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Cross correlation of sensory stimuli and electroencephalogram

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CROSS CORRELATION OF SENSORY STIMULI
AND ELECTROENCEPHALOGRAM

by

R. John Morgan

A Dissertation Submitted to the
Graduate Faculty in Partial Fulfillment of
The Requirements for the Degree of
DOCTOR OF PHILOSOPHY

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1969

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INTRODUCTION

The precise mechanism by which the nervous system perceives pitch is not completely understood. Several theories have been advanced by research physiologists and supporting studies have been reported for most of the theories. Some of these theories postulate synchronous transmittal to the central nervous system for periodic signals with frequencies as high as 5000 Hz. Others hypothesize that such synchronous transmittal stops at much lower frequencies, around 100 Hz.

Whatever the cutoff frequency for synchronous transmittal, frequencies below it, that actually arrive at the audio cortex, should be recoverable from scalp-recorded signals by informational techniques.

This study seeks to devise signal-recovery techniques by which it will be possible to determine if there is synchronous transmission of periodic signals to the auditory cortex, and what the upper frequency limit might be.

The cross-correlation function of communication theory is a mathematical tool by which signals may be recovered from noise. The cross-correlation function is closely allied to the correlation coefficient of statistics. The correlation coefficient compares two signals (events, processes) to measure their similarity. A correlation coefficient of +1 indicates that the two signals are exactly alike. If two signals are alike except that one of them comes after the

other in time, the correlation coefficient will not, in general, show this. However, the cross-correlation function will.

The cross-correlation function makes a similar direct comparison and also shifts one of the signals in time. The cross-correlation function shows its greatest positive value at that time shift for which the two signals are most alike. A simple example of this would be to compare a heavy rainfall on a watershed to the river depth downstream. The cross correlation of these two time functions would show a greatest positive value at a time corresponding to the time it would take the water to travel from where it fell to the river-depth gauge. It is this time-shift feature of the cross-correlation function which is of particular value in studying electrical signals such as those the nervous system produces.

Several signal-recovery schemes were considered and were rejected because of poor sensitivity, poor fidelity, or because of the complexity of the special hardware needed. Digital approximation to the cross-correlation function was the most sensitive and most feasible recovery technique considered. It was augmented by power-spectral-density estimates and auto-correlograms, also calculated digitally.

The dog was chosen as the experimental animal because of the similarity of its auditory system to the human auditory system and because of its availability.

The dogs used in this study were anesthetized, and electroencephalograms and stimuli were recorded during acoustic stimulation. Subsequently the analog records were processed to determine cross correlograms of stimulus with EEG and for power-spectral-density estimates of the EEGs.

It should be emphasized that no attempt at system identification has been made. The auditory system is nonlinear and the identification methods of linear analysis are of little value here. The only question being considered here is: Can one recover, by appropriate techniques, signal frequencies in the output signal (EEG) that were used as inputs (stimuli)?

REVIEW OF LITERATURE

The Auditory Evoked Responses

In order to establish the relationship between scalp-recorded electrical signals and acoustic stimuli, it is desirable to review selected parts of the audio evoked response literature, even though this study does not make use of the audio evoked response within the normal meaning of the term.

H. Davis and P. A. Davis first reported detectable electroencephalographic responses to auditory stimuli in 1939. The responses were small, unreliable, and masked by the background electrical activity. Many detection schemes and enhancement techniques have been suggested and developed since.

A useful method of detecting audio evoked responses used by Mills, Derbyshire, and Carter (1961) considered the whole trace following the stimulus. In this detection method, the centroid of the area under the trace, before and after the stimulus, is found. The location of these centroids is compared for detection of a response to the stimulus. This method yields information about the response amplitude and does not depend on the pattern of the response being constant. Although the method is elegant and is easily adaptable to computer processing, it is not widely used.

Most of the detection methods in wide use depend on the pattern of the evoked response being the same each time. Visual inspection of the electroencephalogram (EEG) for a change in the general pattern of the activity was the first detection method to be widely used. This method is still in wide use today. Some observers have developed rating scales to aid in evaluation of evoked response data (Derbyshire, Fraser, McDermott, and Bridge, 1956). These scales contribute to objectivity in evaluation. The detection of responses on a yes or no basis is computed numerically from measurements made on the EEG trace at specific times after stimulus. As research continued, more sophisticated detection methods developed.

Dawson (1947, 1950) used a photographic superposition technique as an averaging process to study evoked responses. He also reported detailed specifications for a mechanical sampler that automatically averaged responses.

Clark and his co-workers developed the ARC (average response computer) in 1958. Versions of this instrument are now commercially available. This special purpose digital computer is based on the premise that the background EEG activity is completely uncorrelated with the responses evoked by stimuli. Many responses are collected from one recording site on one subject. These are digitally added together--the signal traces are reinforced and the noise tends to cancel out. This results in a very much improved "signal-to-noise"

ratio. A more detailed description of the use of signal averagers to improve signal-to-noise ratio is discussed by Kiang (1961) and by Borsanyi and Blanchard (1962).

Another interpretation of the signal-averaging process is that it computes a cross-correlation estimate of the EEG with a time series of impulse functions that herald the onset of the acoustic stimulus. The very similar autocorrelation technique has not been used very much. Power-spectral density, which is the frequency domain counterpart of autocorrelation, has been used some, according to Brazier (1960). Other electronic aids to data collection and processing have not been neglected, however.

Telemetry of electroencephalograms from unrestrained subjects is reported by Reneau and Mast (1968). Their responses to acoustic stimuli were processed on an average response computer to get the average evoked audio response.

Derbyshire and McCandless (1964) used a different computer technique which compares the response and a template of what the response should be--a sort of matched filter process. If the correct response is known, this is an excellent technique because it gives information from one response, in contrast to the averaging computer which takes many responses.

The validity of the evoked response alone as a test for normal functioning of the auditory tract does not rest on a

completely solid foundation. Marcus, alone (1951) and with collaborators Gibbs and Gibbs (1949), investigated responses of sleeping children to loud sounds. Results were generally favorable, but it is worthy of note that some anomalous results showed up in these studies. A response could not be obtained from some children who showed responses to conditioned reflex audiometry (press the button when you hear a sound) and some children who showed no response to conditioned reflex audiometry showed an alerting response to loud sounds during sleep. Other studies by Perl, Galambos, and Glogig (1953) and by Derbyshire, Fraser, McDermott and Bridge (1956) raised the same kind of questions with attempts to quantify the results.

The exact origin and nature of the evoked responses have been questioned by some investigators. In 1958, Geisler, Frishkopf, and Rosenblith used an average response computer soon after it was reported by Clark (1958). In the Geisler study attention was directed to that portion of the response with an onset latency of 20 msec. and a peak latency of 39 msec. They concluded that this portion of the response was cortical in origin because it was repeatable from the same subject, it was recordable from a wide area of scalp, and monaural stimulation evoked a bilateral response. Later Geisler (1960) made a more extensive study in which he raised a slight question about the conclusion concerning cortical origin of portions of the evoked audio response.

Bickford (1964), as a result of the Geisler (1960) studies, recorded theinion (the external occipital protuberance) response to acoustic stimulation by monaural and binaural clicks and noted a relation between stimulus intensity and response amplitude and latency. They noted that the amplitude of the response increased with increased neck-muscle tension and reduced or disappeared with relaxation, or blocking of the motor nerve. This suggested a myogenic origin, at least in part, for these responses. Borsanyi and Blanchard (1963), Walter (1964a), and Geisler (1960) reported experiments which partly support this suggestion. Kiang, Crist, French and Edwards (1963) reported investigations using clicks in which the post-auricular response amplitude was apparently a function of head position, as well as other factors.

Mast (1963, 1965) found that the response at parietal and vertex positions was easily detected, even with low intensity stimulus. He found the pattern of the response generally stable, and concluded that the primary source of this response was not in the temporalis, frontalis, or neck muscles and that the response was probably made up of both myogenic and neurogenic components.

Walter (1964b) has pointed out that there is habituation to the stimulus and that stimuli which are novel or have special significance usually produce amplified responses and

that monotonous stimuli or stimuli with reduced significance produce smaller responses.

That a relationship between scalp-recorded electrical signals and acoustic stimuli exists seems to be well established. The origin and nature of the electrical signals recorded from scalp electrodes are less certain and conflicting evidence needs to be resolved.

Experimental Acoustic Stimuli

The study reported here used pure-tone (sine wave) stimuli exclusively, though many different kinds of acoustic stimuli have been used in evoked auditory potential studies. Various signals that sound like clicks have been used. Perl, Galambos, and Glorig (1953), and Rapin, Schimmel, Tourk, Krasnegor, and Pollack (1966) used short duration square waves that sounded like clicks. Lowell, Troffer, Ballinger, and Alvig (1961) and Cody, Jacobson, Walker, and Bickford, (1964a, b) used damped sinusoids to produce a click-like sound. Williams and Graham (1963) used pulses made up of the positive half of a pure tone for clicks.

Some investigators observe that it is easier to evoke a response to clicks than to pure tones. Perl, Galambos, and Glorig (1953), Appleby, McDermick, and Scott (1963) and Williams and Graham (1963) suggest that this is because the rise time of a click is shorter than the rise time of a pure tone; therefore the cortical activity evoked by a click is

more diffuse since the frequency content is broader.

McCandless and Best (1966) say that when using an averaging computer, it is as easy to obtain an evoked response with pure tones as it is with clicks. They champion the use of pure tones because it is possible to gain information about the frequency response of the system of auditory pathways.

Derbyshire and his co-workers (1964b, 1965) support the use of words to evoke an auditory response. They claim that the use of word stimuli allows observation of the effect of the semantic content of the stimulus.

Some investigators who have used pure tone stimuli have stated that the frequency of the tone does not affect the form of the evoked response. Rose and Malone (1965) used tones with a 25 msec. rise and decay time and a 4 sec. duration for stimulus and found that on and off effects did not vary as a function of frequency of the tone. The tone frequencies used in this investigation ranged from 200 to 8000 Hz. McCandless and Best (1966) and Suzuki and Taguchi (1965) made similar studies and report no frequency dependent differences in the over-all pattern or latency of the evoked response.

Other factors affecting the pattern, amplitude, and latency of the evoked response are well documented by many observers. Some of these factors are: stimulus intensity, order of change of stimulus intensity, duration of stimulus,

rise and decay time of the stimulus, stimulus presentation rate, and interstimulus period.

Electrode Placement and Recording Methods

In the human, the optimal site for recording evoked responses seems to be near the vertex. Better background activity can be recorded with the active electrode placed somewhat posterior to the vertex. Derbyshire et al. (1964a) finds the best recording site for evoked responses is 3 cm. lateral to the midline in the plane existing between the subject's ears. The reference electrode is attached to the contralateral ear lobe or mastoid. The amplitude of responses to auditory stimuli is greatest when recordings are made from the central area of the interaural plane, according to McCandless and Best (1964).

In 1939 P. A. Davis observed maximal response to acoustic stimulus from electrodes placed at the vertex. Abe (1954) and Davis and Zerlin (1966) also regard this as the best electrode placement for evoked responses. Appleby (1964) working with infants and Walker, Jacobson and Cody (1964) working with adults found the vertex to be the best recording site. Walter (1964a) says that the potential differences are greatest between the mastoid process and the vertex because of the electrical fields which are involved. The recording of eye movement artifacts is minimal with this placement of electrodes. The electrical activity at the vertex is likely a

result of gradient irregularities of the field which is generated by medial and lateral frontal cortex and probably does not result from tissue immediately underlying the vertex.

Teas (1965) recorded responses of adults to wide-band noise. He placed active electrodes on the vertex and indifferent electrodes on the ear lobe. He also placed active electrodes 3 cm. posterior to the vertex, with the indifferent electrodes on the ear lobe. The vertex placement was considered superior for recording the evoked response, while the placement posterior to the vertex was found superior for recording background activity.

Most studies have used monopolar recording techniques. In addition to those investigators mentioned previously, monopolar electrodes also have been used by Hogan and Graham (1967), Lamb and Graham (1967), and by Williams and Graham (1963). Magerison and his associates reported in 1967 on the use of bipolar electrodes.

Pitch Discrimination in the Nervous System

In general, the auditory system depends on an elaborate multiple set of codes for transmitting the information concerning frequency, intensity, and time differences that is contained in the incoming acoustic signals, according to Davis (1961). The classical theories of the coding of auditory information ascribe pitch coding partly to the activation of particular nerve fibers and partly to the repetition rate of

volleys of nerve impulses. The theory assigning specific pitch information to particular nerve fibers is known as the place theory of pitch discrimination.

The cochlea acts as a mechanical-acoustical analyzer, and the position of maximum mechanical activity along the basilar membrane changes as a function of frequency (Bekesy and Rosenblith, 1951; Davis, 1958). An important part of the information concerning the pitch of incoming sound waves, particularly those of high frequency, must be carried by the built-in assignment of specific nerve fibers to specific parts of the basilar membrane. Galambos, Rose and Hughes (1951) and Schuknecht (1960) are among those reporting evidence that supports the place theory of pitch discrimination.

Tunturi (1960), Rose and Woolsey (1958), Woolsey and Walzl (1942), Lilly and Cherry (1954), and Diamond, Chow, and Neff (1958) all report investigations in which there is a point for point mapping of points along the basilar membrane into points in the audio cortex. Tunturi's (1952) frequency representation in anterior ectosylvian gyrus shows a logarithmic increase in the frequency as one moves forward. This map is for the dog. Hind (1953) reports similar results at higher frequencies for the cat.

The volley or frequency theory of pitch discrimination was proposed by Wever (1949) and is sometimes referred to as Wever's volley theory of pitch discrimination. A point of

difficulty that helped give rise to the volley theory is that single nerve fibers which lend themselves to experimental work have an absolute refractory period of about 1 msec. This implies an upper frequency limitation of about 1000 Hz. Some investigators have shown upper frequency limits for auditory nerve fibers that are considerably in excess of 1000 Hz.

This upper limit for auditory nerve has been studied extensively in the cat. In early experiments in 1930, Wever and Bray (1930a, b, c) obtained synchronous responses from single auditory nerve fibers up to about 4100 Hz. Later that year they reported an upper limit of 5200 Hz. with improved recording apparatus. Derbyshire and Davis (1935), among others, have also placed the upper frequency limit in this range for auditory nerve. These figures have been repeatedly challenged by other investigators working with nerve fibers other than auditory nerve.

Among these were Echlin and Fessard (1938) who worked with the sciatic nerve of the frog and Brown et al. (1939) who worked with the saphenous nerve of the cat. In 1943 Galambos and Davis reported 450 Hz. as the upper frequency limit in the auditory nerve of the cat. Whatever the upper limit, it seems safer to use the lower figures. The volley theory is not dependent on any specific upper frequency limit for auditory nerve fibers.

The volley theory of Wever (1949) presumes synchronous transmission of signals along a nerve trunk made up of

individual fibers that have an upper frequency limit below the signal frequency. Individual fibers rotate duty in Gatling gun fashion so that there is an impulse sent down the trunk for each period of the signal.

As an example, consider a nerve trunk made up of ten fibers. Fiber one would transmit an impulse for periods 1, 11, 21, 31, etc. Fiber two would transmit an impulse for periods 2, 12, 22, 32, etc. In a similar fashion each of the ten fibers of the nerve trunk would transmit an impulse every tenth period and the impulses from the nerve trunk would be spatially summed to recover the signal frequency.

In 1960 Schuknecht wrote that it is probably correct to say that most of those who have applied themselves in some way to problems relating to pitch perception have accepted as a working hypothesis the concept that pitch coding is based on both the place and volley theory, with frequency being more important for low tones and place of maximal stimulation along the receptor organ being more important for high tones.

MATERIALS AND METHODS

Experimental Animals

In this study, three purebred, unrelated Greyhounds and two purebred Dalmations were used. The Greyhounds were healthy, normal animals that had been eliminated from race track competition. The two Dalmations were litter mates that had been selected by the breeder as "congenitally deaf," but were otherwise in good health. All the animals had achieved full growth and were between one and two years old. Table 1 lists the animals and their identification numbers.

Table 1. Animal identification

Identification	Animal
8486411	Female, brindle Greyhound, 45 lbs.
649895E	Male, brindle Greyhound, 55 lbs.
2591	Male, black Greyhound, 52 lbs.
D-1	Male, Dalmation, 45 lbs.
D-2	Male, Dalmation, 56 lbs.

Instrumentation and Design of Experiment

The overall objective of this study was to try to find signal recovery techniques which would extract audio frequencies, if present, from the electroencephalogram of a subject hearing a pure (sine wave) tone. It was also postulated that some information should be forthcoming that would allow inferences about the mechanism of pitch discrimination.

With these ends in mind, the subject animals were anesthetized and analog magnetic tape recordings were made of stimulus and EEGs for subsequent data processing.

The dogs were fasted for 24 hours prior to the recording sessions. The recording sessions were held on separate days for each of the five animals. Each time the dog was given sodium pentobarbital to effect surgical anesthesia (stage 3, plane 3) and was held in this stage during the recording session.

Records were made in blocks of four simultaneous recordings according to the schedule given in Table 2. Each block recorded contained the tone stimulus and three channels of EEG data. The tape recorder used was a 14 channel FM magnetic tape recorder¹. Only four channels were recorded at a time due to other equipment limitations. See Figure 1 for recording setup.

The stimulus used was a sine wave generated by an audio oscillator². The oscillator signal was amplified by an amplifier³ which drove a ten-inch speaker in a commercial enclosure⁴. The sound level was not measured, but was adjusted until it could be heard easily. The speaker was mounted six feet from the head end of the plastic-foam padded sling in which the subject was supported.

¹Model FR1300, Ampex Corp., Redwood City, California.

²Model 200CD, Hewlett-Packard, Palo Alto, California.

³Model 1211, General Radio Company, West Concord, Mass.

⁴Frequency response flat from 20 to 8000 Hz.

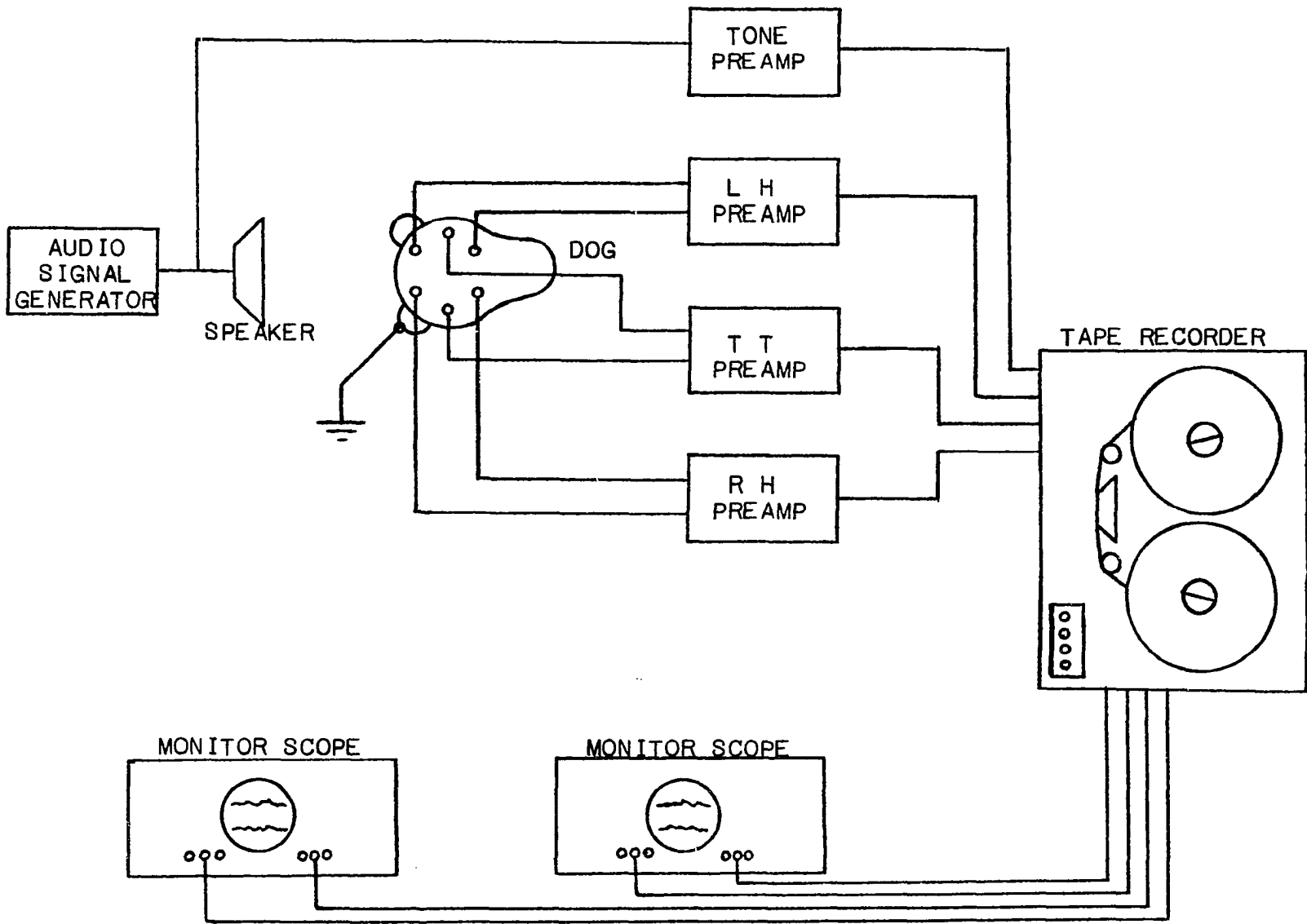
Table 2. Recording schedule

Tone		500 Hz., 2 minutes each, blocks ** A, B, C, D.*
LH+		250 Hz., 2 minutes each, blocks A, B, C, D.
RH		125 Hz., 2 minutes each, blocks A, B, C, D.
TT		1000 Hz., 2 minutes each, blocks A, B, C, D.
Tone		2000 Hz., 2 minutes each, blocks A, B, C, D.
LFT	<p>+ Electrode Code</p> <p>LH Left Hemisphere. RH Right Hemisphere. TT Transtemporal. LFT Left Frontal-Temporal. RFT Right Frontal-Temporal. TO Transoccipital. LTO Left Temporal-Occipital. RTO Right Temporal-Occipital. TF Transfrontal. LA Left Auditory Area. RA Right Auditory Area.</p>	4000 Hz., 2 minutes each, blocks A, B, C, D.
RFT		None 2 minutes each, blocks A, B, C, D.
TO		
Tone		
LTO		
RTO		
TF		
Tone		
TF		
TT		
TO		
Tone		
LA		
RA		
TO		

* Dog 2591, block E was also run for each tone after all other runs were recorded.

** D-1 and D-2, the Dalmations were run on an octave schedule based on 400 Hz., at 400, 200, 100, 800, 1600 and 3200 Hz.

Figure 1. Diagram of Equipment. Shown set up for recording tone stimulus, EEG from Left Hemisphere, Transtemporal EEG, and EEG from Right Hemisphere.



Small (half-centimeter long) needle electrodes were placed subcutaneously in locations as shown in Figure 2. The six sites, left frontal (LF), right frontal (RF), left temporal (LT), right temporal (RT), left occipital (LO), and right occipital (RO) were used for all animals. Electroencephalograms from the left and right auditory areas (LA and RA) of one animal were also recorded. A bipolar (differential input) electrode hookup was used, with the indifferent (reference) electrode hooked to the ear tip of the subject animal. See Table 3 for the bipolar-lead nomenclature used.

Table 3. Bipolar-lead nomenclature

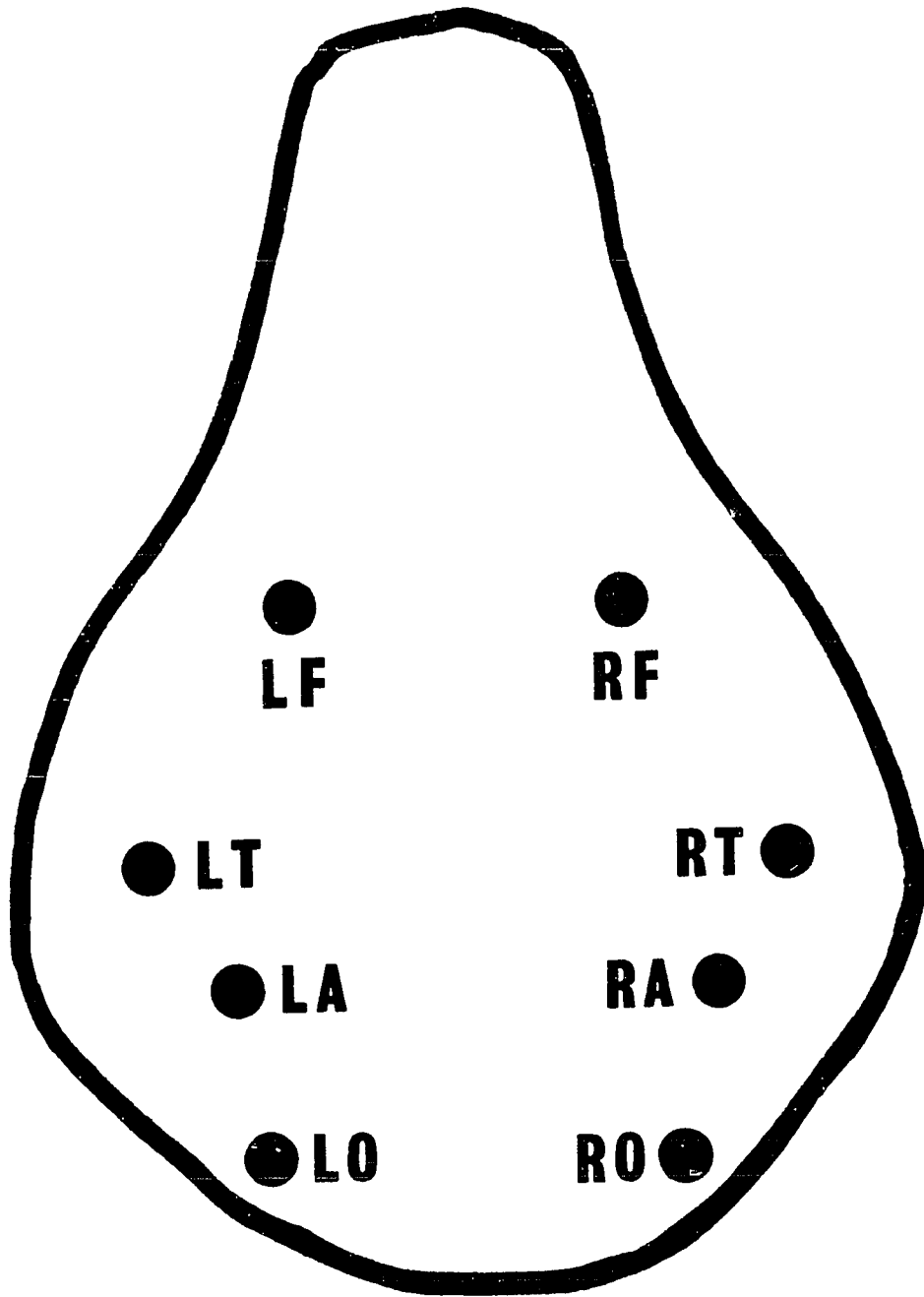
Symbol	Name	Leads at
LH	Left Hemisphere	LF, LO ^a
RH	Right Hemisphere	RF, RO
TT	Transtemporal	LT, RT
LFT	Left Frontal-Temporal	LF, LT
RFT	Right Frontal-Temporal	RF, RT
TO	Transoccipital	LO, RO
LTO	Left Temporal-Occipital	LT, LO
RTO	Right Temporal-Occipital	RT, RO
TF	Transfrontal	LF, RF
LA	Left Auditory Area	LT, LA
RA	Right Auditory Area	RT, RA

^aIndifferent electrode placed at tip of ear.

The three EEG signals recorded in each analog data block were amplified by EEG preamplifiers¹ with a gain of

¹Model 350-2700 EEG preamplifier, Sanborn Company, Waltham, Mass.

Figure 2. Showing electrode positions. LF, left frontal; RF, right frontal; LT, left temporal; RT, right temporal; LA, left auditory; RA, right auditory; LO, left occipital; LO, right occipital.



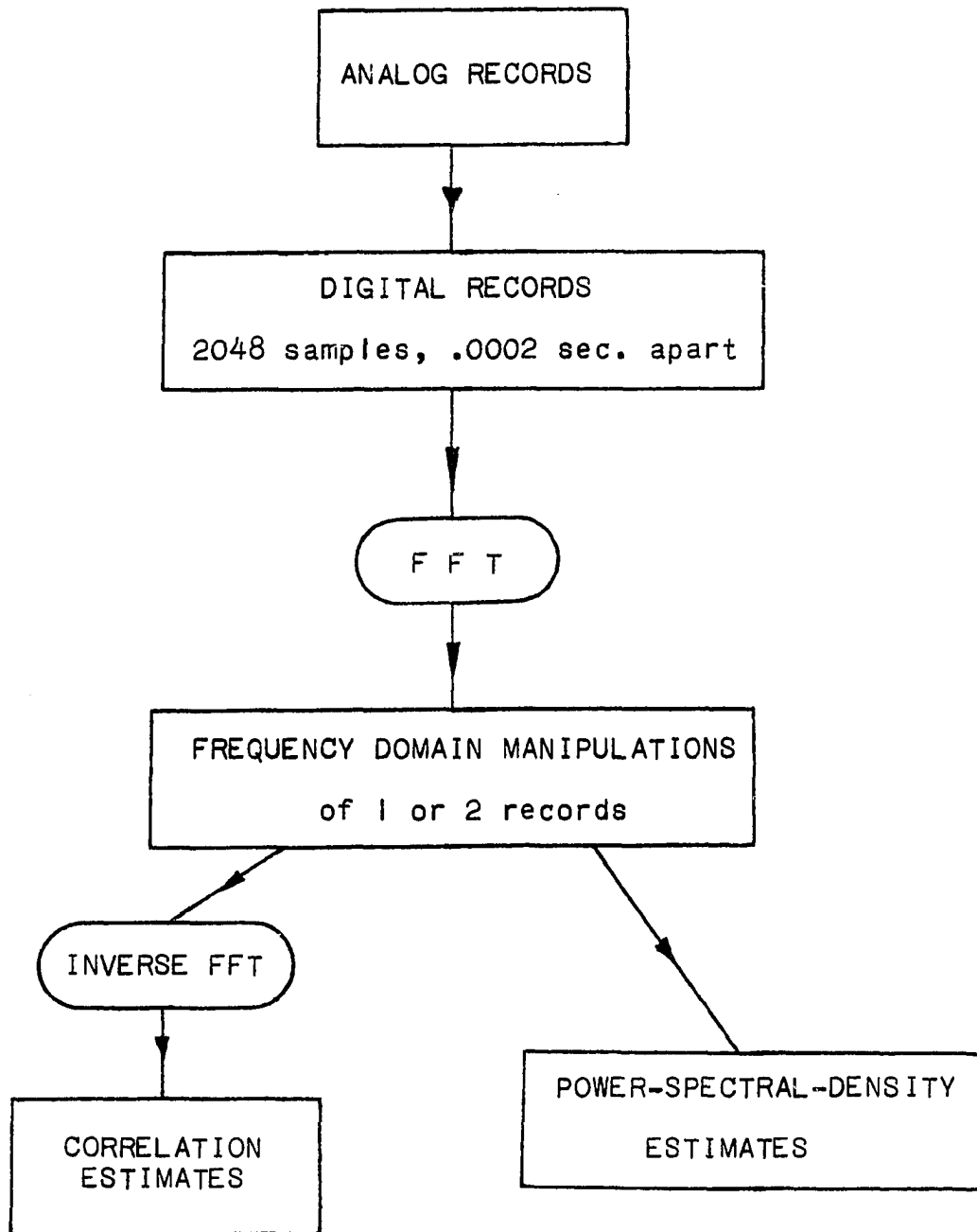
approximately 30,000. The internal filters in the pre-amplifiers were adjusted to give a low cutoff¹ frequency of 1.5 Hz. for all recordings. The high cutoff frequency was set at 1500 Hz. when using stimuli below 1600 Hz. When the stimulus tone was 1600 Hz. or more, the high frequency cutoff was kept at 5000 Hz. The output of each preamplifier was wired directly to a tape recorder input channel. The tape recorder outputs were monitored on two dual-channel oscilloscopes during the recording sessions. After recordings were completed for all five dogs, data processing was started. See Figure 3.

The initial step in the data processing was conversion of the primary analog records to digital samples in a format which the digital computer could read. An analog to digital converter was built which would directly track the analog tape recorder playback, hold the sample for conversion, convert to a ten bit word, and do the other operations necessary to write on a continuous digital tape recorder² at a 5000 word per second rate. This was a sample period of 0.2 msec. which gave a digital cutoff frequency of 2500 Hz. This was doubled when necessary by reducing the analog tape recorder playback speed by a factor of two. Similarly, the digital cutoff frequency was divided by two when necessary by playing the analog tape back at a speed twice that at which it was recorded.

¹ Cutoff frequency is that frequency at which the magnitude of the amplification decreases three decibels.

² Model FR300, Ampex Corp., Redwood City, California.

Figure 3. Flow chart of overall data processing. Starting with analog tape records, chart shows data manipulation through to estimates.



GENERAL DATA PROCESSING SCHEME

Five digital data blocks were taken from each channel of each two-minute analog data block--at least 140 digital data blocks for each animal. Each digital data block (record) contained about 2400 ten bit words, 2048 of which were used in the digital processing. The sample period was 200 msec. for records made during stimulus with 1000 Hz. and below. For records made during stimulation at frequencies higher than 1000 Hz., the sample period for the digital records was 50 msec. All the digital records resulting were not processed, but most of them were.

Cross correlograms were calculated and plotted, at least one for each tone, for each electrode configuration, for each animal. Autocorrelograms were found and plotted for many of the analog records and power spectral density estimates were plotted for some records. It was planned to check each permutation of electrode configuration, tone stimulus, and animal for presence of the stimulus frequency in the electroencephalogram. Except for a small number of those permutations for which the analog records were poor, this plan was carried out. The cross-correlation approximations were regarded as the most sensitive test, so it was the basic test. Autocorrelation approximations were also a sensitive test and were computed as a spot check of the data-processing system. Some power-spectral density estimates were computed also, but they were regarded as a less sensitive test because of the resolution between points.

Digital Software and Hardware

The term "software" is used here in a broad context, referring to all the non-hardware items that act as interfaces between the raw data and processed results. Such things as the digital computer programs, the program languages, data format on digital tapes, and translation of computed results into meaningful presentations comprise software. This section deals mostly with software for the simple reason there is more of it and it takes diverse forms.

Since most of the data processing was done in the frequency domain, it will be convenient to describe first the steps necessary to make the transformation from the time to the frequency domain.

The Fortran IV program first called a tape reading routine which found and removed the binary data from the digital-record tape and stored the data in a specified memory location. This required a maximum of 512 sixty bit words to be stored in core storage. This maximum was a limitation of the peripheral processor.

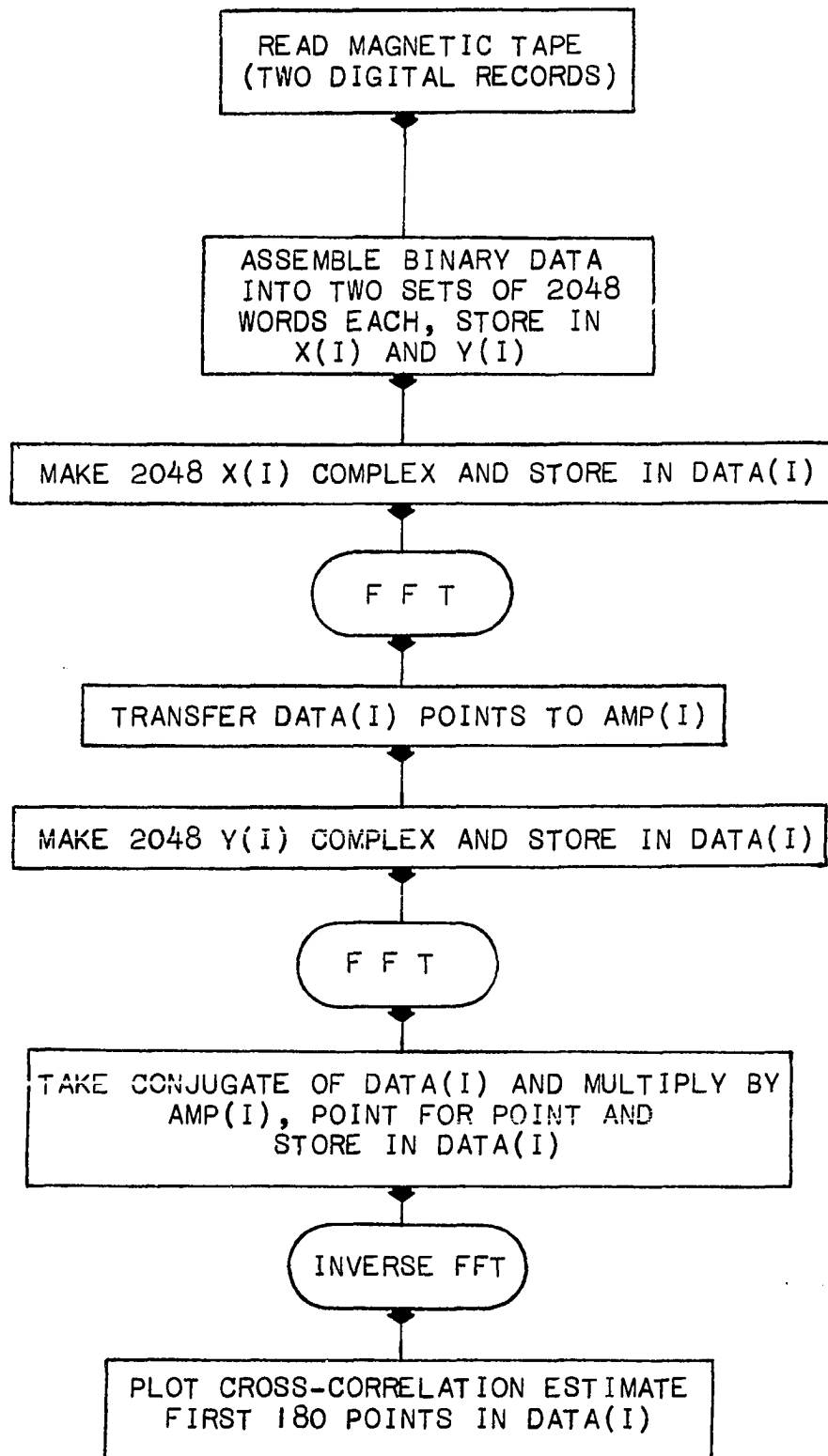
Next, a bit manipulation subroutine was called which reassembled the data into ten bit digital words that were the sampled voltages. The first 2048 of these were put in core storage. These 2048 integers were then made complex numbers by a basic supplied function (of Fortran IV), making the real parts decimal numbers and setting the imaginary parts of each

complex point to zero. This was necessary because the transformation routine uses the same storage location (DATA(I)) for input and output data due to a peculiarity of the algorithm. Since the transformed points are by definition complex, the time series must be made complex before calling the subroutine.

The FFT (Fast Fourier Transform) subroutine was then called and this puts 2048 complex points back in the DATA storage location. These points were the Discrete Fourier Transform of the 2048 original time domain samples. These were separated in the frequency domain by $\Delta f = 1/N\Delta t$, where N was the number of samples and Δt was the time domain sample period. For those time domain records sampled at 0.2 msec., the frequency domain separation was 2.44 Hz. So, the complex value stored at this time in location DATA(1) was the voltage transform for 2.44 Hz. The value in DATA(2) was the voltage transform for 4.88 Hz., and so forth. From this point on, the data processing was different, depending on the specific estimate sought. See the abbreviated flow chart in Figure 4.

For the cross-correlation estimates, the transformed points in DATA were shifted to a new location in storage (AMP(I)), thus clearing the DATA storage location. A new block of digital data was then transformed and stored in DATA. The complex conjugate of the points in DATA was taken with a sign reversal routine and these conjugate points put back in DATA. DATA was then multiplied by AMP, point for point

Figure 4. Abbreviated flow chart of program for cross-correlation estimates.



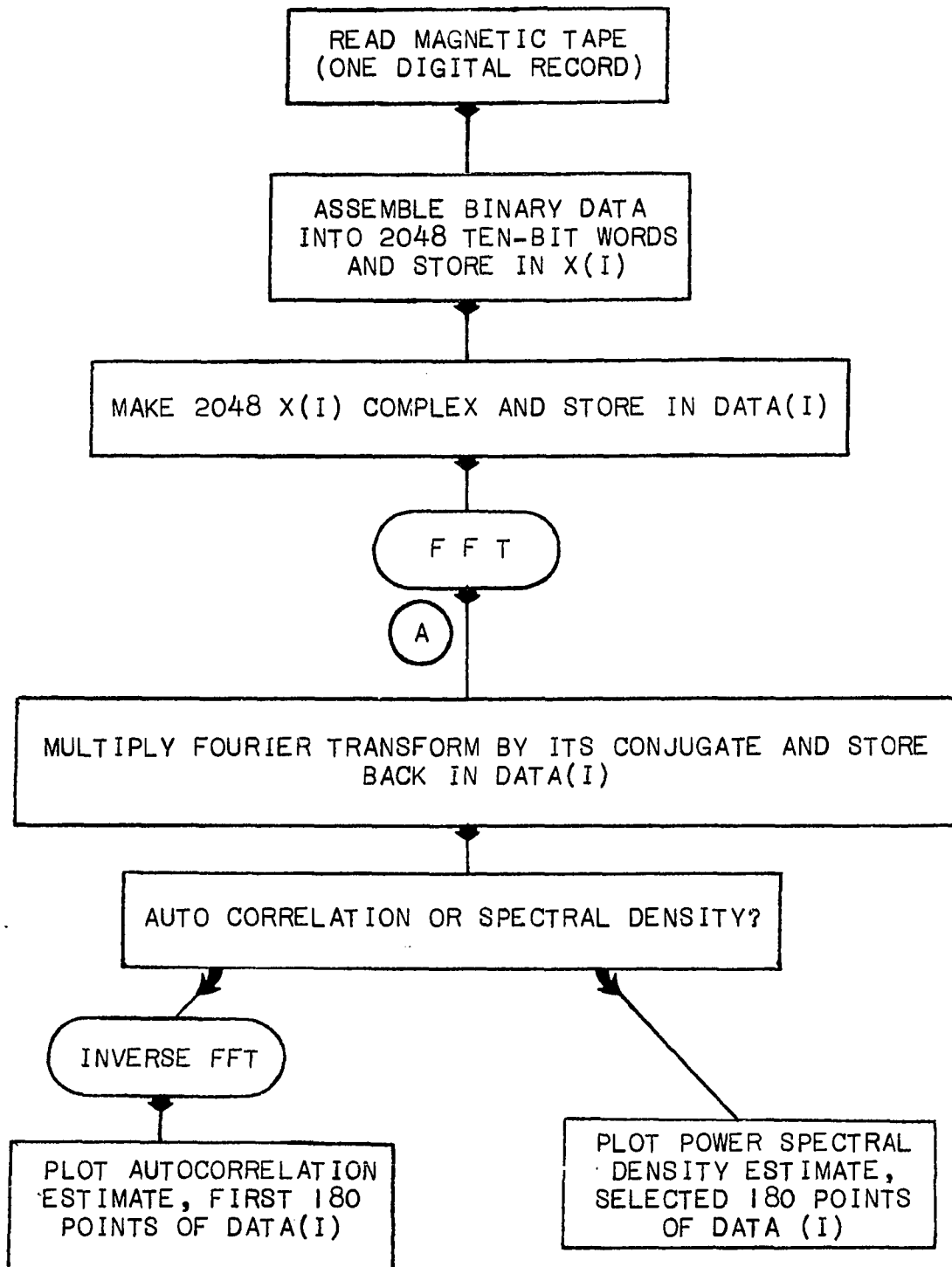
and the resulting 2048 real points stored back in the DATA location. The FFT subroutine was then called to take the inverse transform. At this time 2048 real, time-domain points were stored in DATA, the imaginary parts of the complex points were essentially zero.

These 2048 points were the desired cross-correlation estimate for the two blocks of digital data used. A line-printer plotting subroutine was then called which plotted the real part of the first 180 points in DATA. This was a plot of the cross-correlation estimate. The computation and plotting time for one of these estimates was 4 seconds.

For the autocorrelation estimates, the transformed points in DATA which resulted from one block of digital EEG data were operated on by a basic supplied function which took the absolute value of each point. These absolute values were then squared and put back in DATA. The FFT subroutine was called to take the inverse transform. Then there were 2048 real, time-domain points in DATA which represented the autocorrelation estimate of the original digital data block. The real parts of the first 180 points in DATA were plotted using the line-printer plotting subroutine. The result was a plot of the autocorrelation estimate. This, also, used about four seconds of computer time. See flow chart in Figure 5.

For the power-spectral-density estimates, the autocorrelation program stopped just short of calling the FFT

Figure 5. Abbreviated flow chart of program for autocorrelation estimates and power-spectral-density estimates. The discrete Fourier transform of the original digital record appears at the point in the flow chart that is labelled A.



subroutine for the inverse transform. The points in DATA at this time were plotted by the line printer plotting subroutine, which plotted the part of the spectral density that contained the frequency being investigated.

It is necessary to distinguish the approximations that the foregoing data processing yielded from the continuous functions as generally defined. The approximations to the cross-correlation function that resulted from processing the sampled, truncated time series are called cross-correlation estimates here. Similarly, approximations to the autocorrelation function and to the power-spectral-density function are called the autocorrelation estimate and power-spectral-density estimate, respectively.

The digital computer used to process these data was a Control Data Corporation Model CDC 6400 with core storage of 32,000 sixty-bit words. It was located at the Computer Center at Colorado State University in Fort Collins, Colorado. No analog plotting equipment was available as a peripheral processor at the time of this study.

ANALYSIS

Systems Tests

The EEGs of these animals during stimulation looked very much like EEGs from normal, unstimulated animals in stage 3, plane 3, sodium-pentobarbital-induced anesthesia. There were no visible differences detected by an expert observer¹. So it was evident that the magnitude of any signals in the EEG that were synchronous with the stimulus period was quite small. Therefore the question arose about the limits of detection of small, periodic signals buried in EEG-like noise. This called for determination of the system threshold for the processing techniques used. A description of the threshold determination follows:

Cross correlation of a band-limited white noise and a sine wave inside the band should yield a discernible sine wave since there is some power at that frequency in the noise. This was tested by using noise generated by a General Radio white-noise generator. The noise was recorded in a fashion similar to the data except that the gain of the preamplifier was set at 1. The upper and lower cutoff frequencies were set at 1500 and 1.5 Hz. respectively. The noise generator was band-limited at 20,000 Hz. and the root-mean-square (RMS) output was about 0.5 volts, the largest signal the tape recorder would accommodate.

¹Dr. Calvin C. Turbes, Department of Anatomy, Creighton University School of Medicine, Omaha, Nebraska. Visible differences in EEG. Private communication. 1968.

This resulted in band-limited (1.5 to 1500 Hz.) noise recorded on the analog magnetic tape.

Twenty digital data blocks were taken from the noise recording just described. These twenty sets of digital data were each cross correlated with digitized sine-wave samples taken from stimulus recordings made during the animal recording sessions. These cross-correlation estimates, in general, showed some periodic activity at the sine-wave frequency. The plots showed very degenerate sine waves and in some plots the frequency was not discernible at all. The average for the twenty sets was calculated. The average ratio of the peak-to-peak sine-wave value to the mean-square value of the noise-data sets was $1/250$ (0.004). This value was taken as the system-threshold figure for the cross-correlation estimates.

In making these cross-correlation tests of the system, it was noted that the noise signals did not look (on the monitor oscilloscope) very much like the EEGs of the animal recording sessions. Consequently, the cross-correlation tests described were repeated using EEGs of anesthetized canines recorded without stimulus. Of twenty sets of data, only two or three of the cross-correlation plots showed any periodic activity at the sine-wave (or any other) frequency. The average of these twenty sets showed no detectable periodicity at all. This test was regarded as a much more definitive test of the system capabilities for the time series being investigated.

From the results of these two systems tests of the cross-correlation capabilities of the system, it seems reasonable to conclude that, if the cross-correlation estimate shows a good,

"clean" sine wave of proper frequency, it was present in the electroencephalogram. Especially would this be true if the magnitude exceeded the $1/250$ ratio found for the system threshold with band-limited white noise.

Autocorrelation tests were made on the system by using manufactured signals of known characteristics. Undriven EEG signals taken under sodium pentobarbital surgical anesthesia were mixed in varying ratios with sine waves from a Hewlett-Packard audio oscillator. These were run in the regular autocorrelation program and the plots scanned for sine waves of the proper period.

The signals were manufactured using a resistive mixer. The true RMS reading meter was used to measure the sine wave and EEG signal input values to the mixer. Resistance values in the mixer were changed to obtain the different "signal-to-noise" ratios used. Sine-wave-to-EEG ratios (both measured RMS values) of 0.1, 0.05, 0.02, 0.01, and 0.002 were used.

Results of these tests showed distinct sine waves in the autocorrelation plots for all the signal-to-noise ratios used except the smallest (0.002).

The same signals used in the autocorrelation tests were also used to test the power-spectral density capabilities of the system. Of the signal-to-noise ratios tested, those of 0.02 and higher had the greatest amplitude at the proper

frequency, with this amplitude being at least 3 decibels more than the next largest amplitude. For the 0.01 ratio, the results were doubtful. For the 0.002 ratio, there was no doubt that the sine-wave frequency was not the dominant peak in the power-spectral-density plot. This seems to be somewhat at odds with the autocorrelation system test results.

However, this can be accounted for by the resolution in the frequency domain (2.44 Hz.). If the sine-wave frequency fell between two of the digital points, it would be difficult to detect. For a perfect sine wave of infinite extent, the power-spectral density would be an impulse of infinite height and zero width at the nominal frequency. This perfect case degenerates for the time-limited case, but with a separation of samples points of 2.44 Hz., the width could be 2 Hz. and still be missed completely. The accuracy of the instruments used in this study was not sufficient to allow setting and maintaining the oscillator and the system so that they both fell on a frequency accurate to two or more decimal places. Therefore no attempt was made to solve this problem, especially since a similar problem did not exist with the autocorrelation estimates.

The systems tests showed the data acquisition and processing system capable of recovering the period of signals buried in noise. The cross-correlation estimate gives positive results if the cross-correlation plot shows periodic signals with a peak-to-peak amplitude equal to or greater than 0.004

times the mean-square value of the digital data sample. The autocorrelation estimates will recover signals with a signal-to-noise voltage ratio of 0.01 or higher. The power-spectral-density estimates are a positive indicator for signal-to-noise voltage ratios of 0.02 or greater.

Results and Discussion

The results shown in the cross-correlation plots were generally positive. The ratio of the peak-to-peak amplitude of the periodic signal in the cross-correlation plot to the square of the mean for that digital sample was calculated for those samples for which the mean-square value was computed. This ratio is called the Signal-to-EEG ratio here. In all but four cases (of 65 computed) the ratio exceeded the detection threshold of the system for cross correlation. These ratios, with other information, are listed in Tables 4 through 8.

These Signal-to-EEG ratios, as defined in the previous paragraph, are listed in Table 4 for the 500 Hz. stimulus tone. For the two Dalmations, the octaves used were based on 400 Hz. and so are the figures in Table 4. There is a general trend in this table for these ratios to be highest for the LFT and RFT signal leads. This is borne out, too, by the autocorrelation estimates. Note that in almost half the cases, the Signal-to-EEG ratio for the cross-correlation estimates is at least ten times greater than the system threshold.

Table 4. Signal-to-EEG ratios of cross-correlation estimates with stimulus near 500 Hz.

Dog Signal	2591	649895E	8686411	D-1 ^a	D-2 ^a
LH	0.03	0.02	0.06	0.02	0.03
RH	neg. ^b	0.02	0.07	0.03	0.06
TF	0.04	0.04	0.05	0.04	0.05
LFT	0.03	0.10	0.04	0.06	0.07
RFT	0.02	0.13	0.03	0.04	0.05
TO	0.01	0.08	0.06	0.03	0.02
LTO	0.04	0.08	0.05	0.03	neg.
RTO	0.02	0.09	0.03	0.02	0.02
TF	0.03	0.10	0.03	0.02	0.03
Note: System threshold for cross-correlation estimates was 0.004.					

^a 400 Hz for stimulus for this column.

^b No periodic information in cross-correlation estimate.

Table 5. Signal-to-EEG ratios of cross-correlation estimates for dog 2591

Signal \ Tone	125 Hz.	250 Hz.	500 Hz.	1000 Hz.	2000 Hz.	4000 Hz.
LH	sine ^a	sine	0.03	sine	sine	sine
RH	sine	sine	neg. ^b	sine	sine	sine
TT	sine	sine	0.04	sine	sine	sine
LFT	sine	0.08	0.03	0.03	0.02	0.02
RFT	sine	sine	0.02	sine	sine	sine
TO	sine	0.06	0.01	0.02	0.08	neg.
LTO	0.02	0.01	0.04	sine	sine	sine
RTO	sine	sine	0.02	sine	sine	sine
TF	sine	sine	0.03	sine	sine	sine

Note: System threshold for cross-correlation estimates was 0.004.

^a Clear sine wave of proper frequency in cross-correlation estimate, see text.

^b No periodic information in cross-correlation estimate.

Table 6. Signal-to-EEG ratios for cross-correlation estimates for dog 649895E

Signal \ Tone	125 Hz.	250 Hz.	500 Hz.	1000 Hz.	2000 Hz.	4000 Hz.
LH	0 ^a	0 ^a	0.02	0 ^a	sine ^b	sine
RH			0.02		sine	sine
TT			0.04		sine	sine
LFT			0.10		sine	sine
RFT			0.13		sine	sine
TO			0.08		sine	sine
LTO			0.08		sine	sine
RTO			0.09		sine	sine
TF			0.10		sine	sine
Note: System threshold for cross-correlation estimates was 0.004.						

^aNo analog records for these tones.

^bClear sine wave of proper frequency in cross-correlation estimate, see text.

Table 7. Signal-to-EEG ratios of cross-correlation estimates for dog D-1

Signal \ Tone	100 Hz.	200 Hz.	400 Hz.	800 Hz.	1600 Hz.	3200 Hz.
LH	sine ^a	sine	0.02	sine	sine	sine
RH	sine	sine	0.03	sine	sine	sine
TT	RNG ^b	RNG	0.04	sine	sine	0.06
LFT	sine	sine	0.06	sine	sine	sine
RFT	sine	sine	0.04	sine	sine	sine
TO	RNG	RNG	0.03	sine	sine	neg. ^c
LTO	sine	sine	0.03	sine	sine	sine
RTO	sine	sine	0.02	sine	sine	sine
TF	sine	0.05	0.02	sine	sine	0.05

Note: System threshold for cross-correlation estimates was 0.004.

^aClear sine wave of proper frequency in cross-correlation estimate, see text.

^bAnalog record no good.

^cNo periodic information in cross-correlation estimate.

Table 8. Signal-to-EEG ratio of cross-correlation estimates for dog D-2

Signal \ Tone	100 Hz.	200 Hz.	400 Hz.	800 Hz.	1600 Hz.	3200 Hz.
LH	0.05	sine ^a	0.03	sine	sine	sine
RH	0.04	sine	0.06	sine	sine	sine
TT	0.04	sine	0.05	0.04	sine	sine
LFT	sine	sine	0.07	sine	sine	sine
RFT	sine	sine	0.05	sine	sine	sine
TO	sine	sine	0.02	sine	sine	sine
LTO	sine	sine	neg. ^b	sine	sine	sine
RTO	sine	sine	0.02	sine	sine	sine
TF	sine	sine	0.03	0.04	0.04	sine

Note: System threshold for cross-correlation estimates was 0.004.

^a Clear sine wave of proper frequency in cross-correlation estimate.

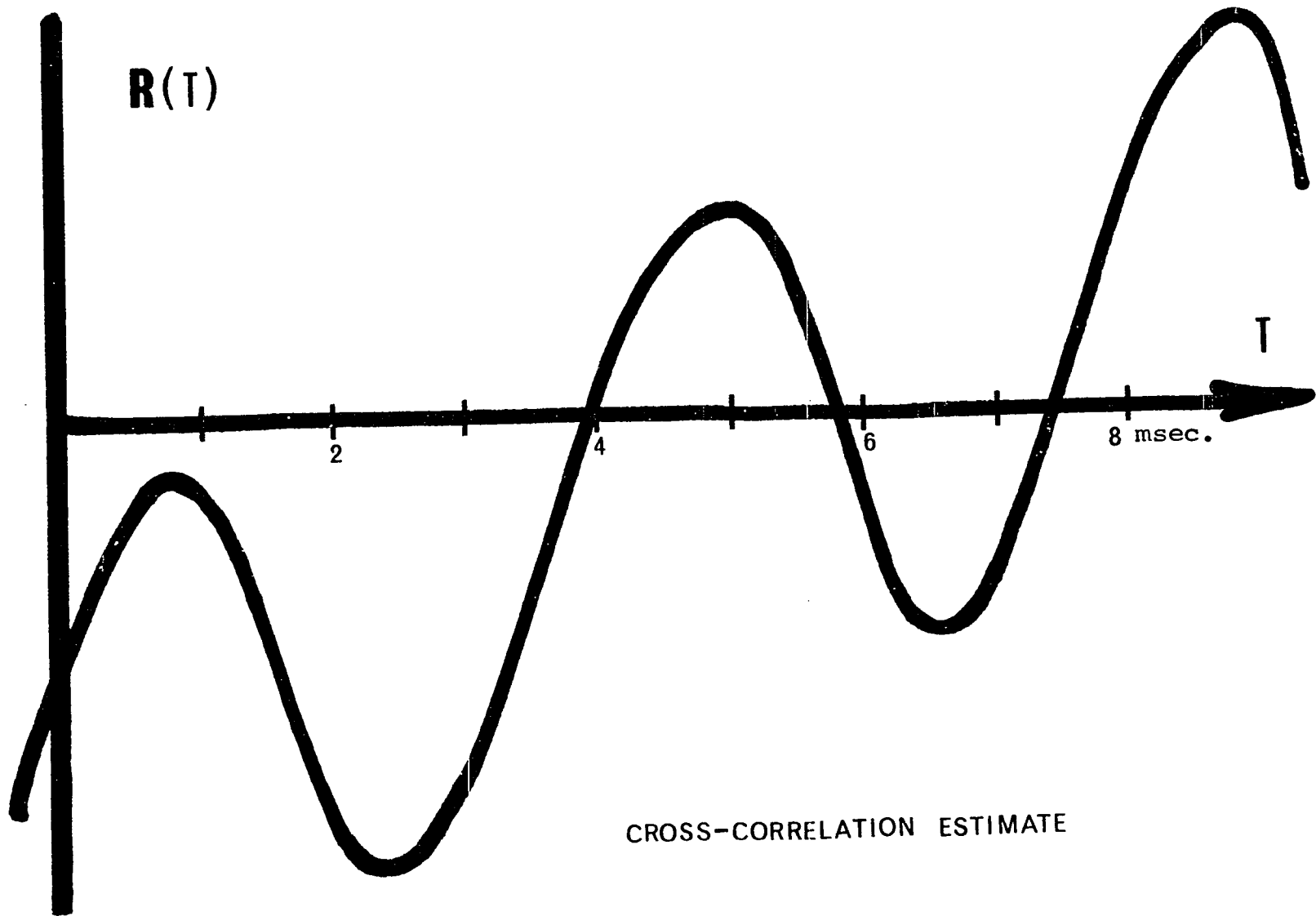
^b No periodic information in cross-correlation estimate.

Tables 5 through 8 give Signal-to-EEG ratios for all the signal leads and tones used for stimulus for each animal. The ratios were not found for many cases, since the mean-square value came from the autocorrelation estimates. The autocorrelation estimate was regarded as a check and it was not found for all records. Where the mean-square value was not known, the cross-correlation plots were scanned for good sine waves at the proper frequency, since one of the systems tests indicated that these were not present for cross-correlation estimates with an undriven EEG. These places in the tables are noted as sine. An example of a cross-correlation showing a good sine wave at 250 Hz. is shown in Figure 6.

Some of the analog records were not usable (no record at all, or records that were highly overdriven) and these are noted in the tables where such is the case. Part of the records were not taken for Greyhound 649895E, and these are also noted. A few records showed no discernible sine wave in the cross-correlation plot and these are designated as neg. in the proper place.

One will note that there is no table for Greyhound 8486411. This animal died as the setup for the second frequency was being made, and the only information on this dog is listed in Table 4 for the 500 Hz. stimulus. Two ml. of cerebrospinal fluid were withdrawn from this dog for another experiment immediately prior to the recording session. This,

Figure 6. Cross-correlation estimate. Left frontal-temporal data from Greyhound 2591 cross correlated with 250 Hz. tone stimulus. The time scale is in msec. The vertical scale is in volts squared, but the magnitude is only relative. The baseline slant is due to long-period variations that were truncated by the finite data sample.



coupled with the anesthetic, may have been responsible for the early death. This fluid sample was not taken from any of the other animals prior to the recording session.

Greyhound 2591 (Table 5) was also a subject for recordings from the left and right auditory areas (LA and RA). Several of these cross-correlation estimates were run for the 125, 500, and 2000 Hz. tones. In every case, these plots showed no periodic information at the stimulus frequency or at any other frequency (excepting the 60 Hz. power-line frequency in two records).

Since some of the records had fairly large Signal-to-EEG ratios, an attempt was made to recover the wave shape from some of the records. Results of one attempt are shown in Figure 7. This figure is a plot of a cross-correlation estimate between a digital data record and an approximation to a series of impulses recurring at the stimulus frequency. Cross-correlation with such an impulse train is analogous to a signal averaging, which also recovers the wave shape. These attempts were not very successful, but indicate that the wave shape is probably not sinusoidal.

Sixty-five autocorrelation estimates were run. Table 9 is a synopsis of those estimates showing positive results. In the others not listed, there was no evidence of periodic information in the plot. Slightly over one-quarter of the autocorrelation estimates run showed positive results; some of the values in the table are averages for more than one

Figure 7. Wave-shape recovery. This is a cross-correlation estimate of data cross correlated with the so-called comb filter described in the text. The horizontal scale is in msec. The stimulus frequency was 1600 Hz. The EEG data were from the left frontal-temporal sites of Dalmation D-2.

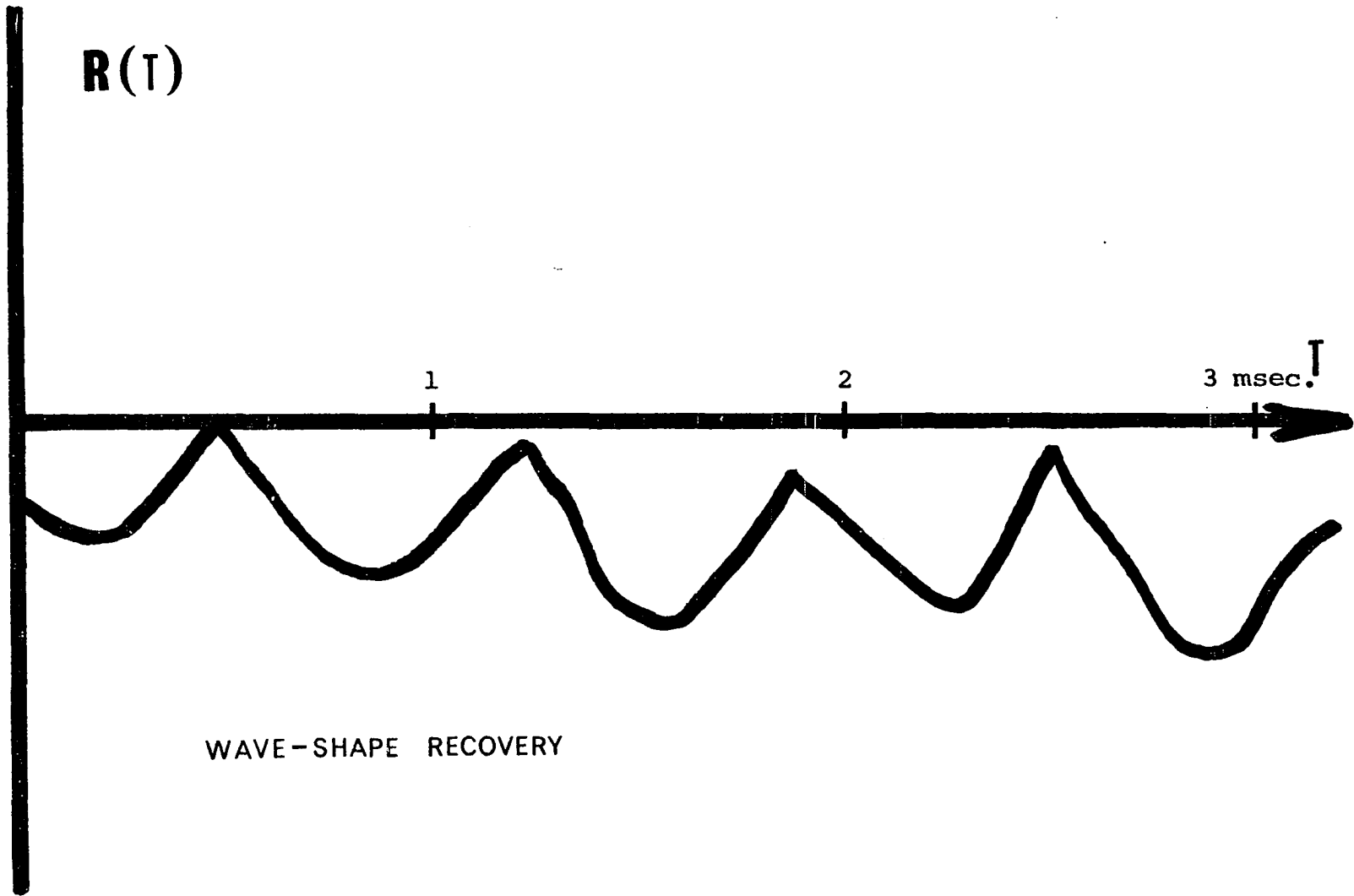


Table 9. Voltage signal-to-noise ratios of autocorrelation estimates

Dog	Signal Tone	LFT	RFT	TO
2591	125 Hz.			0.10
	250 Hz.	0.22		
	1000 Hz.	0.14		0.13
	2000 Hz.	0.16		0.20
	4000 Hz.	0.11		0.08
649895E	500 Hz.	0.10	0.18	
D-2	1600 Hz.			0.07
	3200 Hz.			0.08
Note: System threshold for autocorrelation estimates was 0.01.				

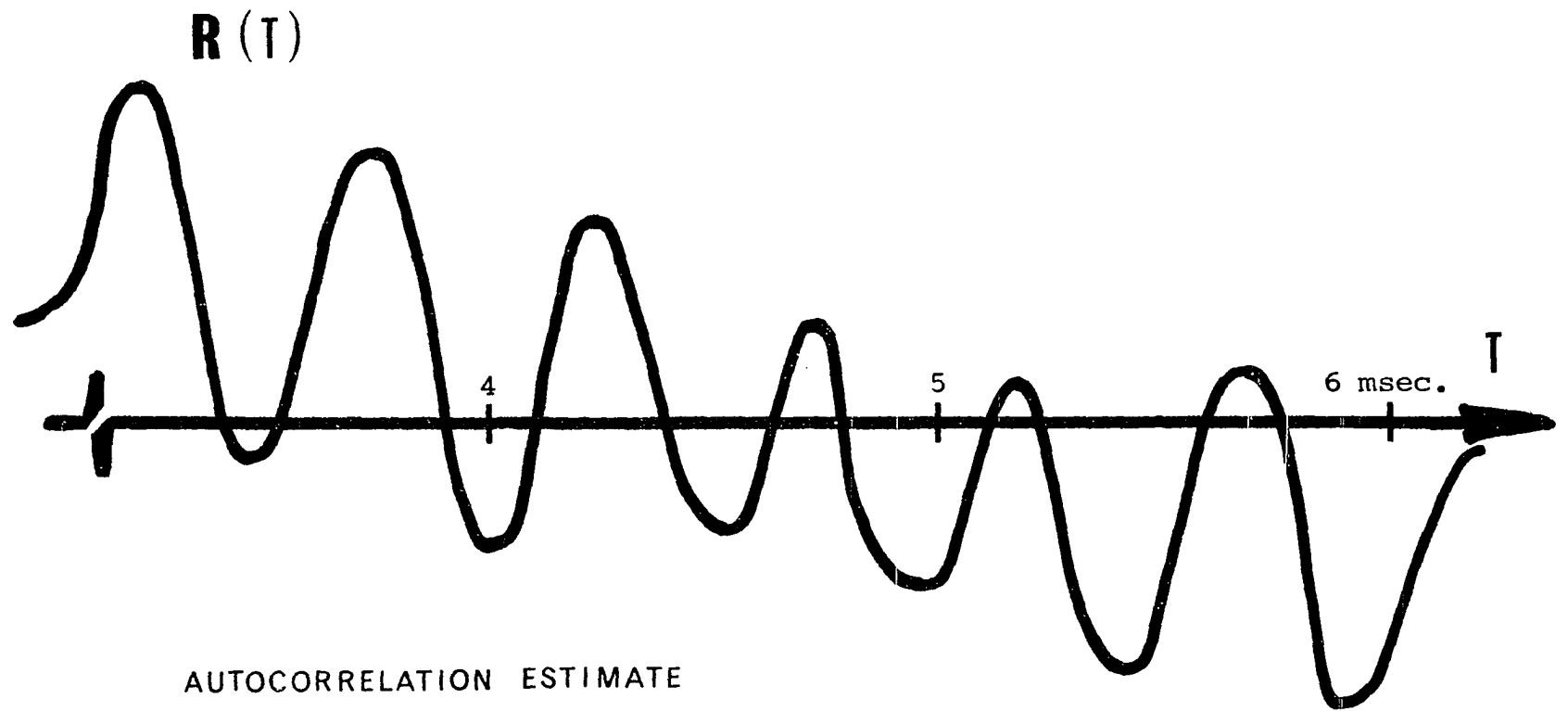
estimate. Figure 8 shows a typical autocorrelation estimate with a 2000 Hz. component.

It is interesting that the positive results in the autocorrelation estimates showed up mainly in the LFT and TO records. The animals were situated in the sling so that neither ear was blocked, and placement of the speaker was such that the sound came from directly behind the animal, not favoring either side.

Thirty power-spectral-density estimates were run on the digital data blocks. In no case was there a peak at the stimulus frequency. This is, perhaps, explained by the digital resolution as discussed in the systems-tests section.

Other evidence also collected was cross-correlation estimates between stimulus sine waves and some of the records for these animals made while no stimulus was being applied. These cross-correlation estimates showed no periodic information in the plots, which also supports the validity of this recovery technique.

Figure 8. Autocorrelation estimate. EEG data from the left frontal-temporal site of Greyhound 2591. The time scale is in msec, the vertical scale is in volts squared but the magnitude is relative. The tone the dog was exposed to was 2000 Hz. The baseline slant is due to long-period variations that were truncated by the finite data sample.



CONCLUSIONS

The preponderance of evidence presented supports the use of the cross-correlation estimate as detailed here in the recovery of periodic signals from EEG-like noise.

Although the incidence of recovery with the autocorrelation estimate used here was not as great (as for the cross-correlation estimate), it, too, shows promise as a technique for processing similar data. Perhaps longer records, or computer averaging of several sets of autocorrelation estimates would yield better results. As it is, the autocorrelation estimate used here is a very positive indicator that periodic signals were in the time series being processed.

The power-spectral-density estimates showed no amplitude peaks at the stimulus frequency. The information must be in them, since all the signal processing used here went through this step. It would help to make the spacing between samples in the frequency domain smaller. This can be accomplished by using a record from the time domain that has a larger number of samples. This larger number of samples requires a longer time-domain record, so the length required may be impractical.

Inferences about pitch discrimination which can be drawn from these data are another matter entirely. It seems certain that the periodic event resulting from the tone stimulus was being recorded from scalp electrodes at frequencies as high as 4000 Hz. It is tempting to say that these frequencies arose

in cortical tissue close to the electrodes.

Even if this were true, its significance to pitch discrimination is not clear. Since the animals were in surgical anesthesia, they were not aware of discriminating pitch at the time of the recording session. The implication is that the middle and inner ear were sensing the tones synchronously and passing this information along the auditory nerve, probably through several pathways to the cortex.

In summation, the correlation techniques used here proved to be useful tools for study of the central nervous system, and they provided information about the processing of auditory information not heretofore reported.

These signal-recovery techniques have not been used widely to study the central nervous system. They appear to hold great promise for such study. The anatomy and function of neural pathways for different sensory modalities can be more precisely detailed using these techniques as tools. Suspected pathways can be followed using stereotaxically-located electrodes. Exact time relationships of signal arrival at specific points in a neural pathway can be found with the cross-correlation estimate. Perhaps inferences about function could then be made from these time relations.

Signal propagation time and direction in a nerve trunk may also be ascertained using the cross-correlation estimate of this study. Such studies will provide more detailed

information about nervous-system control loops, and perhaps, about the sequence of information processing in the brain.

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APPENDIX A

Correlation and Spectral Density

Correlation has long been an important concept in statistics. For certain problems pertaining to the strength of the relation between two random variables, the statistician uses the correlation coefficient. The correlation coefficient is the mean of the product of the two random variables about their respective means, normalized to the product of their standard deviations. When this product is not normalized, it is called covariance.

The correlation function of communication theory is closely related to the correlation coefficient or covariance. The correlation function is a running mean of the product of two random variables as one of them is shifted in time. Covariance is a single value which is calculated for a fixed time relationship (usually no time shift) between the two random variables.

The use of correlation for the spectral analysis of random phenomena is attributed to Taylor (1920, 1938). Taylor had made significant contributions to the theory of diffusion and turbulence using correlation as a basic tool before the incorporation of the concept into communication theory. Prior to this, rudimentary correlation was used to study white light

by periodogram¹ analysis. The first wide-scale, organized application of correlational techniques to physical problems resulted from publication in 1949 of a report by Wiener (1942).

The correlation function and power-spectral density are a Fourier Transform pair (Lee, 1960). Since the transformation is linear, both functions contain the same information, only the presentation is different. Many investigators are more familiar with one of the pair and digital computer processing has recently become much faster in the frequency domain (Cooley and Tukey, 1965). The history of the development of the computer algorithm for this computation is an interesting study which has been reported by Cooley, Lewis, and Welch (1967).

The correlation function of two random variables, $\underline{x}(t)$ and $\underline{y}(t)$ may be found by:

$$R_{xy}(t, T) = \overline{x(t)y(t+T)} \quad (1)$$

This is a definition of the cross-correlation function. If both the time series are stationary, the correlation function does not depend on time \underline{t} , and is only a function of \underline{T} . If $x(t) = y(t)$, $R(\underline{t}, \underline{T})$ is called the autocorrelation function. It, too, is only a function of \underline{T} if the time series is stationary. The Fourier transform of the correlation function is

¹Periodogram is a class term used to designate functions such as the autocorrelogram or cross correlogram, which are time-limited versions of the autocorrelation function and cross-correlation function, respectively.

the spectral density $G(\omega)$:

$$G(\omega) = \int_{-\infty}^{+\infty} R(T) e^{-j\omega T} dT \quad (2)$$

Note that $G(\omega)$ may be either the power-spectral density or the cross-spectral density, depending on $R(T)$. The cross-spectral density is stressed here because many of the cross-correlation estimates were processed in the frequency domain.

Another route to the spectral density function $G_{xy}(\omega)$ is through direct Fourier transformation of the voltage variables. If $x(t)$ and $y(t)$ are random voltage variables and $X(\omega)$ and $Y(\omega)$ their Fourier transforms, respectively, then $G_{xy}(\omega)$, the cross-spectral density, may be found by multiplying $X(\omega)$ by the conjugate of $Y(\omega)$:

$$G_{xy}(\omega) = X(\omega) Y^*(\omega) \quad (3)$$

The correlation function $R_{xy}(T)$ may then be found by taking the inverse Fourier transform of $G(\omega)$:

$$R_{xy}(T) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} X(\omega) Y^*(\omega) e^{jT\omega} d\omega \quad (4)$$

These mathematical relations and their proofs are more completely discussed by Brown and Nilsson (1962), Lee (1960) and Lathi (1965), among others.

The Discrete Fourier Transform (DFT) is of interest in the digital processing of analog data. If one has a finite time series X_k , one can define the DFT of the series X_k , $k = 0, 1, 2, 3, \dots, N-1$ as:

$$A_r = \sum_{k=0}^{N-1} X_k e^{-j \frac{(2\pi r)k}{N}} \quad r = 0, 1, 2, 3, \dots, N-1 \quad (5)$$

where r is the running parameter in the frequency domain. In general the X_k can be complex, but in many applications including those here the X_k form a real time series. When X_k is a real time series with equal time intervals between the elements, r is referred to as the frequency corresponding to the A_r coefficient. The inverse transformation is:

$$X_k = \frac{1}{N} \sum_{r=0}^{N-1} A_r e^{j \frac{(2\pi r)k}{N}} \quad k = 0, 1, 2, 3, \dots, N-1 \quad (6)$$

Note the similarity between the forward and inverse transforms (Equations 5 and 6). The time series X_k and the frequency series A_r have traded places, the exponents have only changed sign, and the inverse transform has a multiplying constant $1/N$. These similarities are a great aid in digital computation, since both the forward and inverse transforms can be calculated by the same manipulations.

The usefulness of the DFT in most applications arises from its correspondence with the integral Fourier transform of a continuous time function $f(t)$ when the sequence X_k is generated by sampling $f(t)$. To demonstrate this correspondence, consider the proof of the sampling theorem. If $F(\omega)$ is the transform of $f(t)$ and $F(\omega) = 0$ for $|\omega| \geq \omega_c$, the transform pair in Equations 7 and 8 is established in the proof of the sampling

theorem (Papoulis, 1963).

$$f(t) = \sum_{n=-\infty}^{\infty} f\left(\frac{n\pi}{\omega_c}\right) \frac{\sin(\omega_c t - n\pi)}{\omega_c t - n\pi} \quad (7)$$

$$F(\omega) = p_{\omega_c}(\omega) \sum_{n=-\infty}^{\infty} \frac{\pi}{\omega_c} f\left(\frac{n\pi}{\omega_c}\right) e^{-j\frac{n\pi\omega}{\omega_c}} \quad (8)$$

where $p_{\omega_c}(\omega) = 1$, $|\omega| < \omega_c$; $p_{\omega_c}(\omega) = 0$, $|\omega| \geq \omega_c$.

For a time limited series of samples this pair reduces to the transform pair of relation 9. Periodic extension of the time limited series is implied to get back to the infinite series.

$$\sum_{n=0}^{N-1} f\left(\frac{n\pi}{\omega_c}\right) \frac{\sin(\omega_c t - n\pi)}{\omega_c t - n\pi} \longleftrightarrow p_{\omega_c}(\omega) \sum_{n=0}^{N-1} \frac{\pi}{\omega_c} f\left(\frac{n\pi}{\omega_c}\right) e^{-j\frac{n\pi\omega}{\omega_c} t} \quad (9)$$

The particular form of the time function of this pair is convenient because it demonstrates the exact correspondence between the truncated continuous time function and its samples. At the sample points, the $\sin x/x$ part reduces to 1, giving the original $f(t)$ for that point. Letting the time-domain sample period be $T = \pi/\omega_c$, and evaluating Equation 8 at $\omega = (2\pi r)/NT$ gives:

$$F\left(\frac{2\pi r}{NT}\right) = T \sum_{k=0}^{N-1} f(kT) e^{-j\frac{(2\pi r)k}{N}} \quad ; r < N/2 \quad (10)$$

Note the correspondence of Equations 5 and 10. Except for the constant T they are equal. This shows the

relationship between the DFT and the integral Fourier transform. The implications of using the sampling theorem in this development should be pointed out. The transform must vanish for frequencies above the cutoff frequency, or significant errors may result. Such errors are called aliasing errors. To avoid these errors, something must be done to the time series to insure it contains no frequency components above the cutoff frequency established by the sampling period. Analog filters usually accomplish this.

Translation of this restriction on frequency gives the restriction on \underline{r} shown in Equation 10. This limitation states clearly that even though \underline{N} samples generate \underline{N} points in the frequency domain, only the first $\underline{N}/2$ are valid. It can be shown that the second $\underline{N}/2$ points are actually the $\underline{N}/2$ points for \underline{r} between minus $\underline{N}/2$ and zero, but they have been shifted by the periodic extension of $\underline{F}(\omega)$ imposed by the sampling theorem.

It can be seen from Equation 10 that computation of one point of the spectral density function requires N operations. For all N points N^2 operations are necessary, thus computational time is proportional to N^2 . By a successive splitting of the X_k time series into odd-numbered and even-numbered terms, the Fast Fourier Transform (FFT) algorithm (Special, 1967) takes a computational time proportional to $N \log_2(N)$. For \underline{N} large the time difference between this and the normal N^2 figure becomes huge.

Another point favoring use of the FFT algorithm for calculation of the transform is that the reduced number of operations also limits the pile up of round-off error in the digital computer. This results in more accurate points in the transform. The entire June 1967 issue of the IEEE Transactions on Audio and Electroacoustics is devoted to the FFT and its applications (Special, 1967).

APPENDIX B

Analog-to-Digital Conversion Electronics

The analog-to-digital conversion electronics was built up around a successive approximation converter¹ that converted an analog voltage between zero and 10.24 volts into a ten-bit word in less than 0.01 msec. Each bit of the binary word represented ten millivolts of analog signal. For example, the binary word 1000010001 (545 in base ten) represented a voltage into the converter of 5.45 volts.

The analog voltage into the successive approximation converter was from a "sample-and-hold" amplifier². This amplifier had an aperture time of 150 nanoseconds, which gave the one-bit resolution at sampling frequencies up to 35,000 Hz. The sample-and-hold amplifier was set up to offset the analog tape recorder signal (1 volt rms) by 5.12 volts and to amplify it three times. The overall gain of the amplifier was negative, so that a zero volt signal on the analog tape was presented to the converter as a 5.12 volt signal. A +1.0 volt signal from the analog tape yielded 2.12 volts into the converter. Similarly, a -1.0 volt signal on the analog tape gave 8.12 volts at the converter input.

¹Model A801, Digital Equipment Corporation, Maynard, Massachusetts.

²Model A400, Digital Equipment Corporation, Maynard, Massachusetts.

After conversion to a ten-bit digital word, it was necessary to process the word into IBM compatible format for the digital tape recorder. A very condensed block diagram of the electronics that accomplished this is shown in Figure 9. This electronics was built up using integrated digital circuit modules. The logic modules used were primarily Diode-Transistor Logic (DTL) modules and a few Transistor-Transistor Logic (TTL) and Resistor-Transistor Logic (RTL) modules. Approximately 200 such multi-function integrated circuits were used in construction of this electronics.

The Ring Counter in Figure 9 kept track of the function being put on the tape. First an inter-record gap; then a two-frame, ten-bit record number; then a pre-selected number of data words; a parity gap; and a horizontal parity check word were counted by the Ring Counter to comprise one block of writing (or physical record) on the digital tape. Figure 10 shows the digital tape format used and should be referred to as the electronic functions are explained.

Five-bit frames, bit positions A8421 in order of descending significance, were passed to the vertical parity generator where the ring sum, modulo two was calculated. A binary "zero" was put in bit position C if the number of ones in the five-bit frame was odd (sum equal one). A binary "one" was established in bit position C if the number of ones in the five-bit frame was even (sum equal zero). A binary "zero" was put in bit position C if the number of ones in the five-bit

Figure 9. Block diagram of analog-to-digital conversion electronics. The continuous digital tape recorder is also shown, but is not part of the conversion electronics.

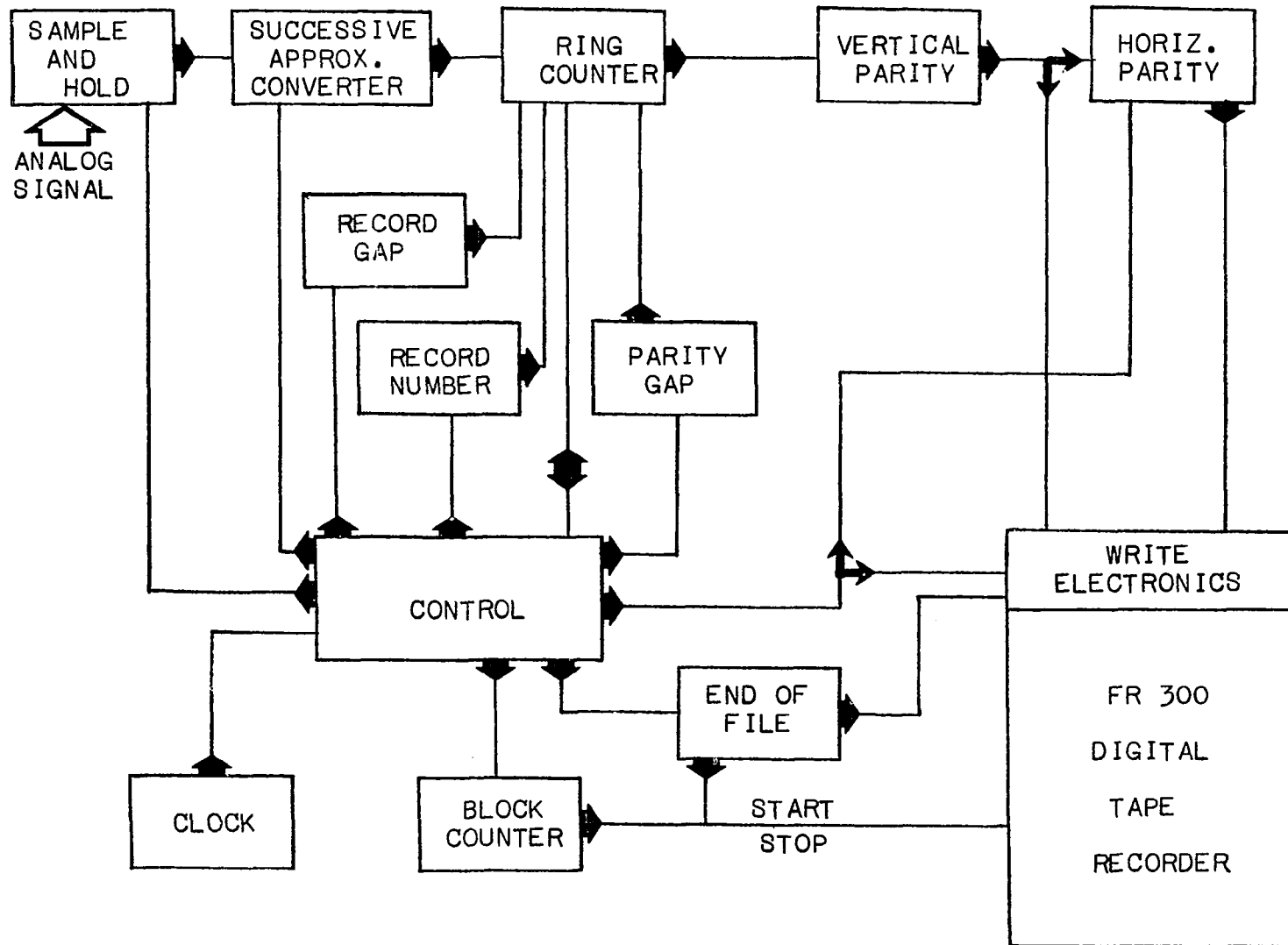
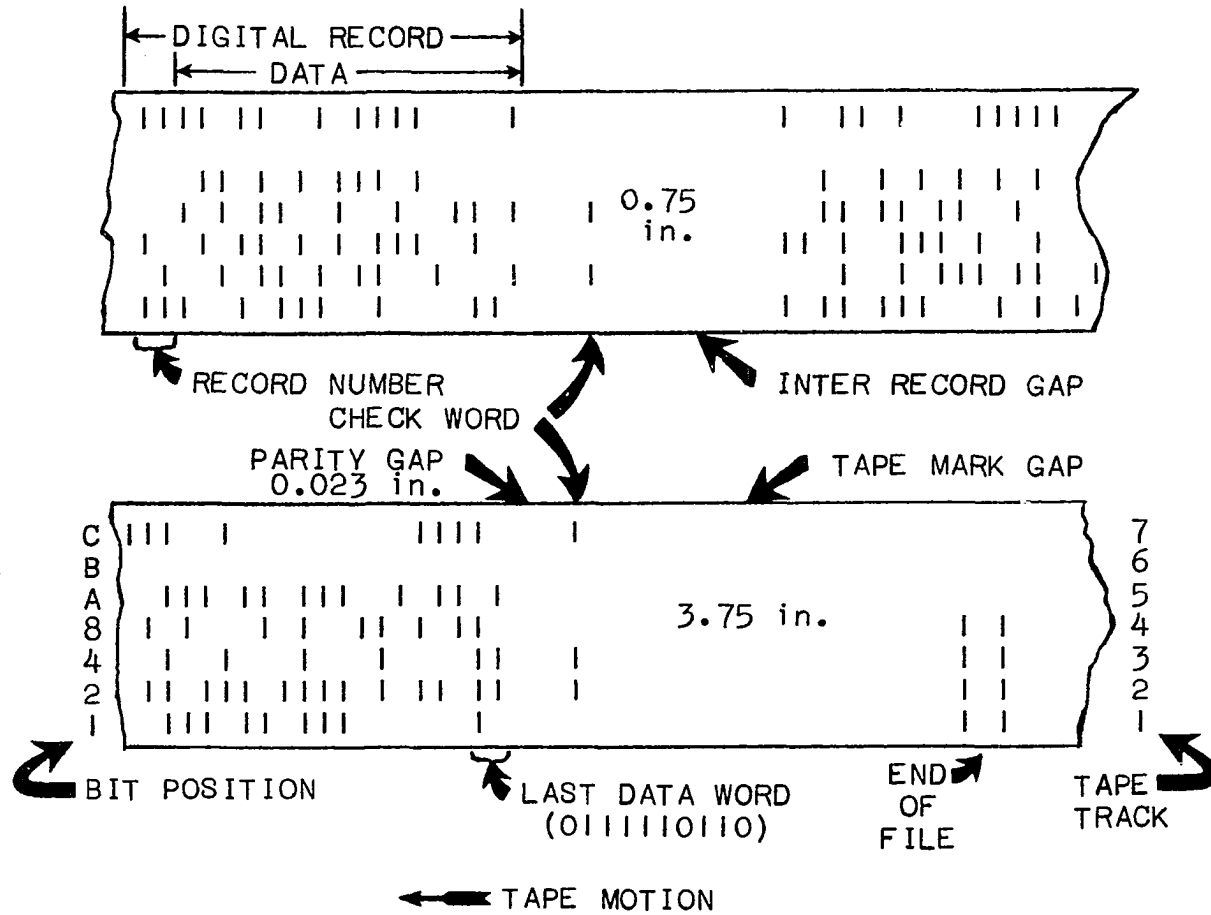


Figure 10. Digital tape format. Format shown is for binary data packed at a density of 200 frames per inch. Bit position C is the vertical parity track and is computed so there are an odd number of ones per frame. Bit position B is vacant in this use. The diagram is shown looking at the dull side of the tape. Tape track 7 is the nearest to the tape recorder body. Ten-bit words representing voltages are written so that the most significant five bits are in bit positions A8421 in an odd frame; the least significant five bits are in bit positions A8421 in the following even frame. See last data word for example.



frame was odd (sum equal one). From here the frame (now five bits plus the vertical parity bit) passed directly to the tape-recorder write electronics and to the horizontal parity generator.

The horizontal parity generator counted the number of ones in each bit position and made up the horizontal parity check word so that the total number of ones in each track in the digital record (including check word) was even.

On a write command from control, the six-bit frame was written on the digital tape. For those tape track positions that contained a one, current in the head was reversed, thus establishing a small magnet in that track on the tape. Zero caused no change.

A limitation of the CDC 6400 peripheral processor was a physical record length of 5120 frames. The conversion electronics first wrote a record number (internally generated and advanced automatically by one for each physical record), then data. Since each ten-bit data word took two frames, the longest digital data record was 2559 words. This record length was selectable on front-panel controls.

The digital tape recorder ran at 50 inches per second. Since the tape was packed at a 200 frame per inch packing density, the time between frames was 100 microseconds. The clock frequency of the conversion electronics was therefore 10,000 Hz. This represented a real-time sample frequency of

5000 Hz. This corresponds to a digital cutoff frequency of 2500 Hz. The analog tape recorder playback speed was made half the recording speed to double the digital cutoff frequency to 5000 Hz. when necessary.

The control electronics had an end-of-file mark generator which generated the 3.75 in. tape mark gap and the octal 17 and repeated it three frames later. A front panel control inserted the end-of-file mark when selected by the operator.

The block length counter kept track of how many physical records were generated successively at one time. This block length was selected by front panel controls.