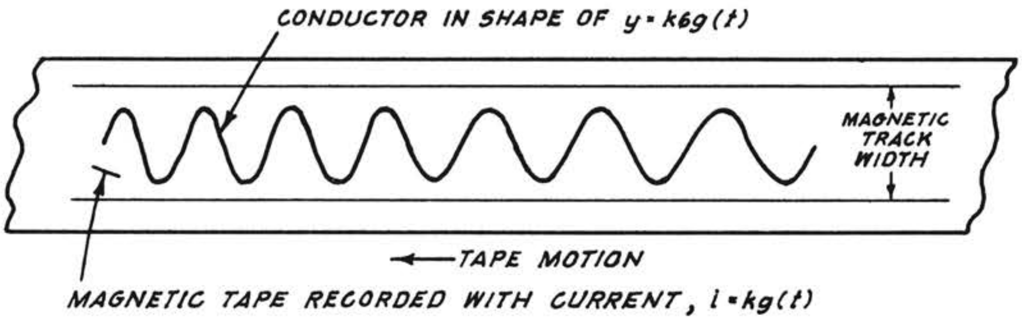

Figure 6. Showing the conductor in contact with the tape.

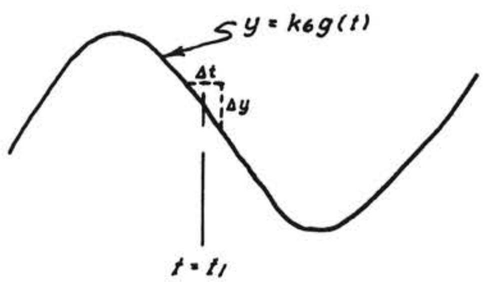

Figure 7. Determining the effective length of the conductor.

the flux lines along the tape.

To determine the effective length of conductor cutting lines of flux at any point , refer to Figure 7.

The effective length of conductor cutting flux lines at point t_1 will be equal to Δy as Δt approaches zero, or

$$dy = k_6 \frac{d[g(t)]\,dt}{dt} \qquad (8)$$

Consequently the incremental voltage induced in the conductor at one point along its length and at one given phase relationship with the magnetic track will be

$$e = KB_s v \, dy \tag{9}$$

Substituting for B_s, equation 4, and dy, equation 8, gives

$$e = vk_7 \frac{d[g(t)]}{dt} \frac{d[g(t)]\,dt}{dt} \tag{10}$$

The voltage induced along the whole length of the conductor, but still for only one phase relationship with the magnetic track, can be found by integrating equation 10 with respect to the variable t over the entire length of the conductor. This then results in

$$e = vk_7 \int_0^{T} \frac{d[g(t)]}{dt} \frac{d[g(t)]}{dt} \, dt \tag{11}$$

where T represents the total length of the conductor expressed in units of time.

To obtain an equation that expresses the voltage induced in the conductor for any phase relationship between it and the magnetic track, equation 11 is modified to be

$$e = vk_7 \int_0^{T} \frac{d[g(t)]}{dt} \frac{d[g(t+\tau)]}{dt} \, dt \tag{12}$$

where τ represents the displacement along the time axis between the conductor and the magnetic track.

It has been shown[2] that for a given autocorrelation function

$$\phi_{11}(\tau) = \frac{1}{T}\int_0^{T} f_1(t)\, f_1(t+\tau)\, dt \tag{13}$$

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[2]Lee, Y. W., Statistical Theory of Communication (New York, 1960), pages 72 and 73.

its second derivative is

$$\phi''_{11}(\tau) = -\frac{1}{T}\int_0^T \frac{d[f_1(t)]}{dt}\,\frac{d[f_1(t+\tau)]}{dt}\,dt \qquad (14)$$

which is also an autocorrelation function. It is the autocorrelation function of the derivative of $f_1(t)$, except for the change of signs.

In comparing equation 12 with equation 14 it is obvious that equation 12 represents an autocorrelation function. The voltage induced in the conductor is therefore proportional to the autocorrelation function of the derivative of g(t).

Consider the case where g(t) represents a linear sweep of frequencies. Then

$$g(t) = A \sin 2\pi\left[f_0 + \frac{(f_1 - f_0)t}{2T}\right]t \qquad (15)$$

where f_0 is the starting frequency, f_1 the ending frequency, and T the length of the sweep in seconds.

Differentiating g(t) with respect to time results in

$$g'(t) = 2\pi A\left[f_0 + \frac{(f_1 - f_0)t}{T}\right]\cos 2\pi\left[f_0 + \frac{(f_1 - f_0)t}{2T}\right]t \qquad (16)$$

where the term $f_0 + \frac{(f_1 - f_0)t}{T}$ is the instantaneous frequency, f_i, at time t. Rewriting and making a trigonometric substitution, equation 16 becomes

$$g'(t) = 2\pi A f_i \sin\left\{2\pi\left[f_0 + \frac{(f_1 - f_0)t}{2T}\right]t + \frac{\pi}{2}\right\} \qquad (17)$$

It is apparent from equation 17 that the derivative of g(t) has an amplitude response that is proportional to the instantaneous frequency and a phase response that leads that of g(t) by 90 degrees at all frequencies in the sweep.

It follows then, that the output of the conductor for a g(t) as given by equation 15 is proportional to the autocorrelation of g(t), but with an amplitude response that varies as the square of the frequency. Its phase spectrum, of course, will be zero.

To obtain a true autocorrelation function of g(t) with the proper amplitude spectrum, the output of the conductor, as given by equation 12, can be compensated with a dcuble integration which would result in an output, ϕ_{gg}, given by

$$\phi_{gg} = vk_7 \int_0^T g(t)\ g(t + \tau)\ dt \qquad (18)$$

Consequently, the magnetic correlation process can be made to perform true correlation.

Applying equation 18 to the "VIBROSEIS" technique, g(t) represents the generated linear control sweep, and its autocorrelation function, ϕ_{gg}, represents zero time on the readout magnetic tape.

For the case of crosscorrelation, equation 18 becomes

$$\phi_{rg} = vk_8 \int_0^T r(t)\ g(t + \tau)\ dt \qquad (19)$$

where r(t) represents the received signal from the geophones and consists essentially of many g(t) signals added together at various time delays. These time delays, of course, represent the travel time of the generated control sweep from the vibrator to various reflecting horizons and back to the geophones. The conductor will have the shape of the waveform of g(t). The signal r(t) is recorded on magnetic tape so that its wavelengths are compatible with those of the conductor. A volttage will be induced in the conductor as it scans the magnetic tape. Compensating the output of the conductor with a double integration will result in an output that is proportional to the crosscorrelation function, ϕ_{rg}, with respect to displacement, τ.

The conductor referred to in this chapter will hereafter be called the copper head. The characteristics and fabrication of the copper head are detailed in Chapter 4.

CHAPTER III

THE OVERALL SYSTEM

The prototype magnetic correlator was designed to take a field magnetic tape, recorded with signals employed by the "VIBROSEIS" technique, and to produce as an end product a correlated readout magnetic tape capable of being reproduced by conventional seismic playback systems. The correlator, as such, shown in Figure 8, is a self-contained unit except for two external power supplies which are not shown. These power supplies supply the 12 volts and 300 volts necessary for the operation of the amplifiers, bias oscillator, and control circuitry. Exploded views of the correlator are shown in Figures 9, 10, 11, and 12.

Physical Description

The correlator is housed in a rigid aluminum framework. The base plate and the three drum shaft bearing plates are made of 3/4 inch aluminum jig plate, while all panels are made of 1/8 inch aluminum plate.

The aluminum input drum is 7.500 inches in diameter and 12 5/8 inches wide. Twelve mechanical fingers across the drum provides a means of holding a standard 11 3/4 inch magnetic tape (the size used for field recording). A groove,

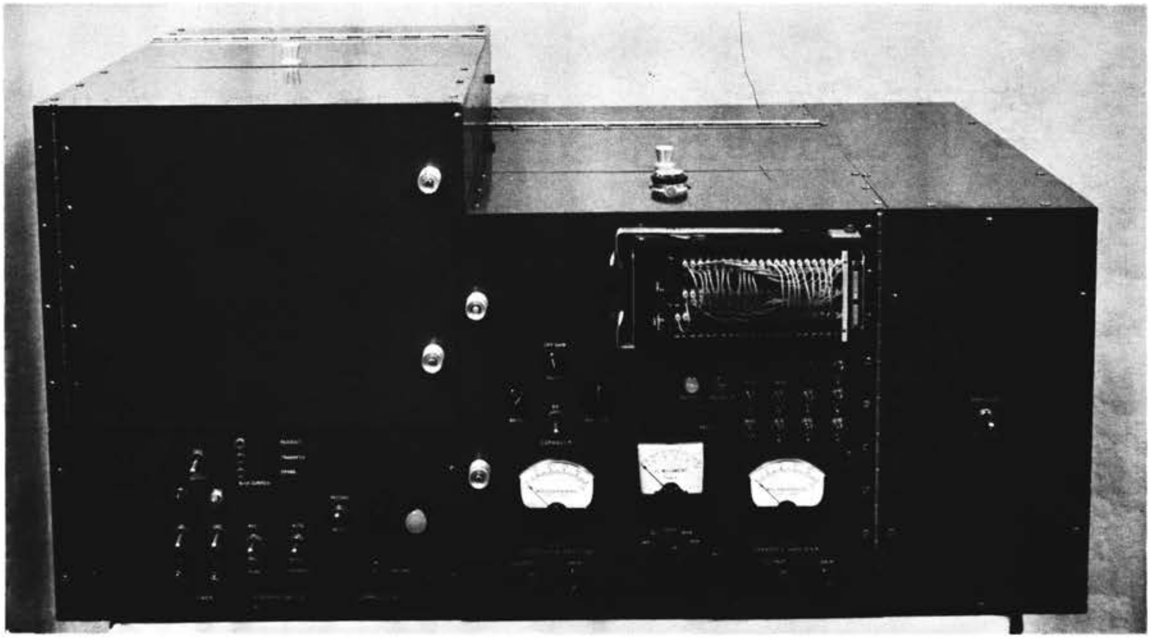

Figure 8. Prototype magnetic correlator, front view.

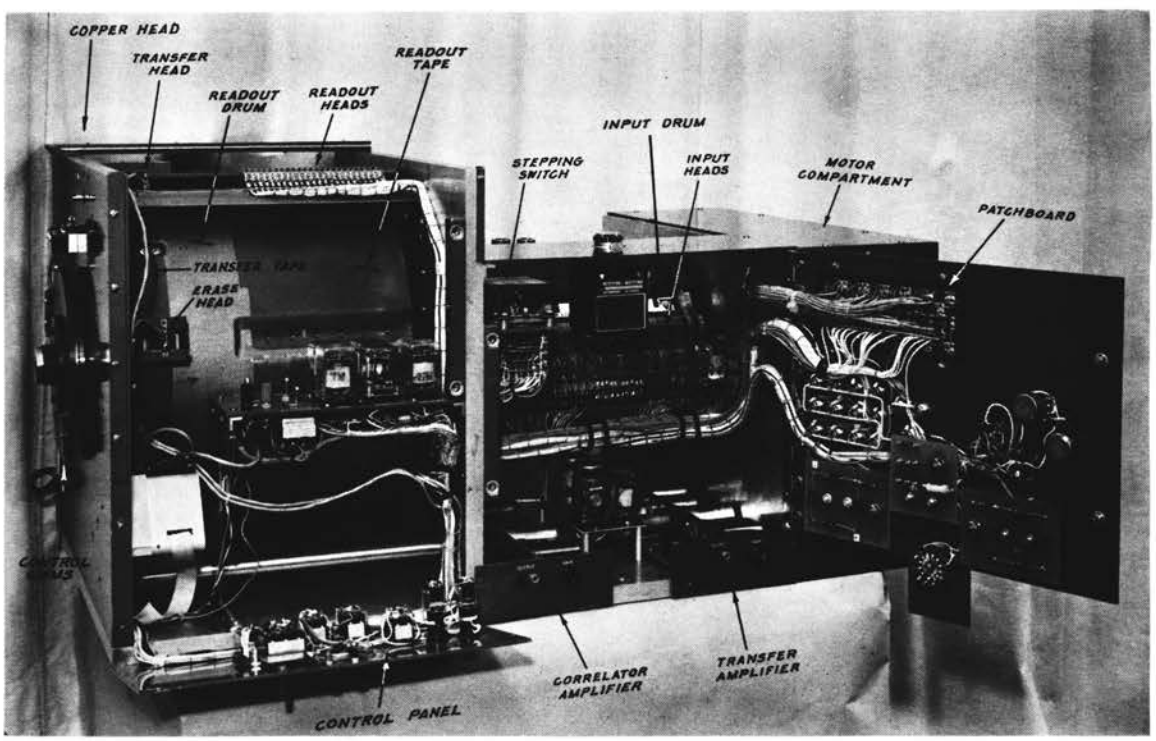

Figure 9. Prototype magnetic correlator, front view with panels removed.

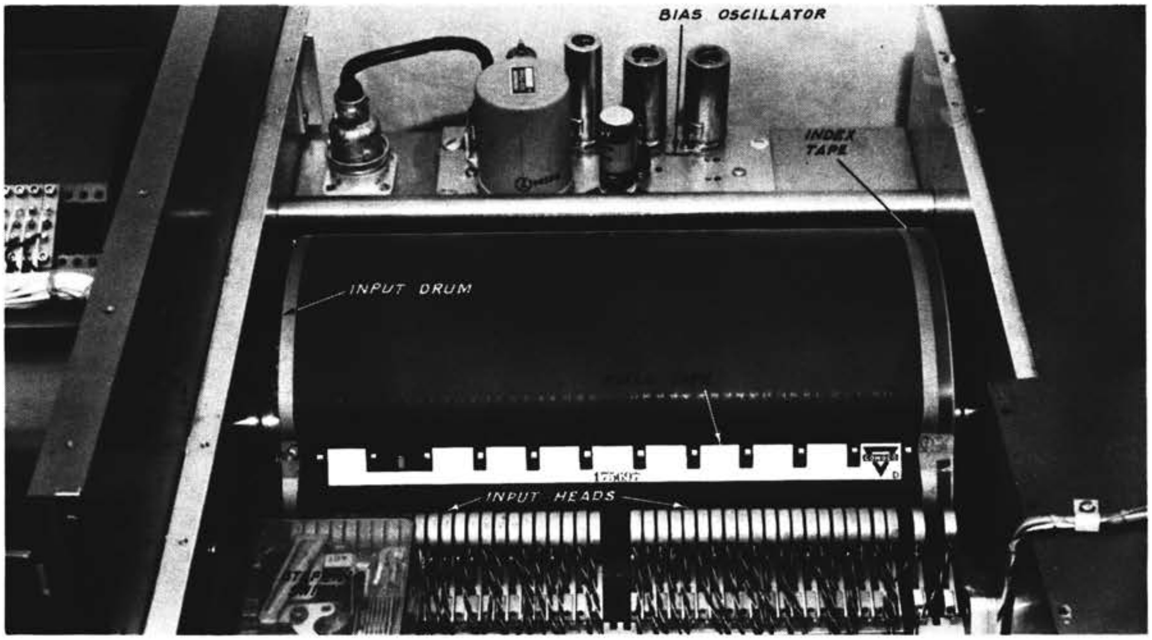

Figure 10. Prototype magnetic correlator, input drum assembly, top view.

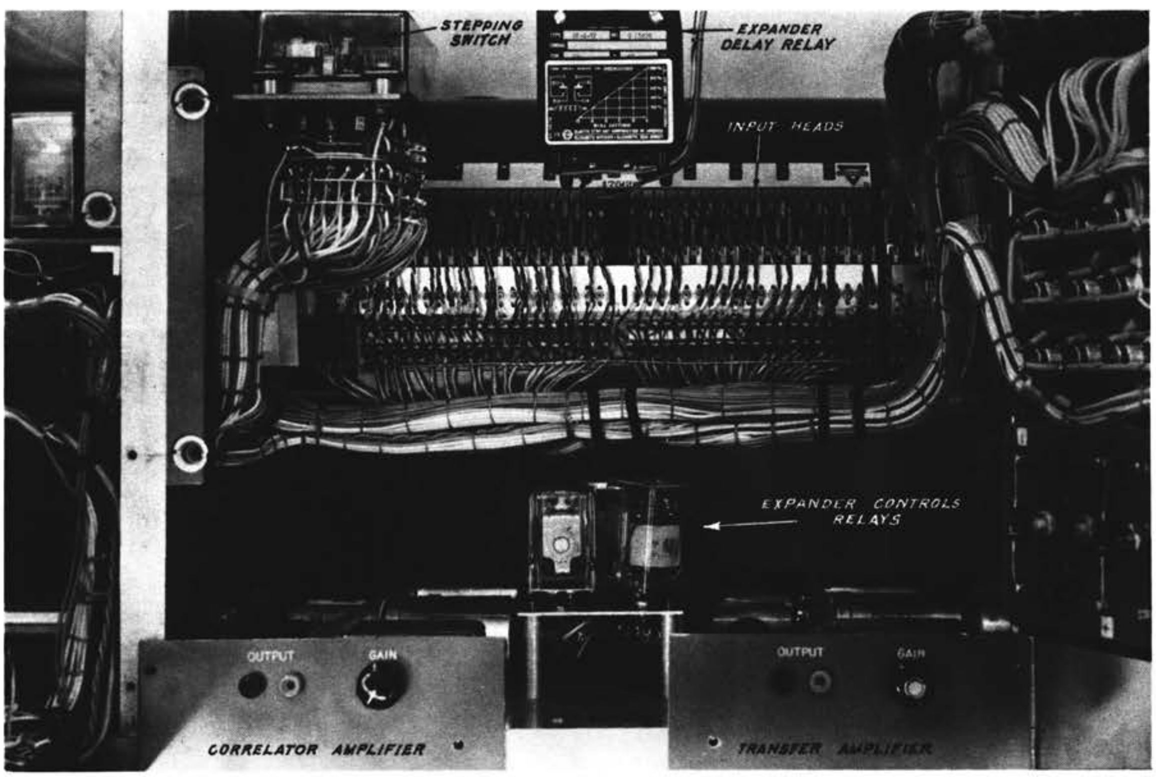

Figure 11. Prototype magnetic correlator, input drum as
front view.

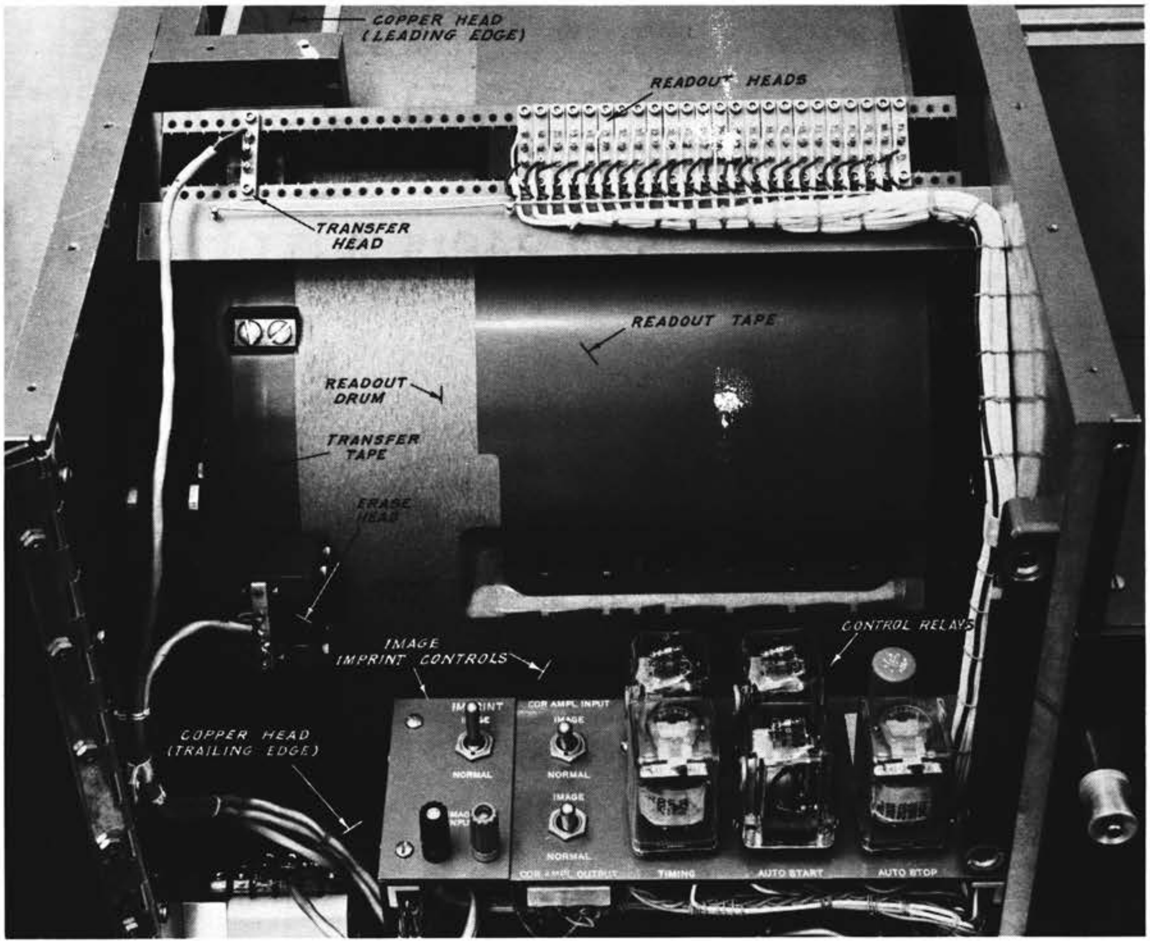

Figure 12. Prototype magnetic correlator, readout drum assembly, top view.

.010 inches deep and .503 inches wide, on the right side of the drum is provided for a 1/2 inch wide index magnetic tape, which contains the control sweep.

The aluminum readout drum is 15.000 inches in diameter and 11 1/2 inches wide. Two sets of six mechanical fingers each across the right side of the drum provides a means of holding each end of a standard 7 inch wide magnetic tape (the size used for the readout tape). This tape, normally used on a 7 1/2 inch diameter drum, covers only one half of the circumference of the drum, therefore a dummy tape is attached to cover the remainder of the drum in order to protect the magnetic heads. A groove, .0065 inches deep ond one inch wide, on the left side of the drum is provided for the one inch wide transfer tape. The transfer tape encircles the drum and both ends of the tape are clamped in a recessed well.

The input and readout drums are rigidly connected together by means of a 1 1/2 inch diameter stainless steel shaft. An 1800 rpm, 115 volt, 60 cps hysteresis synchronous motor is coupled to the drum shaft through an 80 to 42 tooth spur gear reduction in cascade with a 180 to 1 precision spiroid gear reduction. This gives a periphial speed of 1.8 inches per second for the 7 1/2 inch drum and 3.6 inches per second for the 15 inch drum. The record speed for the field magnetic tape is 1.8 inches per second.

Electrical Description

A simplified signal path block diagram of the correlator is shown in Figure 13.

Forty-three fixed magnetic heads are mounted to make contact with the magnetic tape on the input drum. These heads are located to match the magnetic tracks laid down by the field magnetic recorder. Forty of these tracks contain information picked up by the geophone arrays, two contain 100 cps timing signal, and one the linear control sweep used to drive the vibrators.

The outputs of all the heads are connected to individual

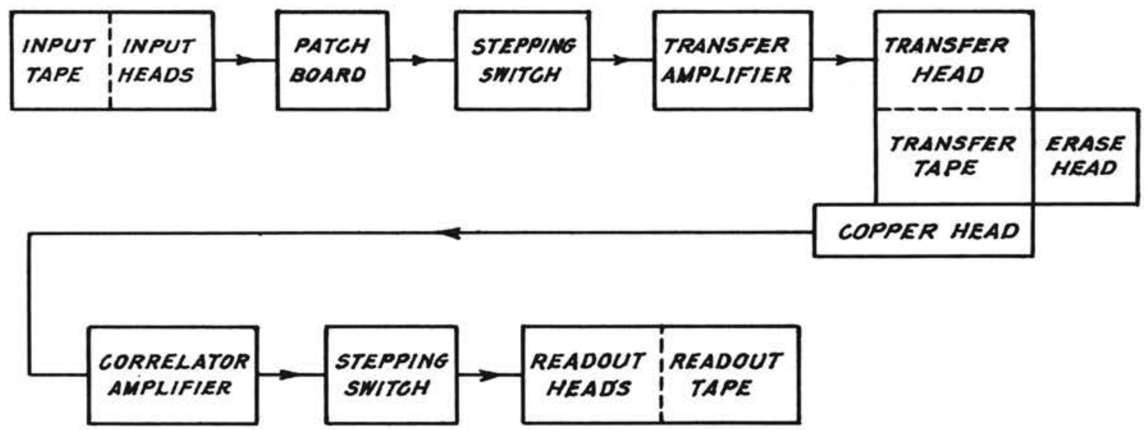

Figure 13. A simplified signal path block diagram.

contacts on the patchboard. Other patchboard contacts are connected to each of twenty-four contacts on the 30 position rotary stepping switch. The patchboard is programmed to composite those received data channels which combine to make one final trace, and to route the composited signal to the proper contacts of one pole of the stepping switch. The moving arm side of this pole of the stepping switch is connected to the input of the transfer amplifier. The output of the transfer amplifier is connected to the transfer head which records the signal on the transfer tape.

Correlation takes place as the transfer tape is rotated in contact with the copper head. The output of the copper head is connected to the input of the correlator amplifier where the correlated signal is amplified and properly compensated. The output of the correlator amplifier is connected to the moving arm of another pole of the stepping switch. The individual contacts of this pole of the stepping switch are connected in proper sequence to the twenty-four readout magnetic heads on the readout drum.

Therefore, in one revolution of the drums, a signal from the field tape, determined by the programming of the patchboard, is amplified, recorded on a transfer tape, correlated, amplified again, and recorded on a predetermined channel of the readout tape. In automatic operation, the stepping switch advances one position for each drum revolution until the prescribed number of channels have been correlated and recorded on the readout tape. An erase head, located between the end of the copper head and the transfer head, keeps the transfer tape in "ready" condition at all times.

In order that a "zero" time be represented on the readout tape, the control sweep is correlated with the copper head, thereby producing an autocorrelation wavelet. The center of this wavelet is the "zero" time from which the other events on the record are timed.

In order to abscribe times to these other events, a 100 cps signal, which is recorded on each of the field tapes by a tuning fork in the recording truck, is transferred to a timing channel on each readout tape. This transfer takes place during the sequential operation of the correlator. The copper head is by-passed for this operation.

A more detail analysis of various components of the prototype magnetic correlator will be given in subsequent chapters.

CHAPTER IV

THE COPPER HEAD

The copper head is the backbone of the magnetic correlator. Its function, as described previously, is to provide an output that is proportional to the crosscorrelation of the control sweep signal and the received signal.

Physical Description

The copper head is made of double copper clad epoxy glass board having an overall thickness of .016 inches. The thickness of the copper on each side of the board is .002 inches, and the thickness of the epoxy glass board is .012 inches. Thinner boards were tried, but had a tendency to bend and crease the copper backing which made it difficult to obtain the necessary uniform contact with the transfer tape. Thicker boards, on the other hand, do not readily conform to the curvature of the drum.

The nominal width of the printed circuit comprising the copper head is 1/2 inches, while the overall width of the device is 2 inches. This additional width provides the head with more dimensional stability, as well as allowing space for possible future developments. The back side of the head is also copper clad to provide the return lead for the head as well

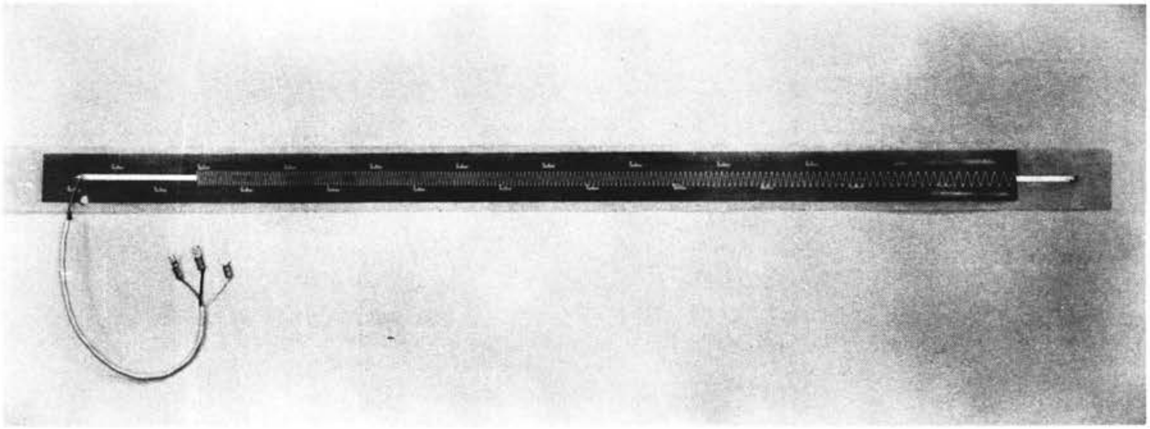

Figure 14. A typical copper head.

as to act as an electrostatic shield for the head.

The copper head is located relative to the transfer tape so that the entire length of its printed circuit is in contact with the transfer tape. This, of course, is essential if correlation is to take place at all frequencies of the control sweep. To allow for slightly different lengths of copper head circuits, the brackets for holding the copper head in place are positioned so that the copper head circuit is in contact with the transfer tape for 210 degrees around the circumference of the drum. Therefore, the maximum usable length of the printed circuit on the copper head is approximately 27.5 inches. This would correspond to a control sweep with a time duration of 7.6 seconds, when reproduced at the field tape speed of 1.8 inches per second.

A typical copper head is shown in Figure 14. The printed circuit shown here is 25.2 inches long and represents a control sweep of 38 to 12 cps over a time duration of seven seconds.

Separation Losses

To protect the copper head printed circuit, as well as the transfer magnetic tape, a 1 3/4 milli-inch thick mylar adhesive tape is placed over the copper head circuit. This, of course, separates the copper head from the transfer tape by 1 3/4 milli-inches. To study the effect of separating the copper head circuit from the transfer tape, tests were run to determine the relative loss in output of the copper head as separation increases. These tests were made by recording a steady state signal on the transfer tape and then measuring the output of the copper head for varying degrees of separation. Since this loss is frequency sensitive, the test was performed for frequencies of 15 cps, 30 cps, and 50 cps. The copper head used for this test represented a control sweep of 58 to 12 cps. These results are shown plotted in Figure 15.

Theoretically, the loss obtained in separating the copper head from the transfer tape should be identical to that of separating a normal reproduce magnetic head from a magnetic tape. This separation loss[3] has been found to be

$$\text{Loss (db)} = 54.6 \frac{d}{\lambda} \tag{20}$$

where d is the separation in inches and λ is the wavelength

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[3] Wallace, R. L., "Reproduction of Magnetically Recorded Signals", <u>The Bell System Technical Journal</u>, Volume XXX, Oct. 1951, Page 1153.

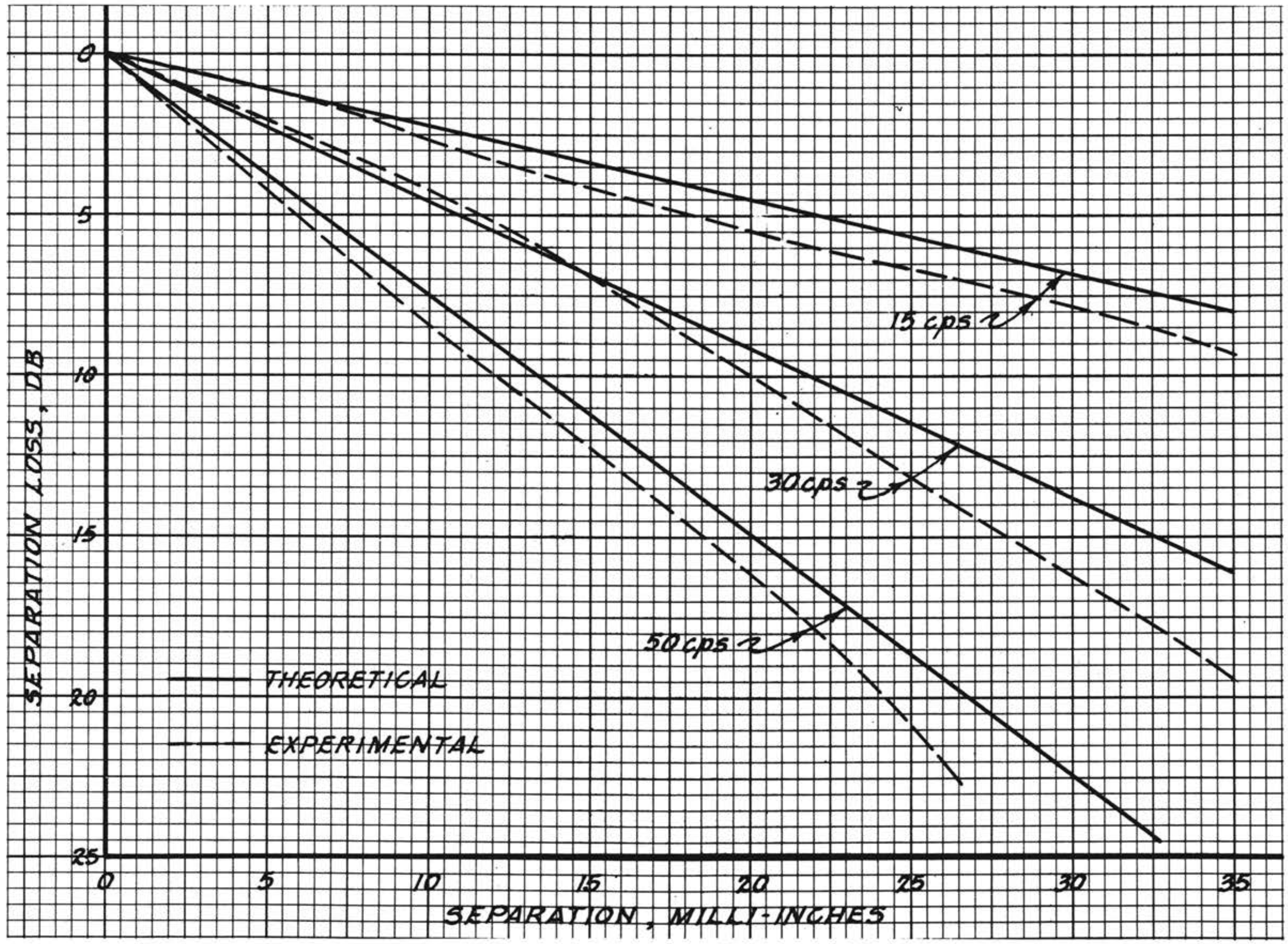


Figure 15. Plot of separation loss versus separation of copper head and transfer tape.

of the recorded signal in inches. Curves were plotted showing this theoretical loss for the same wavelengths and separations as those taken experimentally with the copper head. These curves are also shown in Figure 15.

The experimental and theoretical curves compare very favorably. As would be expected, the results show the separation loss to be directly proportional to the degree of separation and to the recorded signal frequency.

The loss due to the 1 3/4 mil mylar tape separating the copper head from the transfer tape is only 1.3 db at 50 cps. As will be seen later this loss is negligible.

Teflon tape was first tried as a separator because of its low coefficient of friction. It was soon discarded however, due to its tendency to flake off and contaminate the transfer and erase heads. It was also found that mylar tape, which is more readily available in assorted widths and thicknesses, offered negligible drag to the transfer tape. Consequently, the 1 3/4 mil mylar adhesive tape, being the thinnest commercially available adhesive tape, was chosen.

Frequency Response

In order to try to verify the results obtained in the theoretical section, a test was run to determine the frequency response of the copper head printed circuit. The copper head used for this test represented a sweep of 58 to 12 cps. This test was made by recording a steady state signal on the transfer tape and then measuring the output of the copper head.

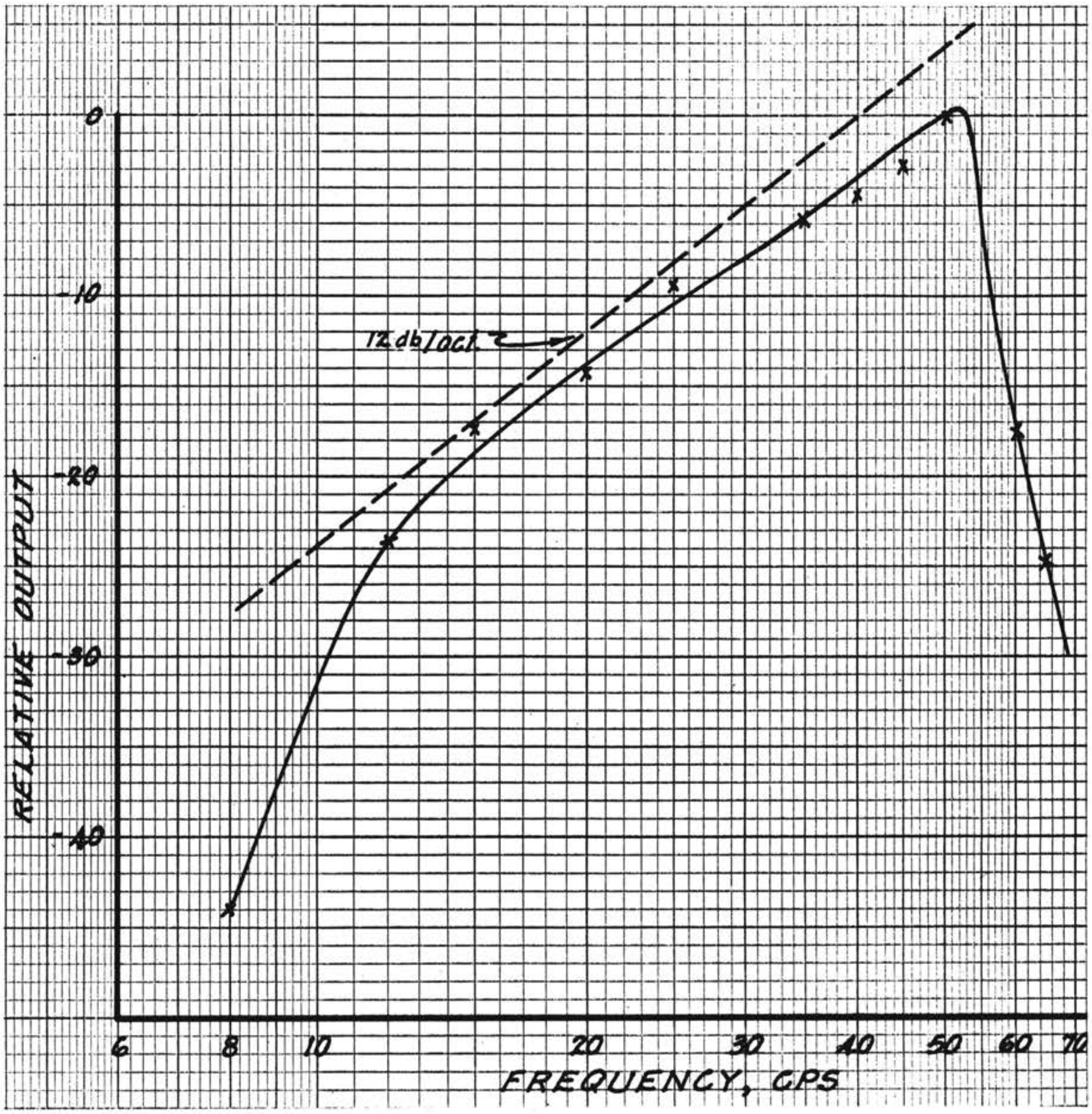


Figure 16. Output response of a 58 to 12 cps copper head.

This procedure was performed for several signal frequencies from 5 to 70 cps. The resultant plot of relative output in db versus frequency is shown in Figure 16. For comparison purposes the theoretical response of 12 db per octave is also shown. It is interesting to note that the test data shows an increase in output of approximately 11 db per octave with frequency within the limits of the control sweep. Accounting for part of this minor difference from the theoretical response is the separation loss, described previously, which, if not present, would increase the output of the upper octave of the sweep about .6 db per octave. The low output of the copper head at these steady state frequencies, especially the lower frequencies, make it difficult to obtain sharp definition at the ends of the sweep.

Another indication of the frequency response of the copper head is found by examining the shape of the waveform of the autocorrelation of the control sweep. A good example of this is shown in Figure 17, which shows the output of a copper head for three different amplitude responses of a 58 to 12 cps control sweep. The phase of the sweep is the same for each case. The output of the copper head is shown in Figure 17A for the case of a control sweep with a flat amplitude response with frequency, in Figure 17B for the case of a control sweep with an amplitude response that decreases at a rate of 6 db per octave with frequency, and in Figure 17C for the case of a control sweep with an amplitude response that decreases at a rate of 12 db per octave with frequency. As would be expected, the autocorrelation wavelet shown in Figure 17A contains too many high frequencies, as is evidenced by the ringing on either side of the wavelet. The same effect, to a lesser degree, is noticeable on the autocorrelation wavelet shown in Figure 17B. The autocorrelation wavelet shown in Figure 17C has a more proper waveform, indicating equal amounts

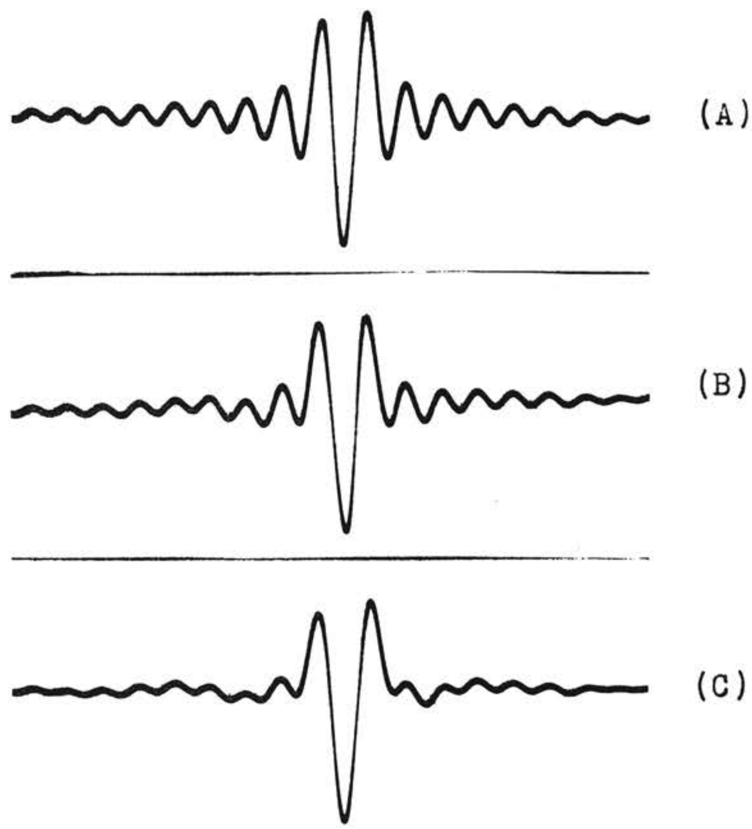


Figure 17. Autocorrelation functions for various amplitude responses.

of all frequencies withing the control sweep spectrum. This again, then, shows the output of the copper head to be very close to that which was predicted.

Fabrication

The process involved in the fabrication of the copper head requires three steps. These are 1) recording the control sweep on magnetic tape, 2) transferring the signal from magnetic tape to photographic film, and 3) etching the printed circuit on the double copper clad epoxy glass board.

The signal used for the control sweep is generated by an electronic sweep generator. The sweep generator, which is capable of generating linear sweeps of varying sweep rates and starting frequencies, is set to produce the desired control sweep over a period of seven seconds. The sweep is recorded on a magnetic tape at a tape speed of 1.8 inches per second. The drive system of this magnetic recorder is belt coupled to minimize wow and flutter. Speed variations occurring during this operation will produce a sweep whose autocorrelation function may contain undesirable background noise, thereby limiting the maximum attainable signal to noise ratio of the system.

Before going to the next step, the control sweep is autocorrelated on an optical correlator to check the shape of the waveform of its autocorrelation function as well as its signal to background noise ratio. As an example of what poor drive systems can do to a sweep, Figure 18 shows the autocorrelation function of a sweep recorded on a magnetic recorder using a gear drive system. The "ghost" to the extreme right of the autocorrelation wavelet was caused by a flutter rate being introduced in the sweep by a pinion gear with a slight amount of eccentricity.

After deciding the control sweep is acceptable, the control sweep tape is placed on the input drum of the magnetic-optical sweep recorder for transcription to film. The magnetic-optical sweep recorder is shown in Figure 19. The input and film drums are connected by a 1 1/2 inch shaft and are driven by a common drive system. This unishaft arrangement eliminates

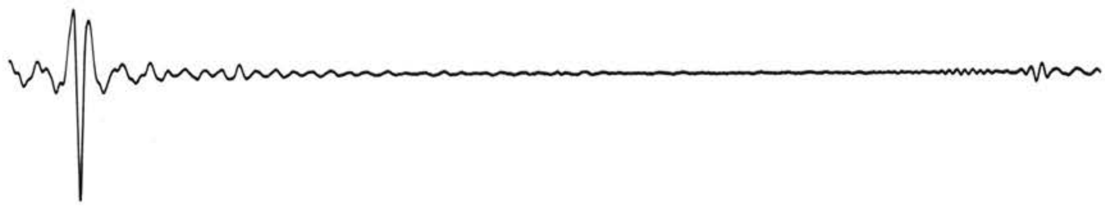


Figure 18. Illustration showing the effect of flutter on a control sweep's autocorrelation wavelet.

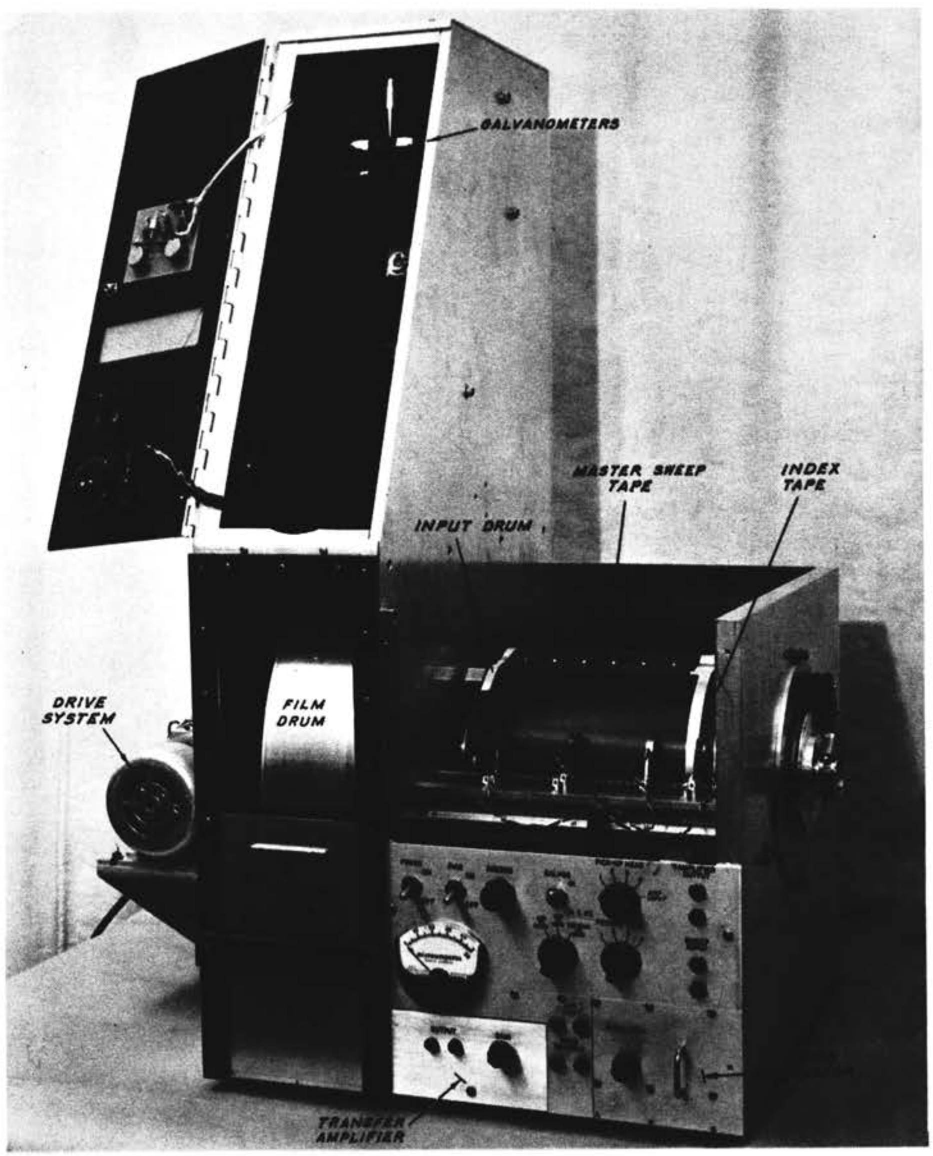


Figure 19. The magnetic-optical sweep recorder.

any ill-effects that might arise from the drive system, which in this case is gear driven. The diameter of the input drum is 7.500 inches which is the same as that of the input drum of the correlator. The diameter of the film drum is 15.023 inches. This diameter was calculated so that the film produced from the master control sweep would allow the fabrication of a copper head of such length that a proper autocorrelation would be obtained from it when the master control sweep tape was placed on the input drum of the magnetic correlator and the correlation performed.

The signal from the master sweep tape is fed to a transfer amplifier, which is properly compensated to correct for the normal head and tape characteristics. The output of the transfer amplifier is connected to a galvanometer. The gain of the amplifier is adjusted to give a maximum galvanometer deflection of 1/2 inches. A strip of photographic film, two inches wide, is loaded on the film drum such that the left edge of the film is flush with the lip on the left side of the drum. The galvanometer spot is located in the exact center of the film. Therefore, the resultant film record contains a control sweep 1/2 inches in amplitude and centered on the two inch film.

After the film has been recorded, it is necessary to make a film positive of it. This is done by making a contact print of the film negative. The final film record, then contains a clear trace on a black background.

The final step of the fabrication process is that of etching the copper clad epoxy glass board from the film positive. Presently, this is farmed out to an engraving firm and is processed much the same way as any printed circuit board. A hand drafted film positive is also provided for etching the reverse side of the board, which is also copper clad. The copper is removed around the edges of the board on the reverse side to provide isolation from the mounting clamps, which hold the copper head in place on the correlator.

Relationship to Index Tape

In order to provide uniform control sweeps for each field setup, the control sweep is recorded on a 1/2 inch wide tape, called the index tape. The index tape fits in a 1/2 inch wide slot on the field magnetic recorder. The control sweep is then transferred from the index tape to each field tape as needed.

Since the output of the copper head must be proportional to the autocorrelation of the control sweep, a definite relationship must exist between the copper head and the index tape. This relationship, however, need only be concerned with the final result obtained on the output of the correlator amplifier. Therefore, by varying the compensation used in the correlator amplifier, it is possible to alter the phase and amplitude relationship of the copper head and index tape, if needed, to facilitate their fabrication.

Ideally, it would seem that the simplest method of producing an index tape, compatible to a given copper head, would be to transcribe it from the same master control sweep, from which that particular copper head had been made. Provisions were made on the magnetic-optical sweep recorder so that this transcription could be performed. The input drum of the recorder provides a .010 inch deep slot for mounting a 1/2 inch wide index tape along side the master control sweep tape. Switching is provided so that the signal from the master sweep tape is routed through the broadband transfer amplifier to the input of a magnetic head located in contact with the index tape. Proper tape modulation is obtained by adjusting the output of the transfer amplifier for an output meter reading of 3.5 (calibrated to indicate milliamperes of signal current). The bias current is pre-adjusted for 18.5 milliamperes. In this way, then, index tapes can be produced very easily and quickly.

Unfortunately, however, it has been found that during the process of fabricating the copper head from the film positive, a dimensional instability exists in one or the other, such that the finished copper head circuit may not exactly overlay its film positive. These inconsistencies in copper head circuit lengths, therefore, make the index tapes produced directly from the master sweep tape incompatible with the copper heads so produced. This problem is presently under study and investigations are being made into other type films, copperclad materials, and methods of etching. Fortunately, the inconsistencies in the copper head circuit lengths are such that the linearity of the printed circuit sweep is not appreciably

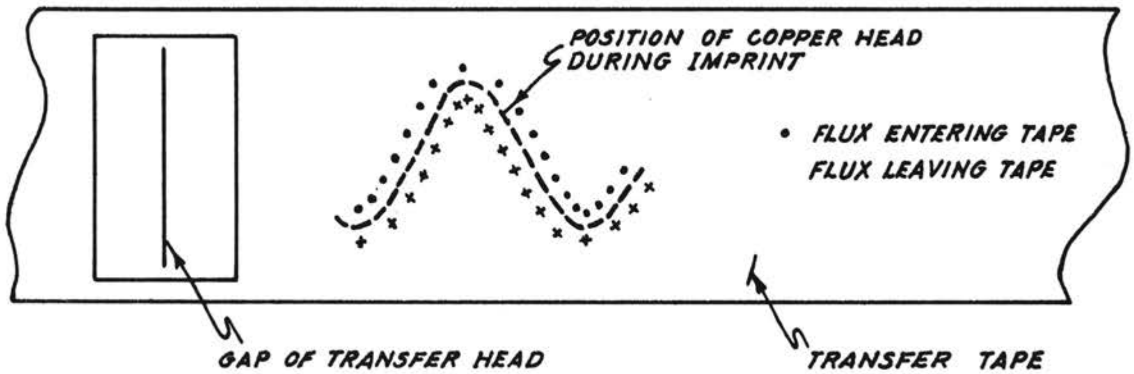


Figure 20. Flux path on the transfer tape after imprinting an image of the copper head.

affected. Therefore, the copper heads, so produced, are usable, provided a compatible index tape can be made. The process of making an index tape directly from a copper head is called imprinting an image of the copper head.

Imprinting an Image

If a current is passed through the copper head circuit in its normal contact position with the transfer tape, a magnetic field will encircle the copper head circuit, thereby inducing a magnetic flux in the transfer tape. The remanent flux left in the tape, after the current has been removed will be proportional to the current that produced it. If the drum is rotated, an instantaneous voltage will be developed in the transfer head that is proportional to the net number of surface flux lines cut at right angles per unit time by the head as the transfer tape passes under it. Figure 20 illustrates the flux paths in relationship to the original position of the copper head circuit.

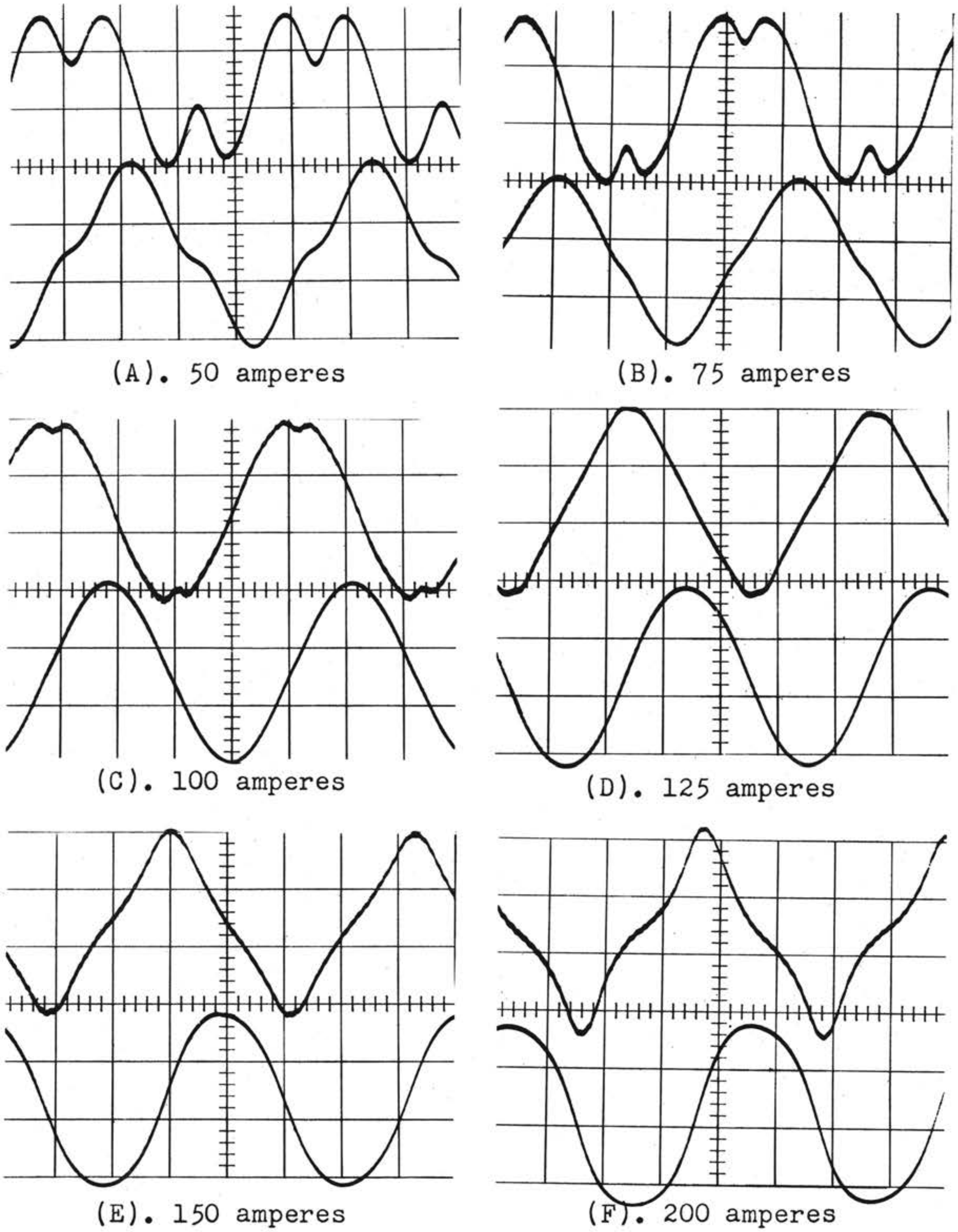
The surface flux shown above the dotted line in Figure 20 is of one polarity, while that shown below the dotted line is of the opposite polarity. It should be remembered that the flux induced in the tape is at right angles to the copper head circuit, while the flux seen by the transfer head is normal to the direction of tape motion. Therefore, the net surface flux seen by the transfer head, at any position, will be the algebraic sum of the horizontal components of the flux at that position. Certain deductions can now be made as to what the output of the transfer head will be. Compared to the original copper head circuit, the output of the transfer head will be of the same frequency and will have the same phase characteristics, except possibly for polarity. Amplitude-wise, however, it is more difficult to deduce its exact response. It would seem that the output would increase with frequency at a rate of between 6 db and 12 db per octave. One 6 db per octave is certain because the rate of change of flux is proportional to frequency. The horizontal component of the flux will also increase with frequency, so this should give rise to another increase of response with frequency, although it is doubtful that it will be a full 6 db per octave since the output of the head is proportional to the net horizontal component of flux cut per unit time.

Close examination of this technique will show that considerable distortion should exist at the peaks and troughs of the output waveform. If it is assumed that no "bunching" of flux takes place at the peaks or troughs, then the output at those points should dip toward zero.

In actual practice, however, it has been found that this distortion can be reduced sufficiently so that a usable output waveform can be obtained.

This is accomplished, in part, by using sufficient current during the imprint process to saturate the transfer tape. Figure 21 illustrates the effect of imprint current on the shape of the output waveform. The copper head imprinted in this example represents a 50 cps steady state signal. For each of the six imprints currents, the upper waveform represents the uncompensated output of the transfer head, while the lower waveform represents an output that has been compensated with one integration. The uncompensated outputs for the lower imprint currents, Figure 21A and 21B, show that the peaks and troughs do tend to dip toward zero as indicated earlier. Obviously too much imprint current will also produce a distorted output as shown in Figure 21E and 21F. Imprint currents of 100 and 125 amperes proved to produce the best looking output waveforms. These are shown in Figure 21C and 21D. The integration helps to remove the harmonics present in the uncompensated waveforms.

It has been found that when imprinting the image of a sweep, the output waveform at the lower frequencies show more distortion than do the higher frequencies. If enough imprint current is used to eliminate the distortion at the lower frequencies then the higher frequencies are distorted due to too much imprint current. Consequently a compromise is made in



(A). 50 amperes

(B). 75 amperes

(C). 100 amperes

(D). 125 amperes

(E). 150 amperes

(F). 200 amperes

Figure 21. Illustrating the effect of imprint current on the shape of the output waveform. For each of the imprint currents the upper waveform represents an uncompensated output, while the lower waveform represents an output that has been integrated.

selecting the proper imprint current for a sweep. It is thought that the reason the higher frequencies require less imprint current is because of the peaked waveform of the copper head at these frequencies. Copper tends to fill in at these peaks, consequently the flux pattern due to the imprint current is different than that obtained at the lower frequencies.

It has been found that a peak imprint current of approximately 120 amperes applied to a copper head circuit containing a control sweep is sufficient to provide an acceptable output waveform. In practice, the imprinting is accomplished by discharging a capacitor, previously charged to the proper voltage, through the copper head circuit. The average copper head has a resistance of approximately seven ohms. Therefore, a voltage source of around 1000 volts is desirable. A capacitor having a capacitance of 8 microfarads is normally used. In order to keep the charging voltage to a minimum value, the resistance of the copper head circuit is kept as low as possible.

Experimental results have shown the output of the transfer head for an image imprint of a sweep to be slightly greater than a 6 db per octave increase with frequency. By integrating the output of the transfer head, an output is obtained that is approximately flat in amplitude, but lagging in phase by 90 degrees at all frequencies in the sweep. As was mentioned earlier in this chapter, the relationship between the copper head and the index tape is only such that the output of the correlator amplifier be an autocorrelation wavelet when these two signals are correlated. Consequently, the signal obtained by the imprint process, after integration, can be used as the control sweep on the index tape as long as proper compensation is provided in the correlator amplifier to compensate for the lagging 90 degrees phase.

CHAPTER V

SYSTEM RESPONSE

The amplitude and phase response of the overall system can best be determined by examining the response of the individual components that make up the system.

Figure 22 shows a block diagram of the system with amplitude and phase plots at various points along the system as well as the amplitude and phase plots of some of the individual components. The following discussion will refer to Figure 22.

First of all, it will be assumed that the control sweep circuit on the copper head is the reference signal. Plot A shows this signal to contain equal amplitudes of all frequencies within its spectrum. The phase plots before correlation, as shown in Plots B, C, and E, are referenced to the phase of the reference signal, while those after correlation, as shown in Plots F, G, and I, are reference to the phase of the signal that would be obtained if true correlation had taken place.

The input signal, for this discussion, will be the control sweep signal as recorded on the field magnetic tape. This control sweep signal, having been transcribed from the index tape to the field tape, will have a flat amplitude response , but a phase response that lags the reference signal by 90 degrees at all frequencies in the sweep. This response

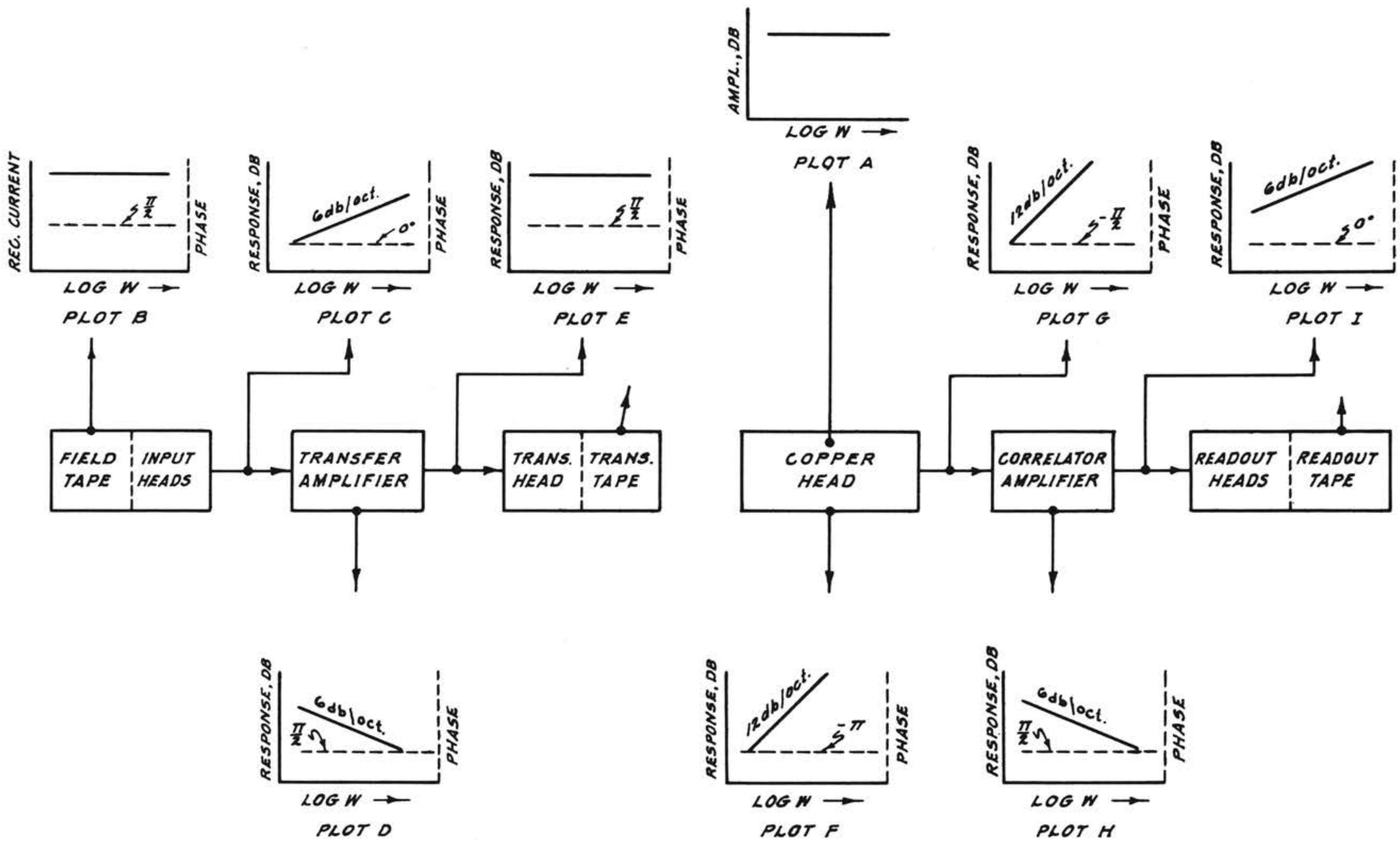


Figure 22. Theoretical amplitude and phase plots of the prototype magnetic correlator.

is shown in Plot B.

In reproducing the input signal from the field tape, the input head differentiates it, thereby producing the response as shown in Plot C. To compensate for this differentiation, the signal is integrated by the transfer amplifier. The response of the transfer amplifier is shown in Plot D, while the response of the input signal at the output of the transfer amplifier is shown in Plot E. Therefore, the signal recorded on the transfer tape is identical to the input signal as recorded on the field tape.

The copper head, which produces a crosscorrelation of the derivative of the two signals involved, has an amplitude and phase response, relative to that of a true correlation, as shown in Plot F. The amplitude response increases with frequency at a 12 db per octave rate, while the phase response is a constant 180 degree lead at all frequencies.

With the input signal, as shown in Plot E, applied, the correlated output of the copper head will have an amplitude response that increases with frequency at a 12 db per octave rate and a phase response that is a constant 90 degree lead when compared to that of a true correlation.

This output is applied to the correlator amplifier which, as shown in Plot H, has an amplitude response that decreases with frequency at a 6 db per octave rate and a phase response that lags its input by a constant 90 degrees.

The correlated signal at the output of the correlator amplifier now has the same phase response as that of a true correlation but an amplitude response that increases with frequency at a 6 db per octave rate. This response, which is also the response of the signal recorded on the readout tape, is shown in Plot I.

Therefore, for this case, the correlator produced an output that represented a true autocorrelation of the control sweep on the copper head, except that its amplitude response, instead of being flat, increased at a 6 db per octave rate with frequency. This, in itself, is of little consequence since the autocorrelation of the control sweep is used only to locate zero time on the readout record. In either case, since the phase is the same, maximum correlation would occur at the same time.

Had the input signal had an amplitude response that decreased with frequency at a rate of 6 db per octave, but with the same phase response as before, the output of the correlator would have been a true autocorrelation of the control sweep signal on the copper head.

The latter condition is more nearly representative of the control sweep signal after it has been transmitted through the earth. The earth acts as a low pass filter, therefore, the higher frequencies are attenuated more than the lower frequencies. Consequently, the magnetic correlator, whose amplitude response is proportional to frequency, helps compensate for this earth characteristic when these returned signals are crosscorrelated with the copper head signal.

CHAPTER VI

OTHER DESIGN CONSIDERATIONS

While it is not the purpose of this thesis to go into a detailed description of all the components of the prototype magnetic correlator, it is pertinent to mention the design considerations of some of these components.

Sequential Operation

In both the electronic and optical correlators, all channels on the field tape were correlated simultaneously. This was done chiefly to conserve operating time, although neither system was very adaptable to any other type of operation. The magnetic correlator, on the other hand, lends itself to sequential operation much better than to multichannel operation. Correlating time is of little concern since each channel can be correlated in one revolution of the drums (13 seconds in this case). If multichannel operation were used, the copper head would have to contain circuits for each channel to be correlated. Many problems would be encountered in the process of fabricating a copper head of this type. Other disadvantages of the multichannel copper head are 1) a more critical copper head mounting problem, 2) an increase in drag on the drive system, 3) a greater susceptibility to open circuits, and 4) a cost proportional to the number of channels. In addition to the multichannel copper head, multichannel amplifiers would also be required.

Sequential operation simplifies these problems, as well as making feasible other improvements, because of only one channel being required.

High Frequency Resolution

The high frequency resolution of the system can be increased by increasing the diameter of the drum on which the correlation takes place. This was accomplished very easily on the prototype magnetic correlator since the readout drum had to be twice the diameter of the input drum in order to record the readout tape at the proper speed. If a separate drum were used for the correlation drum, its diameter, in relationship with that of the input and readout drums, would not be critical as long as all three drums were driven from a common shaft. Of course, the copper head circuit would have to be adjusted in length to be compatible with the transferred signal from the input drum. Factors limiting the diameter of a correlation drum are 1) physical size, 2) drive power requirements, and 3) length of copper head. The third factor is probably the most critical at this time since 36 inches is the longest length of printed circuit that can be etched commercially in this immediate area.

The upper frequency limit of the prototype magnetic correlator is approximately 100 cps.

Magnetic Heads

The output of the copper head is directly proportional to the width of its printed circuit, therefore, the signal to noise ratio of the system can be improved by making the copper head as wide as practical. Factors limiting the width of the copper head are 1) a necessity for wider transfer and erase magnetic heads, 2) an increased drag on the correlation drum, and 3) an increase of impedance with an increase of width of the copper head. The first factor, of course, is the most critical. Availability and cost determined the width of the transfer and erase heads. After taking all of these factors into consideration, the copper head track width was chosen at 1/2 inch. The transfer head, which must produce a track at least as wide as that of the copper head, was chosen to have a track width of 5/8 inches. In the image imprint operation, it is required that the transfer head be of sufficient width to completely include all of the flux pattern created by the copper head, therefore, the transfer head should be slightly wider than the copper head track. The erase head, which must completely erase the signal recorded on the transfer tape by the transfer head, was chosen to have a track width of 3/4 inches.

Correlator Amplifier

The amplitude of the received reflected energy decays with depth due to its attenuation by the earth. Therefore, the correlated output of the copper head will decay with respect to time during its crosscorrelation with this received signal. To compensate for this decay in output, an expander circuit is incorporated into the correlator amplifier. Its function is to provide a base leveled output over the time interval of interest.

Expansion is accomplished in the correlator amplifier by varying the light intensity on a photoconductor that acts as the shunt leg of a voltage divider on the grid of the next to last amplifier stage. The resistance of the photoconductor varies inversely as the intensity of the light. The light intensity is varied by discharging a capacitor through the lamp that provides the light for the photoconductor. The rate of decay is determined by the time constant of the capacitor and the resistance of the lamp. The amount of expansion is determined by the initial charge on the capacitor.

Maximum expansion available in the correlator amplifier is 15 to 1. Decay rates are adjustable to give total expansion in .5, 1, 1.5, or 2 seconds.

An adjustable time delay relay is used to start the gain expansion at the desired time on the correlated signal.

CHAPTER VII

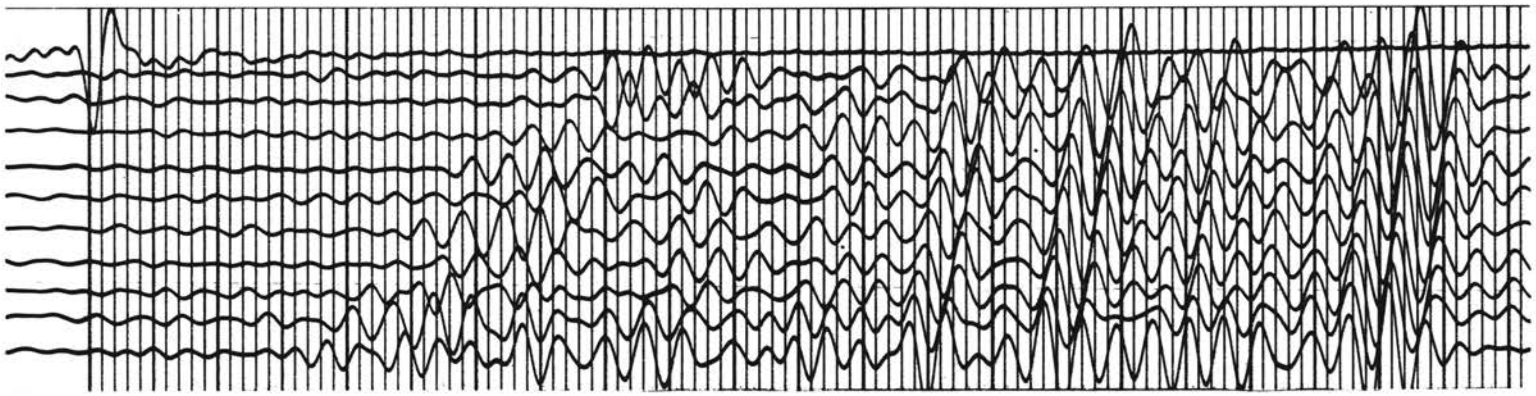
SUMMARY AND CONCLUSIONS

The results obtained thus far with the prototype magnetic correlator have been very gratifying. The magnetic correlator will provide the "VIBROSEIS" technique with a correlator that is 1) less expensive to build and maintain, 2) faster in operation, and 3) smaller in physical size than those presently in use.

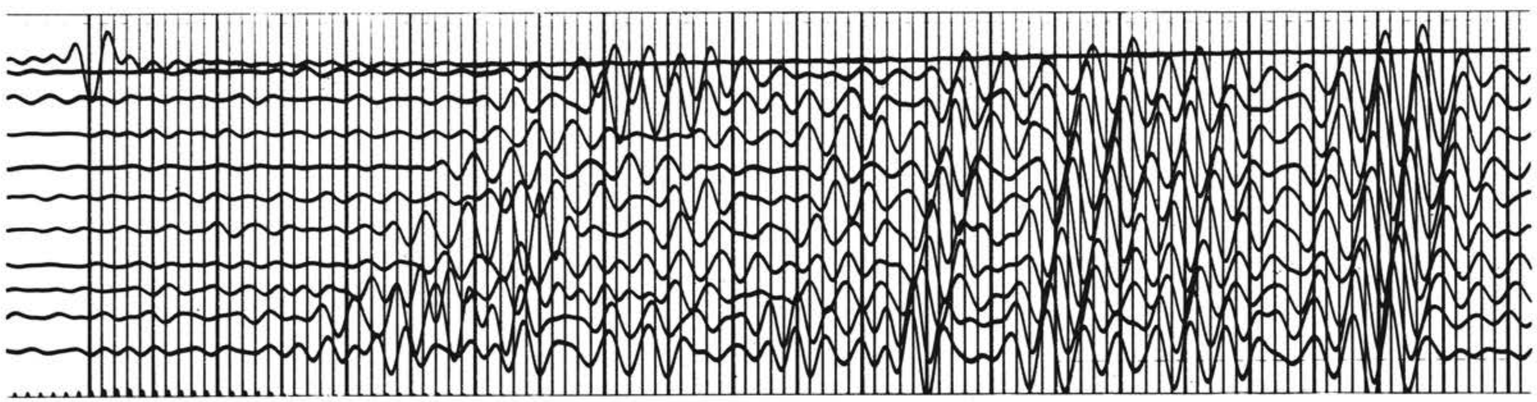
Comparisons made with the optical correlator show the two to produce almost identical results. An example of one of these comparisons is shown in Figure 23.

While the magnetic correlator, in its present state, is an operational piece of equipment, experimentation continues along the lines of copper head fabrication, imprint techniques, and system capabilities.

The rapid advancement of the art of making printed circuit boards will no doubt make it possible to achieve better dimensional stability of the copper heads in the future. Such improved stability might allow using the master control sweeps for making the index tapes instead of having to resort to the imprint technique. Even so, however, there would be special situations that would still require the use of the imprint technique. It is felt that substantial improvement can be



(A). Optical correlator



(B). Magnetic correlator

Figure 23. Correlator comparisons made from the same field tape.

made in the imprint technique by carefully controlling the shape of the copper head circuit.

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