1982

An Investigation of the Contingent Negative Variation Using Signal Processing Methods

Nichols, Martin John

http://hdl.handle.net/10026.1/2555

http://dx.doi.org/10.24382/4149
University of Plymouth

An Investigation of the

Contingent Negative Variation

Using Signal Processing Methods

Martin John Nichols

This thesis is submitted in partial fulfilment of the requirements of the Council for National Academic Awards for the degree of Doctor of Philosophy.

Department of Communication Engineering,
Plymouth Polytechnic,

in collaboration with the

Department of Neurological Sciences,
Freedom Fields Hospital,
Plymouth.

August 1982

Declaration

I hereby declare that whilst registered as a candidate for the degree of Doctor of Philosophy with the Council for National Academic Awards I have not been registered for any other qualification of the CNAA or any other examining body.

Signed M. J. Nichols

In accordance with regulations 3.8 and 3.9 I have attended and participated in the following:-

Lectures in Communication Engineering (Intended for B.Sc Hons. Students) October 1977 - May 1978.

IEE Meeting, Savoy Place, London, "Microprocessors in Medical Instrumentation". 31st May 1978.

BES/HPA, Nottingham, "International Evoked Potentials Symposium". 4th - 6th September 1978.

EPTA, Scientific Meeting, Romford. 25th November 1978.

EURASIP, Lausanne, Switzerland, "First European Signal Processing Conference". 16th - 19th September 1980.

EEG Society, Scientific Meeting, Plymouth. 9th May 1981.

An Investigation of the Contingent Negative Variation Using Signal Processing Methods

M.J. Nichols

Abstract

The Contingent Negative Variation (CNV) is one of many types of electrical response signals which appear in the electroencephalogram (EEG) of man subsequent to one or more stimuli. Generally these responses are small in comparison to the normal background EEG and had always been thought to consist of a response component which was added to the background EEG. Professor B. McA. Sayers of Imperial College suggested that the auditory response might actually be due to a temporary ordering of the phases of the components of the background EEG. A model, allowing for additive and ordering effects, is proposed here. This model was tested on both auditory and CNV responses using statistical tests not previously used in evoked potential studies. The tests showed that while the additive model satisfactorily described the auditory responses, it did not explain the CNV responses so well. However, both sets of responses showed a certain amount of phase ordering and this was consistent with the model which showed that a repetitive additional component would always incorporate the phase ordering effect. In the absence of detectable additivity pure phase re-ordering might alternatively occur as proposed by Sayers.

The CNV's of a patient group were also studied and certain tests are proposed as a possible method of diagnosis. The reliability of these tests was not conclusively proved as much larger control and patient groups would be required to do this.

An important part of this work involved the introduction of a quantitative method for assessing the effectiveness of methods of removing eye movement artefact from the EEG. This allowed the development of a more extensive correction method which was tested against two other techniques and found to be superior. This correction method will provide the basis for further research and the development of a corrector to be made commercially.

References, Tables and Diagrams

For each section the references are numbered [1], [2], ... and are listed at the end of that section.

Tables and diagrams are numbered 'a-b' where 'a' denotes the section number and 'b' the numerical sequence within that section. Diagrams and tables have been inserted after, and as near as possible to the text which first refers to them.

Table of Contents

Page

Page

Page

List of Diagrams

Page

Page

Page

1. Introduction

1.1 The Origins of Electroencephalography

Electrical engineers are frequently surprised to find that electrical activity of the brain was observed as long ago as 1875 [1]. Their surprise is however understandable when one considers the infant state of electrical engineering at that time. The discovery was due to a British Physiologist called Richard Caton. Caton used Thomson's (moving magnet) reflecting galvanometer to observe electrical fluctuations from the exposed surfaces of the brains of rabbits and monkeys. The potentials were of the order of millivolts and the necessary amplification was provided optically by the galvanometer. Using this galvanometer Caton was able to study and subsequently comment on the electrical activity he observed. His findings were presented at a Conference and published in the British Medical Journal in August 1875 [1]. Despite being unable to make graphic recordings of the activity, Caton detected background and stimulus related potentials.

However it was not until 1929 that Hans Berger [2] discovered the electroencephalogram (EEG) in man. He used a string galvanometer connected to electrodes attached to the scalp. Berger tried many different types of electrodes made from different metals. Unfortunately however Berger's work remained unnoticed for a number of years until Adrian and Matthews [3] (1934) and Jasper and Carmichael [4] (1935) reviewed and confirmed it.

1.2 Technological Change

Technological advances at this time made it possible for the electrical activity to be amplified and displayed on a cathode ray tube (CRT). Then resulting waveforms could then be photographed for a permanent record. These early valve amplifiers were usually a.c. coupled and often suffered from pick-up of external interference. An elegant solution to this problem was the advent and adoption of the differential amplifier which was able to reject the common-mode noise at its input. During the 1940's pen recorders became more widely available and for the first time electro-encephalographers could have an immediate permanent record of the brain's electrical activity. Interest in the developing field of EEG analysis grew rapidly. Many workers tried to make objective quantitative analyses of the EEG. A physicist by the name of Dietsch [5] was probably the first worker to examine the frequency of the EEG signals. He performed Fourier analysis on short sections of EEG signals using a mechanical desk calculator in the early 1930's. The method was very tedious and it was not until 1943 that Walter [6] overcame this disadvantage with his frequency analyser. This instrument consisted of a bank of twenty tuned reeds covering the range 1.5 to 30Hz. The movement of each reed was used to switch a charging current into a capacitor and thus to integrate the activity over a ten second period. The outputs of the integrators being roughly proportional to the amount of activity in given frequency band.

During the late 1940's and early 50's a considerable amount of interest was also shown in topographic EEG displays. Typically these devices employed twenty or more CRT's to display simultaneous EEG signals from different points on the scalp. Like the frequency analyser previously described the 'toposcopes' suffered from the instability of the valve technology of the day.

The development of new concepts in statistical communication theory give rise to the EEG signals being considered as a stochastic process. Brazier and Casby [7,8] (1951,1952) were some of the first workers to apply auto and cross-correlation analysis to the EEG. Subsequently this method became quite popular as a shortcut to obtain the power spectrum of the EEG signal.

The major developments of the late 1950's and early 60's were however in the advent and use of the new solid state technology. The equipment was more reliable and required far less maintenance and calibration than the valve equipment that it replaced. Furthermore the advent of the digital computer made the calculation of the power spectrum a much less awesome prospect although it was not until the introduction of the Fast Fourier Transforms (FFT) by Cooley and Tukey [9] in 1965 that this method became practical for multichannel work.

1.3 Evoked Potentials

In parallel with these developments in the analysis of the background EEG signal came developments in the analysis of potentials evoked by some external stimulus. Dawson [10] (1947) was the first person to record potentials evoked by stimulation of a peripheral nerve. He used photographic superimposition whereby the waveform was displayed on a CRT whilst a camera, set for a time exposure, recorded the waveform on film. The stimulation was applied many times each causing a single scan of the CRT screen. The evoked potential is thus visible on the developed photograph due to the re-inforcing effect of the overlapping individual responses. This elaborate technique was necessary because the magnitude of the individual evoked responses were considerably smaller than the normal background EEG activity.

Development of the analysis of evoked potentials was limited by the lack of equipment capable of improving the signal to background EEG ratio. It was realised at an early stage that if it were possible to average a number of evoked responses an improvement in signal to background EEG would be achieved. Early analogue averagers were built but were cumbersome and difficult to use. The advent of digital memory and logic devices made averaging a much more attractive technique and during the early 1960's many discoveries were made in the field of evoked responses. Furthermore, the advent of the general purpose laboratory minicomputer meant that evoked responses could be studied without further special equipment (except the stimulator). It was during the study of certain evoked potentials that Walter [11] discovered a new evoked potential which later became known as the Contingent Negative Variation (CNV). This evoked potential was found to occur between a pair of conventional auditory or visual stimuli provided that the patient was required to perform some action on receiving the second stimuli. The response was found to be a gradual negative shift subsequent to the first, or warning stimulus, and increasing in negativity until the second stimulus when the desired action was performed. Unlike normal visual, auditory or somatosensory evoked responses, the CNV depended on active participation by the subject and thus involves the higher mental processes.

1.4 Additivity and Ordering

Since their discovery, it had always been thought that evoked potentials were due to an additional signal component which was added to the background EEG signal. Professor Sayers [12] questioned this basic assumption and performed several tests to try and establish whether the Auditory Evoked Potential (AEP) could be caused by some other mechanism. One of Sayers tests [12] involving taking a section of normal background EEG and re-arranging the phases of the Fourier components. He found that by doing this the section of background EEG could be made to resemble an AEP. Sayers also found that if the energy contained in an AEP was calculated and compared with that for a section of background EEG, there was no significant difference [12]. This led Sayers to the conclusion that AEP's could in fact be due not to an additional signal, but to some form of phase ordering of the on-going background EEG signal. One could, for example, envisage a number of EEG generators becoming entrained for a short while subsequent to the stimulus presentation. This would give the characteristic shape of the AEP but would not change the energy content of the EEG.

In order to try and verify this, Professor Sayers obtained the Fourier transforms of a set of AEP's. A diagram was then constructed showing the phase angles of the transformed responses for each harmonic [12]. From these diagrams Sayers was able to detect that the phase angles obtained did not form an uniform pattern between $+\pi$ and $-\pi$ but formed groups.

In subsequent studies Sayers used histograms to show these phase ordering effects [13]. For each of a number of the harmonic frequency components histograms were plotted to show the number of times the phase angle fell into any one of twenty-four frequency intervals of width $2\pi/24$ radians (i.e. 15^{o}). From these histograms Sayers observed grouping in harmonics 2 to 5 (the fundamental frequency in these observations was 1.5625 Hz.) The amount of phase aggregation was found to be dependent on the stimulus level but not on the degree of latency. When no stimulus was applied the phases of the transformed EEG formed a roughly uniform distribution [13].

The importance of Sayers' findings were such that it was considered desirable to carry out similar experiments on CNV's to establish whether they were also due to phase re-ordering as had been previously suggested by Walter [14].

1.5 An Application of the CNV to Diagnostic Medicine

Since it was first reported in 1964 the CNV has not been widely used in routine diagnostic medicine. One possible area in which the CNV may be useful is in the early diagnosis of a hereditary neurological disorder known as Huntington's Chorea (HC). This illness affects several areas of the brain including the cortex, the caudate nucleus and other parts of the corpus striatum [15]. These are all areas thought to be involved in the generation of the CNV [16]. The disease is currently diagnosed only in its later stages, usually in middle age, when the chorea (uncontrollable movement) becomes apparent. The condition becomes progressively worse causing pre-senile dementia and after a distressing long illness, ultimately leads to premature death.

A possible diagnostic procedure would therefore be to compare the CNV's of those people at risk (i.e. those with a known family history of HC) with those obtained from a normal population. Significant deviation from the normal CNV may thus indicate the presence of the disease before the other symptoms become apparent. Clearly the clinicians would have to establish the limits of the normal CNV and also whether other neurological conditions could give similar CNV's to those of HC victims. However before this can take place it is necessary to conceive, design, build and test equipment and processing methods suitable for extracting a reliable quantitative description of the CNV.

References for Section 1

[1] Caton R, "The Electric Currents of the Brain"
British Medical Journal, Volume 2, page 278, August 1875.

[2] Berger H, "Uber das Elektrenkephalogramm des Menschen"
Archiv fur Psychiatrie and Nervenkrankheiten, Volume 87
pp 527-570, 1929.

[3] Adrian E D, Matthews B H C, "The Berger Rhythm: Potential Changes from the Occipital Lobes in Man"
Brain, Volume 57, Part 4, pp 355-385, December 1934.

[4] Jasper H H, Carmichael L, "Electrical Potentials from the Intact Human Brain"
Science, Volume 81, pp 51-53, January 1935.

[5] Dietsch G, "Fourier-Analyse von Elektroencephalogrammen des Menschen"
Pflugers Archiv fur die Gesamt Physiologie des Menschen und der Tiere, Volume 230, pp 106-112,1932.

[6] Walter W G, "An Automatic Low Frequency Analyser"
Electronic Engineering, Volume 16, pp 9-13, June 1943.

[7] Brazier M A B, Casby J U, "An application of the M.I.T. digital electronic correlator to a problem in the EEG".
Electroencaphalography and Clinical Neurophysiology
Volume 3, page 375, 1951.

[8] Brazier M A B, Casby J U, "Cross correlation and auto-correlation studies of electroencephalographic potentials"

[8] continued

Electroencephalography and Clinical Neurophysiology, Volume 4 pp 201-211, 1952.

[9] Cooley J W, Tukey J W, "An Algorithm for the Machine Calculation of Complex Fourier Series"
Mathematics of Computation, Volume 19, pp 297-301, 1965

[10] Dawson G D "Cerebral Responses to the Electrical Stimulation of the Peripheral Nerve in Man"
Journal of Neurology, Neurosurgery and Psychiatry, Volume 10, pp 134-140, 1947.

[11] Walter W G, Cooper R, Aldridge V J, McCallum W C, Winter A L, "Contingent Negative Variation: An Electric Sign of Sensorimotor Association and Expectancy in the Human Brain".
Nature, Volume 203, pp 380-384, July 1964.

[12] Sayers B McA, Beagley H A, Henshall W R, "The Mechanism of Auditory Evoked EEG Responses"
Nature, Volume 247, pp 481-483, February 1974.

[13] Sayers B McA, Beagley H A, Riha J, "Pattern Analysis of Auditory-Evoked EEG Potentials"
Audiology, Volume 18, pp 1-16, 1979.

[14] McCallum W C, Knott J R, (Editors) "Event-Related Slow Potentials of the Brain: their relation to behaviour"
Electroencephalography and Clinical Neurophysiology, Supplement No. 33 Part II Discussion, page 128
Published by Elsevier Scientific Publishing Company 1973.

[15] Scott D F, Heathfield K W G, Toone B, Margerison J H,
"The EEG in Huntington's chorea: a clinical and neuropathological study"
Journal of Neurology, Neurosurgery and Psychiatry, Volume 35, pp 97-102, 1972

[16] McCallum W C, Papakostopoulos D, Gombi R, Winter A L, Cooper R, Griffith H B,
"Event Related Slow Potential Changes in Human Brain Stem"
Nature, Volume 242, pp 465-467, 1973.

2. Theoretical Development

2.1 Models for Additivity and Phase Ordering in Evoked Responses

Although introduced as being mutually exclusive, there is no fundamental reason why an evoked response should not be the result of both additive and phase re-ordered components. Furthermore any added signal giving the characteristic shape of either an AEP or a CNV will have its own well defined phase spectrum. Thus the identification of a phase pattern in an evoked response (CNV or AEP) is not in itself sufficient evidence for phase re-ordering. At this point it is as well to define what is meant by phase ordering and phase re-ordering. Phase ordering is used here to describe the situation where a phase spectrum has a recognizable pattern irrespective of the cause of this pattern, whereas phase re-ordering is used to describe the situation where the phases of an existing signal have been changed so as to cause phase ordering. Since phase patterns are not sufficient evidence for phase re-ordering, it is necessary to consider amplitude characteristics as well.

Consider first a finite realisation of the pre-stimulus background EEG signal which is of the same length as the section of EEG containing the evoked response. Because the signal is random the Fourier harmonic components into which it may be analysed will have random amplitudes and phases. If the nth harmonic is selected it may be very conveniently represented in amplitude and phase by a phasor on a phasor diagram. The same procedure can be carried out for each pre-stimulus realisation recorded in a series of trials, i.e. the nth harmonic component of each realisation may be plotted as a phasor on the same phasor diagram. This procedure will result in a diagram such as is shown in Fig. 2-1a, in which the amplitudes are random and the phase angles, which are also random, are distributed approximately uniformly about a circle. For ease of comprehension a circle of arbitrary radius has been superimposed on the phasor diagram. The crosses on the circles indicate the directions of the phasors.

Now consider the effects of a stimulus on this diagram. Assume that the phasor diagram for the post-stimulus section of EEG containing the evoked response may be derived directly from the pre-stimulus phasor diagram. If the evoked response were due to phase re-ordering effects its nth harmonic phasor diagram would be obtained by rotating all of the phasors of Fig. 2-1a towards the preferred phase angle. Thus the phasor diagram of Fig. 2-1b would be obtained. The characteristic feature is that although there is phase ordering present the amplitudes are unaltered. The phase ordering present is responsible for the characteristic waveform of the evoked response. This phase re-ordering model may now be compared with the additive signal model. This will be considered for the two cases of low and high level stimulus. In the low level stimulus case it is assumed that a small additive evoked response is produced which may be analysed into its harmonic components. The nth harmonic component, assumed to be the same in each realisation, is represented as a small phasor which has to be added to each of the phasors of Fig. 2-1a to produce the post-stimulus phasor diagram. This produces Fig. 2-1c. This figure shows that a certain amount of phase ordering is produced while the amplitudes of the nth

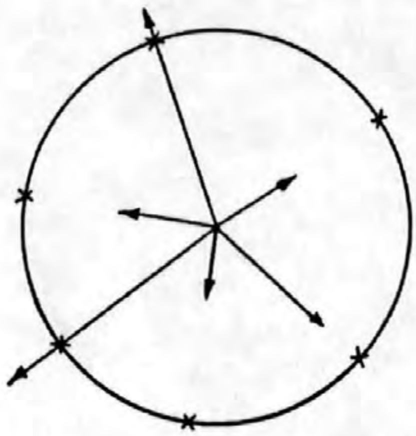


Fig. 2-1a
Background EEG

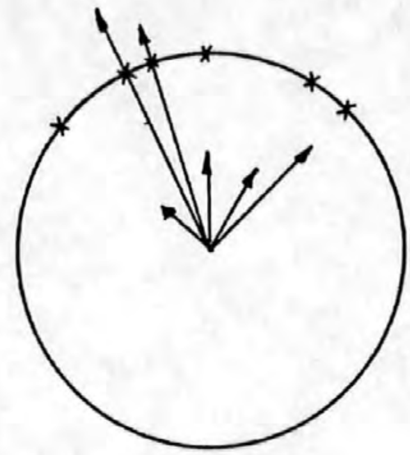


Fig. 2-1b
Phase ordering

Figure 2-1
Phasor diagrams

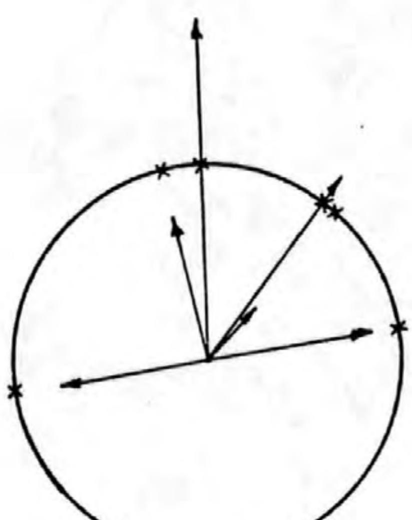


Fig. 2-1c
Small additive component

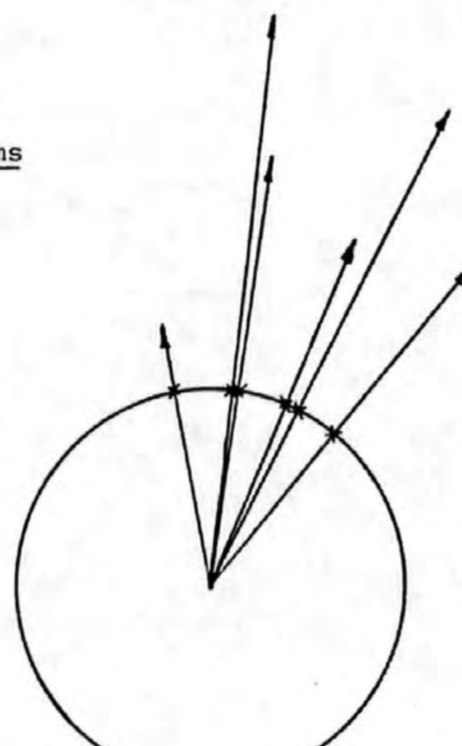


Fig. 2-1d
Large additive component

harmonic are changed. Those phasors directed towards the preferred angle are increased in length, whilst those opposed are decreased. For a small additive signal the average length of the phasors would be virtually unaltered. The same argument may be applied in the case of a high level stimulus. The phasor to be added to Fig. 2-1a is now large and the post-stimulus phasor diagram is as shown in Fig.2-1d. It is seen that the large additive signal results in pronounced phase ordering and a considerable increase in phasor amplitudes.

The models clearly demonstrate that phase ordering will be produced by either mechanism and will increase with stimulus level. The presence of an additive component may be inferred by changes in amplitude of the nth harmonic. In the next section the statistical tests used to detect phase ordering and amplitude and energy changes will be described.

2.2 Tests of the Models

Various processing methods and tests were devised in an attempt to determine which of the above models was the most appropriate to the CNV. Because of the variable nature of the CNV, both from subject to subject, and also from trial to trial with the same subject, evidence for phase ordering has to be sought on a statistical basis. It is possible to detect phase ordering by Fourier transforming the 'Negative Variation' sections of a sequence of CNV's (i.e. that section of the CNV remaining when the two involuntary stimulus responses were ignored) and testing the phase values. One method of visually detecting phase ordering would be to plot phase histograms, whereas the variability of the responses could be judged by plotting amplitude histograms.

2.2.1 Histograms of Phase and Amplitude

The phase values for each harmonic frequency component could be grouped into bands of known angular width such that the range $-\pi$ to π was covered in a number of steps. Histograms could then be plotted showing, for a particular frequency, the distribution of the phase values. If phase ordering were present then the phase histograms would be expected to show aggregation about some particular phase value. Indeed if the responses were identical, then in the absence of any noise the histograms would show a given frequency component of every response as having the same phase value. However if no phase ordering were present then the phase histograms would be expected to exhibit an uniform distribution of phase over the range $-\pi$ to π.

By considering the shape of an ideal CNV response [1] it is possible to predict the values, for each harmonic frequency, around which phase grouping should take place. Figure 2-2 shows an idealised CNV of about one second inter-stimulus interval. Ignoring the evoked responses R_1 and R_2 the responses may be considered as a linear function of time. This may be Fourier transformed as follows:-

$$X(n) = \frac{1}{N} \sum_{i=0}^{N-1} \left[x(i) e^{\frac{-2\pi j i n}{N}} \right] \qquad \ldots\ldots\ldots\ldots\ldots (1)$$

$$= \frac{1}{N} \sum_{i=0}^{N-1} \left[x(i) \left(\cos\left(\frac{2\pi i n}{N}\right) - j \sin\left(\frac{2\pi i n}{N}\right)\right)\right]. \quad (2)$$

but $x(i) = -ki$ over the range $0 \leqslant i < N$

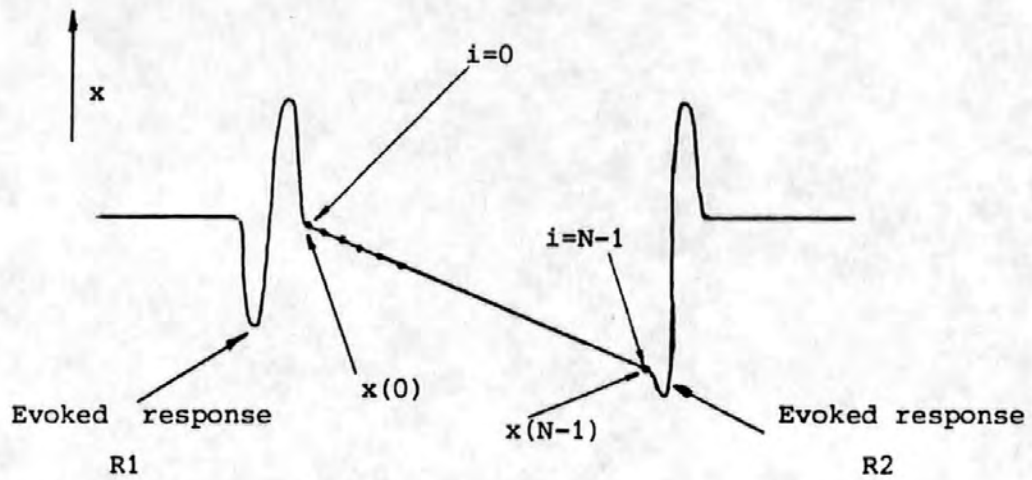


Figure 2-2

An idealized C.N.V response.

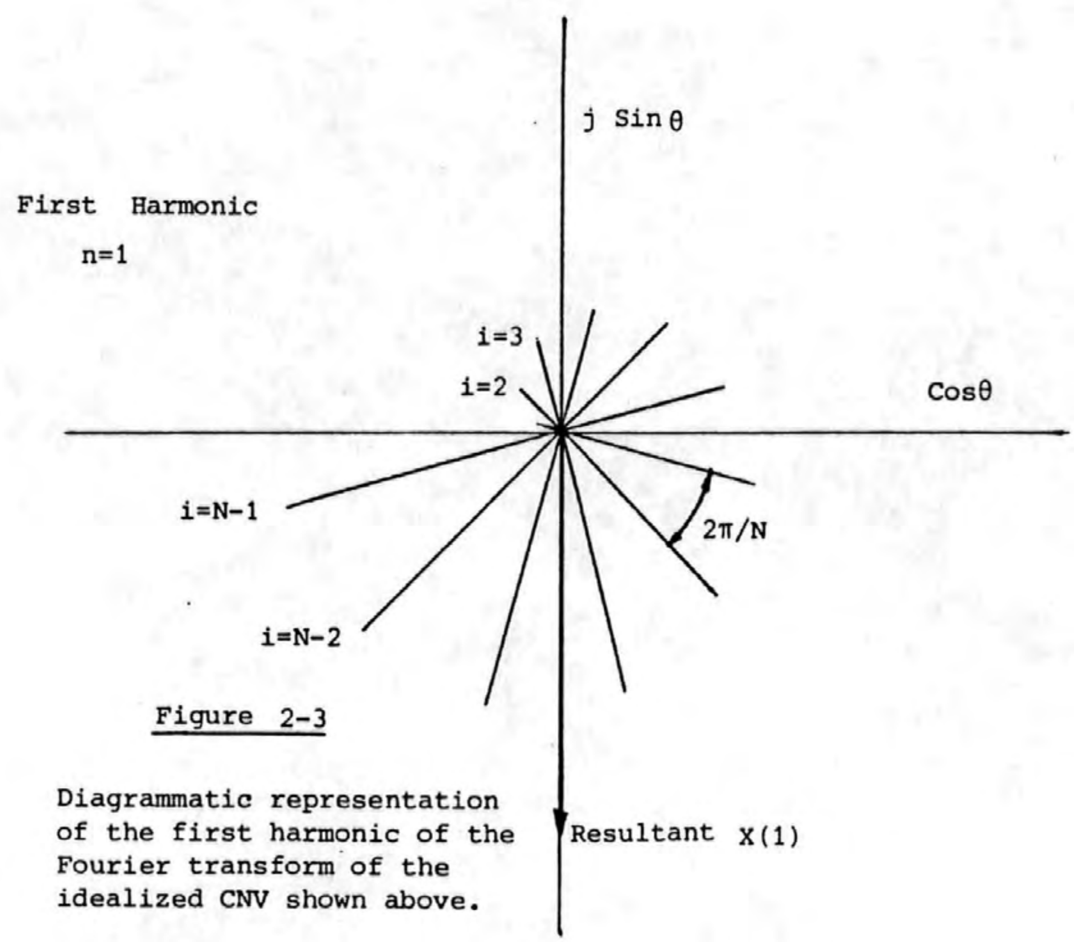


Figure 2-3

Diagrammatic representation of the first harmonic of the Fourier transform of the idealized CNV shown above.

$$X(n) = \frac{1}{N} \sum_{i=0}^{N-1} \left[-ki \cos\left(\frac{2\pi in}{N}\right)\right] + \frac{j}{N} \sum_{i=0}^{N-1} \left[ki \sin \left(\frac{2\pi in}{N}\right)\right] \quad ..(3)$$

The first harmonic component is thus

$$X(1) = \frac{1}{N} \sum_{i=0}^{N-1} \left[-ki \cos\left(\frac{2\pi i}{N}\right)\right] + \frac{j}{N} \sum_{i=0}^{N-1} \left[ki \sin \left(\frac{2\pi i}{N}\right)\right] \quad ....(4)$$

The individual terms of these summations may be represented as shown in Figure 2-3. The resultant (i.e. the first harmonic component) is clearly in either the third or fourth quadrant. In fact calculation shows that for large N the angle approaches -90°. Thus the phase histograms would be expected to show aggregation at this phase angle. Additional calculations (see Appendix 8.1) showed that the phase angles of all of the first 6 harmonics would aggregate at -90°. Furthermore, for longer CNV's (i.e. those with a longer ISI) which often change shape after approximately two seconds [2] the phase angles are also in the third and fourth quadrants. This suggests that all normal CNV's should have phase histograms which show aggregation in the third and fourth quadrants.

One disadvantage of phase histograms is that the phase data is cyclic yet the histogram axis is not. This disadvantage can be illustrated by assuming that, for example, an evoked response has a phase which tends towards π. Instead of a group of phase 'bins' at π one would observe a cluster at π and a cluster at $-\pi$ (i.e. at opposite ends of the angular scale). This problem can be overcome by using either Rose diagrams (see Figure 2-4) or by using the phasor diagrams previously described. Whichever method of display is chosen the question to be resolved remains the same. This is simply whether the phase ordering observed occurs by chance or whether there is some mechanism forcing the phasors to some preferred direction.

Histograms could also be plotted for the amplitude information. Provided the background EEG were negligible, these would give information about the variability of the CNV responses. If, for example, each individual CNV response was identical to the next, then the amplitude histograms would show only one value of amplitude for each frequency component. If, on the other hand, the responses were very variable then the amplitude histograms would show many values of amplitude i.e. a spread of amplitude. This may be useful in the classification of certain subject categories. One difficulty which arises with amplitude histograms is that of the choice of the amplitude scale and interval. Unfortunately this choice might be critical in assessing whether one subjects responses are more variable than anothers.

2.2.2 Angular Statistical Tests for Phase Ordering

To determine whether the grouping of a set of phasors could have occurred by chance it is necessary to perform angular statistical tests on the harmonic components of the sample of individual CNV's. These tests are described below. All three tests are non-parametric.

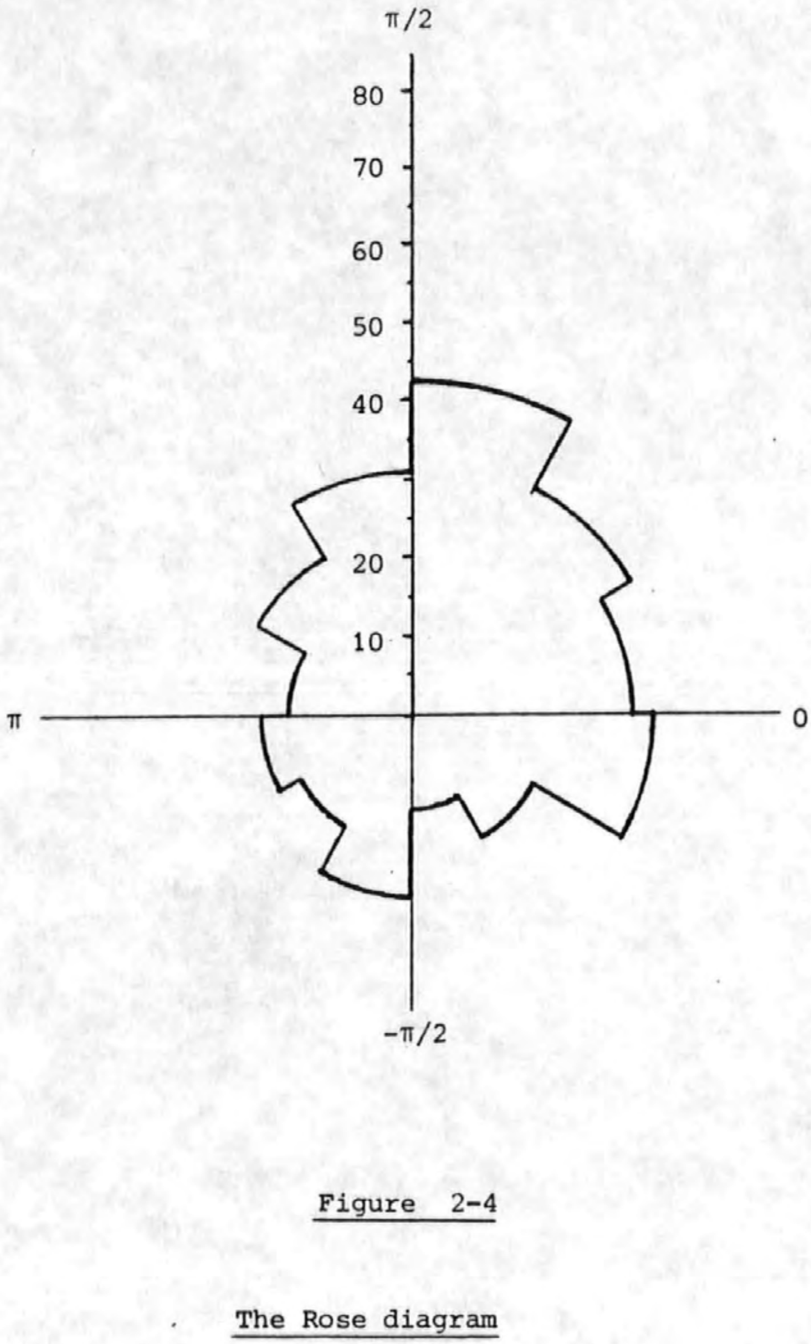


Figure 2-4

The Rose diagram

2.2.2.1 The Rayleigh Test of Circular Variance

This is the first of a number of tests used to determine whether a set of N phase angles $\{\theta_i\}$ are distributed in a non-uniform manner. It could therefore be used to detect phase ordering.

The circular variance can be calculated as follows:- [3]

$$\text{Circular Variance So} = 1 - \overline{R} \qquad \text{..........} \quad (5)$$

$$\text{where } \overline{R} = \sqrt{\overline{C}^2 + \overline{S}^2} \qquad \text{..........} \quad (6)$$

$$\text{and } \overline{C} = \frac{1}{N} \sum_{i=1}^{N} \cos \theta_i \qquad \text{........} \quad (7)$$

$$\overline{S} = \frac{1}{N} \sum_{i=1}^{N} \sin \theta_i \qquad \text{.......} \quad (8)$$

Clearly if $\theta_1 = \theta_2 = \text{.........} = \theta_N = \theta$

then $\overline{C} = \cos \theta$ and $\overline{S} = \sin \theta$

This gives $$\overline{R} = \sqrt{\cos^2\theta + \sin^2\theta} = 1 \qquad \text{......} \quad (9)$$

$$\text{So} = 0 \qquad \text{........} (10)$$

This corresponds to the perfect phase ordering situation where all the phase angles are the same.

Alternatively consider the situation where $\theta_i = \frac{2\pi i}{N}$ i.e. $\{\theta_i\}$ are distributed uniformly over the range 0 to 2π. In this case the summations $\bar{C}$ and $\bar{S}$ are both zero.

$$\text{Hence} \quad \bar{R} = 0 \qquad \text{.............. (11)}$$

$$So = 1 \qquad \text{.............. (12)}$$

This corresponds to the situation where all the phase angles are uniformly distributed. Thus to determine whether a set of angles are distributed in a significantly non-uniform manner, tables of the Rayleigh distribution must be consulted. However the commonly tabulated Rayleigh distribution probabilities [3] are in terms of R not $\bar{R}$. These two quantities are related by the expression $R = N\bar{R}$. (In the broadest sense $\bar{R}$ is more meaningful than R since $\bar{R}$ always lies between zero and one whereas R lies between zero and N).

Alternatively, however the tables can be transformed to yield significance levels for So in place of R. Details of this transformation and the resulting tables for So are given in Appendix 8.2

2.2.2.2 The Modified Rayleigh Test of Circular Variance

In an attempt to take both the amplitude and the phase angle into consideration Johnson [4] suggested the use of the modified test statistic To given by

$$To = 1 - \sqrt{\left[\frac{\sum_{i=1}^{N} r_i \cos \theta_i}{\sum_{i=1}^{N} r_i}\right]^2 + \left[\frac{\sum_{i=1}^{N} r_i \sin \theta_i}{\sum_{i=1}^{N} r_i}\right]^2} \quad \text{.. (13)}$$

Where r_i is the length of the ith phasor

θ_i is the phase angle of the ith phasor

If $\{\theta_i\}$ are all aligned (i.e. $\theta_1 = \theta_2 \ldots\ldots\ldots = \theta_N$) then the statistic To = 0 whereas if the angles are uniformly distributed over the range 0 - 2π and all the phasors have the same length then To = 1.

Unfortunately however the distribution of To is not easily obtainable and is likely to depend critically on the assumptions made in deriving it. However, Moore [5], uses the rank of the phasor magnitudes rather than their magnitudes and thus avoids this problem. Thus a new statistic Uo may be defined.

$$U_o = 1 - \sqrt{\left[\frac{\sum_{i=1}^{N} R_i \cos\theta_i}{\sum_{i=1}^{N} R_i}\right]^2 + \left[\frac{\sum_{i=1}^{N} R_i \sin\theta_i}{\sum_{i=1}^{N} R_i}\right]^2} \quad \ldots (14)$$

Where R_i is the rank of the ith phasor.

This is closely related to the statistic R* proposed by Moore [5] and significance levels for Uo may be obtained from those for R* by use of the formula

$$R^* = \frac{(1 - U_o)\ (N + 1)}{2\sqrt{N}} \quad \ldots\ldots\ldots (15)$$

Tabulated values of the probabilities for Uo are given in Appendix 8.3. Where calculated values of Uo are significantly different from unity then the phasors are non-uniformly distributed.

2.2.2.3 <u>The Hodges-Ajne Test</u>

This is an alternative test used to determine whether a set of angles are distributed in a non-uniform manner. The test statistic, m is given by the minimum number of observations lying in any semi-circle. If the value of m is small in relation to the number of observations, N then the angles are non-uniformly distributed. For given values of m and N the significance level of the test may be calculated from the formula [6].

$$\text{Significance level} = \frac{(N-2m)\,{}^{N}C_{m}}{2^{N-1}} \times 100\% \qquad \ldots\ldots\ldots\ldots(16)$$

$$\text{Provided } m < \frac{N}{3}$$

This test is similar in principle to that used by Sayers [7]. A table of significance levels is given in Appendix 8.4.

2.2.3 <u>Tests of Additivity</u>

These tests were used in an attempt to detect changes in the energy content of the evoked responses. These tests are described below.

2.2.3.1 <u>Pre - and Post - Stimulus Energy Tests</u>

The energy in the pre- and post-stimulus records was compared by means of a two tailed t-test. For a section of pre-stimulus EEG the mean square value was calculated using the formula

$$E = \frac{1}{N} \sum_{i=1}^{N} x_i^2 \qquad \ldots\ldots\ldots\ldots\ldots(17)$$

where E is proportional to the signal energy

N is the number of data points over which E is to be calculated

x_i is the ith value of the signal

This calculation was repeated for the section containing the CNV response and the difference between the two values was noted. For one second ISI CNV's the lengths of the pre- and post- stimulus sections were the same (N = 80 or 640 ms) but for the 4 second ISI CNV's only 200 points (1.6 seconds) of pre- stimulus information was available whereas 400 points (3.2 seconds) were included to encompass the CNV response.

The differences for each of the thirty-two trials were then averaged and the mean of the differences was subjected to a two-tailed t-test (see Appendix 8.5) to determine whether it was significantly different from zero. A non-significant mean value indicated no statistical difference between pre- and post- stimulus energy. A significant positive value indicated that the post-stimulus energy exceeded the pre-stimulus energy, whilst a significant negative value indicated the reverse.

2.2.3.2. Pre - and Post - Stimulus Mean Amplitude Differences Test

This test was also a paired two-tailed t-test. For each of the thirty-two trials the differences between the corresponding pre- and post-stimulus phasor lengths for a given harmonic component were formed. The mean of the differences was calculated and tested to establish whether it was significantly different from zero. A significant positive result indicated that the evoked potential was associated with an additive effect at the nth harmonic, although it gave no indication as to the mechanism involved. Because of the limited amount of pre-stimulus information (see section 2.2.3.1) it was not possible to perform this test on the four second ISI CNV's. (See also Appendix 8.5)

2.2.3.3 Nearest and Furthest Mean Amplitude Test

This test investigated the variation of amplitude with phase angle in the post-stimulus nth harmonic phasor diagram. Increased amplitudes in the direction of preferred phase combined with decreased amplitudes in the opposed direction would be evidence for an additive effect. The mean length of that half of the vectors whose phase angles lay within the smallest arc was calculated as was that of the remaining vectors. A one-tailed t-test was then performed to determine whether the former mean value was greater than the latter. In order to allow for the possibility of unequal variances, a correction was made to the degrees of freedom used in these statistical tests (See Appendix 8.6). A significant result would provide evidence for an additive effect. This test is not infallible, however. The additive signal might combine with an oppositely directed phasor to produce a small phasor in the smallest arc, or alignment of all the phasors in the preferred direction would also render the test unreliable. For these reasons the results of this test should not be examined without reference to the tests for phase ordering previously described.

2.3 Eye Movement Corrections

At an early stage of the investigation it was found to be necessary to remove the effects of eye movements from the measured EEG signal. These effects are due to a steady pot-tential between the cornea and the retina of each eye. When the eyes are moved the proportion of this potential detected at the scalp electrodes varies and hence an artefact related to the ocular position is superimposed on the EEG signal. Because of the relative magnitudes of the EEG and the corneo-retinal potential the artefact introduced is considerably greater than the EEG. Thus the EEG may be completely obscured by the artefact. A number of workers [8,9,10,11,12,13] had published details of methods for removing the artefact but no record of a comparison of the available techniques could be found.

One method of removing the effects of eye movements from the EEG was proposed and used by McCallum and Walter [8]. The method is based on the use of a potentiometer to balance out the effects of vertical eye movements. One end of the potentiometer was connected to a mid-frontal electrode and the other end to an electrode placed on the mastoid processes as shown in Figure 2-5. The centre tap of the potentiometer was used as a reference for a vertex EEG electrode. The operation of the circuit is best explained by the use of a simplified equivalent circuit as depicted by Figure 2-6. The EOG signal (V_{EOG}) is shunted by the resistors R_1, R_2, R_3 in series. These resistors represent the tissue etc. surrounding the eye. At point P_1 along this resistance chain the EEG generator may be considered to be connected. Another point (P_2) represents the mastoid process. If the EEG signal is measured between points P_3 and P_2 then the observed signal will be the sum of both the EEG and a fraction of the EOG. The fraction of the EOG signal contained in the EEG will be given by $R_3/(R_1 + R_2 + R_3)$.

$$\therefore \quad V = V_{EEG} + \frac{R_3 \; V_{EOG}}{R_1+R_2+R_3} \qquad \ldots\ldots\ldots\ldots\ldots (18)$$

If, however, the potentiometer is connected as shown in Figure 2-7a then by adjusting the position of the wiper the vertical EOG component can be balanced out. The point of balance can be derived from the re-drawn circuit Figure 2-7b. The current, I, from the EOG generator splits into I_1 and I_2 at the connection of R_5 and R_1

$$I_1 = \frac{R_1+R_3}{R_1+R_3+R_5} \quad I \qquad \ldots\ldots\ldots\ldots\ldots (19)$$

$$I_2 = \frac{R_5}{R_1+R_3+R_5} \quad I \qquad \ldots\ldots\ldots\ldots\ldots (20)$$

The potentiometer, R_5, may be represented as two resistors in series the common point being the wiper. Thus the two resistors have the values kR_5 and $(1-k)\ R_5$ where

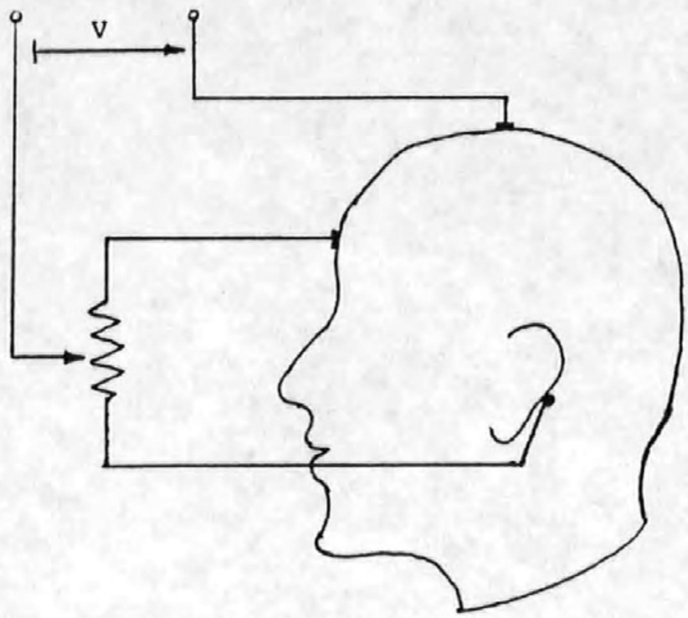


Figure 2-5

Eye movement correction method due to McCallum and Walter.

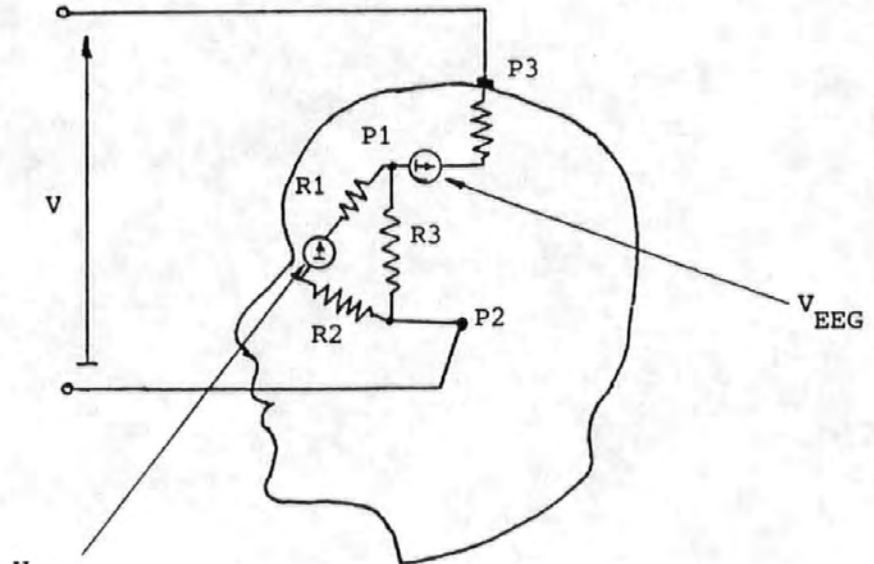


Figure 2-6

The simplified equivalent circuit without potentiometer

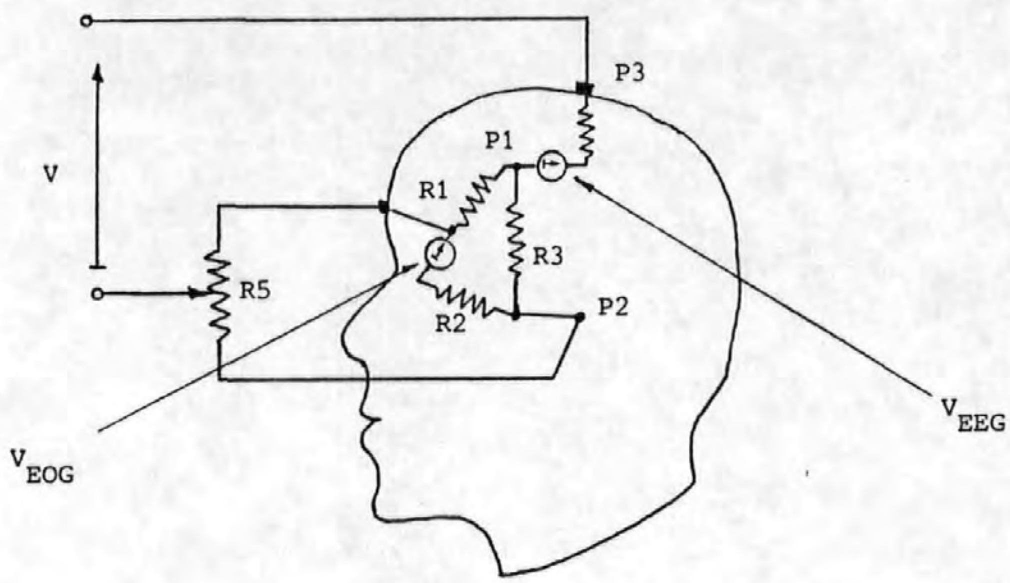


Figure 2-7a

The simplified equivalent circuit with potentiometer.

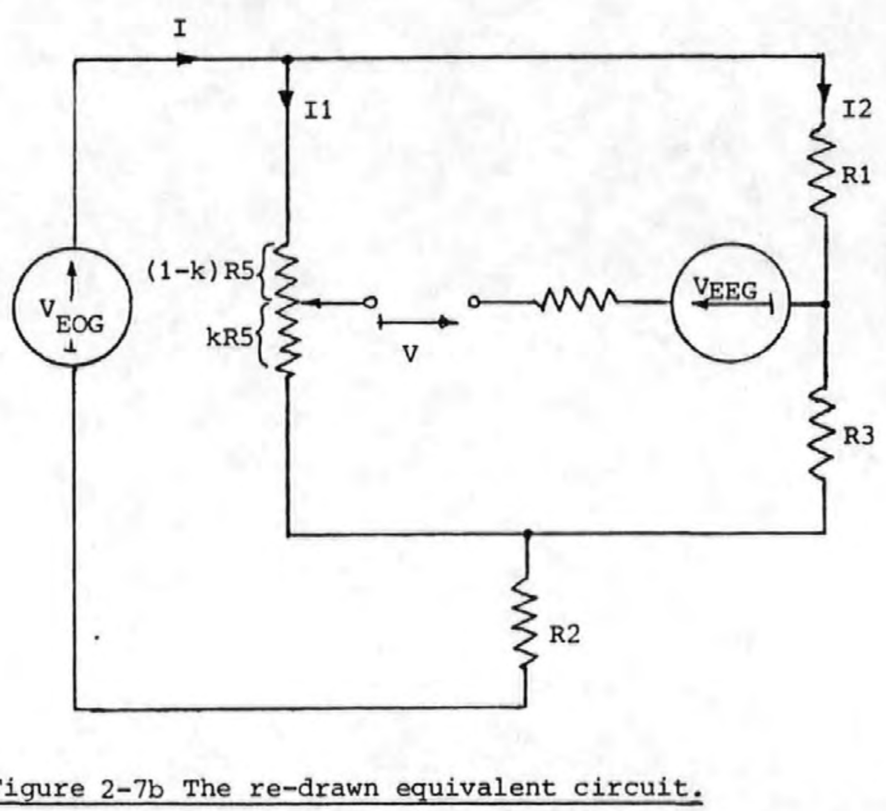


Figure 2-7b The re-drawn equivalent circuit.

k is a fraction between 0 and 1 representing the setting of the potentiometer. When I_1kR_5 equals I_2R_3 then the EOG signal will be eliminated from the EEG.

Thus

$$I_1kR_5 = I_2R_3 \qquad \text{..........(21)}$$

$$\frac{R_1+R_3}{R_1+R_3+R_5} \; I \; kR_5 = \frac{R_5}{R_1+R_3+R_5} \; I \; R_3 \qquad \text{....(22)}$$

$$\therefore \quad (R_1 + R_3)\ k = R_3 \qquad \text{..........(23)}$$

$$\therefore \quad k = \frac{R_3}{R_1+R_3} \qquad \text{..........(24)}$$

Since $\frac{R_3}{R_1+R_3}$ is always in the range 0 to 1 for positive values of R_1 and R_3 the balance point can always be attained.

A variation of this technique was proposed by Girton and Kamiya [9] and is shown in Figure 2-8. The observed EEG signal is again assumed to be the sum of the true EEG and a fraction of the EOG signals. Unlike McCallum and Walters method, this technique allows for the independant correction of both horizontal and vertical components of the EOG in the EEG. The horizontal and vertical components of the EOG are obtained from electrodes placed around the eyes and are amplified by the differential amplifiers A_1 and A_2. The EEG signal is amplified by a further differential amplifier A_3 connected to electrodes at the vertex and at the mastoid processes. Fractions of the amplified EOG components are then tapped off by means of the potentiometers R_1 and R_2.

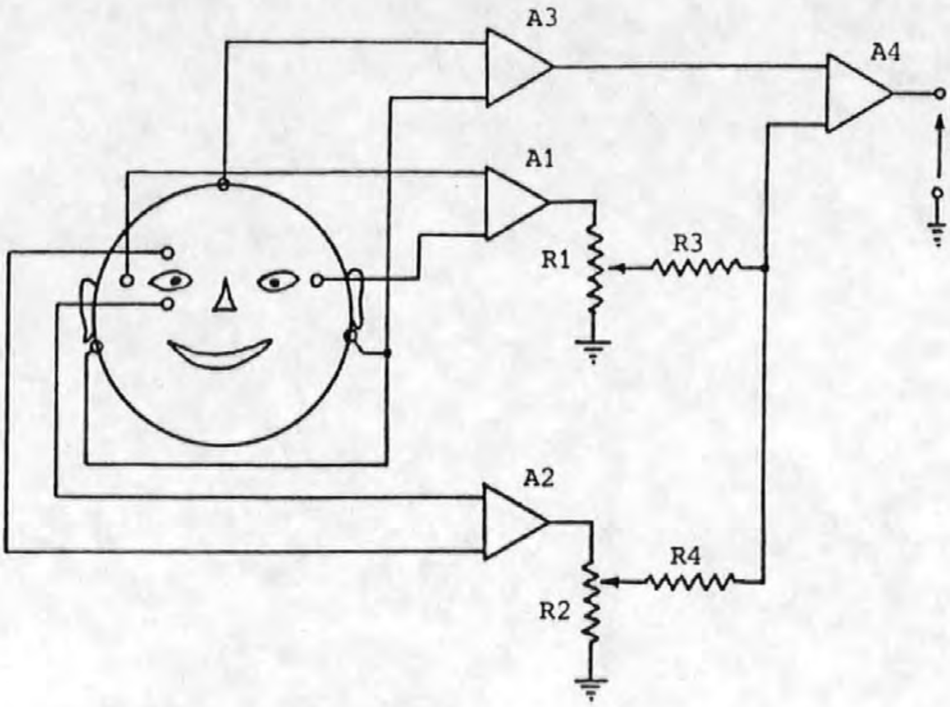


Figure 2-8

The method of Girton and Kamiya

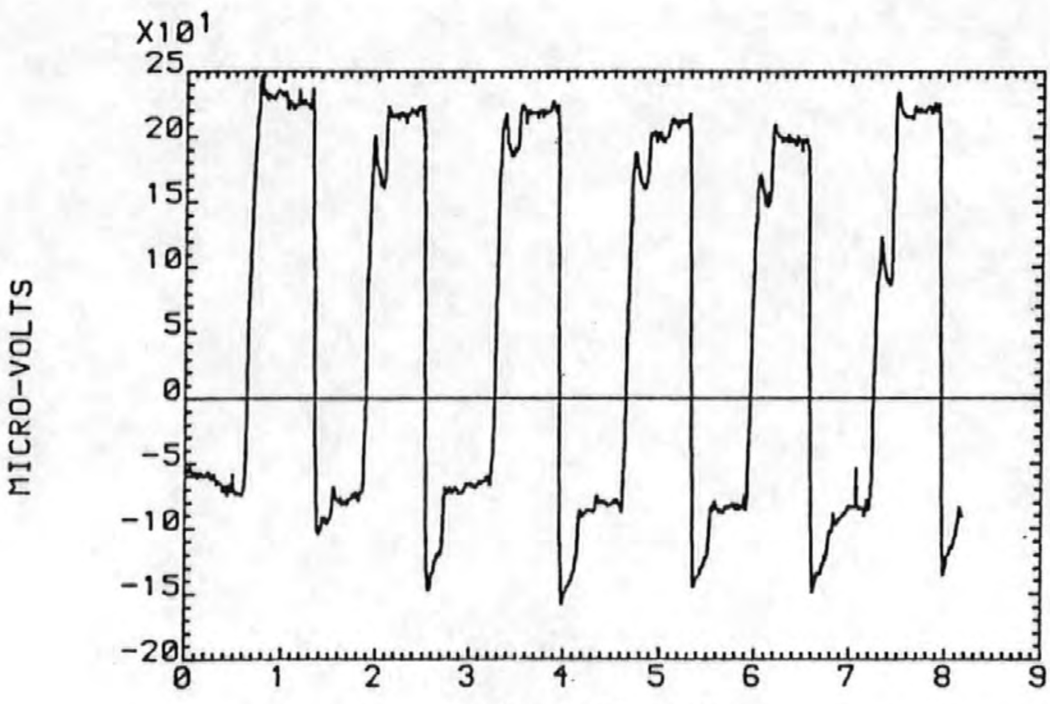


Figure 2-9

A typical vertical left EOG signal during the eye movement correction experiments

These signals are then summed by the resistors R_3 and R_4. Finally the summed EOG components are subtracted from the EEG by means of a further differential amplifier A_4. Thus the output signal V consists of the corrupted EEG signal less fractions of the horizontal and vertical components of the EOG. By adjusting the potentiometers R_1 and R_2 these fractions can be chosen so as to remove the corrupting EOG components in the output signal.

Both these techniques (McCallum and Walters and Girton and Kamiya) rely on the manual adjustment of the potentiometer(s) to obtain maximum artefact rejection. These adjustments are normally made whilst observing the chart output and are thus subjective. As the balance point (i.e. the point of maximum artefact rejection) is approached so the effect of further adjustment becomes more difficult to assess because of the masking nature of the background EEG. The process of adjustment is also rather slow. If, for example, it takes one minute to adjust each potentiometer, then for a 16 channel recording it would take about a quarter of an hour to set the potentiometers for McCallum and Walters method or over half an hour for Girton and Kamiya's method. This would normally be quite unacceptable.

2.4 Assessment of the Eye Movement Correction Methods

The quantitative assessment of the different correction procedures was based on the knowledge that the autocorrelation function (a.c.f.) of a rectangular waveform is triangular. [14] In the experiments described in Section 3.3 the almost periodic eye movements produced an EOG which was nearly a rectangular wave (Figure 2-9) and so the measured EEG's were contaminated by a nearly rectangular wave. It is shown below that incomplete correction may be detected by the presence of a triangular component of the same period as the EEG present in the a.c.f. of the corrected EEG. If the a.c.f. showed no triangular components of similar period to the EOG, then the correction procedure was effective. If the a.c.f. fell rapidly to an average value of zero the efficiency of the corresponding correction was high. This method allowed very small residual EOG signals to be detected in the background EEG activity even in cases where they were visually indiscernable in the corrected waveform.

Let $Q(t)$ be the EEG signal after incomplete correction

Then $C_{qq}(\tau) = \varepsilon[Q(t)Q(t+\tau)]$ ....(25)

Where $C_{qq}(\tau)$ is the autocovariance of Q at lag τ, ε denotes the expected value and all signals are adjusted to have zero mean value.

$Q(t)$ may be considered to be the sum of the uncorrupted EEG signal $E(t)$ and the remaining artefact $I(t)$, so that

$$Q(t) = E(t) + I(t) \quad \text{.................}(26)$$

Hence

$$C_{qq}(\tau) = \varepsilon\{[E(t) + I(t)] \,.\, [E(t+\tau) + I(t+\tau)]\} \quad \text{....}(27)$$

$$= \varepsilon[E(t).E(t+\tau)] + \varepsilon[I(t).I(t+\tau)]$$

$$+\varepsilon[E(t).I(t+\tau)] + \varepsilon[I(t).E(t+\tau)] \quad \text{.......}(28)$$

or $$C_{qq}(\tau) = C_{ee}(\tau) + C_{ii}(\tau) + C_{ei}(\tau) + C_{ie}(\tau) \quad (29)$$

where the suffices indicate the auto and cross covariances.

Because E(t) and I(t) are statistically independant, $C_{ei}(\tau) = C_{ie}(\tau) = 0$, while $C_{ee}(\tau)$ will fall rapidly with increasing τ.†

Hence

$$C_{qq}(\tau) \approx C_{ii}(\tau) \text{ for large } \tau.$$

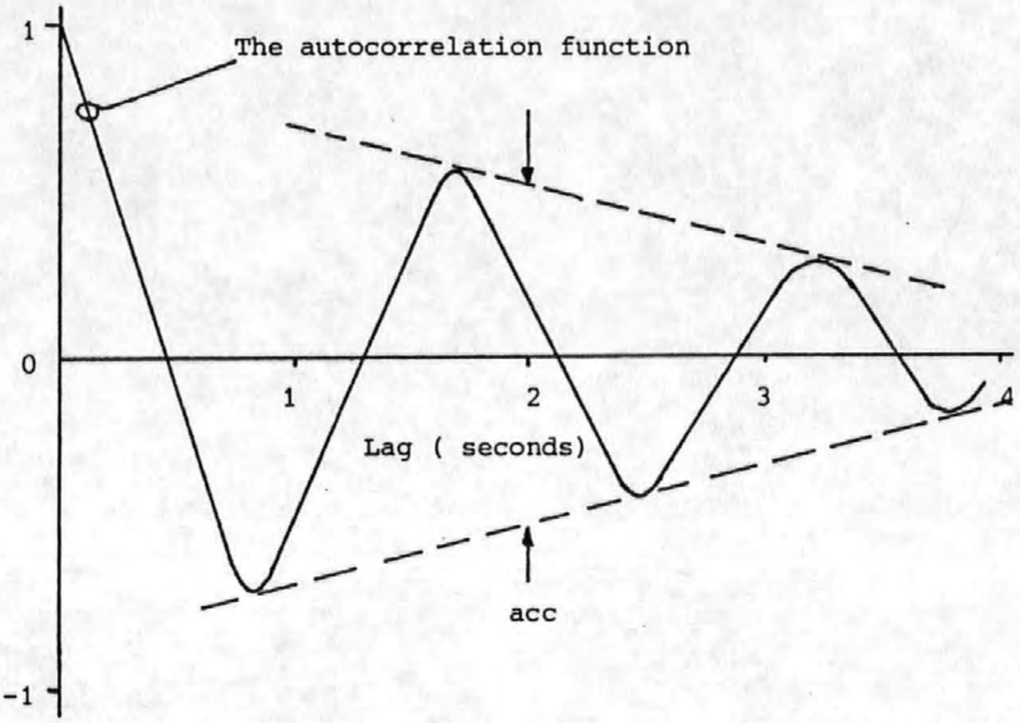
Since the autocorrelation function and the autocovariance function are related by the variance then

$R_{qq}(\tau) \approx R_{ii}(\tau)$ for large τ. (where R denotes the autocorrelation function)

Since I(t) is approximately rectangular then $R_{ii}(\tau)$ and hence $R_{qq}(\tau)$ will be triangular.

Thus to assess the effectiveness of the correction method the autocorrelation function of the corrected waveform was calculated and plotted. Those a.c.f.'s which contained any triangularity were examined further and the period, and the peak to peak envelope amplitude of the triangularity were noted at a lag of two seconds. A two second lag was chosen since the initial decrease in the autocorrelation had always been completed within two seconds (by observation of the a.c.f.'s). Figure 2-10 shows graphically how these measurements were made. The peak to peak amplitude of the a.c.f.'s at this lag is referred to as the autocorrelation co-efficient (a.c.c.)

†The autocovariance function $C_{ee}(\tau)$ of the EEG signal E(t) will fall rapidly to zero with increasing τ since the EEG contains no regular periodic component.



The autocorrelation co-efficient (acc) is the peak to peak amplitude of the envelope of the autocorrelation function at a lag of two seconds.

Figure 2-10

Measurement of the Autocorrelation Co-efficient

As a practical test of the sensitivity of the method a square wave of known amplitude was added to a section of 'eyes open' background EEG. The frequency of the square wave was chosen to be 0·8 Hz as this was about the most common frequency observed in the EOG signals during the eye movement correction experiments. The resultant signal was analysed in the same way as the corrected EEG signals. Table 2-1 shows the results of these tests with differing amounts of square wave added to the synthetic background EEG. From the table it may be deduced that the autocorrelation co-efficient gives a good indication of the magnitude of residual artefact and can detect residual components with amplitudes of only one quarter of the background. Figure 2-11 shows the variation of the a.c.c. with differing amounts of residual square wave present in the EEG.

2.5 The Modified Correction Method

The modified form of Quilters correction method [10] is described here. The fundamental assumption upon which the method is based is that the measured EEG signal can be considered to be formed from a linear combination of the true EEG and the interfering artefact signals. Thus if the artefact signals could be measured independently of the EEG then by subtracting the appropriate fractions of the artefact signals from the observed (corrupted) EEG the true EEG could be established. Fortunately, the artefact signals due to eye movements can be obtained by placing electrodes in close proximity to the eyes, thus if the fractions of these signals present in the observed EEG are known the true EEG can be

Table 2-1

The results of tests performed to determine

the sensitivity of the ACC to residual square wave

SQUARE WAVE BACKGROUND	RATIO dB	ACC OBSERVED	FREQUENCY OBSERVED	COMMENT
100/10	+ 20	1.489	0.8	Triangularity easily visible in ACF Square wave easily visible in EEG.
50/10	+ 14	1.447	0.8	"
40/10	+ 12	1.430	0.8	"
30/10	+ 9.5	1.375	0.8	"
18/10	+ 5.1	1.211	0.8	"
10/10	0	0.885	0.8	Triangularity easily visible in ACF. Square wave visible in EEG but noisy.
7.5/10	- 2.5	0.717	0.8	Triangularity easily visible in ACF. Square wave just visible in EEG.
5/10	- 6.0	0.552	0.82	Triangularity visible in ACF Square wave not visible in EEG.
3.75/10	- 8.5	0.465	0.82	Triangularity visible in ACF
2.5/10	-12.0	0.383	0.78	Triangularity just visible in ACF
0/10	-	0.256	-	No visible periodicity in ACF

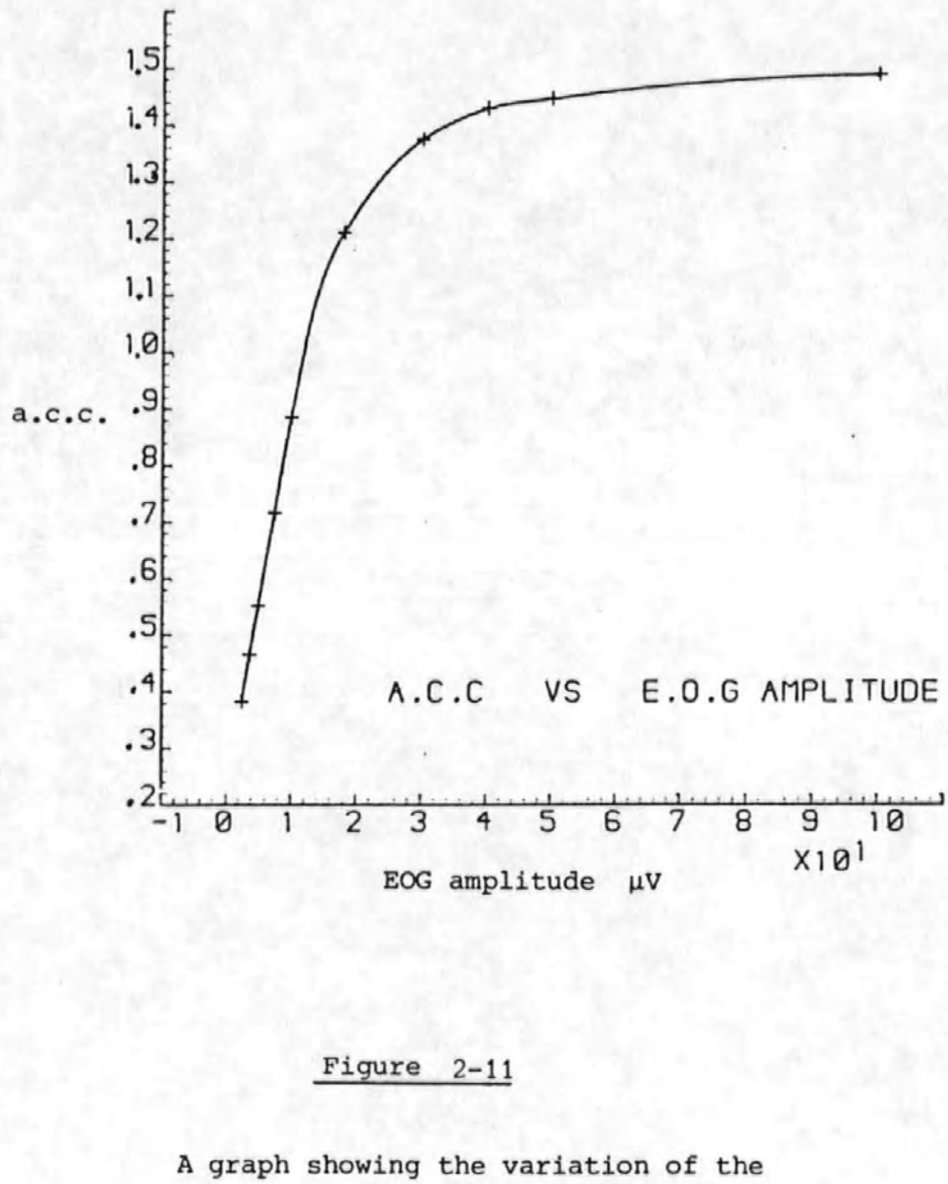


Figure 2-11

A graph showing the variation of the autocorrelation co-efficient with the amplitude of a synthesized square EOG signal.

obtained. Since the eyes are free to swivel about two axes it is necessary to allow for both horizontal and vertical artefact signals. Furthermore since the eyes do not always move in unison or through the same amount of arc, and may have different dipole moments, it may be necessary to allow for horizontal and vertical components from each eye in the EEG.

Assuming that the transmission path between the source and the scalp electrode is linear and $M(t)$ is the measured EEG signal, $E(t)$ is the true EEG signal, K_1, K_2, K_3, K_4 are constants, $V_L(t)$ is the vertical component of the left EOG $H_R(t)$ is the horizontal component of the right EOG etc., then

$$M(t) = E(t) + K_1V_L(t) + K_2V_R(t) + K_3H_L(t) + K_4H_R(t) \quad .....(30)$$

or

$$E(t) = M(t) - [K_1V_L(t) + K_2V_R(t) + K_3H_L(t) + K_4H_R(t)] \quad ...(31)$$

Thus if the constants $K_1.....K_4$ could be found then the uncorrupted EEG signal $E(t)$ could be determined.

Rewriting equation (30) in discrete time form gives

$$M(i) = E(i) + K_1V_L(i) + K_2V_R(i) + K_3H_L(i) + K_4H_R(i) \quad ...(32)$$

where i represents the sample number.

Defining

$$M_{VL} = \Sigma[M(i)V_L(i)] \quad ....(33)$$

$$M_{VR} = \Sigma[M(i)V_R(i)] \quad ....(34)$$

$$M_{HL} = \Sigma[M(i)H_L(i)] \quad ....(35)$$

$$M_{HR} = \Sigma[M(i)H_R(i)] \quad ....(36)$$

Where all the summations are carried out over the range i = 1 to N, the number of data samples.

Substituting equation (32) into equation (33) gives:-

$$M_{VL} = \Sigma[\{E(i)+K_1V_L(i)+K_2V_R(i)+K_3H_L(i)+K_4H_R(i)\}V_L(i)] \quad \ldots(37)$$

$$= \Sigma[E(i)V_L(i)+K_1V_L^2(i)+K_2V_R(i)V_L(i)+K_3H_L(i)V_L(i) + K_4H_R(i)V_L(i)] \quad \ldots\ldots\ldots(38)$$

defining $P_{VL} = \Sigma V_L^2(i)$ ....(39)

$$B = \Sigma[V_R(i)V_L(i)] \quad \ldots\ldots\ldots(40)$$

$$C_{CL} = \Sigma[V_L(i)H_L(i)] \quad \ldots\ldots\ldots(41)$$

$$C = \Sigma[V_L(i)H_R(i)] \quad \ldots\ldots\ldots(42)$$

gives

$$M_{VL} = \Sigma[E(i)V_L(i)] + K_1P_{VL} + K_2B + K_3C_{CL} + K_4C \quad \ldots\ldots\ldots(43)$$

Substituting equation (32) into equation (34) and defining

$$P_{VR} = \Sigma V_R^2(i) \quad \ldots\ldots\ldots(44)$$

$$D = \Sigma[V_R(i)H_L(i)] \quad \ldots\ldots\ldots(45)$$

$$C_{CR} = \Sigma[V_R(i)H_R(i)] \quad \ldots\ldots\ldots(46)$$

gives

$$M_{VR} = \Sigma[E(i)V_R(i)] + K_1B + K_2P_{VR} + K_3D + K_4C_{CR} \quad \ldots\ldots\ldots(47)$$

Substituting equation (32) into equations (35) and (36) in a similar manner and defining

$$P_{HL} = \Sigma H_L^2(i) \quad \ldots\ldots\ldots(48)$$

$$P_{HR} = \Sigma H_R^2(i) \quad \ldots\ldots\ldots(49)$$

$$A = \Sigma[H_L(i)H_R(i)] \quad \ldots\ldots\ldots(50)$$

gives

$$M_{HL} = \Sigma[E(i)H_L(i)] + K_1C_{CL} + K_2D + K_3P_{HL} + K_4A \quad ....(51)$$

and

$$M_{HR} = \Sigma[E(i)H_R(i)] + K_1C + K_2C_{CR} + K_3A + K_4P_{HR} \quad ....(52)$$

Equations (43), (47), (51), (52) may be more conveniently handled if written in matrix form.

$$\begin{bmatrix} M_{VL} \\ M_{VR} \\ M_{HL} \\ M_{HR} \end{bmatrix} = \begin{bmatrix} \Sigma[E(i)V_L(i)] \\ \Sigma[E(i)V_R(i)] \\ \Sigma[E(i)H_L(i)] \\ \Sigma[E(i)H_R(i)] \end{bmatrix} + \begin{bmatrix} P_{VL} & B & C_{CL} & C \\ B & P_{VR} & D & C_{CR} \\ C_{CL} & D & P_{HL} & A \\ C & C_{CR} & A & P_{HR} \end{bmatrix} \begin{bmatrix} K_1 \\ K_2 \\ K_3 \\ K_4 \end{bmatrix} .(53)$$

or

$$\underset{\sim}{M} = \underset{\sim}{Z} + \underset{\sim}{X}.\underset{\sim}{K} \quad ....(54)$$

Where $\underset{\sim}{M}$, $\underset{\sim}{Z}$, $\underset{\sim}{X}$ and $\underset{\sim}{K}$ represent the respective matrices.

The elements of the column matrix $\underset{\sim}{Z}$ may be considered as the cross co-variance between the true EEG signal and the four artefact signals at zero lag.

Provided E(i) does not affect the artefact signals $V_L(i)$ etc. then the correlation between E(i) and the artefact signals will be small. The matrix $\underset{\sim}{Z}$ is thus assumed to be zero.

The values K_1 - K_4 may now be obtained by solving the equation

$$\underset{\sim}{M} = \underset{\sim}{X}.\underset{\sim}{K} \quad ....(55)$$

Since matrices $\underset{\sim}{M}$ and $\underset{\sim}{X}$ only involve quantities which can be obtained from the signals M(i) and $V_L(i)$, $V_R(i)$, $H_L(i)$ and $H_R(i)$.

Therefore $\underset{\sim}{K} = \underset{\sim}{X}^{-1} \underset{\sim}{M}$ .... (56)

The values of $K_1 \ldots\ldots K_4$ may then be substituted into equation (31) and hence the true EEG signal can be calculated.

There are however a number of limitations to this technique. The most important of these are:-

(i) A considerable amount of computation is involved in the calculation of the 'sums of products' terms in matrices $\underset{\sim}{X}$ and $\underset{\sim}{M}$.

(ii) The matrix $\underset{\sim}{Z}$ may not be sufficiently small to be neglected.

(iii) The method (as described) cannot be applied on-line since a prior knowledge of the signals over N data points is required.

Offsetting these disadvantages are:-

(i) No manual setting up is required. (Unlike the methods due to McCallum and Walter and Girton and Kamiya where manual setting of the potentiometers is required. Manual setting up is both time consuming and is subjective and is therefore also inaccurate).

(ii) The method is self-optimizing i.e. New and optimum values of $K_1 - K_4$ are found for each N point data epoch.

References for Section 2

[1] McAdam D W, "Physiological Mechanisms"
Published in "Event-Related Slow Potentials of the Brain: Their relations to Behaviour"
Edited by McCallum W C & Knott J R
Electroencephalography and Clinical Neurophysiology Supplement No. 33, pp 79-86.
Published by Elsevier Scientific Publishing Company 1973.

[2] Rohrbaugh J W, Syndulko K, Lindsley D B, "Brain Wave Components of the Contingent Negative Variation in Humans"
Science, Volume 191, pp 1055-1057, 1976.

[3] Mardia K V, "Statistics of Directional Data"
Published by Academic Press (London), 1972.

[4] Johnson T E, A Private Communication with the Author.

[5] Moore B R, "A Modification of the Rayleigh test for Vector data"
Biometrika, Volume 67, pp 175-180, 1980.

[6] Hodges J L, "A bivariate sign test"
Annals of Mathematical Statistics
Volume 26, pp 523-527, 1955.

[7] Beagley H A, Sayers B McA, Ross A J, "Fully Objective ERA by Phase Spectral Analysis"
Acta Oto-laryngologica, Volume 87, pp 270-278, 1979.

[8] McCallum W C, Walter W G, "The Effects of Attention and Distraction on the Contingent Negative Variation in Normal and Neurotic Subjects" Electroencephalography and Clinical Neurophysiology, Volume 25, pp 319-329, 1968.

[9] Girton D G, Kamiya J, "A simple on-line technique for removing Eye Movement Artifacts from the EEG" Electroencephalography and Clinical Neurophysiology, Volume 34, pp 212-216, 1973.

[10] Quilter P M, MacGillivray B B, Wadbrook D G, "The Removal of Eye Movement Artefact from EEG Signals using correlation Techniques" Random Signals Analysis, IEE Conference Publication No. 159, pp 93-100, 1977.

[11] Whitton J L, Lue F, Moldofsky H, "A spectral Method for removing Eye Movement Artifacts from the EEG" Electroencephalography and Clinical Neurophysiology, Volume 44, pp 735-741, 1978.

[12] Hillyard S A, Galambos R, "Eye Movement Artifact in the CNV" Electroencephalography and Clinical Neurophysiology, Volume 28, pp 173-182, 1970.

[13] Corby J C, Kopell B S, "Differential Contributions of Blinks and Vertical Eye Movements as Artifacts in EEG Recording" Psychophysiology, Volume 9, pp 640-644, November 1972.

[14] Barlow J S, Brazier M A B, "A Note on a Correlator for Electroencephalographic Work" Electroencephalography and Clinical Neurophysiology Volume 6, pp 321-325, 1954.

3. Experimental Techniques

3.1 Initial CNV Tests

In order to gain first hand information about the problems associated with obtaining CNV responses two subjects were examined using conventional evoked response averaging equipment. These tests were carried out using equipment available at Freedom Fields Hospital during the first few months of this investigation. The two stimuli used were an auditory 'click' followed by a flashing lamp. Averaging over 64 trials was performed by a Medelec DAV6 digital averager. The resulting average CNV's are shown in Figure 3-1.

The observations made from these tests shaped the way in which the present measurement system was developed and the tests were performed. These observations are summarized below.

(1) The dynamic range of the averager† was often exceeded causing it to reject some of the trials.

(2) The onset of the visual stimulus caused the subjects to blink in several of the individual trials. These blinks are highly undesirable since they introduce an artefact which is synchronised to the visual stimulus.

†The Medelec DAV6 averager uses an 8 bit analogue-to-digital converter and hence has an inherent dynamic range of one part in 2^8 or 48 dB. at the input. However this range is only fully utilized if the gain of the preceeding analogue stage is set such that the largest input signal just fails to overload the converter. Unfortunately the variable nature of most bioelectric signals means that the amplitude of the largest signal cannot be predicted. Thus either a considerable amount of "Headroom" must be allowed (which in turn reduces the effective dynamic range), or a certain degree of overloading of the converter must be tolerated.

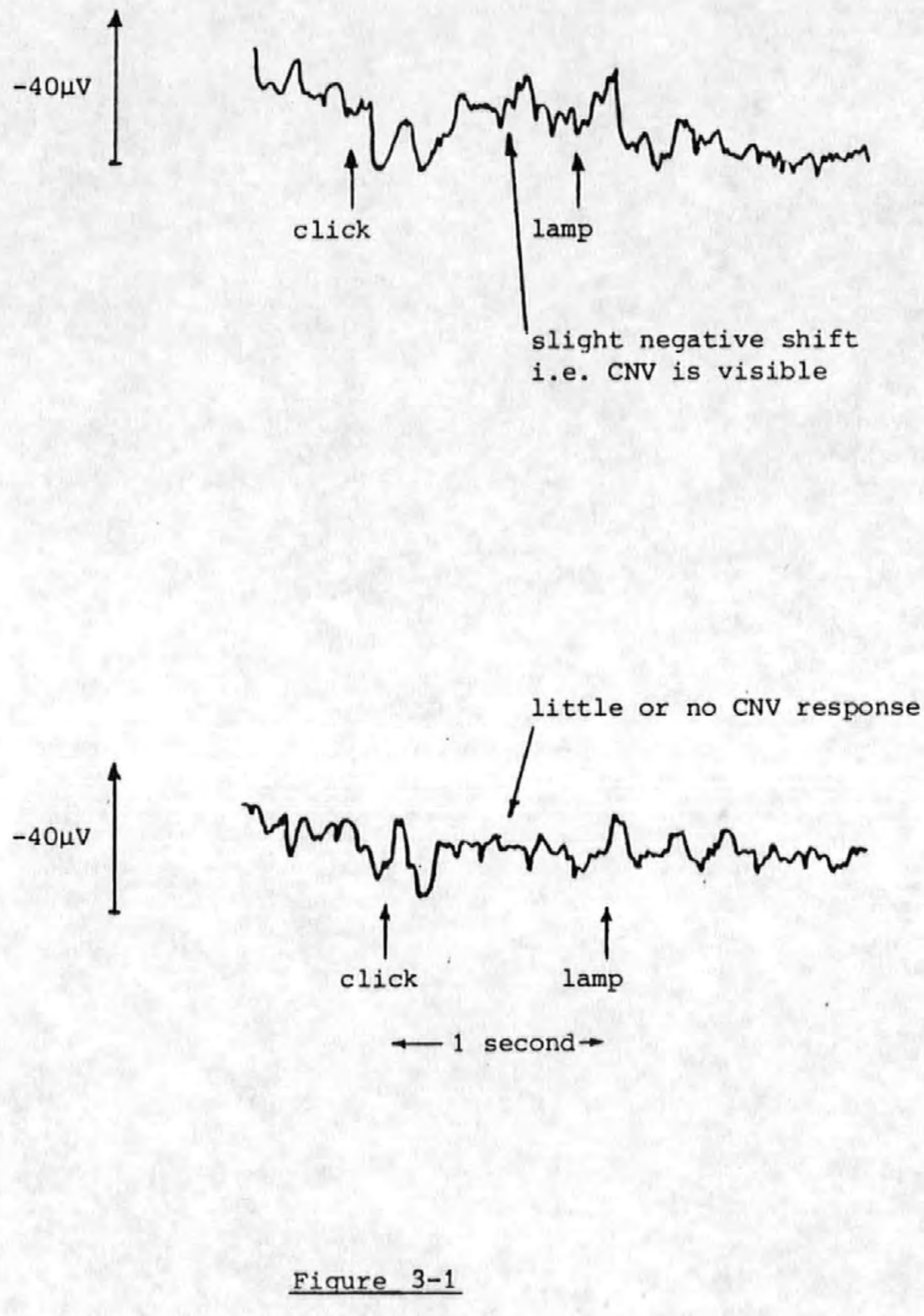


Figure 3-1

The initial attempts at recording CNV responses

(3) The subjects became tired and showed less motivation in the later trials.

(4) The subjects frequently moved their eyes which invariably caused the signal averager to overload. This indicated the presence of quite large artefacts induced by eye movements.

As a result of these observations -

(1) The dynamic range of the proposed data acquisition system was increased to 72 dB.

(2) Two auditory stimuli were used in place of one auditory and one visual.

(3) The possibility of using fewer trials in the averaging process or alternative methods to averaging would clearly have to be considered.

(4) Some method of removing the effects of eye movement artefact would have to be implemented.

3.2 Data Transfer and Preliminary Processing

During transfer from the disk of the minicomputer logging system to a data base on the Polytechnic main computer several tests were performed to verify the authenticity of the data and to ensure that no errors occurred in the transfer. In view of the large amounts of data involved these tests were performed automatically. The eye movement correction experiments involved the transfer of nearly 100,000 twelve bit words for each subject and approximately 400,000 words for each subject for the CNV tests.

For compatibility with conventional hardware each of the twelve bit words was split into two six bit quantities to which parity and marker[1] bits were added. These eight bit quantities (bytes) were initially transferred to the main computer on paper tape although eight inch, single density, single sided, floppy disks were subsequently adopted for speed and ease of handling. To each batch of 1024 words (2048 bytes) were added a batch number, an unique 'start of batch' indicator and a modulo 256 (eight bit) checksum.

When read into the main computer the parity and marker bits were tested for each byte and the checksum re-calculated and compared with that read for each batch. Any errors then found were reported[2] and the faulty batch was rejected. Rejected batches were re-transferred at a later date. The data for each experiment and subject was stored in a sequential access data file along with certain relevant system and other parameters (e.g. the sample rate, the analogue filter cut-off frequencies, the amplitude calibration constants, subjects name etc.) The final test of the transferred data was performed with the aid of a programme written in Fortran IV and using the Gino [1] graphics subroutines. This programme (Appendix 8.7) was used to plot the data on an interactive graphics terminal where a visual comparison[3]

[1] The marker bit was used to indicate whether the six bits concerned were the most (marker bit = 1) or the least (marker bit = 0) significant of the original twelve bit word.

[2] Paper tape error rates $\simeq 1:1.8 \times 10^6$ bits
Floppy disk error rates $< 1:34.7 \times 10^6$ bits.

[3] An identical waveform was not expected since the chart output of the EEG machine had different filtering to that employed in the acquisition electronics.

was made with the relevant section of the chart output of the EEG machine.

3.3 Eye Movement Corrections

As previously mentioned the eye movement artefact is caused by a standing potential between the cornea and the retina of the eye[2]. Whilst the eyes remain stationary the potential recorded from scalp electrodes will contain no artefact (except possibly a d.c. component) but any change in position will result in an artefact being superimposed on the background EEG activity. The amount of artefact introduced is related to the angular displacement of the eye and the position of the measuring electrodes [2]. Several methods of removing the artefact have been suggested based on the subtraction of a fraction of the electro-oculogram (EOG) i.e. the potential measured at electrodes placed in close proximity to the eyes, from the measured EEG [3,4,5]

Other methods involving a considerable degree of co-operation from the subjects [6,7] were examined but rejected on the grounds that such co-operation cannot always be obtained, particularly with very young, old or diseased subjects.

In order to test the effectiveness of the methods due to McCallum & Walter [3], Quilter [5] and a modified form of Quilters method derived here, eye movement experiments were performed on six volunteers. The volunteers were asked to make periodic eye movements whilst the EOG and EEG data was stored for subsequent analysis. To obtain consistent eye movements through a known angle (20^o) the wooden screen described in section 4.5.1 was utilised.

During these experiments the subjects were asked to fixate on the illuminated centre LED. One of the peripheral LED's was then switched on and the subjects were told to look repeatedly from the centre LED to the illuminated one at the periphery of the screen and back.

Whilst the subject was performing this task eight second epochs of data were digitized at 125 samples per second and stored. This procedure was repeated twice for each of the eight LED's around the periphery of the screen and for ten subjects. The data thus obtained consisted of digitized versions of the following six analogue signals:-

(i) The vertical component of the left EOG (electrodes 6 & 7).

(ii) The vertical component of the right EOG (electrodes 2 and 3).

(iii) The horizontal component of the left EOG (electrodes 4 and 5).

(iv) The horizontal component of the right EOG (electrodes 4 & 5).

(v) The vertex EEG referred to linked earlobes.

(vi) The analogue corrected vertex EEG (McCallum and Walters method [3].

The positions of the electrodes for the EOG signals are shown in Figure 3-2.

Prior to the recordings the subjects were asked to make extreme up and down eye movements in order that the balancing potentiometer utilized in the correction method due to McCallum and Walter [3] could be adjusted for the optimum artefact rejection. It should be noted however that this "optimum setting" was somewhat subjective in that it was based on a visual assessment of the residual eye movement artefact present in the chart output of the EEG machine.

The digitized signals were then transferred from the minicomputer logging system to the Polytechnic main computer for analysis. To assess the effectiveness of the correction techniques the procedure described in section 2.4 was utilized.

3.4 Processing of Eye Movement Data

The computer programme in Appendix 8.8 was used to perform the eye movement corrections described in section 2.5 This programme also calculates the auto-correlation function of the corrected signal for analysis of the effectivness of the correction method. It was realized at an early stage that although Quilter's original correction method only used single horizontal and vertical EOG components it should be tried to discover if the modified method was significantly better. Furthermore, since visual examination of the early data showed a high degree of correlation between the left and right vertical EOG components it was thought worthwhile to try a correction based on two horizontal EOG components but only one vertical component. (The horizontal components

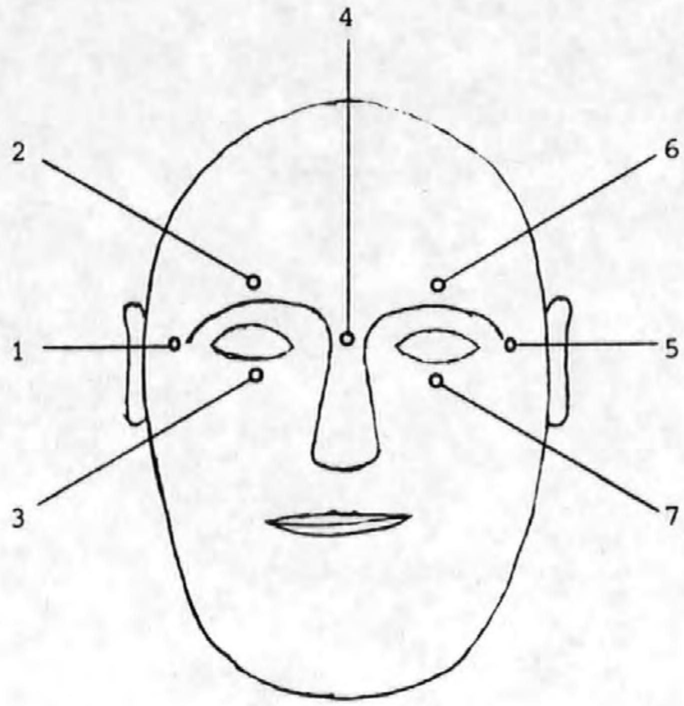


Figure 3-2

Electrode positions for
eye movement corrections

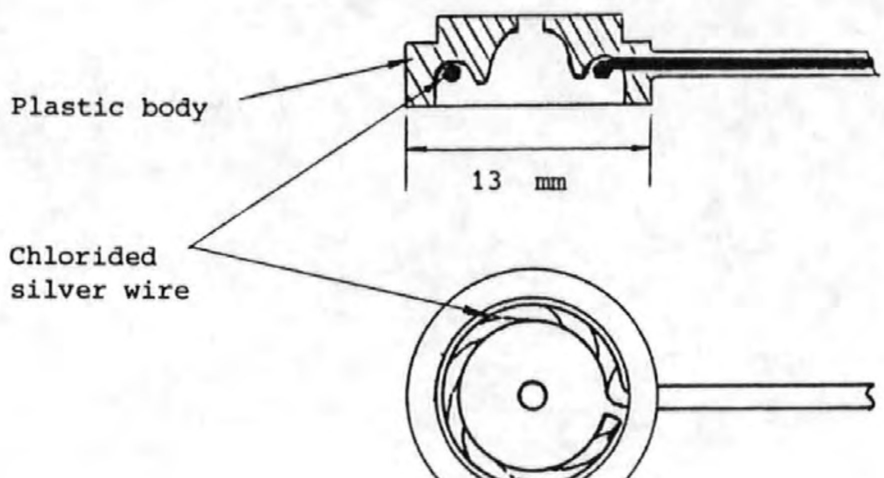


Figure 3-3

Chlorided silver wire
low frequency electrode

of the EOG's were not so highly correlated as the vertical ones). This correction method (the three channel method) may be derived in a similar way to that described in section 2.5 except that the initial equation is

$$M(t) = E(t) + k_1V(t) + k_2H_L(t) + k_3H_R(t) \ldots\ldots\ldots (1)$$

where V(t) is the vertical EOG signal from either the left or the right eye and all other quantities are as described in 2.5

The following processing was thus performed.

(i) Correction by Quilter's method and calculation of autocorrelation function (acf).

(ii) Correction by the three channel method and calculation of the acf.

(iii) Correction by the method described in 2.5 i.e. the four channel method and calculation of the acf.

(iv) Calculation of the acf for the signal corrected by the method of McCallum and Walter.

In the four channel method electrodes 6-7 (vertical left EOG), 4-5 (horizontal left EOG), 2-3 (vertical right EOG) and 4-1 (horizontal right EOG) were used, (see Figure 3.2). In the three channel method all the above electrodes were used with the exception of those giving the vertical right EOG signal. For Quilters method electrodes 6-7 and 4-5 were used. (This is very slightly different to the electrode placements used by Quilter who would have used 6-7 and 5-7 instead of 6-7 and 4-5).

3.5 CNV Acquisition

In an attempt to obtain consistent CNV's from the subjects the recording procedure was standardized. The subjects were seated at one end of the recording room facing, and at about 2 metres distant from the end wall. The silver-silver chloride electrodes were attached to the subject with glue (scalp electrodes) or adhesive tape (facial electrodes). Facial electrodes (see Figure 3-2) were used to record the four components of the EOG for subsequent eye movement artefact correction by the four channel method described in Section 2.5 Two channels of CNV information were obtained from electrodes located at the vertex and at a point on the midline approximately 30mm anterior to the vertex. Both electrodes used a common reference which was obtained from a pair of connected electrodes on the left and right earlobes.

After being attached to the subject the electrodes were filled with 'Neptic' electrode gel by means of a syringe with a blunted needle inserted into the hole in the plastic body of the electrode holder (see Figure 3-3) The blunted needle of the syringe was also used to abraid the skin under the electrode whilst the gel was inserted. This procedure ensured a low impedance between the electrode and the scalp (typically 5kΩ or less). When all the electrodes had been similarly treated the impedance between an arbitrary electrode and each of the others was measured using a Specialised Laboratory Equipment model EIT impedance meter.

This instrument measures (approximately) the modulus of the complex impedance at 13Hz. It is important to note that although the electrode scalp interface impedance is largely resistive at low frequencies, the use of a resistance measuring device with a d.c. internal source must be avoided at all cost when using chlorided silver electrodes [8]. Failure to observe this principle results in a serious degradation of the electrode stability.

If the impedance between any electrode pair was found to be greater than 5kΩ the skin below the offending electrode was further abraided until this value was achieved. When the impedance of all the electrodes was satisfactory they were connected to the EEG machine and the electrode selector switches† set for the required electrode pairs. The filters in the data acquisition system (see Section 4.2) were set for a -3dB passband of 0.016 to 30Hz. The sample rate was 125Hz.

In order to familiarize the subject with the stimuli eight presentations were made during which the subject was not required to respond to the second stimulus. The subject was then told to "press the button as quickly as you can when you hear the tone" and a further thirty-two trials were made constituting the CNV run.

Since one particular area of interest was the effect of the inter-stimulus interval (ISI) i.e. the time delay between the click and the tone, two sets of thirty-two CNV trials were made. The first with a one second ISI and the second with a four second ISI. In each case eight presentations

†These switches allow each of the machines differential amplifiers to be connected to any two electrodes on the scalp.

were made (with the appropriate ISI) before the run.

As with the previous section the digitized signals were transferred from the logging system to the Polytechnic main computer for processing and analysis.

3.6 Processing of CNV's

Because the CNV is of such a small magnitude in comparison to the normal background EEG activity they are difficult to quantify on an individual basis. Typically the CNV may be of 5-20μV in magnitude whereas normal background activity can be 50μV or more. However in favourable circumstances the individual CNV's can be observed in chart output of the EEG machine (see Figure 3-4). The normal method employed to improve CNV to background EEG (which may be regarded as signal to noise) ratio is to take a number of individual CNV's and average them. This process produces an average CNV but since the background EEG is not correlated from trial to trial the background EEG in the average is reduced by a factor proportional to the square root of the number of individual CNV's included in the average. In their original report Walter and colleagues [9] used averages of six or twelve trials.

After verification of the stored CNV data a programme was used to calculate the average CNV and plot this waveform on a graph plotter. The averaging was normally carried out over thirty-two individual CNV's. A typical average CNV is shown in Figure 3-5. Prior to averaging, each individual CNV was processed to remove the effects of eye movements as

Figure 3-4 The raw CNV waveform

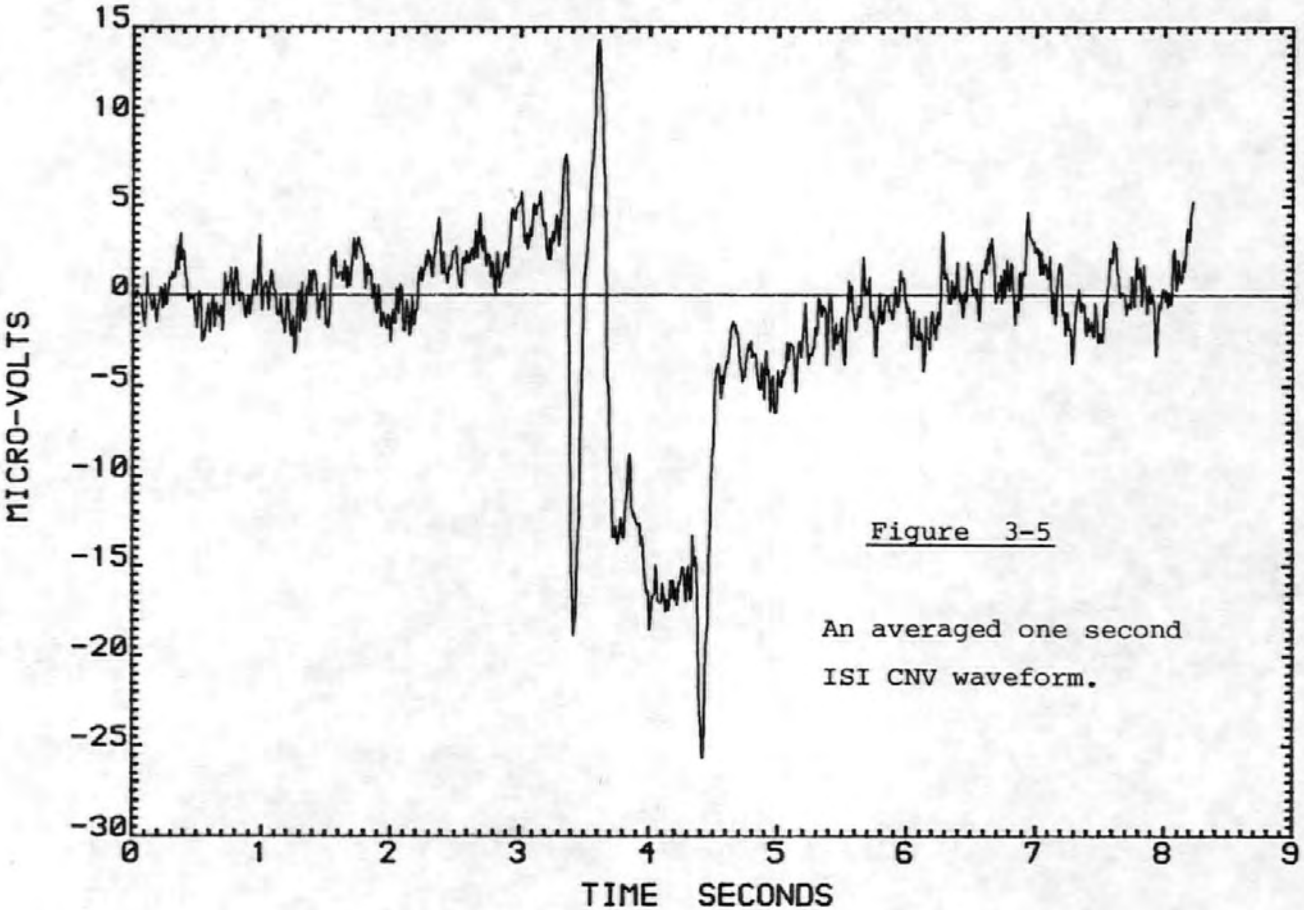


Figure 3-5

An averaged one second ISI CNV waveform.

previously described. In an attempt to further improve the averaged CNV a linear phase digital lowpass filter was used to remove some of the remaining higher frequency background components. A linear phase filter was chosen in order to preserve the shape of the CNV as much as possible. The response and weighting co-efficients of the filter used most often are given in Figure 3-6. This and other filters have been designed with the aid of the computer programme given in the book by Rabiner and Gold [10].

In view of the work of Professor Sayers and colleagues [11, 12, 13, 14, 15, 16] concerning the nature of the auditory evoked response it was decided to perform similar experiments on the CNV. Sayers showed that the auditory evoked response may be due not to an additional response, but to a re-ordering of the phase spectra of the background, i.e. the phases of certain frequencies of the background EEG generators become entrained by the stimulus and hence reshape the background EEG into the characteristic auditory evoked response. One of Sayers' most important tests was to calculate the energy in the EEG before and during the response to the auditory stimulus. According to Sayers if, as had previously been assumed, the response was an additional signal then the energy during the response would be greater than that before or after, whereas if the response was due to a phase re-ordering then the energy would not change. Sayers offered evidence to suggest that this response may indeed be due to a phase re-ordering. A programme was therefore written to calculate the energies of individual background and CNV sections of the EEG. In addition to this test Fast

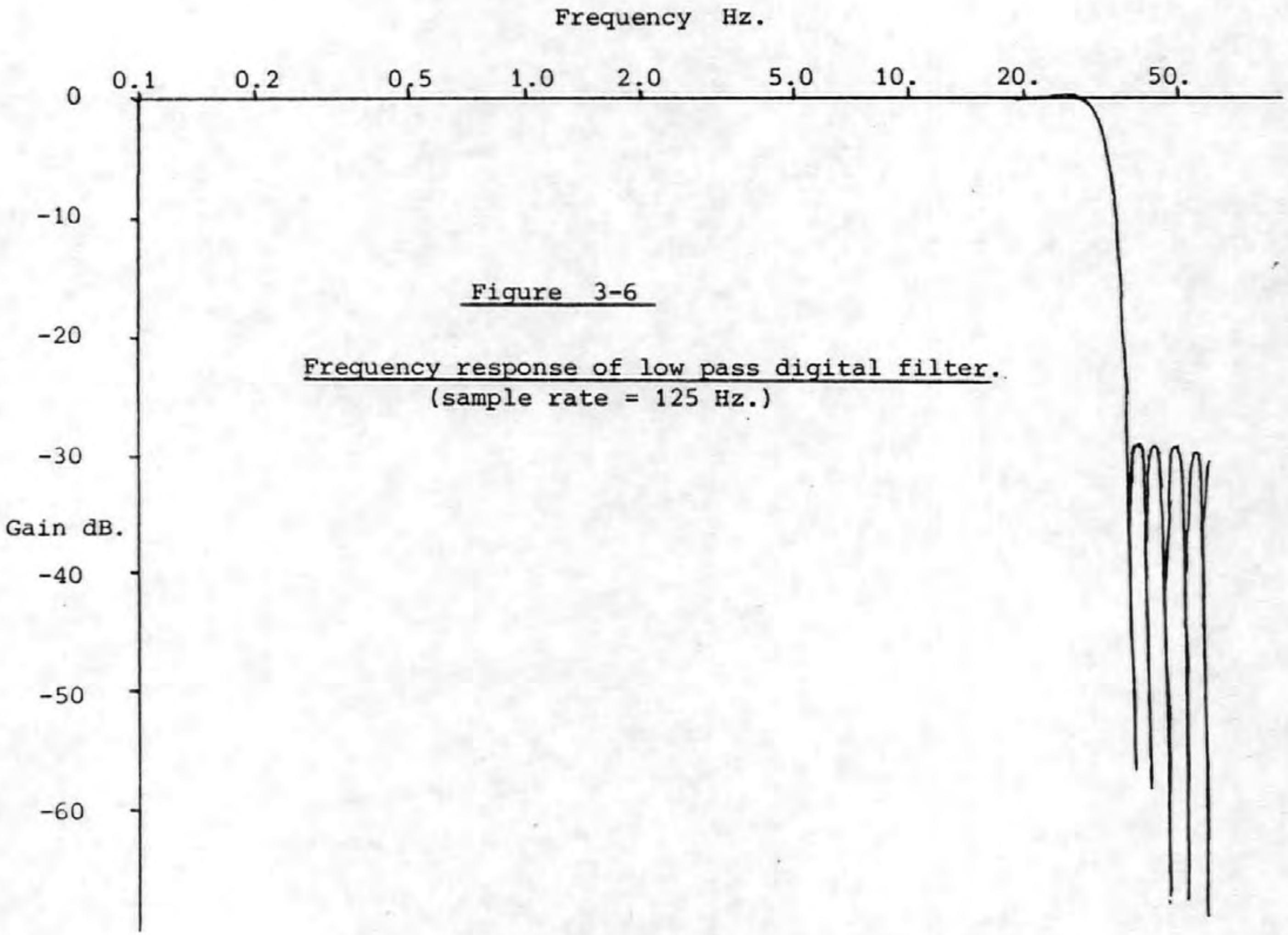


Figure 3-6

Frequency response of low pass digital filter.
(sample rate = 125 Hz.)

Filter co-efficients

H(1)=H(21)= -0.02232808
H(2)=H(20)= 0.01758909
H(3)=H(19)= 0.02921061
H(4)=H(18)= -0.01742668
H(5)=H(17)= -0.02649306
H(6)=H(16)= 0.04697604
H(7)=H(15)= 0.03685932
H(8)=H(14)= -0.09247865
H(9)=H(13)= -0.03773736
H(10)=H(12)= 0.31495064
H(11) = 0.54097712

Fourier transforms of the CNV's were performed and the phases of the first few frequency components were noted. This procedure was repeated for each of the thirty-two CNV measurements for each subject. The phase information for each frequency components was then sorted into twenty four bands of fifteen degrees each. Histograms (Figure 3-7) were then plotted for each frequency component showing the number of times a phase angle occurred within each band.

3.7 AEP Acquisition

In view of the important nature of Professor Sayers work [11, 12, 13] on the Auditory Evoked Potential (AEP), and the possible relevance of his findings to other evoked potentials (e.g. the CNV), it was decided to perform a short series of experiments in an attempt to confirm his results. AEP's were recorded from three subjects whilst relaxed and seated in the measurement room. The recording electrodes were placed at the vertex and on the right mastoid processes for the EEG signal, and in the usual facial positions for the four channel eye movement corrections. The auditory stimulus was obtained from an Amplaid stimulus generator set to deliver 1kHz. tone bursts with 100 ms duration including approximately 10 ms of rise and fall according to a "cosine squared" law. This signal was applied to the right transducer of a pair of Koss K6 stereo headphones. The subjects auditory threshold was then determined by applying the above stimulus with gradually decreasing intensity. When the subject could no longer hear the stimulus tone then the threshold had been found. The experiment then commenced with an

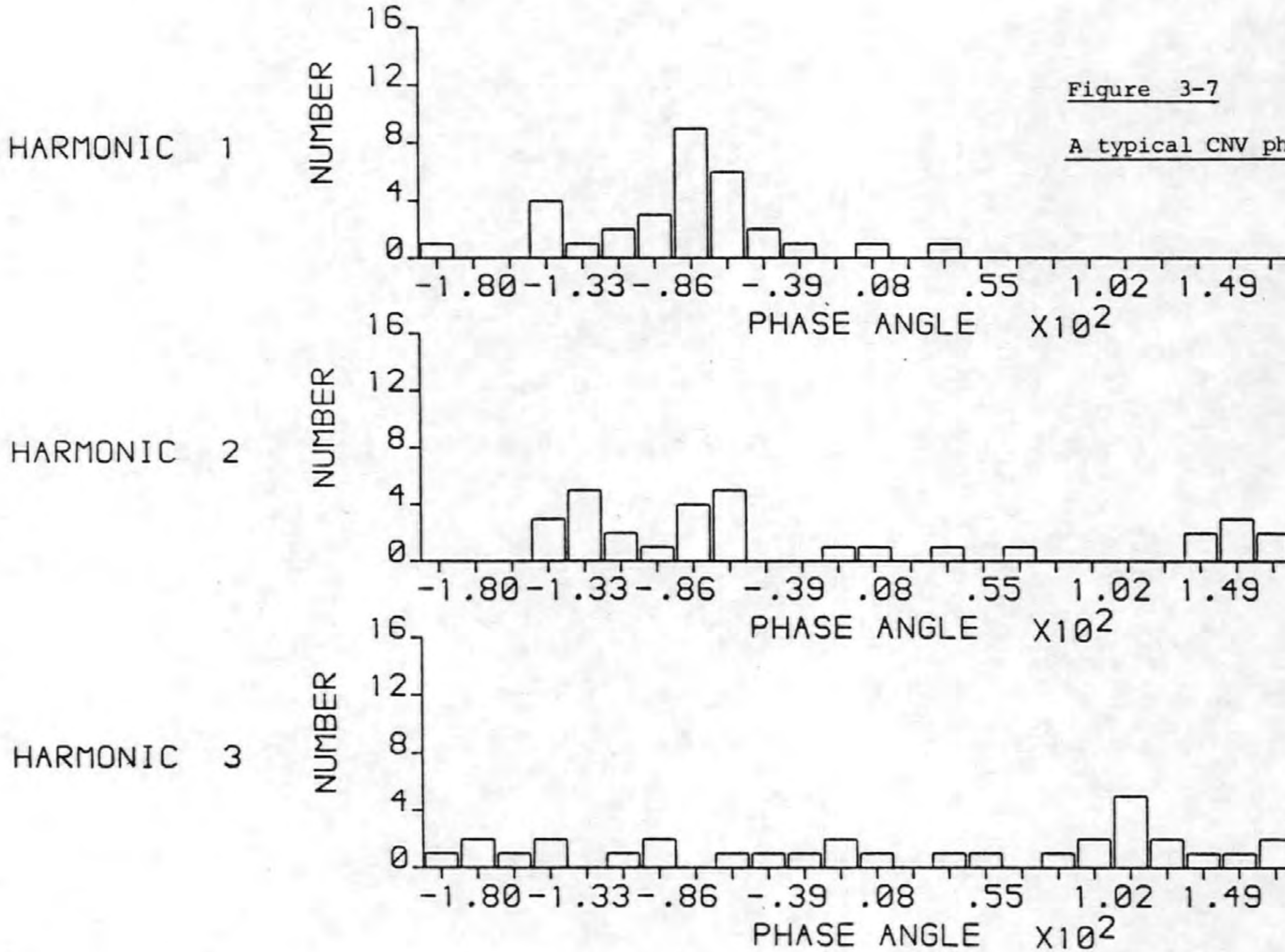


Figure 3-7

A typical CNV phase histogram

auditory stimulus 70dB (65 for one subject) above the threshold. Thirty-two sections of the EEG/EOG signals were then recorded each with two stimulus presentations at known places within each section. This gave a total of 64 evoked responses at this stimulus level. A further thirty-two trials were then made with the stimulus level set to 40dB above the subjects threshold.

3.8 Processing of AEP's

The stored AEP's were first processed to remove any eye movement artefact by the four channel correction method. The average AEP was then calculated and plotted. A typical pair of high and low stimulus averaged AEP's are shown in Figures 3-8a and 3-8b. A test was then performed to determine whether the energy present in the EEG signal after stimulus was any different to that in the signal prior to the stimulus. The "energy" values were calculated by summing the squares of values of the 64 data points preceeding and succeeding the stimulus as described in Section 2.2.3.1 Since the sampling rate was 125Hz this represented 0.512 seconds of data prior and subsequent to the stimulus. The differences betwen the pre- and post-stimulus energey values were calculated for each of the 64 individual responses, and the mean of these differences was subjected to a two-tailed t-test. The result of this test indicated whether the mean of the differences was significantly different from zero.

In an attempt to establish whether phase-ordering was present the eye movement corrected sections of EEG containing the AEP's were subjected to Fourier transformation by a

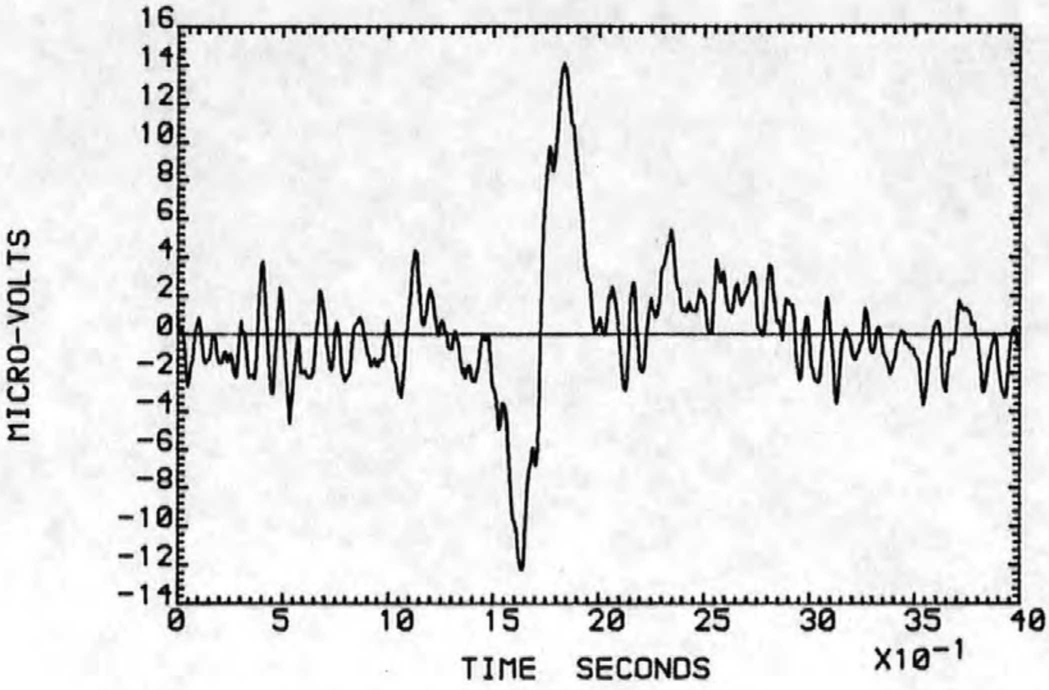


Figure 3-8a An averaged auditory response to a high level stimulus.

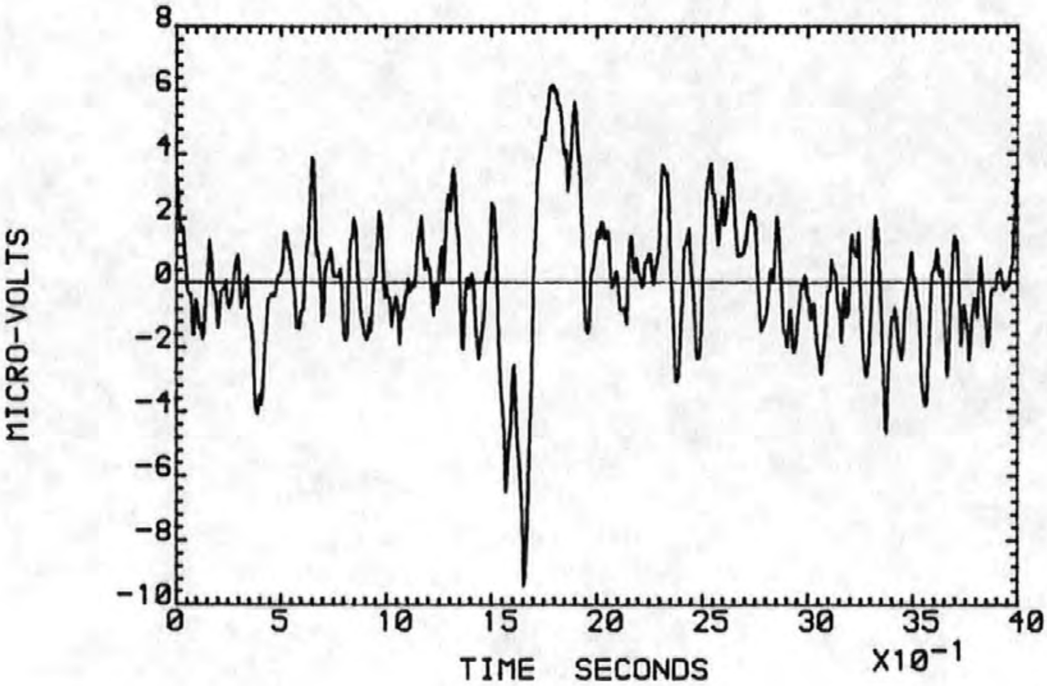


Figure 3-8b. An averaged auditory response to a low level stimulus.

radix two FFT. The phases of the six lowest frequency components (excluding the d.c. term) were stored for each of the 64 AEP's. Histograms were then plotted showing the number of times the phase angle of the transformed AEP's fell within a particular range for each of these six frequency components (sometimes referred to as harmonics).

As an alternative to the phase histogram, phasor diagrams were plotted showing, for a particular harmonic frequency, the amplitudes and phases of the transformed responses. These diagrams were also plotted for the sections of EEG data preceeding the application of the stimulus (i.e. background EEG data). A typical pair of background/AEP phasor diagrams are shown in Figure 3-9. For clarity the phasors were represented by a cross at (what would have been) the tip of the phasor. Also for ease of interpretation a circle of arbitrary radius has been drawn and onto this small triangles have been added to show the phases of the components independently of their amplitudes. Like the phase histograms the phasor diagrams were plotted for each of the first six harmonics. The statistical tests described in Section 2.2.2 were then applied to the phasor diagram information.

3.9 Fourier Transform Considerations

Several of the methods adopted for studying the CNV's and the auditory evoked potentials (AEP's) made use of a time to frequency transformation. A Fast Fourier Transform (FFT) was used to split the responses up into different frequency components which could then be studied in greater detail. A number of important factors were considered in

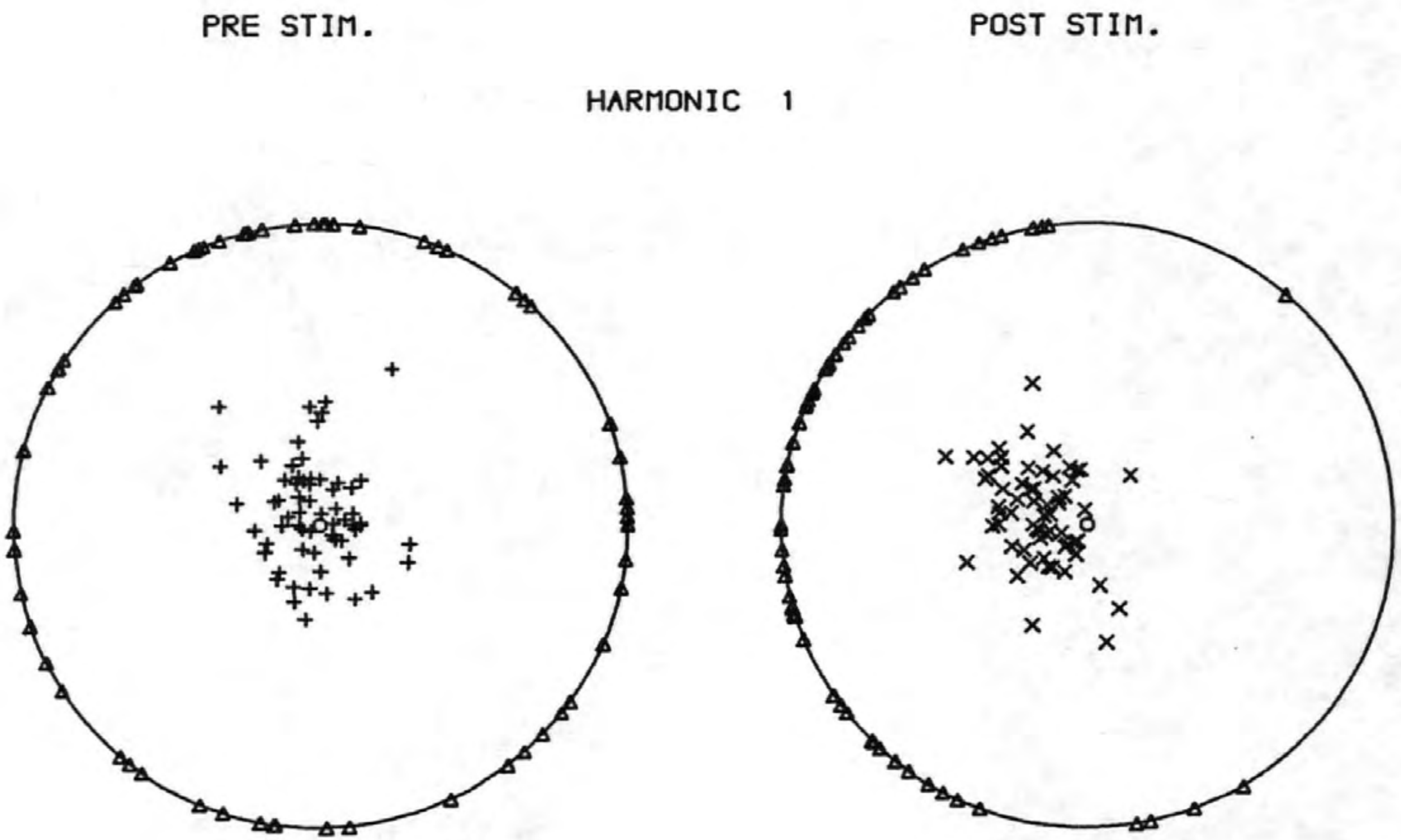


Figure 3-9 A typical AEP phasor diagram

choosing the parameters of the transform. These included the length of the section of data to be transformed, the required spectral resolution, and the time (and cost) of the transformation. However since the lengths of both the CNV's and AEP's were well defined these proved to be the ultimate limitation. In practice the response data was augmented with a number of zero valued "data" points to bring the total number of points up to a value suitable for transformation with the radix 2 FFT.

Because of the finite length (T_m) of the data the spectrum obtained was that of the data convolved with that of the window or truncation function. If, for example, the truncation function was rectangular i.e.

data to be transformed = data multiplied by one ($0<t<T_m$)

= data multiplied by zero elsewhere,

then the spectrum of the data would be convolved with the well known SINC function with zero crossings at frequencies of n/Tm, where n = ...-3, -2, -1, 1, 2, 3............ This would result in distortion of the true spectrum to an extent that would often be unacceptable. For this reason many other truncation functions have been devised which cause much less spectral distortion. The truncation function chosen was the cosine taper (sometimes referred to as the raised cosine) which was applied for 10% of the data length at each end of the data. This function can be described mathematically by the following expressions:-

$$W(t) = \begin{cases} \frac{1}{2}[1 - \cos\{\frac{t\pi}{0.1\ T_m}\}] & 0 < t < 0.1\ T_m \\ 1 & 0.1\ T_m < t < 0.9\ T_m \\ \frac{1}{2}[1 - \cos\{\frac{(1-t)\pi}{0.1 T_m}\}] & 0.9\ T_m < t < T_m \end{cases}$$

This window function has smaller and more rapidly decreasing side lobes than the rectangular window which resulted in much less spectral leakage [17].

Where it was necessary to augment the response data with zeros to fulfil the transform requirements, the windowing was applied prior to the addition of the zeros. Since windowing the zeros does not remove any discontinuity at the end of the true data. Furthermore since the d.c. component was of no interest it was removed by subtracting the mean value of the data from the data.

The FFT algorithm adopted was that described by Robinson [18]. The FORTRAN implementation of this algorithm was capable of forward and inverse Fourier transforms. The data to be transformed was submitted to the subroutine as an array of complex numbers. Since all the input data was real, the imaginary components of the array were set to zero before transformation took place. The N output data points were returned to the calling program in the same array and were generally complex. For some of the analysis methods these were then converted by a further subroutine to modulus and phase information arrays. Although N complex points were returned by the FFT only the first N/2+1 were meaningful since the remaining N/2-1 points represent the negative frequency values. (i.e. a mirror image of the first N/2 points. The zero frequency or d.c. component was not mirrored).

References for Section 3

[1] Computer Aided Design Centre, "GINO-F" and "GINO-GRAF" User Manuals.
Published by the CAD Centre, Madingly Road, Cambridge.

[2] Geddes L A, Baker L E, "Principles of Applied Bio-medical Instrumentation"
Chapter 11, pp 509-517. Published by John Wiley & Sons, New York. 2nd Edition 1975.

[3] McCallum W C, Walter W G, "The Effects of Attention and Distraction on the Contingent Negative Variation in Normal and Neurotic Subjects"
Electroencephalography and Clinical Neurophysiology, Volume 25, pp 319-329, 1968.

[4] Girton D G, Kamiya J, "A simple on-line technique for removing Eye Movement Artifacts from the EEG"
Electroencephalography and Clinical Neurophysiology, Volume 34, pp 212-216, 1973.

[5] Quilter P M, MacGillivray B B, Wadbrook D G, "The Removal of Eye Movement Artefact from EEG Signals using Correlation Techniques".
Random Signals Analysis, IEE Conference Publication No. 159, pp 93-100, 1977.

[6] Hillyard S A, Galambos R, "Eye Movement Artifact in the CNV"
Electroencephalography and Clinical Neurophysiology, Volume 28, pp 173-182, 1970.

[7] Corby J C, Kopell B S, "Differential Contributions of Blinks and Vertical Eye Movements as Artifacts in EEG Recording"
Psychophysiology, Volume 9, pp 640-644, 1972.

[8] Cooper R, Osselton J W, Shaw J C, "EEG Technology"
Chapter 2, page 20 Third Edition,
Published by Butterworths, London, 1980.

[9] Walter, W G, Cooper R, Aldridge V J, McCallum W C, Winter A L, "Contingent Negative Variation": An Electric Sign of Sensorimotor Association and Expectancy in the Human Brain".
Nature, Volume 203, pp 380-384,1964.

[10] Rabiner L R, Gold B, "Theory and Application of Digital Signal Processing"
Chapter 3 and pp 194-204 Published by Prentice-Hall, New Jersey, 1975.

[11] Sayers B McA, Beagley H A, Henshall W R, "The Mechanism of Auditory Evoked EEG Responses"
Nature, Volume 247, pp481-483, 1974.

[12) Sayers B, McA, Beagley H A, "Objective Evaluation of Auditory Evoked EEG Responses".
Nature, Volume 251, pp 608-609, 1974.

[13] Inbar G F (Editor), "Signal Analysis and Pattern Recognition in Biomedical Engineering".
Part 1, pp 7-22 Published by Halsted Press Division, John Wiley & Sons, New York 1975.

[14) Sayers B, McA, Beagley H A, Riha J, "Pattern Analysis of Auditory Evoked EEG Potentials" Audiology, Volume 18, pp 1-16, 1979.

[15] Beagley H A, Sayers B McA, Ross A J, "Fully Objective ERA by Phase Spectral Analysis" Acta Oto-laryngologica Volume 87, pp 270-278, 1979.

[16] Ross A J, Beagley H A, Sayers B McA, "Signal Statistics in Objective Auditory Evoked Potential (Detection by the Phase Spectral Method" Journal of Biomedical Engineering, Volume 2, pp 310-314, 1980.

[17] Otnes R K, Enochson L, "Digital Time Series Analysis" pp 281-285 Published by John Wiley and Sons, 1972.

[18] Robinson E A, "Multichannel Time Series Analysis with Digital Computer Programs" Page 63 Published by Holden-Day, San Francisco Revised Edition 1978.

4. Experimental Apparatus

In order to investigate the processing of EEG signals a data acquisition and storage system was required. Several constraints were placed on the choice of this system. The most serious constraint was the lack of finance to fund such a system. However a considerable amount of equipment was available both at the Polytechnic and at Freedom Fields Hospital. Thus whilst the apparatus described here may not be the most elegant solution possible, it is a solution which, for the main parts, utilised freely available equipment.

4.1 Choice of Apparatus

Two commonly used methods for the storage of the EEG data were initially considered. The first of these being an analogue magnetic tape system. This method has the advantage that large amounts of data may be recorded and stored for subsequent retrieval and analysis. Typical modern instrumentation tape recorders are capable of storing seven channels of data with a bandwidth extending from d.c. (by the use of frequency modulation) to 20kHz or more depending on the tape speed. Since EEG signals are normally of interest between d.c. and 40 Hz. very low tape speeds may be used. With such low speeds many hours of data may be stored on a 366m (1200 feet) spool of tape.

The second technique considered was on-line digital storage. The signals are first amplified and filtered in the normal way but are than digitised instead of being sent to the usual EEG chart recorder. The digitised signal may be stored on any convenient medium but magnetic tape or disk is most common due to the high rates at which the data may be transferred. This method has the advantage that once digitised, the signals are subject to no further noise or distortion. Since two minicomputers were available one of which had a high speed analogue-to-digital converter, multiplexer and numerous other interface components, and the other a flying head disk of approximately 2.5 M bytes capacity, the digital method was chosen. Furthermore, since evoked responses lasting but a few seconds were to be studied the disadvantage of being unable to store more than a few minutes of data was not considered important. An added bonus was that the minicomputer could be programmed to provide pulses at the chosen instant to trigger the external stimulus generators necessary for evoked response studies.

4.2 Analogue Electronics

Figure 4-1 is a block diagram of the complete data acquisition system. The EEG signals were obtained from silver-silver chloride electrodes attached to the subject by glue or adhesive tape. These signals were fed into the electrode selector switches and differential amplifiers of an eight channel Elma-Schönander electroencephalograph. In addition to producing the normal paper chart record, the electroencephalograph was coupled to external amplifiers and filters to allow the information from six of the eight channels to be digitised and stored for subsequent analysis.

The point at which the signals were extracted from the EEG machine was chosen such that the electrode selector

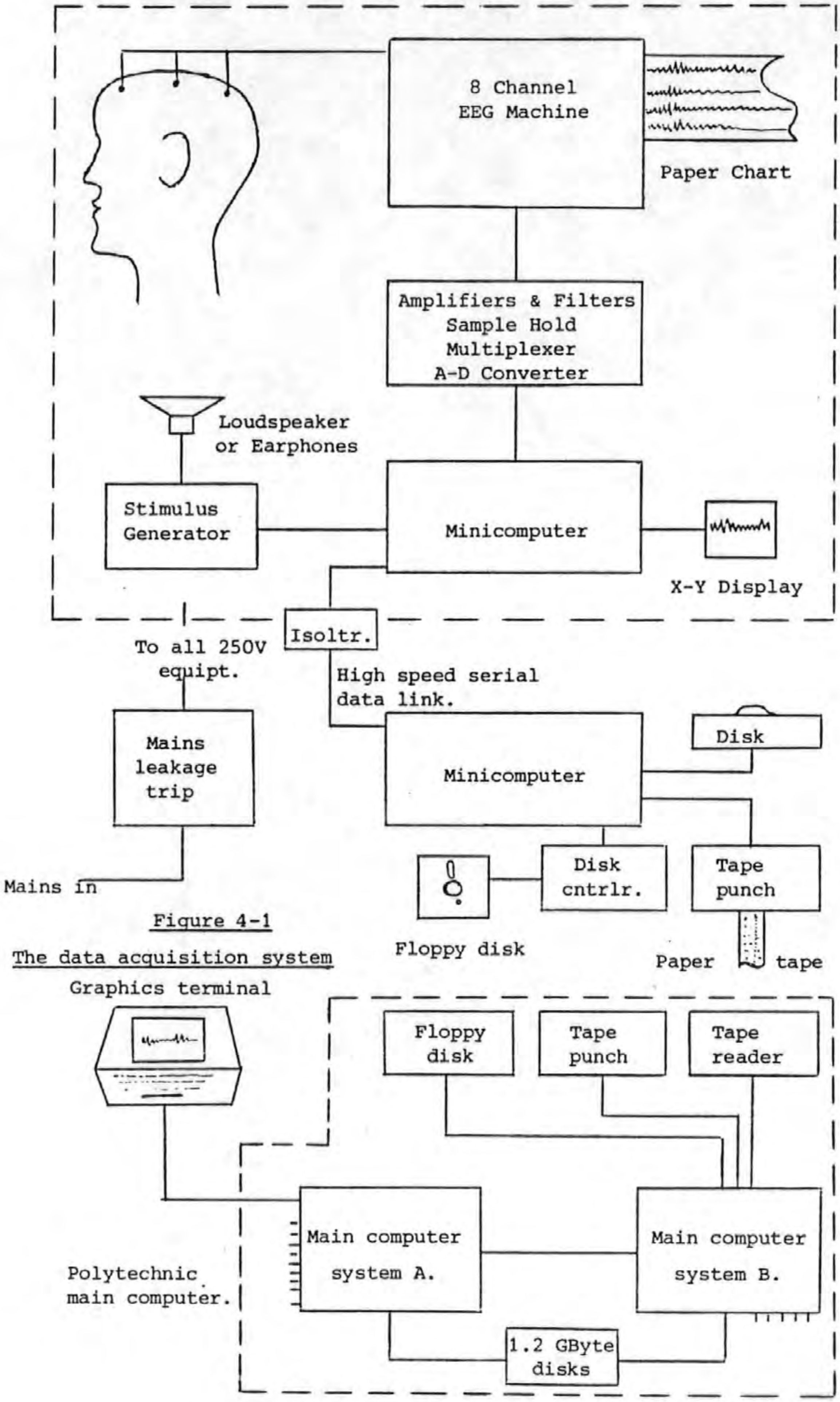


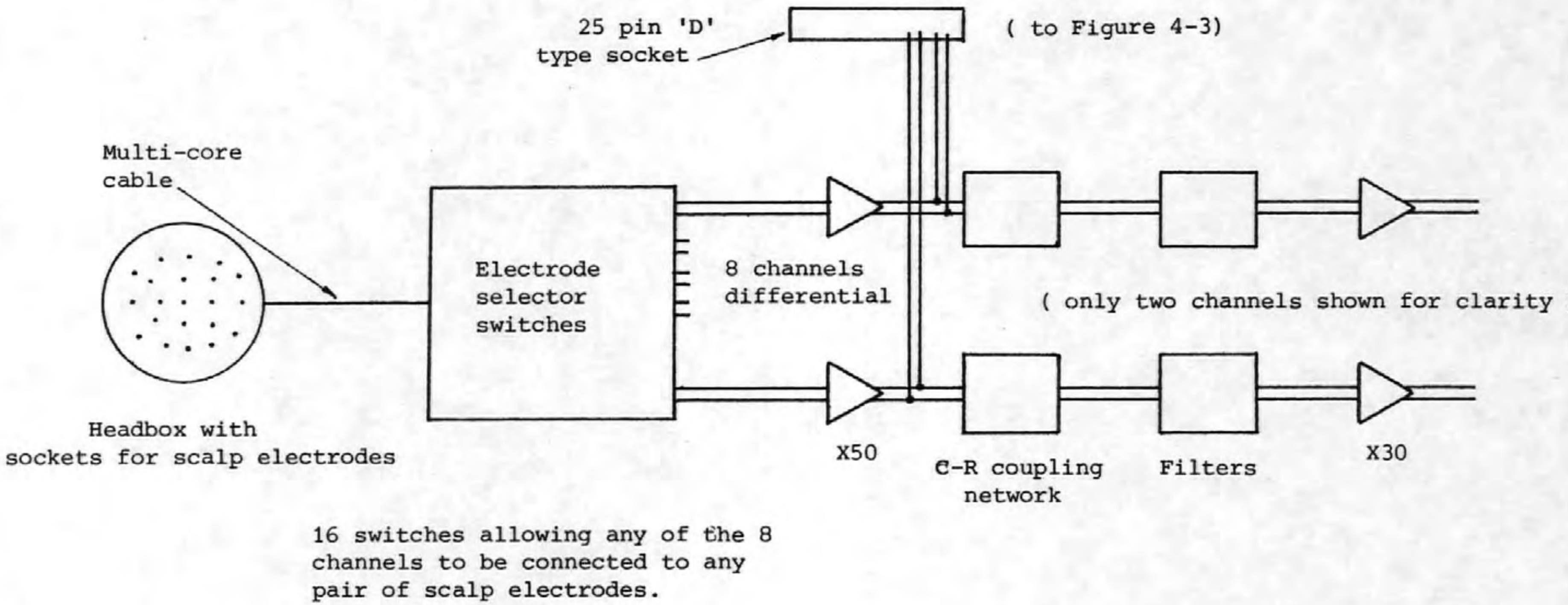
Figure 4-1

The data acquisition system

switches and the first stage (d.c. coupled x 50) of amplification were utilised (see Figure 4-2). The next stage of amplification in the EEG machine could not be used because the interconnection between the first and second stages formed a high pass C-R network with a cut-off frequency of 0·069 Hz. This frequency was not low enough for CNV recordings where 0·016 Hz. is usually considered to be a more appropriate lower limit (this value corresponds to a time constant of 10 seconds). For this reason the differential outputs of the first stage were wired to a 25 pin 'D type' socket on the rear of the EEG machine. In this way the machine was still able to perform its normal duties and could simply be un-plugged from the additional equipment used to digitise the signals. When used for data logging a fairly short screened multicore cable with a 25 pin 'D type' plug at either end was used to connect the EEG machine to a screened box containing modules for amplifying, filtering and sampling six of the eight EEG machine channels (further modules could be added at a later date should it become necessary to digitise all eight channels).

The input circuit of each module (see Figure 4-3) comprised of a differential high pass C-R network with switchable capacitors to give cut-off frequencies of 0·016, 0·034 and 0·16 Hz. The differential signals were then converted to unbalanced form by an amplifier comprising of two BIFET† operational amplifier integrated circuits (RCA type 3140) and a single bipolar operational amplifier (type μA 741). The gain of this stage was adjusted to 100. The variable resistor VR1 was incorporated to allow optimisation of the

†An integrated circuit employing both bipolar and field effect transistors.



<u>Figure 4-2</u>

<u>A block diagram of the input section of the EEG machine.</u>

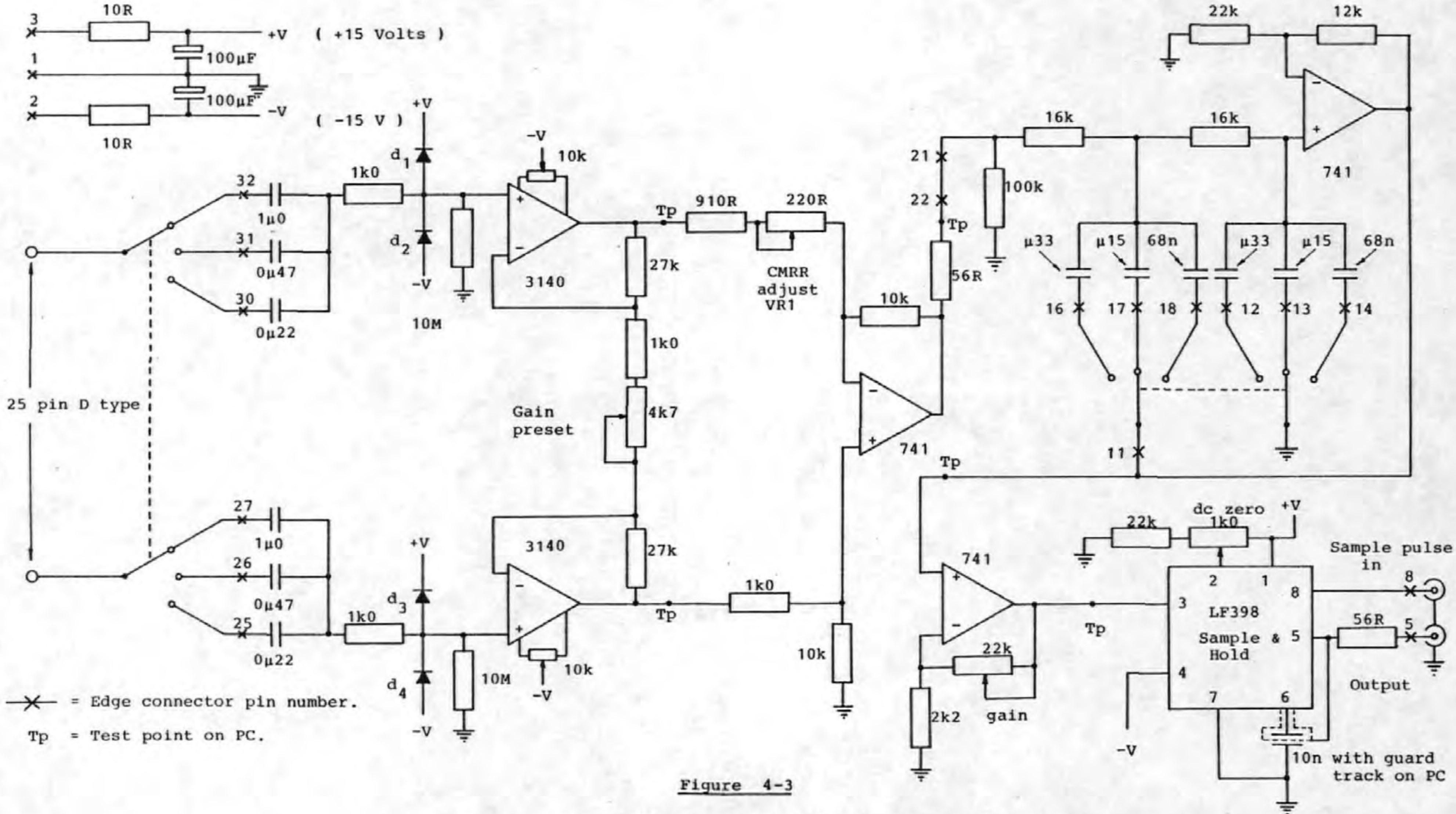


Figure 4-3

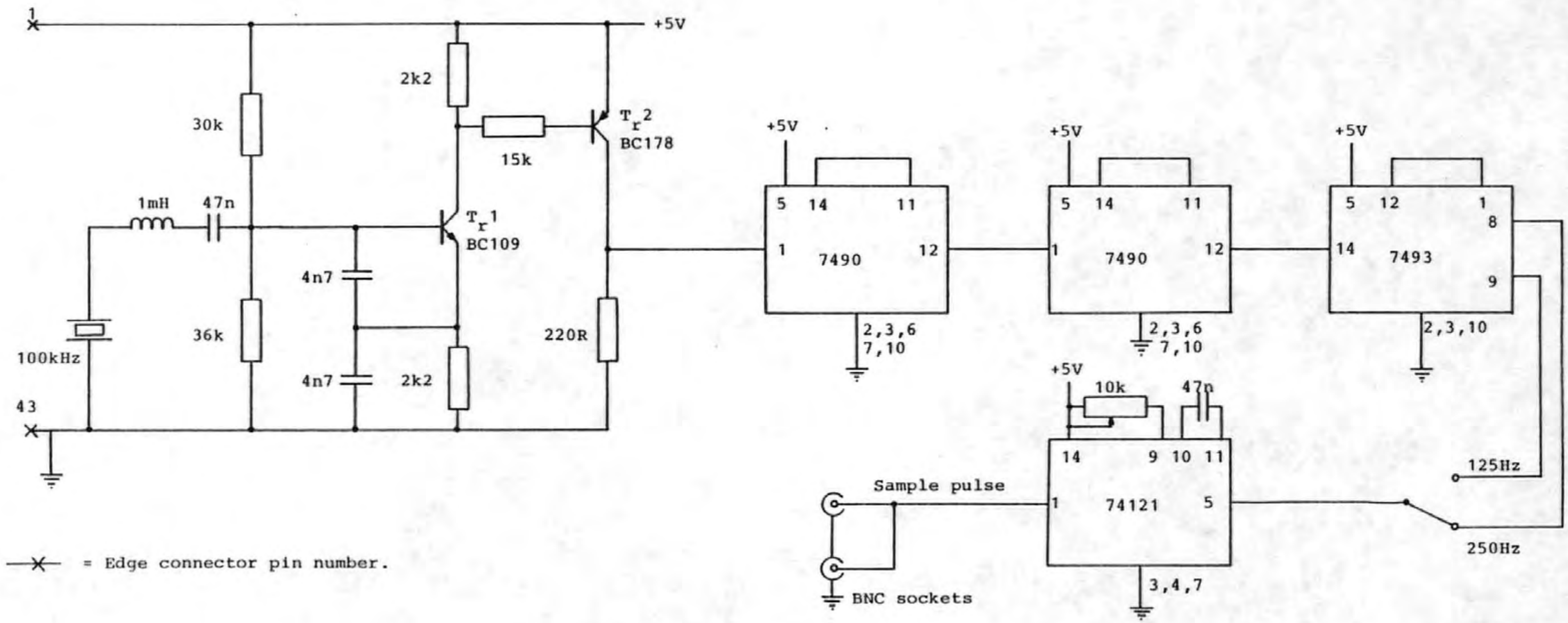
The circuit of an amplifier and sample hold module common mode rejection ratio (CMRR). The diodes d_1 - d_4 were incorporated to protect the input circuits of the 3140 operational amplifiers.

The output of this stage was then fed into a second order active filter based on the Sallen and Key design [1]. The calculation of the circuit elements for the desired cut-off frequencies (30, 70 and 130 Hz. switch selectable) was simplified by the use of the tables given in Millman and Halkias [2]. After careful consideration of the various frequency response characteristics the Butterworth filter was chosen because it had a suitably flat amplitude response in the pass-band without undue phase distortion. The cut-off frequencies of 30, 70 and 130 Hz. were chosen because they are commonly used in EEG work and would therefore make any results obtained from our data logging system comparable with results obtained by other workers. Low pass filtering is necessary to prevent aliasing in the subsequent digitisation stage and to attenuate some of the unwanted higher frequency components (e.g. muscle artefact, power frequency interference etc.) High pass filtering (the CR input network) was included to minimise the drift which can occur because of electrode instability. After low pass filtering the signals were further amplified by an operational amplifier (type µA 741) connected in the non-inverting mode with a variable gain. The gain of these amplifiers was set to utilise the complete range of the 12 bit analogue to digital converter with scalp signals of ± 700µV (channels 1-4) and ± 350µV (channels 5 & 6). The final function of the modules was to sample and hold the output of the final amplifier at the required instant in time.

This function was performed by a Signetics type LF 398 integrated circuit.

In order to sample the analogue signals at the required rate a pulse signal was generated by an oscillator and divider network which was then fed into each of the six sample and hold IC's. This pulse signal was also fed into the PDP 8/f Hybrid Computer Interface [3] so as to cause an interrupt at every sample instant. Since the sampling was to be performed at precisely regular intervals a quartz crystal oscillator and a frequency divider were built specially. The oscillator (Figure 4-4) used a circuit recommended by the crystal manufacturers [4] and provided a signal of approximately 1 volt RMS at a frequency of 100kHz. This signal was squared by T_r2 and divided in frequency by two Transistor-Transistor Logic (TTL) 7490 decade dividers and a TTL 7493 4 bit binary divider as shown in Figure 4-4. The outputs of the 7493 give possible sampling frequencies of 500, 250, 125 or 62·5 Hz. Since only two of these frequencies were likely to be needed (125 or 250 Hz.) a two position toggle switch was employed to select the required frequency and feed it to the input of a TTL 74121 monostable multivibrator. This device was employed to convert the square wave output of the divider chain into a pulse waveform, with a 100 μs active period, necessary for the sample hold circuit. The sampling frequencies are accurate to within approximately one part in 10^5.

The six sampled analogue waveforms were then passed to an Analogue Devices MPX8A multiplexer and a Hybrid Systems Corp. ADC-591-12A-G 12 bit analogue to digital converter. These two devices were part of the PDP 8/f Hybrid Computer Interface



<u>Figure 4-4</u>

<u>The crystal oscillator and divider network</u>

designed and built by Yeats [3].

4.2.1 Testing of the Analogue Electronics

The amplitude and phase responses of one channel of the measurement system are shown in Figures 4-5a and 4-5b. In addition to measuring the amplitude and phase responses other tests were performed to determine the common mode rejection ratio (CMRR) and the effect of the filtering on a ramp waveform (similar to an ideal CNV). The CMRR was measured by connecting the inputs of the channel under test together at the headbox and injecting a 15 Hz. sine wave signal between the connected inputs and earth. The common mode input voltage (V_{ic}) and the output voltage (V_{oc}) were measured and the common mode gain (A_c) found by dividing V_{oc} by V_{ic}. The CMRR was then obtained by dividing the differential gain (A_D) by the common mode gain (A_c). The values of the CMRR for channels 1 and 5 are given in table 4-1.

Table 4-1

The Common Mode Rejection Ratio for Channels 1 and 5

CHANNEL	A_D	A_C	CMRR	CMRR dB
1 †	14290	0·182	78520	97·9
5 †	28570	0·212	134800	102.6

† The time constant was set to 10 seconds and the low pass filter was set to a cut-off frequency of 30 Hz.

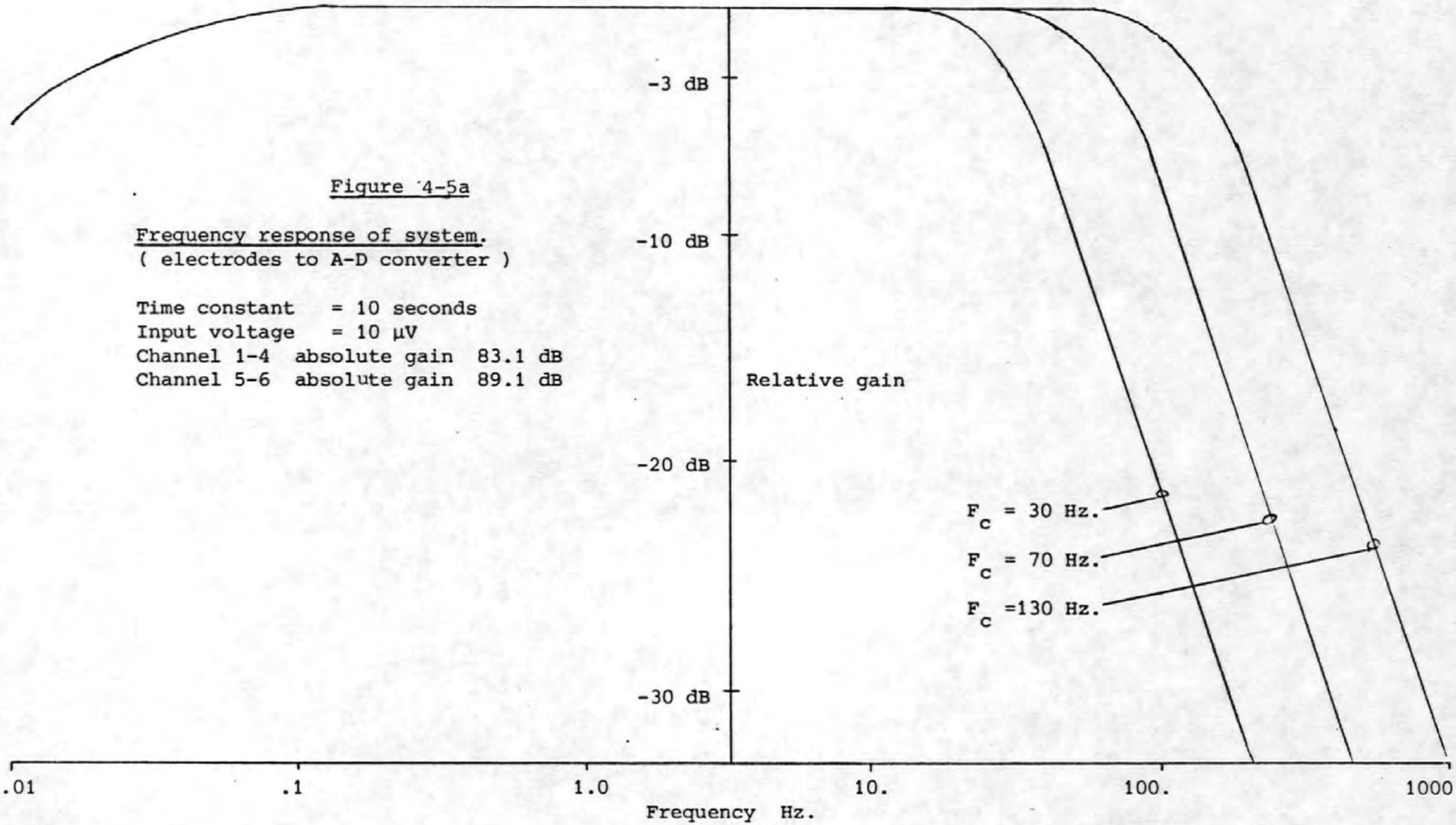


Figure 4-5a

Frequency response of system.
(electrodes to A-D converter)

Time constant = 10 seconds
Input voltage = 10 μV
Channel 1-4 absolute gain 83.1 dB
Channel 5-6 absolute gain 89.1 dB

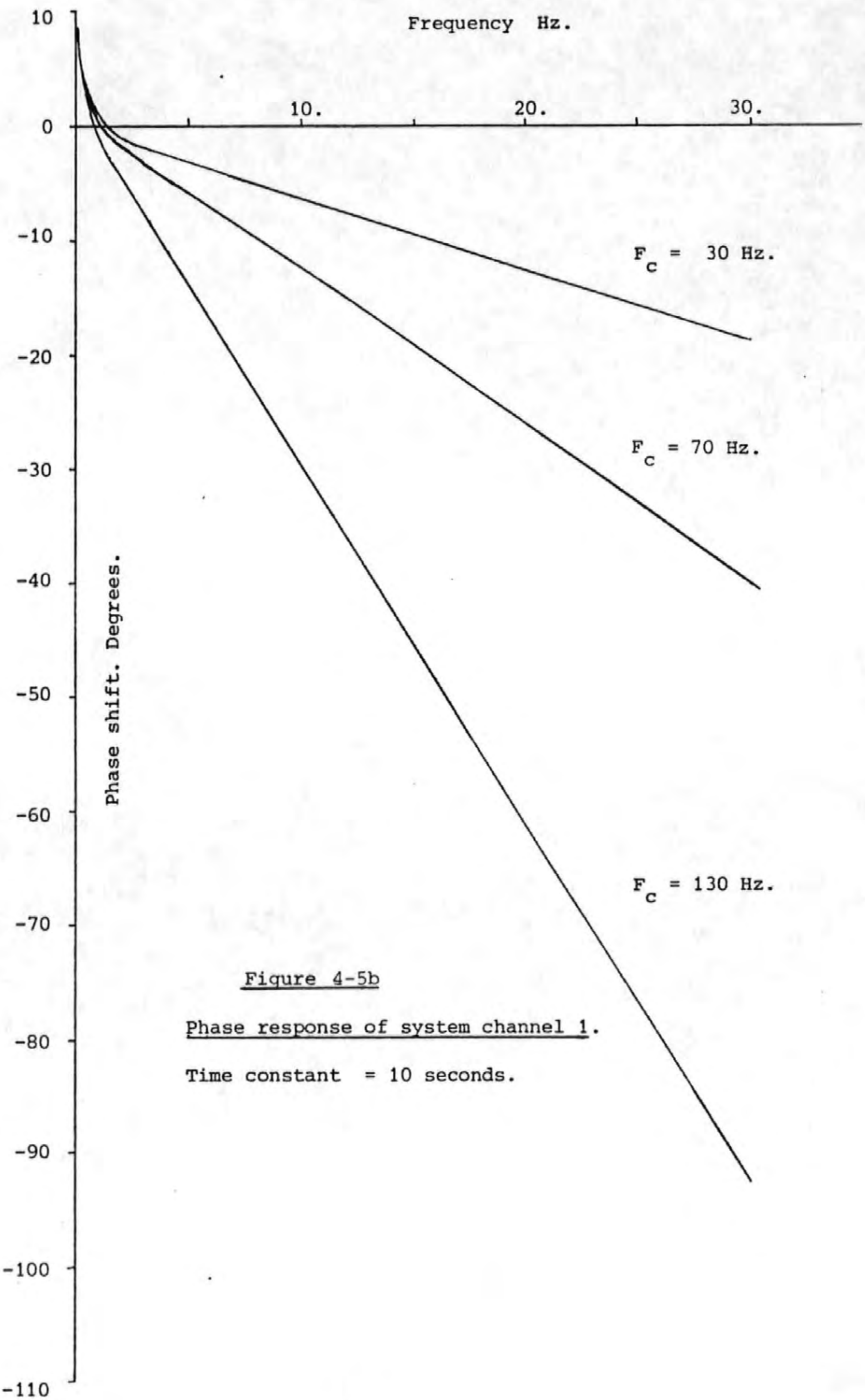


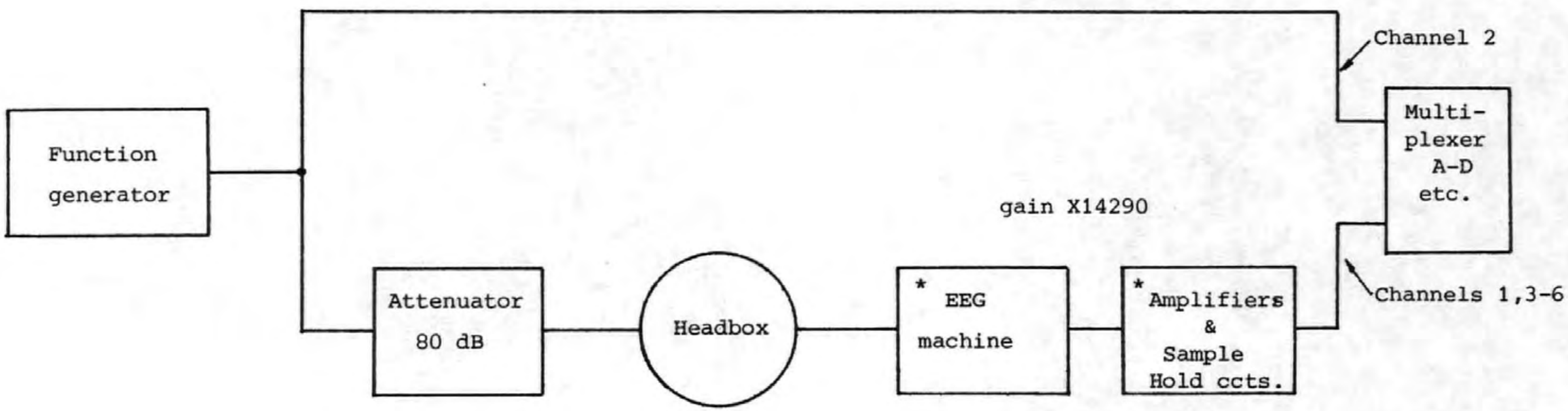
Figure 4-5b

Phase response of system channel 1.

Time constant = 10 seconds.

The circuit of Figure 4-6 was used to show the likely effect of the low and high pass filters on an ideal CNV response. The function generator was set to deliver a ramp waveform which was fed into an attenuator and also to the Channel 2 multiplexer input. The output of the attenuator was fed into the headbox and amplified and filtered in the usual way before being passed on to the multiplexer. Figures 4-7a and 4-7b show the two waveforms, one having been subjected to low and high pass filtering, and the other having undergone no filtering.† It may be observed from these diagrams that the distortion introduced is quite small. The settings of the low and high pass filters were 30 Hz. and 0·016 Hz. (time constant = 10 seconds). The amplitude of the ramp signal at the headbox input connections was as indicated in Figure 4-7b. Because of the unusual connection the voltages indicated in Figure 4-7a must be multiplied by the system gain (14290) to give the true voltage levels.

† except that inherent in the sampling process.



* See Figures 4-2 & 4-3.

Figure 4-6

The connection of the measurement system for the ramp response tests

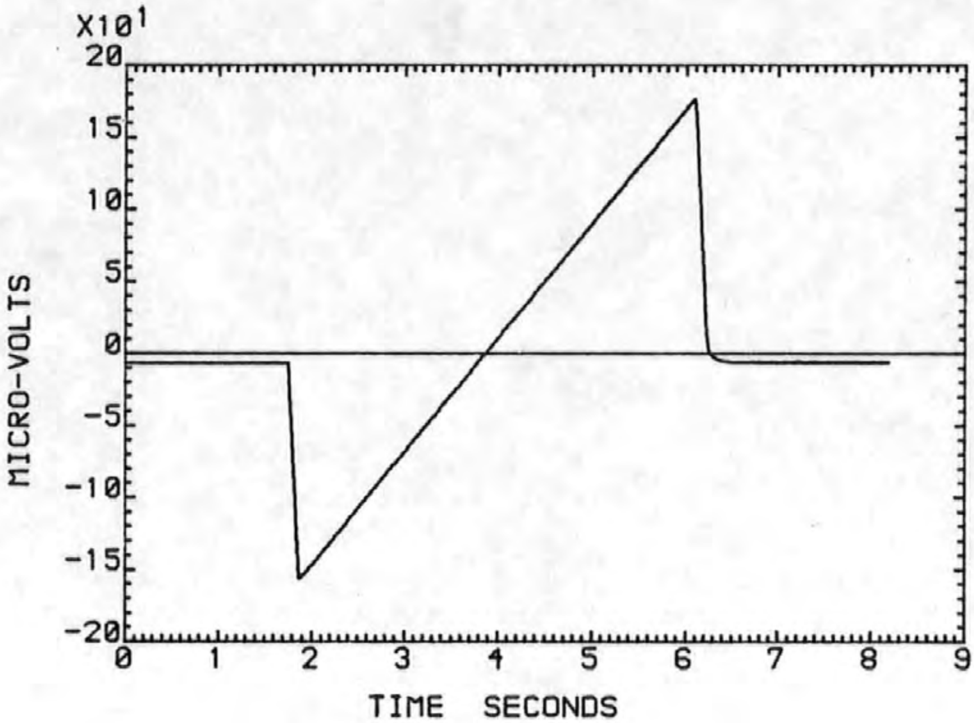


Figure 4-7a

The ramp input waveform (X 14290)

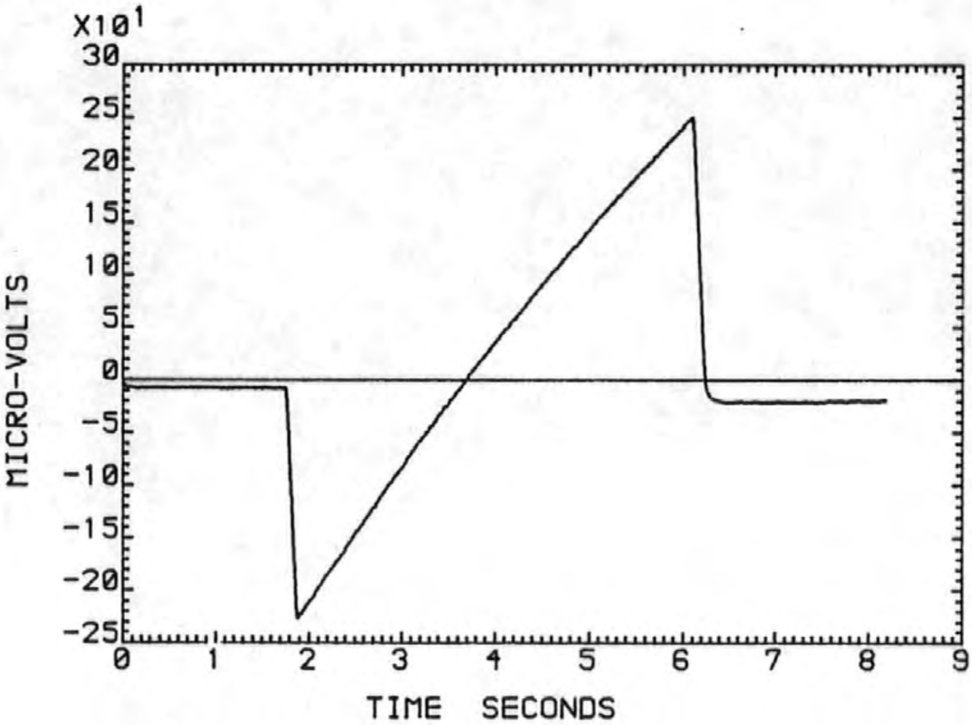


Figure 4-7b

The ramp output waveform.

4.3 High Speed Serial Data Link

In order to transfer the digital data from the minicomputer in the measurement room to the remote minicomputer with the magnetic disk, a pair of high speed serial data transceivers were designed and built. Two identical units were made to allow bi-directional communications to take place over a four-wire link using the 20mA current loop convention. The units were constructed on Vero-cards with 43-way edge connectors suitable for insertion into the extended input/output (I/O) bus racking system with which both the PDP 8's were fitted. This bus comprised of all the input/output timing pulses, the accumulator input and output lines six of the twelve memory buffer lines (from which the I/O devices were addressed), the instruction skip line, the interrupt request line and power supplies of +15, +5, and -15 volts. A block diagram of one of the serial transceivers is given in Figure 4-8. The design of the transceivers was based on two large scale integration integrated circuits. These were the Intersil 6402 Universal Asynchronous Receiver Transmitter (UART) and the Motorola MC 14411 Baud rate generator. The UART is a device capable of translating 8 bit parallel binary data into a serial data stream at a rate determined by an externally supplied clock signal. Simultaneously the device can receive a serial data stream and convert it to an 8 bit parallel binary data word. By means of an internal register, which may be loaded by the user, the device can be instructed to perform many variations on this basic theme. (e.g. the device can be instructed to generate a parity bit and append this to the data being transmitted whilst any received data is

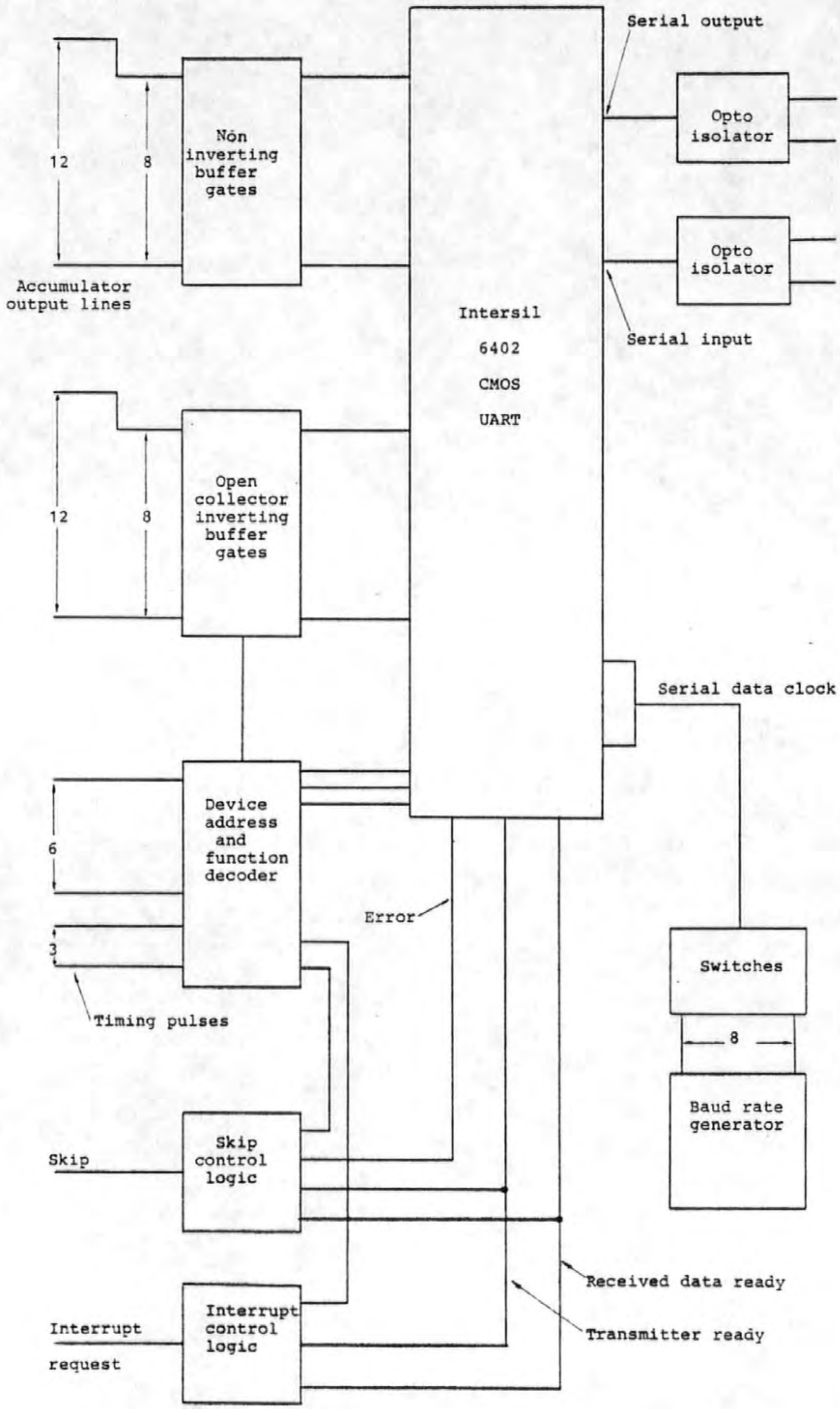


Figure 4-8 A block diagram of the serial transceiver

checked for parity errors). The Baud rate generator was used to generate one of a number of standard frequencies used for serial data transmission. Selection of the particular frequency required was controlled by a group of five dual-in-line switches giving serial data rates from 75 Baud up to 38·4 k Baud. The full circuit diagram of one of the transceivers is given in Figure 4-9. In order to achieve electrical isolation between the equipment in the measuring room and the remote minicomputer, all the data (both transmitted and received) was passed through a pair of opto-isolators.

Numerous Transistor-Transistor Logic (TTL) gates perform the necessary interfacing and decoding between the signals on the 43-way I/O bus and the UART. Additional circuitry, in the form of I/C's 10 and 13, perform the functions associated with the control and generation of programme interrupts. These interrupts may be generated when the UART is ready to transmit another 8 bit word (a transmitter interrupt) or when the UART has just received an 8 bit word (a receiver interrupt). I/C 14 performs an 'inclusive OR' of the three possible receiver error conditions which may then be detected (by the software) upon execution of a 'Skip on error' instruction. Table 4-2 gives a list of the instructions decoded and acted upon by the serial transceivers.

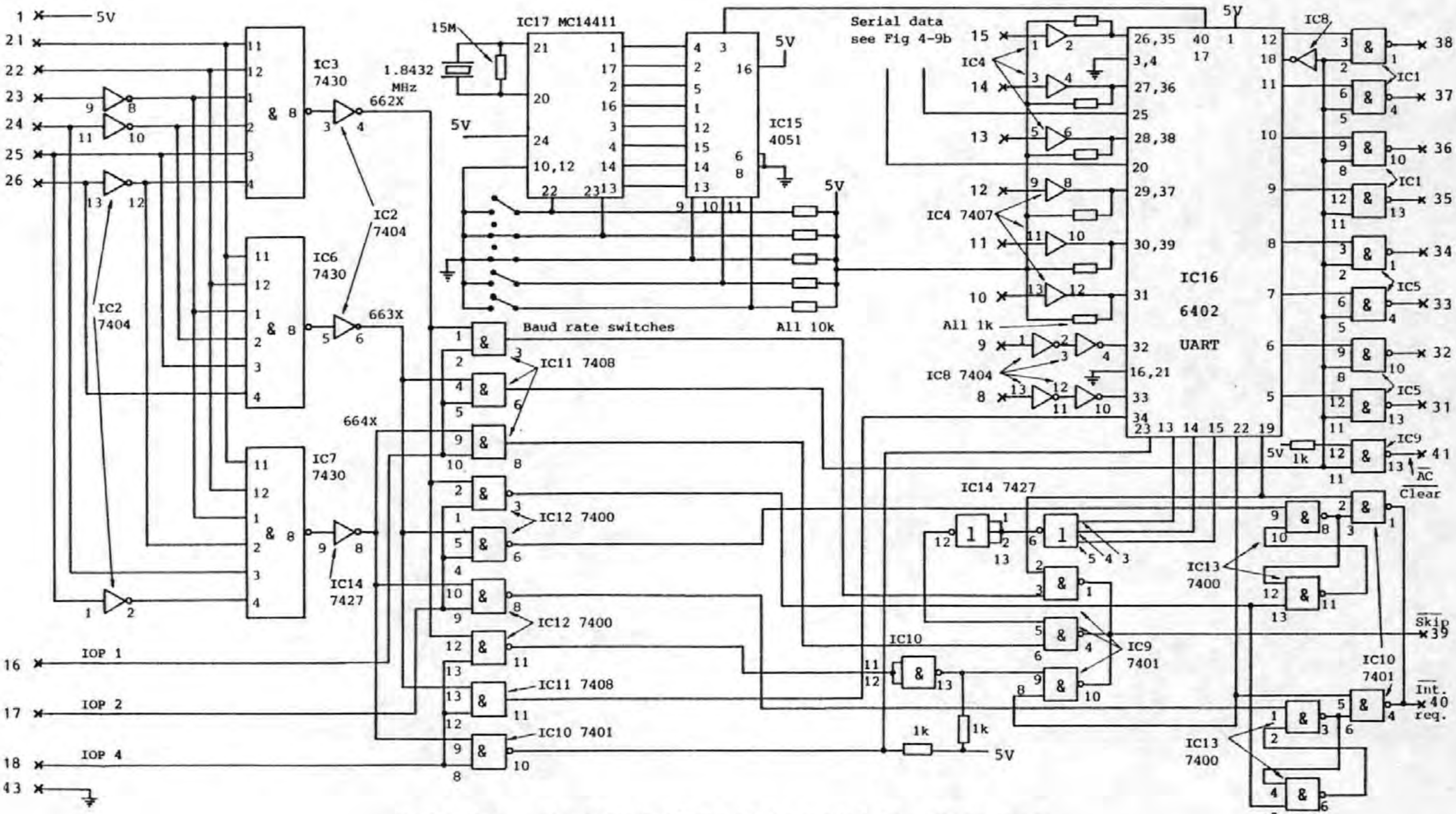
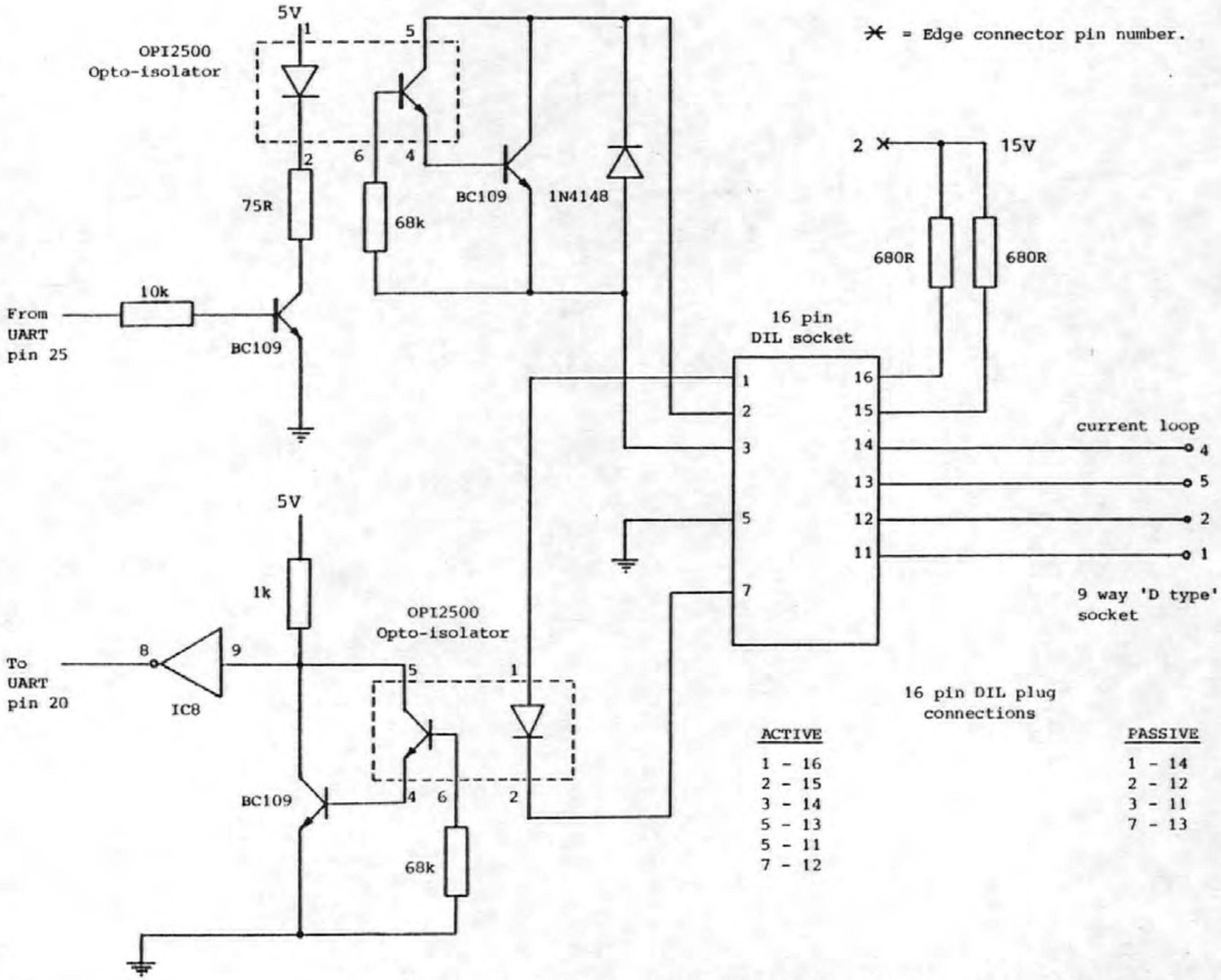


Figure 4-9a The circuit of one of the serial data transceivers



16 pin DIL plug connections

ACTIVE	PASSIVE
1 - 16	1 - 14
2 - 15	2 - 12
3 - 14	3 - 11
5 - 13	7 - 13
5 - 11	
7 - 12	

IC types

IC1	7401
IC2	7404
IC3	7430
IC4	7407
IC5	7401
IC6	7430
IC7	7430
IC8	7404
IC9	7401
IC10	7401
IC11	7408
IC12	7400
IC13	7400
IC14	7427
IC15	4051
IC16	6402
IC17	14411

Figure 4-9b The current loop interface of the serial data transceivers

Table 4-2

Instructions Obeyed By The Serial Data Transceivers

OCTAL INSTRUCTION CODE	MNEMONIC	ACTION
6621	SDR	Skip if the receiver has a data word ready
6631	RUD	Read the data word
6641	SKERR	Skip if an error has been detected
6622	DUI	Disable all interrupts
6632	ERI	Enable receiver interrupts
6642	ETI	Enable transmitter interrupts
6624	STR	Skip if the transmitter is ready for more data
6634	LSTAT	Load the control status register
6644	OUT	Load the data and transmit

A more detailed account of the operation of these instructions and their effect on the serial data transceivers is given in Appendix 8.9.

4.4 Minicomputers and Software

The analogue to digital (A-D) converter and the multiplexer were controlled by a Digital Equipment Co. PDP 8/f minicomputer with 8k words of ferrite core memory. Since evoked potentials were to be studied the computer was also used to present trigger pulses to the external stimulus generators at the appropriate instants. As the digital data was acquired it was stored in the memory of the minicomputer. Simultaneously the data was transmitted over a high speed serial data link to the second PDP 8 minicomputer some distance away from the measurement room for storage on a magnetic disk.

The operation of the complete measuring system can best be described by outlining the sequence of events involved in obtaining a single evoked response.

(i) The minicomputer waits until the operator pushes a button to start the acquisition process.

(ii) Under interrupt control the six analogue data channels are digitised and stored in the memory of the minicomputer. The interrupts are generated by a crystal oscillator and divider giving either 125 or 250 samples per second.

(iii) Under interrupt control the data stored in the memory of the minicomputer is transferred via the serial data link to the second (remote) minicomputer. The interrupts are generated every time the serial data link becomes inactive.

(iv) When not busy (i.e. when not interrupted) the minicomputer displays via two ten bit digital-to-analogue converters and an X-Y CRT display any one of the six incoming data channels.

(v) When each sample is taken the minicomputer checks the sample number and if a preset number have been taken it sends a pulse to trigger the first stimulus generator.

(vi) When each sample is taken the minicomputer checks the sample number and if another preset number have been taken it sends a pulse to trigger the second stimulus generator.

(vii) After each sample has been taken a test is performed to determine whether the required total number of samples have been taken and if so whether they have all been sent to the remote minicomputer for permanent storage.

(viii) If both conditions in (vii) are met then the minicomputer waits for the remote minicomputer to acknowledge that the data has been successfully stored before returning to state (i) above.

The sequence of events for the remote minicomputer is as follows;

(i) Send the 'Ready' signal to the minicomputer in the measurement room.

(ii) Wait for the data and store it in core memory as it arrives. Perform tests to detect transmission errors.

(iii) When all the data for the evoked response has been received store it on the magnetic disk.

(iv) Return to state (i)

The two programmes to perform the above tasks were written in the PAL 8 assembly language and listings are given in Appendices 8.10 and 8.11.

It should be noted that the speed of the serial data link may be greater or less than the rate at which the data is acquired since the computer memory is used as a temporary storage buffer.

For analysis and processing of the evoked responses the data stored on the magnetic disk of the PDP 8 minicomputer was transferred on either paper tape or floppy disks to a large database on the Polytechnic main computer.

4.5 Other Equipment

4.5.1 Eye Movement Correction Screen

Our experiments comparing the effectiveness of various methods of removing eye movement artefact from the EEG were undertaken with the aid of a simple wooden screen shown in Figure 4-10. The screen was approximately 1.3m square into which a set of nine 5 mm red light emitting diodes (L.E.D.'s) were inserted on a 0.55m grid. A remote control box allowed any of the LED's to be switched on or off as required. The procedure adopted for using the screen is described in Section 3.3.

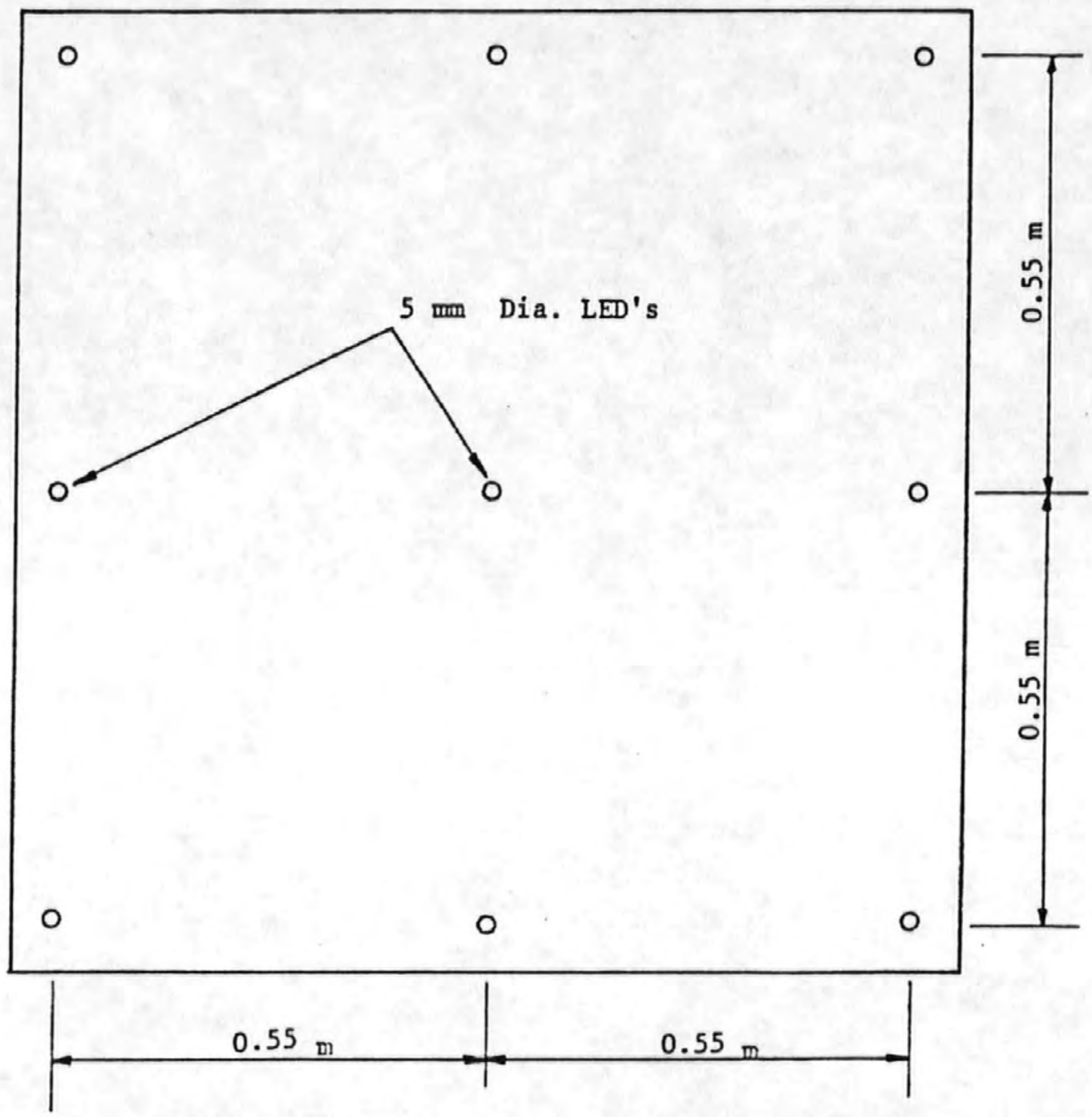


Figure 4-10

The eye movement correction screen.

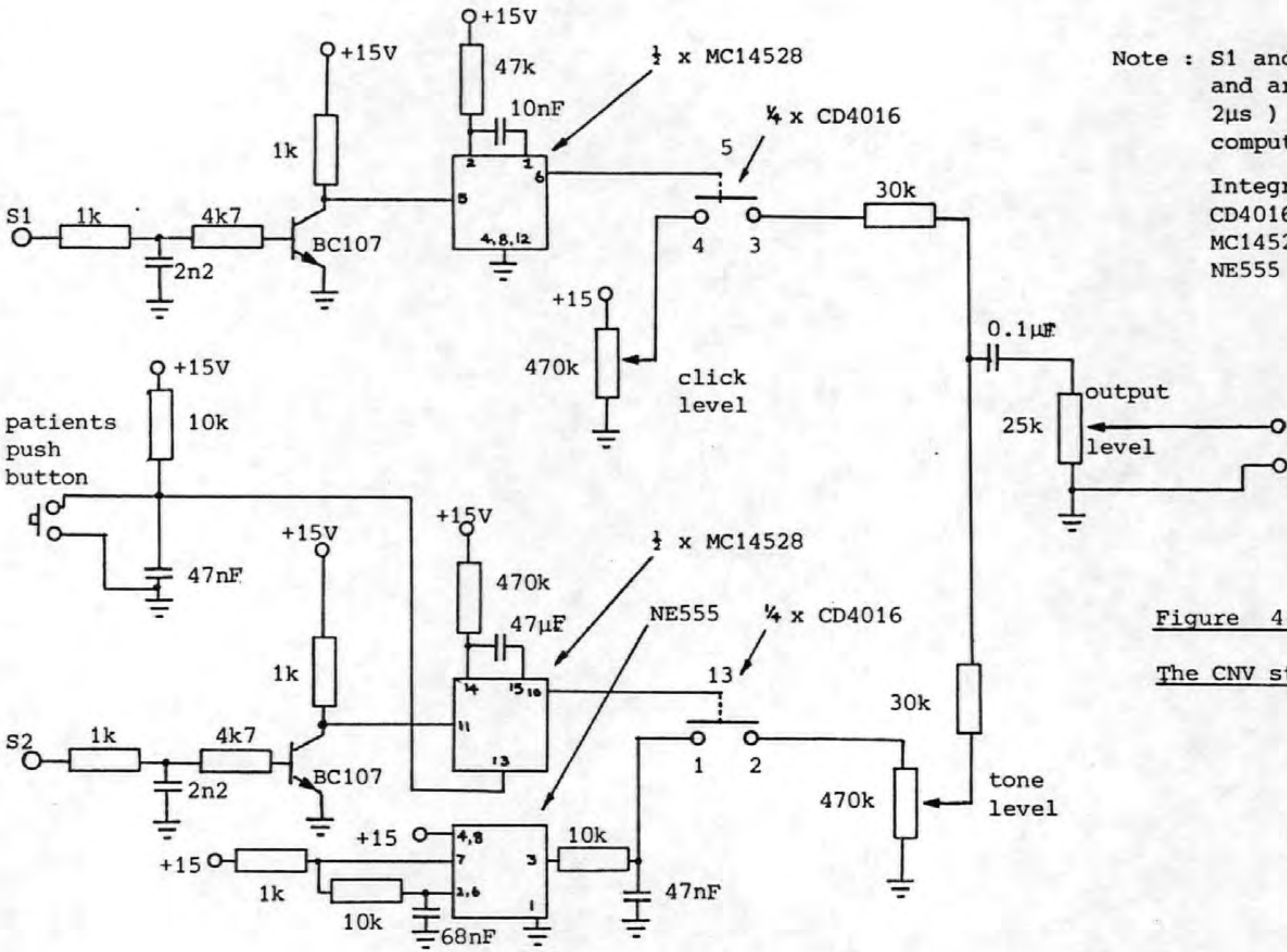
4.5.2 The CNV Stimulus Generator

In order to record CNV's it is necessary to present the subject with some form of stimulus. The type of stimulus is not important to the final result and the two most commonly used stimuli are auditory and visual. Some workers use two auditory stimuli (e.g. a click followed by a tone [5] whereas others use combinations of auditory and visual stimuli (e.g. a click followed by a flashing light [6]. Our initial experiments at Freedom Fields Hospital had indicated that the use of a visual stimulus was to be avoided if possible since this often resulted in the subject blinking and hence introducing an artefact in synchronism with this stimulus.

The stimulus paradigm subsequently chosen was that of a click followed by a 1kHz. tone of 90dB. intensity (A weighting). The circuit used for generating this is given in Figure 4-11.

In order to obtain correct CNV responses the subject must perform some action upon receipt of the second stimulus. It is normal practice to use a hand held push button which the subject is required to press.

It is also normal for the push buttom to be connected to the stimulus generator in order to terminate the second stimulus. This feature gives the subject some motivation for responding to the second stimuli and was incorporated in our stimulus generator.



Note : S1 and S2 are the trigger inputs and are driven by short (approx 2µs) TTL pulses from the mini-computer.

Integrated circuits
CD4016 Quad analogue switch.
MC14528 Dual monostable.
NE555 Timer.

Figure 4-11

The CNV stimulus generator

4.5.3 The AEP Stimulus Generator

The equipment used in the recording of the AEP's was virtually identical to that used for the CNV's. The only difference was in the generation of the stimulus. The auditory stimuli were delivered from an Amplaid stimulus generator to the right transducer of a pair of Koss K6 stereo headphones. Triggering of the stimulus generator was performed at the required instants by the PDP 8 minicomputer. Two different levels of stimulus were applied. A 1kHz. tone of 100ms duration including 10ms of rise and fall according to a cosine squared law was used. The low level stimulus was applied at a level of 40dB. above the subject's auditory threshold, while the high level stimulus was applied 70dB. above it. These stimuli were presented as the subject sat relaxed in a chair.

References for Section 4

[1] Sallen R P, Key E L, "A Practical Method of Designing R C Active Filters"
Institute of Radio Engineers, Transactions on Circuit Theory, Volume CT2, pp 74-85, 1955.

[2] Millman J, Halkias C C, "Integrated Electronics: Analog and Digital Circuits and Systems"
Chapter 16, page 550. Published by McGraw-Hill Kogakusha Ltd., 1972.

[3] Yeats R W, "Hybrid Computing and its Applications"
Internal Report, School of Electrical Engineering, Plymouth Polytechnic, January 1975.

[4] Interface Quartz Devices Ltd., "Typical Oscillator Circuits"
Available from Interface Quartz Devices Ltd., 29 Market Street, Crewkerne, Somerset TA18 7JU.

[5] Hillyard S A, Galambos R, "Eye Movement Artifact in the CNV"
Electroencephalography and Clinical Neurophysiology, Volume 28, pp 173-182, 1970.

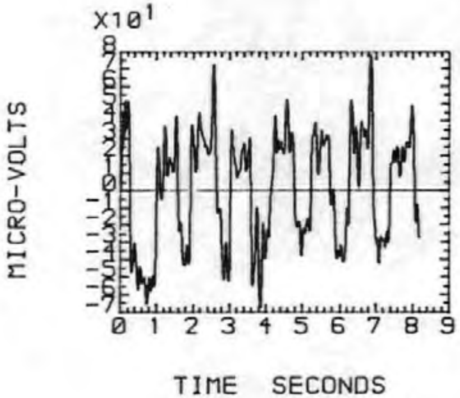
[6] Walter W G, Cooper R, Aldridge V J, McCallum W C, Winter A L, "Contingent Negative Variation: An Electric Sign of Sensorimotor Association and Expectancy in the Human Brain"
Nature, Volume 203, pp 380-384, July 1964.

5. Results and Discussion

5.1 Eye Movement Corrections

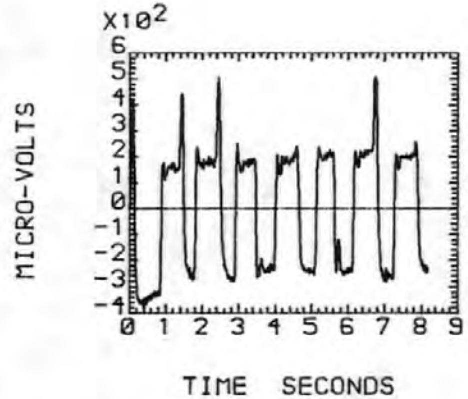
A set of typical waveforms depicting the raw EEG, the raw (vertical left) EOG and the corrected EEG are given in Figure 5-1 (a-c). Also shown are the autocorrelation functions (a.c.f.'s) of the EEG, the EOG and the corrected EEG signals Figure 5-1 (d-f). Table 5-1 gives the results as evaluated from the plots derived from four experiments. This table gives both the frequencies and the autocorrelation co-efficients (a.c.c.'s, see Section 2.4 for details) of each of the corrected EEG's along with the frequency of the EOG deduced from its own a.c.f. Some of the frequencies present appear to be harmonics of the EOG which suggests that the path between the eye and the scalp electrode may be frequency selective or non-linear. If this is so then the proportions of the harmonics making up the rectangular EOG will not be maintained at the scalp electrode. This will result in some harmonics being over or under corrected and thus remaining in the output waveform.

When the artefact contains components due to both eye movements and blinks (which do not have the same effect on the EEG [1]), then the computerised correction will attempt to achieve an optimum correction so that as much as possible of both components is removed. This is still a compromise however, since neither artefact signal can be completely removed by this method whilst the other is present in the same section of signal record. The methods of McCallum and



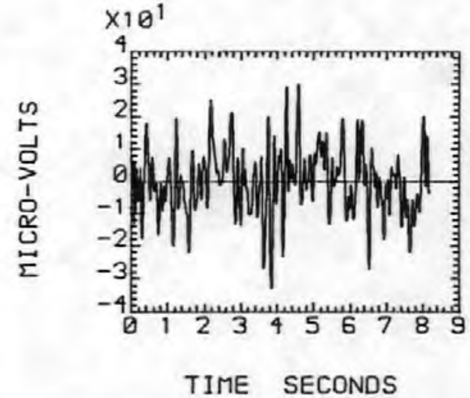
(a)

The raw EEG



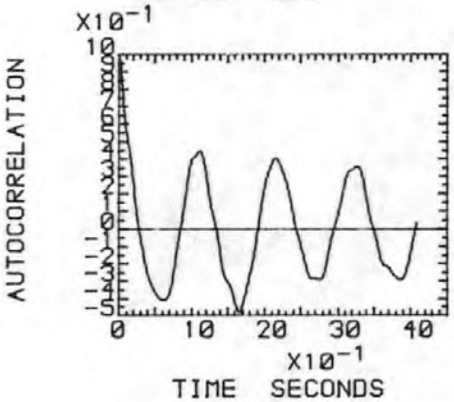
(b)

The raw EOG (V_L)



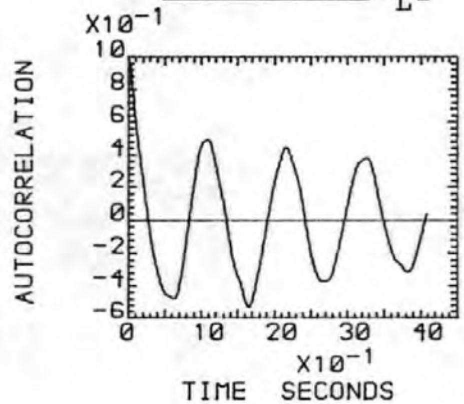
(c)

The corrected EEG



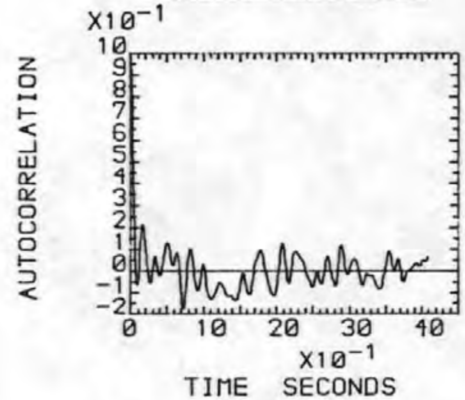
(d)

The ACF of (a)



(e)

The ACF of (b)



(f)

The ACF of (c)

Figure 5-1

Table 5-1

QUANTITATIVE RESULTS OF EYE MOVEMENT

EXPERIMENTS

EYE MOVEMENT	PARAMETER	2 CHANNEL CORRECTION (± 0.02)	3 CHANNEL CORRECTION (± 0.02)	4 CHANNEL CORRECTION (± 0.02)	ANALOGUE CORRECTION (± 0.02)	EOG FREQ. (± 0.02)	INTERPRETATION
DOWN	FREQ.	0.70*	N.P.	N.P.	0.38*	0.38	A B
	r	0.09	N.P.	N.P.	0.38		
LEFT	FREQ.	N.P.	N.P.	N.P.	0.27 +	0.36	A
	r	N.P.	N.P.	N.P.	0.16		
UP	FREQ.	N.P.	N.P.	N.P.	0.33 +	0.38	A
	r	N.P.	N.P.	N.P.	0.22		
RIGHT	FREQ.	0.55*	0.50*	0.50*	0.55*	0.52	A
	r	0.22	0.15	0.15	0.28		

FREQ. = frequency of autocorrelation function (Hz)
r = autocorrelation coefficient at T=2 sec.
N.P. denotes a non-periodic autocorrelation function indicating complete correction.
A means correlation technique better than analogue technique.
B means 4 and 3 channel correction are better than 2 channel.
* denotes a frequency related to the EOG frequency.
+ denotes a frequency unrelated to the EOG frequency.

Walter, and Girton [2] and Kamiya [3] make no allowances at all for the differential contributions of blinks and eye movement artefacts.

The deductions made from forty-eight experiments are summarized in Table 5-2. Due to the amount of computer time involved only the vertical and horizontal eye movements were analysed (i.e. The Forty-eight other experiments involving the subjects looking to the corners of the eye movement screen were, with a few exceptions, not analysed).

Table 5-2

Summary of Results of Quantitative

Eye Movement Experiments

INTERPRETATION	VERTICAL EYE MOVEMENT	HORIZONTAL EYE MOVEMENT
A	20	17
D	3	7
E	3	3
F	2	0
G	1	0
H	1	1

A means the correlation correction method was better than the analogue method.

D means both the correlation correction and the analogue correction were equally effective.

E means the 3-channel correction was better than the 2 channel correction.

F means the 2 channel correction was better than the 3 channel correction.

G means the 4 channel correction was not the best.

H means the correlation correction was incomplete.

From Table 5-2 it was deduced that:

(i) The correlation correction technique was complete in 96% of the cases.

(ii) In the majority of cases (77%) the correlation correction technique was superior to the analogue correction technique.

(iii) In 21% of the cases it was not possible to distinguish between the effectiveness of the analogue and correlation techniques.

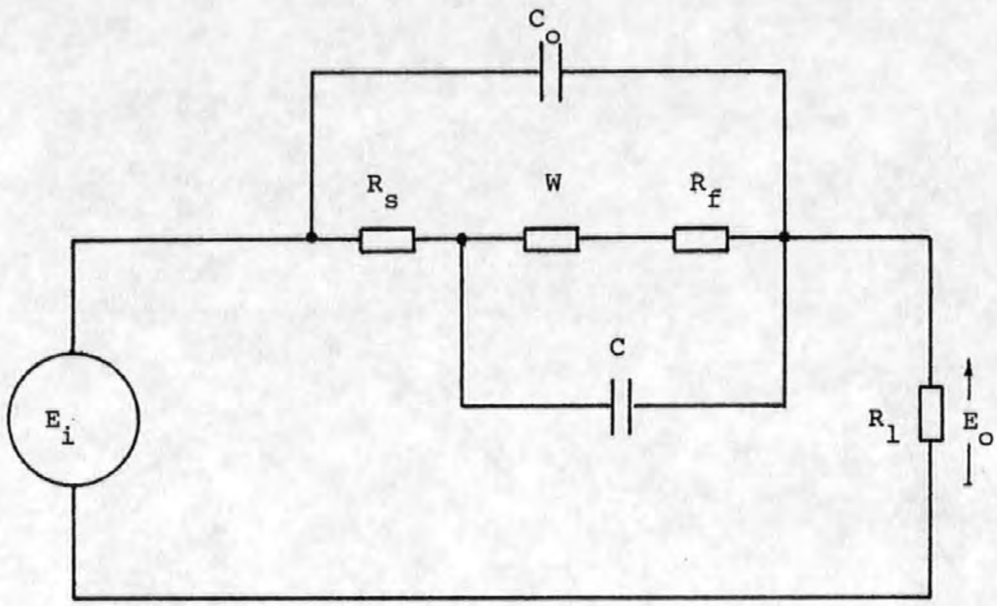
(iv) The evidence from interpretations E and F suggests that to correct for horizontal eye movements it may be necessary always to use the 3-channel correction rather than only a 2-channel correction. This is to be expected since the ocular dipoles tend to oppose each other during horizontal eye movements whereas they re-inforce each other during vertical eye movements.

(v) Interpretation G indicates that in 98% of cases the 4-channel correction is as good as or better than the other methods. However if computing time is at a premium (e.g. in an on-line situation) it would probably be adequate to rely on the 3-channel correction method.

(vi) Interpretation D shows that the analogue technique was as good as the correlation technique more often for horizontal eye movements than for vertical eye movements. (7 times against 3 times out of 48 experiments). Since the analogue technique is not intended to correct for horizontal eye movements, this suggests that it may actually be an unsuitable one to use to correct for vertical eye movements.

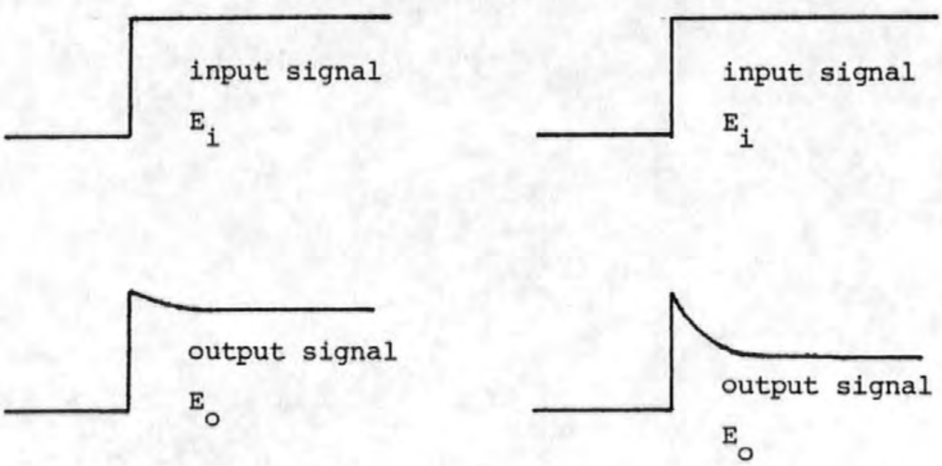
In addition to the points previously mentioned, two other disadvantages of the analogue techniques were noted. Firstly it was difficult to optimise the potentiometer setting required to minimise the artefact and analogue correction would therefore be very time consuming in multi-channel recording. Second, in all the subjects tested there was a degree of coupling between the EOG and EEG when the EOG changed rapidly. This was probably due to the R.C. network formed by the potentiometer resistance (25kΩ) and the electro-chemical capacitance of the electrode-skin interface. This effect was reduced when a larger value potentiometer (1MΩ) was used. Unfortunately however this solution adversely affects the common mode rejection ratio of the EEG machine's differential amplifier (because of the increased source impedance of the input with the 1MΩ potentiometer in circuit). The presence of this R.C. time constant will result in distortion of the EOG and hence false correction of the artefact. This may be the reason behind the evidence in (vi) above that the analogue technique may even be erroneous. This is illustrated in Figure 5-2.

In conclusion it was found that the 4-channel computerised correlation method of correcting the EEG for eye movement artefact gave complete correction in 96% of the cases studied. However, in practice the 3-channel method would normally be adequate. The analogue technique was never the best. Furthermore it was very time consuming and quite possibly erroneous.



E_i	scalp EEG signal.
C_o	stray capacitance (usually negligible).
R_s	resistance of the electrode jelly.
R_f	Faradic resistance.†
W	Warburg impedance.†
C	electro-chemical capacitance.
	see [11] for further details.

† These quantities are usually resistive and small for Ag-AgCl electrodes.



Normal situation when R_l is large in comparison with R_f + W.

The situation when R_l is small.

Figure 5-2 The effect of electrode loading.

Some of the above work has been published [4].

A more detailed account has also been written as a longer paper with the title "Comparison of Methods for Removing Eye Movement Artefact from the EEG" for submission to the IEEE Transactions on Biomedical Engineering. This paper has not yet been submitted at the request of the National Research Development Corporation who have awarded a grant towards the development of a Commercial EEG Eye Movement Artefact Corrector based on the above work which they intend to patent.

5.2 Auditory Evoked Potentials

64 pre-stimulus and 64 post-stimulus realisations each of length 0.512 s were recorded at the two levels of stimulus for three different subjects.

Following the earlier work [5-8], the pre- and post-stimulus realisations were given the statistical test described in 2.2.3.1 above, the test for changes in signal energy, and phase histograms were also plotted for the first six harmonic frequency components. The statistical test showed that only one out of the six sets of results (3 subjects x 2 stimulus levels) exhibited a significant energy difference and in the sense that the energy in the post-stimulus case exceeded that in the pre-stimulus case.

The results of these tests are shown in table 5-3.

Table 5-3

Comparison of Pre- and Post- Stimulus AEP Energy

	Subject	Mean of difference $\times 10^{-8}$	ν (degrees of freedom)	T Statistic	% Significance
LOW	1	0.0075	63	0.129	N-S
LEVEL	2	-.1305	63	-0.709	N-S
STIMULUS (+ 40dB)	3	0.6817	63	2.729	1.0
HIGH	1	0.1265	63	1.548	20
LEVEL	2	0.2238	63	1.129	N-S
STIMULUS (+ 70dB)	* 3	0.2558	63	0.886	N-S

* 65dB. above threshold

The results obtained were in accord with Sayers' findings [5] since he could not establish any consistent difference between the pre- and post- stimulus energies of the averaged waveform. This result led Sayers to the important conclusion that if there were no additional energy in the evoked response, then the characteristic shape of the AEP must be due to some form of phase alignment of certain background components.

However, this test was not considered very reliable since the contribution of every harmonic component was included in the energy calculation and the higher harmonics were probably representative of background noise. Thus the effects of background noise were likely to mask the presence of the AEP. Furthermore, while the phase histograms indicated phase ordering they did not reveal the cause. For these reasons the findings of the previous workers [5-8] although confirmed, were not considered conclusive.

The data was also subjected to the other statistical tests described in sections 2.2.2 and 2.2.3. These tests held potential advantages over the previous test since they were applied to individual harmonic components. They could therefore be used to investigate the first few harmonics which would be expected to constitute the major components of the AEP. The higher harmonics which were expected to be associated with the random background could be ignored. Typical pre- and post- stimulus phasor diagrams are shown in Figure 5-3. The triangles on the circles indicate the directions in which the phasors lie, while the crosses indicate the locations of the phasor tips. The results of the statistical tests carried out for harmonic numbers 1-6 are shown in Table 5-4. Each broad column of results contains the value of the test statistic, the number of degrees of freedom ν and the level at which the result is significant. A significant positive result in column (B) means that the nearest mean amplitude is greater than the furthest. A significant positive result in column (C) means that the post-stimulus amplitude is greater than the pre-stimulus

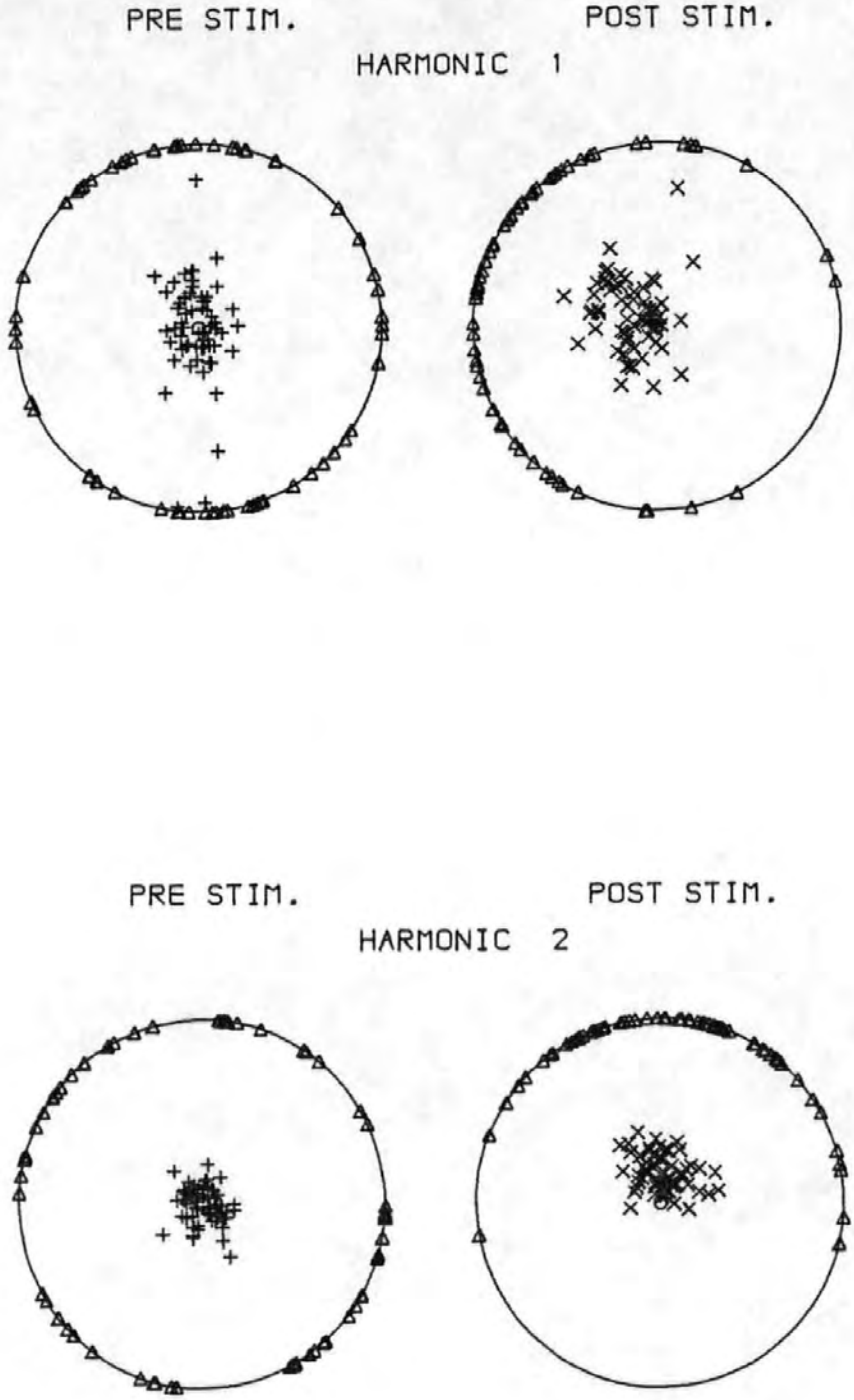


Figure 5-3

Typical Pre- and Post-Stimulus AEP phasor diagrams

Table 5-4

TEST STATISTICS AND LEVELS OF SIGNIFICANCE FOR STATISTICAL TESTS ON AEP PHASOR DIAGRAMS BY HARMONIC NUMBER, STIMULUS LEVEL AND SUBJECT

HARMONIC NUMBER & FREQUENCY	STIMULUS LEVEL	SUBJECT	NEAREST-FURTHEST MEAN AMPLITUDE (B)			PRE-POST MEAN AMPLITUDE DIFFERENCES (C)			RAYLEIGH CIRCULAR VARIANCE (D)		HODGES-AJNE (E)		MODIFIED RAYLEIGH CIRCULAR VARIANCE (F)	
			T	ν	%	T	ν	%	So	%	m	%	Uo	%
1 1.953 Hz	LOW	1	-0.294	63	N-S	-0.273	63	N-S	0.735	5	19	2.5	0.677	1
		2	3.67	64	.05	3.96	63	0.1	0.612	0.1	12	0.001	0.439	0.1
		3	1.69	63	5	1.01	63	N-S	0.398	0.1	7	0	0.345	0.1
	HIGH	1	1.55	62	10	2.80	63	1	0.538	0.1	13	0.005	0.477	0.1
		2	0.550	61	N-S	5.35	63	0.1	0.278	0.1	4	0	0.224	0.1
		3	-0.136	38	N-S	2.50	63	2	0.332	0.1	5	0	0.336	0.1
2 3.906 Hz	LOW	1	1.68	64	5	2.27	63	5	0.584	0.1	14	0.019	0.512	0.1
		2	0.992	58	N-S	4.13	63	0.1	0.487	0.1	11	0	0.461	0.1
		3	0.700	64	N-S	6.78	63	0.1	0.204	0.1	2	0	0.198	0.1
	HIGH	1	-0.513	59	N-S	4.96	63	0.1	0.440	0.1	10	0	0.340	0.1
		2	5.09	55	.05	3.84	63	0.1	0.445	0.1	12	0.001	0.308	0.1
		3	0.851	64	N-S	5.85	63	0.1	0.266	0.1	6	0	0.205	0.1
3 5.893 Hz	LOW	1	2.33	62	2.5	3.57	63	0.1	0.370	0.1	9	0	0.264	0.1
		2	0.480	64	N-S	2.16	63	5	0.605	0.1	17	0.45	0.504	0.1
		3	0.498	63	N-S	0.632	63	N-S	0.643	0.1	16	0.17	0.594	0.1
	HIGH	1	2.83	64	0.5	3.50	63	0.1	0.303	0.1	5	0	0.199	0.1
		2	0.0	63	N-S	1.60	63	20	0.580	0.1	14	0.019	0.550	0.1
		3	-0.763	42	N-S	1.91	63	10	0.572	0.1	13	0.005	0.502	0.1
4 7.812 Hz	LOW	1	1.51	64	10	0.0	63	N-S	0.735	5	20	5.1	0.648	1
		2	-0.362	63	N-S	-0.310	63	N-S	0.757	5	20	5.1	0.789	N-S
		3	3.08	61	0.5	1.75	63	10	0.542	0.1	14	0.019	0.421	0.1
	HIGH	1	1.75	63	5	1.81	63	10	0.403	0.1	7	0	0.282	0.1
		2	-1.18	61	N-S	-1.40*	63	20	0.777	5	22	20	0.797	N-S
		3	0.995	64	N-S	1.75	63	10	0.458	0.1	11	0	0.417	0.1
5 9.765 Hz	LOW	1	-1.21	47	N-S	1.90	63	10	0.787	10	23	20	0.812	N-S
		2	0.07	64	N-S	-0.092	63	N-S	0.848	N-S	24	N-S	0.763	10
		3	0.814	64	N-S	1.81	63	10	0.713	1	17	0.45	0.662	1
	HIGH	1	1.25	59	N-S	-0.772	63	N-S	0.705	1	20	5.1	0.612	0.1
		2	-0.02	64	N-S	-0.983	63	N-S	0.885	N-S	26	N-S	0.891	N-S
		3	0.551	63	N-S	1.81	63	10	0.463	0.1	11	0	0.456	0.1
6 11.718 Hz	LOW	1	1.65	64	10	2.96	63	1	0.686	1	17	0.45	0.566	0.1
		2	0.821	59	N-S	-2.98*	63	1	0.957	N-S	28	N-S	0.932	N-S
		3	1.49	64	10	1.83	63	10	0.638	0.1	17	0.45	0.523	0.1
	HIGH	1	1.19	57	N-S	-1.18	63	N-S	0.875	N-S	26	N-S	0.839	N-S
		2	1.37	64	10	-1.64*	63	20	0.799	10	21	9.8	0.708	5
		3	-1.31*	61	10	1.79	63	10	0.861	N-S	25	N-S	0.934	N-S

amplitude. Positive significant results in the remaining columns indicate phase ordering.

N-S means non-significant. While all levels of significance were recorded in order to extract maximum information, levels in excess of 5% were regarded as non-significant. Some of the test statistics in columns (B) and (C) are negative. The ones marked by an asterisk were significant in a negative direction. This occurred in column (C) and meant that the post-stimulus amplitude was less than the pre-stimulus one. This also occurred once in column (B) and indicated that the more widely spaced phasors were larger than the "grouped" ones. However, examination of the corresponding columns (D), (E) and (F) reveals that no phase ordering i.e. grouping had in fact occurred and the test would therefore be unreliable. (See also section 2.2.3.3). The level of significance between columns (B) and (C) do not always agree. The Nearest and Furthest Mean Amplitude Test (one-tailed) depends specifically upon the details of the assumed additive model and is not infallible, vide statistical Test B. By comparison the Pre- and Post- Stimulus Mean Amplitude Differences Test (two-tailed) tests for an additive effect irrespective of the mechanism by which it occurs. Inspection of column (C) showed that thirteen out of the eighteen results obtained for harmonics 1-3 were significant at the 5% level (i.e. additive signal detected in 72% of cases), while for harmonics 4-6 only two out of the eighteen results were significant. For column (B) the corresponding figures were six out of eighteen and two out of eighteen. Inspection of column (C) showed that only in one case was the mean of the amplitude differences significantly less than zero (i.e. the pre- stimulus phasors were larger than the post stimulus ones). The remaining twenty-one cases were not significant in either direction. On an individual basis and ignoring significance levels nine cases showed a post-stimulus decrease in energy. Taken together these results indicated that additive energy could be detected in a large percentage of the cases for harmonics 1-3. Interestingly the Pre- and Post- Stimulus Mean Amplitude Differences Test applied to the second harmonic gave a positive significant result for each subject and for both levels of stimulus, and was the only test to do this. This may be a useful result audiologically but further investigation would be advised.

Columns (D), (E) and (F) revealed that the Rayleigh Test of Circular Variance, the Hodges-Ajne, and the Modified Rayleigh Test of Circular Variance were all in good agreement for the first three harmonics. However, the modified Rayleigh Test statistic was less than the Rayleigh statistic in 17 cases out of 18 which suggested that the amplitudes were orientated towards the preferred direction. This was not true for harmonics 4-6. In these cases the Rayleigh and Hodges-Ajne tests agreed but the modified Rayleigh Test did not always agree with them. Inspection of the tabulated results revealed that harmonic components 1-3 were strongly phase ordered while harmonics 4-6 showed less phase ordering. Overall, post-stimulus phase ordering was seen to be significant at the 5% level in all but seven of the thirty six cases observed.

Reflection upon all the observations so far made it apparent that harmonics 1-3 exhibited different amplitude and phase properties to harmonics 4-6. Harmonics 4-6 showed less evidence of phase ordering and even less evidence of additive energy. All of this was regarded as evidence that harmonics 4-6 were more representative of the noisy background EEG than of the evoked response. This in turn lent further support to the previously stated opinion that the comparison of pre- and post- stimulus realisation energies was unlikely to provide a reliable means for the investigation of additive energy, due to the masking effects of the higher harmonic noise.

Returning to Table 5-4, Column (C) taken together with Column (D) showed that when the AEP contained an additive component there was also phase ordering. This finding agreed well with the proposed additive model. Thus out of 29 cases exhibiting phase ordering 14 (or 48.3%) contained an additive component. There was also a pronounced tendency for additive and phase ordering effects to be concentrated in the first three harmonics. In other respects the occurrence of ordering or additivity appeared random. For example, for an individual the occurrence of ordering or an additive component in a particular harmonic at one level of stimulus did not necessarily mean that it would be found in the same harmonic for a different level of stimulus.

5.3 The CNV's of Normal Subjects

CNV responses were recorded from a total of five normal subjects between the ages of 18 and 60 years. Both one and four second interstimulus intervals were used according to the procedure described in section 3.5. Prior to further processing all the individual CNV responses were corrected for the effects of eye movement artefact as described in section 2.5.

5.3.1 The Averaged CNV's

After processing to remove eye movement artefact the CNV's were averaged, filtered with the low pass digital filter described in section 3.6 and plotted. The resulting averaged CNV's are shown in Figures 5-4 a-e (1 second ISI) and Figures 5-5 a-e (4 second ISI). The averaged CNV waveforms were then used to determine the section of the response to be analysed in the subsequent sections i.e. the 'Negative Variation' section excluding the evoked responses. This section was determined in terms of 'sample numbers' and for the one second ISI was found to lie between samples 472 and 536 (The stimuli being given concurrently with samples 407 and 532), whereas for the four second ISI it was found to lie between samples 295 and 695 (The stimuli being given concurrently with samples 219 and 719). Since the digital filter was used in most of the subsequent analysis, the sample numbers obtained from the averaged CNV responses included a delay due to the filter identical to that which would be obtained in the subsequent processing. Any processing carried out on unfiltered data used points 462 and 526 (1 second ISI) or points 285 and 685 (4 second ISI).

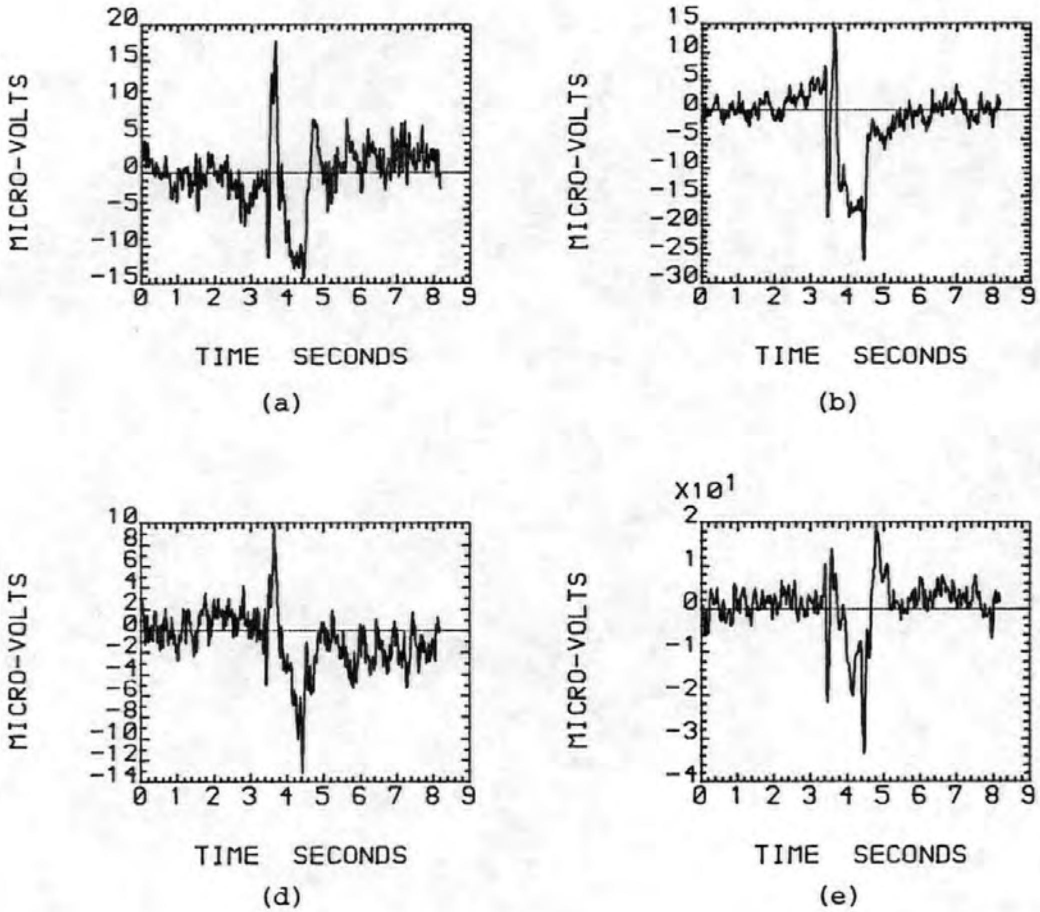
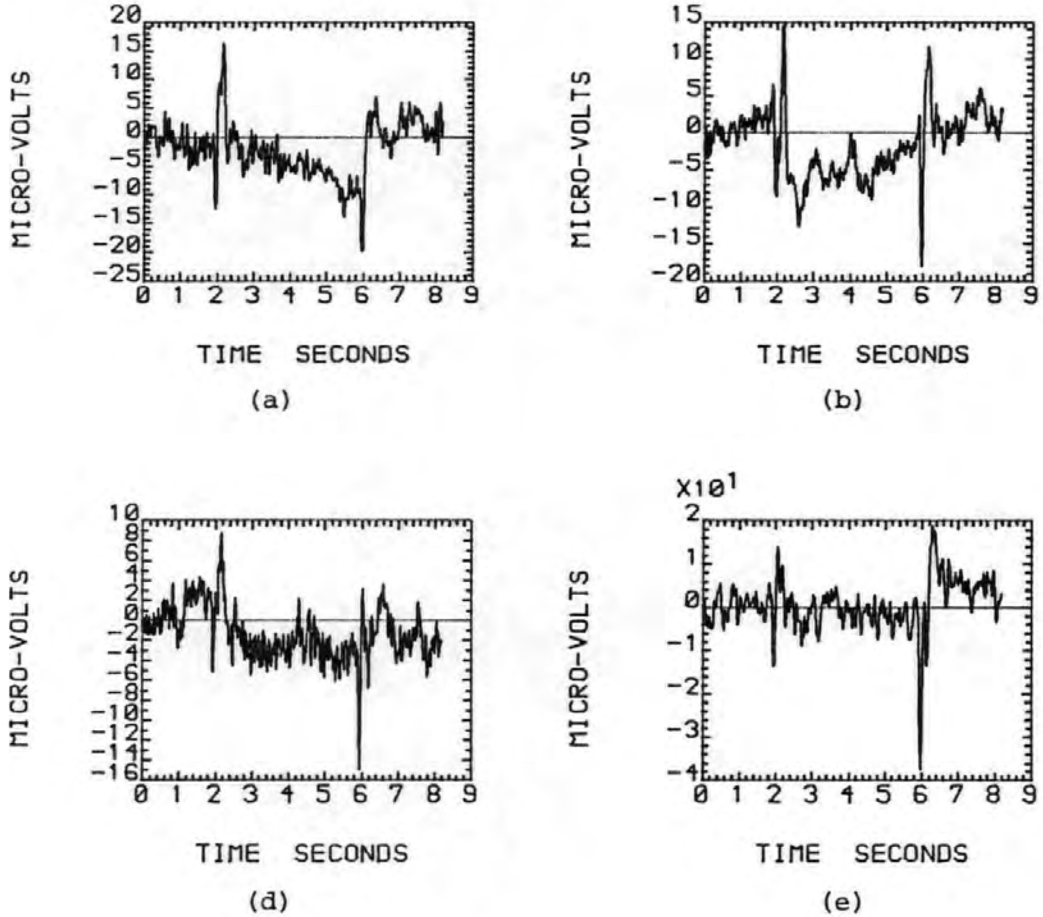


Figure 5-4

The averaged one second ISI CNV's of normal subjects.



<u>Figure 5-5</u>

<u>The averaged four second ISI CNV's</u>

<u>of normal subjects.</u>

5.3.2 Energy Tests

These tests were performed to establish whether any additive component could be detected in the CNV response.

5.3.2.1 Broadband Energy Tests

Prior to the calculation of the mean energy for the pre- and post- stimulus sections of the CNV's, the data was corrected for the effects of eye movements and filtered in the usual manner. One of the side effects of the eye movement correction procedure was to remove any d.c. component present in the data epoch and, where an individual CNV response contained a marked negative shift, the effect of this was to cause a positive shift of the pre- and post-stimulus baselines. Thus prior to the calculations described in section 2.2.3.1 it was necessary to re-establish the true baseline. This was achieved by subtracting the mean signal level, calculated over that section of the data prior to the S1 stimulus, from the data. Furthermore, to allow for any small d.c. drift during the acquisition of the data, the mean signal level was also calculated for that section of the data from a point one second after the S2 stimulus (to allow the S2 evoked response and the CNV to return to the zero level) to the end of the data record. This value was subtracted from this section of the data. Between these two mean values the data was corrected by subtracting the appropriate fraction of the difference between these values. The overall correction was thus:-

Section of data (sample numbers)	Corrections used
$1 \leq k \leq S1$	$x_k = x_k - \frac{1}{S1} \sum_{i=1}^{S1} x_i$
$S1 < k \leq S2{+}D$	$x_k = x_k - \left[\frac{\left(\frac{1}{(N-S2-D)} \sum_{S2+D}^{N} x_i \right) - \left(\frac{1}{S1} \sum_{1}^{S1} x_i \right)}{S2 + D - S1} \right] (k-S1)$
$S2{+}D < k \leq N$	$x_k = x_k - \frac{1}{(N-S2-D)} \sum_{S2+D}^{N} x_i$

Where S1 is the sample number corresponding to the instant of the S1 stimulus application.

S2 as above for S2.

D is the delay after S2 to allow the responses to settle. (a figure of one second (D = 125) was used).

x_i is the i^{th} data point.

N is the total number of data points.

This correction is subsequently referred to as the base-line correction.

After applying this correction to each CNV response the mean energy values were calculated and subjected to a T-test as previously described. The results of these tests are shown in Tables 5-5a and 5-5b.

Table 5-5a

Broadband energy tests of normal subjects

One second ISI CNV's

Subject	Number of Responses	T Statistic	Significance Level %	Number of* Responses Post < pre
1	31	2.91	1.0	7
2	32	7.05	<<0.1	1
3	19	5.22	<<0.1	3
4	32	2.18	5.0	10
5	32	4.69	<<0.1	6

Table 5-5b

Broadband energy tests of normal subjects

Four second ISI CNV's

Subject	Number of Responses	T Statistic	Significance Level %	Number of* Responses Post < pre
1	32	2.47	2.0	11
2	32	3.47	0.2	3
3	32	4.39	<<0.1	5
4	32	3.72	0.1	7
5	32	5.55	<<0.1	5

* The number of individual responses where the post-stimulus energy was less than the pre-stimulus energy.

They show that for both ISI's and to a level of significance of at least 5%, and mostly considerably better, the CNV response contained more energy than the background EEG prior to stimulation. The conclusion drawn from this was that the CNV must contain additional energy. On an individual basis however, 58 out of 306 (18.9%) of the CNV responses contained less energy than the background EEG. This possibly reflected the variability of the background EEG and of the CNV rather than it implied the CNV energy might have been less than the background.

5.3.2.2 Amplitude Histograms

The background EEG has a virtually random amplitude and phase but an added signal component due to the CNV might be expected to have a constant amplitude and phase. If the amplitude of the added component were the same for each stimulus and were large in comparison with the background EEG, then the n^{th} harmonic component of each response would be similar. Hence the n^{th} harmonic amplitude histogram for a sequence of CNV's should exhibit a peak about some preferred value. Amplitude histograms were plotted to test this hypothesis. It was found that the amplitude histogram of the first harmonic of the one second ISI CNV's showed some similarities. In particular most exhibited a lower amplitude limit while the most probable amplitudes were different for different subjects. A typical histogram is shown in Figure 5-6. None of the other harmonics showed any obvious patterns. It was thought that the absence of definite patterns in the histograms of the higher harmonics might indicate the masking effects of the background EEG. Accordingly a comparison of

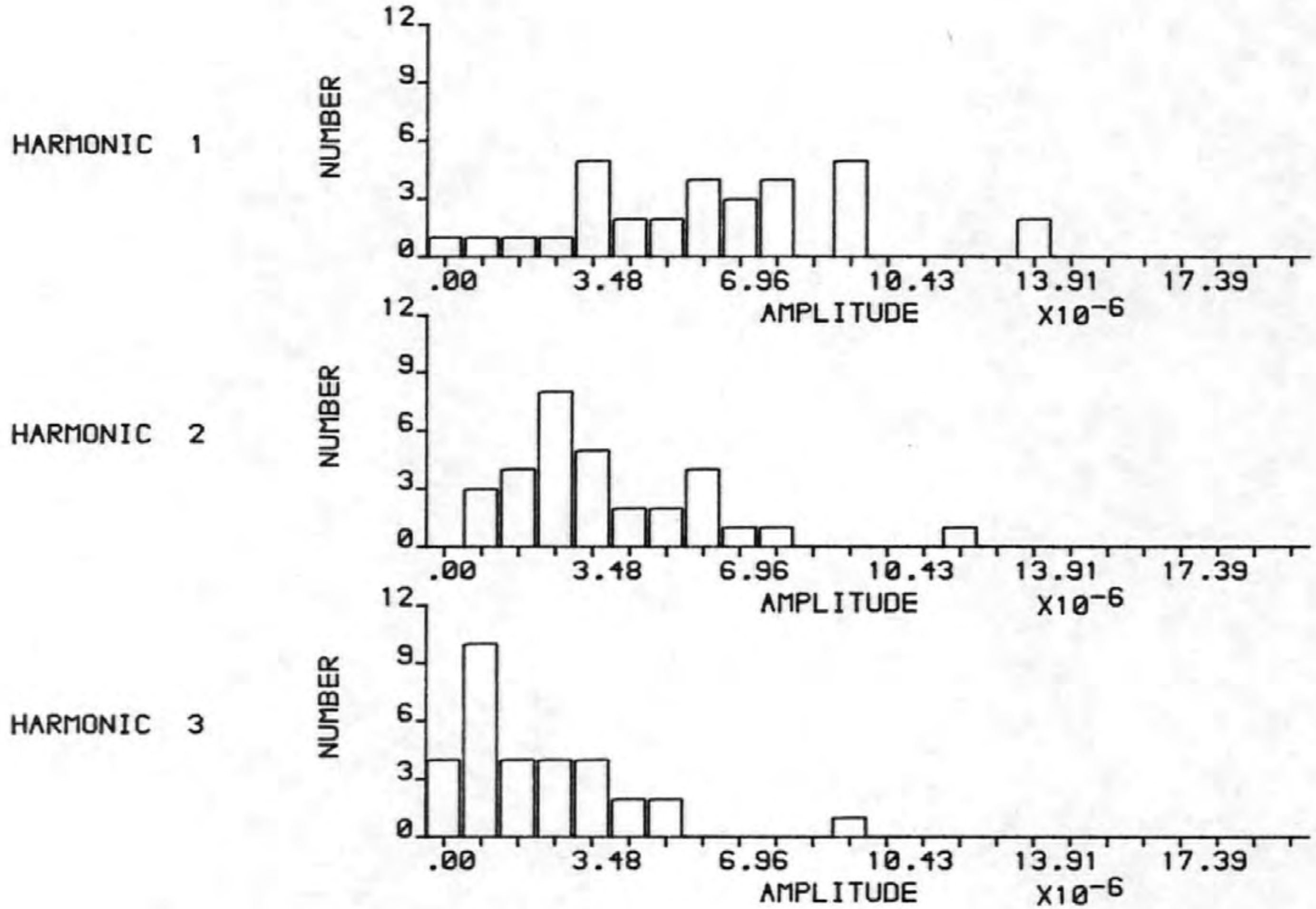


Figure 5-6 Typical amplitude histograms of a one second ISI CNV, Harmonics 1 to 3.

the spectra of the background EEG was made with the spectrum of the averaged CNV. The latter spectrum would be relatively free of background EEG due to the averaging process.

The spectrum of the averaged CNV's displayed the presence of signal power at frequencies of up to 12 Hz. Over this frequency range the signal levels were about 0.5 - 6.5 $\mu V\ Hz.^{-\frac{1}{2}}$ By comparison the background EEG contained signal levels of 1.5 - 13.8 $\mu V\ Hz.^{-\frac{1}{2}}$ over the same range. Thus the frequency components of the background EEG were indeed compatible to or greater in amplitude than those of the CNV, and were therefore capable of masking it.

5.3.2.3 Pre- and Post- Stimulus Mean Amplitude Differences Test

These tests were performed on the mean of the amplitude differences of the pre- and post- stimulus phasors as described in section 2.2.3.2. Because of the limited amount of pre-stimulus information available these tests were not carried out on the four second ISI CNV's. The results of the tests are shown in Table 5-6. The column giving the significance level of any detected difference shows that additivity was only detected in 11 of the 30 results. Furthermore, only 2 of these 11 were significant at the 5% or higher level. Surprisingly however, 13 of the 30 results showed decreased amplitudes in the post-stimulus case (denoted by asterisks in the table) although only 2 of these results were statistically significant at the 5% level.

Table 5-6

Pre- and Post-stimulus Mean Amplitude Differences Tests

For Normal Subjects

Subject Number	Mean of Differences $\times 10^{-5}$	Stand.Dev. of Differences $\times 10^{-5}$	Harmonic Number	T	ν	Significance %
1	0.1586	0.4696	1	1.88	30	10
	0.0144	0.3228	2	0.248	30	N-S
	-0.0381	0.2387	3	-0.888*	30	N-S
	0.0709	0.2889	4	1.37	30	20
	0.0974	0.4162	5	1.30	30	N-S
	-0.1399	0.2229	6	-3.49*	30	0.2
2	0.1561	0.4827	1	1.83	31	10
	0.0651	0.2817	2	1.31	31	20
	0.0449	0.1978	3	1.28	31	N-S
	0.0110	0.1883	4	0.33	31	N-S
	-0.0079	0.1341	5	-0.33*	31	N-S
	-0.0261	0.1218	6	-1.21*	31	N-S
3	-0.0974	0.4229	1	-1.00*	18	N-S
	0.0362	0.4806	2	0.33	18	N-S
	0.0884	0.2425	3	1.59	18	20
	-0.0780	0.2308	4	-1.47*	18	20
	-0.0451	0.1543	5	-1.27*	18	N-S
	0.0292	0.1971	6	0.65	18	N-S
4	0.0880	0.3578	1	1.39	31	20
	0.0797	0.2526	2	1.79	31	10
	0.0435	0.1776	3	1.39	31	20
	-0.0532	0.1367	4	-2.20*	31	5
	-0.0355	0.2242	5	-0.896*	31	N-S
	-0.0412	0.1477	6	-1.58*	31	20
5	0.2115	0.8769	1	1.36	31	20
	0.2965	0.6157	2	2.72	31	2
	0.2428	0.4536	3	3.03	31	1
	-0.1074	0.3109	4	-1.95*	31	10
	-0.0951	0.3153	5	-1.71*	31	10
	-0.0671	0.2202	6	-1.72*	31	10

* denotes that the post-stimulus amplitudes were smaller than the pre-stimulus amplitudes.

5.3.2.4 Nearest and Furthest Mean Amplitude Test

These tests were performed on the amplitudes of post-stimulus phasors for the one and four second ISI CNV's described in section 2.2.3.3. The results are shown in Tables 5-7a and 5-7b for the one and four second ISI's respectively. For the one second ISI the significance column shows that additivity was detected in 7 cases out of 30, but of these only 4 were significant at the 5% level. In one case (i.e. subject 4, harmonic 3), the furthest phasors had larger amplitudes than the nearest. For the four second ISI CNV's additivity was detected in 4 cases and of these only 2 were significant at the 5% level. The furthest phasors had larger amplitudes than the nearest in 2 cases.

Table 5-7a

Nearest and Furthest Mean Amplitude Test

For 1 second ISI CNV's of Normal Subjects

Subject Number	Nearest		Furthest		Harmonic	T	ν	Significance %
	Mean $x10^{-5}$	St.Dev. $x10^{-5}$	Mean $x10^{-5}$	St.Dev. $x10^{-5}$				
1	1.04	0.353	0.761	0.523	1	1.76	28	5
	0.650	0.361	0.514	0.269	2	1.19	28	N-S
	0.380	0.251	0.382	0.328	3	-0.017	30	N-S
	0.485	0.311	0.560	0.380	4	-0.609	31	N-S
	0.807	0.431	0.831	0.535	5	-0.137	30	N-S
	0.418	0.168	0.354	0.234	6	0.882	29	N-S
2	1.24	0.457	0.769	0.363	1	3.23	30	0.5
	0.643	0.368	0.456	0.301	2	1.58	31	10
	0.439	0.237	0.415	0.192	3	0.322	31	N-S
	0.308	0.202	0.309	0.217	4	-0.017	32	N-S
	0.293	0.134	0.211	0.114	5	1.86	31	5
	0.276	0.107	0.216	0.107	6	1.58	32	10
3	0.805	0.434	0.781	0.337	1	0.131	17	N-S
	0.660	0.288	0.675	0.426	2	-0.09	18	N-S
	0.575	0.258	0.554	0.318	3	0.165	19	N-S
	0.362	0.200	0.241	0.149	4	1.48	16	10
	0.274	0.156	0.303	0.162	5	-0.396	19	N-S
	0.329	0.219	0.253	0.257	6	0.690	19	N-S
4	0.813	0.388	0.641	0.383	1	1.26	32	N-S
	0.525	0.337	0.419	0.254	2	1.00	30	N-S
	0.332	0.168	0.432	0.171	3	-1.65*	32	10
	0.243	0.162	0.259	0.101	4	-0.337	27	N-S
	0.298	0.110	0.359	0.258	5	-0.868	21	N-S
	0.202	0.142	0.239	0.125	6	-0.777	32	N-S
5	2.16	0.813	1.52	0.800	1	2.24	32	2.5
	1.17	0.463	1.47	0.817	2	-1.26	25	N-S
	0.985	0.541	0.973	0.607	3	0.061	32	N-S
	0.603	0.247	0.506	0.274	4	1.05	32	N-S
	0.548	0.276	0.456	0.305	5	0.895	32	N-S
	0.340	0.216	0.335	0.164	6	0.08	30	N-S

Table 5-7b

Nearest and Furthest Mean Amplitude Test

For 4 second ISI CNV's of Normal Subjects

Subject	Nearest		Furthest		Harmonic	T	ν	Significance %
	Mean $\times 10^{-5}$	St.Dev. $\times 10^{-5}$	Mean $\times 10^{-5}$	St.Dev. $\times 10^{-5}$				
1	0.740	0.304	0.491	0.267	1	2.47	32	1
	0.370	0.219	0.448	0.243	2	-0.958	32	N-S
	0.451	0.246	0.324	0.120	3	1.85	23	5
	0.357	0.125	0.308	0.163	4	0.954	30	N-S
	0.430	0.176	0.460	0.221	5	-0.429	30	N-S
	0.342	0.252	0.432	0.190	6	-1.03	30	N-S
2	1.119	0.554	0.912	1.13	1	0.663	23	N-S
	0.943	1.05	0.744	0.349	2	0.721	19	N-S
	0.347	0.230	0.624	0.583	3	-1.77*	20	5
	0.721	0.744	0.462	0.260	4	1.32	19	N-S
	0.531	0.514	0.327	0.152	5	1.52	18	10
	0.383	0.221	0.354	0.213	6	0.369	32	N-S
3	0.806	0.382	0.879	0.373	1	-0.547	32	N-S
	0.715	0.324	0.741	0.372	2	-0.214	31	N-S
	0.510	0.323	0.606	0.280	3	-0.903	31	N-S
	0.475	0.237	0.401	0.176	4	1.00	29	N-S
	0.437	0.177	0.341	0.152	5	1.65	31	10
	0.370	0.152	0.333	0.171	6	0.648	32	N-S
4	0.554	0.226	0.503	0.259	1	0.615	31	N-S
	0.428	0.235	0.449	0.268	2	-0.227	31	N-S
	0.419	0.177	0.378	0.141	3	0.738	30	N-S
	0.330	0.176	0.279	0.160	4	0.845	32	N-S
	0.331	0.192	0.435	0.219	5	-1.43*	31	10
	0.312	0.184	0.320	0.124	6	-0.147	28	N-S
5	1.06	0.951	1.09	0.806	1	-0.114	31	N-S
	0.864	0.499	0.930	0.488	2	-0.382	32	N-S
	0.789	0.444	0.684	0.479	3	0.642	32	N-S
	0.887	0.353	0.866	0.645	4	0.110	24	N-S
	0.728	0.418	0.663	0.330	5	0.485	30	N-S
	0.577	0.377	0.602	0.452	6	-0.166	31	N-S

* denotes that the furthest phasors were larger than the nearest phasors.

5.3.2.5. Discussion of Results of Energy Tests

The results of the Pre- and Post- Stimulus Mean Amplitude Differences tests and of the Nearest and Furthest Mean Amplitude tests, which indicated additivity for only a minority of the harmonic components, were in contrast to those of the pre-stimulus and CNV broadband energy tests which offered strong evidence of additivity. The differences may be attributed to either the effects of the background EEG or to the suitability of the tests. For example, the Nearest and Furthest Mean Amplitude test could be prone to error and while positive results supported the additivity model, negative ones did not necessarily disprove it. It was assumed that for each trial the noise and signal amplitudes were the same and that the response was the same in both amplitude and phase. These assumptions may not have been sufficiently true and if, for example, the response had a random phase there would be no detectable preferred direction even though added energy was present. Also in the additive model a phasor could have been reversed from a large phasor in one direction to a small phasor in the preferred direction. This would have been contrary to the general assumption that phasors would be larger in the preferred direction. Thus the test was not infallible and there may have been added energy in some of the other cases. The Pre- and Post-Stimulus Mean Amplitude Differences test could have been affected by variations in the background EEG and thus made unreliable. Alternatively the extra energy detected by the broadband tests could have been at frequencies other than those examined.

5.3.3 Tests for Phase Ordering

The following tests were performed to establish whether any phase ordering could be detected in the CNV response.

5.3.3.1 Phase Histograms

It was found that the phase histograms of the first harmonic of the CNV's were visually similar for all subjects and for both one second and four second ISI's as predicted in Section 2.2.1 and Appendix 8.1. Typical phase histograms for both ISI's are shown in Figures 5-7a and 5-7b. The patterns observed in these histograms are evidence for phase ordering. Similar histograms, for the higher harmonic frequency components, did not exhibit any noticeable phase patterns or ordering. Because of the limited number of observations made and the relatively large number of phase intervals necessary to observe patterns and ordering, the phase histograms were not considered to be very reliable indicators of these effects. Furthermore, since it was necessary to judge visually the presence (or absence) of phase patterns only limited credence could be given to these histograms.

5.3.3.2 Rayleigh Test of Circular Variance

The results of this test are given in tables 5-8a and 5-8b for the one second and four second ISI CNV's respectively. For the one second ISI the test gave a significant result in 10 out of the 30 cases studied while of these only 6 were significant at the 5% level. In the case of the

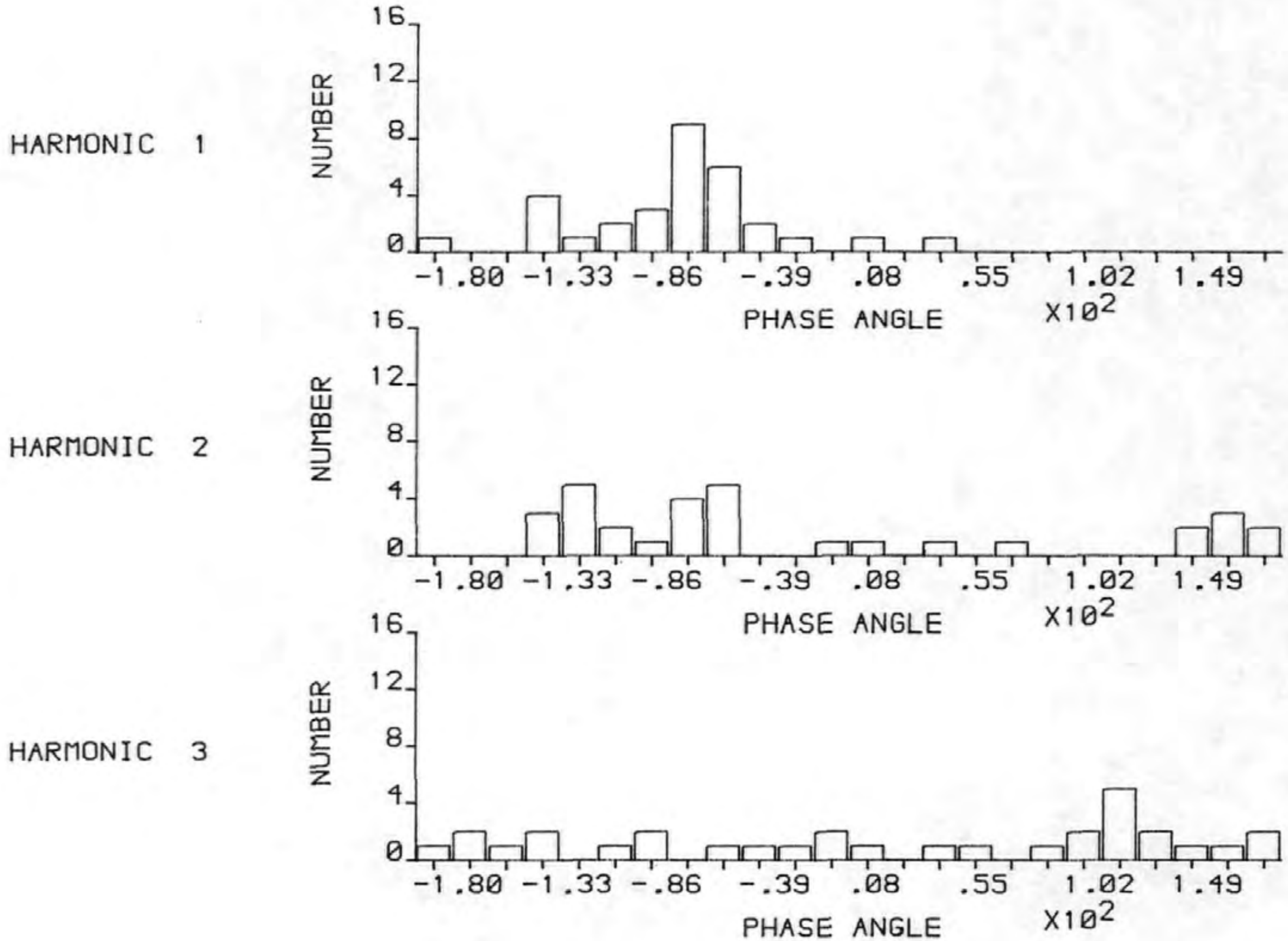


Figure 5-7a A typical one second ISI phase histogram of a normal subject

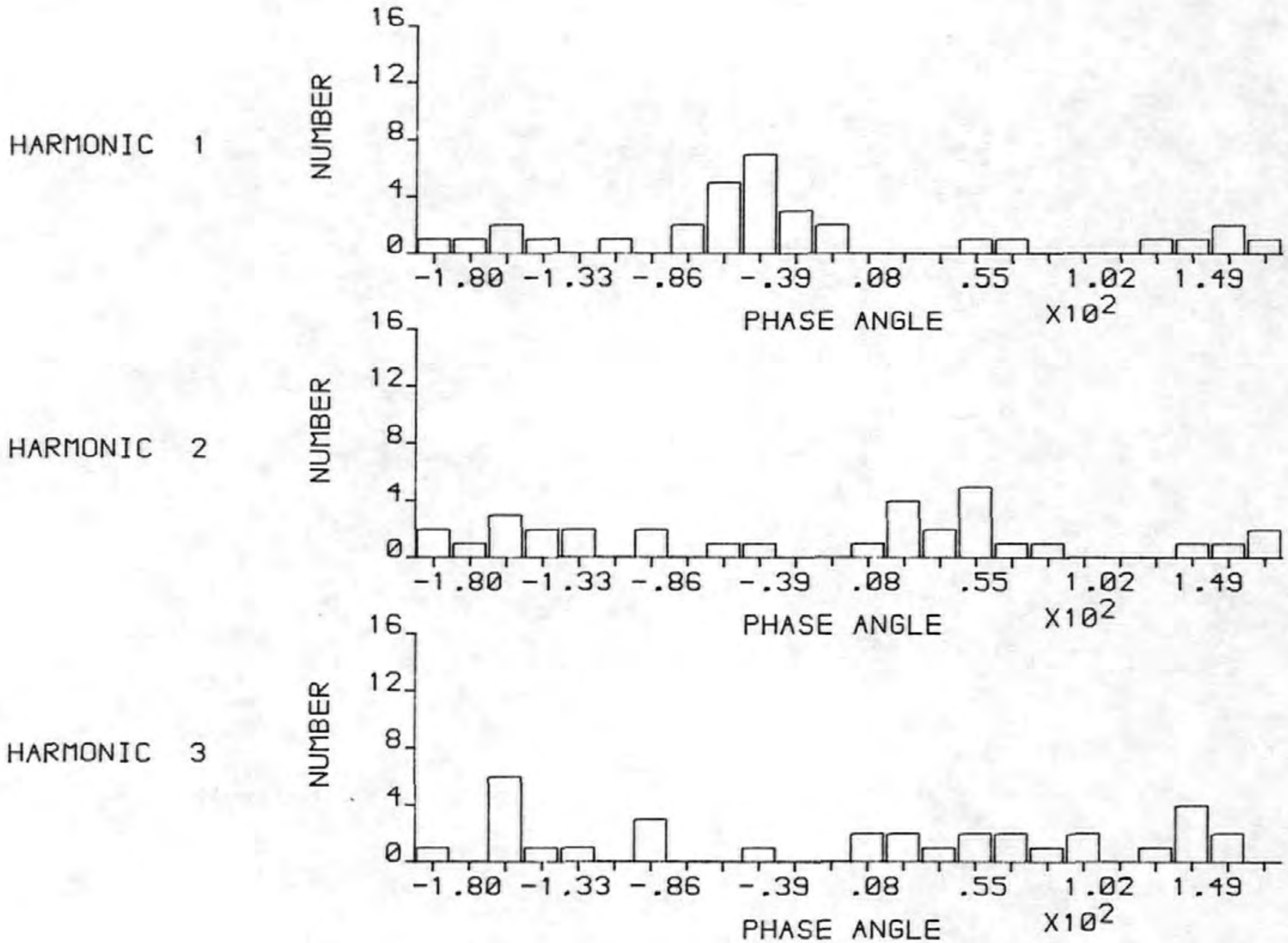


Figure 5-7b A typical four second ISI phase histogram of a normal subject

Table 5-8a

Circular Variance for 1 second ISI CNV's of Normal Subjects

Subject	Harmonic	Number of Trials	So	Significance %
1	1	31	0.202	0.1
	2	31	0.554	1.0
	3	31	0.787	N-S
	4	31	0.916	N-S
	5	31	0.713	10.0
	6	31	0.806	N-S
2	1	32	0.683	5.0
	2	32	0.893	N-S
	3	32	0.940	N-S
	4	32	0.804	N-S
	5	32	0.848	N-S
	6	32	0.796	N-S
3	1	19	0.642	10
	2	19	0.699	N-S
	3	19	0.781	N-S
	4	19	0.425	1.0
	5	19	0.694	N-S
	6	19	0.855	N-S
4	1	32	0.747	N-S
	2	32	0.695	10.0
	3	32	0.841	N-S
	4	32	0.700	10.0
	5	32	0.902	N-S
	6	32	0.780	N-S
5	1	32	0.354	0.1
	2	32	0.990	N-S
	3	32	0.661	5.0
	4	32	0.792	N-S
	5	32	0.877	N-S
	6	32	0.771	N-S

Table 5-8b

Circular Variance for 4 second ISI CNV's of Normal Subjects

Subject	Harmonic	Number of Trials	So	Significance %
1	1	32	0.599	1.0
	2	32	0.973	N-S
	3	32	0.807	N-S
	4	32	0.935	N-S
	5	32	0.926	N-S
	6	32	0.945	N-S
2	1	32	0.867	N-S
	2	32	0.882	N-S
	3	32	0.779	N-S
	4	32	0.699	10.0
	5	32	0.799	N-S
	6	32	0.916	N-S
3	1	32	0.822	N-S
	2	32	0.877	N-S
	3	32	0.993	N-S
	4	32	0.897	N-S
	5	32	0.914	N-S
	6	32	0.896	N-S
4	1	32	0.957	N-S
	2	32	0.724	N-S
	3	32	0.856	N-S
	4	32	0.790	N-S
	5	32	0.861	N-S
	6	32	0.883	N-S
5	1	32	0.808	N-S
	2	32	0.793	N-S
	3	32	0.835	N-S
	4	32	0.896	N-S
	5	32	0.949	N-S
	6	32	0.811	N-S

four second ISI CNV's only 2 out of the 30 cases were significant and of them only 1 was significant at the 5% level. Thus phase ordering appeared to be less pronounced in the case of the four second ISI CNV's. This difference reflected the more complex composition of the longer ISI CNV's.

5.3.3.3 Modified Rayleigh Test of Circular Variance

The results of these tests are shown in tables 5-9a and 5-9b for the two ISI's used. For the one second ISI phase ordering was significant in 10 out of the 30 cases, being significant at the 5% level in 7 cases. For the four second ISI the figures were 4 and 3 respectively. Thus the phase again appeared to be less pronounced in the four second ISI CNV's.

5.3.3.4 Hodges-Ajne Test

Tables 5-10a and 5-10b show the results of these tests for the one and four second ISI CNV's respectively. The one second ISI CNV's exhibited ordering in 5 cases out of 30 and of these 4 were significant at the 5% level. There were only 2 cases of ordering in the results for the four second ISI CNV's and only 1 was significant at the 5% level.

Table 5-9a

The Modified Circular Variance Tests for the 1 second ISI CNV's of Normal Subjects

Subject	Harmonic	Number of Trials	Uo	Significance %
1	1	31	0.166	0.1
	2	31	0.453	0.1
	3	31	0.739	N-S
	4	31	0.961	N-S
	5	31	0.721	N-S
	6	31	0.672	10.0
2	1	32	0.530	1.0
	2	32	0.795	N-S
	3	32	0.807	N-S
	4	32	0.802	N-S
	5	32	0.727	N-S
	6	32	0.715	N-S
3	1	19	0.526	5.0
	2	19	0.806	N-S
	3	19	0.828	N-S
	4	19	0.307	0.1
	5	19	0.726	N-S
	6	19	0.818	N-S
4	1	32	0.672	10.0
	2	32	0.607	5.0
	3	32	0.915	N-S
	4	32	0.743	N-S
	5	32	0.863	N-S
	6	32	0.731	N-S
5	1	32	0.216	0.1
	2	32	0.949	N-S
	3	32	0.678	10.0
	4	32	0.777	N-S
	5	32	0.892	N-S
	6	32	0.772	N-S

Table 5-9b

The Modified Circular Variance Tests for the 4 second ISI CNV's of Normal Subjects

Subject	Harmonic	Number of Trials	Uo	Significance %
1	1	32	0.506	1.0
	2	32	0.929	N-S
	3	32	0.717	N-S
	4	32	0.848	N-S
	5	32	0.873	N-S
	6	32	0.832	N-S
2	1	32	0.743	N-S
	2	32	0.970	N-S
	3	32	0.857	N-S
	4	32	0.651	5.0
	5	32	0.623	5.0
	6	32	0.848	N-S
3	1	32	0.959	N-S
	2	32	0.912	N-S
	3	32	0.953	N-S
	4	32	0.788	N-S
	5	32	0.827	N-S
	6	32	0.790	N-S
4	1	32	0.947	N-S
	2	32	0.679	10.0
	3	32	0.845	N-S
	4	32	0.777	N-S
	5	32	0.966	N-S
	6	32	0.921	N-S
5	1	32	0.816	N-S
	2	32	0.770	N-S
	3	32	0.746	N-S
	4	32	0.796	N-S
	5	32	0.962	N-S
	6	32	0.758	N-S

Table 5-10a

The Hodges-Ajne test for the 1 second ISI CNV's of normals

Subject	Harmonic	Number of Trials	M	Significance %
1	1	31	2	0.001
	2	31	4	0.067
	3	31	10	N-S
	4	31	13	N-S
	5	31	9	N-S
	6	31	11	N-S
2	1	32	10	N-S
	2	32	12	N-S
	3	32	14	N-S
	4	32	10	N-S
	5	32	12	N-S
	6	32	11	N-S
3	1	19	4	16.0
	2	19	5	N-S
	3	19	5	N-S
	4	19	2	0.9
	5	19	6	N-S
	6	19	6	N-S
4	1	32	10	N-S
	2	32	9	N-S
	3	32	12	N-S
	4	32	9	N-S
	5	32	12	N-S
	6	32	12	N-S
5	1	32	3	0.006
	2	32	13	N-S
	3	32	9	N-S
	4	32	10	N-S
	5	32	12	N-S
	6	32	10	N-S

Table 5-10b

The Hodges-Ajne test for the 4 second ISI CNV's of normals

Subject	Harmonic	Number of Trials	M	Significance %
1	1	32	6	0.8
	2	32	13	N-S
	3	32	10	N-S
	4	32	12	N-S
	5	32	13	N-S
	6	32	14	N-S
2	1	32	12	N-S
	2	32	12	N-S
	3	32	11	N-S
	4	32	8	7·8
	5	32	11	N-S
	6	32	13	N-S
3	1	32	11	N-S
	2	32	12	N-S
	3	32	14	N-S
	4	32	12	N-S
	5	32	13	N-S
	6	32	13	N-S
4	1	32	13	N-S
	2	32	10	N-S
	3	32	11	N-S
	4	32	12	N-S
	5	32	12	N-S
	6	32	12	N-S
5	1	32	11	N-S
	2	32	10	N-S
	3	32	11	N-S
	4	32	12	N-S
	5	32	13	N-S
	6	32	12	N-S

5.3.4. Discussion of Energy and Phase Results

Table 5-11 summarises the additivity and phase ordering results which were found to be significant at the 5% level.

That part of the table concerned with phase ordering was inspected in order to compare the results of the different tests. Asterisks were used to indicate similar results which were given by either two or three of the tests. Scanning of the rows showed that the results of the phase ordering tests were mainly consistent and therefore probably reliable. The Modified Rayleigh test tended to produce more results which were significant than either of the other two tests and this was because it took into account both amplitude and phase information. For the one second ISI CNV's phase ordering was detected in 8 cases out of 30 at the 5% level. For the four second ISI CNV's only 3 of the 30 were significant at the 5% level.

It was stated above (Section 5.3.3.1) that the phase histograms of the first harmonic for both the one and four second ISI CNV's had similar patterns which were evidence of phase ordering, but that the effect was less obvious for the higher harmonics. Inspection of the results of the statistical tests for phase ordering partly confirms those findings. Table 5-12 shows the mean directions of the phasors and the levels of significance for some of the results. It can be seen that for the one second ISI CNV's the mean direction of the phasors falls in the theoretically predicted

Table 5-11

Summary of Additivity and Phase Ordering Results Significant

at the 5% level for Normal Subjects

		ADDITIVITY		PHASE ORDERING		
ISI	SUBJECT NUMBER	NEAREST & FURTHEST MEAN AMPLITUDE	PRE & POST MEAN AMPLITUDE DIFFERENCES	RAYLEIGH CIRCULAR VARIANCE	MODIFIED RAYLEIGH CIRCULAR VARIANCE	HODGES-AJNE
1	1	H1		H1*, H2*	H1*, H2*	H1*, H2*
	2	H1, H5+		H1*	H1*	
	3			H4*	H1, H4*	H4*
	4				H2	
	5	H1	H2+, H3	H1*, H3	H1*	H1*
4	1	H1, H3+		H1*	H1*	H1*
	2				H4 ,H5	

Hn indicates that the nth harmonic had a significant result.

\+ indicates additivity with no accompanying ordering.

* indicates agreement between two or more tests.

Table 5-12

Mean Directions and Significance for Selected Cases

ISI	HARMONIC NUMBER	SUBJECT NUMBER	NUMBER OF RESPONSES	MEAN DIRECTION	SIGNIFICANCE OF PHASE ORDERING†
1	1	1	31	-70	S
		2	32	-75	S
		3	19	106	S
		4	32	-82	N-S
		5	32	-81	S
	2	1	31	-102	S
		2	32	114	N-S
		3	19	116	N-S
		4	32	-76	S
		5	32	51	N-S
	3	1	31	140	N-S
		2	32	-24	N-S
		3	19	-125	N-S
		4	32	-36	N-S
		5	32	57	S
4	1	1	32	-57	S
		2	32	108	N-S
		3	32	138	N-S
		4	32	-129	N-S
		5	32	-159	N-S
	2	1	32	-5	N-S
		2	32	-125	N-S
		3	32	7	N-S
		4	32	10	N-S
		5	32	131	N-S
	3	1	32	155	N-S
		2	32	104	N-S
		3	32	95	N-S
		4	32	-150	N-S
		5	32	36	N-S

† S indicates phase ordering detected by any of the three tests significant at the 5% level.

N-S indicates no significant phase ordering.

range of 0^{o} to -90^{o} in 4 out of 5 cases and for 3 of these there was also significant phase ordering. Hence a distinctive pattern would indeed be anticipated in the phase histogram. The mean direction is less likely to be in the predicted range and the degree of ordering is also seen to be decreased as the harmonic number increases. This is in agreement with the reduced observable phase ordering in the phase histograms of the higher harmonics. The results for the four second ISI CNV's showed little phase ordering and many of the angles were outside the predicted range. This did not agree with the conclusion reached by visual inspection of the phase histograms. This discrepancy was probably due to the unreliability of the phase histograms for the reasons previously mentioned.

Table 5-11 was also inspected to check whether additivity was always accompanied by phase ordering as the additivity model would suggest. It was noted that in three cases additivity was detected in the absence of detectable phase ordering. This may have been due to the limitations of the tests or it may indicate that the CNV response cannot be described by the additivity model.

Overall it appears that the CNV responses of normal subjects may contain a certain amount of added random energy and are therefore probably less deterministic in nature then, for example, an auditory evoked response.

5.4 The CNV's of Abnormal Subjects

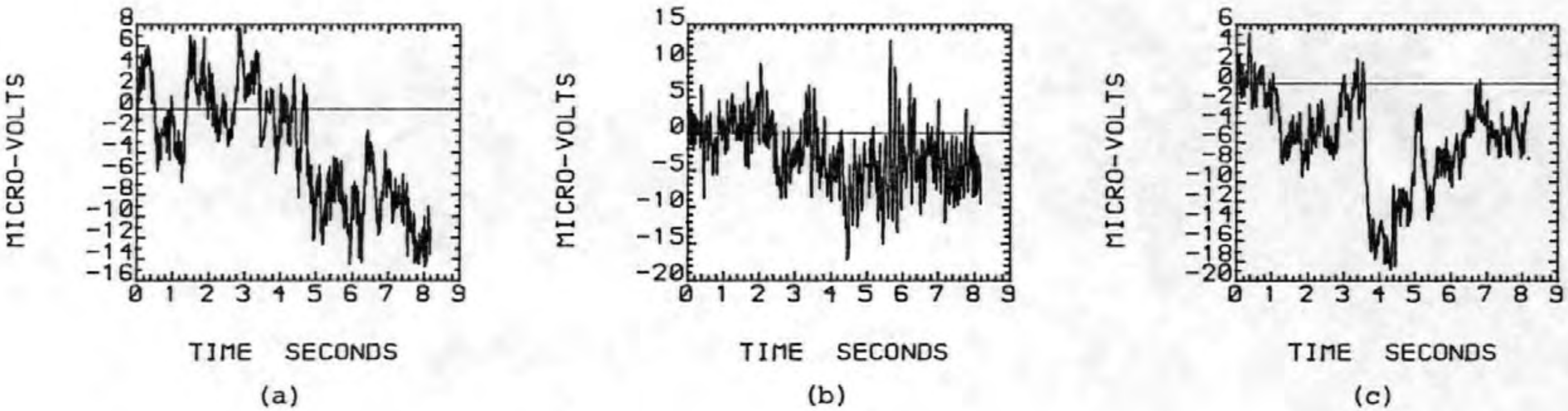
CNV responses were also recorded from a total of five patients for whom Huntington's chorea had been diagnosed. Once again two interstimulus intervals were used (one and four seconds) and prior to further processing the individual responses were corrected for the effects of eye movement as described in Section 2.5

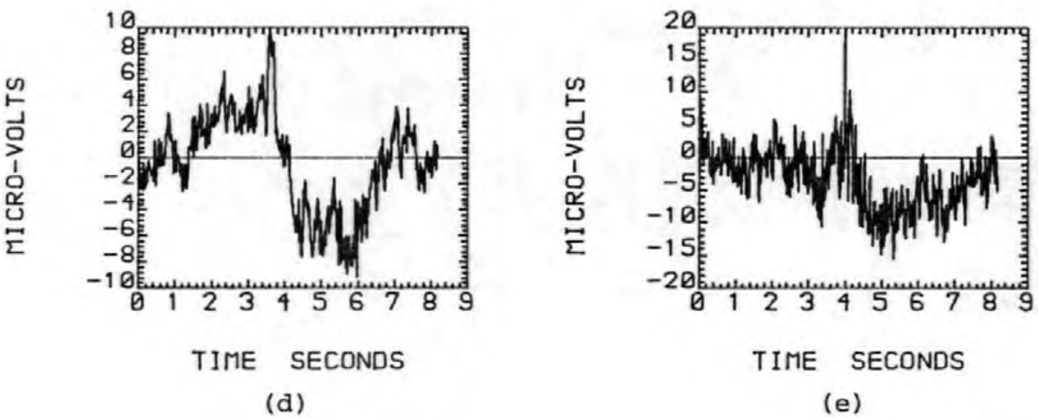
5.4.1 The Averaged CNV's

After processing to remove eye movement artefact the CNV's were averaged, filtered with the low pass digital filter described in Section 3.6 and plotted. The results of this procedure are shown in Figures 5-8 a-e and 5-9 a-e. A characteristic feature of some of these CNV's was the slow return to the baseline subsequent to the S2 stimulus. This feature, known as the Post Imperative Negative Variation, has been described elsewhere [9] although not in connection with Huntington's chorea. Some of the averaged CNV's were generally similar to those obtained from normal subjects (e.g. Figure 5-8c) whilst others (e.g. Figure 5-8b) showed very little evidence of a CNV response at all. The differences in the averaged waveforms of normals and patients were exploited in distinguishing between the two categories as described in Section 5.5

5.4.2. Energy Tests

These tests were performed to establish whether any additive component could be detected in the CNV response of the H.C. patient group.





<u>Figure 5-8</u>

<u>The averaged one second ISI CNV's</u>

<u>of abnormal subjects.</u>

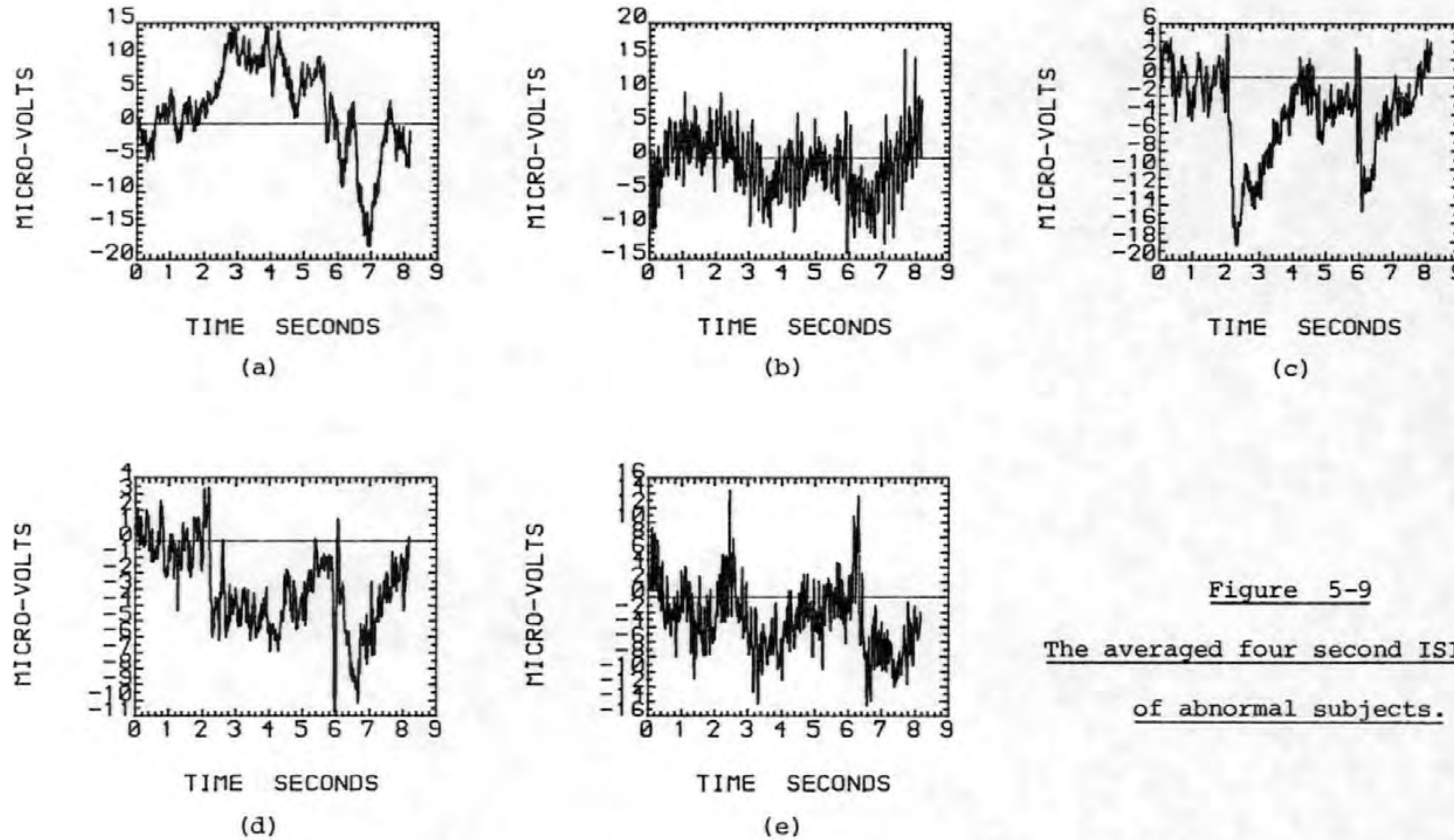


Figure 5-9

The averaged four second ISI CNV's of abnormal subjects.

5.4.2.1 Broadband Energy Tests

The same processing procedure was used in these tests as that described in Section 5.3.2.1. The results of the tests are shown in Tables 5-13a and 5-13b. In the case of the one second ISI CNV's there was evidence of added energy at the 5% level of significance in 3 cases out of the 5 subjects investigated. There was considerably more added energy in the case of subject 5. For the four second ISI CNV's 4 of the subjects showed evidence of added energy at the 5% significance level. Thus for both ISI's the majority of the subjects showed increased energy in the post stimulus realizations. However, as indicated by the right most column in Tables 5-13a and 5-13b, there were a number of individual responses where the pre-stimulus energy was greater than the post-stimulus energy.

5.4.2.2 Amplitude Histograms

Some amplitude histograms were produced as it was thought that they might have shown some differences to those of normal subjects. However, they did not exhibit any characteristic feature which could be of diagnostic value.

5.4.2.3 Pre- and Post-stimulus Mean Amplitude Differences Test

The results of this test on the one second ISI CNV's are shown in Table 5-14. All but one of the results showed evidence of added energy in at least one harmonic at the 5% level. It was not possible to discover any pattern in the occurrence of significant results. Once more it was noted

Table 5-13a

Broadband Energy Tests of Abnormal Subjects one second ISI CNV's

Subject	Number of Responses	T Statistic	Significance Level %	Number of Responses Post < Pre *
1	32	1.89	10	10
2	32	1.81	10	10
3	32	3.75	0.1	8
4	32	3.47	0.2	7
5	32	4.82	<<0.1	4

Table 5-13b

Broadband Energy Tests of Abnormal Subjects four second ISI CNV's

Subject	Number of Responses	T Statistic	Significance Level %	Number of Responses Post < Pre *
1	30	3.73	0.1	4
2	32	2.56	2.0	9
3	32	1.64	20	7
4	32	5.16	<<0.1	6
5	32	3.16	1.0	8

* The number of individual responses where the post-stimulus energy was LESS than the pre-stimulus energy.

Table 5-14

Pre- and Post-Stimulus Mean Amplitude Differences Test

for Abnormal Subjects

1 second ISI

Subject Number	Mean of Differences $\times 10^{-5}$	St.Dev. of Differences $\times 10^{-5}$	Harmonic Number	T	ν	Significance %
1	0.178	1.02	1	0.990	31	N-S
	0.179	0.403	2	2.52	31	2.0
	-0.003	0.318	3	-0.059*	31	N-S
	-0.053	0.260	4	-1.15 *	31	N-S
	0.019	0.252	5	0.434	31	N-S
	0.069	0.209	6	1.86	31	10
2	0.189	0.576	1	1.94	31	10
	0.065	0.509	2	0.727	31	N-S
	-0.064	0.646	3	-0.557*	31	N-S
	0.379	0.887	4	2.42	31	5.0
	-0.168	0.724	5	-1.31 *	31	20
	-0.010	0.504	6	-0.118*	31	N-S
3	-0.067	0.666	1	-0.568*	31	N-S
	0.029	0.555	2	0.297	31	N-S
	-0.139	0.356	3	-2.21 *	31	5
	0.035	0.336	4	0.585	31	N-S
	-0.089	0.337	5	-1.49 *	31	20
	-0.070	0.252	6	-1.58 *	31	20
4	-0.016	0.502	1	-0.184*	31	N-S
	0.147	0.242	2	3.44	31	0.2
	0.05	0.136	3	2.08	31	5
	-0.017	0.113	4	-0.85 *	31	N-S
	-0.051	0.117	5	-2.46 *	31	2
	-0.021	0.159	6	-0.747*	31	N-S
5	0.202	0.622	1	1.84	31	10
	0.213	0.572	2	2.11	31	5
	0.409	0.664	3	3.49	31	0.2
	0.901	0.731	4	6.98	31	<<0.1
	0.507	0.677	5	4.23	31	<<0.1
	0.246	0.580	6	2.40	31	5

* denotes a reduction in the post stimulus amplitude

that subject 5 showed enhanced evidence of additivity in each of the harmonics. Those cases in which the energy showed a decrease were marked by an asterisk in the table.

5.4.2.4 Nearest and Furthest Mean Amplitude Test

The results of these tests are shown in Tables 5-15a and 5-15b. The single tailed paired t-test produced only one result which was significant for the one second ISI CNV's and this was evidence that the nearest phasors were smaller than the furthest. Thus this test provided no evidence for increased energy. In the case of the four second ISI CNV's there were 5 significant cases and 4 of these were significant at the 5% level.

5.4.2.5 Discussion of Results of Energy Tests

Comparison of the results in Tables 5-13a, 5-14 and 5-15a for the one second ISI CNV's did not reveal any noticeable correlations. However, it was noted that the Pre- and Post-Stimulus Mean Amplitude Differences tests offered more evidence of additivity than the Nearest and Furthest Mean Amplitude test. The results obtained from it were therefore more in agreement with the detection of added energy by the Broadband Energy test. However, there were discrepancies between these tests although they were based on exactly the same pre- and post- stimulus data. For example according to Table 5-14 there was no evidence of additivity for subject 3 but according to the Broadband Energy test additivity was detected at a level of significance of 0.1%. It was thought that this discrepancy may have occurred because the added energy of the response was located in higher harmonics than those considered.

Table 5-15a

Nearest and Furthest Mean Amplitude Test for Abnormal Subjects

1 second ISI

	Nearest		Furthest					
Subject Number	Mean $x10^{-5}$	St.Dev. $x\ 10^{-5}$	Mean $x10^{-5}$	St.Dev. $x\ 10^{-5}$	Harmonic	T	ν	Significance %
1	1.24	0.657	1.07	0.977	1	0.599	28	N-S
	0.564	0.496	0.550	0.290	2	0.100	25	N-S
	0.312	0.192	0.267	0.213	3	0.631	32	N-S
	0.191	0.090	0.265	0.133	4	-1.84	28	* 5
	0.204	0.149	0.229	0.231	5	-0.367	27	N-S
	0.233	0.232	0.226	0.094	6	0.110	21	N-S
2	0.874	0.386	0.802	0.398	1	0.519	32	N-S
	0.596	0.540	0.569	0.395	2	0.166	29	N-S
	0.483	0.309	0.581	0.497	3	-0.673	26	N-S
	1.02	0.857	0.869	0.799	4	0.504	32	N-S
	0.423	0.368	0.482	0.473	5	-0.399	30	N-S
	0.439	0.454	0.326	0.219	6	0.894	23	N-S
3	0.667	0.236	0.681	0.393	1	-0.116	26	N-S
	0.476	0.196	0.437	0.270	2	0.466	29	N-S
	0.220	0.137	0.220	0.118	3	0.014	31	N-S
	0.354	0.282	0.309	0.159	4	0.553	25	N-S
	0.307	0.163	0.269	0.134	5	0.713	31	N-S
	0.176	0.126	0.242	0.191	6	-1.15	28	N-S
4	0.498	0.352	0.498	0.319	1	0.00	32	N-S
	0.430	0.200	0.364	0.214	2	0.899	32	N-S
	0.251	0.159	0.224	0.137	3	0.511	31	N-S
	0.129	0.088	0.166	0.088	4	-1.16	32	N-S
	0.133	0.078	0.154	0.062	5	-0.821	30	N-S
	0.143	0.079	0.173	0.099	6	-0.947	31	N-S
5	0.972	0.534	0.908	0.486	1	0.352	32	N-S
	0.803	0.555	0.695	0.415	2	0.620	30	N-S
	0.980	0.682	0.776	0.500	3	0.966	29	N-S
	1.55	0.730	1.25	0.650	4	1.20	32	N-S
	1.00	0.601	1.10	0.628	5	-0.453	32	N-S
	0.625	0.324	0.725	0.746	6	-0.493	21	N-S

* denotes that the furthest phasors were larger than the nearest phasors.

Table 5-15b

Nearest and Furthest Mean Amplitude Test for Abnormal Subjects

4 second ISI

	Nearest		Furthest					
Subject Number	Mean $\times 10^{-5}$	St.Dev. $\times 10^{-5}$	Mean $\times 10^{-5}$	St.Dev. $\times 10^{-5}$	Harmonic	T	ν	Significance %
1	1.59	0.774	1.00	0.451	1	2.52	24	1
	1.17	0.736	1.49	0.584	2	-1.33	28	* 10
	1.18	0.504	1.07	0.471	3	0.613	30	N-S
	0.857	0.600	0.952	0.508	4	-0.467	29	N-S
	0.814	0.392	0.919	0.382	5	-0.741	30	N-S
	0.783	0.344	0.752	0.422	6	0.225	29	N-S
2	1.51	0.857	1.42	1.25	1	0.233	28	N-S
	1.46	1.44	1.06	0.583	2	1.02	20	N-S
	0.909	0.670	0.727	0.467	3	0.895	28	N-S
	0.567	0.416	0.609	0.326	4	-0.318	30	N-S
	0.541	0.390	0.482	0.327	5	0.467	31	N-S
	0.403	0.181	0.475	0.258	6	-0.908	28	N-S
3	1.30	0.869	0.847	0.317	1	1.96	19	5
	1.10	0.578	0.574	0.252	2	3.33	21	0.5
	0.781	0.541	0.794	0.477	3	-0.069	32	N-S
	0.685	0.529	0.581	0.450	4	0.600	31	N-S
	0.493	0.428	0.560	0.377	5	-0.474	32	N-S
	0.616	0.232	0.555	0.256	6	0.703	32	N-S
4	0.457	0.225	0.667	0.356	1	-1.99	27	* 5
	0.617	0.361	0.484	0.284	2	1.16	30	N-S
	0.399	0.211	0.459	0.274	3	-0.693	30	N-S
	0.381	0.230	0.449	0.151	4	-0.989	27	N-S
	0.288	0.166	0.373	0.220	5	-1.24	30	N-S
	0.409	0.261	0.312	0.168	6	1.24	27	N-S
5	1.05	0.504	0.949	0.416	1	0.632	31	N-S
	1.19	0.557	0.870	0.409	2	1.87	29	5
	0.699	0.273	0.811	0.400	3	-0.922	28	N-S
	0.876	0.399	0.655	0.342	4	1.69	31	10
	0.647	0.270	0.608	0.348	5	0.350	30	N-S
	0.421	0.334	0.742	0.409	6	-2.43	31	* 2.5

* denotes that the furthest phasors were larger than the nearest phasors.

However it was considered unlikely that CNV energy would be found at higher harmonics without also being present in the lower harmonics (i.e. those more near to the fundamental frequency of the response). Hence the added energy may have been associated with a random element of the response or to an artefact. In other cases the test results on the harmonic components may have been subject to errors in either the transformation process or the subsequent testing (e.g. the limitations of the Nearest and Furthest Mean Amplitude test described in Section 2.2.3.3). While much of this remains conjecture a clear conclusion must be that although the responses of abnormal subjects may sometimes contain added energy it is not possible to exploit this in any useful way because the results are essentially random.

Comparison of the results for the four second ISI CNV's given in Tables 5-13b and 5-15b confirmed the lack of correlation between the Broadband Energy test and the Nearest and Furthest Mean Amplitude test. The former of these tests offered far more evidence of additivity, again suggesting that the added energy may have been present mainly in the higher harmonics.

5.4.3 Tests for Phase Ordering

The tests described below were carried out in an attempt to detect any phase ordering present in the CNV responses of the patient group.

5.4.3.1 Phase Histograms

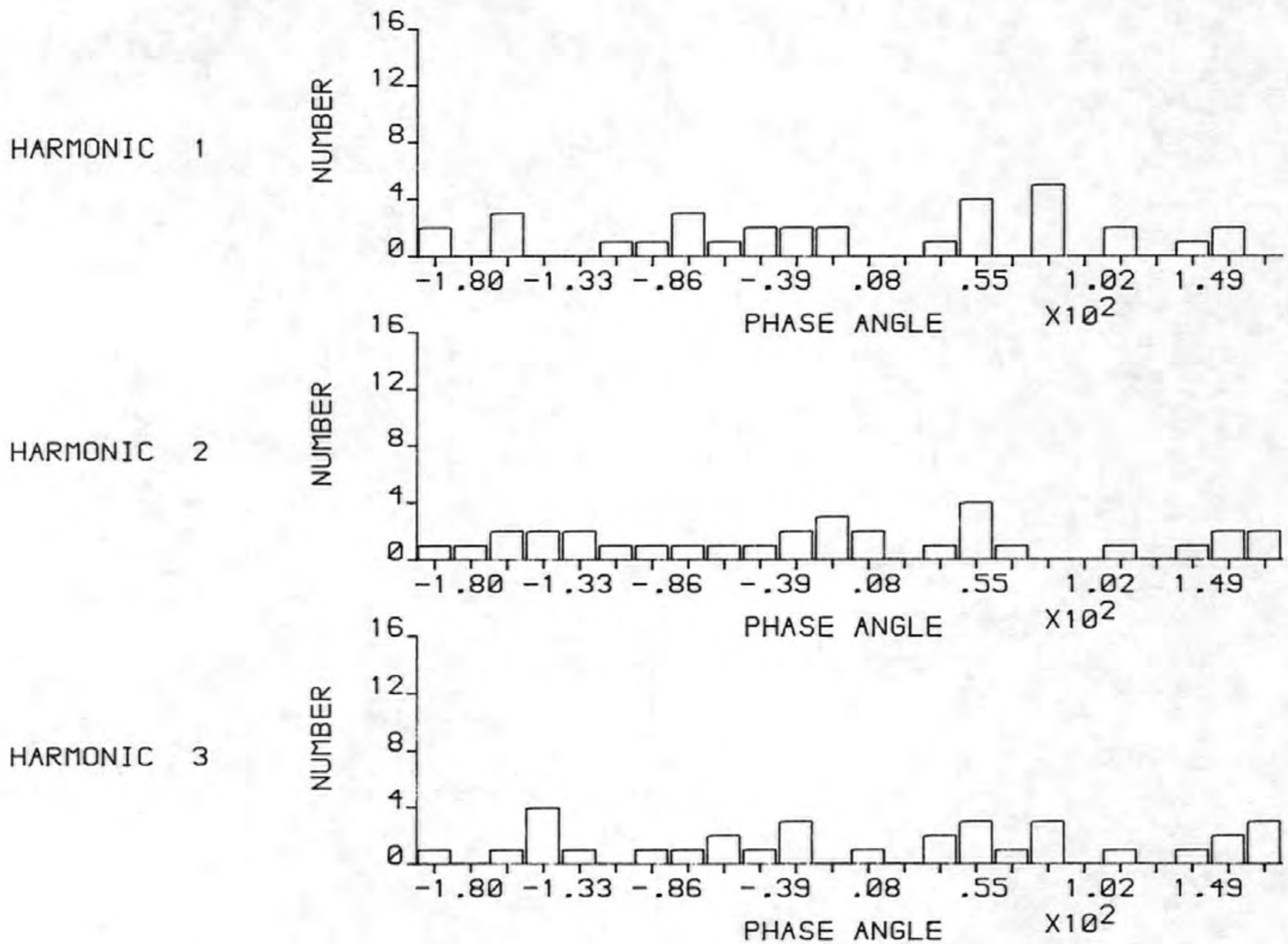
From the one second ISI CNV phase histograms it was noticed that angles of about 10^{o} tended not to occur. A similar minimum in the phase pattern had been observed in the case of normal subjects. By contrast to the histograms of normals, those of the abnormals showed an accumulation of values in the vicinity of $+180^{o}$. They also exhibited a smaller peak at negative angles (-80^{o} to 180^{o}). Thus it appeared that there might be a method, based on phase angles, to at least partially differentiate between patients and normals. A typical one second ISI CNV phase histogram for an abnormal is shown in Figure 5-10a.

The four second ISI CNV phase histograms of the abnormals showed a larger peak in the vicinity of 150^{o} than either the one second ISI CNV phase histograms of abnormals or normals. A typical phase histogram is shown in Figure 5-10b.

Thus whilst for normal subjects the one and four second ISI CNV phase histograms were similar those for the patients were not.

5.4.3.2 Rayleigh Test of Circular Variance

Tables 5-16a and 5-16b show that there was very little evidence for phase ordering for either ISI CNV. At the 5% significance level there were only 2 (out of 30) positive results for the one second ISI and only 4 (out of 30) positive results for the four second ISI CNV's.



<u>Figure 5-10a A typical one second ISI phase histogram of an abnormal subject</u>

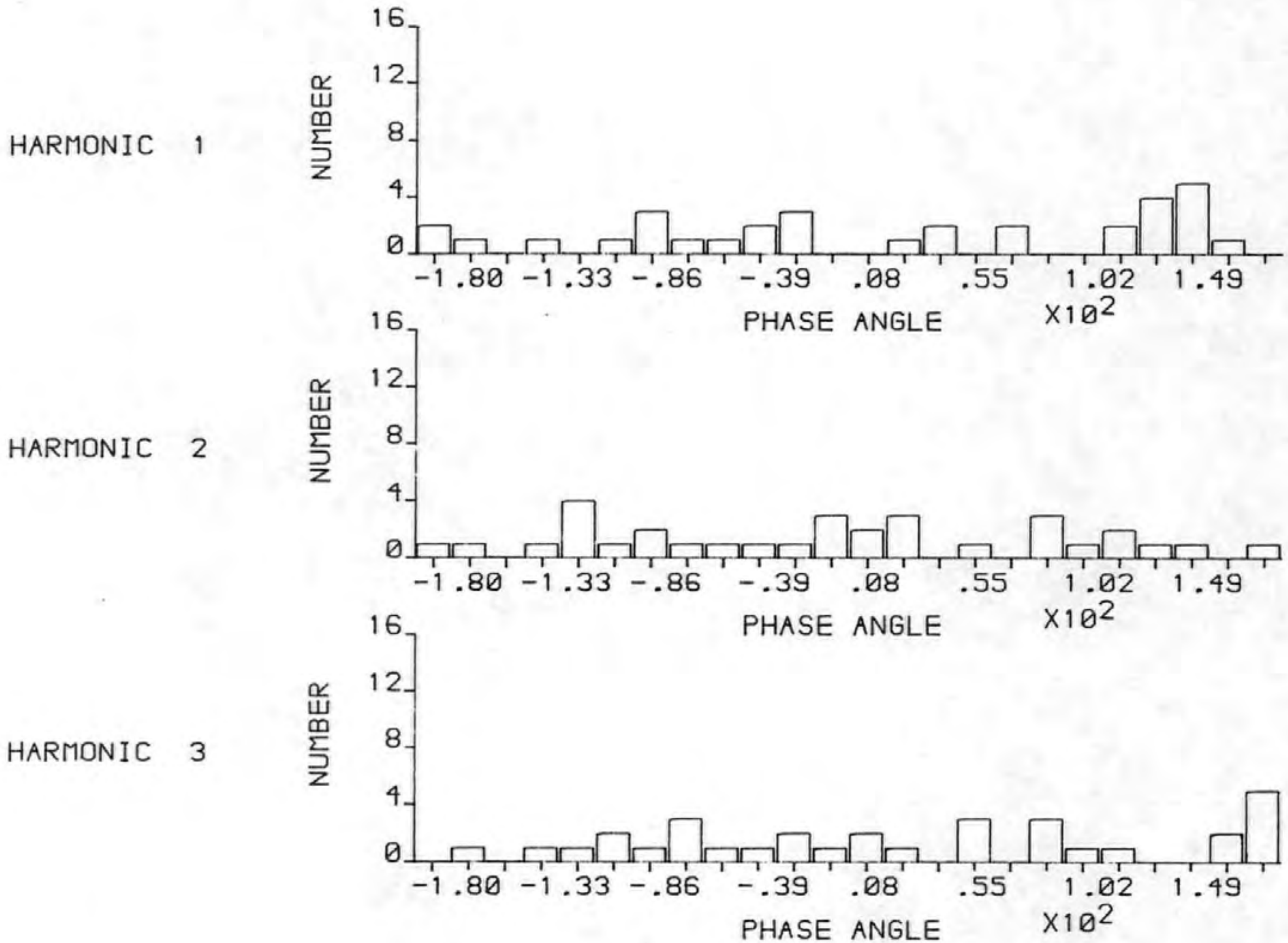


Figure 5-10b A typical four second ISI phase histogram of an abnormal subject

Table 5-16a

Circular Variance for 1 second ISI CNV's

of Abnormal Subjects

Subject	Harmonic	Number of Trials	So	Significance %
1	1	32	0.868	N-S
	2	32	0.873	N-S
	3	32	0.737	N-S
	4	32	0.829	N-S
	5	32	0.624	5
	6	32	0.869	N-S
2	1	32	0.889	N-S
	2	32	0.896	N-S
	3	32	0.991	N-S
	4	32	0.807	N-S
	5	32	0.874	N-S
	6	32	0.808	N-S
3	1	32	0.966	N-S
	2	32	0.744	N-S
	3	32	0.946	N-S
	4	32	0.847	N-S
	5	32	0.870	N-S
	6	32	0.895	N-S
4	1	32	0.805	N-S
	2	32	0.771	N-S
	3	32	0.858	N-S
	4	32	0.788	N-S
	5	32	0.681	5
	6	32	0.995	N-S
5	1	32	0.694	10
	2	32	0.809	N-S
	3	32	0.751	N-S
	4	32	0.800	N-S
	5	32	0.794	N-S
	6	32	0.762	N-S

Table 5-16b

Circular Variance for 4 second ISI CNV's

of Abnormal Subjects

Subject	Harmonic	Number of Trials	So	Significance %
1	1	30	0.844	N-S
	2	30	0.901	N-S
	3	30	0.761	N-S
	4	30	0.934	N-S
	5	30	0.812	N-S
	6	30	0.885	N-S
2	1	32	0.874	N-S
	2	32	0.853	N-S
	3	32	0.954	N-S
	4	32	0.720	10
	5	32	0.925	N-S
	6	32	0.983	N-S
3	1	32	0.403	0.1
	2	32	0.653	5
	3	32	0 859	N-S
	4	32	0.771	N-S
	5	32	0.963	N-S
	6	32	0.857	N-S
4	1	32	0.738	N-S
	2	32	0.811	N-S
	3	32	0.897	N-S
	4	32	0.868	N-S
	5	32	0.784	N-S
	6	32	0.784	N-S
5	1	32	0.657	5
	2	32	0.689	5
	3	32	0.910	N-S
	4	32	0.815	N-S
	5	32	0.863	N-S
	6	32	0.858	N-S

5.4.3.3 Modified Rayleigh Test of Circular Variance

These results (Tables 5-17a and 5-17b) were similar to those of the Rayleigh Test. There were no cases of significance at the 5% level for the one second ISI CNV's and only 3 cases for the four second ISI CNV's.

5.4.3.4 Hodges-Ajne Test

This test indicated only one case of phase ordering at the 5% level for the one second ISI CNV's and only one case for the four second ISI CNV's. The results are shown in Tables 5-18a and 5-18b.

5.4.4 Discussion of Energy and Phase Results

Table 5-19 summarises the results of energy and phase tests applied to the harmonics which were significant at the 5% (or better) level. Harmonic numbers which are asterisked indicate those cases in which phase ordering was detected by at least two of the tests. The Rayleigh test indicated some results to be significant which the other two tests did not substantiate. Examination of the additivity results shows that the Nearest and Furthest Mean Amplitude test did not reveal any cases of significant additivity for the one second ISI CNV's although the Pre- and Post- Stimulus Mean Amplitude Differences test did. It is even more interesting to note that the former test however did indicate cases of significant additivity for the four second ISI CNV's. This contrasting result probably reflected the different composition of the one and four second ISI CNV's. In fact the averaged four second ISI CNV responses were more like the averaged four

Table 5-17a

The Modified Rayleigh Test of Circular Variance for

1 second ISI CNV's of Abnormal Subjects

Subject	Harmonic	Number of Trials	Uo	Significance %
1	1	32	0.764	N-S
	2	32	0.856	N-S
	3	32	0.662	10
	4	32	0.894	N-S
	5	32	0.682	10
	6	32	0.874	N-S
2	1	32	0.773	N-S
	2	32	0.805	N-S
	3	32	0 925	N-S
	4	32	0.799	N-S
	5	32	0.906	N-S
	6	32	0.801	N-S
3	1	32	0.909	N-S
	2	32	0.671	10
	3	32	0.900	N-S
	4	32	0.829	N-S
	5	32	0.879	N-S
	6	32	0.958	N-S
4	1	32	0.806	N-S
	2	32	0.672	10
	3	32	0.771	N-S
	4	32	0.833	N-S
	5	32	0.695	N-S
	6	32	0.947	N-S
5	1	32	0.691	10
	2	32	0.810	N-S
	3	32	0.706	N-S
	4	32	0.726	N-S
	5	32	0.805	N-S
	6	32	0.696	N-S

Table 5-17b

The Modified Rayleigh Test of Circular Variance for

4 second ISI CNV's of Abnormal Subjects

Subject	Harmonic	Number of Trials	Uo	Significance %
1	1	30	0.665	10
	2	30	0.858	N-S
	3	30	0.698	N-S
	4	30	0.867	N-S
	5	30	0.846	N-S
	6	30	0.861	N-S
2	1	32	0.835	N-S
	2	32	0.901	N-S
	3	32	0.920	N-S
	4	32	0.765	N-S
	5	32	0.813	N-S
	6	32	0.914	N-S
3	1	32	0.338	0.1
	2	32	0.484	0.1
	3	32	0.860	N-S
	4	32	0.674	10
	5	32	0.939	N-S
	6	32	0.812	N-S
4	1	32	0.831	N-S
	2	32	0.787	N-S
	3	32	0.914	N-S
	4	32	0.913	N-S
	5	32	0.823	N-S
	6	32	0.695	N-S
5	1	32	0.704	N-S
	2	32	0.590	5
	3	32	0.886	N-S
	4	32	0.736	N-S
	5	32	0.821	N-S
	6	32	0.932	N-S

Table 5-18a

Results of the Hodges-Ajne Test for 1 second ISI CNV's of Abnormal Subjects

Subject	Harmonic	Number of Trials	M	Significance %
1	1	32	12	N-S
	2	32	12	N-S
	3	32	9	18
	4	32	12	N-S
	5	32	7	2.8
	6	32	12	N-S
2	1	32	12	N-S
	2	32	13	N-S
	3	32	14	N-S
	4	32	11	N-S
	5	32	11	N-S
	6	32	11	N-S
3	1	32	13	N-S
	2	32	9	18
	3	32	13	N-S
	4	32	12	N-S
	5	32	12	N-S
	6	32	12	N-S
4	1	32	11	N-S
	2	32	9	18
	3	32	13	N-S
	4	32	11	N-S
	5	32	8	7.8
	6	32	14	N-S
5	1	32	8	7.8
	2	32	11	N-S
	3	32	10	N-S
	4	32	11	N-S
	5	32	10	N-S
	6	32	10	N-S

Table 5-18b

Results of the Hodges-Ajne Test for 4 second ISI CNV's of Abnormal Subjects

Subject	Harmonic	Number of Trials	M	Significance %
1	1	30	10	N-S
	2	30	11	N-S
	3	30	10	N-S
	4	30	13	N-S
	5	30	10	N-S
	6	30	12	N-S
2	1	32	11	N-S
	2	32	12	N-S
	3	32	12	N-S
	4	32	8	7.8
	5	32	13	N-S
	6	32	13	N-S
3	1	32	4	0
	2	32	9	18
	3	32	12	N-S
	4	32	10	N-S
	5	32	12	N-S
	6	32	12	N-S
4	1	32	9	18
	2	32	9	18
	3	32	12	N-S
	4	32	10	N-S
	5	32	11	N-S
	6	32	11	N-S
5	1	32	8	7.8
	2	32	10	N-S
	3	32	13	N-S
	4	32	10	N-S
	5	32	11	N-S
	6	32	11	N-S

Table 5-19

Summary of Additivity and Phase Ordering Results Significant at the 5% level for the Patient Group

ADDITIVITY				PHASE ORDERING		
ISI	SUBJECT NUMBER	NEAREST & FURTHEST MEAN AMPLITUDE	PRE-POST MEAN AMPLITUDE DIFFERENCES	CIRCULAR VARIANCE	MODIFIED CIRCULAR VARIANCE	HODGES-AJNE
1	1		$H2^{+}$	H5 *		H5 *
	2		$H4^{+}$			
	3					
	4		$H2^{+}$ $H3^{+}$	H5		
	5		$H2^{+}H3^{+}H4^{+}$ $H5^{+}H6^{+}$			
4	1	$H1^{+}$				
	2					
	3	H1 H2		$H1^{*}H2^{*}$	$H1^{*}H2^{*}$	H1 *
	4					
	5	H2		H1 H2*	H2*	

Hn indicates that the nth harmonic had a significant result.

\+ denotes additivity without phase ordering.

* denotes two or more ordering tests are in agreement.

second ISI CNV responses of normals than were the one second ISI responses. The table also shows that a number of instances of additivity without phase ordering occurred. For the one second ISI CNV's there were 9 spread between 4 different subjects and for the four second ISI CNV's there was only 1 case.

The conclusions must therefore be that (i) the CNV responses of abnormals may contain added energy but that this may be random in nature rather than part of a true CNV response, (ii) the responses show very little phase ordering and (iii) additivity may occur unaccompanied by phase ordering.

5.5 Distinction Between Patients and Normals on the Basis of their CNV's

The previous two sections have shown that the CNV responses of patients tend to be more random than those of normals. It has also been shown that their averaged CNV waveforms were generally different (Section 5.4.1). Further attempts were therefore made to distinguish between the two subject categories in a quantitative manner on the basis of their averaged CNV responses. In particular (i) the distribution of amplitude and phase of the individual harmonics of the averaged CNV were compared and (ii) plots of amplitude verses phase angle with subject as a parameter were also compared. Attempts to distinguish between patients and normals on the basis of the trial-by-trial development of the CNV's are described in the next section.

In the case of the first three harmonics of the one second ISI CNV's of normals (see Table 5-20) it was found that with

Table 5-20

Phase Angles of the Fourier Components of the Averaged one second ISI CNV's of Normal and Abnormal Subjects

		NORMAL SUBJECTS	ABNORMAL SUBJECTS
Subject No.	Harmonic	Phase Angle ^{o}	Phase Angle ^{o}
1	1	- 63.9	159.6
	2	- 79.4	40.0
	3	- 99.4	25.0
2	1	- 43.1	88.0
	2	-103.7	73.6
	3	-175.7	88.9
3	1	- 87.8	-136.1
	2	-104.6	67.5
	3	12.2	- 72.9
4	1	-103.5	-109.5
	2	- 42.3	- 36.0
	3	- 92.8	- 99.8
5	1	- 78.9	-139.6
	2	-157.6	- 54.4
	3	-141.2	44.4

only one exception the phase angles were negative. By contrast the patients had phase angles covering a wider range ($+160^0$ to -140^0 compared with -176^0 to $+12^0$ for normals).

Plots of amplitude verses phase angle with subject as a parameter indicated on the graphs are shown in Figures 5-11a and 5-11b for the one and four second ISI's respectively. The baseline correction procedure used in obtaining these plots was different to that described in Section 5.3.2.1 and used previously. The reason for this change was that the slow return to baseline found in some of the abnormal subjects averaged CNV's made it difficult to obtain a meaningful post S2 average background EEG level. Therefore the averaged CNV's of both patients and normals were baseline adjusted by subtracting the mean value calculated over a one second length of background EEG preceeding the S1 stimulus. This is a technique which has been adopted previously by other workers [10].

Inspection of Figures 5-11a and 5-11b reveals that separate areas of the graphs may be ascribed to the normals and patients, although there are instances where the points for the two groups are close together. This method of distinguishing between normals and patients therefore requires more research in order to establish its reliability and usefulness. Similar comments apply in the case of the second harmonic where there is slightly more of an overlap between the areas ascribed to patients and normals (Figures 5-12a and 5-12b). It is possible that such plots may offer useful additional diagnostic evidence for the clinician. It is really necessary first,

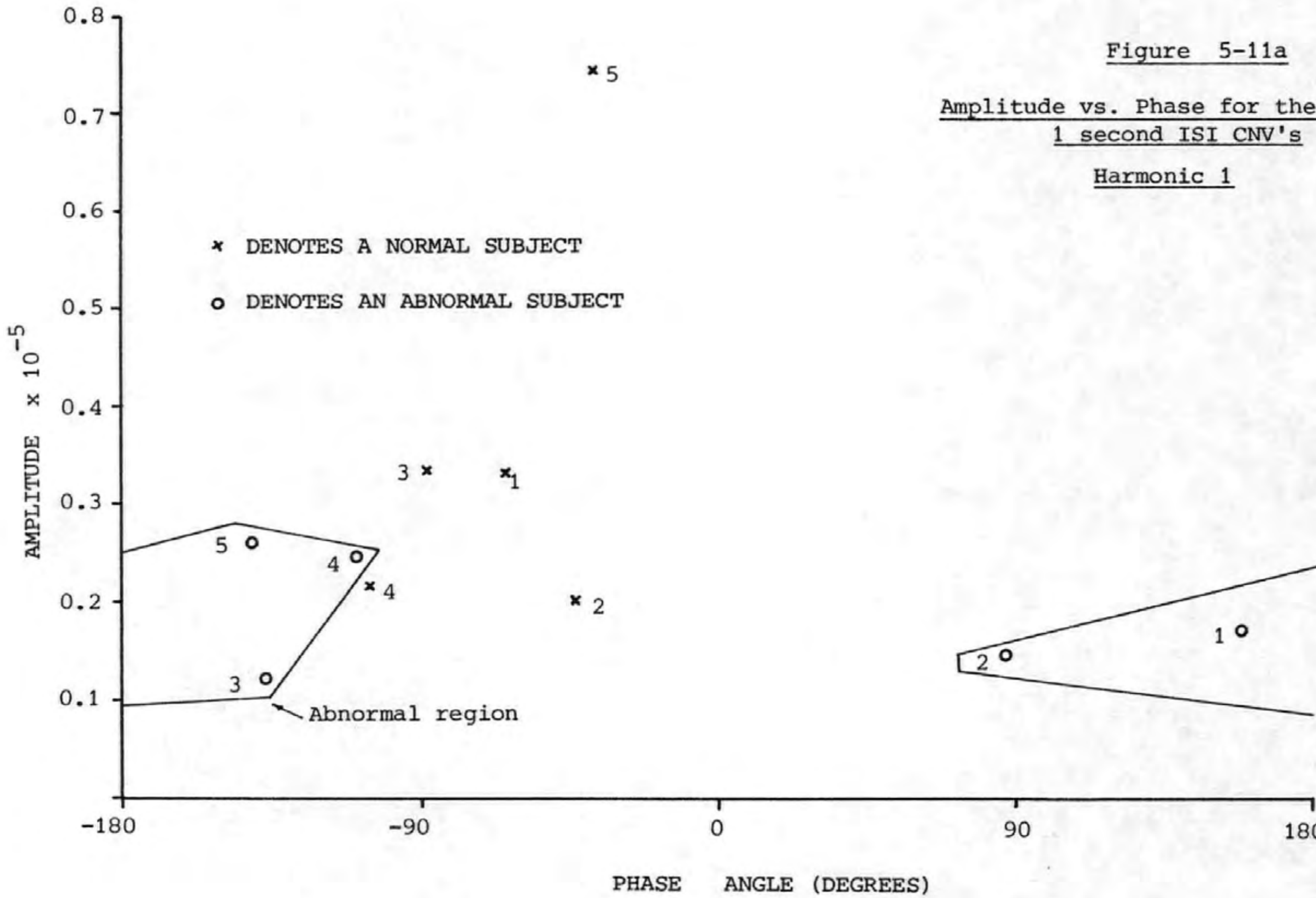


Figure 5-11a

Amplitude vs. Phase for the averaged 1 second ISI CNV's

Harmonic 1

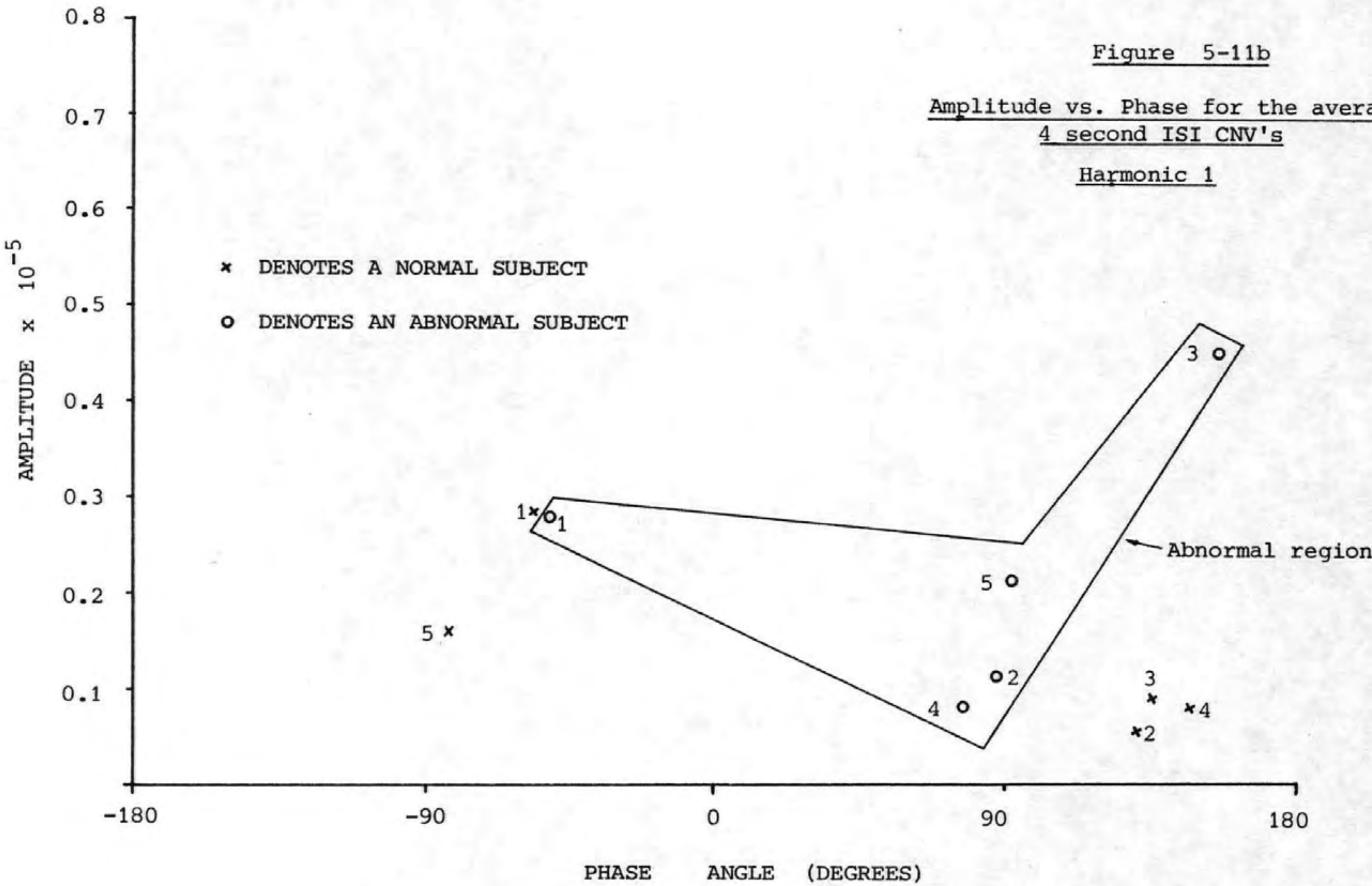


Figure 5-11b

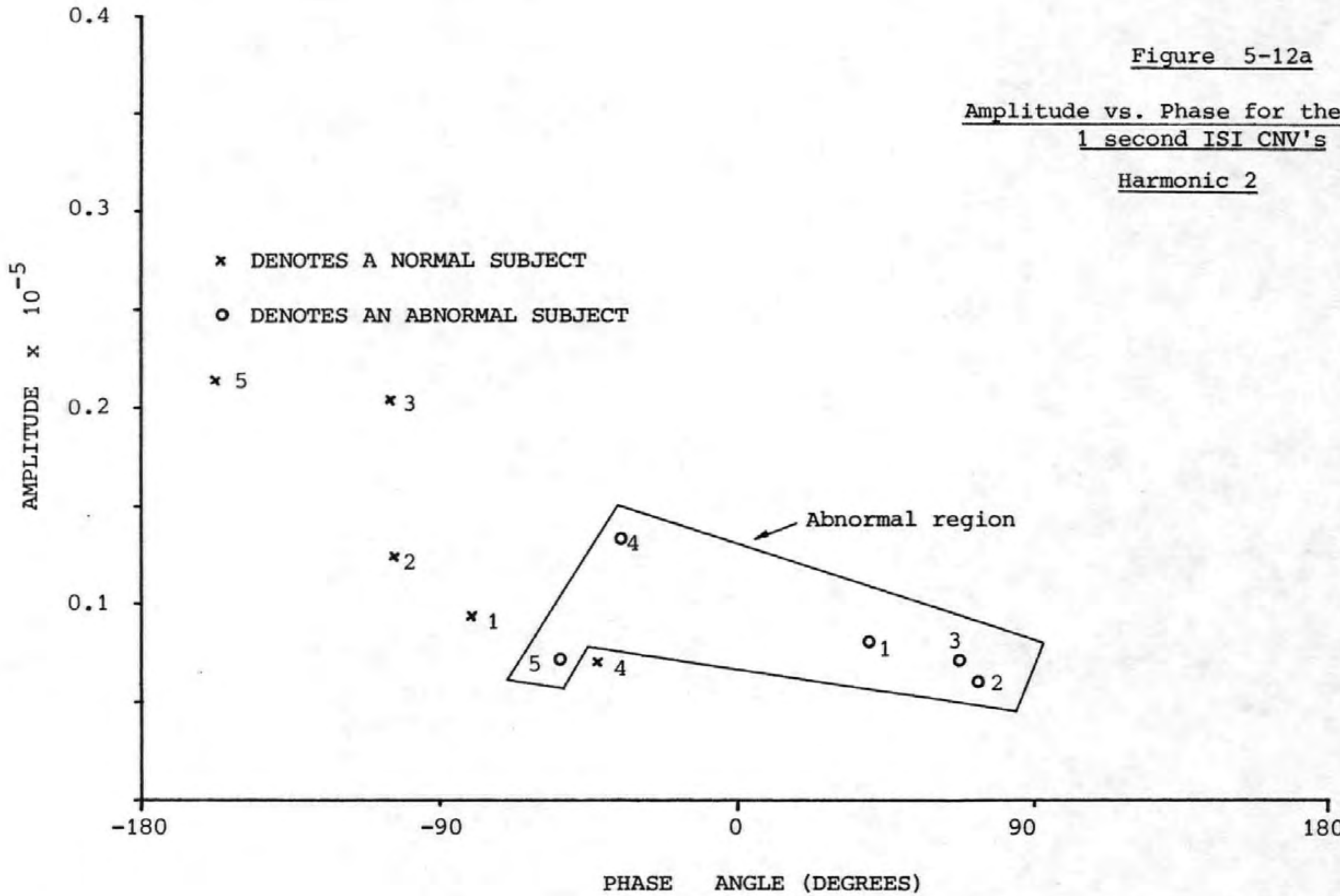
Amplitude vs. Phase for the averaged 4 second ISI CNV's

Harmonic 1

Figure 5-12a

Amplitude vs. Phase for the averaged 1 second ISI CNV's

Harmonic 2



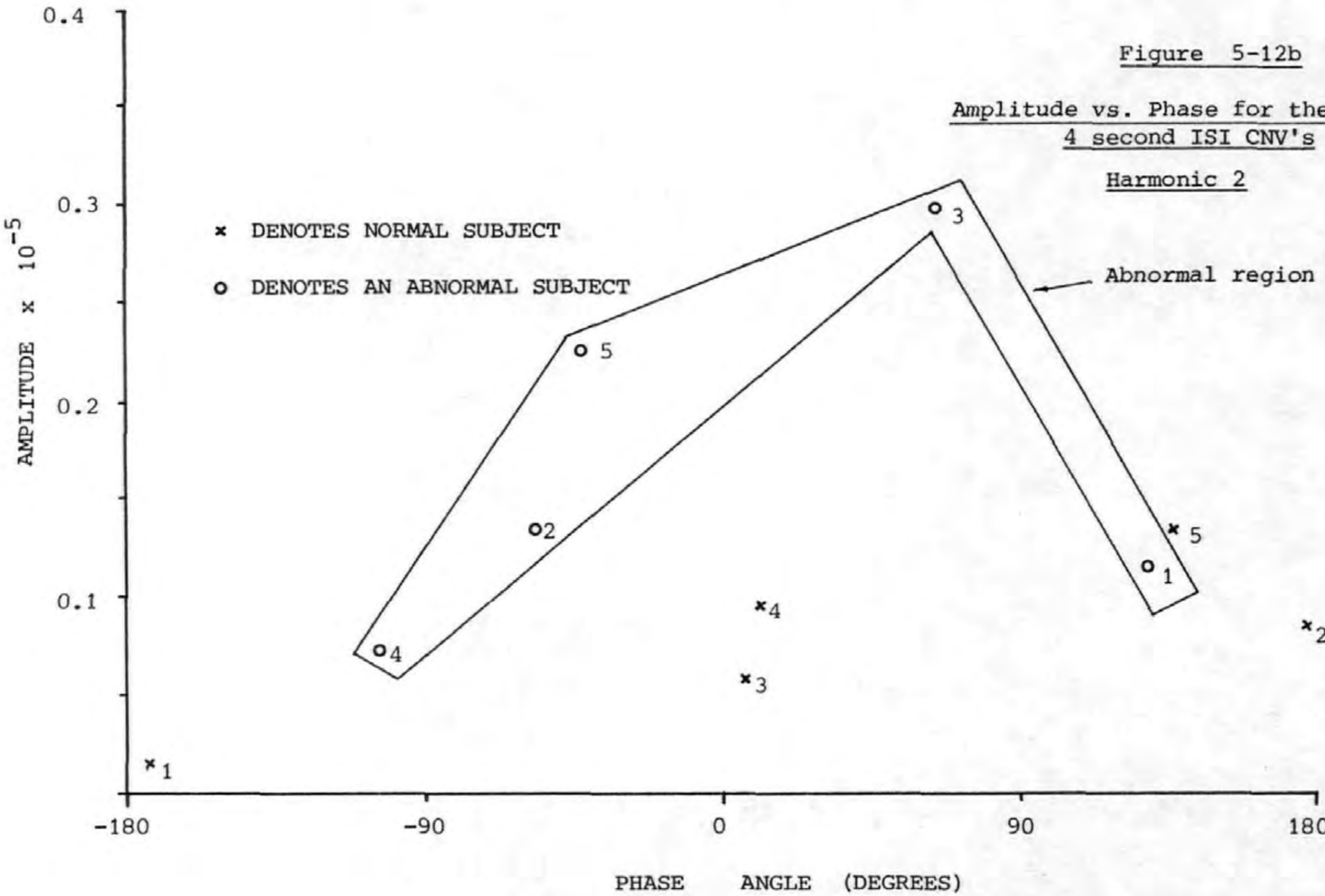


Figure 5-12b

Amplitude vs. Phase for the averaged 4 second ISI CNV's

Harmonic 2

however, to investigate much larger populations of patients and normals.

5.6 The Development of the CNV from trial-to-trial in Normals and Patients

In order to examine the trial-by-trial development of the CNV plots of harmonic amplitude and phase verses trial number were produced for both normal and abnormal subjects. In the case of the one second ISI CNV's of normal subjects the plots for harmonic two, subjects 1 and 2 exhibited slight evidence for increased amplitudes i.e. a plateau, over the range of trial numbers 9 to 20 and 12 to 22 respectively. These plots are shown in Figures 5-13a and 5-13b. None of the other amplitude plots, either of normal or abnormal subjects, showed any obvious patterns.

There was some evidence in the plots of phase verses trial number that the development of the one second ISI CNV response was different in abnormal subjects to that in normal subjects. Thus whilst for the normals there was a tendency in the case of harmonic 1 for only negative phase angles to occur in the earlier trials with positive angles only occurring in the subsequent trials, (see Figure 5-14), the abnormals showed that both positive and negative phase angles could occur throughout the acquisition sequence (see Figure 5-15). There was also some evidence from the amplitudes verses phase plots for the averaged CNV's to suggest that those normals whose amplitude and phase co-ordinates were furthest from those of patients had trial-by-trial phase angles which were negative up to the final few trials. Thus the phase angles

AMPLITUDE VS TRIAL NUMBER HARMONIC 2

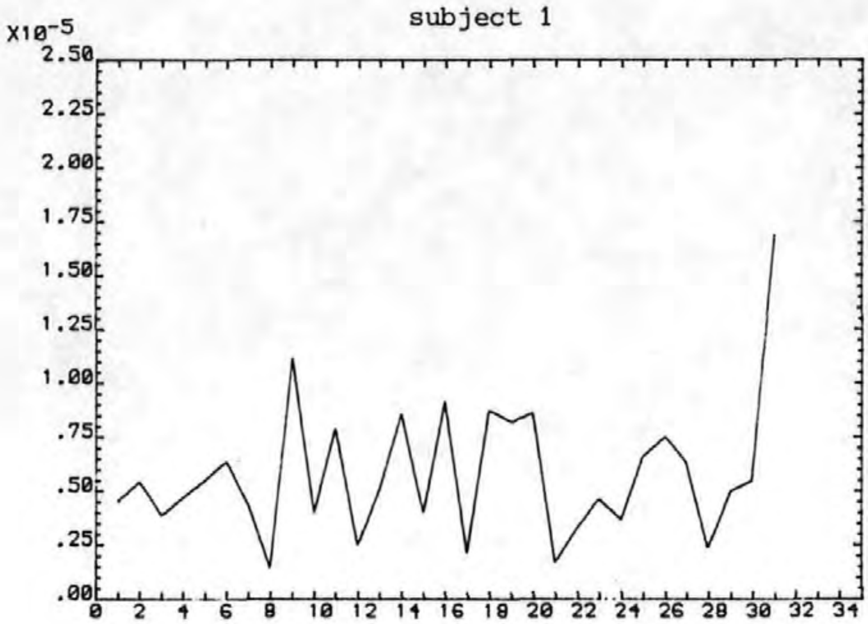


Figure 5-13a

Amplitude vs Trial number for a 1sec. ISI CNV of a normal subject. Harmonic 2.

AMPLITUDE VS TRIAL NUMBER HARMONIC 2

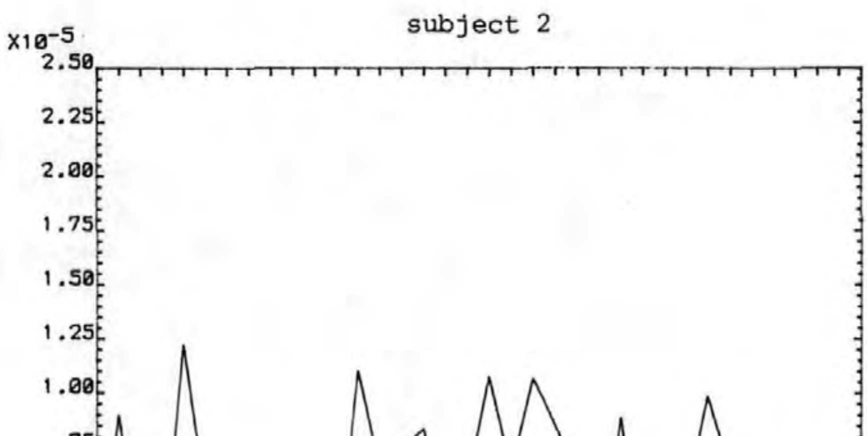


Figure 5-13b

Amplitude vs Trial number for a 1sec. ISI CNV of a normal subject. Harmonic 2.

PHASE VS TRIAL NUMBER HARMONIC 1

subject 2

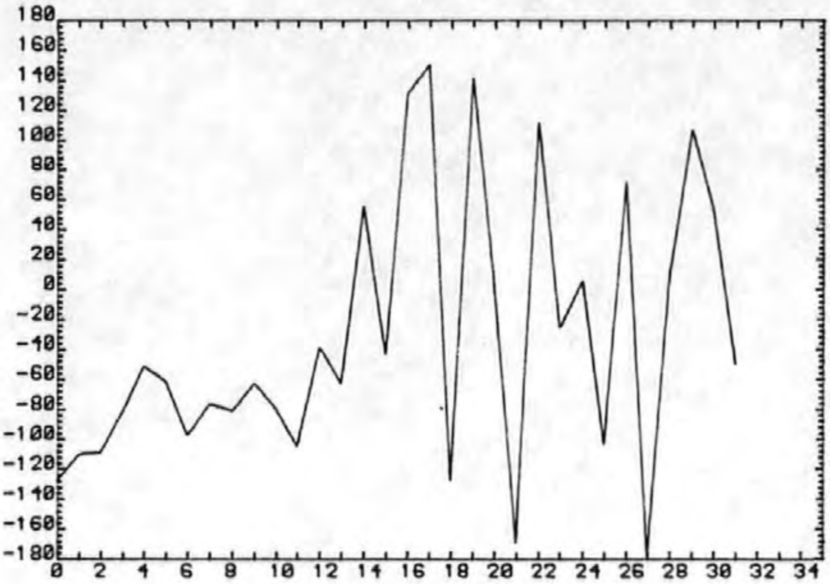


Figure 5-14

Phase vs Trial number for a 1sec. ISI CNV of a normal subject.

PHASE VS TRIAL NUMBER HARMONIC 1

subject 1

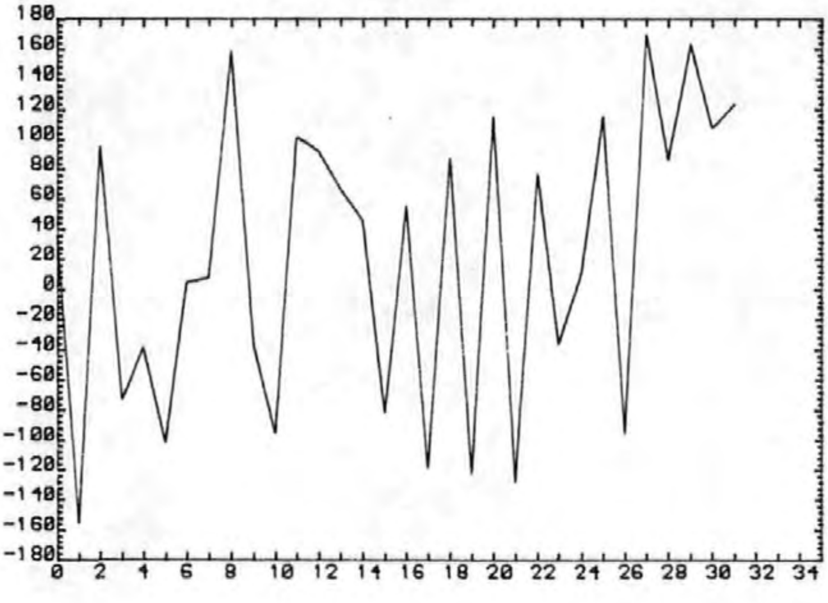


Figure 5-15

Phase vs Trial number for a 1sec. ISI CNV of an abnormal subject.

of the most "normal" subjects were characteristically negative for the earlier trials whilst those of the abnormals were characteristically randomly positive or negative. This difference may provide another means for differentiating between the two groups but again more results would be required to confirm these findings. In the case of harmonic 2 both positive and negative phase angles were found throughout the acquisition sequence and for both normals and patients (see Figure 5-16a and 5-16b).

Plots of amplitude verses trial number for the first harmonic of the four second ISI CNV's of the normals did not reveal any definite pattern, although in some cases the mid-trial values may be slightly larger (see Figure 5-17). No similar evidence could be found for the abnormal subjects.

The plots of phase angle verses trial number for the first harmonic of the four second ISI CNV's were inspected. The phase angles for the initial trials were either negative or positive for the normal subjects (see Figure 5-18) but were positive for each of the abnormal subjects (see Figure 5-19). Again this may be useful but more results would be required to confirm these findings.

The corresponding plots of amplitude and phase for the second harmonic of the four second ISI CNV's of both patients and normals revealed little further information.

In conclusion it would appear that the phase properties of the harmonic components are more significant than those of the amplitude. In particular the phase properties of the

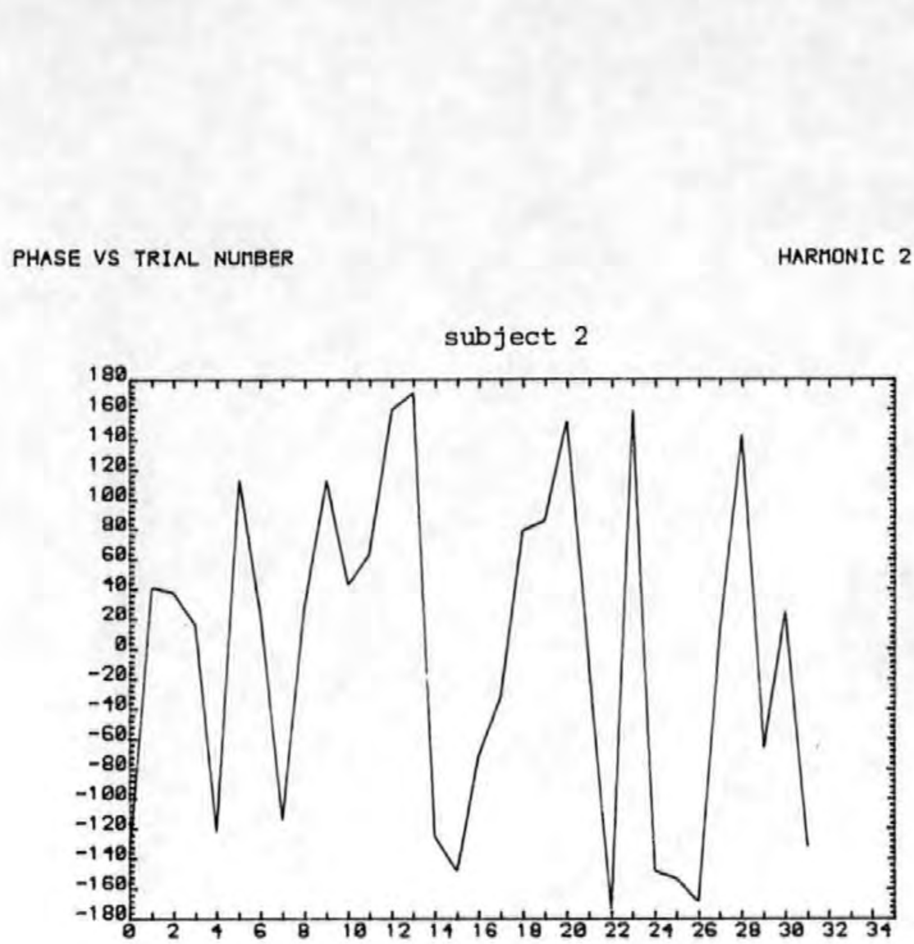


Figure 5-16a

Phase vs Trial number for a 1sec. ISI CNV of a normal subject.

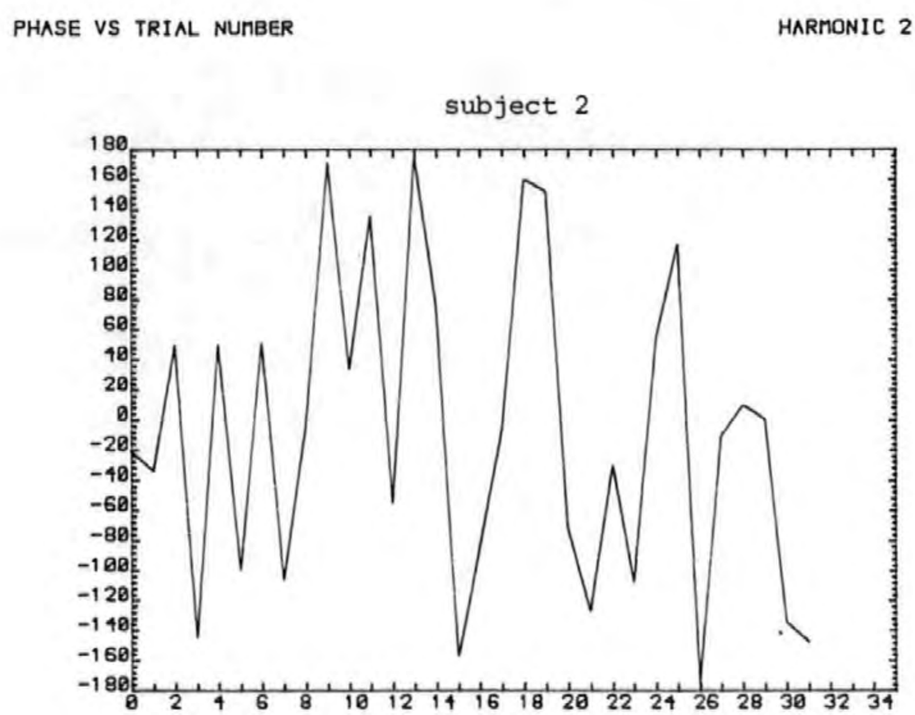


Figure 5-16b

Phase vs Trial number for a 1sec. ISI CNV of an abnormal subject.

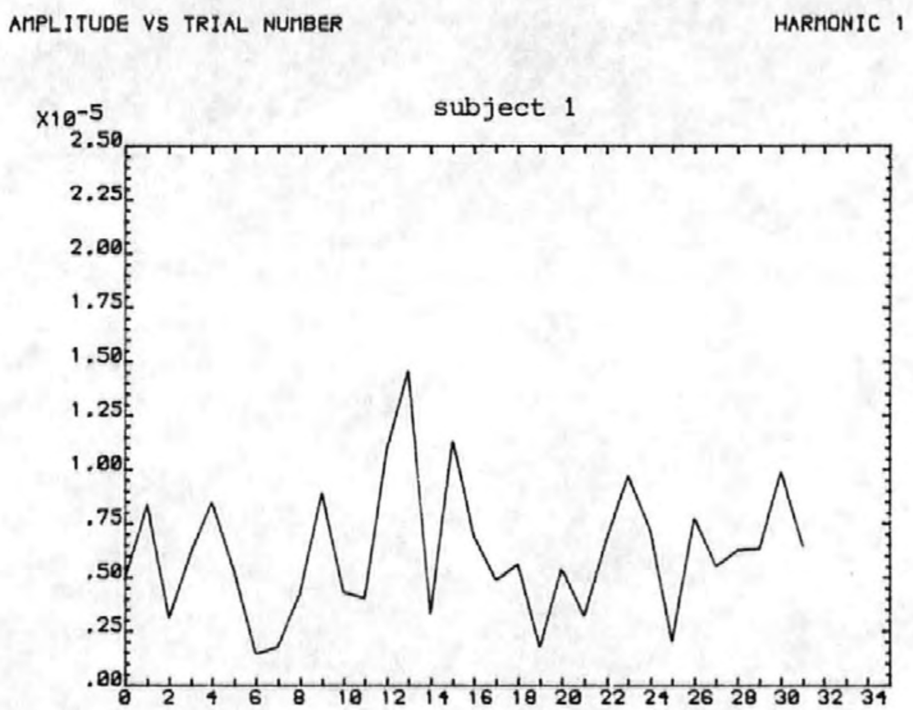


Figure 5-17

Amplitude vs Trial number for a 4sec. ISI CNV of a normal subject.

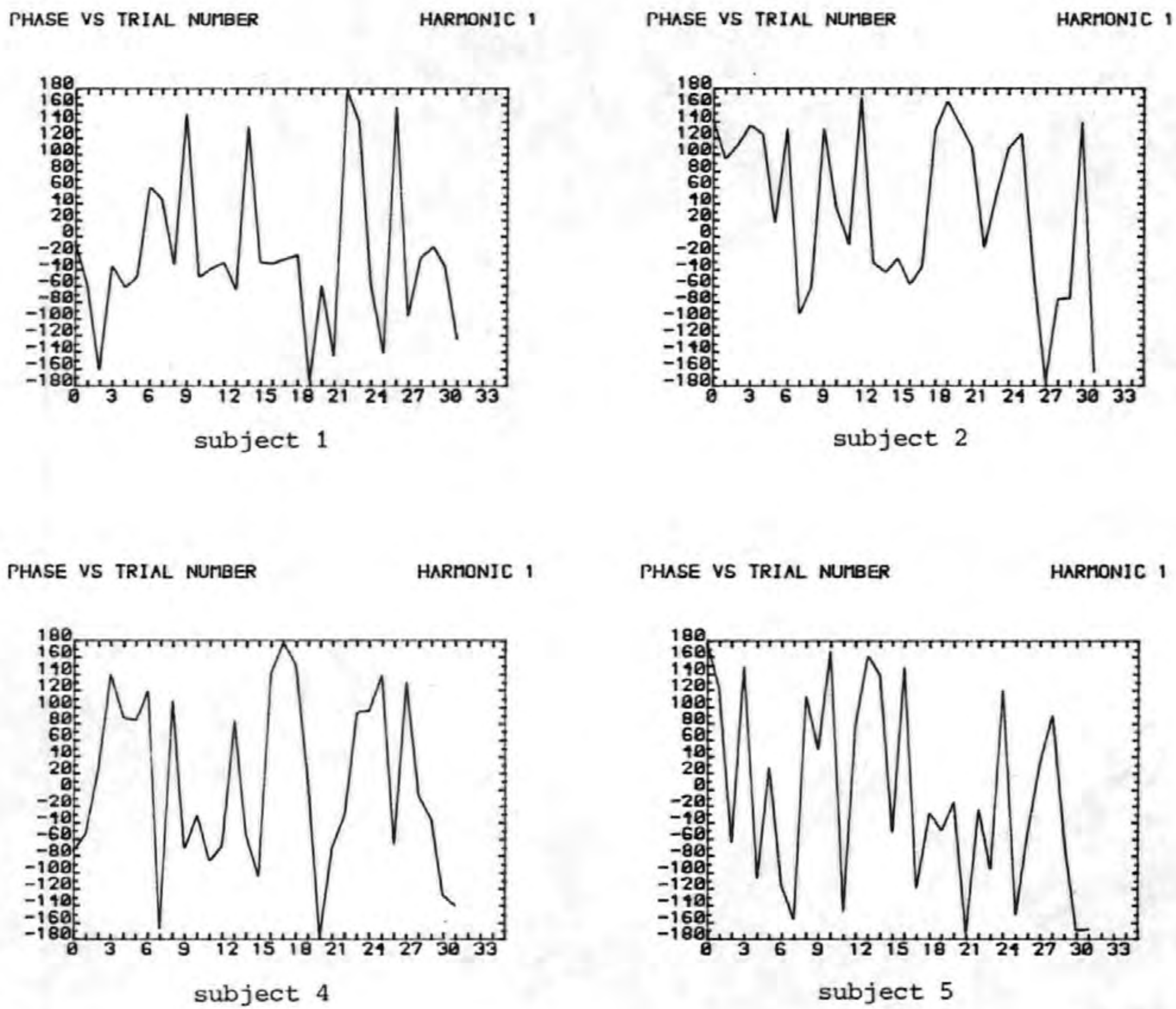
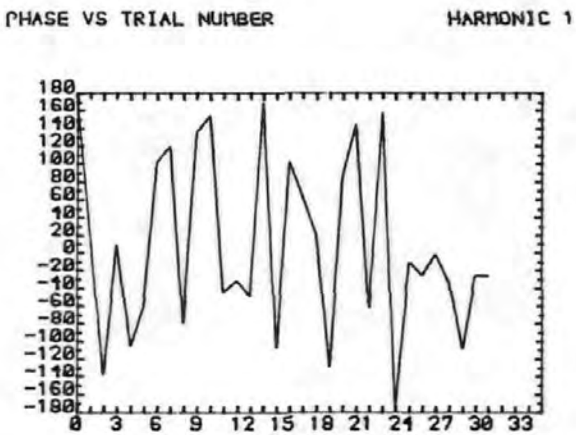
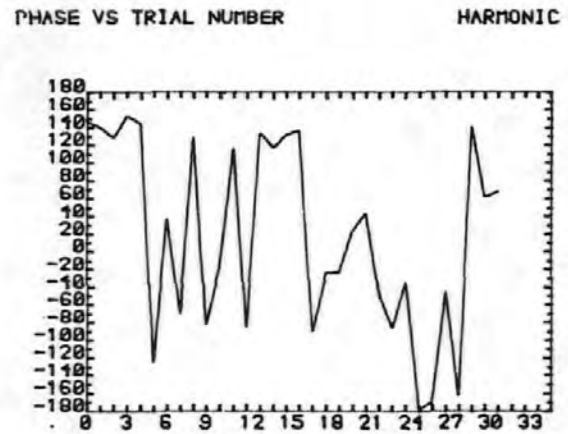


Figure 5-18

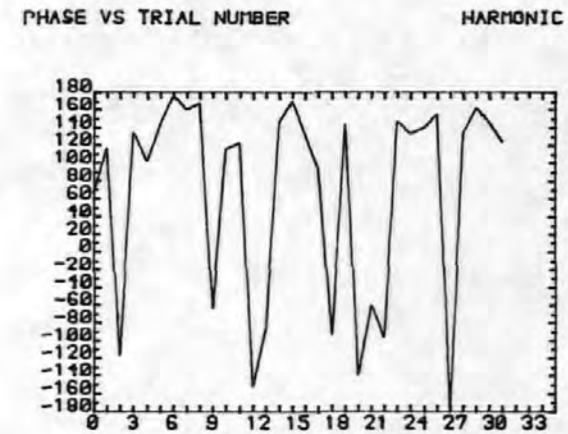
Phase vs Trial number for the 4sec. ISI CNV's of the normal subjects.



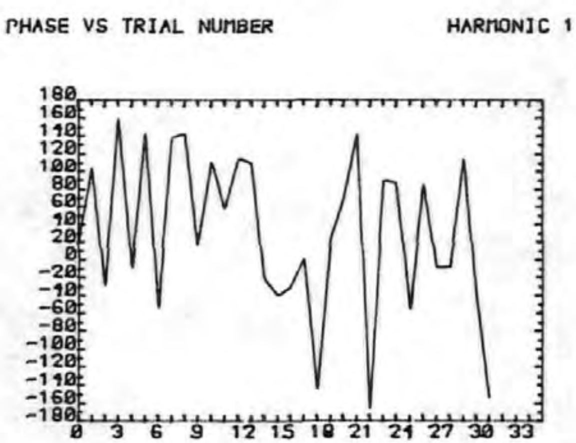
subject 1



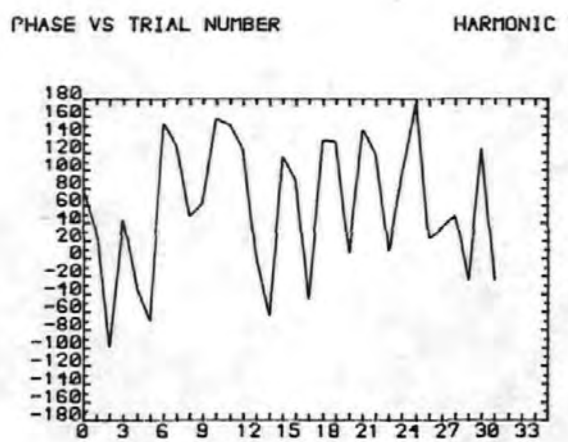
subject 2



subject 3



subject 4



subject 5

Figure 5-19

Phase vs Trial number for the 4sec. ISI CNV's of the abnormal subjects.

first harmonic of the one second ISI CNV response may, subject to confirmation, allow differentiation between the normal and patient groups. In this case the initial phase angles are negative for the normals and either positive or negative for the patients. The onset of positive phase values occurs at much later trial numbers for normals than for the patients.

References for Section 5

[1] Corby J C, Kopell B S, "Differential Contributions of Blinks and Vertical Eye Movements as Artifacts in EEG Recording" Psychophysiology, Volume 9, pp 640-644, November 1972.

[2] McCallum W C, Walter W G, "The Effects of Attention and Distraction on the Contingent Negative Variation in Normal and Neurotic Subjects" Electroencephalography and Clinical Neurophysiology, Volume 25, pp 319-329, 1968.

[3] Girton D G, Kamiya J, "A Simple on-line Technique for Removing Eye Movement Artifacts from the EEG" Electroencephalography and Clinical Neurophysiology, Volume 34, pp 212-216, 1973.

[4] Jervis, B W, Nichols M J, Allen E, Hudson N G, Johnson T E, "The Quantitative Assessment of Electro-encephalograms Corrected for Eye Movement Artefact" EUSIPCO-80, Short communication and poster digest, Swiss Federal Institute of Technology, Lausanne, Switzerland 1980.

[5] Sayers B McA, Beagley H A, Henshall W R, "The Mechanism of Auditory Evoked EEG Responses" Nature, Volume 247, pp 481-483, 1974.

[6] Sayers B McA, Beagley H A, Riha J, "Pattern Analysis of Auditory-Evoked EEG Potentials" Audiology, Volume 18, pp 1-16, 1979.

[7] Beagley H A, Sayers B McA, Ross A J, "Fully objective ERA by Phase Spectral Analysis" Acta Otolaryngology, Volume 87, pp 270-278, 1979.

[8] Sayers B McA, "Science and Judgement in Biological Signal Analysis" in "Signal analysis and pattern recognition in biomedical engineering" Edited by Inbar G F, Halstead Press, New York, pp 3-32, 1975.

[9] Dongier M, "Separation of the various independant phenomena among the slow potential changes (Contingent Negative Variations)" Electroencephalography and Clinical Neurophysiology, Volume 27, pp 108-109, 1969.

[10] Loveless N E, Sanford A J, "The CNV Baseline: Considerations of Internal Consistency of Data" Published in "Event-Related Slow Potentials of the Brain: Their relations to Behaviour", Edited by McCallum W C & Knott J R. Electroencephalography and Clinical Neurophysiology Supplement No. 33, pp 19-23. Published by Elsevier Scientific Publishing Company, 1973.

[11] Cooper R, Osselton J W, Shaw J C, "EEG Technology" page 13. Published by Butterworths, 1969.

6. Conclusions

6.1 Eye Movement Artefact Removal

A method of testing the effectiveness of eye movement artefact removal techniques has been derived. This procedure was used to test four methods of removing eye movement artefact from the EEG. These four methods were (i) the analogue method using a potentiometer due to McCallum and Walter [1], (ii) The computational method due to Quilter et al [2], (iii) our extension of Quilters method to incorporate three EOG components, (iv) our extension of Quilters to incorporate four EOG components. Recordings were made from normal volunteer subjects who were asked to make deliberate eye movements and the various methods of removing the artefact from the EEG were compared.

It was found that the computational correction method gave excellent results particularly when the horizontal and vertical components of the EOG of both eyes were taken into account. However it was possible to obtain good artefact removal using both horizontal, but only one vertical EOG component (i.e. the three EOG components method). The reduction in the computational effort obtained by this simplification may be important in an on-line multi-channel situation.

The four EOG component method of eye movement artefact removal was used in all the subsequent investigations.

6.2 Evoked Potentials

New models have been developed to describe the fundamental nature of evoked potentials in terms of additive and phase re-ordered components. The models showed that a repetitive additional component or an alignment of existing background EEG components could give rise to observable phase ordering in the post stimulus response. Tests were then contrived in an attempt to determine which of these mechanisms was operative in both auditory evoked potentials and the much longer Contingent Negative Variations.

6.3 Auditory Evoked Potentials

The tests mentioned above were applied to the auditory evoked potentials recorded from normal volunteer subjects. Of the 36 sets of results (3 subjects, 2 stimulus levels, 6 harmonics) 29 exhibited phase ordering. Some of the harmonic components were found to contain additional energy and all of these exhibited phase ordering. This finding was consistent with the proposed additivity model although a combination of the additive and phase re-ordered models could give the same results. However, 15 of the 29 results showing phase ordering did not show any additive effects. Thus either the additivity tests were not sufficiently sensitive to detect small additional components, or pure phase re-ordering was also present.

For all the subjects tested, and for both levels of auditory stimulation, the first three harmonic components all showed significant phase ordering. Furthermore, in all but one harmonic for one subject, the results of all three phase ordering tests were significant at 0.1% or better. This result may be useful in the diagnosis of audiological defects or establishing auditory thresholds, since the statistical results give a quantitative indication of the presence or absence of a response whereas inspection of the averaged waveform is rather subjective.

6.4 The CNV's of Normal Subjects

The pre- and post- stimulus (i.e. broadband) energy tests showed that all the CNV's of the normal subjects contained additional energy. However only a small proportion of the harmonics examined showed any evidence of this feature. Thus the additional energy must have been at frequencies other than those studied. Some of the harmonics exhibited phase ordering although this feature was much less pronounced than the phase ordering observed in the auditory evoked potentials. The one second ISI CNV's showed more ordering than the four second and most of the ordering observed was confined to the lower harmonics. There were some examples of phase ordering without any accompanying additivity. Thus like the auditory responses the CNV's might be explained in terms of a mixture of the additive and phase re-ordered models.

However some results were in conflict with this conclusion. There were instances where additivity was detected in the absence of any phase ordering. This may have been the effect of a non-repetitive additional component.

The trial-by-trial analysis of the phase components of the CNV's revealed that for the first harmonic negative phase angles tended to occur in the early trials. Some of the second harmonic amplitude components showed a plateau in the middle of the acquisition sequence.

6.5 The CNV's of Abnormal Subjects

The broadband energy tests revealed fewer instances of additivity in the CNV's of the abnormal subjects than for the normal subjects. However the individual harmonics showed a slightly higher number with detectable additivity than those of the normals.

There were fewer cases of phase ordering than for the CNV's of the normal subjects. Thus the CNV's of the abnormal subjects did not fit either the additive or phase re-ordered models so well as those of the normal subjects. This may have been due to the limitations of the models or it may have indicated the differing nature of the responses obtained from the Huntingtons Chorea group.

The averaged CNV waveforms tended to support the latter theory since the one second CNV's showed little similarity with those of the normals. The four second CNV's however, particularly those for subjects three and five, did appear slightly more like the normal CNV's. These observations are supported by the phase ordering tests. The one second ISI CNV's exhibited no phase ordering in the lower harmonics whereas those of subjects three and five for the four second

ISI CNV's did.

Generally the CNV's of the patient group were most easily characterised by their averaged waveforms. These waveforms sometimes showed a slow return to baseline.

6.6 Distinctions between the CNV's of Normals and Patients

As stated above the averaged CNV waveforms of the HC patients tended to be rather different to those of the normal group. This may be a sufficient difference to aid the detection of H.C. However, the patients for whom H.C. had only recently been diagnosed (i.e. those at an early stage of the illness) showed more normal averaged CNV's than did those for whom the disease was at an advanced stage. (Compare the recently diagnosed H.C. of Figure 5-8c with Figures 5-4a-e).

Another feature of the averaged waveforms of the patient group was that of the slow return to baseline subsequent to the S2 stimulus exhibited by some of the subjects. This may also be a useful diagnostic feature.

An alternative to the averaged waveform was provided by the plots of amplitude verses phase for the various normal and abnormal subjects. It may be possible to ascribe certain areas of these graphs to each of the two populations.

The analysis of the phase angle of the first harmonic on a trial-by-trial nature may also be of diagnostic value since all the normal subjects tested produced negative phase angles for the initial trials whereas the patient group did not.

6.7 Future Work

6.7.1 Eye Movement Artefact Removal

As previously mentioned hardware to perform the eye movement artefact removal procedure is to be developed and produced commercially. There are a number of improvements and tests which should be carried out before this is done. The method should first be tested to ensure that any frontal EEG activity which may be present in the EOG signals is not superimposed on the EEG by the correction procedure. One possible way of achieving this would be to experiment with the placement of EOG electrodes in order to find electrode positions which maximise the EOG and minimise the EEG amplitudes.

The presence of harmonics of the EOG in the corrected EEG signal may be due to a frequency selective path between the eye and the scalp. The most likely characteristic of such a path would be that of a low pass filter. The correction procedure assumes that the path between the eye and the scalp is linear and has an infinite bandwidth. The correction method may thus overcorrect the higher harmonics of the EOG and hence leave traces of these components in the corrected signal. A possible cure for this phenomena would be to introduce a filter (either electrical or digital) into the EOG signal path. The filter would have to have the same properties as those of the electrical path between the eye and the scalp. This may simply be of a frequency selective nature or may include non-linearities. It might even be possible for the correction procedure to have a 'set-up' mode whereby the nature of this network is determined by the correction system before the corrector is used.

6.7.2 Auditory Evoked Potentials

The statistical tests for phase ordering should be applied to a much larger sample of auditory evoked potentials covering a wide range of auditory stimulation levels. The results of the statistical tests should then be correlated with the findings of audiologists to determine whether the statistical tests for phase ordering would be audiologically useful.

6.7.3 The CNV's of Patients and Normals

Although several possible diagnostic procedures have been suggested, much larger samples of normals, patients with H.C. and patients with other neurological defects must be examined before these procedures could safely be adopted.

Further research should be aimed at establishing why the broadband energy tests do show additional energy whereas the tests on the individual harmonics sometimes do not. It should be possible to account for this extra energy and hence balance the energy figures. The extra energy may be contained in the d.c. term or in the higher harmonics.

The time to return to the baseline should be measured to establish whether any correlation can be detected between this and the severity of the disease.

References for Section 6

[1] McCullum W C, Walter W G, "The Effects of Attention and Distraction on the Contingent Negative Variation in Normal and Neurotic Subjects" Electroencephalography and Clinical Neurophysiology, Volume 25, pp 319-329, 1968.

[2] Quilter P M, MacGillivray B B, Wadbrook D G, "The Removal of Eye Movement Artefacts from EEG Signals using Correlation Techniques" Random Signals Analysis, IEE Conference Publication No. 159, pp 93-100.

7. Acknowledgements

I would like to thank the many people who have given me help and advice throughout the course of this research project. In particular special thanks must go to my Supervisors, Drs. Barrie Jervis (Dept. of Communication Engineering, Plymouth Polytechnic), Elaine Allen (Dept. of Neurological Sciences, Freedom Fields Hospital, Plymouth), and John Fryer (Dept. of Mathematics Statistics and Operational Research, Exeter University) for their unwavering support and encouragement. Special thanks must also go to Dr. Terry Johnson (Dept. of Mathematics, Statistics and Computing, Plymouth Polytechnic) for his advice on the use of angular statistics and allowing me to use his computer subroutines to calculate these statistics. I would particularly like to thank Mr. Nigel Hudson (Dept. of Neurological Sciences, Freedom Fields Hospital), for applying and removing the measuring electrodes from the subjects and for liaising with the consultants and next of kin of the Huntington's chorea patients.

Thanks are also due to the members of staff, both academic and technical of the Departments of Communication Engineering and Electrical & Electronic Engineering who have given their advice so freely. Special mention must be made to the advice given by Mr. Alan Roberts and Mr. Adrian Jerram concerning the PDP8 minicomputers and the hybrid computer interface utilized in the data acquisition system.

I would also like to thank the past and present members of staff of the Plymouth Polytechnic Computer Centre for their help and advice on programming matters.

For financial support I would like to thank the Devon County Local Education Authority and the Nuffield Foundation.

For permission to use their facilities I would like to thank Mr. B.R. Webster, Head of the Department of Electrical & Electronic Engineering.

For showing me their facilities and for several hours of useful and interesting discussion I would like to thank Drs. W.C. McCallum and R. Cooper of the Burden Neurological Institute, Bristol and Dr. P. Fenwick of St. Thomas' Hospital and The Institute of Psychiatry, London.

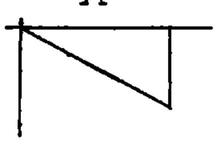
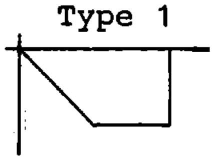
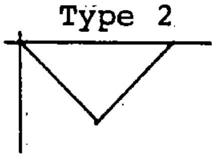
For her accurate and painstaking typing of this thesis I would like to thank Mrs. L. Mortimore.

Finally I would like to thank all those volunteers who participated in the tests and without whom this research would not have been possible.

APPENDIX 8.1

Calculation of Expected Phase Values for Idealized CNV's

By considering the CNV as one of the simple shapes shown below it is possible to calculate the resulting phase angles for each of the harmonic frequency components. These calculations were performed using a microcomputer to compute the discrete Fourier transform of each of the possible CNV shapes. The listing of the computer programme and the results are given below.

WAVESHAPE	HARMONIC					
	1	2	3	4	5	6
Type 0 	-90	-90	-90	-90	-90	-90
Type 1 	-57.4	-89.6	-77.5	-89.3	-81.9	-88.9
Type 2 	0	*	0	*	0	*

* Phase angles are indeterminate due to zero amplitudes of these harmonic components.

```
10 PI=3.14159265
20 INPUT " NUMBER OF POINTS ";N
30 DIM FT(N-1)
40 INPUT " MAXIMUM AMPLITUDE ";K
50 INPUT " WHICH TYPE OF CNV WAVESHAPE ";Q
60 IF Q=0 THEN SL=K/N
70 IF Q>0 THEN SL=2*K/N
80 INPUT " HARMONIC NUMBER ";H
90 FOR I=0 TO N-1
100 IF I < N/2 THEN FT(I)=SL*I : GOTO 140
110 IF Q=0 THEN FT(I)=SL*I
120 IF Q=1 THEN FT(I)=K
130 IF Q=3 THEN FT(I)=-SL*I+2*K
140 NEXT I
150 C=0
160 S=0
170 FOR I=0 TO N-1
180 C=C+FT(I)*COS(2*PI*I*H/N)
190 S=S-FT(I)*SIN(2*PI*I*H/N)
200 NEXT I
210 C=C/N
220 S=S/N
230 PRINT "REAL=";C;"  ";"IMAG=";S
240 TH=180/PI*ATN(S/C)
250 IF C>0  GOTO 290
260 IF S>0  THEN TH=TH+180 : GOTO 290
270 TH=TH-180
280 GOTO 290
290 PRINT "THETA=";TH
300 GOTO 80
```

APPENDIX 8.2

Transformation of the Rayleigh Probabilities to those of Circular Variance

Using the definitions given in section 2.2.2.1 a relationship may be derived between the Rayleigh statistic R and the circular variance statistic S_O. For a set of N angles $\{\theta_i\}$ the Rayleigh statistic is given by

$$R = \sqrt{\left[\sum_{i=1}^{N} \cos \theta_i\right]^2 + \left[\sum_{i=1}^{N} \sin \theta_i\right]^2}$$

Clearly this is simply N times $\bar{R}$ as defined by equation 6 of section 2.2.2.1.

$$\text{since } S_O = 1 - \bar{R}$$

$$\text{then } S_O = 1 - \frac{R}{N}$$

Hence a table of critical values of S_O may be compiled from a table of critical values of R by dividing each 'R' value by N and subtracting the resulting value from unity.

A table thus obtained is given overleaf.

Table of Critical Values of S_o

N	P			
	0.10	0.05	0.01	0.001
5	0.333	0.246	0.121	0.009
6	0.382	0.310	0.175	0.060
7	0.428	0.358	0.229	0.109
8	0.465	0.398	0.275	0.153
9	0.496	0.431	0.313	0.192
10	0.552	0.460	0.335	0.225
11	0.544	0.484	0.373	0.257
12	0.563	0.506	0.398	0.284
13	0.580	0.525	0.420	0.308
14	0.595	0.542	0.440	0.331
15	0.609	0.557	0.458	0.351
16	0.621	0.571	0.475	0.370
17	0.633	0.583	0.490	0.387
18	0.643	0.595	0.540	0.403
19	0.652	0.606	0.516	0.417
20	0.661	0.615	0.528	0.431
21	0.669	0.625	0.539	0.444
22	0.677	0.633	0.549	0.456
23	0.684	0.641	0.559	0.467
24	0.691	0.649	0.568	0.478
25	0.697	0.656	0.577	0.488
30	0.723	0.685	0.613	0.530
35	0.744	0.708	0.641	0.564
40	0.760	0.727	0.664	0.591
45	0.774	0.743	0.682	0.614
50	0.786	0.756	0.699	0.633
64	0.810	0.784	0.732	0.672

APPENDIX 8.3

Probability Levels for the Modified Rayleigh Test

The following table gives the critical values of U_o as derived from Moore [section 2 reference 5]. The derivations are calculated from

$$U_o = 1 - \frac{2\sqrt{N}\ R^*}{(N+1)}$$

Table of Critical Values of U_o

N	P 0.1	0.05	0.01	0.001
5	0.264	0.192	0.094	
6	0.320	0.248	0.139	
7	0.365	0.295	0.181	
8	0.404	0.334	0.219	
9	0.436	0.368	0.253	
10	0.462	0.397	0.282	0.176
12	0.506	0.444	0.332	0.224
14	0.541	0.483	0.375	0.266
16	0.570	0.515	0.412	0.304
18	0.594	0.541	0.443	0.336
20	0.614	0.563	0.469	0.365
22	0.631	0.583	0.491	0.389
24	0.647	0.600	0.512	0.413
30	0.684	0.641	0.560	0.470
32	0.692	0.652	0.573	0.485
40	0.725	0.688	0.617	0.535
60	0.774	0.744	0.684	0.617
64	0.782	0.752	0.695	0.629
80	0.804	0.778	0.726	0.667
100	0.826	0.802	0.755	0.700

APPENDIX 8.4

Probability Levels for the Hodges-Ajne Test

The following table gives the critical values of m for the Hodges-Ajne test.

Table of Critical Values of m

N	P			
	0.10	0.05	0.025	0.01
9	0	0	0	0
10	1	0	0	0
11	1	0	0	0
12	1	1	0	0
13	1	1	1	0
14	2	1	1	0
15	2	2	1	1
16	2	2	1	1
17	3	2	2	1
18	3	3	2	2
19	3	3	2	2
20	4	3	3	2
21	4	4	3	2
22	5	4	3	3
23	5	4	4	3
24	5	5	4	3
25	6	5	4	4
30	7	7	6	5
35	9	9	8	7
40	11	10	10	9
50	15	14	13	12
60	19	18	14	13

APPENDIX 8.5

The Paired t-Test

Where a set of experimental results fall naturally into pairs the above statistical test may be employed to establish whether a consistent difference between each of the paired values exists. An example will best illustrate the method.

Two students, X and Y, measured the resistance of twelve resistors. Each student measured all the resistors and the results they obtained are shown in the table.

	RESISTOR											
STUDENT	1	2	3	4	5	6	7	8	9	10	11	12
X	100	90	130	110	117	75	32	88	41	57	18	67
Y	105	91	128	109	119	77	32	87	36	60	21	72

Are one students results consistently higher than the others?

The differences are first calculated;

$$x = -5 \quad -1 \quad 2 \quad 1 \quad -2 \quad -2 \quad 0 \quad 1 \quad 5 \quad -3 \quad -3 \quad -5$$

If there was no consistent difference between the students measurements then the differences should form a zero mean normal distribution. The t-test is used to test this hypothesis.

$$\text{Mean value} = \bar{x} = \frac{\Sigma x}{N}$$

$$= \frac{-12}{12}$$

$$\bar{x} = -1$$

An estimate of the variance is given by

$$\hat{\sigma}^2 = \frac{1}{N-1}\left[\Sigma x^2 - \frac{(\Sigma x)^2}{N}\right]$$

$$= \frac{1}{12-1}\left[108 - \frac{(-12)^2}{12}\right]$$

$$= 8.73$$

$$\therefore \quad \hat{\sigma} = 2.95$$

The t statistic is given by

$$t = \frac{|\bar{x} - \mu|}{\frac{\hat{\sigma}}{\sqrt{N}}}$$

$$= \frac{|-1 - 0|}{2.95} \qquad 12$$

$$t = 1.17 \text{ with } (N-1) \text{ degrees of freedom.}$$

Tables of the t statistic show that with 11 degrees of freedom a value of 1.17 is not significant. Hence there is no evidence that one students measurements are higher than the others.

APPENDIX 8.6

The t-Test

Because of the relatively small number of observations made in some of our tests the t statistic was used in preference to the normal Z statistic. Frequently the question to be resolved was "could these two sets of observiatons have come from the same parent population?"

Where this was so the test statistic was calculated according to the formula

$$t = \frac{\bar{X}_A - \bar{X}_B}{\sqrt{\frac{S_A^2}{N_A} + \frac{S_B^2}{N_B}}}$$

where $\bar{X}_A$ was the calculated mean of the N_A observations

$\bar{X}_B$ was the calculated mean of the N_B observations

S_A was the standard deviation of the 'A' observations

S_B was the standard deviation of the 'B' observations

Furthermore since the variances S_A^2 and S_B^2 were only estimates of the variances of the entire population, a 'pooled sum of squares' method was used to estimate the number of degrees of freedom to be used with the t statistic. This was calculated from the formula

$$\nu = \frac{\left[\frac{S_A^2}{N_A} + \frac{S_B^2}{N_B}\right]^2}{\frac{\left[\frac{S_A^2}{N_A}\right]^2}{N_A + 1} + \frac{\left[\frac{S_B^2}{N_B}\right]^2}{N_B + 1}} - 2$$

which although rather complex, caused no extra work since both the t statistic and the number of degrees of freedom were calculated by computer. (Had the calculations been made by hand then the F test would have been used to establish whether the variances S_A^2 and S_B^2 were sufficiently different to warrant calculation of ν by the formula given in place of $N_A + N_B - 2$).

When the appropriate values of t and ν had been ascertained then the tables were consulted to determine whether the test was significant or not. If the test was "is $\overline{X}_A$ less than $\overline{X}_B$?" or "is $\overline{X}_A$ greater than $\overline{X}_B$?" then a 'one tailed' test was performed whereas if the test was "is $\overline{X}_A$ different from $\overline{X}_B$?" then a two tailed test was performed. The only difference between these two tests is that the tables give areas (i.e. probabilities) for one tail only. Thus for two tailed tests the probabilities must be doubled.

APPENDIX 8.7

FORTRAN Programme 'DATAPLOT'

This programme was used for plotting the raw EOG/EEG data on a graphics terminal or graph plotter. The programme uses the GINO graphics subroutines. Listings of subroutines 'DATIN' and 'GETNAM' which are used to read the data in from a data file and to obtain a filename from the user are given in Appendix 8.12.

The listing of programme 'DATAPLOT' follows.

```
C           A PROGRAMME TO PLOT THE EOG / EEG DATA
C           ON THE TEKTRONIX 4010.
C
      INTEGER*2 INP(1024),RNAME(20),IBATNO
      LOGICAL CSE
      DATA CSE/.FALSE./
    1 WRITE(1,2)
    2 FORMAT('TEKTRONIX(0) OR CALCOMP(1) OUTPUT')
      READ(1,*,ERR=1)IDEVIC
C           NOMINATE THE REQUIRED DEVICE
      IF(IDEVIC.EQ.1)CALL CC906
      IF(IDEVIC .EQ. 0)CALL T4010
      IBAUD=1200
      CALL DEVSPE(IBAUD)
      CALL UNITS(0.24)
      CALL GETNAM(RNAME)
   18 WRITE(1,20)
   20 FORMAT('WHICH BATCH')
   22 READ(1,*,ERR=18)IBATNO
      IF(IBATNO .LT. 0)GO TO 999
      IF(FLOAT(IBATNO/6) .NE. FLOAT(IBATNO)/6.)GO TO 18
   24 WRITE(1,27)
   27 FORMAT('SCALE FACTOR')
      READ(1,*,ERR=24)SCALE
C           SET FOR SOLID LINES.
C           AND CLEAR THE SCREEN.
      CALL PICCLE
      CALL BROKEN(0)
      STX=150.
      X=STX
      STY=70.
      Y=0.
      CALL MOVTO2(X,Y)
      DO 200 I=1,6
      Y=Y+20.
      CALL MOVTO2(X,Y)
      Y=Y+100.
  200 CALL LINTO2(X,Y)
      Y=70.
      DO 300 I=1,6
      X=STX
      CALL MOVTO2(X,Y)
      X=950.
      CALL LINTO2(X,Y)
  300 Y=Y+120.
      KBAT=IBATNO
      CALL MOVTO2(40.,740.)
      CALL CHAHOL('DATA FROM FILE *.')
      CALL CHAARR(RNAME,20,2)
      CALL MOVTO2(0.,690.)
      CALL CHAHOL('VL EOG*.')
      CALL MOVTO2(20.,650.)
      CALL CHAINT(KBAT,3)
      CALL MOVTO2(0.,570.)
      CALL CHAHOL('VR EOG*.')
      KBAT=KBAT+1
      CALL MOVTO2(20.,530.)
      CALL CHAINT(KBAT,3)
      CALL MOVTO2(0.,450.)
      CALL CHAHOL('HL EOG*.')
      KBAT=KBAT+1
      CALL MOVTO2(20.,410.)
      CALL CHAINT(KBAT,3)
      CALL MOVTO2(0.,330.)
      CALL CHAHOL('HR EOG*.')
      KBAT=KBAT+1
      CALL MOVTO2(20.,290.)
      CALL CHAINT(KBAT,3)
      CALL MOVTO2(0.,210.)
      CALL CHAHOL('M1 EEG*.')
      KBAT=KBAT+1
      CALL MOVTO2(20.,170.)
      CALL CHAINT(KBAT,3)
      CALL MOVTO2(0.,90.)
      CALL CHAHOL('M2 EEG*.')
      KBAT=KBAT+1
      CALL MOVTO2(20.,50.)
      CALL CHAINT(KBAT,3)
      YD=600.
      LE=IBATNO
```

```
      DO 400 L=1,6
      Y=STY+YD
      X=STX
      CALL MOVTO2(X,Y)
      CALL DATIN(LE,INP,RNAME,SF1,SF2,SAMRAT,CSE)
      DO 350 I=1,1024
      Y=FLOAT(INP(I))*SF1*SCALE
      IF(L .GE. 5)Y=Y*SF2/SF1
      Y=Y/10. + STY + YD
      X=X+0.78125
  350 CALL LINTO2(X,Y)
      LE=LE+1
  400 YD=YD-120.
      CALL MOVTO2(0.,0.)
      CALL CHAMOD
      GO TO 22
  999 CALL PICCLE
      CALL DEVEND
      CSE=.TRUE.
      CALL DATIN(IBATNO,INP,RNAME,SF1,SF2,SAMRAT,CSE)
      CALL EXIT
      END
```

APPENDIX 8.8

FORTRAN Programme used in the Analysis of the Eye Movement Correction Methods

This programme was used to calculate the correction constants for the four channel eye movement correction method. The calculated constants were printed and applied to the data to give the corrected EEG signal. The autocorrelation function of the corrected signal was subsequently calculated and plotted on a graphic terminal. Subroutine 'MES1' was then used to measure both the a.c.c. and the frequency of the a.c.f. by means of the graphics cursor which was set by the user to the appropriate points on the graph.

The autocorrelation function of the signal corrected by the method of McCallum and Walter (and stored as the sixth data channel) was finally calculated and plotted. Once again subroutine 'MES1' was used to estimate the a.c.c. and the frequency of the a.c.f.

The subroutines used are listed after the main programme. Although having similar names these subroutines are not necessarily the same as some of those listed in Appendix 8.12.

The programme listing follows:-

```
C             THIS PROGRAM IS INTENDED TO MINIMISE THE AMOUNT OF
C             E.O.G POWER IN THE E.E.G. IT USES THE MODIFIED
C             QUILTER TECHNIQUE. HORIZONTAL AND VERTICAL COMPONENTS
C             OF BOTH EYES ARE TAKEN INTO CONSIDERATION.
C             THE PROGRAM REMOVES ANY D.C OFFSET ON ANY OF
C             THE INPUT DATA CHANELS.
      REAL M1M,M2M
      REAL VL(1024),VR(1024),HL(1024),HR(1024),M1(1024),M2(1024)
      DIMENSION X1(4,5),X2(4,5),RM1(4),RM2(4)
      DIMENSION CORI(1024)
      DIMENSION COVAR1(512),COVAR2(512)
      INTEGER*2 BATNO,INP(1024),FNAME(7)
      LOGICAL CSE
      CSE=.FALSE.
      N=1024
      NCORL=512
C             READ THE NUMBER OF THE FIRST BATCH OF DATA
C             TO BE PROCESSED.
C             THE DATA IS ASSUMED TO BE IN THE FOLLOWING
C             ORDER ; VL , VR , HL , HR , M1 , M2
C             M1 IS  THE CHANNEL TO BE CORRECTED BY THE
C             MODIFIED QUILTER TECHNIQUE.
C             M2 IS THE CHANNEL CORRECTED BY THE BURDEN TECHNIQUE.
C             GET THE SCALE FACTORS FROM THE DATA FILE.
C             SF1 FOR EOG DATA. SF2 FOR EEG DATA.
    5 WRITE(1,6)
    6 FORMAT('4 CHANNEL EYE MOVEMENT CORRECTION PROGRAM')
      CALL GETNAM(FNAME)
      WRITE(1,10)
   10 FORMAT('WHICH BATCH OR -1 TO QUIT')
      READ(1,*)BATNO
      IF(BATNO .LT. 0)GO TO 5000
C             CHECK THAT THE BATCH NUMBER IS VALID.
      IF(BATNO .GT. 191)GO TO 2999
      IF(FLOAT(BATNO/6) .NE. FLOAT(BATNO)/6.)GO TO 2999
      WRITE(1,14)
   14 FORMAT('FILTER THE BURDEN SIGNAL(0) NO (1) YES')
      READ(1,*)IBRDFL
      WRITE(1,16)
   16 FORMAT('FILTER THE CORRECTED SIGNAL(0) NO (1) YES')
      READ(1,*)ICRRFL
      WRITE(1,18)
   18 FORMAT('PLOT THE CORRECTED WAVEFORM')
      READ(1,*)IPLTCR

   20 WRITE(1,22)BATNO
   22 FORMAT('EYE MOVEMENT CORRECTIONS 4 CHAN. BATCH',I5)
      WRITE(1,24)FNAME
   24 FORMAT('DATA FILE ',7A2,///)
      L=BATNO
C             READ THE DATA AND CONVERT TO REAL FORMAT.
      CALL DATIN(L,INP,FNAME,SF1,SF2,SAMRAT,CSE)
      DO 32 I=1,N
   32 VL(I)=FLOAT(INP(I))*SF1
      L=L+1
      CALL DATIN(L,INP,FNAME,SF1,SF2,SAMRAT,CSE)
      DO 34 I=1,N
   34 VR(I)=FLOAT(INP(I))*SF1
      L=L+1
      CALL DATIN(L,INP,FNAME,SF1,SF2,SAMRAT,CSE)
      DO 36 I=1,N
   36 HL(I)=FLOAT(INP(I))*SF1
      L=L+1
      CALL DATIN(L,INP,FNAME,SF1,SF2,SAMRAT,CSE)
      DO 38 I=1,N
   38 HR(I)=FLOAT(INP(I))*SF1
      L=L+1
      CALL DATIN(L,INP,FNAME,SF1,SF2,SAMRAT,CSE)
      DO 40 I=1,N
   40 M1(I)=FLOAT(INP(I))*SF2
      L=L+1
      CALL DATIN(L,INP,FNAME,SF1,SF2,SAMRAT,CSE)
      DO 52 I=1,N
   52 M2(I)=FLOAT(INP(I))*SF2
      WRITE(1,56)SF1,SF2
   56 FORMAT('SF1= ',F8.6,'   SF2= ',F8.6)
C             SUBTRACT THE MEAN OF EACH DATA BATCH FROM THE DATA.
      CALL SMEAN(N,VL,VLM)
      CALL SMEAN(N,VR,VRM)
      CALL SMEAN(N,HL,HLM)
```

```
      CALL SMEAN(N,HR,HRM)
      CALL SMEAN(N,M1,M1M)
C             FORM THE CORRELATION SUMS OF PRODUCTS.
      A=0.
      B=0.
      C=0.
      D=0.
      E=0.
      F=0.
      G=0.
      P=0.
      Q=0.
      R=0.
      S=0.
      T=0.
      U=0.
      V=0.
      DO 100 I=1,N
      A=A+VL(I)*VL(I)
      B=B+VL(I)*VR(I)
      C=C+VL(I)*HL(I)
      D=D+VL(I)*HR(I)
      E=E+VR(I)*VR(I)
      F=F+VR(I)*HL(I)
      G=G+VR(I)*HR(I)
      P=P+HL(I)*HL(I)
      Q=Q+HL(I)*HR(I)
      R=R+HR(I)*HR(I)
      S=S+M1(I)*VL(I)
      T=T+M1(I)*VR(I)
      U=U+M1(I)*HL(I)
      V=V+M1(I)*HR(I)
  100 CONTINUE
      X1(1,1)=A
      X1(1,2)=B
      X1(1,3)=C
      X1(1,4)=D
      X1(2,2)=E
      X1(2,3)=F
      X1(2,4)=G
      X1(3,3)=P
      X1(3,4)=Q
      X1(4,4)=R
      X1(1,5)=S
      X1(2,5)=T
      X1(3,5)=U
      X1(4,5)=V
C             SET UP SYMMETRICAL MATRIX.
      X1(2,1)=X1(1,2)
      X1(3,1)=X1(1,3)
      X1(4,1)=X1(1,4)
      X1(3,2)=X1(2,3)
      X1(4,2)=X1(2,4)
      X1(4,3)=X1(3,4)
C             SOLVE THE SIMULTANEOUS EQUATIONS BY THE
C             GAUSS PIVOTAL METHOD.
      MSIZE=4
      CALL GAUSS(MSIZE,X1,RM1)
      IF(IBRDFL .EQ. 1)CALL FILTER(N,M2)
      WRITE(1,150)
  150 FORMAT(' THE CORRECTION CONSTANTS ARE ',//)
      WRITE(1,160)
  160 FORMAT(10X,'VL * ',10X,'VR * ',10X,'HL * ',10X,'HR * ')
      WRITE(1,200)(RM1(I),I=1,4)
  200 FORMAT(4(3X,F12.5))
C             APPLY THE CORRECTIONS TO THE DATA.
      DO 220 I=1,N
      COR1(I)=M1(I) - (RM1(1)*VL(I) + RM1(2)*VR(I) + RM1(3)*HL(I)
     1+ RM1(4)*HR(I))
  220 CONTINUE
C             PLOT THE CORRECTED DATA.
C             CALCULATE AND PRINT THE CROSS CORRELATIONS
      IF(ICRRFL .EQ. 1)CALL FILTER(N,COR1)
      IF(IPLTCR .EQ. 1)CALL GRAPH3(N,COR1,SAMRAT)
      SC=200.
      CALL AUTCO(N,COR1,NCORL,COVAR1)
      CALL GRAPH3(NCORL,COVAR1,SAMRAT)
      WRITE(1,240)
  240 FORMAT('MEASURE(0) NO (1) YES')
      READ(1,*)IMES
```

```
      IF(IMES .EQ. 1)CALL MES1
      CALL AUTCO(N,M2,NCORL,COVAR2)
      CALL TNOUA('WAITING, BURDEN ACF NEXT',24)
      READ(1,*)IWT
      CALL GRAPH3(NCORL,COVAR2,SAMRAT)
      WRITE(1,240)
      READ(1,*)IMES
      IF(IMES .EQ. 1)CALL MES1
      GO TO 5
2999  WRITE(1,4000)BATNO
4000  FORMAT(' BATCH NUMBER INCORRECT',I6)
5000  CSE=.TRUE.
      CALL DATIN(L,INP,FNAME,SF1,SF2,SAMRAT,CSE)
      CALL DEVEND
      CALL EXIT
      END
```

```
      SUBROUTINE MES1
C
C                 MEASURES THE ACC & FREQUENCY
C                 BY MEANS OF THE GRAPHICS CURSOR.
C
      WRITE(1,10)
   10 FORMAT('GIVE CO-ORDS. FOR ACF')
      CENLIN=0.
      XM=400.
      XS=100.
      YS=390.
      CALL CURSOR(ICOM,X,Y)
      X=X-XS
      Y=Y-YS
      CALL CURSOR(ICOM,X1,Y1)
      X1=X1-XS
      Y1=Y1-YS
      S1=(Y-Y1)/(X-X1)
      C1=Y1-S1*X1
C             DRAW FIRST CONSTRUCTION LINE
C
      XL1=50.
      XL2=750.
      YL1=S1*XL1 + C1
      CALL MOVTO2(XL1+XS,YL1+YS)
      YL2=S1*XL2 + C1
      CALL LINTO2(XL2+XS,YL2+YS)
      CALL CURSOR(ICOM,X,Y)
      X=X-XS
      Y=Y-YS
      CALL CURSOR(ICOM,X1,Y1)
      X1=X1-XS
      Y1=Y1-YS
      S2=(Y-Y1)/(X-X1)
      C2=Y1-S2*X1
C              DRAW SECOND CONSTRUCTION LINE
C
      YL1=S2*XL1 + C2
      CALL MOVTO2(XL1+XS,YL1+YS)
      YL2=S2*XL2 + C2
      CALL LINTO2(XL2+XS,YL2+YS)
C
      A=(ATAN(S1)+ATAN(S2))/2.
      S=SIN(A)/COS(A)
      C=(C1+C2)/2.
      IF(CENLIN .EQ. 1.)CALL MOVTO2(XL1+XS,YS+S*XL1+C)
      IF(CENLIN .EQ. 1.)CALL LINTO2(XL2+XS,YS+S*XL2+C)
C              TEST FOR ZERO SLOPE
C
      IF(S .EQ. 0.)GO TO 100
      S3=-1./S
      YM=S*XM+C
      C3=YM-S3*XM
      XP1=(C1-C3)/(S3-S1)
      XP2=(C2-C3)/(S3-S2)
      YP1=S3*XP1 + C3
      YP2=S3*XP2 + C3
      DY=SQRT((XP1-XP2)*(XP1-XP2) + (YP1-YP2)*(YP1-YP2))/400.
      GO TO 200
  100 YP1=S1*XM + C1
      YP2=S2*XM + C2
      DY=ABS(YP1-YP2)/400.
  200 CALL MOVTO2(0.,700.)
      CALL CHAMOD
      WRITE(1,210)
  210 FORMAT('GIVE CO-ORDS. FOR TIME MEASUREMENT')
      CALL CURSOR(ICOM,X,Y)
      CALL CURSOR(ICOM,X1,Y1)
      DX=(ABS(X-X1)/800.)*4.096
      F=1./DX
      CALL MOVTO2(0.,650.)
      CALL CHAMOD
      WRITE(1,240)DY,F
  240 FORMAT('ACF = ',F8.4,10X,'FREQ = ',F9.6)
      RETURN
      END

      SUBROUTINE GETNAM(NAME)
C
C                GETS A FILENAME FROM THE USER
```

```
C
      INTEGER*2 NAME(7),TBUFF(7)
      DATA TBUFF / 'NO','NA','ME','GI','VE','N ','!!'/
    6 WRITE(1,8)
    8 FORMAT('GIVE NAME OF FILE TO BE PROCESSED')
      READ(1,10)NAME
   10 FORMAT(7A2)
      IF(NAME(1) .EQ. '  ')GO TO 100
      DO 20 I=1,7
   20 TBUFF(I)=NAME(I)
      RETURN
  100 DO 120 I=1,7
  120 NAME(I)=TBUFF(I)
      RETURN
      END

      SUBROUTINE AUTCO(NPOINT,DATA,NCOREL,AUTOCF)
C
C               CALCULATES THE ACF
C
      DIMENSION DATA(NPOINT),AUTOCF(NCOREL),DATAZM(1024)
      INTEGER*2 Z1
      AMEAN=0.
      DO 10 I=1,NPOINT
   10 AMEAN=AMEAN+DATA(I)
      AMEAN=AMEAN/FLOAT(NPOINT)
      DO 15 I=1,NPOINT
   15 DATAZM(I)=DATA(I)-AMEAN
      DO 25 I=1,NCOREL
      II=I-1
      STORE=0.
      Z1=NPOINT-II
      DO 20 J=1,Z1
   20 STORE=STORE+DATAZM(J)*DATAZM(J+II)
   25 AUTOCF(I)=STORE
      STORE=ABS(AUTOCF(1))
      DO 30 I=1,NCOREL
   30 AUTOCF(I)=AUTOCF(I)/STORE
      RETURN
  999 WRITE(1,40)NPOINT,NCOREL
   40 FORMAT('ERROR IN NUMBER OF CORRELATIONS',2I8)
      STOP
      END

      SUBROUTINE SMEAN(NPTS,DATA,RMEAN)
C
C               SUBTRACTS THE MEAN VALUE FROM THE DATA.
C
      DIMENSION DATA(NPTS)
      RMEAN=0.
      DO 20 I=1,NPTS
   20 RMEAN=RMEAN+DATA(I)
      RMEAN=RMEAN/NPTS
      DO 30 I=1,NPTS
   30 DATA(I)=DATA(I)-RMEAN
      RETURN
      END

      SUBROUTINE FILTER(NPTS,XT)
C
C               LOW PASS FILTER THE DATA.
C
      DIMENSION XT(NPTS),ZA(11),ZB(21),DATOUT(1024)
      ZA(1)=0.03125
      ZA(2)=0.
      ZA(3)=-0.09375
      ZA(4)=0.
      ZA(5)=0.3125
      ZA(6)=0.5
      ZA(7)=0.3125
      ZA(8)=0.
      ZA(9)=-0.09375
      ZA(10)=0.
      ZA(11)=0.03125
      ZB(1)=0.03125
      ZB(2)=0.
      ZB(3)=0.
      ZB(4)=0.
      ZB(5)=-0.09375
      ZB(6)=0.
```

```
      ZB(7)=0.
      ZB(8)=0.
      ZB(9)=0.3125
      ZB(10)=0.
      ZB(11)=0.5
      ZB(12)=0.
      ZB(13)=0.3125
      ZB(14)=0.
      ZB(15)=0.
      ZB(16)=0.
      ZB(17)=-0.09375
      ZB(18)=0.
      ZB(19)=0.
      ZB(20)=0.
      ZB(21)=0.03125
      M=11
      DO 21 I=1,NPTS
      J=M
      STORE=0.
      IF(M .LT. I)GO TO 19
      STORE=XT(I)
      GO TO 21
   19 DO 20 K=1,J
   20 STORE=STORE + XT(I-K+1)*ZA(K)
   21 DATOUT(I)=STORE
      DO 30 I=1,NPTS
   30 XT(I)=DATOUT(I)
      M=21
      DO 41 I=1,NPTS
      J=M
      STORE=0.
      IF(M .LT. I)GO TO 39
      STORE=XT(I)
      GO TO 41
   39 DO 40 K=1,J
   40 STORE=STORE + XT(I-K+1)*ZB(K)
   41 DATOUT(I)=STORE
      DO 50 I=1,NPTS
   50 XT(I)=DATOUT(I)
      RETURN
      END

      SUBROUTINE GAUSS(K,B,X)
C                      A SUBROUTINE TO SOLVE SIMULTANEOUS
C                      EQUATIONS BY THE GAUSS PIVOTAL METHOD
      DIMENSION A(4,5),X(4),B(4,5)
      INTEGER*2 Z1,Z2,Z3,Z4,Z5,Z6,Z7
      Z1=K+1
      DO 10 I=1,K
      DO 10 J=1,Z1
   10 A(I,J)=B(I,J)
C                      SAVE INPUT DATA
      Z2=K-1
      DO 35 I=1,Z2
      L=I
      DO 15 J=I,K
   15 IF(ABS(A(L,I)) .LT. ABS(A(J,I)))L=J
      IF(ABS(A(L,I)) .EQ. 0.)GO TO 60
      IF(L .EQ. I)GO TO 21
      Z3=K+1
      DO 20 N=I,Z3
      SAVE=A(I,N)
      A(I,N)=A(L,N)
   20 A(L,N)=SAVE
C                      PIVOTAL REDUCTION
   21 Z4=I+1
      DO 35 M=Z4,K
      D=A(M,I)/A(I,I)
      Z5=I+1
      Z6=K+1
      DO 35 J=Z5,Z6
   35 A(M,J)=A(M,J)-D*A(I,J)
C                      BACK SUBSTITUTION
      DO 50 L=1,K
      J=K+1-L
      IF(J .EQ. K)GO TO 45
      Y=A(J,K+1)
      Z7=K-1
      DO 40 M=J,Z7
   40 Y=Y-A(J,M+1)*X(M+1)
```

```
      X(J)= Y/A(J,J)
      IF(J .NE. K)GO TO 50
   45 X(J)=A(J,K+1)/A(J,J)
   50 CONTINUE
      RETURN
   60 WRITE(1,65)
   65 FORMAT('ERROR MESSAGE ZERO COLUMN FOUND')
      STOP
      END

      SUBROUTINE DATIN(IBATNO,IDATA,RNAME,SF1,SF2,SAMRAT,CSE)
C
C                GETS DATA FROM THE DATA FROM SPECIFIED
C                DATA FILE.
C
$INSERT SYSCOM>A$KEYS
      INTEGER*2 IDATA(1024),ONAME(7),RNAME(7),TITLE(36),NME(6)
      INTEGER*2 RWKEY,NLEN,NLEN2,PRIMNO,NBAT,IBATNO,IAA1(4)
      LOGICAL OPEN,NEOPEN,CSE
      DATA NEOPEN /.FALSE./
      RWKEY=1
      PRIMNO=1
      NLEN=14
      NLEN2=NLEN/2
      IF(NEOPEN)GO TO 1300
      IF(CSE)RETURN
  900 OPEN=OPEN$A(RWKEY,RNAME,NLEN,PRIMNO)
      IF(.NOT. OPEN)GO TO 1700
      DO 1000 IC=1,NLEN2
 1000 ONAME(IC)=RNAME(IC)
      NEOPEN=.TRUE.
      READ(5,3000,END=1800,ERR=1900)NME,SF1,SF2
      READ(5,3010,END=1800,ERR=1900)MAXBAT
      READ(5,3020,END=1800,ERR=1900)TITLE
      DO 234 IL=1,4
  234 IAA1(IL)=TITLE(IL+20)
      DECODE (8,236,IAA1)SAMRAT
  236 FORMAT(F8.4)
 1100 READ(5,END=1800,ERR=1900)NBAT
      READ(5,END=1800,ERR=1900)(IDATA(I),I=1,1024)
      IF(NBAT .NE. IBATNO)GO TO 1100
      NBAT=NBAT+1
      RETURN
 1200 OPEN=CLOS$A(PRIMNO)
      IF(.NOT. OPEN)GO TO 1600
      NEOPEN=.FALSE.
      RETURN
 1300 IF(CSE)GO TO 1200
      DO 1400 IC=1,NLEN2
 1400 IF(ONAME(IC) .NE. RNAME(IC))GO TO 1500
      IF(IBATNO .GE. NBAT)GO TO 1100
 1500 OPEN=CLOS$A(PRIMNO)
      IF(OPEN)GO TO 900
 1600 WRITE(1,1610)ONAME
 1610 FORMAT('*** CANT CLOSE FILE ',7A2,' ***')
      STOP 1
 1700 WRITE(1,1710)RNAME
 1710 FORMAT('*** CANT OPEN FILE ',7A2,' ***')
      STOP 2
 1800 WRITE(1,1810)RNAME
 1810 FORMAT('*** END OF FILE ',7A2,' ***')
      STOP 3
 1900 WRITE(1,1910)IBATNO,RNAME
 1910 FORMAT('*** ERROR TRYING TO READ BATCH ',I5,' FROM FILE ',7A2,
     +' ***')
      STOP 4
 3000 FORMAT(6A2,2F8.6)
 3010 FORMAT(I4)
 3020 FORMAT(36A2)
      END

      SUBROUTINE GRAPH3(N,DATA,SAMRAT)
C
C                PLOTS A GRAPH ON THE REQUESTED GRAPHICS DEVICE.
C
      DIMENSION DATA(N),XARRY(1024),YARRY(1024)
      INTEGER*2 IYLAB(7),IYLAB2(9)
      LOGICAL INIT
      DATA INIT/.FALSE./
      DATA IYLAB / 'MI','CR','O-','VO','LT','S ','*.' /
```

```
      DATA IYLAB2 / 'AU','TO','CO','RR','EL','AT','IO','NS','*.' /
      IACF=0
      IF(INIT)GO TO 50
      CALL T4010
      IBAUD=1200
      CALL DEVSPE(IBAUD)
      CALL UNITS(0.24)
   50 CALL PICCLE
      CALL WINDOW(0)
      CALL CHASIZ(15.,15.)
      DO 60 I=1,N
      XARRY(I)=FLOAT(I)/SAMRAT
      YARRY(I)=DATA(I)
   60 CONTINUE
      CALL MOVTO2(450.,0.)
      CALL CHAHOL('TIME  SECONDS*.')
      CALL MOVTO2(50.,300.)
      CALL CHAANG(90.)
      IF(IACF .EQ. 0)GO TO 100
      CALL CHAARR(IYLAB2,9,2)
      GO TO 150
  100 CALL CHAARR(IYLAB,7,2)
  150 CALL CHAANG(0.)
      CALL GRAF(XARRY,YARRY,N,0)
      CALL MOVTO2(0.,779.)
      CALL CHAMOD
      INIT=.TRUE.
      RETURN
      END
```

APPENDIX 8.9

Special Instructions for Peripheral Control

The following instructions were used to control the peripheral devices connected to the PDP8 minicomputer. Since these peripherals were not part of the standard PDP8 equipment, the instructions controlling them are described in detail in this appendix.

OCTAL CODE	MNEMONIC	DESCRIPTION
6056	OUTX	Load the 10 least significant bits of the accumulator into the X 10 bit D/A converter and convert to analogue. Pulse the Z modulation output. This instruction was used for X-Y display of stored data.
6066	OUTY	As above but for the Y D/A converter.
6412	SION*	Enable the interrupt facility from the hybrid computer interface Skip/Interrupt inputs.
6414	SIOF*	Disable the interrupt facility from the the hybrid computer interface Skip/ Interrupt inputs.
6441	ADINP*	Load the 12 bit word from the analogue to digital converter into the accumulator.
6442	STC *	Start the conversion process on the 12 bit A/D converter. (Conversion takes approximately 3.5μs)
6451	MXR *	Set the multiplexer to select the channel number given by the 3 least significant bits of the accumulator. (i.e. channels 0-7).
6501	ACOUT*	Load the accumulator into the output register available on the hybrid computer Patch Panel.

OCTAL CODE	MNEMONIC	DESCRIPTION
6504	ACIN*	Load the accumulator from the input register on the hybrid computer interface Patch Panel.
6511	SK1*	Skip the next instruction if the Patch Panel number one input is at a logical '1'.
6221	SDR	Skip the next instruction if the serial data transceiver has received a byte of data.
6622	DUI	Disable interrupts from the serial data transceiver.
6624	STR	Skip the next instruction if the serial data transceiver is ready to transmit a new data byte.
6631	RUD	Read the received data from the serial data transceiver into the 8 †1 least significant bits of the accumulator. Clear the SDR flag.
6632	ERI	Enable the received data interrupt facility on the serial data transceiver (i.e. allow interrupts to occur when serial data is received).
6634	LSTAT	Load the 5 least significant bits of the accumulator into the serial data transceiver status control register †2.
6641	SKERR	Skip the next instruction if either a praming, parity or over-run error has occurred in receiving serial data.
6642	ETI	Enable the transmitter interrupt facility on the serial data transceiver. (i.e. allow interrupts to occur whenever the serial data transmitter is not busy).
6644	OUT	Load the 8 †1 least significant bits of the accumulator into the serial data transmitter and transmit. Clear the STR flag.

Notes

* These peripherals are part of the Hybrid Computer Interface [see Section 4 reference 3].

†1 May be less than 8 bits. This depends on the setting of the Universal Asynchronous Receiver Transmitter status control register.

†2 The 5 control bits have the following functions

ACCUMULATOR BIT	FUNCTION
11	Parity inhibit. A '1' disables the generation and checking of the parity bit.
10	Stop bit select. A '1' gives two stop bits. A '0' gives one stop bit.
9	Character length select. Bits 8 and 9 allow characters of either 5,6,7 or 8 bits to be transmitted and received.
8	bit 8 9 0 0 5 bits 0 1 6 bits 1 0 7 bits 1 1 8 bits
7	Even parity enable. A logical '1' selects even parity. A logical '0' selects odd parity. (Subject to bit 11 being a logical '1'.

APPENDIX 8.10

PAL 8 Computer Programme Used to Control the Data Acquisition Process

This programme was used to control the A-D converter, the multiplexer, the serial interface, the stimulus presentation and an X-Y display during the acquisition of the EEG data. The programme was started and controlled by means of the console switches. The starting address is 200_8 in field zero. Two locations (131_8 and 132_8) must be set, by means of the console switch register, to contain the two's complement of the sample numbers at which time the stimulus pulses are to be presented.

e.g. If the S1 stimulus is to be presented after 200_{10} samples have been taken, then location 131_8 must be set to contain 7470_8. ($200_{10} \equiv 310_8$)

Whilst running the programme will show on an X-Y display whichever channel is selected by the three least significant console switches.

The assembly language listing follows.

```
                    / ON LINE CNV DATA AQUISITION PROGRAM
                    / ---------------------------------
                    /
                    /
                    /  THIS PROGRAM CONTROLS
                    /  THE MULTIPLEXER, THE A-D CONVERTER
                    /  THE S1 AND S2 SIGNALS AND THE SERIAL
                    /  DATA OUTPUT DURING THE ACQUISITION OF 6
                    /  CHANNELS OF ANALOGUE DATA.
                    /
                    /
                    /       MEMORY MAP
                    /       ----------
                    /
                    / FIELD ZERO
                    / ----------
                    /
                    / 0000 TO 2777          AREA FOR PROGRAM
                    /
                    / 3000 TO 3577          SOFTWARE STACK AREA
                    /
                    / 3600 TO 5577          CHANNEL 4
                    /
                    / 5600 TO 7577          CHANNEL 5
                    /
                    / 7600 TO 7777          DEC SOFTWARE (RIM & BIN)
                    /
                    / FIELD ONE
                    / ---------
                    /
                    / 0000 TO 1777          CHANNEL 0
                    /
                    / 2000 TO 3777          CHANNEL 1
                    /
                    / 4000 TO 5777          CHANNEL 2
                    /
                    / 6000 TO 7777          CHANNEL 3
                    /
                    /-------------------------------------------
      0000  *0
00000 0000          0
00001 5440          JMP I ISERV
      0020  *20
                            /
                            / SUBROUTINE POINTERS
                            /
00020 0517  IUARTT, UARTTX
00021 1101  ITTYRX, TTYRX
00022 1046  ITTYTX, TTYTX
00023 0464  ITIMR,  TIMER
00024 1000  ISAM,   SAMPLE
00025 1070  ICVRT,  CVRT
00026 1034  IMPXR,  MPXR
00027 0600  IINC,   INCR1
00030 0436  IRETN,  RETN
00031 0632  IPOIN1, POIN1
00032 0673  IPOIN2, POIN2
00033 0615  IINCR2, INCR2
00034 1102  IRSTIN, RSTIN
00035 1121  IRSTOU, RSTOU
00036 1047  IWTBL,  WTBL
00037 1061  IRNDWT, RNDWT
00040 0400  ISERV,  SERV
00041 0421  ISTRT,  STRT
00042 1200  IDISP,  DISPLA
00043 1157  IINC3,  INC3
00044 1232  IPOIN3, POIN3
00045 1140  IRSTD,  RSTD
                            /
                            / CONSTANTS ETC.
                            /
```

```
00046  0000  TAC,     0
00047  0000  TFG,     0
00050  0000  PRIOR,   0
00051  0000  P0,      0
00052  2000  P1,      2000
00053  4000  P2,      4000
00054  6000  P3,      6000
00055  3600  P4,      3600
00056  5600  P5,      5600
00057  0000  ZEROP,   0
00060  0000  ONEP,    0
00061  0000  TWOP,    0
00062  0000  THREEP,  0
00063  0000  FOURP,   0
00064  0000  FIVEP,   0
00065  0000  D0P,     0
00066  0000  D1P,     0
00067  0000  D2P,     0
00070  0000  D3P,     0
00071  0000  D4P,     0
00072  0000  D5P,     0
00073  0000  D0P,     0
00074  0000  D1P,     0
00075  0000  D2P,     0
00076  0000  D3P,     0
00077  0000  D4P,     0
00100  0000  D5P,     0
00101  0000  SAVE,    0
00102  0000  MADD,    0
00103  0000  OUCHN,   0
00104  0000  CURPNT,  0
00105  0000  CUROP,   0
00106  0000  SWSP,    0
00107  4400  SWSPL,   4400
00110  0001  O1,      1
00111  0003  O3,      3
00112  0007  O7,      7
00113  7777  M1,      7777
00114  7776  M2,      7776
00115  7775  M3,      7775
00116  7774  M4,      7774
00117  7773  M5,      7773
00120  6000  NOSAMS,  6000
00121  7772  LIMIT,   7772
00122  0000  TRIAL,   0
00123  7740  TRIALS,  7740
00124  0000  SW,      0
00125  0026  STATUS,  26
00126  3000  SP,      3000
00127  0052  STCODE,  52
00130  0001  LGT,     1
00131  7604  MS1,     7604
00132  6226  MS2,     6226
00133  0003  S1,      3
00134  0005  S2,      5
00135  0000  DISNUM,  0
00136  0000  XDIS,    0
00137  0000  CPTR,    0
       0200  *200
00200  6002  START,   IOF                    / INITIALIZE CONSTANTS ETC.
00201  6622           DUI
00202  6414           SIOF
00203  4434           JMS I IRSTIN
00204  4435           JMS I IRSTOU
00205  7300           CLA CLL
00206  3102           DCA MADD
00207  3050           DCA PRIOR
00210  3122           DCA TRIAL
00211  3124           DCA SW
00212  3103           DCA OUCHN
00213  1126           TAD SP
00214  3106           DCA SWSP
00215  1125           TAD STATUS
```

```
00216  6634           LSTAT
00217  6631           RUD              / DUMMY READ TO CLEAR UART BUFFER.
00220  6631           RUD
00221  6030           KCF
00222  6042           TCF
00223  4436           JMS I IWTBL
00224  4437           JMS I IRNDWT
00225  6412           SION
00226  6642           ETI
00227  6001           ION
00230  5442  WAIT,    JMP I IDISP
00231  7200  TRIEND,  CLA
00232  1126           TAD SP
00233  3105           DCA SWSP
00234  3102           DCA MADD
00235  3103           DCA OUCHN
00236  4434           JMS I IRSTIN
00237  4435           JMS I IRSTOU
00240  2122           ISZ TRIAL
00241  1122           TAD TRIAL
00242  1123           TAD TRIALS
00243  7650           SNA CLA
00244  5254           JMP FINSH
00245  4436           JMS I IWTBL
00246  4437           JMS I IRNDWT
00247  7300           CLA CLL
00250  3050           DCA PRIOR
00251  6412           SION
00252  6642           ETI
00253  5442           JMP I IDISP
00254  6002  FINSH,   IOF
00255  5442           JMP I IDISP
       0400  *400
00400  3506  SERV,    DCA I SWSP       / THIS SECTION SAVES THE
00401  6004           GTF              / AC, LINK AND STATUS.
00402  2106           ISZ SWSP
00403  3506           DCA I SWSP
00404  2106           ISZ SWSP
00405  1000           TAD 0            / GET RETURN ADDRESS
00406  3506           DCA I SWSP
00407  2106           ISZ SWSP
00410  1106           TAD SWSP
00411  1107           TAD SWSPL
00412  7700           SMA CLA
00413  7402           HLT
00414  1050           TAD PRIOR
00415  1041           TAD ISTRT
00416  3220           DCA .+2
00417  5620           JMP I .+1
00420  0000           0
00421  6511  STRT,    SK1              / SKIP ON TIMER
00422  5224           JMP .+2
00423  5423           JMP I ITIMR
00424  6624           STR              / SKIP ON UART TX
00425  5227           JMP .+2
00426  5420           JMP I IUARTT
00427  6031           KSF
00430  5232           JMP .+2
00431  5421           JMP I ITTYRX
00432  6041           TSF
00433  5235           JMP .+2
00434  5422           JMP I ITTYTX
00435  7402           HLT              / SHOULD NOT GET HERE !!
                                 /
                                 / THIS SECTION RESTORES THE AC LINK
                                 / AND RETURNS TO THE INTERRUPTED
                                 / SECTION.
                                 /
00436  6002  RETN,    IOF
00437  6203           CDIO
00440  7340           CLA CLL CMA
00441  1106           TAD SWSP
00442  3106           DCA SWSP
```

```
00443  1506           TAD I SWSP
00444  3000           DCA 0
00445  7340           CLA CLL CMA
00446  1106           TAD SWSP
00447  3106           DCA SWSP
00450  1506           TAD I SWSP
00451  3047           DCA TFG
00452  7340           CLA CLL CMA
00453  1106           TAD SWSP
00454  3106           DCA SWSP
00455  1506           TAD I SWSP
00456  3046           DCA TAC
00457  1047           TAD TFG
00460  6005           RTF
00461  7200           CLA
00462  1046           TAD TAC
00463  5400           JMP I 0
                              /
                              / THIS SECTION SAMPLES AND STORES THE
                              / DATA IN THE CORE BUFFER.
                              /
00464  7300  TIMER,   CLA CLL
00465  6451           MXR                / SET MULTIPLEXER TO CHAN. 0
00466  4424           JMS I ISAM         / SEND S1 OR S2 IF NECESSARY
00467  4425  NXCHNL,  JMS I ICVRT        / CONVERT CURRENT CHAN.
00470  3101           DCA SAVE
00471  7327           CLA CLL CML IAC RTL
00472  6451           MXR                / GROUND MULTIPLEXER INPUT TO
00473  6442           STC                / MINIMISE CROSSTALK.
00474  7300           CLA CLL
00475  1102           TAD MADD
00476  4431           JMS I IPOIN1
00477  3104           DCA CURPNT
00500  1101           TAD SAVE
00501  3504           DCA I CURPNT
00502  4426           JMS I IMPXR
00503  7620           SNL CLA
00504  5267           JMP NXCHNL
00505  7327           CLA CLL CML IAC RTL
00506  6451           MXR
00507  4427           JMS I IINC
00510  7420           SNL
00511  5430           JMP I IRETN
00512  6414           SIOF               / TAKEN ALL SAMPLES SO DISABLE
00513  7300           CLA CLL            / TIMER INTERRUPT.
00514  1111           TAD O3
00515  3050           DCA PRIOR
00516  5430           JMP I IRETN
                              /

                              / THIS SECTION TAKES DATA FROM THE
                              / CORE BUFFER AND TRANSMITS IT OVER
                              / THE SERIAL DATA LINE.
                              /
00517  6622  UARTTX,  DUI
00520  6001           ION
00521  7300           CLA CLL            / FIRST OR SECOND SIX BITS ?
00522  1124           TAD SW
00523  7640           SZA CLA
00524  5346           JMP SECND
00525  1057           TAD ZEROP          / WAIT TILL AT LEAST ONE SAMPLE
00526  7450           SNA                / HAS BEEN TAKEN.
00527  5343           JMP TXEND
00530  7041           CIA
00531  1065           TAD OOP            / HAVE ALL THE SAMPLES SO FAR
00532  7700           SMA  CLA           / TAKEN BEEN SENT ?
00533  5343           JMP TXEND
00534  1103           TAD OUCHN
00535  4432           JMS I IPOIN2
00536  3105           DCA CUROP
00537  1505           TAD I CUROP
00540  6644           OUT
```

```
00541  7201              CLA IAC          / SET SWITCH FOR 2nd SIX BITS.
00542  3124              DCA SW
00543  6002     TXEND,   IOF
00544  6642              ETI
00545  5430              JMP I IRETN
00546  3124     SECND,   DCA SW           / RESET SWITCH.
00547  1103              TAD OUCHN
00550  4432              JMS I IPOIN2
00551  3105              DCA CUROP
00552  1505              TAD I CUROP
00553  7002              BSW
00554  6644              OUT
00555  7300              CLA CLL
00556  2103              ISZ OUCHN
00557  1103              TAD OUCHN
00560  1121              TAD LIMIT
00561  7710              SPA CLA
00562  5343              JMP TXEND
00563  3103              DCA OUCHN
00564  4433              JMS I IINCR2
00565  7420              SNL
00566  5343              JMP TXEND
00567  5777'             JMP TRIEND
00577  0231
       0600     *600
00600  0000     INCR1,   0
00601  7300              CLA CLL
00602  2057              ISZ ZEROP
00603  2060              ISZ ONEP
00604  2061              ISZ TWOP
00605  2062              ISZ THREEP
00606  7000              NOP
00607  2063              ISZ FOURP
00610  2064              ISZ FIVEP
00611  1057              TAD ZEROP
00612  1120              TAD NOSAMS
00613  7200              CLA
00614  5600              JMP I INCR1
00615  0000     INCR2,   0
00616  7300              CLA CLL
00617  2065              ISZ O0P
00620  2066              ISZ O1P
00621  2067              ISZ O2P
00622  2070              ISZ O3P
00623  7000              NOP
00624  2071              ISZ O4P
00625  2072              ISZ O5P
00626  1065              TAD O0P
00627  1120              TAD NOSAMS
00630  7200              CLA
00631  5615              JMP I INCR2
00632  0000     POIN1,   0
00633  7041              CIA
00634  6211              CDF+10
00635  7450              SNA
00636  5271              JMP ZERO
00637  7001              IAC
00640  7450              SNA
00641  5267              JMP ONE
00642  7001              IAC
00643  7450              SNA
00644  5265              JMP TWO
00645  7001              IAC
00646  7450              SNA
00647  5263              JMP THREE
00650  6201              CDF+0
00651  7001              IAC
00652  7450              SNA
00653  5261              JMP FOUR
00654  7001              IAC
00655  7440              SZA
00656  7402              HLT
00657  1064              TAD FIVEP
```

```
00660  5632            JMP I POIN1
00661  1063  FOUR,     TAD FOURP
00662  5632            JMP I POIN1
00663  1062  THREE,    TAD THREEP
00664  5632            JMP I POIN1
00665  1061  TWO,      TAD TWOP
00666  5632            JMP I POIN1
00667  1060  ONE,      TAD ONEP
00670  5632            JMP I POIN1
00671  1057  ZERO,     TAD ZEROP
00672  5632            JMP I POIN1
00673  0000  POIN2,    0
00674  7041            CIA
00675  6211            CDF+10
00676  7450            SNA
00677  5332            JMP ZER
00700  7001            IAC
00701  7450            SNA
00702  5330            JMP O
00703  7001            IAC
00704  7450            SNA
00705  5326            JMP T
00706  7001            IAC
00707  7450            SNA
00710  5324            JMP TH
00711  6201            CDF+0
00712  7001            IAC
00713  7450            SNA
00714  5322            JMP F
00715  7001            IAC
00716  7440            SZA
00717  7402            HLT
00720  1072            TAD O5P
00721  5673            JMP I POIN2
00722  1071  F,        TAD O4P
00723  5673            JMP I POIN2
00724  1070  TH,       TAD O3P
00725  5673            JMP I POIN2
00726  1067  T,        TAD O2P
00727  5673            JMP I POIN2
00730  1066  O,        TAD O1P
00731  5673            JMP I POIN2
00732  1065  ZER,      TAD O0P
00733  5673            JMP I POIN2
       1000  *1000
01000  0000  SAMPLE,   0
01001  7300            CLA CLL
01002  1233            TAD LOGOUT
01003  7040            CMA
01004  6501            ACOUT             / AC TO PATCH PNL. 6501
01005  7340            CLA CLL CMA
01006  6501            ACOUT
01007  7300            CLA CLL
01010  1057            TAD ZEROP
01011  1131            TAD MS1
01012  7650            SNA CLA
01013  5225            JMP TS1
01014  1130            TAD LGT
01015  3233            DCA LOGOUT
01016  1057            TAD ZEROP
01017  1132            TAD MS2
01020  7650            SNA CLA
01021  5230            JMP TS2
01022  1130            TAD LGT
01023  3233            DCA LOGOUT
01024  5600            JMP I SAMPLE
01025  1133  TS1,      TAD S1
01026  3233            DCA LOGOUT
01027  5600            JMP I SAMPLE
01030  1134  TS2,      TAD S2
01031  3233            DCA LOGOUT
01032  5600            JMP I SAMPLE
01033  0001  LOGOUT,   1
```

```
01034  0000  MPXR,   0
01035  7300          CLA CLL
01036  2102          ISZ MADD
01037  1102          TAD MADD
01040  1121          TAD LIMIT
01041  7650          SNA CLA
01042  3102          DCA MADD
01043  1102          TAD MADD
01044  6451          MXR                / AC TO MULTIPLEXER. 6451
01045  5634          JMP I MPXR
01046  7402  TTYTX,  HLT
01047  0000  WTBL,   0
01050  7300          CLA CLL
01051  6621          SDR
01052  5251          JMP .-1
01053  6631          RUD
01054  7041          CIA
01055  1127          TAD STCODE
01056  7640          SZA CLA
01057  5251          JMP .-6
01060  5647          JMP I WTBL
01061  0000  RNDWT,  0
01062  7300          CLA CLL
01063  6504          ACIN
01064  0110          AND 01
01065  7650          SNA CLA
01066  5263          JMP .-3
01067  5661          JMP I RNDWT
01070  0000  CVRT,   0
01071  6442          STC                / START AD CONVERSION. 6442
01072  7300          CLA CLL
01073  7000          NOP
01074  7000          NOP
01075  7000          NOP
01076  7000          NOP
01077  6441          ADINP              / GET DATA FROM AD. 6441
01100  5670          JMP I CVRT
01101  7402  TTYRX,  HLT

01102  0000  RSTIN,  0
01103  7300          CLA CLL
01104  1051          TAD P0
01105  3057          DCA ZEROP
01106  1052          TAD P1
01107  3060          DCA ONEP
01110  1053          TAD P2
01111  3061          DCA TWOP
01112  1054          TAD P3
01113  3062          DCA THREEP
01114  1055          TAD P4
01115  3063          DCA FOURP
01116  1056          TAD P5
01117  3064          DCA FIVEP
01120  5702          JMP I RSTIN
01121  0000  RSTOU,  0
01122  7300          CLA CLL
01123  1051          TAD P0
01124  3065          DCA 00P
01125  1052          TAD P1
01126  3066          DCA 01P
01127  1053          TAD P2
01130  3067          DCA 02P
01131  1054          TAD P3
01132  3070          DCA 03P
01133  1055          TAD P4
01134  3071          DCA 04P
01135  1056          TAD P5
01136  3072          DCA 05P
01137  5721          JMP I RSTOU
01140  0000  RSTD,   0
01141  7300          CLA CLL
01142  1051          TAD P0
```

```
01143  3073           DCA DOP
01144  1052           TAD P1
01145  3074           DCA D1P
01146  1053           TAD P2
01147  3075           DCA D2P
01150  1054           TAD P3
01151  3076           DCA D3P
01152  1055           TAD P4
01153  3077           DCA D4P
01154  1056           TAD P5
01155  3100           DCA D5P
01156  5740           JMP I RSTD
01157  0000  INC3,    0
01160  7300           CLA CLL
01161  2073           ISZ DOP
01162  2074           ISZ D1P
01163  2075           ISZ D2P
01164  2076           ISZ D3P
01165  7000           NOP
01166  2077           ISZ D4P
01167  2100           ISZ D5P
01170  1073           TAD DOP
01171  1120           TAD NOSAMS
01172  7200           CLA
01173  5757           JMP I INC3
       1200  *1200
01200  7300  DISPLA,  CLA CLL
01201  7604           LAS
01202  0112           AND O7
01203  3135           DCA DISNUM
01204  3136           DCA XDIS
01205  1135  NXLOC,   TAD DISNUM
01206  4444           JMS I IPOIN3
01207  3137           DCA CPTR
01210  7330           CLA CLL CML RAR
01211  1537           TAD I CPTR
01212  6201           CDF+0
01213  7110           CLL RAR
01214  7110           CLL RAR
01215  6062           OUTY
01216  7300           CLA CLL
01217  1136           TAD XDIS
01220  6052           OUTX
01221  2136           ISZ XDIS
01222  4443           JMS I IINC3
01223  1136           TAD XDIS
01224  7041           CIA
01225  1052           TAD P1
01226  7640           SZA CLA
01227  5205           JMP NXLOC
01230  4445           JMS I IRSTD
01231  5201           JMP NXLOC-4
01232  0000  POIN3,   0
01233  7041           CIA
01234  6211           CDF+10
01235  7450           SNA
01236  5271           JMP DZ
01237  7001           IAC
01240  7450           SNA
01241  5267           JMP DO
01242  7001           IAC
01243  7450           SNA
01244  5265           JMP DTWO
01245  7001           IAC
01246  7450           SNA
01247  5263           JMP DTHREE
01250  6201           CDF+0
01251  7001           IAC
01252  7450           SNA
01253  5261           JMP DFOUR
01254  7001           IAC
01255  7440           SZA
01256  7402           HLT
```

```
01257  1100              TAD D5P
01260  5632              JMP I POIN3
01261  1077   DFOUR,     TAD D4P
01262  5632              JMP I POIN3
01263  1076   DTHREE,    TAD D3P
01264  5632              JMP I POIN3
01265  1075   DTWO,      TAD D2P
01266  5632              JMP I POIN3
01267  1074   DO,        TAD D1P
01270  5632              JMP I POIN3
01271  1073   DZ,        TAD DOP
01272  5632              JMP I POIN3
                                 /
                                 / SPECIAL INSTRUCTIONS
                                 /
       6062              OUTY=6062
       6052              OUTX=6052
       6511              SK1=6511
       6621              SDR=6621
       6624              STR=6624
       6442              STC=6442
       6451              MXR=6451
       6501              ACOUT=6501
       6504              ACIN=6504
       6644              OUT=6644
       6634              LSTAT=6634
       6642              ETI=6642
       6632              ERI=6632
       6622              DUI=6622
       6641              SKERR=6641
       6441              ADINP=6441
       6412              SION=6412
       6414              SIOF=6414
       6631              RUD=6631
       6203              CDIO=6203
              $
```

```
ACIN    6504      LIMIT   0121      SKERR   6641
ACOUT   6501      LOGOUT  1033      SK1     6511
ADINP   6441      LSTAT   6634      SP      0126
CDIO    6203      MADD    0102      START   0200
CPTR    0137      MPXR    1034      STATUS  0125
CUROP   0105      MS1     0131      STC     6442
CURPNT  0104      MS2     0132      STCODE  0127
CVRT    1070      MXR     6451      STR     6624
DFOUR   1261      M1      0113      STRT    0421
DISNUM  0135      M2      0114      SW      0124
DISPLA  1200      M3      0115      SWSP    0106
DO      1267      M4      0116      SWSPL   0107
DTHREE  1263      M5      0117      S1      0133
DTWO    1265      NOSAMS  0120      S2      0134
DUI     6622      NXCHNL  0467      T       0726
DZ      1271      NXLOC   1205      TAC     0046
DOP     0073      O       0730      TFG     0047
D1P     0074      ONE     0667      TH      0724
D2P     0075      ONEP    0060      THREE   0663
D3P     0076      OUCHN   0103      THREEP  0062
D4P     0077      OUT     6644      TIMER   0464
D5P     0100      OUTX    6052      TRIAL   0122
ERI     6632      OUTY    6062      TRIALS  0123
ETI     6642      OOP     0065      TRIEND  0231
F       0722      O1      0110      TS1     1025
FINSH   0254      O1P     0066      TS2     1030
FIVEP   0064      O2P     0067      TTYRX   1101
FOUR    0661      O3      0111      TTYTX   1046
FOURP   0063      O3P     0070      TWO     0665
ICVRT   0025      O4P     0071      TWOP    0061
IDISP   0042      O5P     0072      TXEND   0543
IINC    0027      O7      0112      UARTTX  0517
IINCR2  0033      POIN1   0632      WAIT    0230
IINC3   0043      POIN2   0673      WTBL    1047
IMPXR   0026      POIN3   1232      XDIS    0136
```

```
INCR1   0600     PRIOR   0050     ZER     0732
INCR2   0615     P0      0051     ZERO    0671
INC3    1157     P1      0052     ZEROP   0057
IPOIN1  0031     P2      0053
IPOIN2  0032     P3      0054
IPOIN3  0044     P4      0055
IRETN   0030     P5      0056
IRNDWT  0037     RETN    0436
IRSTD   0045     RNDWT   1061
IRSTIN  0034     RSTD    1140
IRSTOU  0035     RSTIN   1102
ISAM    0024     RSTOU   1121
ISERV   0040     RUD     6631
ISTRT   0041     SAMPLE  1000
ITIMR   0023     SAVE    0101
ITTYRX  0021     SDR     6621
ITTYTX  0022     SECND   0546
IUARTT  0020     SERV    0400
IWTBL   0036     SIOF    6414
LGT     0130     SION    6412


ERRORS DETECTED: 0
LINKS GENERATED: 1
```

APPENDIX 8.11

PAL 8 Computer Programme Used to Store the Data onto Disk

This programme was used to store the data on a magnetic disk. It made use of the OS8 operating system User Service Routine (USR) to create core image files into which the data were transferred. Details of the USR may be found in the OS8 Software Support Handbook available from the Digital Equipment Company.

The programme consists of two sections:-

a) Memory locations 0_8-3652_8 (Disk store programme). This section stores the data received over the high speed serial interface in a memory buffer, checks for transmission errors and calls the USR to create data files and store the data. Each data file is automatically given a new filename based on a "seed" name specified by the operator. (e.g. If the operator specified the "seed" name as MJN000 then the subsequent files would have the names MJN001, MJN002, MJN003........)

b) Memory locations 16000_8-16777_8 (Data examine and transfer programme).

This section is stored on disk with the data in every data file. Subsequent to the completion of the data acquisition process it allows the operator to display (via D-A converters and an X-Y display) any of the six stored channels in the data file. It also allows the operator to send the data to floppy disk (or paper tape) for transfer to the main computer. These functions are controlled by simple commands typed at the console terminal.

e.g.	.R XYZ007	would cause OS8 to load the data in file XYZ007.SV and start the Data examine and transfer programme.
	D 0	would display channel zero on the X-Y display.
	H 48	would set the initial batch number transferred onto floppy disk (or paper tape) to 48.
	P	would transfer the data to floppy disk or paper tape (depending on which of these was connected).
	Control & C	would transfer control back to OS8.

The programme is started by giving the OS8 command "R DDS44".

The assembly language listing of the programme follows.

```
                        / DISK DATA STORE.
                        / ---------------
                        /
                        /
                        / THIS PROGRAM STORES THE DATA RECEIVED FROM
                        / THE SERIAL DATA INTERFACE ON AN RK05 DISK.
                        /
                        /
                        /       MEMORY MAP
                        /       ----------
                        /
                        / FIELD ZERO
                        / ----------
                        /
                        / 0000 TO 0777          DISK STORE PROG.
                        /
                        / 1000 TO 1377          CORE CONTROL BLOCK
                        /
                        / 1400 TO 3377          CHANNEL 0
                        /
                        /       OVERLAY FOR FILENAME AT 2000
                        /       THIS IS ONCE ONLY CODE.
                        /
                        / 3400 TO 5377          CHANNEL 1
                        /
                        / 5400 TO 7377          CHANNEL 2
                        /
                        / 7400 TO 7577          DEVICE HANDLER
                        /
                        / 7600 TO 7777          DEC SOFTWARE
                        /
                        / FIELD ONE
                        / ---------
                        /
                        / 0000 TO 1777          CHANNEL 3
                        /
                        / 2000 TO 3777          CHANNEL 4
                        /
                        / 4000 TO 5777          CHANNEL 5
                        /
                        / 6000 TO 6777          DATA EX. AND PUNCH PROG.
                        /
                        / 7600 TO 7777          DEC SOFTWARE
                        /
                        /-------------------------------------------
                                /
                                / SPECIAL INSTRUCTIONS.
                                /
      6634              LSTAT=6634      / LOAD UART CONTROL REGISTER.
      6631              RUD=6631        / READ UART DATA.
      6644              OUT=6644        / OUTPUT SERIAL DATA.
      6621              SDR=6621        / SKIP IF UART DATA READY.
      6641              SKERR=6641      / SKIP IF UART RX. ERROR.
      6056              OUTX=6056       / OUTPUT X TO  D-A AND BR. UP.
      6066              OUTY=6066       / OUTPUT Y TO D-A AND BR. UP.

      6624              STR=6624        / SKIP IF TX. BUFFER MT.
      0000      *0
00000 0000              0
00001 7402              HLT     / BEWARE OF INTERRUPTS.
      0020      *20
00020 7700      USR,    7700    / FIELD 1. USR CALL ADDRESS.
00021 7600      MONST,  7600    / MONITOR RESTART ADDRESS.
00022 0026      STATUS, 26      / UART CONTROL WORD.
00023 0000      TMPST,  0
00024 0000      TRIALS, 0
00025 0052      STCODE, 52      / INDICATES TO 8F THAT 8L IS READY.
00026 0040      TRILIM, 40      / NUMBER OF TRIALS TO BE STORED.
00027 0324      ZT,     324
00030 0325      ZU,     325
00031 0330      ZX,     330
```

```
00032  0303  ZC,      303
00033  0305  ZE,      305
00034  7775  MCNC,    -3
00035  0336  UPARRO,  336
00036  0215  CR,      215
00037  0212  LF,      212
00040  0007  D7,      7
00041  0016  D16,     16
00042  0017  D17,     17
00043  0060  D60,     60
00044  0077  D77,     77
00045  0177  D177,    177
00046  0377  D377,    377
00047  4000  D4000,   4000
00050  7700  D7700,   7700
00051  7777  M1,      -1
00052  7776  M2,      -2
00053  7775  M3,      -3
00054  7774  M4,      -4
00055  7773  M5,      -5
00056  7772  M6,      -6
00057  7771  M7,      -7
00060  7766  M12,     -12
00061  7746  M32,     -32
00062  7720  M50,     -60
00063  7706  M72,     -72
00064  7677  M101,    -101
00065  0000  MADD,    0
00066  0000  CURPNT,  0
00067  6000  NOSAMS,  6000     / - NUMBER OF SAMPLES TO BE TAKEN.
00070  0000  SVE,     0
00071  0000  TEMP,    0
00072  0000  TEMP2,   0
00073  0000  TEMP3,   0
00074  0000  ACMLTR,  0
00075  7400  HANADR,  7400     / ADDRESS AT WHICH THE DEVICE HANDLER
                               / MAY BE PLACED. NOTE THAT THIS IS A DUMMY
                               / ADDRESS SINCE THE DEVICE (BEING THE
                               / SYSTEM DEVICE) IS ALWAYS (?) RESIDENT.
00076  0317  DEVNME,  DEVICE COPY
00077  2031
00100  0101  NAMEP,   NAM1     / POINTS TO FILENAME.
00101  0401  NAM1,    401      / FILENAME  DEFAULTS TO
00102  2460  NAM2,    2460     / DAT000.SV

00103  6060  NAM3,    6060
00104  2326  NAM4,    2326
00105  1400  HK5,     1400     / START OF BUFFER AREA (FIELD 0).
00106  0000  CPYNUM,  0        / DEVICE NUMBER. DETERMINED BY 'FETCH'.
00107  0000  CPYNTY,  0        / HANDLER ENTRY ADDRESS. DETERMINED
                               / BY 'FETCH'.
00110  0033  NUMBLK,  33       / NUMBER OF BLOCKS FOR EACH FILE.
00111  0000  STBLK,   0        / NEXT FREE BLOCK ON DISK.
00112  1000  CCBARA,  1000     / LOCATION AT WHICH THE CORE
                               / IMAGE OF THE CCB IS STORED.
00113  4200  CCBFCW,  4200     / FUNCTION CONT. WORD  FOR STORING
                               / THE CCB.
00114  7410  FCW1,    7410     / FUNCTION CONTROL WORD.
00115  7000  FCW2,    7000     / SEE DSB SOFTWARE SUPPORT MANUAL
                               / PAGE 4-2.
00116  4000  PNTR,    4000
00117  0000  CARRY,   0
00120  0000  XDIS,    0
00121  0000  DISNUM,  0
                               / INITIAL BUFFER ADDRESSES.
00122  1400  P0,      1400     / FIELD 0
00123  3400  P1,      3400     / FIELD 0
00124  5400  P2,      5400     / FIELD 0
00125  0000  P3,      0        / FIELD 1
00126  2000  P4,      2000     / FIELD 1
00127  4000  P5,      4000     / FIELD 1
                               / CURRENT BUFFER POINTERS.
00130  0000  ZEROP,   0
```

```
00131  0000  ONEP,    0
00132  0000  TWOP,    0
00133  0000  THREEP,  0
00134  0000  FOURP,   0
00135  0000  FIVEP,   0
                               / SUBROUTINE POINTERS.
00136  0347  ICHRO,   ZCHRO
00137  0660  INPRT,   NUMPNT
00140  0250  IRENME,  RENAME
00141  0400  IDSK,    DSK
00142  0542  IINCR,   INCR1
00143  0556  IMAINC,  MAINC
00144  0600  IPOIN1,  POIN1
00145  0566  IGTWRD,  GETWRD
00146  0703  IGETBY,  GETBY
00147  0641  IRSTIN,  RSTIN
00150  0000  SAVE1,   0
00151  0000  SAVE3,   0
00152  0240  ZSPCE,   240
00153  7000  NOPER,   7000
00154  0000  PTR,     0
00155  3000  PPTR,    3000
00156  0000  TPTR,    0
00157  4773  LIMIT,   -3005
       0200  *200
00200  7300           CLA CLL         / INITIALISE PROGRAM.
00201  6046           TLS
00202  1022           TAD STATUS
00203  6634           LSTAT
00204  6631           RUD
00205  6631           RUD             / ENSURE UART BUFFERS EMPTY.
00206  4777' GNME,    JMS     FNME
00207  7300           CLA CLL
00210  3024           DCA TRIALS
00211  3065  TRL,     DCA MADD        / GET DATA AND STORE IN CORE.
00212  4547           JMS I IRSTIN
00213  4537           JMS I INPRT     / PRINT NEXT BATCH NUMBER
00214  1025           TAD STCODE
00215  6644           OUT             / SEND "READY" SIGNAL.
00216  4545  NEXT,    JMS I IGTWRD
00217  3151           DCA SAVE3
00220  1065           TAD MADD
00221  4544           JMS I IPOIN1
00222  3066           DCA CURPNT
00223  1151           TAD SAVE3
00224  3466           DCA I CURPNT
00225  6201           CDF+0
00226  4543           JMS I IMAINC
00227  7620           SNL CLA         / SKIP IF ALL CHANNELS DONE.
00230  5216           JMP NEXT
00231  3065           DCA MADD
00232  4542           JMS I IINCR     / INCREMENT ALL POINTERS.
00233  7420           SNL             / SKIP IF ALL SAMPLES TAKEN.
00234  5216           JMP NEXT
00235  4541           JMS I IDSK      / TRANSFER CORE BUFFER TO DISK.
00236  4540           JMS I IRENME    / UPDATE FILE NAME.
00237  7301           CLA CLL IAC
00240  1024           TAD TRIALS
00241  3024           DCA TRIALS
00242  1026           TAD TRILIM
00243  7041           CIA
00244  1024           TAD TRIALS
00245  7640           SZA CLA         / SKIP IF ALL TRIALS COMPLETE.
00246  5211           JMP TRL
00247  5421           JMP I MONST     / JUMP BACK TO MONITOR.
                               /
                               / THIS SUBROUTINE UPDATES THE FILENAME.
                               /
00250  0000  RENAME,  0
00251  7300           CLA CLL
00252  1103           TAD NAM3
00253  4325           JMS INC
00254  7640           SZA CLA
```

```
00255  5261          JMP LBY
00256  1043          TAD 060
00257  3071          DCA TEMP
00260  2117          ISZ CARRY
00261  1103  LBY,    TAD NAM3
00262  0050          AND 07700
00263  1071          TAD TEMP
00264  3103          DCA NAM3
00265  1117          TAD CARRY
00266  7650          SNA CLA
00267  5650          JMP I RENAME
00270  1103          TAD NAM3
00271  4335          JMS PBSW
00272  4325          JMS INC
00273  7640          SZA CLA
00274  5300          JMP MBY
00275  1043          TAD 060
00276  3071          DCA TEMP
00277  2117          ISZ CARRY
00300  1071  MBY,    TAD TEMP
00301  4335          JMS PBSW
00302  3071          DCA TEMP
00303  1103          TAD NAM3
00304  0044          AND 077
00305  1071          TAD TEMP
00306  3103          DCA NAM3
00307  1117          TAD CARRY
00310  7650          SNA CLA
00311  5650          JMP I RENAME
00312  1102          TAD NAM2
00313  4325          JMS INC
00314  7640          SZA CLA
00315  5320          JMP HBY
00316  1043          TAD 060
00317  3071          DCA TEMP
00320  1102  HBY,    TAD NAM2
00321  0050          AND 07700
00322  1071          TAD TEMP
00323  3102          DCA NAM2
00324  5650          JMP I RENAME
00325  0000  INC,    0
00326  0044          AND 077
00327  7001          IAC
00330  3071          DCA TEMP
00331  3117          DCA CARRY
00332  1071          TAD TEMP
00333  1063          TAD M72
00334  5725          JMP I INC
                               / THIS SUBROUTINE SIMULATES THE
                               / PDP8E 'BSW' INSTRUCTION.
                               / IT WAS WRITTEN BY A. JERRAM.
00335  0000  PBSW,   0
00336  7100          CLL
00337  3150          DCA SAVE1
00340  1150          TAD SAVE1
00341  0050          AND 07700
00342  1150          TAD SAVE1
00343  7006          RTL
00344  7006          RTL
00345  7006          RTL
00346  5735          JMP I PBSW
00347  0000  ZCHRO,  0
00350  6041          TSF
00351  5350          JMP .-1
00352  6046          TLS
00353  7300          CLA CLL
00354  5747          JMP I ZCHRO
00377  2000
       0400  *400
                               / THIS SUBROUTINE USES THE USR
                               / TO STORE THE DATA ON THE
                               / RK05 DISK.
00400  0000  DSK,    0
```

```
00401  7300           CLA CLL
00402  1076           TAD DEVNME        / GET DEVICE NAME FROM CONSTANT
00403  3224           DCA FARG1         / AREA AND PREPARE TO FETCH THE
00404  1077           TAD DEVNME+1      / DEVICE HANDLER.
00405  3225           DCA FARG2
00406  1075           TAD HANADR        / GET THE LOCATION AT WHICH THE
00407  3226           DCA FARG3         / HANDLER MAY BE PLACED.
00410  1100           TAD NAMEP         / POINTS TO THE FILENAME.
00411  3247           DCA EARG1
00412  3250           DCA EARG2         / CLEAR 2ND. ARG.
00413  1100           TAD NAMEP
00414  3336           DCA CARG1
00415  1110           TAD NUMBLK        / GET THE FILE LENGTH.
00416  3337           DCA CARG2         / ( IN BLOCKS ).
00417  7300           CLA CLL
00420  6201           CDF+0
00421  6212           CIF+10
00422  4420           JMS I USR         / JUMP TO USR.
00423  0001           1                 / DENOTES "FETCH" FUNCTION.
00424  0000  FARG1,   0
00425  0000  FARG2,   0
00426  0000  FARG3,   0
00427  7402           HLT               / ERROR IN GETTING HANDLER.
00430  7300           CLA CLL
00431  1225           TAD FARG2         / NOW THE DEVICE NUMBER.
00432  0042           AND 017           / MASK OFF UPPER BITS.
00433  3106           DCA CPYNUM
00434  1226           TAD FARG3         / ENTRY POINT OF HANDLER.
00435  3107           DCA CPYNTY
00436  1110           TAD NUMBLK        / CALCULATE VALUE IN AC
00437  0046           AND 0377          / ON ENTRY TO USR IN THE
00440  7106           CLL RTL           / "ENTER" MODE. SEE OSB
00441  7006           RTL               / SOFTWARE SUPPORT MANUAL
00442  1106           TAD CPYNUM        / PAGE 2-7.
00443  6201           CDF+0
00444  6212           CIF+10
00445  4420           JMS I USR
00446  0003           3                 / DENOTES "ENTER" FUNCTION.
00447  0000  EARG1,   0
00450  0000  EARG2,   0
00451  7402           HLT               / ERROR RETURN.
00452  7300           CLA CLL
00453  1247           TAD EARG1         / NOW THE FIRST EMPTY
00454  3111           DCA STBLK         / BLOCK ON THE DEVICE.
00455  1113           TAD CCBFCW        / CONTROL WORD FOR THE CCB AREA.
00456  3306           DCA CHARG1
00457  1112           TAD CCBARA        / LOCATION AT WHICH THE CCB
00460  3307           DCA CHARG2        / IS STORED IN CORE.
00461  1111           TAD STBLK         / FIRST M.T. BLOCK.
00462  3310           DCA CHARG3
00463  2111           ISZ STBLK         / ALLOW ONE BLOCK FOR THE CCBB.
00464  7000           NOP
00465  1114           TAD FCW1          / GET FIELD 1 FCW.
00466  3315           DCA HARG1
00467  3316           DCA HARG2         / FIELD 1 BUFFER STARTS AT 0.
00470  1111           TAD STBLK         / NEXT M.T. BLOCK AFTER CCB.
00471  3317           DCA HARG3
00472  1115           TAD FCW2          / GET FIELD 0 FCW.
00473  3324           DCA HARG4
00474  1105           TAD HK5           / START OF FIELD 0 BUFFER.
00475  3325           DCA HARG5
00476  1111           TAD STBLK         / ALLOW FOR FIELD 1 DATA.
00477  1041           TAD 016           / =14 DATA, 2 PROG.=16 (8 ).
00500  3111           DCA STBLK
00501  1111           TAD STBLK
00502  3326           DCA HARG6
00503  6201           CDF+0
00504  6202           CIF+0
00505  4507           JMS I CPYNTY      / SAVE CCB.
00506  0000  CHARG1,  0
00507  0000  CHARG2,  0
00510  0000  CHARG3,  0
00511  7402           HLT
```

```
00512  6201           CDF+0
00513  6202           CIF+0
00514  4507           JMS I CPYNTY    / SAVE FIELD 1 DATA AND PROG.
00515  0000  HARG1,   0
00516  0000  HARG2,   0
00517  0000  HARG3,   0
00520  7402           HLT
00521  6201           CDF+0
00522  6202           CIF+0
00523  4507           JMS I CPYNTY    / SAVE FIELD 0 DATA.
00524  0000  HARG4,   0
00525  0000  HARG5,   0
00526  0000  HARG6,   0
00527  7402           HLT
00530  7300           CLA CLL
00531  1106           TAD CPYNUM
00532  6201           CDF+0
00533  6212           CIF+10
00534  4420           JMS I USR
00535  0004           4
00536  0000  CARG1,   0
00537  0000  CARG2,   0
00540  7402           HLT
00541  5600           JMP I DSK
                              / THIS SUBROUTINE INCREMENTS ALL THE
                              / DATA POINTERS AND SETS THE LINK
                              / IF ALL THE SAMPLES HAVE BEEN TAKEN.
00542  0000  INCR1,   0
00543  7300           CLA CLL
00544  2130           ISZ ZEROP
00545  2131           ISZ ONEP
00546  2132           ISZ TWOP
00547  2133           ISZ THREEP
00550  2134           ISZ FOURP
00551  2135           ISZ FIVEP
00552  1133           TAD THREEP
00553  1067           TAD NOSAMS
00554  7200           CLA
00555  5742           JMP I INCR1
00556  0000  MAINC,   0
00557  7301           CLA CLL IAC
00560  1065           TAD MADD
00561  3065           DCA MADD
00562  1056           TAD M6
00563  1065           TAD MADD
00564  7200           CLA
00565  5756           JMP I MAINC
00566  0000  GETWRD,  0
00567  4546           JMS I IGETBY
00570  3070           DCA SVE
00571  4546           JMS I IGETBY
00572  7106           CLL RTL
00573  7106           CLL RTL
00574  7106           CLL RTL
00575  1070           TAD SVE
00576  5766           JMP I GETWRD
       0600  *600             / THIS SUBROUTINE RETURNS THE CURRENT
                              / POINTER FOR THE CHANNEL REQUESTED BY
                              / THE AC CONTENTS. IT ALSO SETS THE
                              / DATA FIELD.
00600  0000  POIN1,   0
00601  7041           CIA
00602  6201           CDF+0
00603  7450           SNA
00604  5237           JMP ZERO
00605  7001           IAC
00606  7450           SNA
00607  5235           JMP ONE
00610  7001           IAC
00611  7450           SNA
00612  5233           JMP TWO
00613  6211           CDF+10
00614  7001           IAC
```

```
00615  7450           SNA
00616  5231           JMP THREE
00617  7001           IAC
00620  7450           SNA
00621  5227           JMP FOUR
00622  7001           IAC
00623  7440           SZA
00624  7402           HLT
00625  1135           TAD FIVEP
00626  5600           JMP I POIN1
00627  1134  FOUR,    TAD FOURP
00630  5600           JMP I POIN1
00631  1133  THREE,   TAD THREEP
00632  5600           JMP I POIN1
00633  1132  TWO,     TAD TWOP
00634  5600           JMP I POIN1
00635  1131  ONE,     TAD ONEP
00636  5600           JMP I POIN1
00637  1130  ZERO,    TAD ZEROP
00640  5600           JMP I POIN1
00641  0000  RSTIN,   0
00642  7300           CLA CLL
00643  1122           TAD P0
00644  3130           DCA ZEROP
00645  1123           TAD P1
00646  3131           DCA ONEP
00647  1124           TAD P2
00650  3132           DCA TWOP
00651  1125           TAD P3
00652  3133           DCA THREEP
00653  1126           TAD P4
00654  3134           DCA FOURP
00655  1127           TAD P5
00656  3135           DCA FIVEP
00657  5641           JMP I RSTIN
00660  0000  NUMPNT,  0
00661  7300           CLA CLL
00662  1035           TAD CR
00663  4536           JMS I ICHRO
00664  1037           TAD LF
00665  4536           JMS I ICHRO
00666  1102           TAD NAM2
00667  0044           AND 077
00670  4536           JMS I ICHRO
00671  1103           TAD NAM3
00672  7012           RTR
00673  7012           RTR
00674  7012           RTR
00675  0044           AND 077
00676  4536           JMS I ICHRO
00677  1103           TAD NAM3
00700  0044           AND 077
00701  4536           JMS I ICHRO
00702  5660           JMP I NUMPNT
00703  0000  GETBY,   0
00704  7300           CLA CLL
00705  6621  WAIT,    SBR
00706  5325           JMP CNTRLC
00707  6631           RUD
00710  0044           AND 077
00711  6641           SKERR   / TEST FOR ERRORS.
00712  5703           JMP I GETBY
00713  7300           CLA CLL
00714  1152           TAD ZSPCE
00715  4536           JMS I ICHRO
00716  1027           TAD ZT
00717  4536           JMS I ICHRO
00720  1031           TAD ZX
00721  4536           JMS I ICHRO
00722  1033           TAD ZE
00723  4536           JMS I ICHRO
00724  5777'          JMP TRL
00725  6031  CNTRLC,  KSF
```

```
00726  5305             JMP WAIT
00727  6036             KRB
00730  0045             AND 0177
00731  1034             TAD MCNC
00732  7640             SZA CLA
00733  5305             JMP WAIT
00734  1035             TAD UPARRO
00735  4536             JMS I ICHRO
00736  1032             TAD ZC
00737  4536             JMS I ICHRO
00740  6201             CDF+0
00741  5421 '           JMP I MONST
00777  0211 '
       1000    *1000
                        / CORE CONTROL BLOCK
01000  7776             7776     / 2 SEGMENTS
01001  6213             6213     / STARTING FIELD
01002  6000             6000     / STARTING ADDRESS
01003  1400             1400     / JOB STATUS WORD
01004  0000             0000     / CORE ORIGIN
01005  3410             3410     / 34 PAGES, FIELD 1
01006  1400             1400     / CORE ORIGIN
01007  3000             3000     / 30 PAGES, FIELD 0
       2000    *2000    / CHARACTER INPUT ROUTINE
                        / HANDLES ^U,^C,^C,^J &RUBOUT.
02000  0000    FNME,    0
02001  7300             CLA CLL
02002  1153             TAD NOPER
02003  3777'            DCA GNME          / RESET JMS TO NOP
02004  6046             TLS
02005  7300    START,   CLA CLL
02006  1360             TAD PSTRG
02007  4776'            JMS PRINT         / PRINT PROMPT
02010  7300             CLA CLL
02011  3357             DCA FLAG          / CLEAR RUBOUT FLAG
02012  1155             TAD PPTR          / GET START OF BUFFER
02013  3154             DCA PTR           / AND SAVE IN PTR
02014  4775'   GTCR,    JMS ZCHRI         / GET A CHARACTER
02015  3073             DCA TEMP3
02016  1073             TAD TEMP3
02017  1355             TAD MCRET         / = C.R. ?
02020  7650             SNA CLA
02021  5305             JMP OK5
02022  1073             TAD TEMP3
02023  1352             TAD MRBOUT        / WAS IT A RUBOUT ?
02024  7650             SNA CLA           / SKIP IF NOT
02025  5330             JMP ROUT          / JUMP TO RUBOUT IF WAS
02026  1357             TAD FLAG
02027  7650             SNA CLA           / WAS RUBOUT FLAG SET ?
02030  5234             JMP NOFLG         / NO SO JUMP OVER NEXT BIT.
02031  1356             TAD SLSH
02032  4536             JMS I ICHRO
02033  3357             DCA FLAG          / AND CLEAR THE FLAG
02034  1073    NOFLG,   TAD TEMP3
02035  1353             TAD MCNTU         / WAS IT A ^U ?
02036  7640             SZA CLA
02037  5245             JMP NOCU          / NO SO JUMP OVER NEXT BIT.
02040  1035             TAD UPARRO        / YES SO ECH ^
02041  4536             JMS I ICHRO
02042  1030             TAD ZU
02043  4536             JMS I ICHRO       / AND "U"
02044  5205             JMP START         / AND JUMP BACK.
02045  1073    NOCU,    TAD TEMP3
02046  1354             TAD MCNTJ
02047  7650             SNA CLA           / WAS IT A ^J ?
02050  5313             JMP LFEED
02051  1073             TAD TEMP3         / NO SO TEST FOR ^C
02052  1034             TAD MCNC
02053  7640             SZA CLA
02054  5263             JMP NOCC          / NO SO JUMP OVER NEXT BIT.
02055  1035             TAD UPARRO        / YES SO ECHO "^"
02056  4536             JMS I ICHRO
02057  1032             TAD ZC            / AND "C"
```

```
02060  4536          JMS I ICHRO
02061  6203          CDF CIF+0      / ENSURE I/F AND D/F = 0
02062  5421          JMP I MONST
02063  1073  NOCC,   TAD TEMP3
02064  1062          TAD M60        / NOW CHECK FOR NUMBER 0-9 OR
02065  7510          SPA            / LETTER A-Z (UPPER CASE).
02066  5214          JMP GTCR
02067  1060          TAD M12
02070  7510          SPA
02071  5300          JMP OK         / WAS A NUMBER
02072  1057          TAD M7
02073  7510          SPA
02074  5214          JMP GTCR       / CODE WAS 72-100 OCTAL SO ERROR.
02075  1061          TAD M32
02076  7500          SMA
02077  5214          JMP GTCR       / CODE WAS > 132 (Z) SO ERROR.
02100  7300  OK,     CLA CLL
02101  1073          TAD TEMP3
02102  3554          DCA I PTR
02103  1073          TAD TEMP3
02104  4536          JMS I ICHRO    / ECHO TO TTY.
02105  2154  OK5,    ISZ PTR        / INCREMENT POINTER.
02106  1073          TAD TEMP3
02107  1355          TAD MCRET      / TEST FOR RETURN.
02110  7440          SZA
02111  5214          JMP GTCR
02112  5774'         JMP TSTNME
02113  4773' LFEED,  JMS CRLF       / PRINT RETURN AND LINEFEED.
02114  1155          TAD PPTR       / SET TEMP3 POINTER=START
02115  3156          DCA TPTR
02116  1154  NXCH,   TAD PTR
02117  7041          CIA
02120  1156          TAD TPTR
02121  7700          SMA CLA
02122  5214          JMP GTCR       / JUMP BACK IF FINISHED
02123  1556          TAD I TPTR     / GET CURRENT CHAR.
02124  4536          JMS I ICHRO
02125  7300          CLA CLL
02126  2156          ISZ TPTR       / INCREMENT POINTER.
02127  5316          JMP NXCH
02130  1357  ROUT,   TAD FLAG       / GET FLAG
02131  7440          SZA
02132  5337          JMP FLSET
02133  7001          IAC
02134  3357          DCA FLAG       / SET FLAG
02135  1356          TAD SLSH       / AND PRINT "/"
02136  4536          JMS I ICHRO
02137  7340  FLSET,  CLA CLL CMA    / SET AC=-1
02140  1154          TAD PTR        / DEC POINTER.
02141  3154          DCA PTR
02142  1155          TAD PPTR
02143  7041          CIA
02144  1154          TAD PTR
02145  7710          SPA CLA        / BACK TO START OF BUFFER.
02146  5205          JMP START      / YES SO BACK TO START.
02147  1554          TAD I PTR      / GET CHAR.
02150  4536          JMS I ICHRO    / AND ECHO IT.
02151  5214          JMP GTCR
02152  7601  MRBOUT, -177
02153  7753  MCNTU,  -25
02154  7766  MCNTJ,  -12
02155  7763  MCRET,  -15
02156  0057  SLSH,   57
02157  0000  FLAG,   0
02160  3500  PSTRG,  STRING
02173  2200
02174  2224
02175  2206
02176  2214
02177  0206
       2200  PAGE
02200  0000  CRLF,   0
02201  1036          TAD CR
```

```
02202  4536           JMS I ICHRO
02203  1037           TAD LF
02204  4536           JMS I ICHRO
02205  5600           JMP I CRLF
02206  0000  ZCHRI,   0
02207  6031           KSF
02210  5207           JMP .-1
02211  6036           KRB
02212  0045           AND 0177
02213  5606           JMP I ZCHRI
02214  0000  PRINT,   0
02215  3072           DCA TEMP2
02216  1472           TAD I TEMP2
02217  7450           SNA
02220  5614           JMP I PRINT
02221  4536           JMS I ICHRO
02222  2072           ISZ TEMP2
02223  5216           JMP PRINT+2
02224  7300  TSTNME,  CLA CLL         / TEST THE FILENAME IS VALID.
02225  1155           TAD PPTR        / CHECK THE LENGTH FIRST.
02226  7041           CIA
02227  1154           TAD PTR
02230  1057           TAD M7
02231  7640           SZA CLA
02232  5265           JMP ERMESS
02233  1555           TAD I PPTR      / IS THE FIRST CHARACTER ALPHA.
02234  1064           TAD M101
02235  7710           SPA CLA
02236  5265           JMP ERMESS
02237  1100           TAD NAMEP
02240  3156           DCA TPTR        / NAME LOOKS OK SO PACK INTO
02241  1155           TAD PPTR        / 6 BIT OCTAL.
02242  3154           DCA PTR
02243  1554  NXCHRP,  TAD I PTR
02244  0044           AND 077
02245  7106           CLL RTL
02246  7006           RTL
02247  7006           RTL
02250  3071           DCA TEMP
02251  2154           ISZ PTR
02252  1554           TAD I PTR
02253  0044           AND 077
02254  1071           TAD TEMP
02255  3556           DCA I TPTR
02256  2154           ISZ PTR
02257  2156           ISZ TPTR
02260  1154           TAD PTR
02261  1157           TAD LIMIT
02262  7710           SPA CLA
02263  5243           JMP NXCHRP
02264  5777'          JMP GNME
02265  7300  ERMESS,  CLA CLL
02266  1271           TAD PSTRIN
02267  4214           JMS PRINT
02270  5776'          JMP START
02271  3632  PSTRIN,  STRIN2
02376  2005
02377  0206
       3600  *3600
03600  0212  STRING,  212
03601  0215           215
03602  0320           "P
03603  0314           "L
03604  0305           "E
03605  0301           "A
03606  0323           "S
03607  0305           "E
03610  0240           "
03611  0324           "T
03612  0331           "Y
03613  0320           "P
03614  0305           "E
03615  0240           "
```

```
03616  0306           "F
03617  0311           "I
03620  0314           "L
03621  0305           "E
03622  0316           "N
03623  0301           "A
03624  0315           "M
03625  0305           "E
03626  0212           212
03627  0215           215
03630  0276           ">
03631  0000           0
03632  0212  STRIN2,  212
03633  0215           215
03634  0311           "I
03635  0316           "N
03636  0326           "V
03637  0301           "A
03640  0314           "L
03641  0311           "I
03642  0304           "D
03643  0240           "
03644  0316           "N
03645  0301           "A
03646  0315           "M
03647  0305           "E
03650  0212           212
03651  0215           215
03652  0000           0
       0001  FIELD 1          / THIS IS STORED AT THE SAME TIME
       6000  *6000            / AS THE DATA. IT ENABLES THE USER TO
16000  7300           CLA CLL / EXAMINE (ON AN X-Y DISPLAY)OR TRANSFER
16001  6026           PLS     / THE DATA TO THE SERIAL LINE OUTPUT
16002  6046           TLS     / BY USING THE OS8 'RUN DEV:FILENAME'
16003  1350           TAD STUS/ COMMAND. ONCE RUNNING THE USER MAY TYPE
16004  6634           LSTAT   / THE FOLLOWING COMMANNDS;
                              / "D 0","D 1", ETC TO DISPLAY THE DATA.
                              / "H NNN" TO SET THE BATCH NUMBER TO NNN.
                              / "P" TO TRANSFER THE DATA TO THE SERIAL
                              /       LINE.
16005  7300  NXCMD,   CLA CLL
16006  6211           CDF+10
16007  4777'          JMS PCRLF
16010  4776'          JMS GETCHR
16011  3356           DCA CMND
16012  1356           TAD CMND
16013  1357           TAD MH
16014  7650           SNA CLA
16015  5233           JMP HDR
16016  1356           TAD CMND
16017  1360           TAD MP
16020  7650           SNA CLA
16021  5775'          JMP PUNCH
16022  1356           TAD CMND
16023  1361           TAD MD
16024  7650           SNA CLA
16025  5774'          JMP DISP
16026  1362  ERROR,   TAD SPCE
16027  4773'          JMS CHROUT
16030  1363           TAD QMK
16031  4773'          JMS CHROUT
16032  5205           JMP NXCMD
16033  1362  HDR,     TAD SPCE
16034  4773'          JMS CHROUT
16035  1365           TAD BUFF
16036  3366           DCA BUFFP
16037  4776' GET,     JMS GETCHR
16040  3355           DCA TMPSTR
16041  1355           TAD TMPSTR
16042  1352           TAD M260
16043  7710           SPA CLA
16044  5256           JMP ENDCHK
16045  1255           TAD TMPSTR
```

```
16046  1353           TAD M272
16047  7700           SMA CLA
16050  5226           JMP ERROR
16051  1355           TAD TMPSTR
16052  1352           TAD M260
16053  3766           DCA I BUFFP
16054  2366           ISZ BUFFP
16055  5237           JMP GET
16056  1355  ENDCHK,  TAD TMPSTR
16057  1354           TAD MCR
16060  7640           SZA CLA
16061  5226           JMP ERROR
16062  3364           DCA BATNO
16063  1366           TAD BUFFP
16064  7041           CIA
16065  1365           TAD BUFF
16066  7650           SNA CLA
16067  5314           JMP ENDHDR
16070  4324           JMS BUFDEC
16071  3364           DCA BATNO
16072  1366           TAD BUFFP
16073  7041           CIA
16074  1365           TAD BUFF
16075  7650           SNA CLA
16076  5314           JMP ENDHDR
16077  4324           JMS BUFDEC
16100  4332           JMS TENS
16101  1364           TAD BATNO
16102  3364           DCA BATNO
16103  1366           TAD BUFFP
16104  7041           CIA
16105  1365           TAD BUFF
16106  7650           SNA CLA
16107  5314           JMP ENDHDR
16110  4324           JMS BUFDEC
16111  4341           JMS HUNS
16112  1364           TAD BATNO
16113  3364           DCA BATNO
16114  7300  ENDHDR,  CLA  CLL
16115  1364           TAD BATNO
16116  7510           SPA
16117  5226           JMP ERROR
16120  1351           TAD PM193
16121  7710           SPA CLA
16122  5205           JMP NXCMD
16123  5226           JMP ERROR
16124  0000  BUFDEC,  0
16125  7340           CLA CLL CMA
16126  1366           TAD BUFFP
16127  3366           DCA BUFFP
16130  1766           TAD I BUFFP
16131  5724           JMP I BUFDEC
16132  0000  TENS,    0
16133  7041           CIA
16134  3371           DCA T1
16135  1370           TAD KTEN
16136  2371           ISZ T1
16137  5335           JMP .-2
16140  5732           JMP I TENS
16141  0000  HUNS,    0
16142  7041           CIA
16143  3371           DCA T1
16144  1367           TAD KHUN
16145  2371           ISZ T1
16146  5344           JMP .-2
16147  5741           JMP I HUNS
                      / CONSTANTS
16150  0017  STUS,    17
16151  7477  PM193,   7477
16152  7520  M260,    -260
16153  7506  M272,    -272
16154  7563  MCR,     7563
16155  0000  TMPSTR,  0
```

```
16156  0000   CMND,    0
16157  7470   MH,      7470
16160  7460   MP,      7460
16161  7474   MD,      7474
16162  0240   SPCE,    240
16163  0277   QMK,     277
16164  0000   BATNO,   0
16165  7000   BUFF,    7000
16166  0000   BUFFP,   0
16167  0144   KHUN,    144
16170  0012   KTEN,    12
16171  0000   T1,      0
16173  6317
16174  6254
16175  6200
16176  6600
16177  6325
       6200   *6200
16200  4777'  PUNCH,   JMS LLDR
16201  4777'           JMS LLDR
16202  3352            DCA CHNO
16203  1776'  STRT,    TAD P0377
16204  4333            JMS UAOUT
16205  1776'           TAD P0377
16206  4333            JMS UAOUT
16207  1775'           TAD BATNO
16210  4774'           JMS WRDOUT
16211  7300            CLA CLL
16212  3355            DCA CKSM
16213  1353            TAD MCNT
16214  3351            DCA CNTR
16215  1352            TAD CHNO
16216  4773'           JMS POINT
16217  3345            DCA CPTR
16220  6214            RDF
16221  3354            DCA DFLD
16222  1354   GDAT,    TAD DFLD
16223  7650            SNA CLA
16224  6201            CDF+0
16225  1745            TAD I CPTR
16226  6211            CDF+10
16227  4774'           JMS WRDOUT
16230  2345            ISZ CPTR
16231  7000            NOP
16232  2351            ISZ CNTR
16233  5222            JMP GDAT
16234  1346            TAD P0300
16235  4333            JMS UAOUT
16236  1355            TAD CKSM
16237  4333            JMS UAOUT
16240  2352            ISZ CHNO
16241  1352            TAD CHNO
16242  1350            TAD PM6
16243  7700            SMA CLA
16244  5251            JMP FIN
16245  2775'           ISZ BATNO
16246  7000            NOP
16247  4777'           JMS LLDR
16250  5203            JMP STRT
16251  4777'  FIN,     JMS LLDR
16252  4777'           JMS LLDR
16253  5772'           JMP NXCMD
16254  7300   DISP,    CLA CLL / DISPLAY SLECTED CHANNEL.
16255  1771'           TAD SPCE
16256  4317            JMS CHROUT
16257  4770'           JMS GETNO
16260  3343            DCA CHAN
16261  3344            DCA PXDIS
16262  1343            TAD CHAN
16263  4773'           JMS POINT
16264  3345            DCA CPTR
16265  7330   NXLOC,   CLA CLL CML RAR
16266  1745            TAD I CPTR
```

```
16267  7110            CLL RAR
16270  7110            CLL RAR
16271  6066            OUTY
16272  7300            CLA CLL
16273  1344            TAD PXDIS
16274  6056            OUTX
16275  2345            ISZ CPTR
16276  7300            CLA CLL
16277  2344            ISZ PXDIS
16300  1344            TAD PXDIS
16301  1347            TAD PM2000
16302  7710            SPA CLA
16303  5265            JMP NXLOC
16304  6031            KSF
16305  5261            JMP DISP+5
16306  5772'           JMP NXCMD
16307  0000  CHRIN,    0
16310  7300            CLA CLL
16311  6031            KSF
16312  5311            JMP .-1
16313  6036            KRB
16314  0767'           AND P0177
16315  1766'           TAD P0200
16316  5707            JMP I CHRIN
16317  0000  CHROUT,   0
16320  6041            TSF
16321  5320            JMP .-1
16322  6046            TLS
16323  7300            CLA CLL
16324  5717            JMP I CHROUT
16325  0000  PCRLF,    0
16326  1341            TAD PCR
16327  4317            JMS CHROUT
16330  1342            TAD PLF
16331  4317            JMS CHROUT
16332  5725            JMP I PCRLF
16333  0000  UAOUT,    0
16334  6624            STR
16335  5334            JMP .-1
16336  6644            OUT
16337  7300            CLA CLL
16340  5733            JMP I UAOUT
16341  0215  PCR,      215
16342  0212  PLF,      212


16343  0000  CHAN,     0
16344  0000  PXDIS,    0
16345  0000  CPTR,     0
16346  0300  P0300,    300
16347  6000  PM2000,   6000
16350  7772  PM6,      7772
16351  0000  CNTR,     0
16352  0000  CHNO,     0
16353  6000  MCNT,     6000
16354  0000  DFLD,     0
16355  0000  CKSM,     0
16366  6557
16367  6556
16370  6532
16371  6162
16372  6005
16373  6471
16374  6411
16375  6164
16376  6560
16377  6400
       6400  *6400
16400  0000  LLDR,     0
16401  7300            CLA CLL
16402  1362            TAD KLD
16403  3346            DCA T2
16404  4777'           JMS UAOUT
```

```
16405  2346           ISZ T2
16406  5204           JMP .-2
16407  5600           JMP I LLDR
16410  0100  P0100,   100
16411  0000  WRDOUT,  0
16412  3347           DCA T3
16413  7300           CLA CLL
16414  1347           TAD T3
16415  0361           AND P07700
16416  7012           RTR
16417  7012           RTR
16420  7012           RTR
16421  1210           TAD P0100
16422  4245           JMS EPTY
16423  3346           DCA T2
16424  1346           TAD T2
16425  1776'          TAD CKSM
16426  0360           AND P0377
16427  3776'          DCA CKSM
16430  1346           TAD T2
16431  4777'          JMS UAOUT
16432  1347           TAD T3
16433  0355           AND P077
16434  4245           JMS EPTY
16435  3346           DCA T2
16436  1346           TAD T2
16437  1776'          TAD CKSM
16440  0360           AND P0377
16441  3776'          DCA CKSM
16442  1346           TAD T2
16443  4777'          JMS UAOUT
16444  5611           JMP I WRDOUT
16445  0000  EPTY,    0
16446  0356           AND P0177
16447  3351           DCA T6
16450  1354           TAD PM7
16451  3352           DCA T7
16452  3353           DCA BITS
16453  1351           TAD T6
16454  7010           RAR
16455  7430           SZL
16456  2353           ISZ BITS
16457  2352           ISZ T7
16460  5254           JMP .-4
16461  7300           CLA CLL
16462  1353           TAD BITS
16463  7010           RAR
16464  7200           CLA
16465  1351           TAD T6
16466  7430           SZL
16467  1357           TAD P0200
16470  5645           JMP I EPTY
16471  0000  POINT,   0
16472  7041           CIA
16473  6201           CDF+0
16474  7450           SNA
16475  5330           JMP DZ
16476  7001           IAC
16477  7450           SNA
16500  5326           JMP DO
16501  7001           IAC
16502  7450           SNA
16503  5324           JMP DTW
16504  6211           CDF+10
16505  7001           IAC
16506  7450           SNA
16507  5322           JMP DTH
16510  7001           IAC
16511  7450           SNA
16512  5320           JMP DF
16513  7001           IAC
16514  7440           SZA
16515  7402           HLT
```

```
16516  1363            TAD FIP
16517  5671            JMP I POINT
16520  1364  DF,       TAD FOP
16521  5671            JMP I POINT
16522  1365  DTH,      TAD THP
16523  5671            JMP I POINT
16524  1366  DTW,      TAD TWP
16525  5671            JMP I POINT
16526  1367  DO,       TAD OP
16527  5671            JMP I POINT
16530  1370  DZ,       TAD ZP
16531  5671            JMP I POINT
16532  0000  GETNO,    0
16533  4775'           JMS GETCHR
16534  1774'           TAD M260
16535  3350            DCA T4
16536  1350            TAD T4
16537  7510            SPA
16540  5773'           JMP ERROR
16541  1772'           TAD PM6
16542  7700            SMA CLA
16543  5773'           JMP ERROR
16544  1350            TAD T4
16545  5732            JMP I GETNO
16546  0000  T2,       0
16547  0000  T3,       0
16550  0000  T4,       0
16551  0000  T6,       0
16552  0000  T7,       0
16553  0000  BITS,     0
16554  7771  PM7,      7771
16555  0077  P077,     77
16556  0177  P0177,    177
16557  0200  P0200,    200
16560  0377  P0377,    377
16561  7700  P07700,   7700
16562  7730  KLD,      7730
16563  4000  FIP,      4000
16564  2000  FOP,      2000
16565  0000  THP,      0
16566  5400  TWP,      5400
16567  3400  OP,       3400
16570  1400  ZP,       1400
16572  6350
16573  6026
16574  6152
16575  6600
16576  6355
16577  6333
       6600  *16600
16600  0000  GETCHR,   0
16601  4777'           JMS CHRIN
16602  3222            DCA SAVE
16603  1222            TAD SAVE
16604  1223            TAD MCC
16605  7650            SNA CLA
16606  5213            JMP EXIT
16607  1222            TAD SAVE
16610  4776'           JMS CHROUT
16611  1222            TAD SAVE
16612  5600            JMP I GETCHR
16613  1224  EXIT,     TAD UPARR
16614  4776'           JMS CHROUT
16615  1225            TAD CHC
16616  4776'           JMS CHROUT
16617  6203            CDF CIF+0
16620  5621            JMP I .+1
16621  7600            7600
16622  0000  SAVE,     0
16623  7575  MCC,      7575
16624  0336  UPARR,    336
16625  0303  CHC,      303
16776  6317
```

16777 6307

ACMLTR	0074
BATNO	6164
BITS	6553
BUFDEC	6124
BUFF	6165
BUFFP	6166
CARG1	0536
CARG2	0537
CARRY	0117
CCBARA	0112
CCBFCW	0113
CHAN	6343
CHARG1	0506
CHARG2	0507
CHARG3	0510
CHC	6625
CHNO	6352
CHRIN	6307
CHROUT	6317
CKSM	6355
CMND	6156
CNTR	6351
CNTRLC	0725
CPTR	6345
CPYNTY	0107
CPYNUM	0106
CR	0036
CRLF	2200
CURPNT	0066
DEVNME	0076
DF	6520
DFLD	6354
DISNUM	0121
DISP	6254
DO	6526
DSK	0400
DTH	6522
DTW	6524
DZ	6530
EARG1	0447
EARG2	0450
ENDCHK	6056
ENDHDR	6114
EPTY	6445
ERMESS	2265
ERROR	6026
EXIT	6513
FARG1	0424
FARG2	0425
FARG3	0426
FCW1	0114
FCW2	0115
FIN	6251
FIP	6563
FIVEP	0135
FLAG	2157
FLSET	2137
FNME	2000
FOP	6564
FOUR	0627
FOURP	0134
GDAT	6222
GET	6037
GETBY	0703
GETCHR	6600
GETNO	6532
GETWRD	0566
GNME	0206
GTCR	2014
HANADR	0075
HARG1	0515
HARG2	0516
HARG3	0517
HARG4	0524
HARG5	0525
HARG6	0526
HBY	0320
HDR	6033
HK5	0105
HUNS	6141
ICHRO	0136
IDSK	0141
IGETBY	0146
IGTWRD	0145
IINCR	0142
IMAINC	0143
INC	0325
INCR1	0542
INPRT	0137
IPOIN1	0144
IRENME	0140
IRSTIN	0147
KHUN	6167
KLD	6562
KTEN	6170
LBY	0261
LF	0037
LFEED	2113
LIMIT	0157
LLDR	6400
LSTAT	6634
MADD	0065
MAINC	0556
MBY	0300
MCC	6623
MCNC	0034
MCNT	6353
MCNTJ	2154
MCNTU	2153
MCR	6154
MCRET	2155
MD	6161
MH	6157
MONST	0021
MP	6160
MRBOUT	2152
M1	0051
M101	0064
M12	0060
M2	0052
M260	6152
M272	6153
M3	0053
M32	0061
M4	0054
M5	0055
M6	0056
M60	0062
M7	0057
M72	0063
NAMEP	0100
NAM1	0101
NAM2	0102
NAM3	0103
NAM4	0104
NEXT	0216
NOCC	2063
NOCU	2045
NOFLG	2034
NOPER	0153
NOSAMS	0067
NUMBLK	0110
NUMPNT	0660
NXCH	2116
NXCHRP	2243
NXCMD	6005
NXLOC	6265
OK	2100
OK5	2105
ONE	0635
ONEP	0131
OP	6567
OUT	6644
OUTX	6056
OUTY	6066
O16	0041
O17	0042
O177	0045
O377	0046
O4000	0047
O60	0043
O7	0040
O77	0044
O7700	0050
PBSW	0335
PCR	6341
PCRLF	6325
PLF	6342
PM193	6151
PM2000	6347
PM6	6350
PM7	6554
PNTR	0116
POINT	6471
POIN1	0600
PO100	6410
PO177	6556
PO200	6557
PO300	6346
PO377	6560
PO77	6555
PO7700	6561
PPTR	0155
PRINT	2214
PSTRG	2160
PSTRIN	2271
PTR	0154
PUNCH	6200
PXDIS	6344
P0	0122
P1	0123
P2	0124
P3	0125
P4	0126
P5	0127
QMK	6163
RENAME	0250
ROUT	2130
RSTIN	0641
RUD	6631
SAVE	6622
SAVE1	0150
SAVE3	0151
SDR	6621
SKERR	6641
SLSH	2156
SPCE	6162
START	2005
STATUS	0022
STBLK	0111
STCODE	0025
STR	6624
STRING	3600
STRIN2	3632
STRT	6203
STUS	6150
SVE	0070
TEMP	0071
TEMP2	0072
TEMP3	0073
TENS	6132
THP	6565
THREE	0631
THREEP	0133
TMPST	0023
TMPSTR	6155
TPTR	0156
TRIALS	0024
TRILIM	0026
TRL	0211
TSTNME	2224
TWO	0633

```
TWOP    0132
TWP     6566
T1      6171
T2      6546
T3      6547
T4      6550
T6      6551
T7      6552
UAOUT   6333
UPARR   6624
UPARRO  0035
USR     0020
WAIT    0705
WRDOUT  6411
XDIS    0120
ZC      0032
ZCHRI   2206
ZCHRO   0347
ZE      0033
ZERO    0637
ZEROP   0130
ZP      6570
ZSPCE   0152
ZT      0027
ZU      0030
ZX      0031

ERRORS DETECTED: 0
LINKS GENERATED: 52
```

APPENDIX 8.12

FORTRAN Programmes used in the Analysis of the CNV Data

The listings of the three major analysis programmes are given in this appendix together with their associated subroutines. These programmes perform (i) The Pre- and Post- Stimulus (Broadband) Energy Test as described in section 2.2.3.1; (ii) The tests described in sections 2.2.2.1 (The Rayleigh Test of Circular Variance), 2.2.2.2 (The Modified Rayleigh Test), 2.2.2.3 (The Hodges-Ajne Test) and 2.2.3.3 (The Nearest and Furthest Mean Amplitude Test); (iii) All the tests in (ii) and in addition the test described in section 2.2.3.2 (The Pre- and Post- Stimulus Mean Amplitude differences test). All the CNV data were tested using programme (i). The one second ISI CNV's were tested using Programme (iii) whilst the four second ISI CNV's could only be tested using Programme (ii) because of the limited amount of pre-stimulus information available.

Programmes similar to (i) and (iii) were used in the analysis of the auditory responses.

The programmes listed in this appendix and in appendices 8.7 and 8.8 use a number library subroutines and functions specific to the Prime 750/550 system installed at Plymouth Polytechnic.

Brief details of these are as follows:-

1) Input and Output

a) On the Prime computer system the FORTRAN input / output unit numbers are as follows:-

unit 1 = Input / output from / to the users terminal.

unit 5 = Input / output from / to PRIMOS file unit 1.

unit 6 = Input / output from / to PRIMOS file unit 2.

Thus READ(1,*)A,I would perform a READ operation from the users terminal. The '*' infers free format whereby any numbers separated by spaces or commas are assigned to the elements of the variable list.

2) Applications Library and Operating System Subroutines.

The following routines are part of the PRIMOS applications library.

CLOS$A† Closes a file by its PRIMOS file unit number.

EXST$A Tests whether the file specified exists or not.

FILL$A Fills an array with a specified ASCII character.

MSUB$A	Copies a string of characters into another string.
NLEN$A	Returns the number of non-blank characters in a string array.
OPEN$A†	Opens a file for reading or writing on a specified PRIMOS file unit.
TREE$A	Tests a string of characters to establish whether they constitute a valid file treename. The file need not exist.
YSNO$A	Prompts the user with a specified string and requests a YES or NO answer. Returns a logical .TRUE. or .FALSE. according to the users reply.

† May be treated as Functions or Subroutines.

The following routines are part of the PRIMOS operating system.

EXIT	Returns from FORTRAN to PRIMOS.
TNOUA	Transfers a character string to the users terminal without appending a 'newline' sequence.
TODEC	Writes the argument as a decimal number on the users terminal.

T1IN Obtains a single character from the users terminal.

3) Graphics subroutines

The following subroutines form part of the GINO graphics package. For further details see the GINOGRAF and GINO-F manuals or contact The GINO-F Support Team, C.A.D. Centre, Madingley Road, Cambridge, CB3 0HB.

ARCTO2	DEVEND
BROKEN	DEVSPE
CC81	LINTO2
CC906	MOVTO2
CHAANG	PENSEL
CHAARR	PICCLE
CHAFLO	S5660
CHAINT	SYMBOL
CHAHAR	T4010
CHAHOL	
CHAMOD	UNITS
CHASIZ	WINDO2
CURSOR	WINDOW

The following subroutine is part of the GINOGRAF graphics package.

GRAF

```
C        BROADBAND POWER ANALYSIS OF PRE- AND POST-STIMULUS CNV'S
C        ---------------------------------------------------------
C
C
C
C        INPUT FILES: DATA
C        OUTPUT FILES: RESULTS>ENG.CNV.....
$INSERT SYSCOM>A$KEYS
      REAL DATA(1024),SSPRS1(32),SSS1(32),MUPR,MUS1
      DIMENSION TRDAT(1024)
      INTEGER*2 FNAME(20),CHANAN,BATNRS(32),BLINE,DEL
      INTEGER*2 SSR,EP1,EP2
      INTEGER BATNO,CHNO,RESNAM(20),RESLEN,ODEV
      LOGICAL FILE
      COMMON ODEV
      DATA ODEV/99/
      FILE=.TRUE.
      N=1024
      ICHAR='  '
      DEL=125
C
C                GET THE DETAILS OF THE SECTIONS TO BE
C                           ANALYSED.
C
    1 WRITE(1,2)
    2 FORMAT('LENGTH OF SECTION 1')
      READ(1,*,ERR=1)NL1
    3 WRITE(1,4)
    4 FORMAT('LENGTH OF SECTION 2')
      READ(1,*,ERR=3)NL2
    5 WRITE(1,6)
    6 FORMAT('START OF SECTION 1')
      READ(1,*,ERR=5)EP1
    7 WRITE(1,8)
    8 FORMAT('START OF SECTION 2')
      READ(1,*,ERR=7)EP2
C
C                 ONE SECOND STIMULUS POINTS
C
      IS1=407
      IS2=532
    9 WRITE(1,10)
   10 FORMAT('ONE OR FOUR SECOND PARADIGM')
      READ(1,*,ERR=9)IPARA
   11 WRITE(1,12)
   12 FORMAT('PERFORM BASELINE CORRECTIONS')
      READ(1,*,ERR=11)BLINE
      IF(BLINE .LT. 0 .OR. BLINE .GT. 1)GO TO 11
      IF(BLINE .EQ. 1)ICHAR='B'
      IF(IPARA .EQ. 1)GO TO 14
      IS1=219
      IS2=719
      IF(IPARA .NE. 4)GO TO 9
   14 IF(.NOT. YSNO$A('STORE RESULTS IN A FILE',23,A$DYES))
     +     FILE=.FALSE.
C
C                 PREPARE THE FILENAME FOR THE RESULTS
C
      CALL FILL$A(RESNAM,40,' ')
      ENCODE(19,15,RESNAM)ICHAR
   15 FORMAT('P03400>RESULTS>ENG',A1)
      RESLEN=NLEN$A(RESNAM,40)
C
C                 GET THE FILENAME OF THE DATA TO BE PROCESSED.
C
   18 CALL GETNAM(FNAME)
      NL=NLEN$A(FNAME,40)
C
C                 TEST FOR A VALID NAME.
C
      IF (.NOT. TREE$A(FNAME,NL,NT,NTL))GO TO 18
C
C                 ADD THE NAME OF THE DATA INPUT FILE
C                 TO THE RESULTS FILENAME TO GIVE A UNIQUE
C                 FILENAME.
C
      I9=MSUB$A(FNAME,NL,NT,NT+NTL-1,RESNAM,40,RESLEN+1,RESLEN+NTL)
      RESLEN=NLEN$A(RESNAM,40)
C
C                GET THE NUMBER OF THE CHANNEL TO BE ANALYSED.
```

```
C
   20 WRITE(1,30)
   30 FORMAT('CHANNEL 4 OR 5')
      READ(1,*,ERR=20)CHNO
      IF(CHNO .NE. 4 .AND. CHNO .NE. 5)GO TO 20
      CHANAN=CHNO-3
C
C               ECORR=1 IF DATA IS TO BE CORRECTED FOR EYE MOVEMENTS.
C                    =0 IF NOT.
C
      ECORR=1
C
C               IFILT=1 IF DATA IS TO BE FILTERED.
C                    =0 IF NOT.
C
      IFILT=1
C
C               GET THE NUMBERS OF THE BATCHES TO BE ANALYSED.
C
      CALL BATNOS(BATNRS,MBAT)
C
C               NOW THE ITERATIVE BIT
C
      DO 240 IC=1,MBAT
      BATNO=BATNRS(IC)
   54 WRITE(1,55)BATNO
   55 FORMAT('PROCESSING BATCH ',I4)
C
C               GET THE CORRECTED OR UNCORRECTED DATA.
C
      CALL EYECOR(FNAME,BATNO,CHANAN,DATA,SF1,SF2,SAMRAT,ECORR)
      IF(BLINE .EQ. 1)CALL BASLNE(DATA,N,1,IS1,IS2+DEL,N)
C
C               APPLY FILTER IF REQUIRED.
C
      IF(IFILT .EQ. 1)CALL FILTER(N,DATA)
C
C               SSR=SUBSAMPLING RATE
C
      SSR=1
C
C               EP1=START OF PRE-S1 DATA
C
      N1=NL1*SSR
      N2=SSR
C
C               REMOVE PRE-STIMULUS DATA AT REQUIRED POINTS
C               AND PERFORM ANALYSIS. STORE RESULTS IN ARRAY
C               SSPRS1.
C
      L1=0
      DO 135 I=1,N1,N2
      L1=L1+1
  135 TRDAT(L1)=DATA(I+EP1-1)
      CALL SSQRE(NL1,TRDAT,SSPRS1(IC))
C
C               NOW THE SAME FOR POST-STIMULUS AND PUT THE
C               RESULTS INTO ARRAY SSS1.
C
      N1=NL2*SSR
      L1=0
      DO 200 I=1,N1,N2
      L1=L1+1
  200 TRDAT(L1)=DATA(I+EP2-1)
      CALL SSQRE(NL2,TRDAT,SSS1(IC))
  240 CONTINUE
C
C               CALCULATE MEAN AND ST. DEV. FOR PRE-STIM. DATA.
C
      CALL STDMN(MBAT,SSPRS1,MUPR,SIGPR)
      WRITE(1,510)MUPR,SIGPR
  510 FORMAT('MEAN OF PRE-S1 ',E16.8,'   STANDARD DEV.',E16.8)
C
C               CALCULATE MEAN AND ST. DEV. FOR POST-STIM. DATA.
C
      CALL STDMN(MBAT,SSS1,MUS1,SIGS1)
      WRITE(1,520)MUS1,SIGS1
  520 FORMAT('MEAN OF S1 ',E16.8,'   STANDARD DEV. ',E16.8)
      IF(.NOT. FILE)GO TO 560
      IF(.NOT. EXST$A(RESNAM,RESLEN))GO TO 550
```

```
      WRITE(1,540)RESNAM
  540 FORMAT('OVERWRITE EXISTING FILE :    ',20A2)
      IF(.NOT. YSNO$A('YES OR NO ',10,A$DNO))FILE=.FALSE.
      IF(.NOT. FILE)GO TO 560
  550 IF(.NOT. OPEN$A(2,RESNAM,RESLEN,2))GO TO 2900
  560 DO 600 IC=1,MBAT
      DIFF=SSS1(IC)-SSPRS1(IC)
      WRITE(1,730)BATNRS(IC),SSPRS1(IC),SSS1(IC),DIFF
      IF(FILE)WRITE(6,735)BATNRS(IC),SSPRS1(IC),SSS1(IC),DIFF
  600 CONTINUE
  730 FORMAT('BATCH ',I3,'  PRE S1 ',E16.8,5X,'  POST S1 ',
     *E16.8,'   DIFFERENCE ',E16.8)
  735 FORMAT(I3,3(E16.8,2X))
      IF(FILE)CALL CLOS$A(2)
 1900 CALL CLOS$A(1)
      CALL EXIT
 2900 WRITE(1,2901)RESNAM
 2901 FORMAT('CANT OPEN RESULTS FILE :  ',20A2)
      STOP
      END
```

```
C                   PHASOR DIAGRAM ANALYSIS OF CNV
C                   ------------------------------
C
C
C                   INPUT FILES: DATA
C                   OUTPUT FILES: NONE
C
$INSERT SYSCOM>A$KEYS
C
      REAL DATA(1024)
      COMPLEX TDATA(512),S1(6,32)    /* 6 HARMONICS, 32 TRIALS
      DIMENSION TRDAT(512),ANGLE(32),RAD(32)
      INTEGER*2 FNAME(20),CHANAN,BATNRS(32),SSR,BLINE
      INTEGER*2 TDLEN,BATNO
      INTEGER*2 LAB1(40),EP1,ODEV,DEL
      COMMON ODEV
      DATA ODEV / 99 /
      PI=3.14159265
      WRITE(1,1)
    1 FORMAT('CNV PHASOR DIAGRAM ANALYSIS')
C
C                    FIND OUT WHICH GRAPHICAL OUTPUT
C                    DEVICE IS TO BE USED.
C
      WRITE(1,2)
    2 FORMAT('WHICH OUTPUT DEVICE FOR GRAPHIC DATA')
    3 WRITE(1,5)
    5 FORMAT('TEKTRONIX(0), CALCOMP(1) OR SIGMA(2)')
      READ(1,*,ERR=3)IDEV
    6 WRITE(1,7)
    7 FORMAT('CNV PARADIGM 1 OR 4 SECONDS')
      READ(1,*,ERR=6)IPARA
      IF(IPARA .EQ. 1 .OR. IPARA .EQ. 4)GO TO 10
      GO TO 6
   10 N=1024
C
C                THESE PARAMETERS ARE GOVERNED
C                BY THE CNV PARADIGM
C                EP1 IS THE START OF THE POST- S1 DATA.
C                NP IS THE LENGTH OF THE POST- S1 DATA.
C                IS1 IS THE S1 STIMULUS POINT
C                IS2 IS THE S2 STIMULUS POINT
C                DEL IS A DELAY FROM S2 TO ALLOW THE AEP & CNV TO SETTLE.
C                ALL VALUES ARE IN TERMS OF 'SAMPLE NUMBER' 1  N  1024
C
      NP=64
      TDLEN=64
      DEL=125
C
C                    FOR ONE SECOND CNV'S
C
      EP1=472
      IS1=407
      IS2=532
      IF(IPARA .EQ. 1)GO TO 20
      NP=400
      TDLEN=512
C
C                    FOR FOUR SECOND CNV'S
C
      EP1=295
      IS1=219
      IS2=719
C
C                    GET THE NAME OF THE INPUT DATA FILE.
C
   20 CALL GETNAM(FNAME)
      LGTDLN=IFIX(ALOG10(FLOAT(TDLEN))/ALOG10(2.) + 0.5)
      ITL=TDLEN/2 + 1
      CHANAN=4
C                         STUDY CHANNEL 4 I.E. VERTEX
C
      CHANAN=CHANAN-3
   25 WRITE(1,30)
   30 FORMAT('PERFORM EYE MOVEMENT CORRECTIONS')
      READ(1,*,ERR=25)ECORR
   31 WRITE(1,35)
   35 FORMAT('PERFORM BASELINE CORRECTIONS')
      READ(1,*,ERR=31)BLINE
   38 WRITE(1,40)
```

```
   40 FORMAT('FILTER')
      READ(1,*,ERR=38)IFILT
C
C                ALLOW VARIABLE SCALE FACTORS SO AS TO GET
C                ALL THE POINTS ON THE PHASOR DIAGRAM.
C
   45 WRITE(1,50)
   50 FORMAT('MULTIPLICATION FACTOR')
      READ(1,*,ERR=45)SF
      SF=SF*1.5E6
C
C                FIND OUT WHICH BATCHES ARE TO BE ANALYSED.
C
      CALL BATNOS(BATNRS,MBAT)
      SSR=1
      N1=NP*SSR
      CALL FILL$A(LAB1,40,' ')
      ENCODE(57,52,LAB1)TDLEN,NP,SSR,EP1,BLINE
   52 FORMAT(I3,' PT FFT,',I3,' DATA PTS, SSR= ',I2,', POST =',I3,
     +4X,'B. LINE=',I2)
C
C                   NOW THE ITERATIVE BIT
C
      DO 640 IC=1,MBAT
      BATNO=BATNRS(IC)
   54 WRITE(1,55)BATNO
   55 FORMAT('PROCESSING BATCH ',I4)
      CALL EYECOR(FNAME,BATNO,CHANAN,DATA,SF1,SF2,SAMRAT,ECORR)
      IF(BLINE .EQ. 1)CALL BASLNE(DATA,N,1,IS1,IS2+DEL,N)
      IF(IFILT .EQ. 1)CALL FILTER(N,DATA)
      ISTRT=EP1-1
C
C               EXTRACT DATA TO BE ANALYSED AND PUT
C               INTO TRDAT.
C
      L1=0
      DO 135 I=1,N1,SSR
      L1=L1+1
  135 TRDAT(L1)=DATA(I+ISTRT)
C
C               TAPER THE DATA.
C
      CALL TAPER2(TRDAT,NP)
      DO 136 I=1,TDLEN
      TDATA(I)=CMPLX(0.,0.)
  136 IF(I .LE. NP)TDATA(I)=CMPLX(TRDAT(I),0.)
C
C               CALL FFT SUBROUTINE
C
  151 CALL NLOGN(LGTDLN,TDATA,-1.)
      DO 160 IHAR=1,6      /* STUDY HARMONICS 1-6
C
C               NOT INTERESTED IN DC TERM
C               I.E. TDATA(1)
C
  160 S1(IHAR,IC)=TDATA(IHAR+1)*2./FLOAT(NP)
  640 CONTINUE
      CALL PHASR1(S1,MBAT,SF,SAMRAT,FNAME,LAB1,IDEV)
      CALL PHASR1(S1,MBAT,SF,SAMRAT,FNAME,LAB1,-1)
      IF(IDEV .EQ. 0 .OR. IDEV .EQ. 2)CALL T1IN(IXYZ)
      DO 1650 IHAR=1,6
      DO 1630 K=1,MBAT
      ANGLE(K)=ATAN2(AIMAG(S1(IHAR,K)),REAL(S1(IHAR,K)))
      RAD(K)=CABS(S1(IHAR,K))
 1630 CONTINUE
C
C               NOW DO THE STATISTICAL TESTS.
C
      WRITE(1,1635)IHAR
 1635 FORMAT(20X,'ANGULAR STATISTICS FOR POST-STIMULUS CNV HARMONIC',
     +I3,//)
      CALL RSTAT1(RAD,MBAT)
      CALL ASTAT1(ANGLE,MBAT)
      CALL ASTAT2(ANGLE,MBAT)
      CALL VSTAT1(ANGLE,RAD,MBAT)
      CALL VSTAT3(ANGLE,RAD,MBAT)
      CALL VSTAT2(ANGLE,RAD,MBAT)
      WRITE(1,1640)
 1640 FORMAT(////)
 1650 CONTINUE
```

```
1900 CALL CLOSSA(1)
     CALL EXIT
     END
```

```
C                  PHASOR DIAGRAM ANALYSIS OF 1 SECOND ISI CNV
C                          (PRE- AND POST-STIMULUS)
C                  ------------------------------------------
C
C
C
C                  INPUT FILES: DATA
C                  OUTPUT FILES: NONE
C
$INSERT SYSCOM>A$KEYS
C
      REAL DATA(1024)
      COMPLEX TDATA(64),PRES1(6,32),S1(6,32)   /* 6 HARS., 32 TRIALS
      DIMENSION TRDAT(64),ANGLE(32),RAD(32),RADDIF(6,32)
      INTEGER*2 FNAME(20),CHANAN,BATNRS(32),SSR,DEL,BLINE
      INTEGER*2 TDLEN,BATNO
      INTEGER*2 LAB1(40),PRES,POSS,ODEV
      COMMON ODEV
      DATA ODEV / 99 /
      PI=3.14159265
      N=1024
    4 WRITE(1,5)
    5 FORMAT('TEKTRONIX(0) OR CALCOMP(1)')
      READ(1,*,ERR=4)IDEV
      CALL GETNAM(FNAME)
      CHANAN=4
   28 WRITE(1,30)
   30 FORMAT('PERFORM EYE MOVEMENT CORRECTIONS')
      READ(1,*,ERR=28)ECORR
   32 WRITE(1,35)
   35 FORMAT('PERFORM BASELINE CORRECTIONS')
      READ(1,*,ERR=32)BLINE
   40 WRITE(1,45)
   45 FORMAT('FILTER')
      READ(1,*,ERR=40)IFILT
   48 WRITE(1,50)
   50 FORMAT('MULTIPLICATION FACTOR')
      READ(1,*,ERR=48)SF
      SF=SF*1.5E6
      CALL BATNOS(BATNRS,MBAT)
      TDLEN=64
      ITL=TDLEN/2 + 1
      LGTDLN=6
      NP=64
      SSR=1
      N1=NP*SSR
C
C               THESE PARAMETERS ARE GOVERNED
C               BY THE CNV PARADIGM
C               IS1 IS THE S1 STIMULUS
C               IS2 IS THE S2 STIMULUS
C               PRES IS THE START OF THE PRE. STIM. DATA TO BE ANALYSED.
C               POSS IS THE START OF THE POST STIM. DATA TO BE ANALYSED.
C               ALL VALUES ARE IN TERMS OF 'SAMPLE NUMBER' 1  N  1024
C
      PRES=1
      POSS=472
      IS1=407
      IS2=532
      DEL=125
      CALL FILL$A(LAB1,80,' ')
      ENCODE(71,52,LAB1)TDLEN,NP,SSR,PRES,POSS,CHANAN,BLINE
   52 FORMAT(I3,' PT FFT,',I3,' DATA PTS, SSR= ',I2,' PRE =',I3,
     +', POST =',I3,' CH',I2,4X,'B. LINE=',I2)
C
C                    NOW THE ITERATIVE BIT
C
      DO 640 IC=1,MBAT
      BATNO=BATNRS(IC)
   54 WRITE(1,55)BATNO
   55 FORMAT('PROCESSING BATCH ',I4)
      CALL EYECOR(FNAME,BATNO,CHANAN-3,DATA,SF1,SF2,SAMRAT,ECORR)
      IF(BLINE .EQ. 1)CALL BASLNE(DATA,N,1,IS1,IS2+DEL,N)
      IF(IFILT .EQ. 1)CALL FILTER(N,DATA)
C
C                  PRE STIMULUS
      ISTRT=PRES-1
      L1=0
      DO 135 I=1,N1,SSR
      L1=L1+1
```

```
 135 TRDAT(L1)=DATA(I+ISTRT)
     CALL TAPER2(TRDAT,NP)
     DO 136 I=1,TDLEN
     TDATA(I)=CMPLX(0.,0.)
 136 IF(I .LE. NP)TDATA(I)=CMPLX(TRDAT(I),0.)
 151 CALL NLOGN(LGTDLN,TDATA,-1.)
     DO 160 IHAR=1,6     /* STUDY HARMONICS 1-6
 160 PRES1(IHAR,IC)=TDATA(IHAR+1)*2./FLOAT(NP)
C
C                     POST STIMULUS
     ISTRT=POSS-1
     L1=0
     DO 200 I=1,N1,SSR
     L1=L1+1
 200 TRDAT(L1)=DATA(I+ISTRT)
     CALL TAPER2(TRDAT,NP)
     DO 220 I=1,TDLEN
     TDATA(I)=CMPLX(0.,0.)
 220 IF(I .LE. NP)TDATA(I)=CMPLX(TRDAT(I),0.)
     CALL NLOGN(LGTDLN,TDATA,-1.)
     DO 230 IHAR=1,6
 230 S1(IHAR,IC)=TDATA(IHAR+1)*2./FLOAT(NP)
 640 CONTINUE
     CALL PHASOR(PRES1,S1,MBAT,SF,SAMRAT,FNAME,LAB1,IDEV)
     CALL PHASOR(PRES1,S1,MBAT,SF,SAMRAT,FNAME,LAB1,-1)
     IF(IDEV .EQ. 0)CALL T1IN(IXYZ)
     DO 1650 IHAR=1,6
     DO 1600 K=1,MBAT
     ANGLE(K)=ATAN2(AIMAG(PRES1(IHAR,K)),REAL(PRES1(IHAR,K)))
     RAD(K)=CABS(PRES1(IHAR,K))
1600 CONTINUE
     WRITE(1,1610)IHAR
1610 FORMAT(20X,'ANGULAR STATISTICS FOR PRE-STIMULUS HARMONIC ',I3)
     CALL RSTAT1(RAD,MBAT)
     CALL ASTAT1(ANGLE,MBAT)
     CALL ASTAT2(ANGLE,MBAT)
     CALL VSTAT1(ANGLE,RAD,MBAT)
     CALL VSTAT3(ANGLE,RAD,MBAT)
     CALL VSTAT2(ANGLE,RAD,MBAT)
     WRITE(1,1620)
1620 FORMAT(/////)
     DO 1630 K=1,MBAT
     ANGLE(K)=ATAN2(AIMAG(S1(IHAR,K)),REAL(S1(IHAR,K)))
     RAD(K)=CABS(S1(IHAR,K))
     RADDIF(IHAR,K)=CABS(S1(IHAR,K))-CABS(PRES1(IHAR,K))
1630 CONTINUE
     WRITE(1,1635)IHAR
1635 FORMAT(20X,'ANGULAR STATISTICS FOR POST-STIMULUS HARMONIC ',I3)
     CALL RSTAT1(RAD,MBAT)
     CALL ASTAT1(ANGLE,MBAT)
     CALL ASTAT2(ANGLE,MBAT)
     CALL VSTAT1(ANGLE,RAD,MBAT)
     CALL VSTAT3(ANGLE,RAD,MBAT)
     CALL VSTAT2(ANGLE,RAD,MBAT)
     WRITE(1,1640)
1640 FORMAT(////)
1650 CONTINUE
1900 CALL CLOS$A(1)
     WRITE(1,2200)
2200 FORMAT(//,'RESULTS OF A PAIRED T-TEST ON THE PRE-POST RADIUS '
    'LENGTHS',///)
     MBAT1=MBAT-1
     DO 3000 IHAR=1,6
     SUM=0.
     DO 2000 I=1,MBAT
2000 SUM=SUM+RADDIF(IHAR,I)
     RMEAN=SUM/FLOAT(MBAT)
     SUMSQ=0.
     DO 2100 I=1,MBAT
2100 SUMSQ=SUMSQ+(RADDIF(IHAR,I)-RMEAN)*(RADDIF(IHAR,I)-RMEAN)
     STDEV=SQRT(SUMSQ/FLOAT(MBAT1))
     TSTAT=RMEAN/(STDEV/SQRT(FLOAT(MBAT)))
     WRITE(1,2210)IHAR,RMEAN,STDEV,TSTAT,MBAT1
2210 FORMAT('HARMONIC= ',I2,5X,'MEAN= ',E14.8,5X,
    &'ST. DEV= ',E14.8,5X,'T= ',F8.4,5X,'WITH',5X,I3,'  DF')
3000 CONTINUE
     CALL EXIT
     END
```

```
      SUBROUTINE ASTAT1(ANGLE,N)
C
C  THIS SUBROUTINE CALCULATES SUMMARY STATISTICS FOR THE N ANGULAR
C  VALUES (RADIANS) STORED IN ARRAY 'ANGLE'.
C
C  MEAN DIRECTION ....  THETA=ATAN(S/C)
C
C      WHERE  C = AVERAGE COSINE VALUE
C             S = AVERAGE SINE VALUE
C
C  CIRCULAR VARIANCE ....  VO=1-SQRT(C*C+S*S)
C
C      VO HAS A VALUE 1 FOR COMPLETE UNIFORMITY ON THE CIRCLE
C                     0 FOR A SET OF IDENTICAL ANGLES
C.....................................................................
C
C
C  WRITTEN BY TERRY JOHNSON. DEPT. OF MATHS. STATS. & COMPUTING
C  PLYMOUTH POLYTECHNIC.
C
      DIMENSION ANGLE(N)
      DATA PI/3.1415926536/
      C=0
      S=0
      DO 1 I=1,N
      C=C+COS(ANGLE(I))
 1    S=S+SIN(ANGLE(I))
      C=C/N
      S=S/N
      THETA=ATAN2(S,C)
      VO=1-SQRT(C*C+S*S)
      WRITE(1,100) THETA
      THETA=THETA*180/PI
      WRITE(1,102) THETA
      WRITE(1,101) VO
100   FORMAT(/'MEAN DIRECTION',13X,'= ',F10.5,'  RADIANS')
101   FORMAT('CIRCULAR VARIANCE',10X,'= ',F10.5)
102   FORMAT(27X,'= ',F10.5,'  DEGREES')
      RETURN
      END

      SUBROUTINE ASTAT2(ANGLE,N)
C
C  THIS SUBROUTINE TESTS THE N ANGULAR VALUES IN ARRAY 'ANGLE'
C  FOR UNIFORMITY OF DISTRIBUTION ON THE CIRCLE USING THE
C  HODGES-AJNE TEST. THE TEST STATISTIC IS M WHERE M IS THE
C  MINIMUM NUMBER OF OBSERVATIONS FOUND IN ANY SEMI-CIRCLE.
C
C.....................................................................
C
C  WRITTEN BY TERRY JOHNSON. DEPT. OF MATHS. STATS. & COMPUTING
C  PLYMOUTH POLYTECHNIC.
C
      DIMENSION ANGLE(N)
      DOUBLE PRECISION S
      DATA PI/3.1415926536/
      M=N
      DO 1 I=1,N
      NR=0
      IF(ANGLE(I).GT.0.0) GO TO 3
      AMIN=ANGLE(I)
      AMAX=AMIN+PI
      DO 2 J=1,N
      IF(ANGLE(J).GT.AMIN.AND.ANGLE(J).LE.AMAX) NR=NR+1
 2    CONTINUE
      GO TO 5
 3    AMAX=ANGLE(I)
      AMIN=AMAX-PI
      DO 4 J=1,N
      IF(ANGLE(J).GE.AMIN.AND.ANGLE(J).LT.AMAX) NR=NR+1
 4    CONTINUE
 5    IF(NR.LT.M) M=NR
      IF(N-NR.LT.M) M=N-NR
 1    CONTINUE
      WRITE(1,100) M
C
C     FOR M LESS THAN (N/3) EXACT SIGNIFICANCE IS GIVEN BY
C
C                      N   (1-N)
C          S = (N-2*M). C .2
```

```
C                          M
C
      IF(M.GT.N/3) RETURN
      S=(N-2*M)/(2.0**(N-1))
      IF(M.EQ.0) GO TO 7
      DO 6 I=1,M
 6    S=S*(N+1-I)/I
 7    WRITE(1,101) S
 100  FORMAT(/'HODGES-AJNE TEST STATISTIC = ',I4)
 101  FORMAT('LEVEL OF SIGNIFICANCE       = ',F10.5)
      RETURN
      END

      SUBROUTINE BASLNE(DATA,N,NP1,NP2,NP3,NP4)
C
C               CORRECT THE BASELINE OF A SECTION OF EEG
C               BY AVERAGING BETWEEN NP1&NP2 AND ALSO
C               BETWEEN NP3&NP4. CALCULATE THE DIFFERENCE
C               BETWEEN THE AVERAGES AND SUBTRACT THE
C               APPROPRIATE FRACTION FROM THE DATA.
C               FINALLY ADJUST THE SECTIONS NP1-NP2 AND
C               NP3-NP4 TO HAVE A ZERO MEAN.
C
      INTEGER*2 N,NP1,NP2,NP3,NP4,Z1,Z2
      DIMENSION DATA(N)
      CALL SECTAV(NP1,NP2,DATA,SAV1)
      CALL SECTAV(NP3,NP4,DATA,SAV2)
      GRAD=(SAV2-SAV1)/(FLOAT(NP3-NP2))
      DO 70 I=1,NP2
   70 DATA(I)=DATA(I)-SAV1
      Z1=NP2+1
      DO 72 I=Z1,NP3
   72 DATA(I)=DATA(I)-SAV1-GRAD*(I-NP2)
      Z2=NP3+1
      DO 74 I=Z2,N
   74 DATA(I)=DATA(I)-SAV2
      RETURN
      END

      SUBROUTINE BATNOS(BATS,MAX)
C
C               GET A SEQUENCE OF BATCH NUMBERS
C               FROM THE USER.
C
      INTEGER*2 BATS(32)
      LOGICAL YSNO$A
   10 WRITE(1,20)
   20 FORMAT('HOW MANY BATCHES TO BE PROCESSED')
      READ(1,*,ERR=10)MAX
      IF(MAX .GT. 32 .OR. MAX .LT. 1)GO TO 10
      IF(MAX .EQ. 32)GO TO 100
      ITBAT=0
      I=1
   40 CALL TNOUA('BATCH',5)
      CALL TODEC(ITBAT)
      IF(.NOT. YSNO$A(' TO BE INCLUDED ',16,1))GO TO 50
      BATS(I)=ITBAT
      I=I+1
   50 ITBAT=ITBAT+6
      IF(I .LE. MAX)GO TO 40
      RETURN
  100 DO 120 I=1,MAX
      BATS(I)=(I-1)*6
  120 CONTINUE
      RETURN
      END

      SUBROUTINE DATIN(IBATNO,IDATA,RNAME,SF1,SF2,SAMRAT,CSE)
C
C               THIS SUBROUTINE READS DATA FROM A DATA FILE
C               SPECIFIED BY ARGUMENT RNAME.
C               THE BATCH SPECIFIED IS READ INTO IDATA.
C               THE PROGRAM ALSO RETURNS THE SCALE FACTORS
C               SF1, SF2, AND THE SAMPLE RATE. (SAMRAT)
C               SETTING CSE = -1 CLOSES ANY OPEN FILE AND
C               RETURNS.
C
      LOGICAL CLOS$A,OPEN$A
      INTEGER*2 IDATA(1024),ONAME(20),RNAME(20),TITLE(36),NME(6)
      INTEGER*2 RWKEY,NLEN,NLEN2,PRIMNO,NBAT,IBATNO,IAA1(4)
```

```
      LOGICAL NEOPEN,CSE
      DATA NEOPEN /.FALSE./
      RWKEY=1
      PRIMNO=1
      NLEN=40
      NLEN2=NLEN/2
      IF(NEOPEN)GO TO 1300
      IF(CSE)RETURN
  900 IF(.NOT. OPEN$A(RWKEY,RNAME,NLEN,PRIMNO))GO TO 1700
      DO 1000 IC=1,NLEN2
 1000 ONAME(IC)=RNAME(IC)
      NEOPEN=.TRUE.
      READ(5,3000,END=1800,ERR=1900)NME,SF1,SF2
      READ(5,3010,END=1800,ERR=1900)MAXBAT
      READ(5,3020,END=1800,ERR=1900)TITLE
      DO 234 IL=1,4
  234 IAA1(IL)=TITLE(IL+20)
      DECODE (8,236,IAA1)SAMRAT
  236 FORMAT(F8.4)
 1100 READ(5,END=1800,ERR=1900)NBAT
      READ(5,END=1800,ERR=1900)(IDATA(I),I=1,1024)
      IF(NBAT .NE. IBATNO)GO TO 1100
      NBAT=NBAT+1
      RETURN
 1200 IF(.NOT. CLOS$A(PRIMNO))GO TO 1600
      NEOPEN=.FALSE.
      RETURN
 1300 IF(CSE)GO TO 1200
      DO 1400 IC=1,NLEN2
 1400 IF(ONAME(IC) .NE. RNAME(IC))GO TO 1500
      IF(IBATNO .GE. NBAT)GO TO 1100
 1500 IF(CLOS$A(PRIMNO))GO TO 900
 1600 WRITE(1,1610)ONAME
 1610 FORMAT('*** CAN NOT CLOSE FILE ',20A2,' ***')
      STOP 1
 1700 WRITE(1,1710)RNAME
 1710 FORMAT('*** CAN NOT OPEN FILE ',20A2,' ***')
      STOP 2
 1800 WRITE(1,1810)RNAME
 1810 FORMAT('*** END OF FILE ',20A2,' ***')
      STOP 3
 1900 WRITE(1,1910)IBATNO,RNAME
 1910 FORMAT('*** ERROR TRYING TO READ BATCH ',I5,' FROM FILE ',
     +20A2,' ***')
      STOP 4
 3000 FORMAT(6A2,2F8.6)
 3010 FORMAT(I4)
 3020 FORMAT(36A2)
      END

      SUBROUTINE EYECOR(FNAME,BATNO,ICHAN,COR1,SF1,SF2,SAMRAT,ECORR)
C             THIS PROGRAM IS INTENDED TO MINIMISE THE AMOUNT OF
C             E.O.G POWER IN THE E.E.G. IT USES THE MODIFIED
C             QUILTER TECHNIQUE. HORIZONTAL AND VERTICAL COMPONENTS
C             OF BOTH EYES ARE TAKEN INTO CONSIDERATION.
C             THE PROGRAM REMOVES ANY D.C OFFSET ON ANY OF
C             THE INPUT DATA CHANNELS.
      REAL VL(1024),VR(1024),HL(1024),HR(1024),E1(1024),COR1(1024)
      DIMENSION X1(4,5),RM1(4),RHS(4)
      INTEGER*2 BATNO,INP(1024),FNAME(20)
      LOGICAL CSE
      DATA CSE /.FALSE./
      N=1024
C             THE DATA IS ASSUMED TO BE IN THE FOLLOWING
C             ORDER ; VL , VR , HL , HR , M1 , M2
C             M1 OR M2 ARE  THE CHANNELS TO BE CORRECTED BY THE
C             MODIFIED QUILTER TECHNIQUE.
C             SF1 FOR EOG DATA. SF2 FOR EEG DATA.
C             CHECK THAT THE BATCH NUMBER IS VALID.
      IF (BATNO .LT. 0 .OR. BATNO .GT. 191)GO TO 2999
      IF(FLOAT(BATNO/6) .NE. FLOAT(BATNO)/6.)GO TO 2999
      L=BATNO
C             READ THE DATA AND CONVERT TO REAL FORMAT.
      CALL DATIN(L,INP,FNAME,SF1,SF2,SAMRAT,CSE)
      DO 22 I=1,N
   22 VL(I)=FLOAT(INP(I))*SF1*1.E-06
      L=L+1
      CALL DATIN(L,INP,FNAME,SF1,SF2,SAMRAT,CSE)
      DO 24 I=1,N
   24 VR(I)=FLOAT(INP(I))*SF1*1.E-06
```

```
      L=L+1
      CALL DATIN(L,INP,FNAME,SF1,SF2,SAMRAT,CSE)
      DO 26 I=1,N
   26 HL(I)=FLOAT(INP(I))*SF1*1.E-06
      L=L+1
      CALL DATIN(L,INP,FNAME,SF1,SF2,SAMRAT,CSE)
      DO 28 I=1,N
   28 HR(I)=FLOAT(INP(I))*SF1*1.E-06
      L=L+1
C
C                 CHECK WHICH CHANNEL
C                 IS TO BE CORRECTED.
C                 IF CHANNEL 5 INCREMENT L.
C
      IF(ICHAN .GE. 2)L=L+1
      CALL DATIN(L,INP,FNAME,SF1,SF2,SAMRAT,CSE)
      DO 30 I=1,N
   30 E1(I)=FLOAT(INP(I))*SF2*1.E-06
C               SUBTRACT THE MEAN OF EACH DATA BATCH FROM THE DATA.
      CALL SMEAN(N,E1,E1AV)
      IF(ECORR .NE. 1.)GO TO 1000
      CALL SMEAN(N,VL,VLM)
      CALL SMEAN(N,VR,VRM)
      CALL SMEAN(N,HL,HLM)
      CALL SMEAN(N,HR,HRM)
C               FORM THE CORRELATION SUMS OF PRODUCTS.
      A=0.
      B=0.
      C=0.
      D=0.
      E=0.
      F=0.
      G=0.
      P=0.
      Q=0.
      R=0.
      S=0.
      T=0.
      U=0.
      V=0.
      DO 100 I=1,N
      A=A+VL(I)*VL(I)
      B=B+VL(I)*VR(I)
      C=C+VL(I)*HL(I)
      D=D+VL(I)*HR(I)
      E=E+VR(I)*VR(I)
      F=F+VR(I)*HL(I)
      G=G+VR(I)*HR(I)
      P=P+HL(I)*HL(I)
      Q=Q+HL(I)*HR(I)
      R=R+HR(I)*HR(I)
      S=S+E1(I)*VL(I)
      T=T+E1(I)*VR(I)
      U=U+E1(I)*HL(I)
      V=V+E1(I)*HR(I)
  100 CONTINUE
      X1(1,1)=A
      X1(1,2)=B
      X1(1,3)=C
      X1(1,4)=D
      X1(2,2)=E
      X1(2,3)=F
      X1(2,4)=G
      X1(3,3)=P
      X1(3,4)=Q
      X1(4,4)=R
      RHS(1)=S
      RHS(2)=T
      RHS(3)=U
      RHS(4)=V
C               SET UP SYMMETRICAL MATRIX.
      X1(2,1)=X1(1,2)
      X1(3,1)=X1(1,3)
      X1(4,1)=X1(1,4)
      X1(3,2)=X1(2,3)
      X1(4,2)=X1(2,4)
      X1(4,3)=X1(3,4)
C               SOLVE THE SIMULTANEOUS EQUATIONS BY THE
C               GAUSS PIVOTAL METHOD.
      CALL GAUSS(4,X1,RHS,RM1)
```

```
C               APPLY THE CORRECTIONS TO THE DATA.
      DO 220 I=1,N
      COR1(I)=E1(I) - (RM1(1)*VL(I) + RM1(2)*VR(I) + RM1(3)*HL(I)
     1+ RM1(4)*HR(I))
  220 CONTINUE
      RETURN
 1000 DO 1010 I=1,N
 1010 COR1(I)=E1(I)
      RETURN
 2999 WRITE(1,4000)BATNO
 4000 FORMAT(///,' BATCH NUMBER INCORRECT',I6)
      STOP 8
      END

      SUBROUTINE FILTER(NPTS,XT)
C
C                     DIGITAL FILTER THE DATA.
C
      DIMENSION XT(NPTS),DATOUT(1024),H(128)
      REAL H
      LOGICAL GOTEM,OPEN$A,CLOS$A
      INTEGER*2 WTFILE(20),NLEN$A
      DATA GOTEM / .FALSE. /
      IF(GOTEM)GO TO 60
    4 WRITE(1,5)
    5 FORMAT('NAME OF FILTER CO-EFFICIENT FILE')
      READ(1,8,ERR=4)WTFILE
    8 FORMAT(20A2)
      NLEN=NLEN$A(WTFILE,40)
      IF(.NOT. OPEN$A(1,WTFILE,NLEN,2))GO TO 100
      READ(6,10)
   10 FORMAT(/)
      READ(6,15)ICASE
   15 FORMAT(6X,I2)
C               CASE 1 = ODD LENGTH, SYMMETRICAL
C               CASE 2 = EVEN LENGTH, SYMMETRICAL
C               CASE 3 = ODD LENGTH, ANTI-SYMMETRICAL
C               CASE 4 = EVEN LENGTH, ANTI-SYMMETRICAL
      ISGN=1
      IF(ICASE .EQ. 3 .OR. ICASE .EQ. 4)ISGN=-1
      READ(6,20)N
   20 FORMAT(16X,I4)
      N2=(N+1)/2
      DO 50 I=1,N2
      READ(6,40)H(I)
   40 FORMAT(9X,E15.8)
   50 H(N+1-I)=H(I)*FLOAT(ISGN)
      GOTEM=.TRUE.
      IF(.NOT. CLOS$A(2))GO TO 110
   60 DO 80 I=1,NPTS
      STORE=0.
      IF(N .LT. I)GO TO 70
      STORE=XT(I)
      GO TO 80
   70 DO 75 K=1,N
   75 STORE=STORE + XT(I-K+1)*H(K)
   80 DATOUT(I)=STORE
      DO 85 I=1,NPTS
   85 XT(I)=DATOUT(I)
      RETURN
  100 WRITE(1,105)WTFILE
  105 FORMAT('CANT OPEN FILE',10A2)
      STOP
  110 WRITE(1,115)WTFILE
  115 FORMAT('CANT CLOSE FILE',10A2)
      STOP
      END

      SUBROUTINE GAUSS(K,B,RHS,X)
C                     A SUBROUTINE TO SOLVE SIMULTANEOUS
C                     EQUATIONS BY THE GAUSS PIVOTAL METHOD
      DIMENSION A(7,8),X(K),B(K,K),RHS(K)
      INTEGER*2 Z2,Z3,Z4,Z5,Z6,Z7
C
C                 AUGMENT INPUT MATRICES
C                 AND SAVE INPUT DATA.
C
      DO 12 I=1,K
      DO 10 J=1,K
   10 A(I,J)=B(I,J)
```

```
   12 A(I,K+1)=RHS(I)
      Z2=K-1
      DO 35 I=1,Z2
      L=I
      DO 15 J=I,K
   15 IF(ABS(A(L,I)) .LT. ABS(A(J,I)))L=J
      IF(ABS(A(L,I)) .EQ. 0.)GO TO 60
      IF(L .EQ. I)GO TO 21
      Z3=K+1
      DO 20 N=I,Z3
      SAVE=A(I,N)
      A(I,N)=A(L,N)
   20 A(L,N)=SAVE
C                        PIVOTAL REDUCTION
   21 Z4=I+1
      DO 35 M=Z4,K
      D=A(M,I)/A(I,I)
      Z5=I+1
      Z6=K+1
      DO 35 J=Z5,Z6
   35 A(M,J)=A(M,J)-D*A(I,J)
C                        BACK SUBSTITUTION
      DO 50 L=1,K
      J=K+1-L
      IF(J .EQ. K)GO TO 45
      Y=A(J,K+1)
      Z7=K-1
      DO 40 M=J,Z7
   40 Y=Y-A(J,M+1)*X(M+1)
      X(J)= Y/A(J,J)
      IF(J .NE. K)GO TO 50
   45 X(J)=A(J,K+1)/A(J,J)
   50 CONTINUE
      RETURN
   60 WRITE(1,65)
   65 FORMAT('   ERROR MESSAGE ZERO COLUMN FOUND')
      STOP
      END

      SUBROUTINE GETNAM(NAME)
C
C                 GET A VALID FILENAME FROM THE USER.
C
      INTEGER*2 NAME(20),TBUFF(20),NLEN$A
      LOGICAL EXST$A
      DATA TBUFF /'NONAMEGIVEN                                  '/
    6 WRITE(1,8)
    8 FORMAT('GIVE NAME OF FILE TO BE PROCESSED')
      READ(1,10)NAME
   10 FORMAT(20A2)
      IF(NAME(1) .EQ. '  ')GO TO 100
      DO 20 I=1,20
   20 TBUFF(I)=NAME(I)
      GO TO 130
  100 DO 120 I=1,20
  120 NAME(I)=TBUFF(I)
  130 IF(EXST$A(NAME,NLEN$A(NAME,40)))RETURN
      WRITE(1,140)NAME
  140 FORMAT('INVALID OR NON-EXISTANT FILE : ',20A2)
      GO TO 6
      END

      SUBROUTINE NLOGN(N,X,SIGN)
C               THIS PROGRAM PERFORMS THE FFT.
C               N=BASE  2 LOG OF NO. OF POINTS.
C               X= COMPLEX ARRAY OF DATA FOR TRANSFORMATION.
C               SIGN= -1. FOR FFT.
C               SIGN= +1. FOR IFFT.
C               TRANSFORMED DATA IS RETURNED IN X.
C
C               WRITTEN BY E. A. ROBINSON.
C
      DIMENSION M(12)
      COMPLEX WK,HOLD,Q,X(2048)
      LX=2**N
      DO 1 I=1,N
    1 M(I)=2**(N-I)
      DO 4 L=1,N
      NBLOCK=2**(L-1)
      LBLOCK=LX/NBLOCK
```

```
      LBHALF=LBLOCK/2
      K=0
      DO 4 IBLOCK=1,NBLOCK
      FK=K
      FLX=LX
      V=SIGN*6.283185308*FK/FLX
      WK=CMPLX(COS(V),SIN(V))
      ISTART=LBLOCK*(IBLOCK-1)
      DO 2 I=1,LBHALF
      J=ISTART+I
      JH=J+LBHALF
      Q=X(JH)*WK
      X(JH)=X(J)-Q
      X(J)=X(J)+Q
    2 CONTINUE
      DO 3 I=2,N
      II=I
      IF(K.LT.M(I))GO TO 4
    3 K=K-M(I)
    4 K=K+M(II)
      K=0
      DO 7 J=1,LX
      IF(K.LT.J)GO TO 5
      HOLD=X(J)
      X(J)=X(K+1)
      X(K+1)=HOLD
    5 DO 6 I=1,N
      II=I
      IF(K.LT.M(I))GO TO 7
    6 K=K-M(I)
    7 K=K+M(II)
      IF(SIGN.LT.0.)RETURN
      DO 8 I=1,LX
    8 X(I)=X(I)/FLX
      RETURN
      END

      SUBROUTINE PHASOR(PRE,POST,NMAX,SF,SAMRAT,FNAME,ILAB1,DEVICE)
C
C                 PRE- AND POST-STIMULUS PHASOR DIAGRAMS.
C
      COMPLEX PRE(6,64),POST(6,64)
      INTEGER*2 DEVICE,ODEV,ILAB1(40),FNAME(20)
      COMMON ODEV
C                 TEST FOR A VALID DEVICE CODE
C                 CURRENTLY 0=TEKTRONIX
C                           1=CALCOMP 536 VIA 906
C                           2=SIGMA 5670 COLOUR.
      IF(DEVICE .GT. 3)GO TO 999
C
C                 SKIP THE INITIALISATION IF THIS
C                 DEVICE ALREADY BEEN INITIALISED
C
      IF(DEVICE .EQ. ODEV)GO TO 50
      IF(DEVICE .LT. 0)GO TO 600
C
C                 DE-ASSIGN CURRENT DEVICE IF
C                 DIFFERENT DEVICE REQUESTED.
C
      IF(ODEV .NE. 99)CALL DEVEND
C
C                 ASSIGN REQUESTED DEVICE
C
      IF(DEVICE .EQ. 0)CALL T4010
      IF(DEVICE .EQ. 1)CALL CC906
      IF(DEVICE .EQ. 2)CALL S5660
      IF(DEVICE .EQ. 3)CALL CC81
      IBAUD=1200
      CALL DEVSPE(IBAUD)
      IF(DEVICE .EQ. 0)CALL UNITS(1.0)
      IF(DEVICE .EQ. 1)CALL UNITS(1.0)
      IF(DEVICE .EQ. 2)CALL UNITS(1.5)
      IF(DEVICE .EQ. 3)CALL UNITS(0.75)
      ODEV=DEVICE
   50 CALL CHAHAR(1,0)
      XS=46.
      YS=70.
      XD=100.
      CRAD=40.
      CALL WINDO2(0.,250.,0.,200.)
```

```
      CALL WINDOW(1)
      DO 400 IHAR=1,6
      CALL TITLE(FNAME,ILAB1,DEVICE)
C
C               PRE STIM CIRCLE DIAGRAM OUTLINE.
C
      IF(DEVICE .EQ. 2)CALL PENSEL(6,0.,0)      /* RED
      CALL MOVTO2(XS,YS)
      CALL SYMBOL(7)
      CALL MOVTO2(XS-CRAD,YS)
      CALL ARCTO2(XS,YS,XS-CRAD,YS,0)
C
C               POST STIM CIRCLE DIAGRAM OUTLINE.
C
      IF(DEVICE .EQ. 2)CALL PENSEL(5,0.,0)      /* BLUE
      CALL MOVTO2(XS+XD,YS)
      CALL SYMBOL(7)
      CALL MOVTO2(XS+XD-CRAD,YS)
      CALL ARCTO2(XS+XD,YS,XS+XD-CRAD,YS,0)
      IF(DEVICE .EQ. 2)CALL PENSEL(7,0.,0)      /* WHITE
      CALL MOVTO2(XS-15.,135.)
      CALL CHAHOL('PRE STIM.*.')
      CALL MOVTO2(XS+XD-15.,135.)
      CALL CHAHOL('POST STIM.*.')
      CALL MOVTO2(XS+XD/2-15.,125.)
      CALL CHAHOL('HARMONIC *.')
      CALL CHAINT(IHAR,2)
C
C               DRAW PRE STIMULUS DIAGRAM
C               RADSM=SUM OF RADII.
C               RADMN=AVERAGE RADII.
C               RADSTD=STANDARD DEVIATION OF RADII.
C
      RADSM=0.
      RADSMS=0.
      IF(DEVICE .EQ. 2)CALL PENSEL(3,0.,0)      /* GREEN
      DO 250 NTR=1,NMAX
      X=REAL(PRE(IHAR,NTR))
      Y=AIMAG(PRE(IHAR,NTR))
C
C             CALCULATE SUMS AND SUMS OF SQUARES.
C
      RAD=CABS(PRE(IHAR,NTR))
      RADSM=RADSM+RAD
      RADSMS=RADSMS+RAD*RAD
C
C             CALCULATE ANGLE.
C
      PHI=ATAN2(Y,X)
      X1=CRAD*COS(PHI)
      Y1=CRAD*SIN(PHI)
C
C               PUT TRIANGLE ON CIRCLE AT CORRECT ANGLE.
C
      CALL MOVTO2(X1+XS,Y1+YS)
      CALL SYMBOL(1)
C
C              PUT CROSS AT END OF PHASOR.
C
      CALL MOVTO2(SF*X+XS,SF*Y+YS)
  250 CALL SYMBOL(3)
      IF(DEVICE .EQ. 2)CALL PENSEL(7,0.,0)      /* WHITE
C
C              CALCULATE STATISTICS.
C
      RADMN=RADSM/FLOAT(NMAX)
      RADSTD=SQRT((RADSMS-RADSM*RADSM/FLOAT(NMAX))/FLOAT(NMAX-1))
C
C              PUT RESULTS ON GRAPH.
C
      CALL MOVTO2(10.,10.)
      CALL CHAHOL('AV. RAD= *.')
      CALL MOVTO2(40.,10.)
      CALL CHAFLO(RADMN,10)
      CALL MOVTO2(10.,4.)
      CALL CHAHOL('ST. DEV= *.')
      CALL MOVTO2(40.,4.)
      CALL CHAFLO(RADSTD,10)
C
C              DRAW POST STIMULUS DIAGRAM
```

```
C
      RADSM=0.
      RADSMS=0.
      IF(DEVICE .EQ. 2)CALL PENSEL(2,0.,0)      /* YELLOW
      DO 300 NTR=1,NMAX
      X=REAL(POST(IHAR,NTR))
      Y=AIMAG(POST(IHAR,NTR))
      RAD=CABS(POST(IHAR,NTR))
      RADSM=RADSM+RAD
      RADSMS=RADSMS+RAD*RAD
      PHI=ATAN2(Y,X)
      X1=CRAD*COS(PHI)
      Y1=CRAD*SIN(PHI)
      CALL MOVTO2(X1+XS+XD,Y1+YS)
      CALL SYMBOL(1)
      CALL MOVTO2(SF*X+XS+XD,SF*Y+YS)
  300 CALL SYMBOL(4)
      IF(DEVICE .EQ. 2)CALL PENSEL(7,0.,0)      /* WHITE
      RADMN=RADSM/FLOAT(NMAX)
      RADSTD=SQRT((RADSMS-RADSM*RADSM/FLOAT(NMAX))/FLOAT(NMAX-1))
      CALL MOVTO2(108.,10.)
      CALL CHAHOL('AV. RAD= *.')
      CALL MOVTO2(138.,10.)
      CALL CHAFLO(RADMN,10)
      CALL MOVTO2(108.,4.)
      CALL CHAHOL('ST. DEV= *.')
      CALL MOVTO2(138.,4.)
      CALL CHAFLO(RADSTD,10)
      CALL MOVTO2(0.,180.)
      CALL CHAMOD
      IF(DEVICE .EQ. 0 .OR. DEVICE .EQ. 2)CALL T1IN(IXYZ)
  400 CONTINUE
      ODEV=DEVICE
      RETURN
  600 ODEV=99
      CALL DEVEND
      RETURN
  999 WRITE(1,1000)DEVICE
 1000 FORMAT('INVALID PLOTTING DEVICE CODE',I5)
      STOP 1
      END

      SUBROUTINE PHASR1(DATA,NMAX,SF,SAMRAT,FNAME,ILAB1,DEVICE)
C
C                SINGLE PHASOR DIAGRAM
C
      COMPLEX DATA(6,32)
      INTEGER*2 DEVICE,ODEV,ILAB1(40),FNAME(20)
      COMMON ODEV
C                TEST FOR A VALID DEVICE CODE
C                CURRENTLY 0=TEKTRONIX
C                          1=CALCOMP 536 VIA 906
C                          2=SIGMA 5670 COLOUR.
      IF(DEVICE .GT. 2)GO TO 999
C
C                SKIP THE INITIALISATION IF THIS
C                DEVICE ALREADY BEEN INITIALISED
C
      IF(DEVICE .EQ. ODEV)GO TO 50
      IF(DEVICE .LT. 0)GO TO 600
C
C                DE-ASSIGN CURRENT DEVICE IF
C                DIFFERENT DEVICE REQUESTED.
C
      IF(ODEV .NE. 99)CALL DEVEND
C
C                ASSIGN REQUESTED DEVICE
C
      IF(DEVICE .EQ. 0)CALL T4010
      IF(DEVICE .EQ. 1)CALL CC906
      IF(DEVICE .EQ. 2)CALL S5660
      IBAUD=1200
      CALL DEVSPE(IBAUD)
      IF(DEVICE .EQ. 0)CALL UNITS(1.0)
      IF(DEVICE .EQ. 1)CALL UNITS(1.0)
      IF(DEVICE .EQ. 2)CALL UNITS(1.5)
      ODEV=DEVICE
   50 CALL CHAHAR(1,0)
      XS=100.
      YS=70.
```

```
      CRAD=50.
      CALL WINDO2(0.,250.,0.,200.)
      CALL WINDOW(1)
      DO 400 IHAR=1,6
      CALL TITLE(FNAME,ILAB1,DEVICE)
      CALL MOVTO2(XS,YS)
      CALL SYMBOL(7)
      CALL MOVTO2(XS-CRAD,YS)
      CALL ARCTO2(XS,YS,XS-CRAD,YS,0)
      CALL MOVTO2(XS-15.,145.)
      CALL CHAHOL('CNV DATA.*.')
      CALL MOVTO2(XS-15.,135.)
      CALL CHAHOL('HARMONIC *.')
      CALL CHAINT(IHAR,2)
C
C                DRAW PHASOR DIAGRAM
C                RADSM=SUM OF RADII.
C                RADMN=AVERAGE RADII.
C                RADSTD=STANDARD DEVIATION OF RADII.
C
      RADSM=0.
      RADSMS=0.
      DO 250 NTR=1,NMAX
      X=REAL(DATA(IHAR,NTR))
      Y=AIMAG(DATA(IHAR,NTR))
C
C              CALCULATE SUMS AND SUMS OF SQUARES.
C
      RAD=CABS(DATA(IHAR,NTR))
      RADSM=RADSM+RAD
      RADSMS=RADSMS+RAD*RAD
C
C              CALCULATE ANGLE.
C
      PHI=ATAN2(Y,X)
      X1=CRAD*COS(PHI)
      Y1=CRAD*SIN(PHI)
C
C                PUT TRIANGLE ON CIRCLE AT CORRECT ANGLE.
C
      CALL MOVTO2(X1+XS,Y1+YS)
      CALL SYMBOL(1)
C
C               PUT CROSS AT END OF PHASOR.
C
      CALL MOVTO2(SF*X+XS,SF*Y+YS)
  250 CALL SYMBOL(3)
C
C               CALCULATE STATISTICS.
C
      RADMN=RADSM/FLOAT(NMAX)
      RADSTD=SQRT((RADSMS-RADSM*RADSM/FLOAT(NMAX))/FLOAT(NMAX-1))
C
C               PUT RESULTS ON GRAPH.
C
      CALL MOVTO2(30.,10.)
      CALL CHAHOL('AV. RAD= *.')
      CALL MOVTO2(70.,10.)
      CALL CHAFLO(RADMN,10)
      CALL MOVTO2(30.,4.)
      CALL CHAHOL('ST. DEV= *.')
      CALL MOVTO2(70.,4.)
      CALL CHAFLO(RADSTD,10)
      CALL MOVTO2(0.,180.)
      CALL CHAMOD
      IF(DEVICE .EQ. 0)CALL T1IN(IXYZ)
  400 CONTINUE
      ODEV=DEVICE
      RETURN
  600 ODEV=99
      CALL DEVEND
      RETURN
  999 WRITE(1,1000)DEVICE
 1000 FORMAT('INVALID PLOTTING DEVICE CODE',I5)
      STOP 1
      END

      SUBROUTINE RSTAT1(RAD,N)
C
C                CALCULATE MEAN AND SD OF RADIUS LENGTHS.
```

```
C
      DIMENSION RAD(N)
      SUM=0.
      SUMSQ=0.
      DO 10 I=1,N
      SUM=SUM+RAD(I)
      SUMSQ=SUMSQ+RAD(I)*RAD(I)
   10 CONTINUE
      RADMN=SUM/FLOAT(N)
      RADSTD=SQRT((SUMSQ-SUM*SUM/FLOAT(N))/FLOAT(N-1))
      WRITE(1,20)RADMN,RADSTD
   20 FORMAT(/,'MEAN RADIUS LENGTH',9X,'= ',E11.4,
     +/,'STANDARD DEV. OF RADIUS',4X,'= ',E11.4)
      RETURN
      END

      SUBROUTINE SECTAV(N1,N2,A,AV)
C
C               FIND THE MEAN VALUE OF THE DATA
C               BETWEEN POINTS N1 AND N2.
C
      DIMENSION A(1024)
      AV=0.
      DO 10 I=N1,N2
   10 AV=AV+A(I)
      AV=AV/FLOAT(N2-N1)
      RETURN
      END

      SUBROUTINE SMEAN(NPTS,DATA,RMEAN)
C
C               REMOVE THE MEAN VALUE FROM THE DATA.
C
      DIMENSION DATA(NPTS)
      RMEAN=0.
      DO 20 I=1,NPTS
   20 RMEAN=RMEAN+DATA(I)
      RMEAN=RMEAN/NPTS
      DO 30 I=1,NPTS
   30 DATA(I)=DATA(I)-RMEAN
      RETURN
      END

      SUBROUTINE SSQRE(N,DATA,SUMSQ)
C
C               CALCULATE THE SUMS OF THE SQUARES
C               OF THE SIGNAL AND DIVIDE BY THE
C               NUMBER OF POINTS.
C
      DIMENSION DATA(N)
      SUMSQ=0.
      DO 200 I=1,N
  200 SUMSQ=SUMSQ + (DATA(I))*(DATA(I))
      SUMSQ=SUMSQ/FLOAT(N)
      RETURN
      END

      SUBROUTINE STDMN(N,DATA,MEAN,STDEV)
C
C               CALCULATE THE MEAN AND SD.
C
      REAL MEAN
      DIMENSION DATA(N)
      SUM=0.
      DO 100 I=1,N
  100 SUM=SUM + DATA(I)
      MEAN=SUM/FLOAT(N)
      SUM=0.
      DO 200 I=1,N
  200 SUM=SUM + (DATA(I) - MEAN)*(DATA(I) - MEAN)
      STDEV=SQRT(SUM/FLOAT(N-1))
      RETURN
      END

      SUBROUTINE TAPER2(X,N)
C
C     TAPERS ARRAY X AND SUBTRACTS MEAN
C
      DIMENSION X(N)
      DOUBLE PRECISION SUM1,SUM2,SUM3
```

```
C
      SUM1=0.0
      SUM2=0.0
      SUM3=0.0
      DO 1 I=1,N
      W=WINDY(I,N)
      SUM1=SUM1+W
      SUM3=SUM3+W*W
  1   SUM2=SUM2+W*X(I)
      SUM2=SUM2/SUM1
      SUM3=SQRT(N/SUM3)
      DO 2 I=1,N
  2   X(I)=(X(I)-SUM2)*SUM3*WINDY(I,N)
      RETURN
      END

      FUNCTION WINDY(J,N1)
      PARAMETER (PI=3.1415926536)
      TL=0.125
      AN=FLOAT(N1)
      AN1=AN-1
C
C                TL IS THE TAPER LENGTH ( PER UNIT )
C
      NTL=IFIX(TL*AN + 0.5)
      WINDY=1.0
      AJ=J-0.5
      IF(J .GE. NTL .AND. J .LE. (N1-NTL))RETURN
      WINDY=(1. - COS(PI*AJ/(AN1*TL)))/2.
      IF(J .GT. (N1-NTL))
     +WINDY=(1. + COS(PI*(AJ+NTL-AN1)/(AN1*TL)))/2.
      RETURN
      END

      SUBROUTINE TITLE(FNAME,GENINF,DEVICE)
C
C                PUTS A TITLE AND FILENAME ON A GRAPH.
C
      INTEGER*2 FNAME(20),GENINF(40),ODEV,DEVICE,NLEN$A,GL
      COMMON ODEV
C
C                TEST FOR A VALID DEVICE CODE
C                CURRENTLY 0=TEKTRONIX
C                          1=CALCOMP 536 VIA 906
C                          2=SIGMA 5660 (5670)
C                          3=CALCOMP 81
C
      IF(DEVICE .GT. 3)GO TO 999
C
C                SKIP THE INITIALISATION IF THIS
C                DEVICE ALREADY BEEN INITIALISED
C
      IF(DEVICE .EQ. ODEV)GO TO 50
      IF(DEVICE .LT. 0)GO TO 200
C
C                DE-ASSIGN CURRENT DEVICE IF
C                DIFFERENT DEVICE REQUESTED.
C
      IF(ODEV .NE. 99)CALL DEVEND
C
C                ASSIGN REQUESTED DEVICE
C
      IF(DEVICE .EQ. 0)CALL T4010
      IF(DEVICE .EQ. 1)CALL CC906
      IF(DEVICE .EQ. 2)CALL S5660
      IF(DEVICE .EQ. 3)CALL CC81
      IBAUD=1200
      CALL DEVSPE(IBAUD)
      IF(DEVICE .EQ. 0)CALL UNITS(1.0)
      IF(DEVICE .EQ. 1)CALL UNITS(1.0)
      IF(DEVICE .EQ. 2)CALL UNITS(1.5)
      IF(DEVICE .EQ. 3)CALL UNITS(0.75)
 50   CALL PICCLE
      CALL WINDO2(0.,240.,0.,185.)
      CALL WINDOW(1)
      CALL MOVTO2(80.,180.)
      CALL CHAHAR(1,0)
      CALL CHAHOL('DATA FILE: *.')
      NL=IFIX(FLOAT(NLEN$A(FNAME,40))/2. + 0.5)
      CALL CHAARR(FNAME,NL,2)
```

```
      CALL MOVTO2(0.,174.)
      GL=IFIX(FLOAT(NLEN$A(GENINF,80))/2. + 0.5)
      CALL CHAARR(GENINF,GL,2)
      CALL MOVTO2(0.,170.)
      CALL CHAMOD
      ODEV=DEVICE
      RETURN
  200 ODEV=99
      CALL DEVEND
      RETURN
  999 WRITE(1,1000)DEVICE
 1000 FORMAT('INVALID PLOTTING DEVICE CODE ',I5)
      STOP 1
      END

      SUBROUTINE VSTAT1(ANGLE,RAD,N)
C
C  THIS SUBROUTINE CALCULATES SUMMARY STATISTICS FOR THE N VECTORS
C  WHOSE DIRECTIONS ARE STORED IN ARRAY 'ANGLE' AND WHOSE MAGNITUDES
C  ARE STORED IN ARRAY 'RAD'.
C
C  RESULTANT DIRECTION   ....   THETA=ATAN(S/C)
C
C            WHERE     S = WEIGHTED AVERAGE OF SINE VALUES
C                      C = WEIGHTED AVERAGE OF COSINE VALUES
C            AND THE WEIGHTING FACTORS ARE THE VECTOR MAGNITUDES.
C
C  DISPERSION FACTOR  ....  U0=1-SQRT(S*S+C*C)
C
C            U0 HAS VALUE 1 FOR A ZERO MAGNITUDE RESULTANT VECTOR
C                         0 FOR A SET OF ALIGNED VECTORS
C
C
C
C  WRITTEN BY TERRY JOHNSON. DEPT. OF MATHS. STATS. & COMPUTING
C  PLYMOUTH POLYTECHNIC.
C
      DIMENSION ANGLE(N),RAD(N)
      DATA PI/3.1415926536/
      C=0
      S=0
      SUMRAD=0.0
      DO 1 I=1,N
      SUMRAD=SUMRAD+RAD(I)
      C=C+RAD(I)*COS(ANGLE(I))
    1 S=S+RAD(I)*SIN(ANGLE(I))
      C=C/SUMRAD
      S=S/SUMRAD
      THETA=ATAN2(S,C)
      U0=1-SQRT(S*S+C*C)
      WRITE(1,100) THETA
      THETA=THETA*180/PI
      WRITE(1,101) THETA
      WRITE(1,102) U0
  100 FORMAT(/'RESULTANT DIRECTION',8X,'= ',F10.5,'  RADIANS')
  101 FORMAT(27X,'= ',F10.5,'  DEGREES')
  102 FORMAT('DISPERSION FACTOR',10X,'= ',F10.5)
      RETURN
      END

      SUBROUTINE VSTAT2(ANGLE,RAD,N)
C
C  THIS SUBROUTINE EXAMINES THE N VECTORS WHOSE DIRECTIONS ARE STORED
C  IN ARRAY ANGLE AND WHOSE MAGNITUDES ARE STORED IN ARRAY RAD. THE
C  PROGRAM IDENTIFIES THE (N/2) VECTORS WHICH LIE IN THE SMALLEST ARC
C  AND COMPARES THE AVERAGE LENGTH OF THESE VECTORS WITH THE AVERAGE
C  LENGTH OF THE REMAINING VECTORS. COMPARISON IS MADE BY A T-TEST
C  WITH AN APPROXIMATE CORRECTION FOR (POSSIBLE) UNEQUAL VARIANCES.
C
C
C
C  WRITTEN BY TERRY JOHNSON. DEPT. OF MATHS. STATS. & COMPUTING
C  PLYMOUTH POLYTECHNIC.
C
      DIMENSION ANGLE(N),RAD(N),TEMP(100)
      DOUBLE PRECISION SUM11,SUM12,SUM21,SUM22
      DATA PI/3.1415926536/
C
C  STORES ANGLES IN A TEMPORARY ARRAY AND ARRANGES IN ASCENDING
C  ORDER USING A BUBBLE SORT.
```

```
C
      DO 1 I=1,N
  1   TEMP(I)=ANGLE(I)
      DO 2 I=2,N
      MAX=1
      AMAX=TEMP(1)
      NMAX=N-I+2
      DO 3 J=2,NMAX
      IF(TEMP(J).LE.AMAX) GO TO 3
      AMAX=TEMP(J)
      MAX=J
  3   CONTINUE
      TEMP(MAX)=TEMP(NMAX)
  2   TEMP(NMAX)=AMAX
C
C     FIND THE (N/2) VALUES LYING IN THE SMALLEST ARC.
C
      N2=N/2
      DMIN=TEMP(N2)-TEMP(1)
      AMIN=TEMP(1)
      AMAX=TEMP(N2)
      DO 4 I=2,N
      IU=I+N2-1
      IF(IU .LE. N)UPPER=TEMP(IU)
      IF(IU .GT. N)UPPER=TEMP(IU-N)+2.*PI
      IF((UPPER-TEMP(I)) .GE. DMIN)GO TO 4
      DMIN=UPPER-TEMP(I)
      AMIN=TEMP(I)
      AMAX=UPPER
  4   CONTINUE
C
C     CALCULATES MEAN AND VARIANCE FOR BOTH SETS OF DATA
C
      SUM11=0.0
      SUM12=0.0
      SUM21=0.0
      SUM22=0.0
      N2=0
      N21=0
      CONST=0.
      IF(AMAX.GT.PI) CONST=2*PI
      DO 5 I=1,N
      A=ANGLE(I)
      IF(A .LT. 0.)A=A+CONST
      IF(A .LT. AMIN .OR. A .GT. AMAX)GO TO 6
      N2=N2+1
      SUM11=SUM11+RAD(I)
      SUM12=SUM12+RAD(I)*RAD(I)
      GO TO 5
  6   SUM21=SUM21+RAD(I)
      N21=N21+1
      SUM22=SUM22+RAD(I)*RAD(I)
  5   CONTINUE
      SUM11=SUM11/N2
      SUM21=SUM21/N21
      SUM12=(SUM12/N2-SUM11*SUM11)/(N2-1)
      SUM22=(SUM22/N21-SUM21*SUM21)/(N21-1)
C
C     CALCULATES T-STATISTIC AND OUTPUTS RESULTS
C
      TSTAT=SNGL((SUM11-SUM21)/DSQRT(SUM12+SUM22))
      DF=(SUM12+SUM22)*(SUM12+SUM22)
      DF=DF/(SUM12*SUM12/(N2+1)+SUM22*SUM22/(N21+1))-2
      SUM12=DSQRT(SUM12*N2)
      SUM22=DSQRT(SUM22*N21)
      WRITE(1,100)N2,SUM11,SUM12
      WRITE(1,101)N21,SUM21,SUM22
      WRITE(1,102)TSTAT,DF
100   FORMAT(/'MEAN AND S.D. OF LENGTHS OF THE',I4,' CLOSEST '
     +'VECTORS    = ',E16.8,E16.8)
101   FORMAT('MEAN AND S.D. OF LENGTHS OF THE',I4,' REMAINING '
     +'VECTORS =',E16.8,E16.8)
102   FORMAT(/'T-STATISTIC =',F10.5,' WITH ',F6.1,
     +'  DEGREES OF FREEDOM')
      RETURN
      END

      SUBROUTINE VSTAT3(ANGLE,RAD,N)
C
C  THIS SUBROUTINE CALCULATES A 'MODIFIED DISPERSION' STATISTIC FOR
```

```
C  'N' VECTORS WHOSE DIRECTIONS ARE STORED IN ARRAY 'ANGLE' AND WHOSE
C  MAGNITUDES ARE STORED IN ARRAY 'RAD'.
C
C  MODIFIED DISPERSION FACTOR .....  UM=1-SQRT(S*S+C*C)
C
C  WHERE    S= WEIGHTED AVERAGE OF SINE VALUES
C           C= WEIGHTED AVERAGE OF COSINE VALUES
C
C  AND THE WEIGHTING FACTORS ARE THE RANK ORDERS OF THE VECTORS
C
C  UM HAS VALUE 1 FOR A ZERO MAGINTUDE RESULTANT VECTOR
C               0 FOR A SET OF ALIGNED VECTORS
C
C.................................................................
C
C  WRITTEN BY TERRY JOHNSON. DEPT. OF MATHS. STATS. & COMPUTING
C  PLYMOUTH POLYTECHNIC.
C
      DIMENSION ANGLE(N),RAD(N),TEMPA(100),TEMPR(100)
      DO 1 I=1,N
      TEMPA(I)=ANGLE(I)
 1    TEMPR(I)=RAD(I)
      C=0.0
      S=0.0
      DO 2 I=2,N
      MAX=1
      AMAX=TEMPR(1)
      NMAX=N-I+2
      DO 3 J=2,NMAX
      IF (TEMPR(J).LE.AMAX) GO TO 3
      AMAX=TEMPR(J)
      MAX=J
 3    CONTINUE
      C=C+NMAX*COS(TEMPA(MAX))
      S=S+NMAX*SIN(TEMPA(MAX))
      TEMPR(MAX)=TEMPR(NMAX)
 2    TEMPA(MAX)=TEMPA(NMAX)
      C=C+COS(TEMPA(1))
      S=S+SIN(TEMPA(1))
      SUMN=N*(N+1)/2
      C=C/SUMN
      S=S/SUMN
      UM=1.0-SQRT(S*S+C*C)
      WRITE(1,100) UM
 100  FORMAT(/'MODIFIED DISPERSION FACTOR = ',F10.5)
      RETURN
      END
```