29/7/82

MICROPROCESSOR BASED SPECTRUM ANALYSER

by KEVIN J ROGERS B E (Honours)

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degree of MASTER OF ENGINEERING SCIENCE
at the University of Adelaide, October 1979.

This thesis embodies the results of
supervised project work making up
two-thirds of the work for the degree.

SUMMARY

The purpose of this project is to make a low frequency spectrum analyser which has good resolution and dynamic range but is not too expensive. This is achieved by digitizing the analogue input signal and calculating the spectrum using an 8 bit INTELL 8080A microprocessor.

The method for digitally calculating the spectrum of signals has been exploited considerably since Cooley and Tukey introduced the Fast Fourier Transform in the 1960's and the fourier theory used in this project has already been well developed over the past twenty years. The uniqueness of this project lies in the fact that an 8-bit microprocessor is used for a complex "number crunching" application formerly reserved for larger and more powerful computers or minicomputers. Thus a flexible instrument with considerable potential has been built for a capital cost of approximately $1 000 which is much less than commercial units currently available. However the disadvantage of using a microprocessor is the programming time required to generate efficient software.

The hardware for the spectrum analyser consists of the microprocessor system, power supply, analogue to digital and digital to analogue circuitry and input filters. It was also found necessary to build a digital hardware multiplier to keep calculation time to a reasonable level. The analyser is used in conjunction with a Cathode Ray Oscilloscope or a paper recorder to provide a medium for observing results.

The software was written in INTELL 8080 assembly language. The reason for choosing assembly language rather than a high level language such as PLM was to minimise required memory capacity and execution time.

The spectrum analyser was built with a view to analysing mechanical vibrations at Torrens Island Power Station. The use for which the instrument was built determined the specification and hence the design approach but the application method is not the subject of this thesis.

DECLARATION

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university and to the best of the author's knowledge and belief contains no material previously published or written by another person, except where due reference is made in the text of the thesis.

ACKNOWLEDGEMENTS

Thanks are due to my supervisors Dr B Davis and Dr D Pucknell from the University of Adelaide and to a technical officer at the Torrens Island Power Station, R Vear, for his assistance in construction and debugging.

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1. INTRODUCTION

The recent advances in large-scale integrated circuit technology have brought substantial improvements to the performance of instrumentation and control equipment. In particular, the microprocessor has opened up the possibility of new approaches to portable equipment which, for reasons of cost and size, were formerly impracticable. In this project Fourier Transform techniques in the form of the Discrete Fourier Transform are applied using a microprocessor as the calculating medium to produce a Spectrum Analyser.

1.1 Alternative Approaches to Spectrum Analysis

The purpose of a spectrum analyser is basically to display the frequency content of a signal giving also the magnitude of the frequency components that are present. This subject has been of interest to communication and acoustic engineers for many years and, of late, there has been a fast growing use of spectrum analysis for the examination of mechanical vibration. There are different methods of achieving spectrum analysis but in the following paragraphs three fundamental approaches are listed :

1.1 (a) Third Octave Filters

In this approach the input signal is fed to the inputs of a bank of bandpass filters. The outputs of the filters are sequentially selected by a switching network and fed to a unit which measures the magnitude of the output and this is fed in turn to a recording instrument. Typically the centre frequencys are separated by 1/3rd of an octave. Hence each filter has a passband of approximately 50% of the centre frequency.

The resolution is poor and for low frequency work it is time consuming but this type of analyser has still been used for many applications, especially acoustics.

1.1 (b) Spectrum Analyser Based on Heterodyne Principle

This analyser operates on the principle that the input signal is multiplied with a local oscillator LO. The result is a signal consisting of sum and difference frequencies which are then fed to a fixed frequency bandpass filter. By sweeping the frequency of the local oscillator the magnitude of a range of frequency components can be detected on the output of the bandpass filter. This approach has a constant bandwidth resolution over the frequency range of interest and is the predominant technique used for analysing communication frequencies. However at low frequencies (where the bandwidth of the filter is required to be small) this approach is time consuming to operate.

1.1 (c) Digital Spectrum Analysis

This is achieved by sampling the input signal and then calculating the spectrum from the samples using a digital computing unit. The basic calculation method is called the Digital Fourier Transform (DFT) and is generally implemented by a faster calculation routine called the Fast Fourier Transform (FFT). More detail is given regarding these methods in later chapters.

This approach is far superior for low frequencies as the operation time is virtually confined to the time taken to sample the input signal. The upper frequency limit is of the order of 1 MHz, the limit being due to maximum sampling rates of analogue to digital converters (A/D) and computer processing speeds.

Digital Spectrum analysis has been implemented by recording the signal on location and then 'playing back' to an 'in house' computer or alternatively transporting a mini-computer to the location to get direct results. Units employing the latter method have been available for the last couple of years for prices in the range : $20 000 - $50 000.

1.2 The Application

This project arose out of the need for a spectrum analyser to examine mechanical vibrations at the Torrens Island Power Station. Typical applications are examination of turbo - generator rotor vibrations to assist in a preventative maintenance program or to predict the cause of a particular vibration mode. The analyser would be useful to monitor most other rotating machinery at the power station and also to examine boiler vibrations.

The use of an analyser for these purposes is a complicated study in itself and is not covered in this thesis but the application for which the analyser was designed determined the specifications and the approach required. These are :

(a) Highest frequency of interest is the order of 5 KHz.

(b) Linear Frequency response since detection of harmonics of fundamentals is required.

(c) High resolution.

These requirements can be most easily met using digital spectrum analysis. However, for many applications the price tag of $20 000 to $50 000 for a minicomputer model can be prohibitive. It was hence decided to attempt to build a spectrum analyser which met the requirements of the application by using a microprocessor as the computational element. This proposition has several advantageous features :

(a) Capital cost of parts is relatively cheap (of the order of $1 000) thus presenting the possibility of using the spectrum analyser for dedicated applications.

(b) Microprocessor software can be modified easily to suit the particular user's application.

(c) The user could use the same instrument for entirely different applications simply by exchanging software eg. it could be used for a general purpose input-output controller.

1.3 Specifications for the Spectrum Analyser

The specifications for the spectrum analyser were determined such that maximum use could be made of the vibrometers with which it would be used. They are as follows :

(a) Input Voltage Range :

Maximum peak to peak input voltage is selectable in 10 db steps from 10 mV p-p to 1 V p-p.

(b) Frequency Range :

0 - 100 Hz
0 - 200 Hz
0 - 500 Hz

0 - 1 KHz

0 - 2 KHz

0 - 5 KHz

ie. there are 6 frequency ranges which are selectable and there are 100 frequency output points in each range. Therefore the maximum frequency resolution is nominally 1%.

(c) Dynamic Range :

A dynamic range of 50 db is adequate.

2 FOURIER THEORY

2.1 The Fourier Transform

For an input signal x (t) the fourier transform (FT) is defined as :

$$X(f) = \int_{-\infty}^{+\infty} x(t) \exp(-j 2\Pi ft)\, dt$$

and gives the magnitude of the frequency content of x (t) at any frequency f.

The inverse fourier transform (IFT) can be shown to be :

$$x(t) = \int_{-\infty}^{+\infty} X(f) \exp(j 2\Pi ft)\, df$$

2.2 Properties of the Fourier Transform

1. If x (t) is real then

   $X(-f) = X^*(f)$

2. Let X (f), Y (f), Z (f) be the fourier transforms of x (t), y (t), z (t) respectively.

   if $z(t) = \int_{-\infty}^{+\infty} x(\lambda)\, y(t-\lambda)\, d\lambda$

   then $Z(f) = X(f).\ Y(f)$

   if $Z(f) = \int_{-\infty}^{+\infty} X(\lambda)\, Y(f-\lambda)\, d\lambda$

   then $z(t) = x(t)\ y(t)$

   ie. convolution in the time domain corresponds to multiplication in the frequency domain and vice versa.

2.3 Practical Limitations

When the fourier integral is evaluated numerically there are three limitations :

1. The signal x (t) is evaluated over a finite interval.
2. The signal is sampled at a finite number of points within that interval.

3. The transform is calculated for a finite number of frequencies.

The first two of these limitations are a source of error and their effects and remedies need to be considered :

$$\text{Let } \bar{X}(f) = \int_{-T/2}^{T/2} x(t) \exp(-j\, 2\Pi\, ft)\, dt$$

$$= \int_{-\infty}^{+\infty} \text{rect}(t/T)\, x(t) \exp(-j\, 2\Pi\, ft)\, dt$$

$$\text{Where rect}(t) = \begin{cases} 1 & \text{for } -0.5 \leqslant t \leqslant 0.5 \\ 0 & \text{otherwise} \end{cases}$$

The F.T. of rect (t/T) = sinc (f)

$$\text{Where sinc}(f) = \begin{cases} 1 & \text{for } f = 0 \\ \dfrac{\sin \Pi f}{\Pi f} & \text{otherwise} \end{cases}$$

By applying the rule that multiplication in the time domain corresponds to convolution in the frequency domain it is obvious that :

$$\bar{X}(f) = \int_{-\infty}^{+\infty} X(\lambda)\, T \,\text{sinc}\,(f-\lambda)\, T \; d\lambda$$

In other words the true spectrum is 'smeared' by the sinc function, the effect of which can be illustrated by the following example for a 5Hz sinusoid :

$$\text{Let } x(t) = \cos 2\Pi (5)\, t$$

$$\therefore \quad X(f) = \tfrac{1}{2}\,\delta(f-5) + \tfrac{1}{2}\,\delta(f+5)$$

Where δ is the dirac - delta function. Figures 2.1 and 2.2 show x (t) and X (f) respectively.

If x (t) is measured only over the interval (-0.5, 0.5) seconds then the estimate for X (f) would be :

$$\bar{X}(f) = \tfrac{1}{2}\,\text{sinc}\,(f-5) + \tfrac{1}{2}\,\text{sinc}\,(f+5)$$

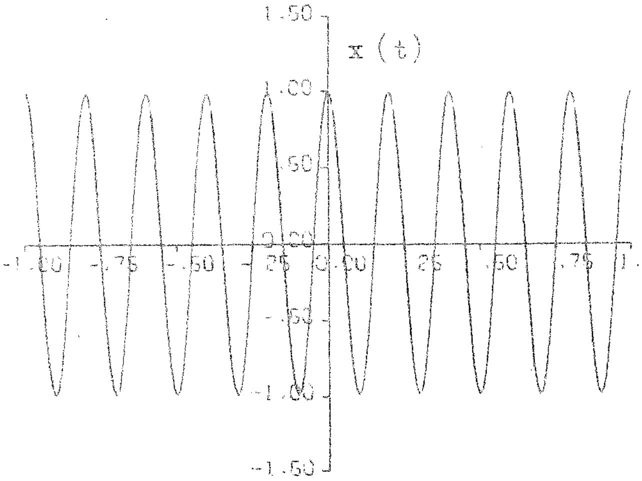

Figure 2.1 : x (t)

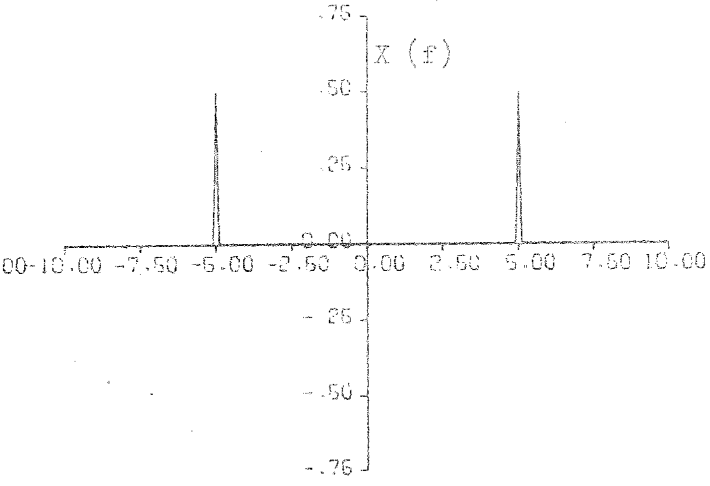

Figure 2.2 : X (f)

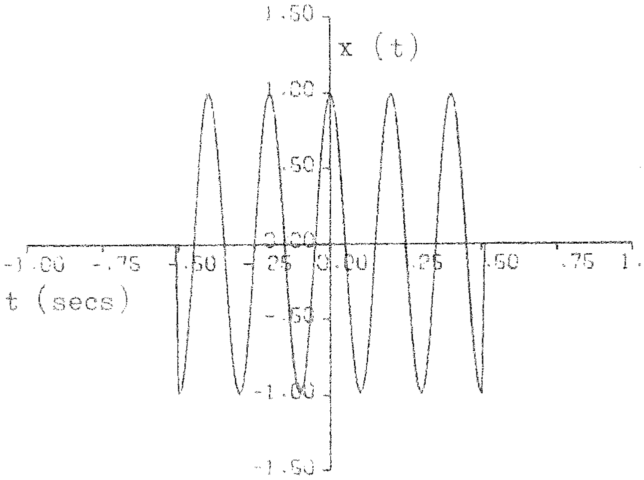

Figure 2.3 : $\bar{x}$ (t)

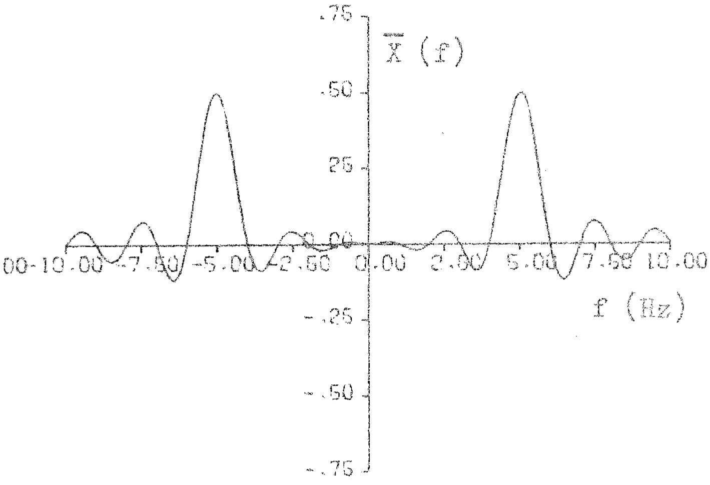

Figure 2.4 : $\bar{X}$ (f)

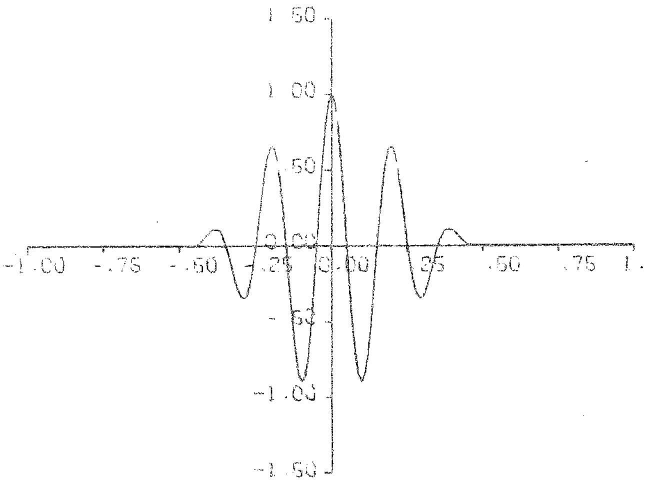

Figure 2.5 : $\tilde{x}$ (t)

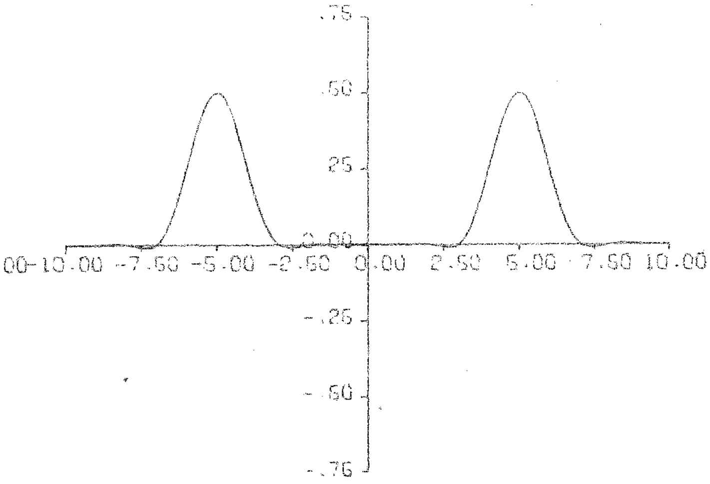

Figure 2.6 : $\tilde{X}$ (f)

Figures 2.3 and 2.4 show $\bar{x}(t)$ and $\bar{X}(f)$ respectively and it is obvious that the original spectrum has been degraded by the appearance of sidelobes which may possibly conceal another smaller frequency component at say 7.5 Hz.

The problem can be partially overcome by premultiplying the input data by a window function $w(t)$. This function is chosen to minimise the sidelobes in the frequency domain and thus increase the selectivity of the analyser. As an example the half raised cosine will be considered.

$$\text{ie.}\quad w(t) = \begin{cases} \frac{1}{2} + \frac{1}{2}\cos 2\Pi t & \text{for } -0.5 \leqslant t \leqslant 0.5 \\ 0 & \text{otherwise} \end{cases}$$

$$W(f) = 0.25 \operatorname{sinc}(f-1) + 0.5 \operatorname{sinc}(f) + 0.25 \operatorname{sinc}(f+1)$$

$$\text{Let}\quad \tilde{x}(t) = x(t).\,w(t)$$

$$\text{Let}\quad \tilde{X}(f) = \text{FT of } \tilde{X}(t)$$

These two functions are shown in figures 2.5 and 2.6 respectively.

The choice of the window function is a subject of debate. The windows chosen for this project were the half raised cosine window and a modified Bingham* Window. These are shown in figures 2.9 to 2.12 together with the magnitude of the spectrum (expressed in db). Figures 2.7 and 2.8 show the rectangular function and its transform for the sake of comparison.

The second limitation leads to the problem of aliassing distortion and can be expressed in the following manner.

Let $x(t)$ be sampled at rate fc times/second.

$\therefore$ the sampled signal:

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* "Modified Bingham" window is the name used in the remainder of the text to refer to the window function shown in figure 2.11 which is similar to that proposed by Bingham et al in reference [4].

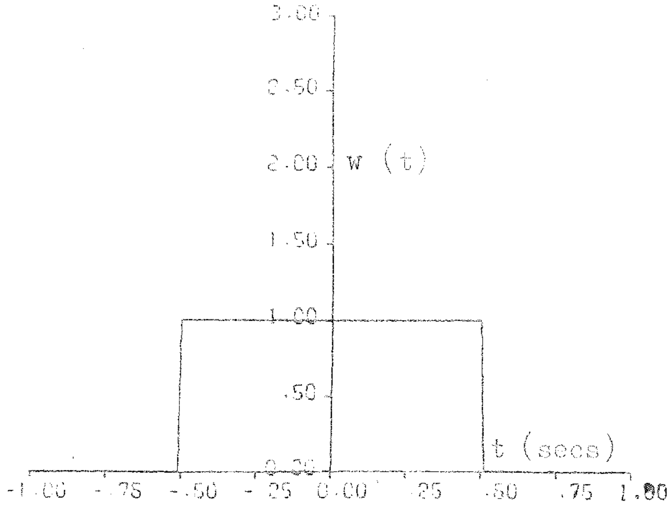


Figure 2.7 : Rectangular Window

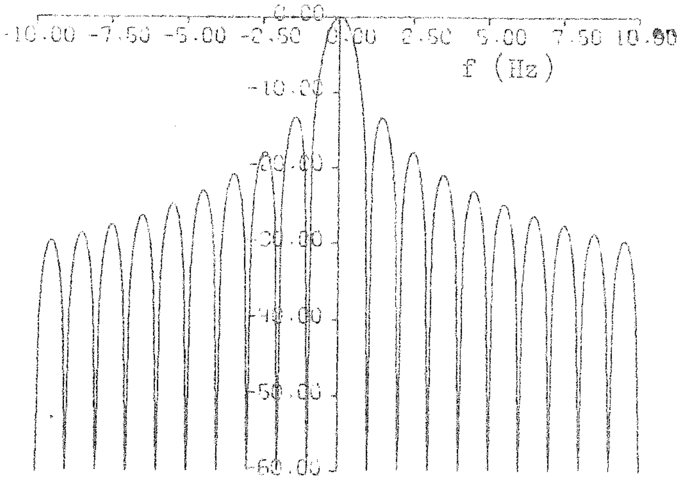


Figure 2.8 :

Spectrum of Rectangular Window

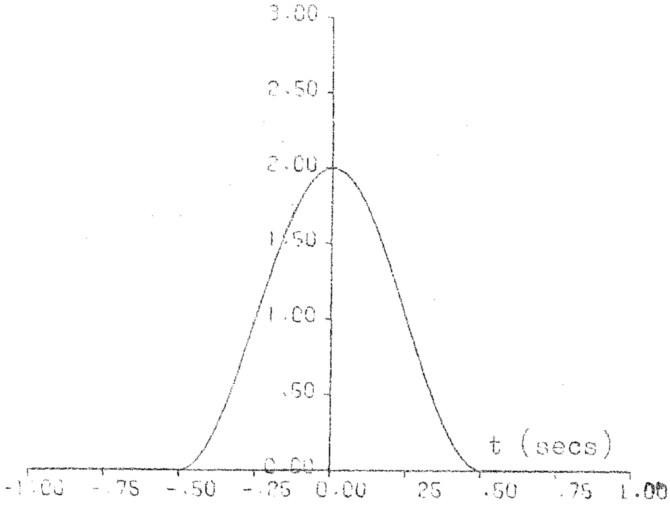


Figure 2.9 : Hanning Window

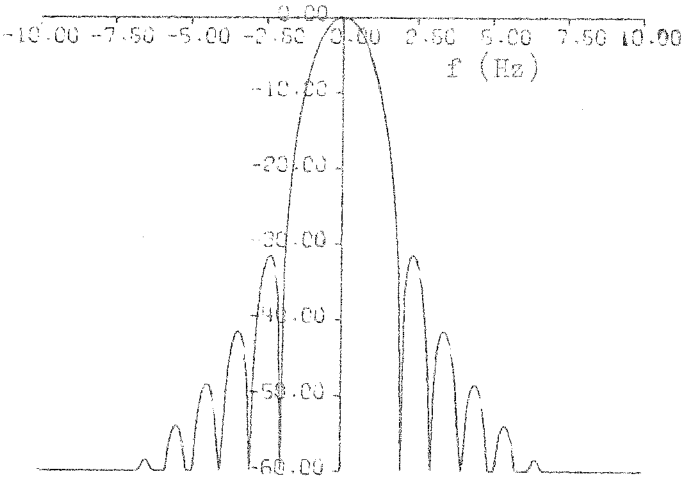


Figure 2.10 : Hanning Window Spectrum

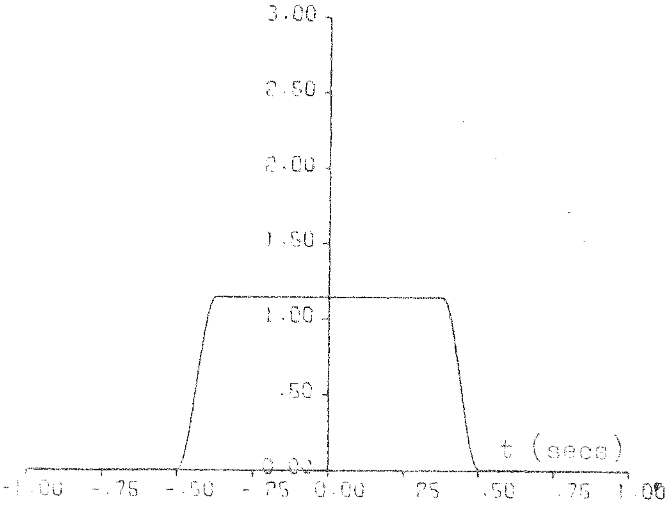


Figure 2.11 : Modified Bingham

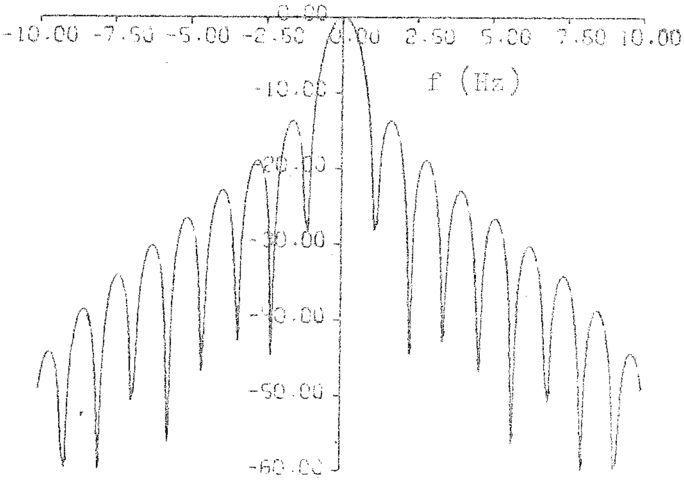


Figure 2.12 :

Spectrum of Modified Bingham

$$\hat{x}\,(t) = x\,(t)\sum_{n=-\infty}^{+\infty} \delta\,(t - n\,\Delta t)$$

Where $\Delta t = 1/fc$

$$\therefore \quad \hat{X}\,(f) = \sum_{n=-\infty}^{+\infty} X\,(f - fc)$$

From this equation it can be shown that X (f) is periodic with period fc and that if X (f) has components greater than fc/2 the adjacent spectra interfere with each other. However, if the input signal is filtered to eliminate components greater that fc/2 then:

$$\hat{X}\,(f) = X\,(f) \quad \text{for} \quad |f| < fc/2.$$

2.4 Numerical Evaluation of the Fourier Transform

$$\text{Let} \quad \bar{X}\,(f) = \int_0^T x\,(t) \; \exp\,(-j\,2\pi\,ft)\,dt$$

By applying the trapezoidal rule of integration this can be approximated by :

$$\bar{X}\,(f) \approx \left\{ \sum_{i=0}^{N-1} x\,(i\Delta t) \; \exp\,(-j\,2\pi\,fi\,t) - x\,(0) + x\,(N\Delta t)\,\exp\,(-j\,2\pi\,fN\Delta t) \right\} \Delta t$$

Where $\Delta t = T/N$

$\bar{X}\,(f)$ is only calculated at a finite number of points $\therefore$

if $\Delta f = 1/T$

$$\bar{X}\,(k\Delta f) = \Delta t \left\{ \sum_{i=0}^{N-1} x\,(i\Delta t) \; \exp\,(-j\,2\pi\,ik/N) - x\,(0) + x\,(T) \right\}$$

Let $xi = x\,(i\Delta t)$

$\bar{X}\,k = \bar{X}\,(k\Delta f)$

$$\therefore \bar{X}k = \Delta t \left\{ \sum_{i=0}^{N-1} xi \; \exp\,(-j\,2\pi\,ik/N) - xo + xN \right\}$$

The expression

$$Xk = \sum_{i=0}^{N-1} xi \; \exp\,(-j\,2\pi\,ik/N)$$

is an approximation to the Fourier Transform and is known as the Discrete Fourier Transform (DFT). If this expression is evaluated directly for N frequencies then N^2 complex multiplications need to be executed which can require a large amount of computer time as N becomes large. However in 1965 Cooley and Tukey [1] published an algorithm for a more efficient method to evaluate the DFT which is called the Fast Fourier Transform (FFT). This technique is well documented and will not be outlined here but the particular method used for this project is the decimation in time routine outlined in pages 173 - 182 of reference [2]. Where N is a power of 2 the number of complex multiplications required is now $\frac{1}{2}N \log_2 N$. For this project a 256 point transform is used.

$$\text{Hence calculation saving ratio} = (N^2/(\tfrac{1}{2}N \log_2 N)) = 2N/\log_2 N$$

$$= 64 \text{ times for } N = 256.$$

[illegible] Power Spectral Density (PSD)

The power spectral density of signal x (t) at frequency f is defined as :

$$G(f) = \lim_{\Delta f \to 0} \frac{1}{\Delta f} \left\{ \lim_{T \to \infty} \frac{1}{T} \int_{(f - \Delta f/2)}^{(f + \Delta f/2)} |X(\lambda)|^2 \, d\lambda \right\}$$

ie. the average power between frequencies f_1 and f_2 =

$$\int_{f_1}^{f_2} G(f)\, df.$$

Let $Sk = G(k\Delta f)$

It can be shown [3] that $Sk \approx |Xk|^2$

If the input signal has a random component as well as a fixed frequency component then the spectrum measured from one transform to the next will differ. However if many spectra are calculated and then averaged the error is reduced in proportion to the square root of the number of spectra averaged.

eg. this analyser can average up to 128 spectra which gives an increase in accuracy of measurement greater than 11 times compared with a single calculation.

References:

[1] "An algorithm for the machine calculation of complex Fourier series" by J Cooley and J Tukey. Math. Comput., 19, p.297, 1965.

[2] "Digital Processing of Signals" by Gold and Rader.

[3] "Random Vibrations and Spectral Analysis" by D. E. Newland.

[4] "Modern Techniques of Power Spectrum Estimation" by C. Bingham, M.D. Godfrey and J.W. Tukey, IEEE Trans. Audio and Electroacoustics, Vol. AU-15, 1967, No.2, 56-66.

3 HARDWARE

The controlling and calculating component of the spectrum analyser is an INTELL 8080A microprocessor which is coupled to inputs and outputs via 8255 input-output ports. The structure used is similar to that of the SDK-80 kit but the CPU, ROM and an extended RAM are built on separate circuit boards using wire-wrap for construction. For the sake of simplicity, the diagrams used in this chapter will be basically block diagram form but detailed circuit diagrams are given in Appendix 1.

3.1 THE CENTRAL PROCESSOR UNIT (figure 3.1)

The 8080 microprocessor integrated circuit is used in conjunction with two other IC's which are the 8224 clock generator and the 8228 System controller. The clock generator uses an 18.432 Mhz crystal and divides this by 9 to produce a 2.048 Mhz 2 phase clock for the 8080. An asynchronous reset signal is received by the 8224 and clocked into the 8080 at the correct machine cycle. In this way the microprocessor program counter is reset to zero and program execution is initiated from the first location in memory. The 8228 system controller reads an 8 bit data stream plus some other control signals from the 8080 and decodes these into the 8 bit bidirectional data bus and the control bus. This 3 chip arrangement is standard for the 8080 system but later devices substitute 1 integrated circuit to achieve the same effect (eg the 8085). The two 8212 input-output ports serve as an address bus buffer which is required to drive the large memory array. An 7494 flip-flop is used to divide the 18.432 Mhz by 2 to provide a 9.216 Mhz clock for the hardware multiplier and 3 counters divide the 18.432 Mhz by 2640 to provide a 6982 Hz clock for the teletype board.

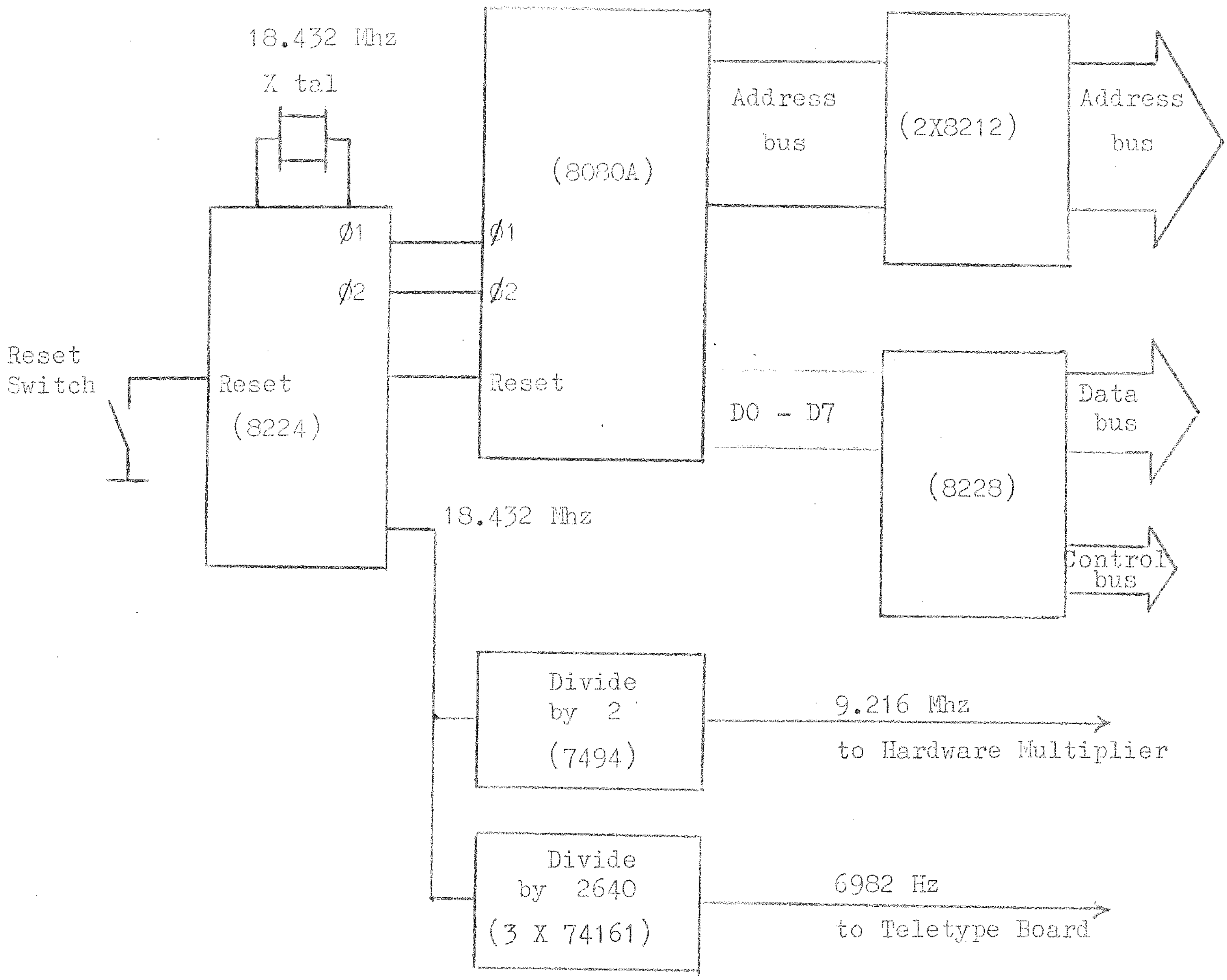


Figure 3.1 : CPU Board

3.2 READ ONLY MEMORY

A circuit board is reserved for read only memory (ROM) in which program code and look up tables are stored. The block diagram for the circuit board is shown in figure 3.2. Four 8708 ultraviolet erasable read only memory chips are used together with an 8205 1 of 8 decoder for address decoding. Bits 0 to 9 of the address bus are connected to all the memory chips and bits 10, 11 and 12 are fed to the decoder. Hence the memory chips are given the following addresses :

Device 1 : 000 -- 3FF
Device 2 : 400 -- 7FF
Device 3 : 800 -- BFF
Device 4 : C00 -- FFF

The addresses are specified by the hexadecimal number system. The data bus is driven by the ROM board only when an address within this range is requested and the control line $\overline{\text{MEMR}}$ is low.

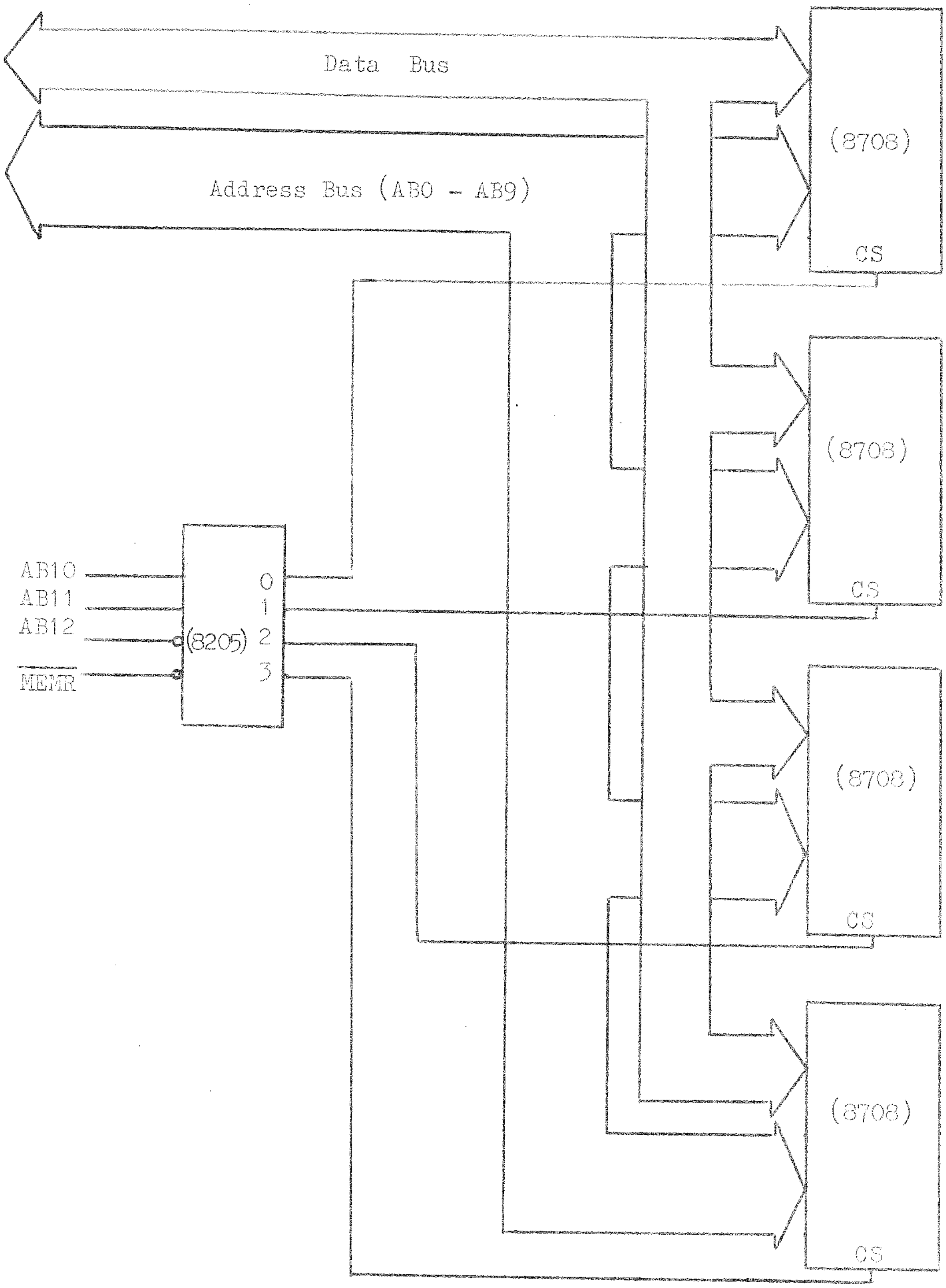


Figure 3.2 : Read Only Memory Board

3.3 RANDOM ACCESS MEMORY

The random access memory (RAM) requirement of the analyser is for 2048 words of 8 bit length. This is met by using 16 of the 8111 static MOS RAM (256 X 4) as shown in figure 3.3. Address bits AB0 to AB7 are fed to every RAM chip and each 8 bit word is achieved by using two 4-bit data ports. The 8 pairs of chips are selected by an 8205 1 of 8 binary decoder. This device is controlled by address bits AB8 to AB12. By this means 2K of RAM is available between addresses 1000 to 17FF (hexadecimal).

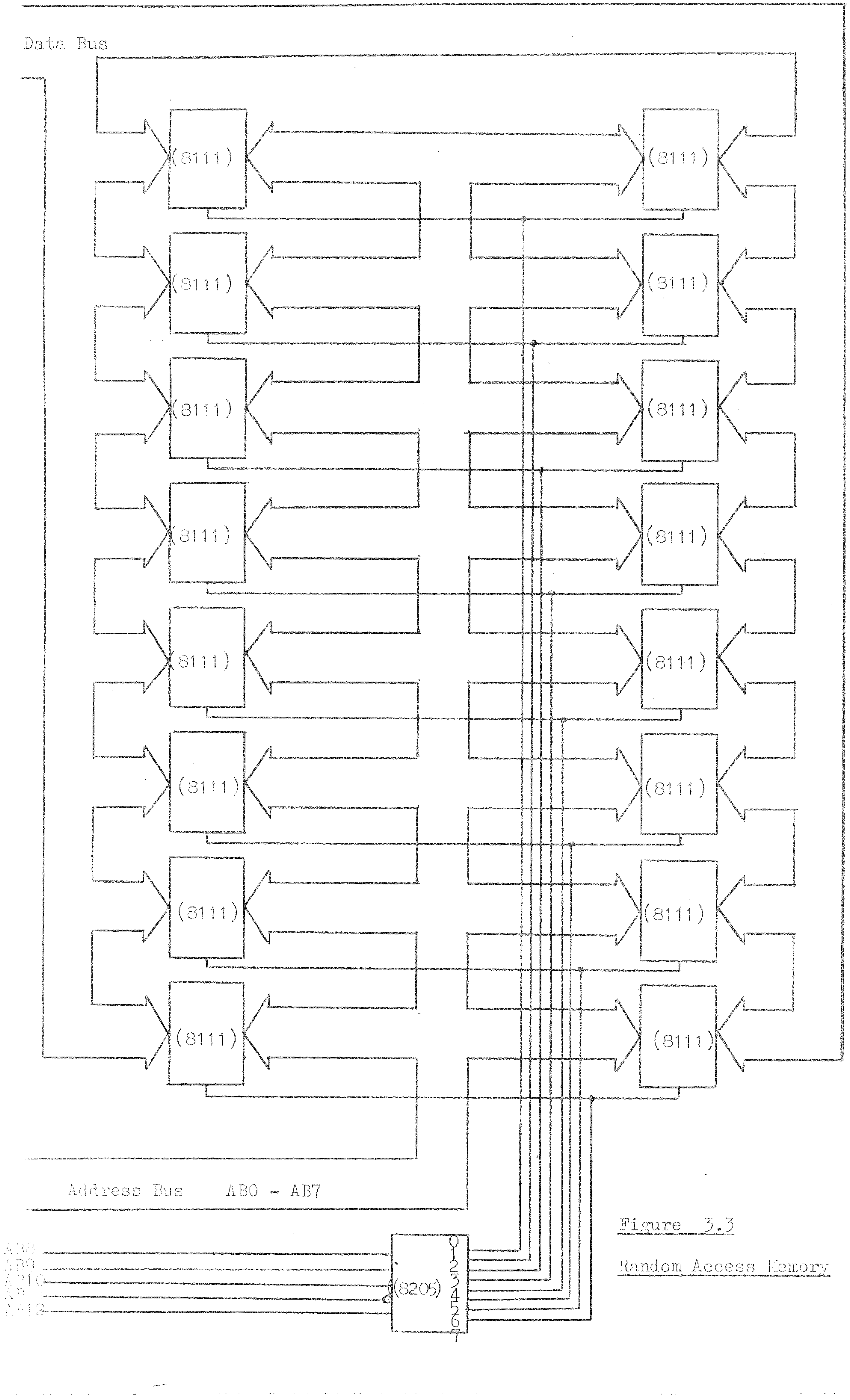


Figure 3.3

Random Access Memory

3.4 TELETYPE COMMUNICATIONS BOARD

The final spectrum analyser runs without teletype control and at that stage the teletype communications board is redundant. However during the development stage the analyser is controlled by a teletype terminal using a 110 baud serial communication link. An 8251 Programmable Communication Interface integrated circuit and a level translator (built from discrete devices) is used to convert the 8 bit TTL level data bus bits into a serial format and voltage level suitable for operating with a teletype. This board is removed in the final product.

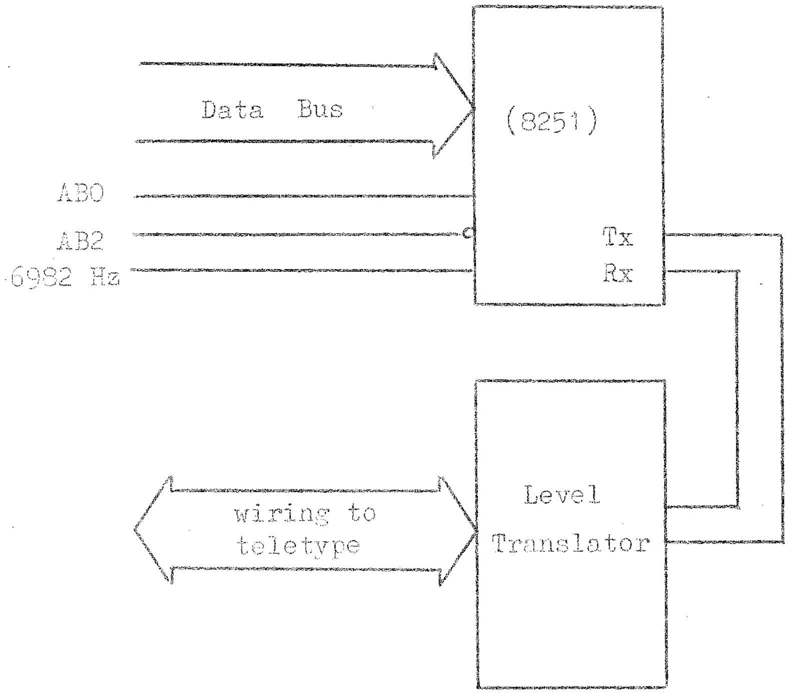


Figure 3.4 : Teletype Communications Board

3.5 HARDWARE MULTIPLIER BOARD

Because of the large number of multiplications that are required to be done in the spectrum analyser the overall execution time can be reduced by a factor of 10 to 20 by using a hardware multiplier rather than using a software multiplication routine. The heart of the multiplier is a pair of Am 25LS14 Serial/Parallel Two's Complement Multiplier integrated circuits. The Am 25LS14 is an 8 bit by 1 bit sequential logic element that performs digital multiplication of two numbers represented in two's complement form to produce a two's complement product without correction by using Booth's Algorithm internally.

The 16 bit multiplier is loaded in parallel into two 8 bit shift registers (DM 74166). The 16 bit multiplicand is held at the two 8-bit multiplicand inputs of the AM 25LS14's and the multiplier is fed in serially. The result comes out serially and is fed into three 8-bit serial/parallel registers (Am 25LS22). The multiplier could produce a 32-bit result but only the 24 most significant bits are required. Data flow between the multiplier and the microprocessor data bus is achieved via input/output ports. The timing and control circuitry is achieved by 2 counters (DM 74161) and some logic and the multiplication routine is initiated every time there is an input/output/write operation by the microprocessor. The multiplication time is less than 4 usecs. Faster all-parallel multipliers are available but the microprocessor input/output operations are too slow to take advantage of them.

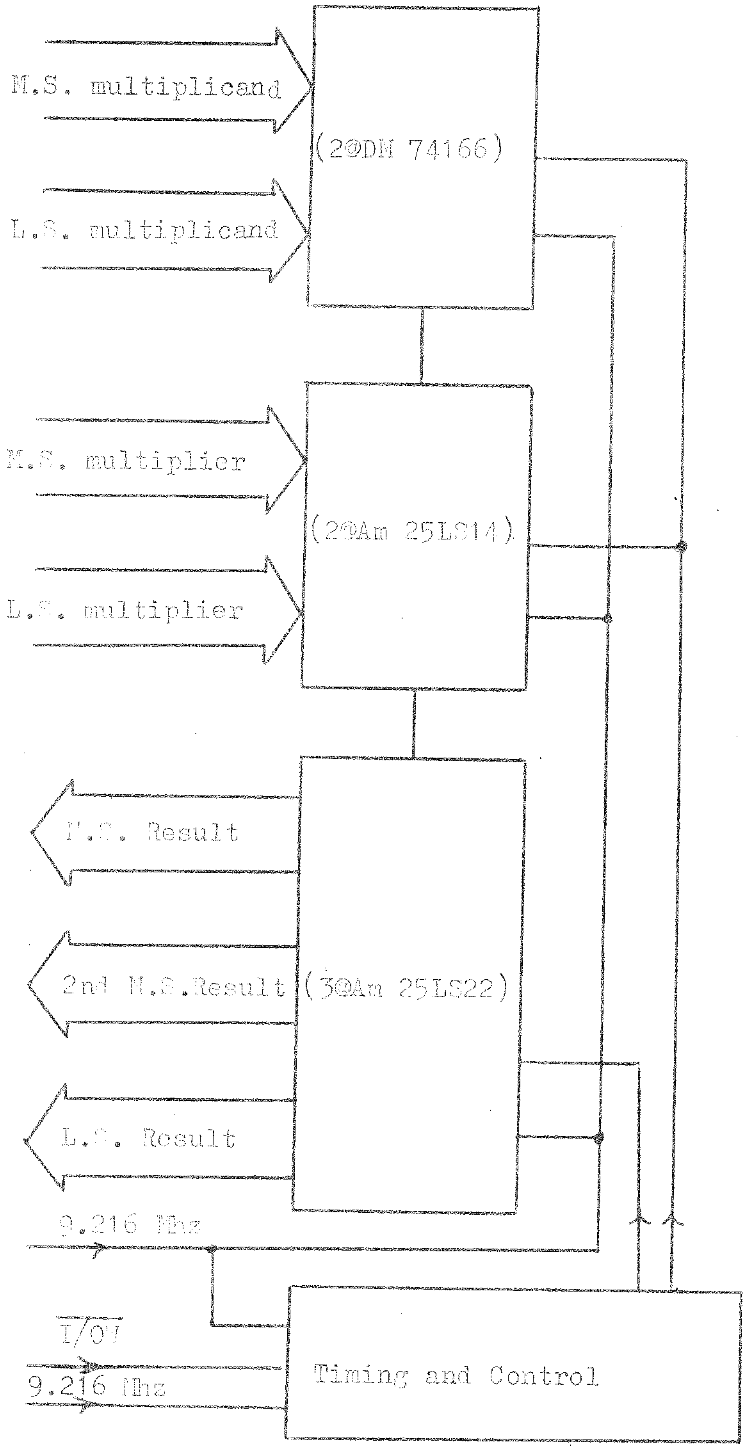


Figure 3.5 : Hardware Multiplier Board

3.6 SAMPLE RATE GENERATOR

The purpose of the Sample Rate Generator is to produce several clock frequencies which are used by other sections of the analyser for timing purposes. The Generator as shown in figure 3.6 consists of a crystal oscillator which drives a chain of counters which provide frequency division. The 1.6384 Mhz crystal frequency is divided by 2 to give an 819.2 Khz frequency which is used as the clock for the successive approximation register (SAR) of the A/D converter.

The frequencies : 256 Hz to 12.8 Khz are selected to control the sampling rate of the A/D converter. The 256 Hz signal is also used to control the writing rate for the output recorder.

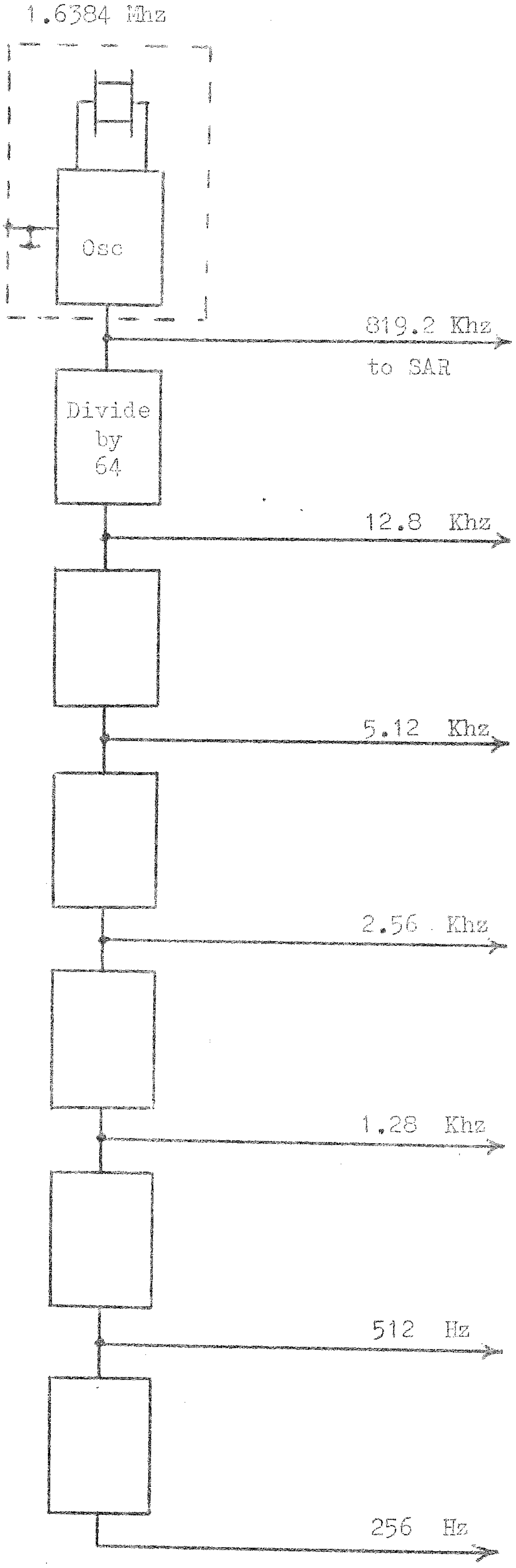


Figure 3.6 : Sample Rate Generator

3.7 INPUT AMPLIFIER (figure 3.7)

The input amplifier is required to amplify very low level signals on the high gain range and to keep noise levels down several precautions have been taken :

(a) The operational amplifier used is an OP-01 low noise device.

(b) Ground leads for digital and analogue devices have been separated to eliminate 'cross-talk'.

(c) The complete amplifier assembly (including the selector switch and feedback resistors) are enclosed in a shield which is connected to the body of the BNC connector to which the input leads are connected.

(d) The BNC connecter is connected to ground only through the input return lead to prevent ground circulating currents.

The output of the amplifier is fed via the first bank of frequency selector switches to the input low pass filters.

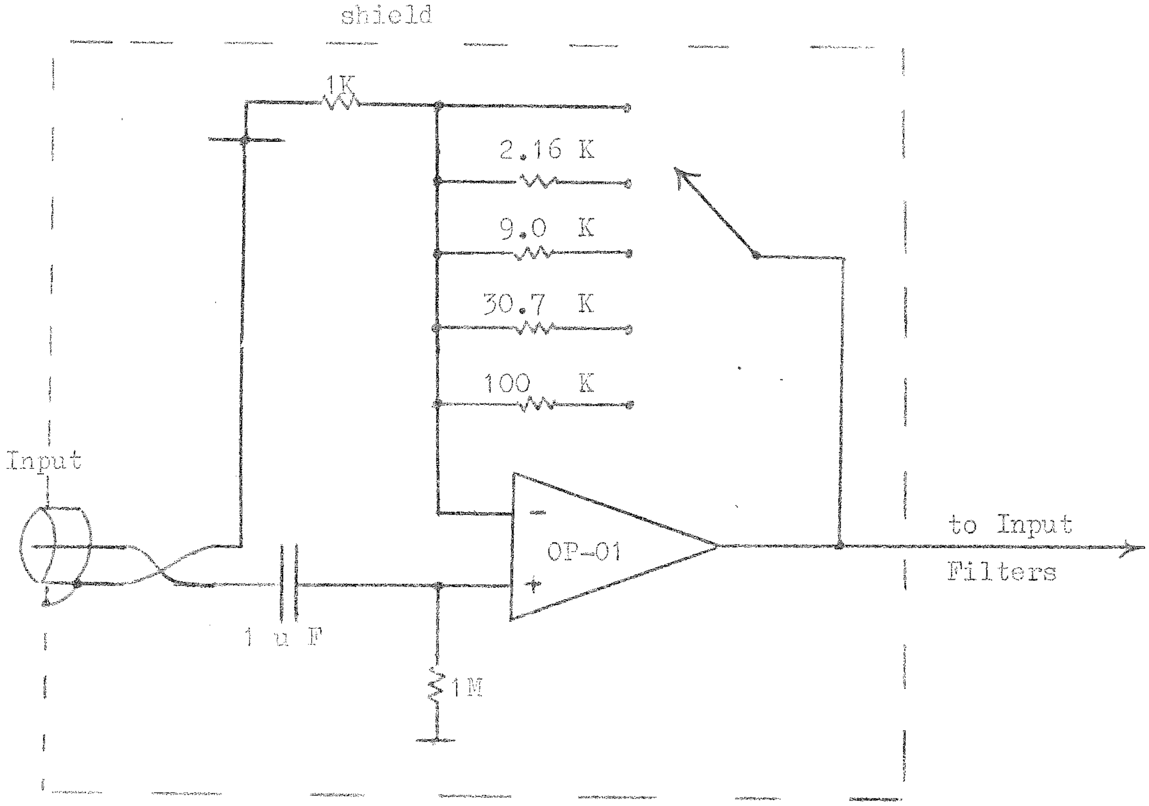


Figure 3.7 : Input Amplifier

3.8 INPUT FILTERS

The purpose of the input filters is to attenuate any frequencies above half the sampling rate. The filters are low pass 5th Order Ellptic filters. The transfer function is of the form :

$$T(S) = \frac{a_4S^4 + a_2S^2 + 1}{b_5S^5 + b_4S^4 + b_3S^3 + b_2S^2 + b_1S + 1} \quad \text{where } S = jw$$

The 'Handbook of Filter Synthesis' by Anatol Zverev was used to select the poles and zeroes of this transfer function and these are listed below for a 1 radian/second cut-off frequency :

Poles :
$S = -0.5573$
$S = -0.10672 \pm j1.0457$
$S = -0.37187 \pm j0.7375$

Zeroes :
$S = \pm j2.4377$
$S = \pm j1.617$

The stopband begins at 1.56c/sec and there is greater than 48 db attenuation in the stop band. The overall response is shown in figure 3.8(a).

To obtain the required transfer function T(S) is expressed as the product of 2 biquadratic functions and a single pole :

$$\text{ie. } T(S) = \frac{.55734}{S + .55734} \times \frac{S^L + 5.924}{S^2 + 0.21344S + 1.10488} \times \frac{S^2 + 2.6147}{S^2 + .74374S + 0.68219}$$

Each biquadratic transfer function is simulated by the B1-QUAD active filter arrangement as shown in figure 3.8(b) and the single pole is realized by an R-C filter.

The operational amplifier used is the LM324 Quad OP-AMP. Hence 2 of these are required for each filter.

3.8(cont.)

There are 6 filters wired on 2 boards which are selected by the frequency selector switches. The cut-off frequencies and corresponding sampling rates are listed below :

Cut-off Frequency (Hz) fc	Sampling Rate (Hz)
100	256
200	512
500	1280
1000	2560
2000	5120
5000	12800

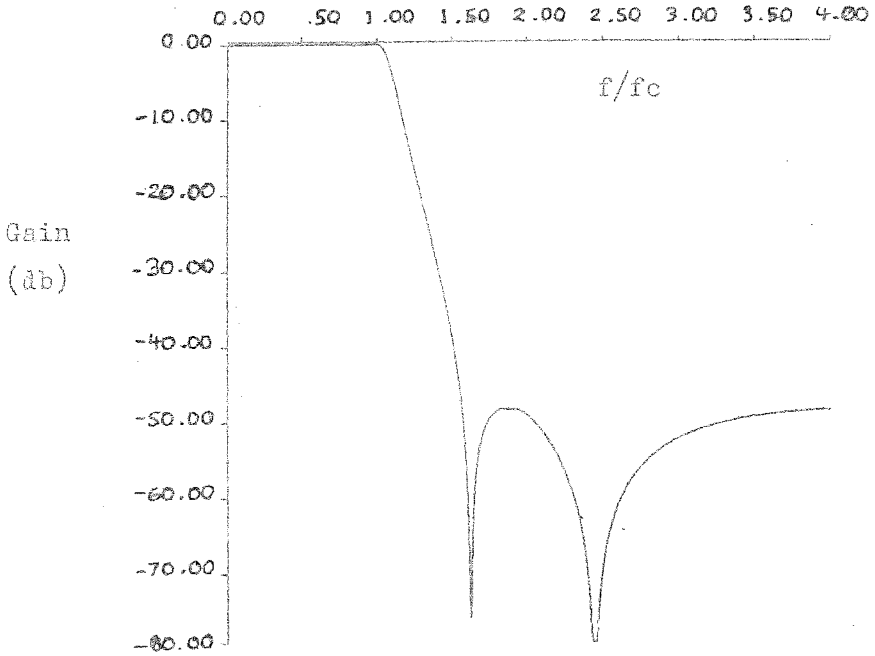


Figure 3.8(a) : Transfer Function of Input Filters

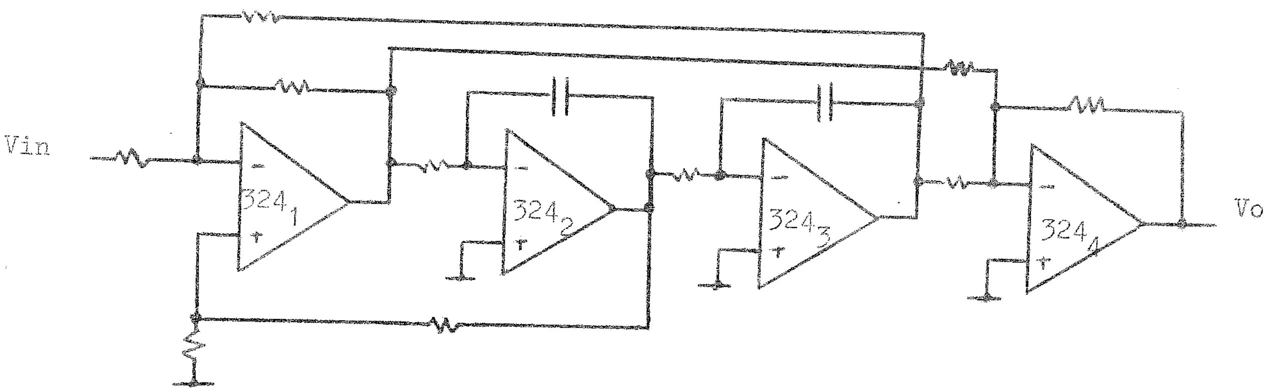


Figure 3.8(b) : Bi-Quad Active Filter

3.9 ANALOGUE TO DIGITAL CONVERSION

The analogue signal received from the input filters is sampled and digitized by an analogue to digital converter. The A/D converter is a conventional successive approximation type of converter consisting of a D/A converter, a comparator and a successive approximation register (SAR) as shown in figure 3.9. The result is a 10-bit two's complement binary number at the completion of each conversion. The SAR is clocked by the 819.2 Khz clock from the sample rate generator board and each conversion is initiated by the sampling frequency. The sample and hold device (S/H) samples the signal until conversion commences and holds the signal at a constant voltage until after the conversion is complete. The 10-bit result is read by an input-output port (8255).

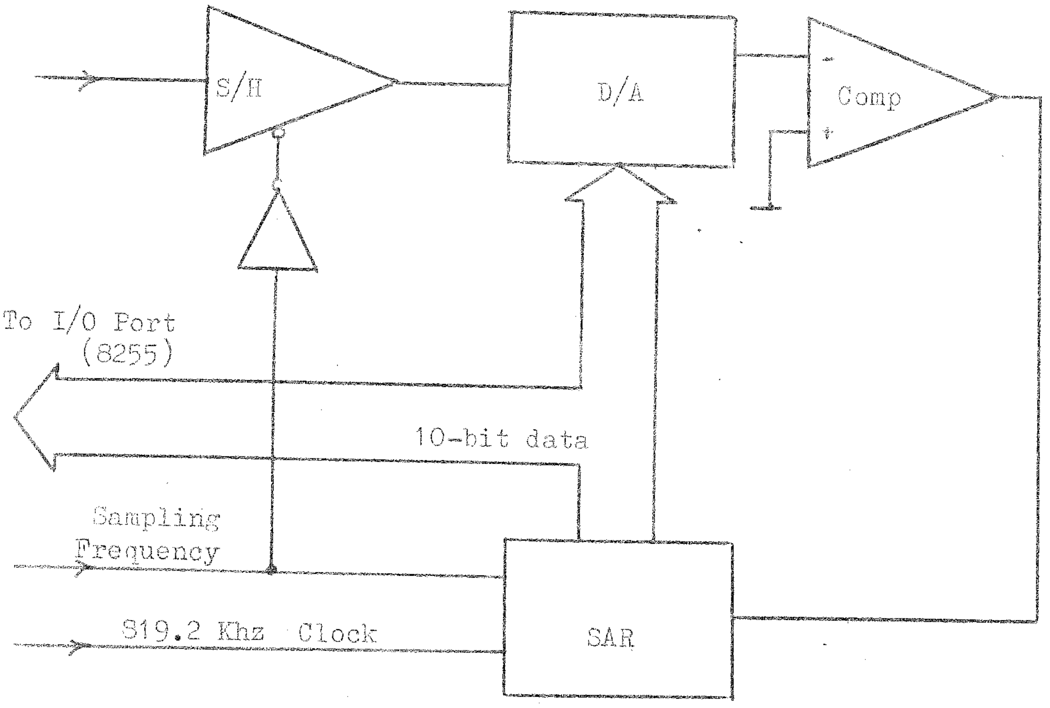


Figure 3.9 : Analogue to Digital Conversion

3.10 DIGITAL TO ANALOGUE CONVERSION

The spectrum analyser displays the spectra on a CRO or a paper recorder. To do this the numerical values calculated by the microprocessor must be converted into analogue voltages which is achieved by digital to analogue conversion as shown in figure 3.10.

The 8-bit digital number is fed from the microprocessor data bus to a D/A converter (DAC100) via an input/output port (8255). The DAC100 produces a current output which is converted to voltage by an operational amplifier. This voltage is fed to a resistor attenuator (used for scaling) and 4 CMOS switches direct the voltage to either the CRO output or the recorder output. The state of the switches is controlled by the microprocessor via the input/output port.

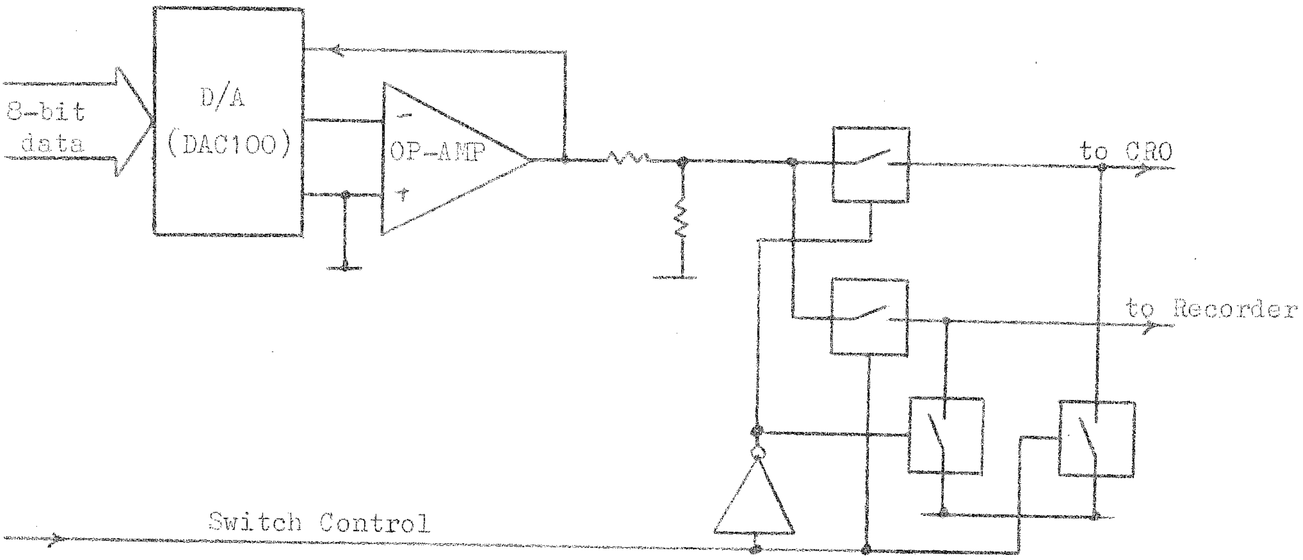


Figure 3.10 : Digital to Analogue Conversion

3.11 FREQUENCY DISPLAY AND CURSOR CONTROL

To facilitate reading of the spectrum on the CRO two signals are sent to the CRO ie. the spectrum and the display trigger. The CRO is triggerod from the negative edge of the display trigger and the positive edge (also displayed on the CRO) corresponds to the indicated frequency on the frequency display. The frequency display (figure 3.11) consists of 4 seven-segment displays which are driven by 4 BCD-7 segment decoders which receive their information from the microprocessor via an input/output port (8255). The position of the frequency selector switch and the state of the cursor control switch are read by the same input/output port.

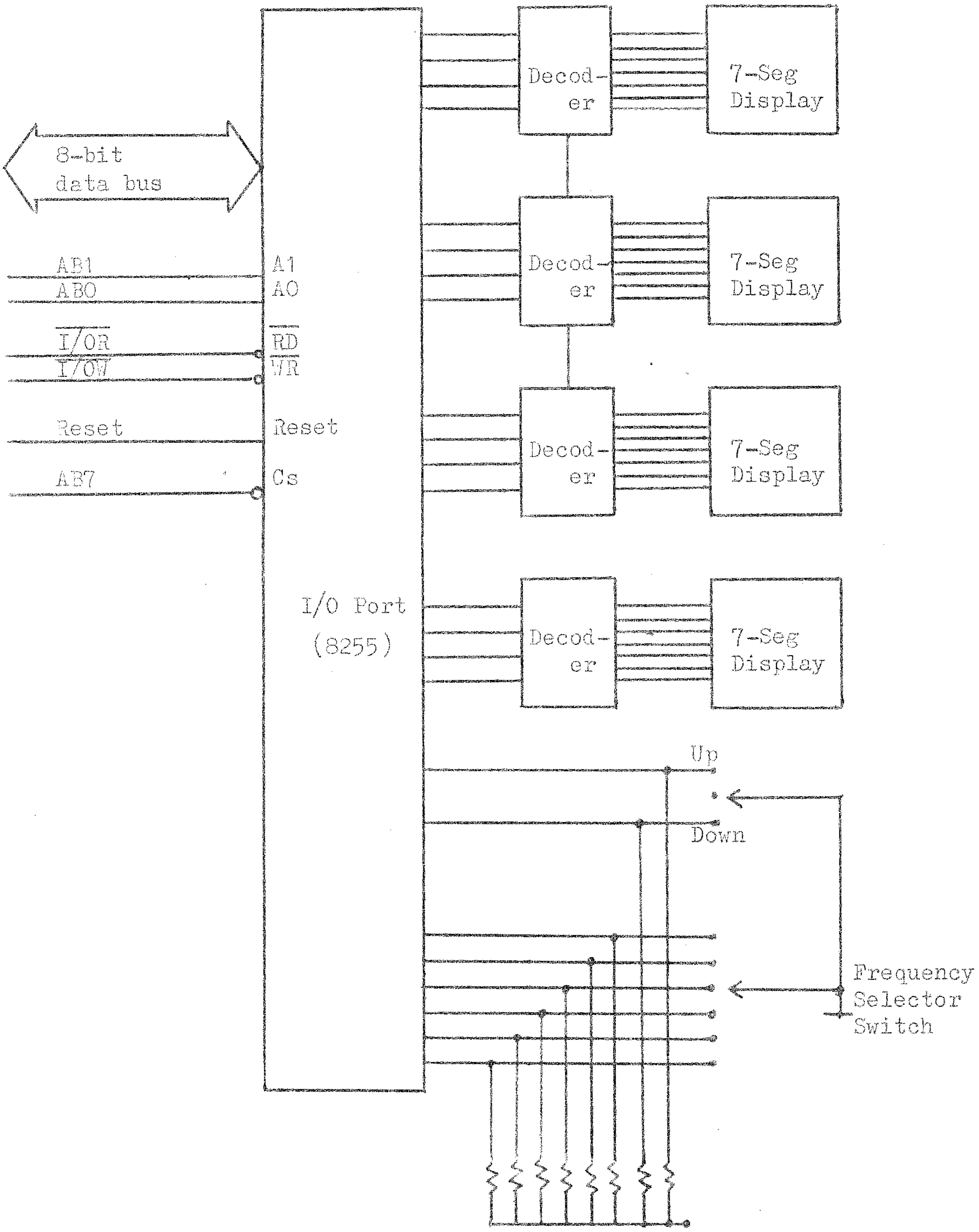


Figure 3.11 : Frequency Display and Cursor Control

3.12 POWER SUPPLY

The power supplies are a conventional series regulated design where the regulators are integrated 3 terminal devices. The ± 12 and 5V supplies are for digital circuitry and the ± 15 V supplies are for analogue circuitry. The ground lines for the digital and analogue circuitry are kept separate to prevent 'cross talk'.

REFERENCE

[1] "Digital Signal Processing Handbook"
by John R Mick, Advanced Micro Devices, 1976.

[2] "8080 Microcomputer Peripherals User's Manual"
INTEL Corporation 1976.

[3] "INTEL 8080 Microcomputer Systems User's Manual"
INTEL Corporation, September 1975.

4 SOFTWARE

4.1 DEBUGGING TECHNIQUE

In practice the spectrum analyser is to be controlled by a reset button which initiates a calculation cycle. The first instruction executed is stored at location zero and is the beginning of the main program. This set-up however is unsuitable as a means of development as it provides no means for interrogating the inevitable mistakes.

To provide an interrogation facility a 'monitor' program, stored on an EPROM, is placed in the first K (1024 words) of memory which enables a teletype terminal to control the microprocessor. This facility allows hexadecimal memory data to be stored, displayed or shifted and sections of program can be tested individually.

The EPROM (Erasable Programmable Read Only Memory) containing the main program is placed in the third K of memory and has a few 'RST 1' instructions which cause program execution to jump back to monitor program which restores control to the teletype. Some of the subroutines are also stored in the same EPROM as the main program. The remainder of the subroutines and the sine look-up table are stored in another EPROM occupying the second K of memory. The 4th K of memory was also loaded with the same program as the 3rd except that only one 'RST 1' instruction was used and inserted at the end of the main program so that the whole program can be tested at once yet retaining teletype control.

4.2 PROGRAMMING OF EPROMS

The program was originally written in INTELL 8080 assembly language and punched onto cards. The assembly language was converted into machine code (hexadecimal) using a library routine (INTELLBN) available on the university CDC Cyber 173 computer. The machine code was punched onto paper tape which enabled the code to be loaded onto a PROMPT80 which is an instrument manufactured by INTELL to be used as a teaching aid but also has a facility for programming the 8708 EPROM. There are many other ways to program EPROMS but the way chosen was the most convenient for the given situation.

4.3 ALLOCATION OF RANDOM ACCESS MEMORY (RAM)

The spectrum analyser uses 2 K words of RAM (ie. 2048) which is located in the hexadecimal address range 1000 to 17FF. The way in which each section of RAM is used is illustrated in figure 4.1. The Accumulated Power Spectral Density is stored in locations 1000 to 12FF and is represented by PSD (L) where L = 0...255. The area of memory allocated to FFT calculations is 1400 to 17FF.

X (L) = real part of array.
Y (L) = imaginary part of array.

Each PSD (L) entry consists of 3 bytes (ie. 24 bits).

Each X (L) and Y (L) entry consists of 2 bytes (ie. 16 bits).

(1000)	(10FF)	Most Significant byte of PSD (L)
(1100)	(11FF)	2nd M.S. byte of PSD (L)
(1200)	(12FF)	3rd M.S. byte of PSD (L)
(1300)	(137F)	Output Display Array
(1380)	(13FF)	General Purpose
(1400)	(14FF)	M.S. byte of X(L)
(1500)	(15FF)	L.S. byte of X(L)
(16FF)	(16FF)	M.S. byte of Y(L)
(1700)	(17FF)	L.S. byte of Y(L)

Figure 4.1: Allocation of RAM

4.4 NUMBER REPRESENTATION

Two types of number representation are used :

(a) Integer Representation

This representation is used most frequently for counters controlling the flow of programs.

eg. 0000 1000 = 8

(b) Twos Complement Representations

This representation is used for most of the values and arrays which are the object of the computations (ie. X (L), Y (L), and PSD (L)).

The range of possible values are $(-\frac{1}{2}, +\frac{1}{2})$.

The most significant bit of a word indicates sign.

eg. 1 000 = $-\frac{1}{2}$

0 100 = $+\frac{1}{4}$

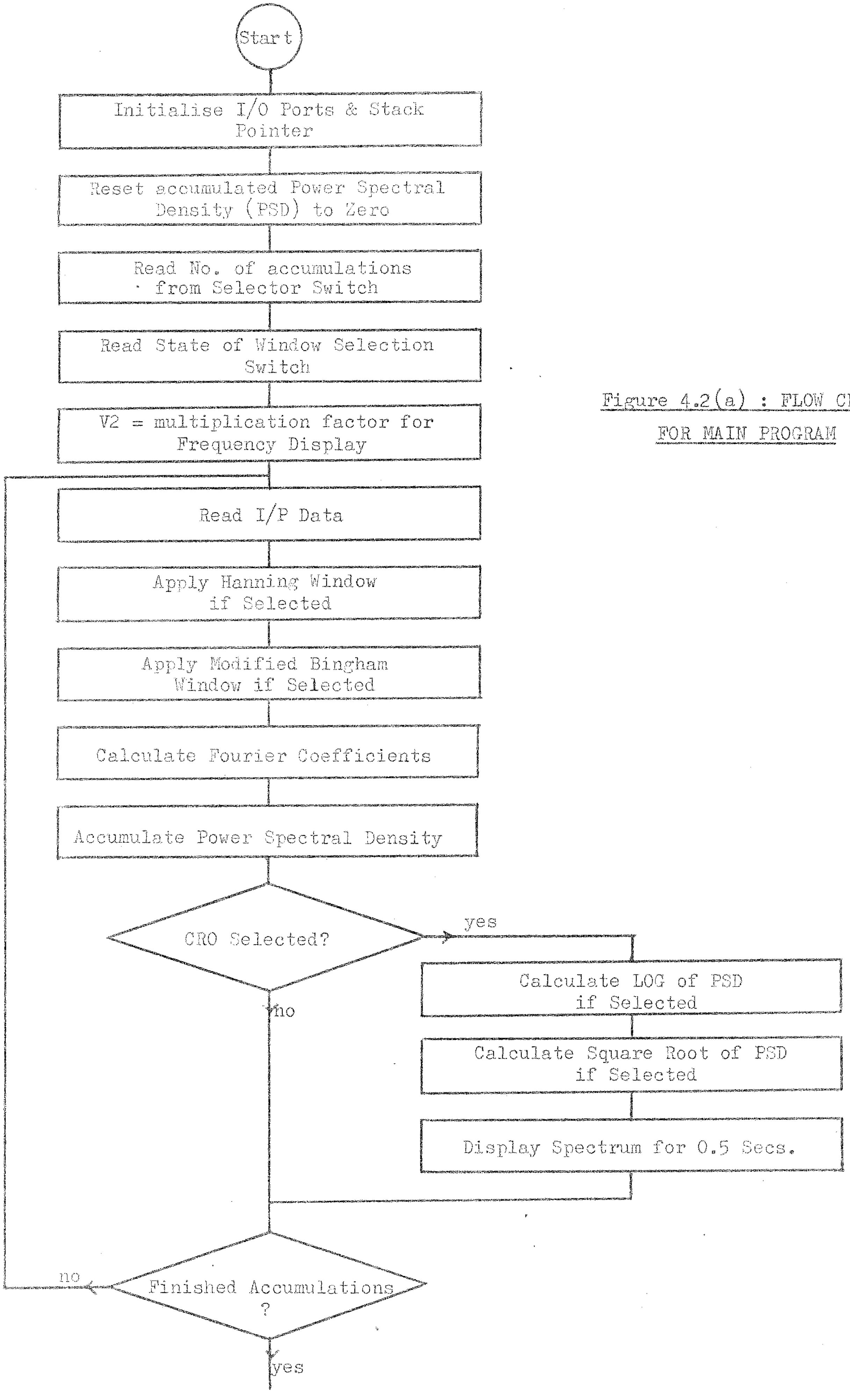
4.5 THE MAIN PROGRAM

The flow chart for the main program is shown in figures 4.2 (a) and 4.2 (b) and the actual coding for the main program as well as the subroutines and sine look-up table is listed in Appendix 2.

The function of the main program is to:

(1) initialize input-output ports and the microprocessor.
(2) read the state of front-panel switches.
(3) set up initial conditions.
(4) control the calling of subroutines.

Some of the switch conditions are read once only per calculation routine ie. Window Selection, no. of accumulations and bandwidth selection are not able to be changed until the next calculation since otherwise the result would be meaningless. However switch positions which control the mode of displaying the result such as CRO or recorder output, or logarithmic or linear output, are regularly monitored for a change of state.



(A)

Figure 4.2(a) : FLOW CHART FOR MAIN PROGRAM

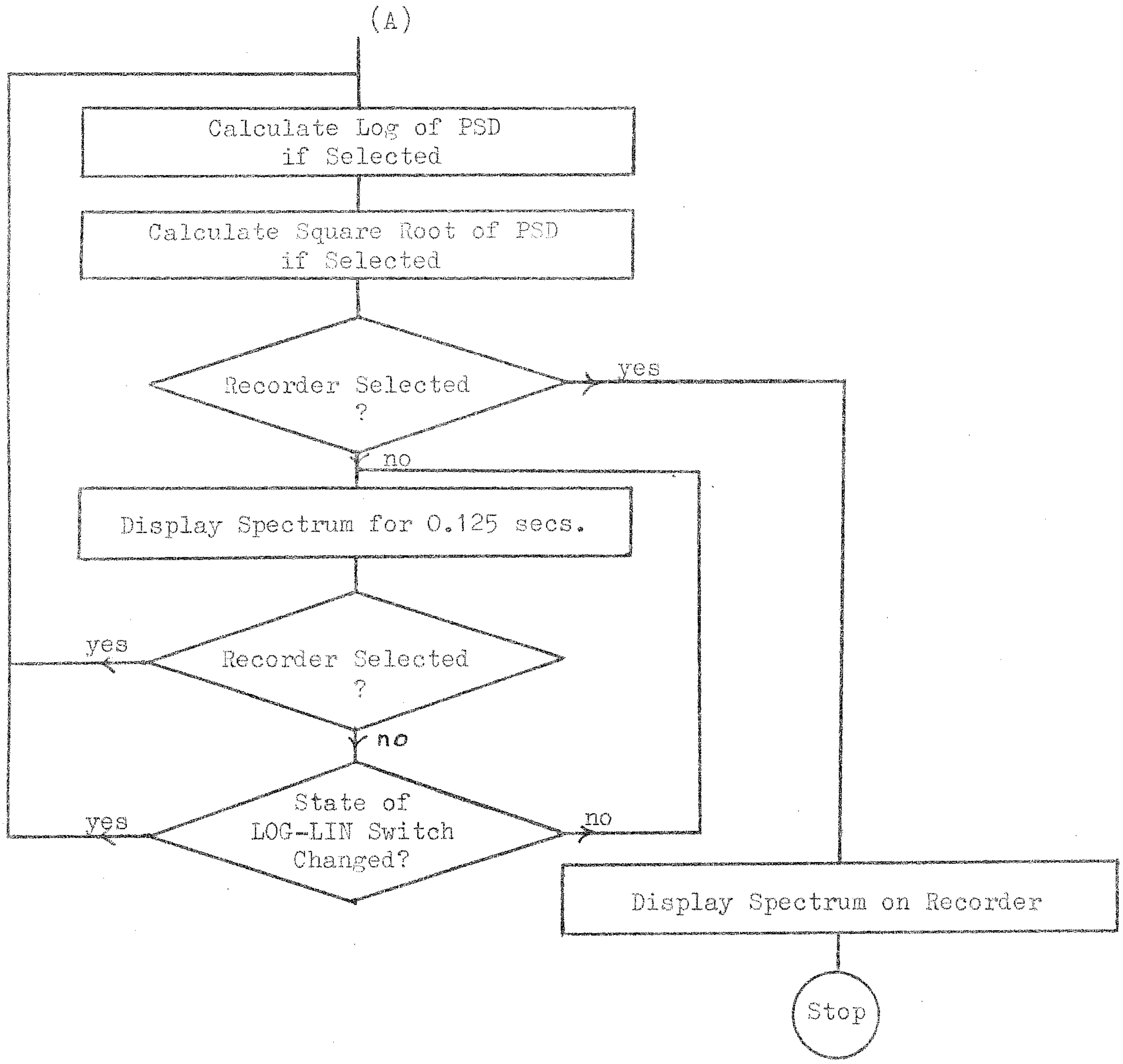


Figure 4.2(b) : FLOW CHART FOR MAIN PROGRAM

4.6 INPUT ROUTINE

The Input Routine is a subroutine called from the main program and performs the following functions (refer to figure 4.3):

(a) Sample Input Signal

A clock signal selected from the sample rate controller board is monitored by an I/O port and the analogue to digital (A/D) converter is read 15 to 20 usecs after a low to high (LO-HI) transition. This clock signal initiates an A/D conversion and the time delay allows enough time to complete the conversion. The program reads 256 10-bit samples (X (L)). The most significant 8 bits are stored in locations 1400 to 14FF and the remaining 2 bits are stored in locations 1500 to 15FF. (The address locations are expressed in the hexadecimal number base as will be assumed for the rest of the text).

(b) Store Zeroes in Imaginary Area of Memory

The fast fourier transform operates on complex data and so operates on arrays of memory which consist of real and imaginary parts. The transform is to operate on the input signal which is a real array and so the area of memory allocated to imaginary data is set to zero prior to the FFT being executed. This area of memory comprises locations 1600 to 17FF.

(c) Check Input Data for Overload

If the input signal is too large for the A/D converter to handle then the numbers read will be limited to positive or negative maximum. Hence during this section of the program the most significant byte of each sample is tested for equality with the hexadecimal numbers 7F (positive maximum) or 80 (negative maximum).

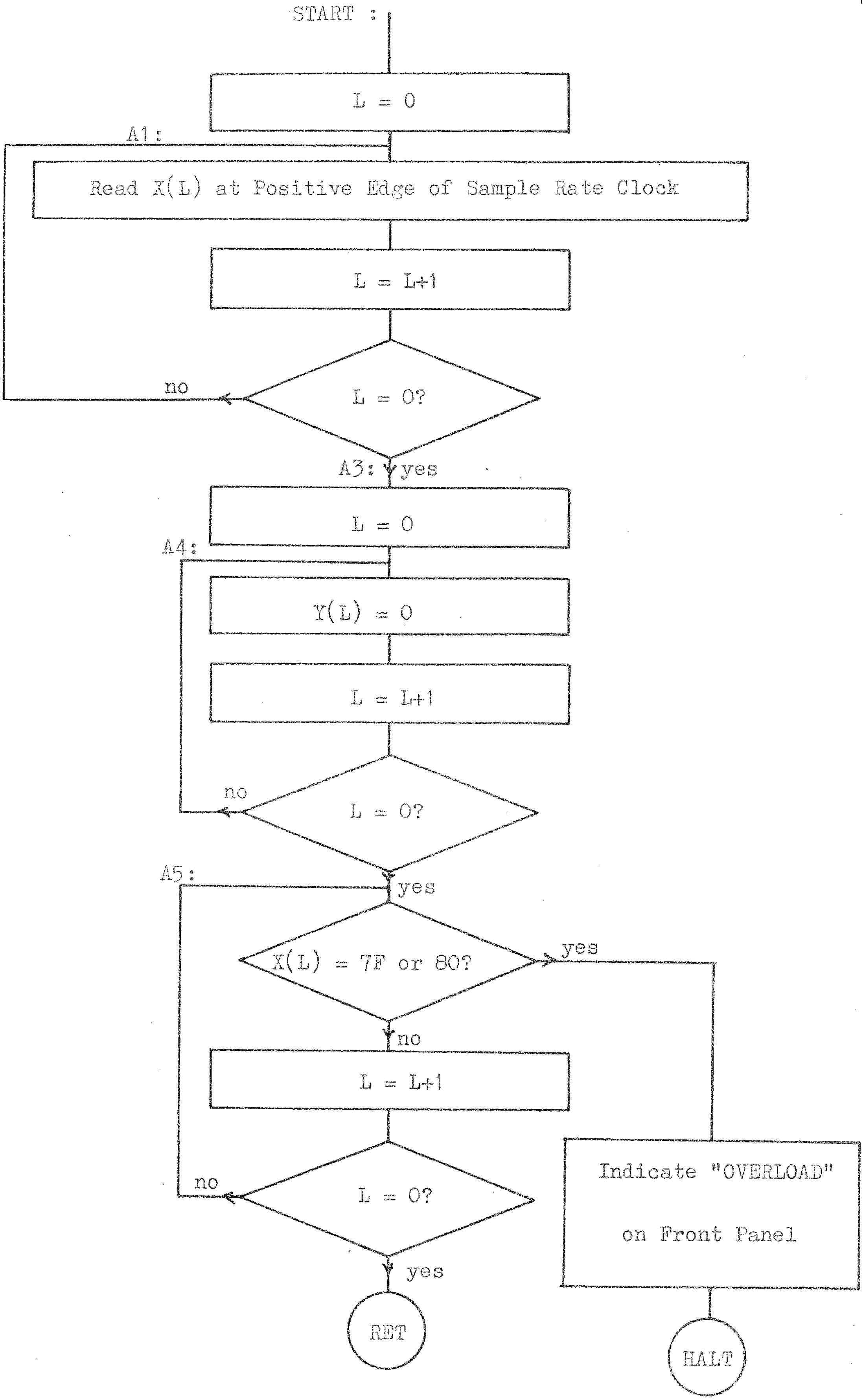


Figure 4.3 : Input Routine

If this condition is met the appropriate LED on the front panel is energised and the program is stopped. If overload has not occurred then execution is returned to the main program.

4.7 PREMULTIPLICATION OF INPUT DATA BY A WINDOW FUNCTION

As mentioned in section 2.3, the spectrum can be improved by premultiplying the input signal by certain functions over the sample range. Three window functions can be selected by a 3 position switch on the front panel which is interrogated by the main program. These 3 functions are :

(a) Rectangular Window (ie. No Window)

(b) Modified Bingham Window

(c) Hanning Window

The Rectangular Window simply describes the case of not applying any window ie. the input data is unmodified. The remaining 2 window functions have been described in section 2.3 and are achieved in practice by the microprocessor executing the flow charts shown in figures 4.4 and 4.5 respectively. These flow charts are given in terms of machine registers A, B, C, D, E, H and L. In interpreting the flow charts these registers are treated as integers of moduli 256. The sine look-up table is represented by S (I) = sin (2*П*I/256) for I = 0...255. This convention is adhered to for all remaining flowcharts.

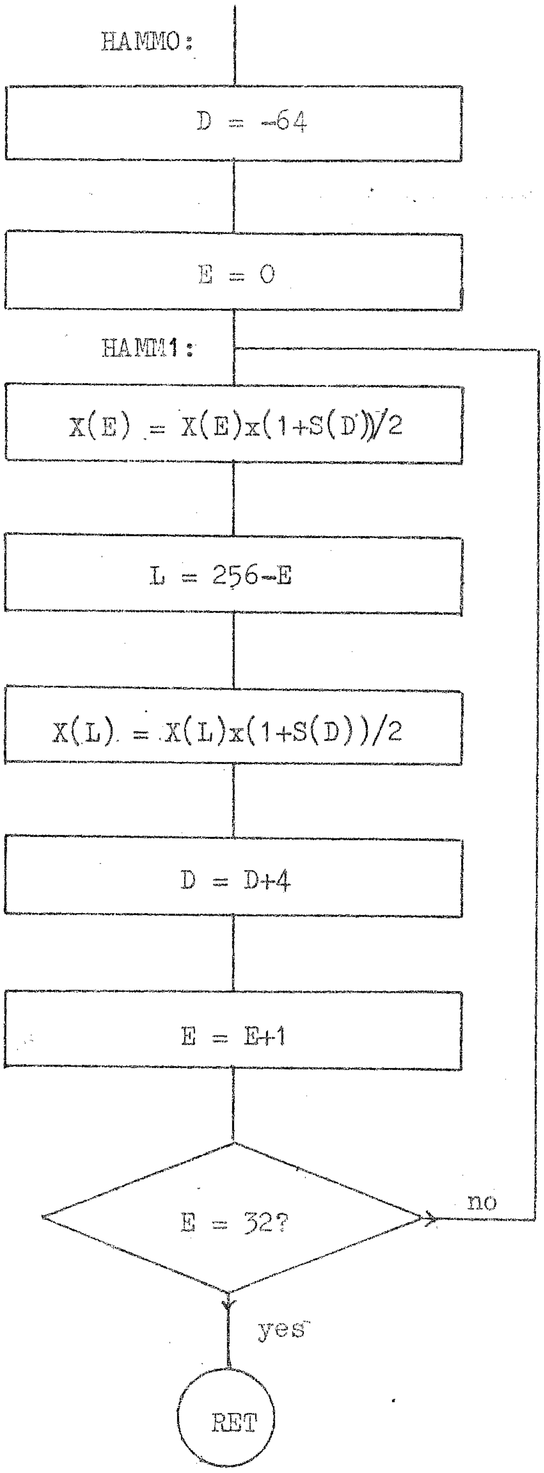


Figure 4.4 : Modified Bingham Window

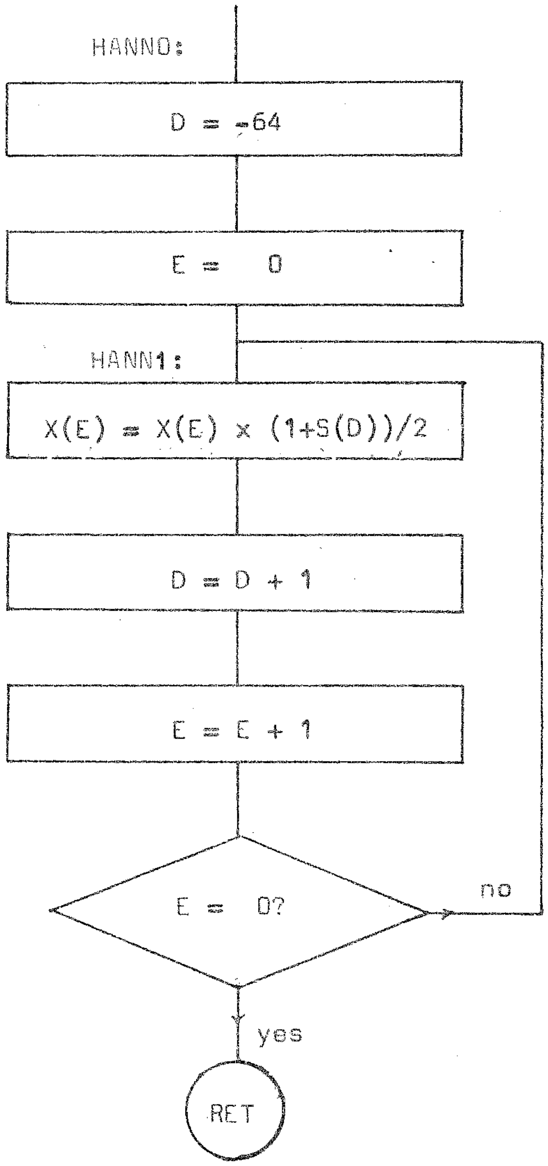


Figure 4.5 : Hanning Window

4.8 CALCULATION OF FOURIER COEFFICIENTS

The DFT of the input data is calculated using the Fast Fourier Transform (FFT) technique. This is achieved by 2 subroutines which are :

(a) Reshuffle data in bit reversed order

(c) FFT using decimation in time

4.8(a) RESHUFFLE DATA IN BIT REVERSED ORDER

This subroutine is simply preparatory for the FFT decimation in time routine. It involves rearranging the data in bit reversed order.

Eg. consider X (3)

In binary representation (8 bits) 3 is represented by :

0000 0011 = 3

If this number is bit reversed the result is :

1100 0000 = 192

Therefore the 2 data points X (3) and X (192) are interchanged. This process is carried out for all 256 data points. The flow chart for this processs is shown in figure 4.6.

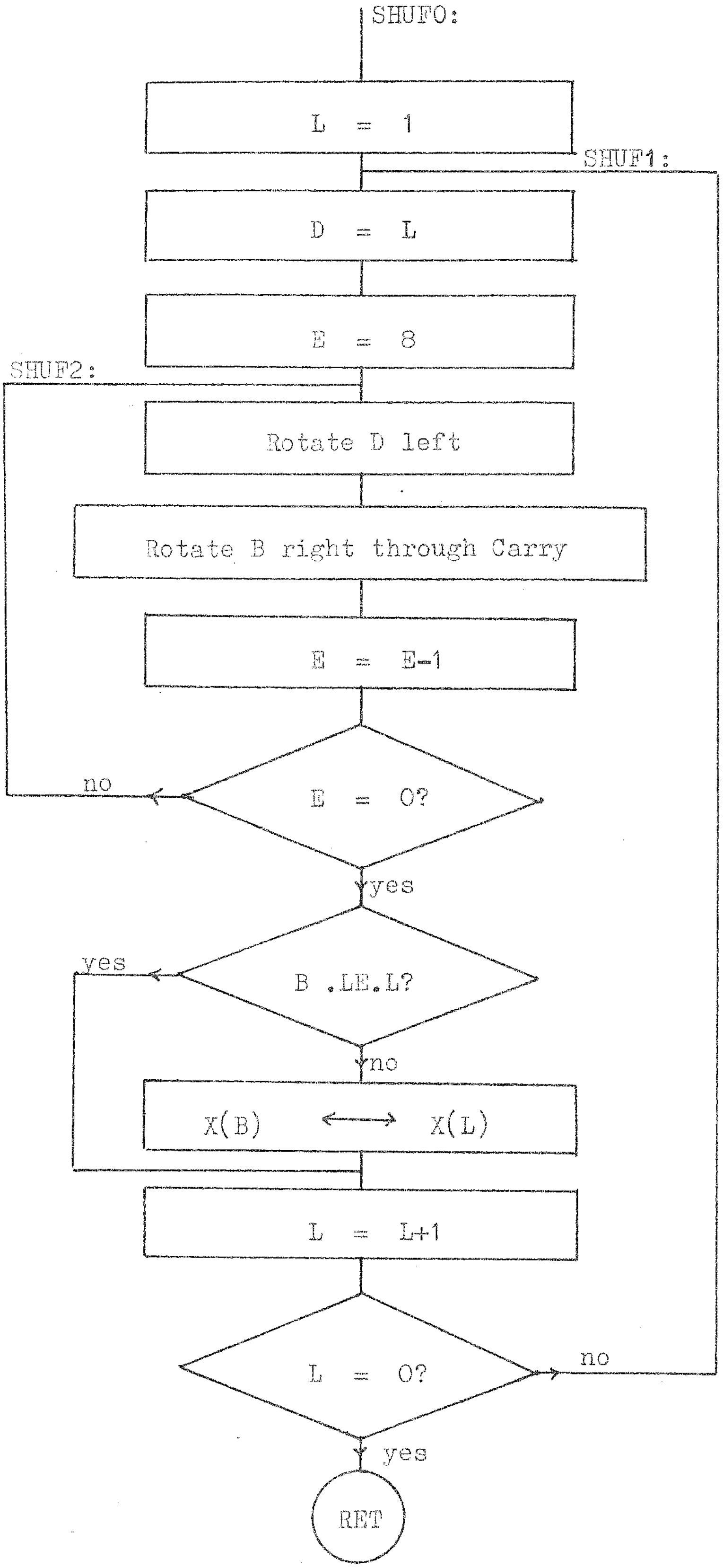


Figure 4.6: Reshuffle Data

4.8(b) FFT DECIMATION IN TIME

The flow chart for this routine is shown in figure 4.7. The notation in the flow chart is according to the following convention

X (I) = real part of array entry I.

Y (I) = imaginary part of array entry I.

It was noted in a previous section that :

S (I) = sin (2*II*I/256)   I = 0...255

The cosine CO (I) = cos (2*II*I/256) can be calculated by :

CO (I) = S (I + 64) from the sine look-up table.

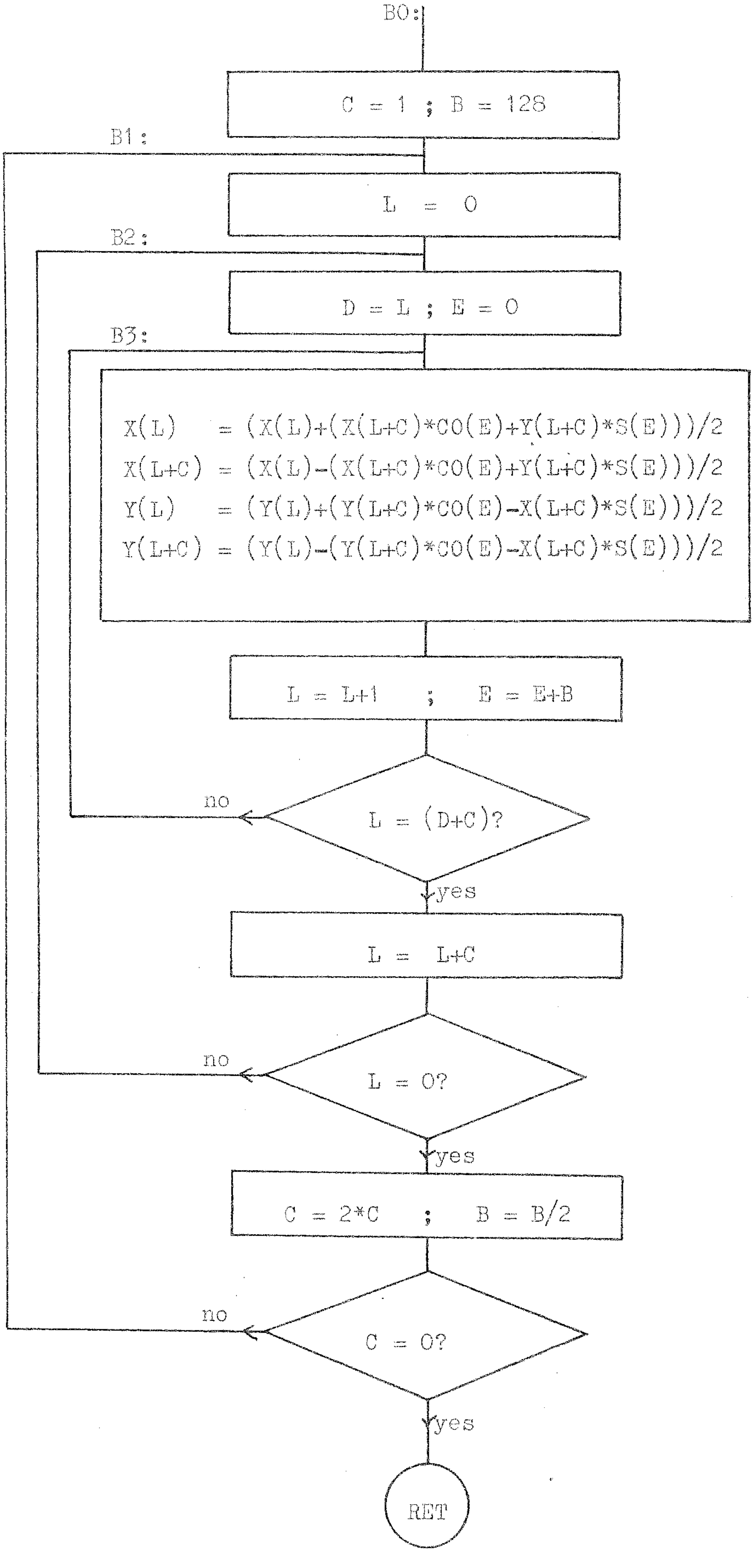


Figure 4.7 : FFT Decimation in Time

4.9 AMPLITUDE CORRECTION DUE TO WINDOWING AND ACCUMULATION OF POWER SPECTRAL DENSITY

Once the DFT has been calculated, the result is an array which consists of real and imaginary parts. At this stage the DFT components are multiplied throughout by scalar correction factors to compensate for the amplitude error caused by windowing. This correction factor is inversely proportional to the area under the particular window function. The power spectral density array (PSD (I)) is then accumulated by the sum of the squares of the real and imaginary parts of the DFT (X (I) and Y (I) respectively) divided by the total number of accumulations (NA). (NA was read by the main program from the front panel). This process is repeated for each frequency component I = 0...255. The flow chart is shown in figure 4.8.

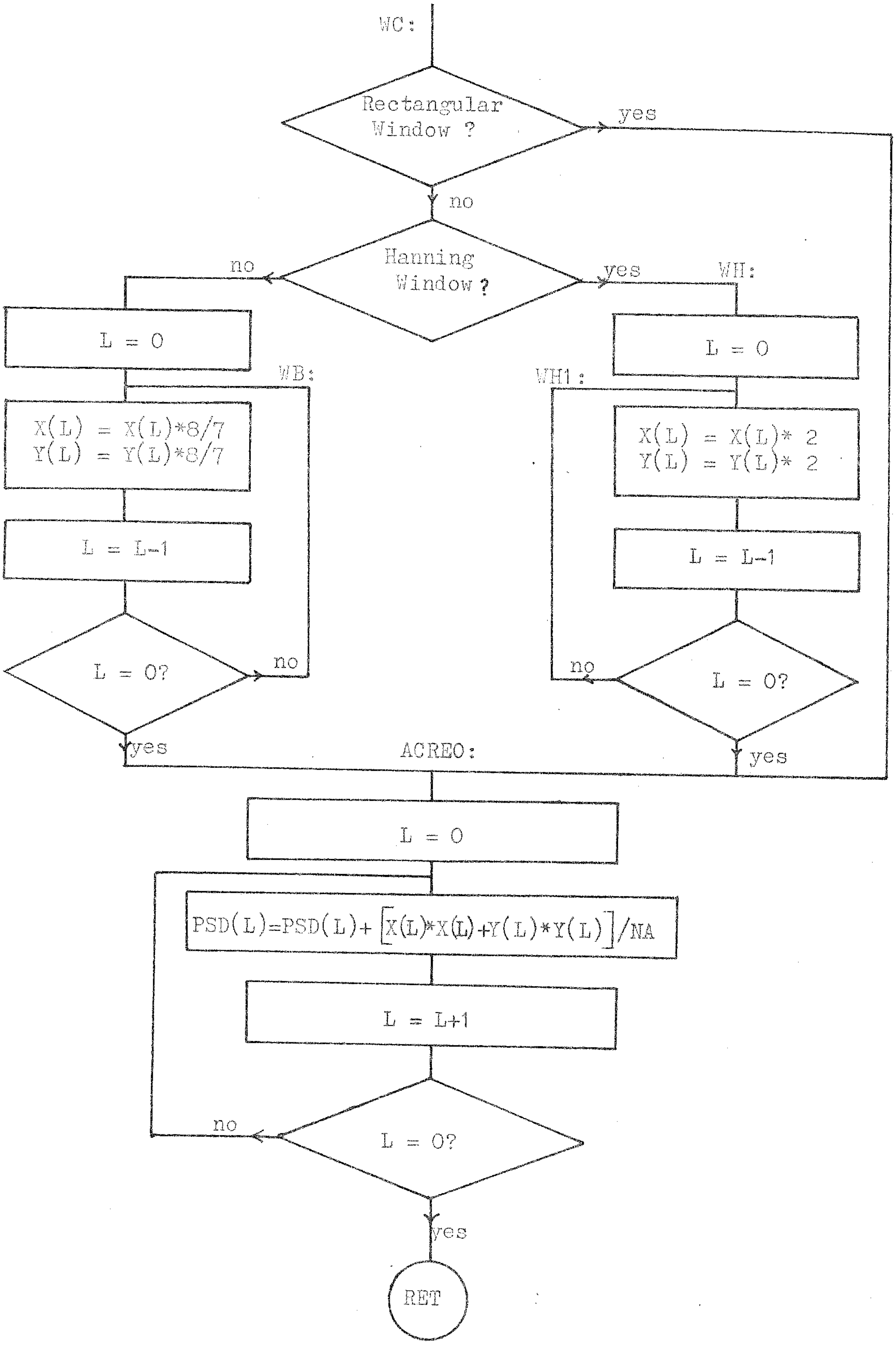


Figure 4.8 : Amplitude Correction due to Windowing and Accumulation of Power Spectral Density

4.10 CALCULATION OF LOGARITHM OF POWER SPECTRAL DENSITY

To display the power spectral density of a signal over a wide dynamic range of amplitude it is necessary to display the spectra on a logarithmic scale. The flow chart for the subroutine 'LOG' is shown in figure 4.9. This program calculates the base 2 logarithm of a 3 byte no. to produce a 3 byte integer result.
ie. $DIS(L) = 220 + 10 \log_2 (PSD(L))$ where $L = 0 \ldots 127$

An attenuator is set to a specific value in the D/A converter for displaying results so that the final result can be read in decibel units.

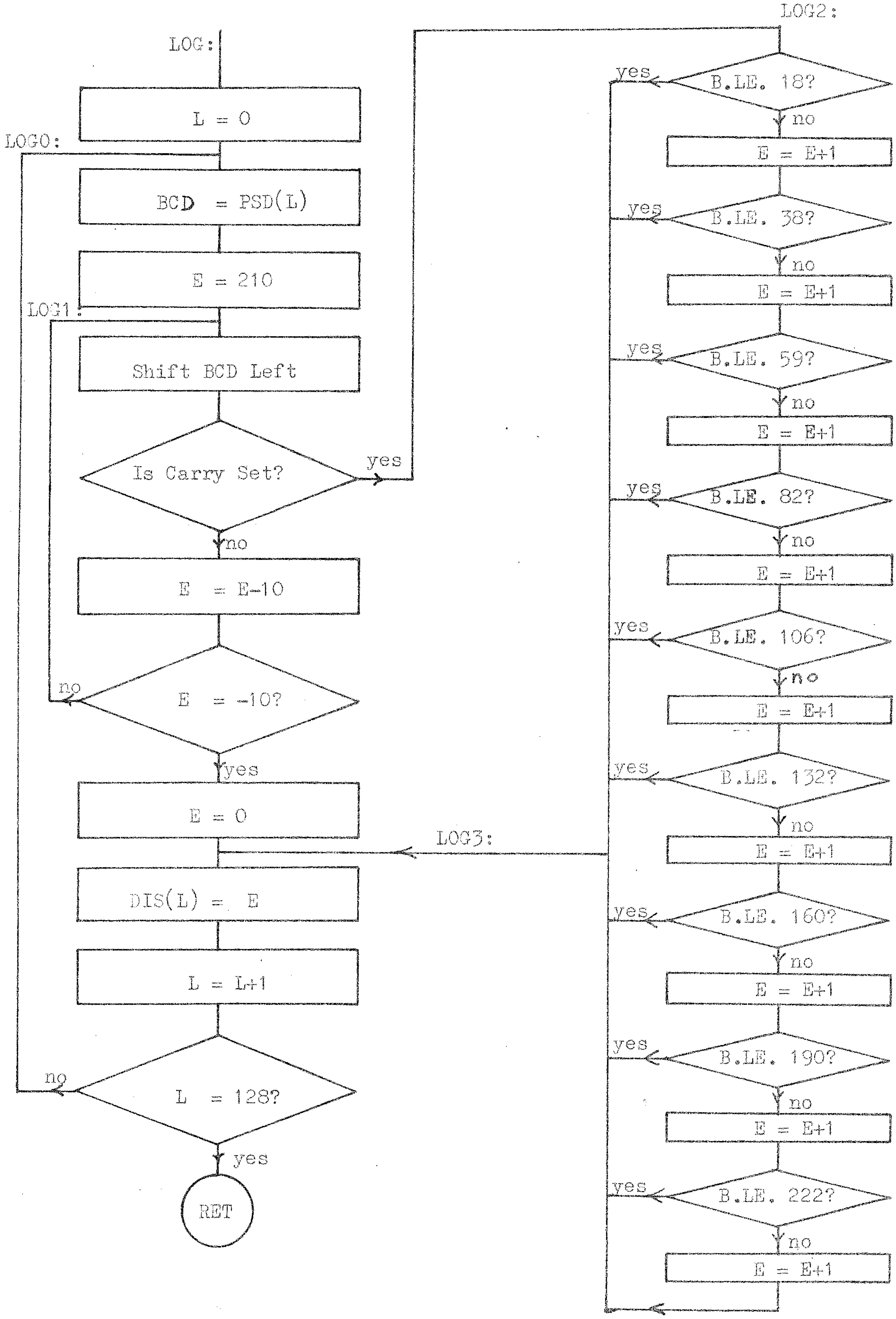


Figure 4.9 : Calculation of Logarithm of Power Spectral Density

4.11 CALCULATION OF SQUARE ROOT OF THE POWER SPECTRAL DENSITY

Quite often it is desirable to display the magnitude of frequency components on a linear scale. This is simply the Pythagorean sum of the result of the FFT operation ie.:

$$= \mathrm{SQRT}\ (X\ (L)*\ X\ (L) + Y\ (L)*\ Y\ (L))$$

$$= \mathrm{SQRT}\ (\mathrm{PSD}\ (L))$$

The flow chart for achieving this is shown in figure 4.10. Firstly, each power spectral component is multiplied by a scalar factor (1.68) so that the final result will be compatible with the attenuator setting of the D/A converter. The routine for finding the square root of a number is based on the fact that any perfect square integer is equal to the sum of a series of odd integers.

ie. 4 = 2*2 = 1 + 3
9 = 3*3 = 1 + 3 + 5
16 = 4*4 = 1 + 3 + 5 + 7
25 = 5*5 = 1 + 3 + 5 + 7 + 9
etc.

The actual method for exploiting this law is commonly known and is presented in texts such as reference [1] and is adapted in this case to binary arithmetic.

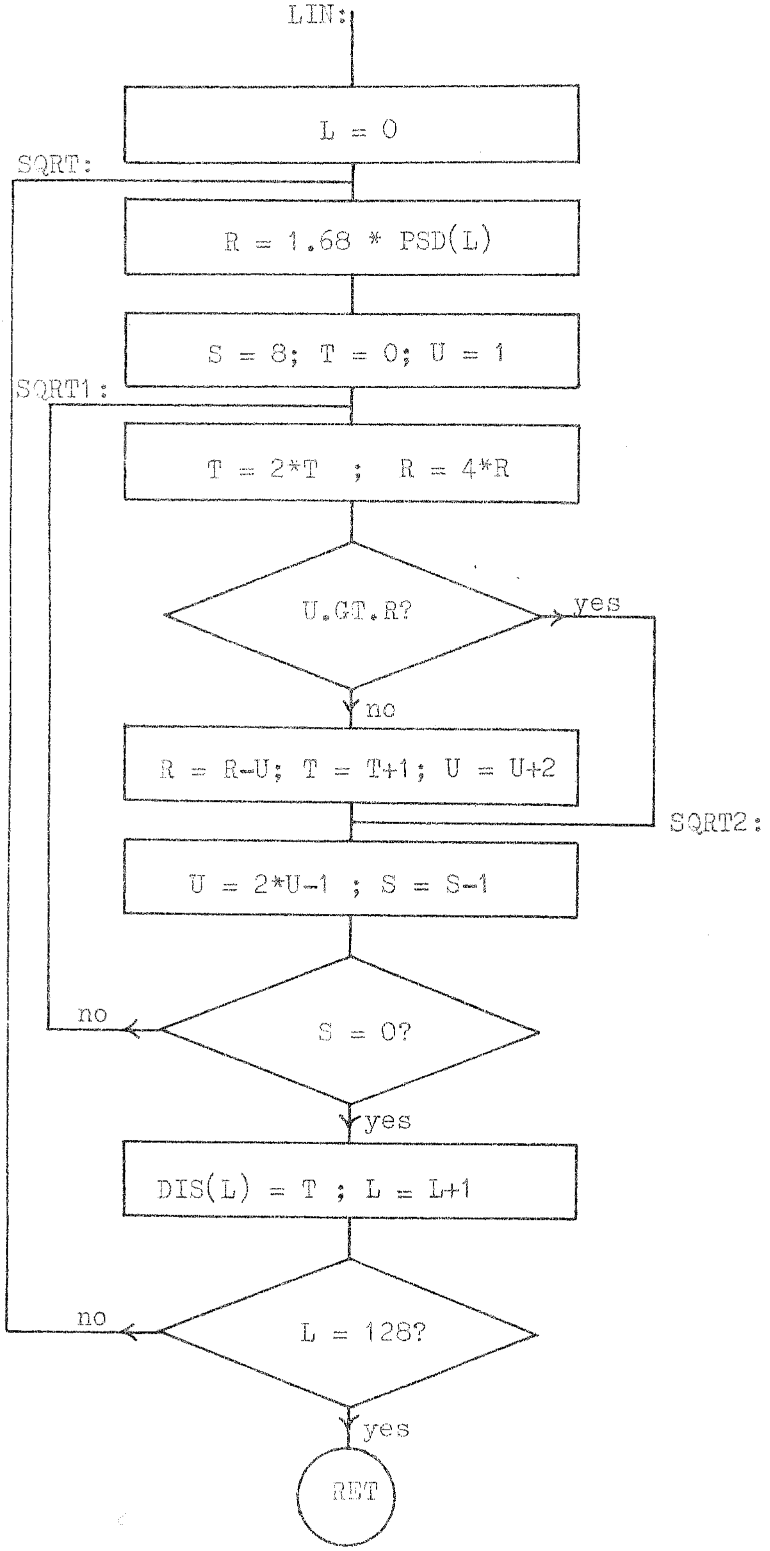


Figure 4.10 : Calculation of Square Root of Power Spectral Density

4.12 DISPLAY OF SPECTRUM ON A CATHODE RAY OSCILLOSCOPE

The flow chart for this routine is shown in figure 4.11. It assumes that the spectrum analyser is connected to a dual beam CRO with one Y input connected to the 'CRO Output' connector and the second Y input connected to the 'trigger output' connector. The CRO is set to trigger on the negative transition of the second input. The positive edge of the second trace coincides with the frequency which is displayed on the front panel of the analyser. This positive edge is referred to as the 'cursor' and its horizontal position on the screen can be controlled by a 'cursor control' switch on the front panel. This facility enables easy identification of spectral components by moving the cursor to coincide with a particular component and then reading the frequency from the display. The shape of the spectrum is displayed on the Y 1 input continuously for 1/8th of a second by this routine. Near the end of the main program this routine is called repeatedly until the recorder is selected. This enables the cursor to be moved at the rate of 8 components/second. Illustration of its use can be seen in the chapter 'Results'.

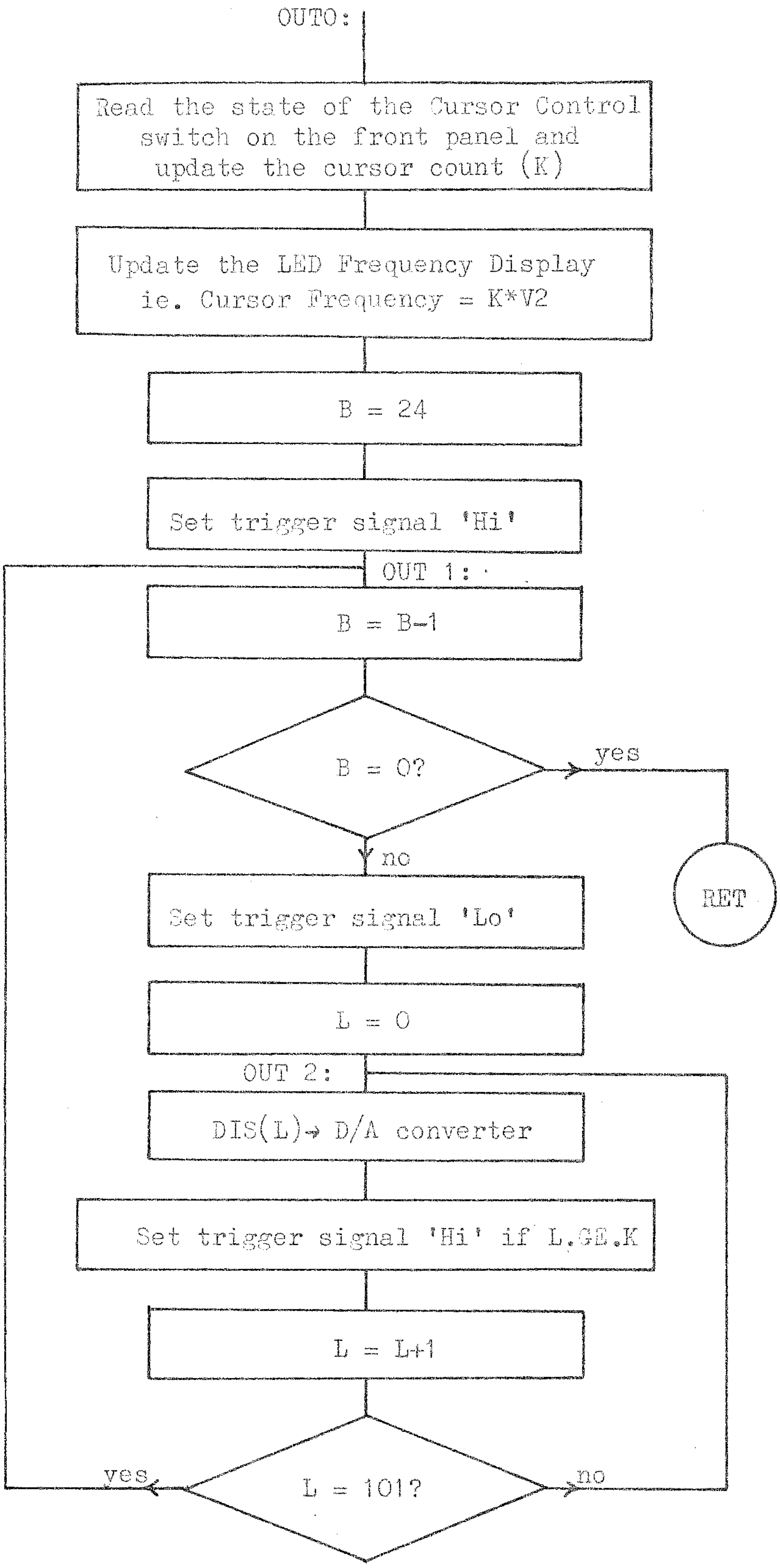


Figure 4.11 : Display of Spectrum on a Cathode Ray Oscilloscope

4.13 DISPLAY OF SPECTRUM ON A PAPER RECORDER

The flow chart for this routine is shown in figure 4.12. This facility allows a permanent record to be made of a particular spectrum. The recorder used had a fairly slow pen movement and paper speed and so this routine is time consuming ie. the output rate is one spectral point/sec which gives 100 seconds for a complete record. To facilitate reading the record a marker pen is energized at every tenth spectral point.

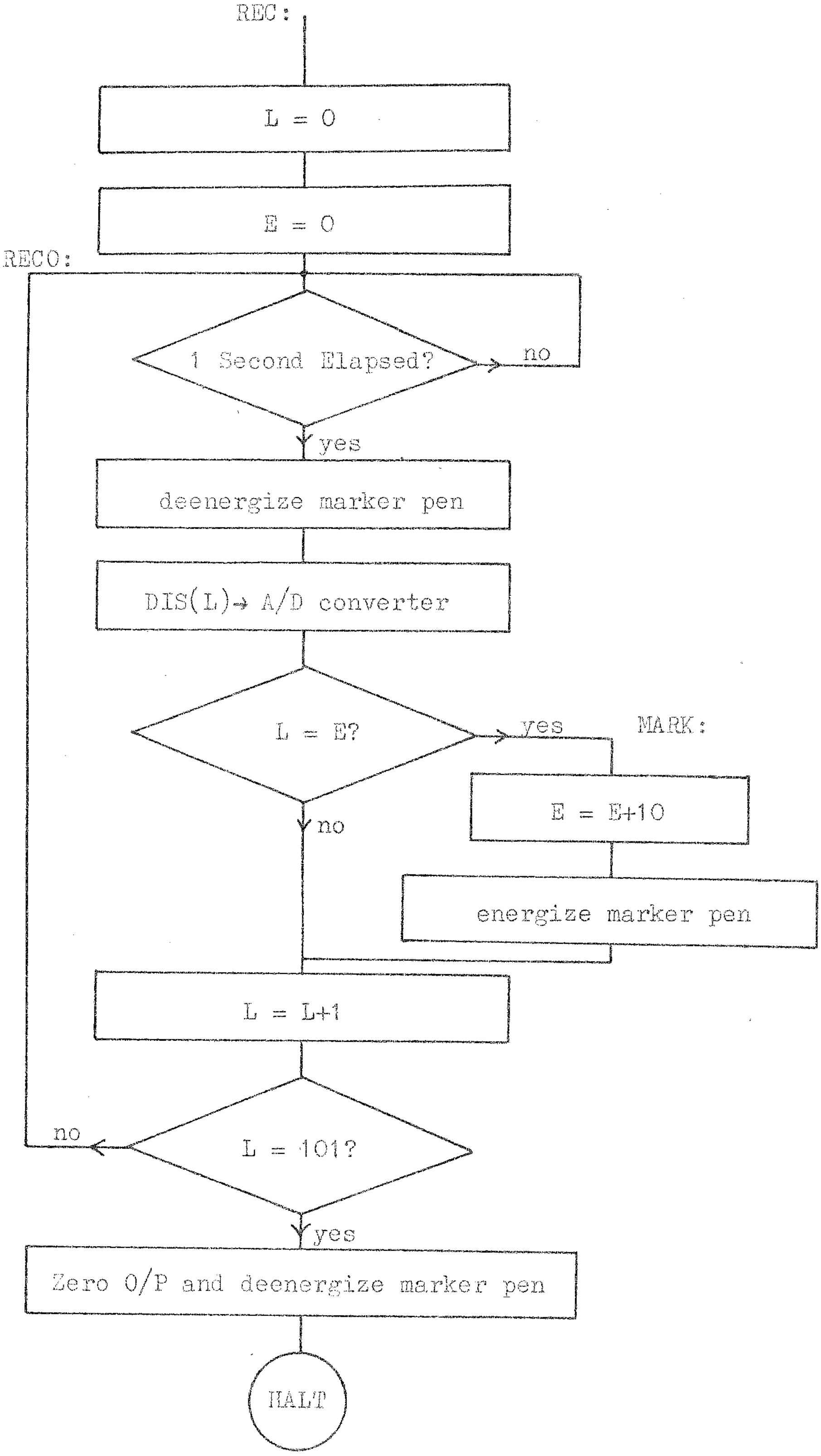


Figure 4.12 : Display of Spectrum on a Paper Recorder

REFERENCE

[1] pp 59 - 62 of "Understanding Digital Computers"
by Paul Siegel, published by Wiley and Sons.

[2] "INTEL 8080 Assembly Language Programming Manual"
INTEL Corporation, Santa Clara, USA, 1976.

[3] "Instructions for running the INTEL 8080 Cross-Assembler,
Cross-Compiler and Simulator"
Local Publication 411, Computing Centre,
University of Adelaide, December 1977.

[4] "INTERP/80 User's Manual"
INTEL Corporation, Santa Clara, USA 1975.

5 RESULTS

In this chapter the results are presented in the form of photographs of traces exhibited on a CRO. The CRO is triggered by the top trace and where applicable the positive edge of that trace represents the cursor.

In figures 5.1 to 5.9 the signal being examined is a 27 Hz sinusoid. The bandwidth setting of the analyser is set to 100 Hz. For this setting the input signal is sampled 256 times for each analysis at a rate of 256 samples/second. Hence the total sample duration = 1 second and so the spectral output samples are separated by 1 Hz. Thus 27 Hz corresponds exactly to one of the output spectral samples.

Figure 5.1 was produced by consecutively outputting the sampled sinusoid to a D/A converter. Figure 5.2 is the spectrum of the sampled signal on a linear scale. It consists of a single spectral line corresponding to 27 Hz which could also be seen at the time on the frequency display because the cursor has been aligned with this component. The scale is approximately .4 volt/cm. Figure 5.3 is the same spectrum but using a logarithmic scale which highlights the smaller components which were not apparent on the linear scale. The scale is approximately 20 db/cm. Several features require explanation.

There is a component at the beginning of the spectral record which corresponds to zero frequency. This is due to a d.c. component introduced by the offset voltage of the A/D converter and associated amplifiers.

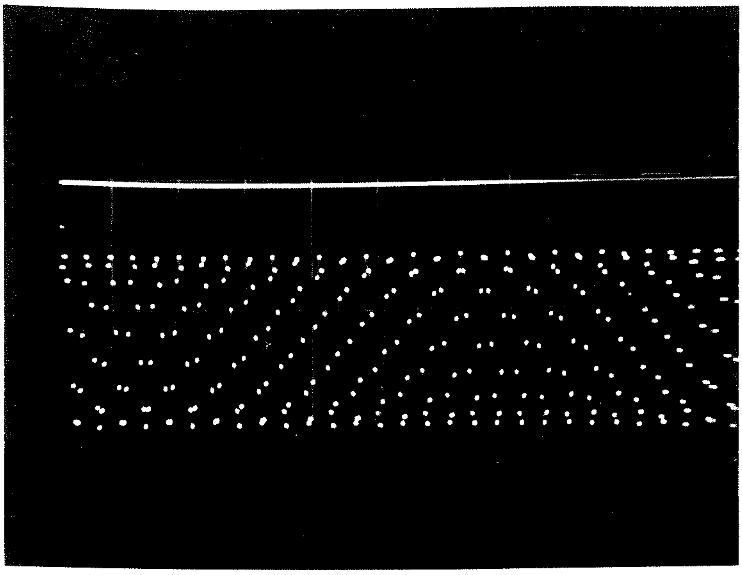


Figure 5.1:

27Hz sinusoid sampled at 256 samples/sec. No windowing.

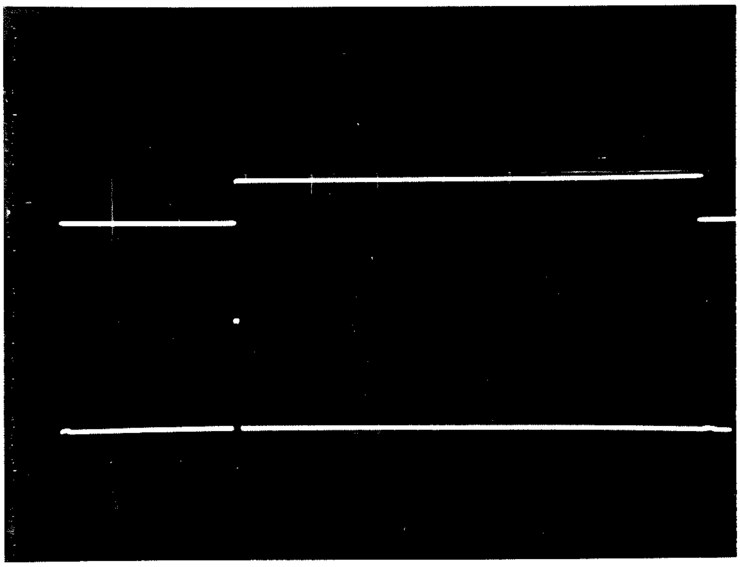


Figure 5.2:

Spectrum of sampled signal on a linear scale

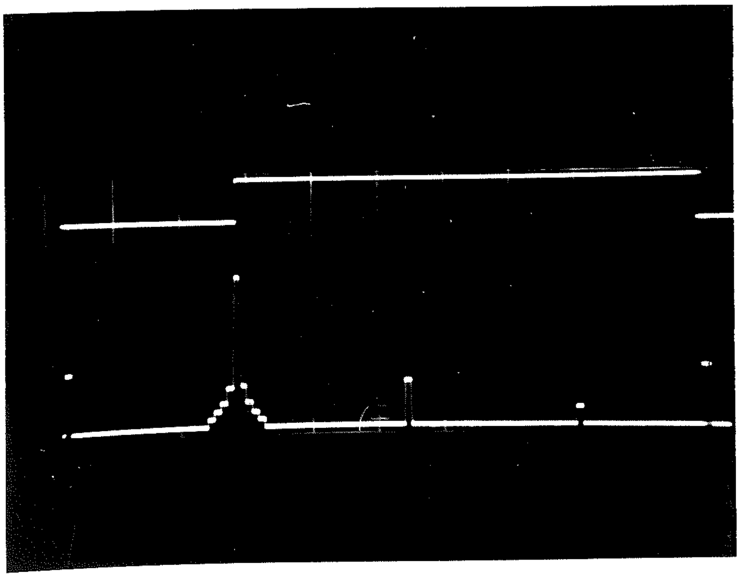


Figure 5.3:

Spectrum of sampled signal on a logarithmic scale

This same component can also be seen on the far right of the screen where the spectrum is repeating itself. The two components to the right of the 27 Hz component are the 2nd and 3rd harmonics of the fundamental. Another interesting feature is the occurrence of side-lobes about the fundamental. These are small compared with later records but can be made to disappear entirely by carefully adjusting the input frequency to coincide exactly with an output component.

Figure 5.4 shows a sampled 27 Hz sinusoid with the samples at the beginning and end of the record attenuated by multiplying the input array by the modified Bingham Window. Figures 5.5 and 5.6 are the spectrum of this signal on linear and logarithmic scales respectively. The features of this spectrum are similar to 5.2 and 5.3 except that there are larger side-lobes about the fundamental.

Figure 5.7 shows a 27 Hz sampled sinusoid operated on by a Hanning Window and figures 5.8 and 5.9 show the spectrum of this signal on linear and logarithmic scales respectively. Again the spectrum is similar to 5.2 and 5.3 except that the spectral components have been broadened. It is no longer possible to get a single spectral line corresponding to a pure sinusoid. The single line has been fattened by 2 adjacent components at half value. This effect is also evident in the d.c. component and the 2nd harmonic. There are other spurious components appearing in figure 5.9 which are approximately 50 db below the fundamental. This is probably due to a small amount of numerical noise being introduced by the Hanning Window routine.

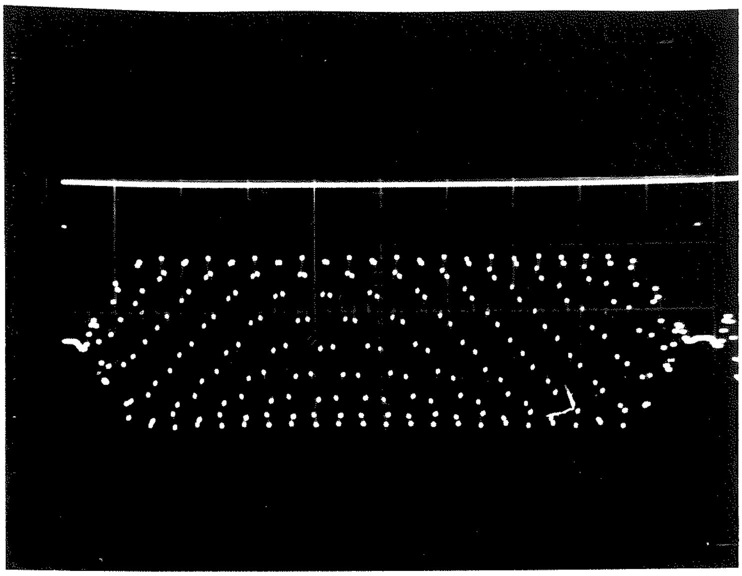


Figure 5.4:

27Hz sinusoid weighted by modified Bingham window

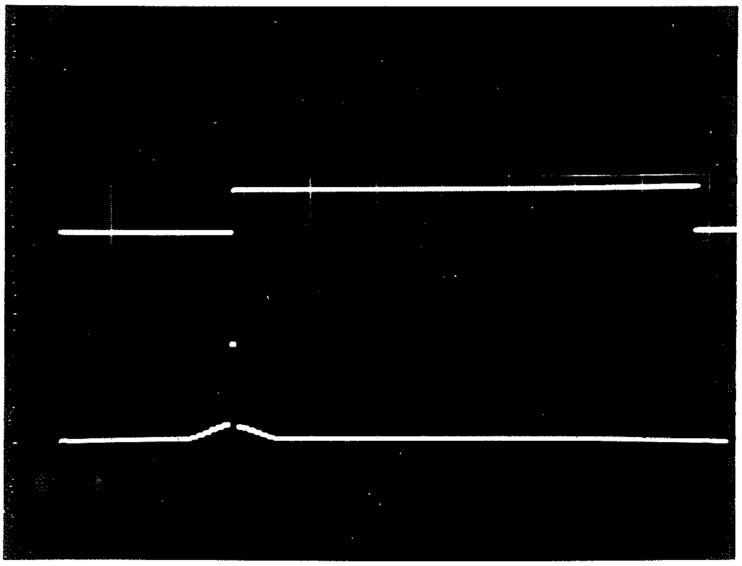


Figure 5.5:

Spectrum of sampled signal on a linear scale

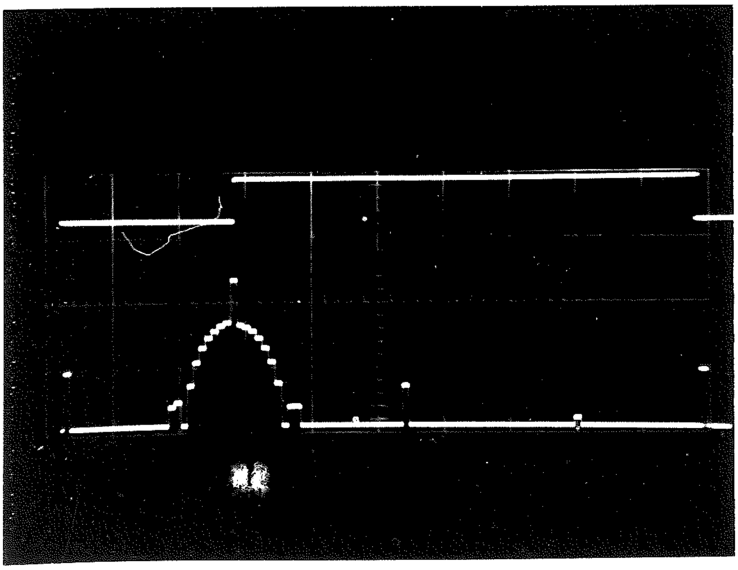


Figure 5.6:

Spectrum of sampled signal on a logarithmic scale

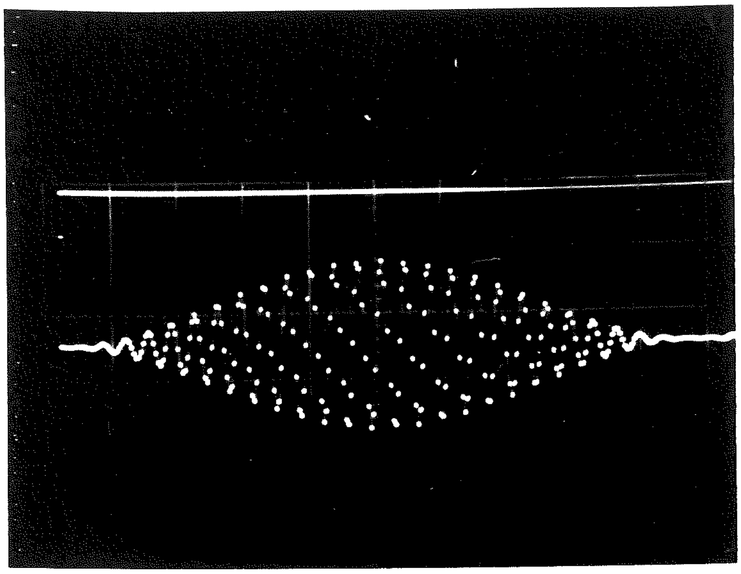


Figure 5.7:

27Hz sinusoid weighted by Hanning window

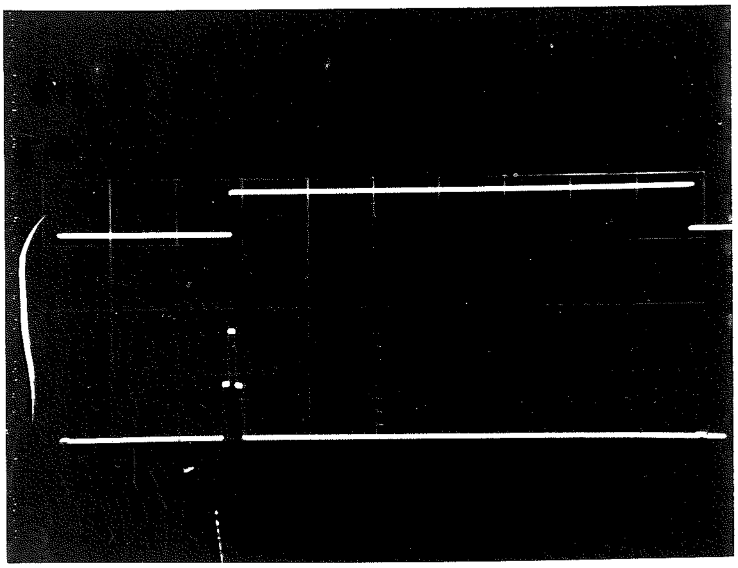


Figure 5.8:

Spectrum of sampled signal on a linear scale

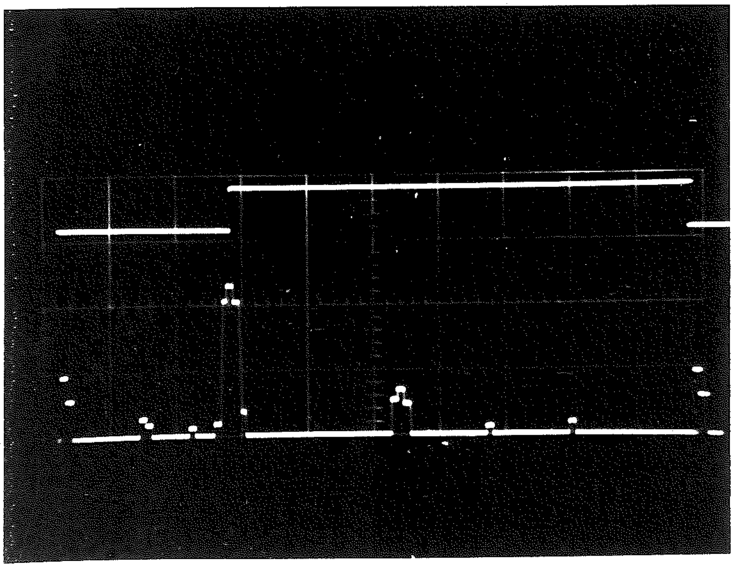


Figure 5.9:

Spectrum of sampled signal on a logarithmic scale

At this stage it may appear that windowing the input signal offers no advantage but this is only the case when the input signal has its frequency components corresponding very closely to the output frequency samples.

In figures 5.10 to 5.15 the spectra of a sinusoid are again shown but the frequency has been adjusted to approximately 26.5 Hz which is half-way between 2 output spectral samples (ie. 26 Hz and 27 Hz).

Figures 5.10 and 5.11 show the spectrum of the 26.5 Hz sinusoid on linear and logarithmic scales respectively with no windowing applied. The fundamental is represented by 2 approximately equal adjacent components. However the side-lobes associated with the fundamental are now so large that they nearly obscure entirely the presence of the d.c. component and the harmonics.

Figures 5.12 and 5.13 show the spectrum of the 26.5 Hz sinusoid with the modified Bingham Window applied. The fundamental is again represented by 2 approximately equal adjacent components. However the side-lobes are reduced sufficiently so that the d.c. component or any harmonic content are clearly evident.

The spectrum of the 26.5 Hz signal is repeated in figures 5.14 and 5.15 but this time a Hanning Window is used. The reduction in side-lobes is further improved. From figures 5.1 to 5.15 it can therefore be seen that, although in some cases a 'superior' spectrum can be achieved by not using any windowing, in general a more consistent and desirable spectrum is obtained by using an appropriate window function.

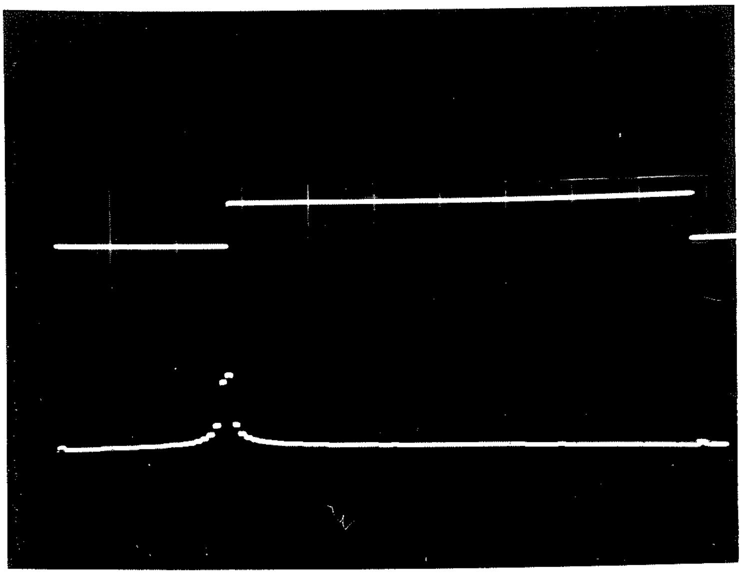


Figure 5.10: Linear spectrum of a 26.5Hz sinusoid with no windowing

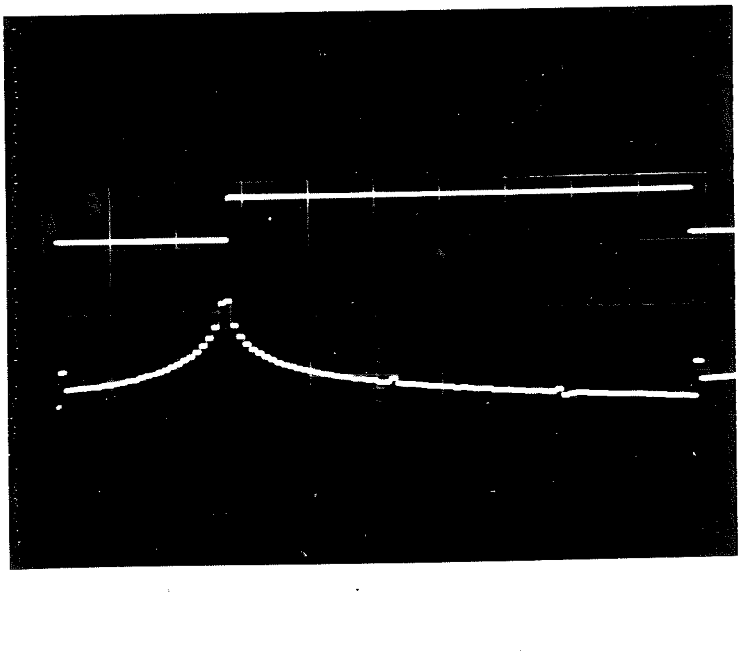


Figure 5.11: Logarithmic spectrum of a 26.5Hz signal with no windowing

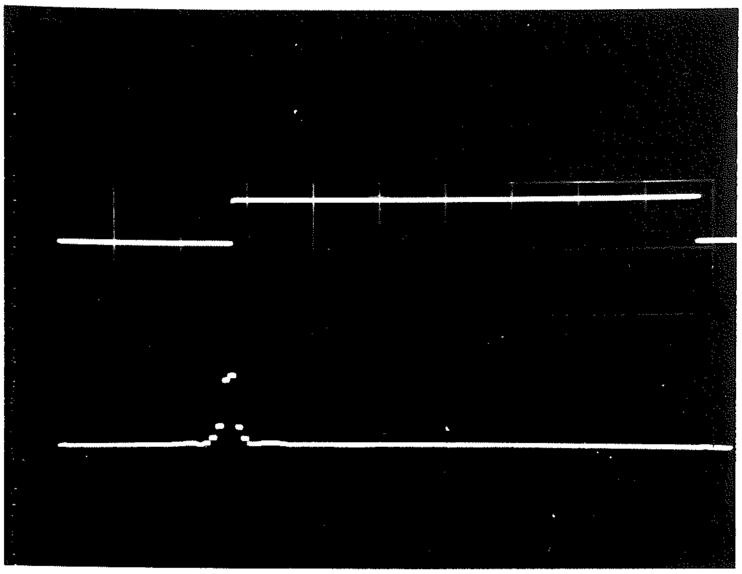


Figure 5.12: Linear spectrum of a 26.5Hz sinusoid weighted by a modified Bingham window

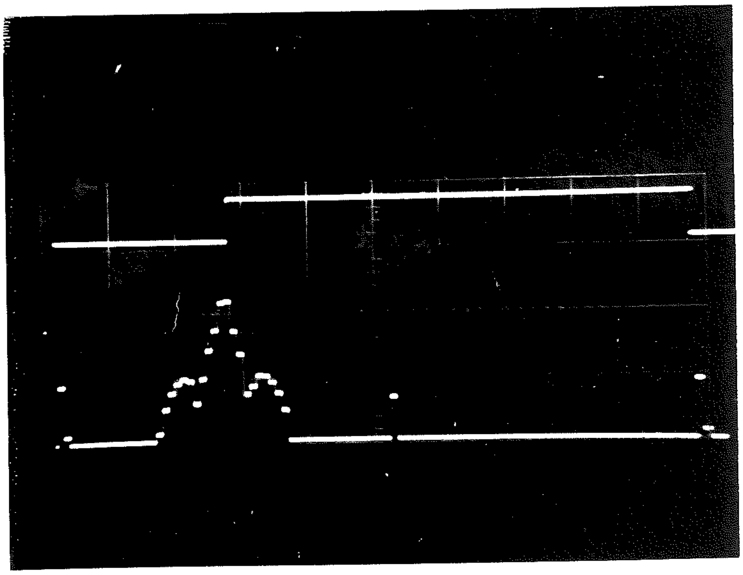


Figure 5.13: Logarithmic spectrum of a 26.5Hz sinusoid weighted by a modified Bingham window

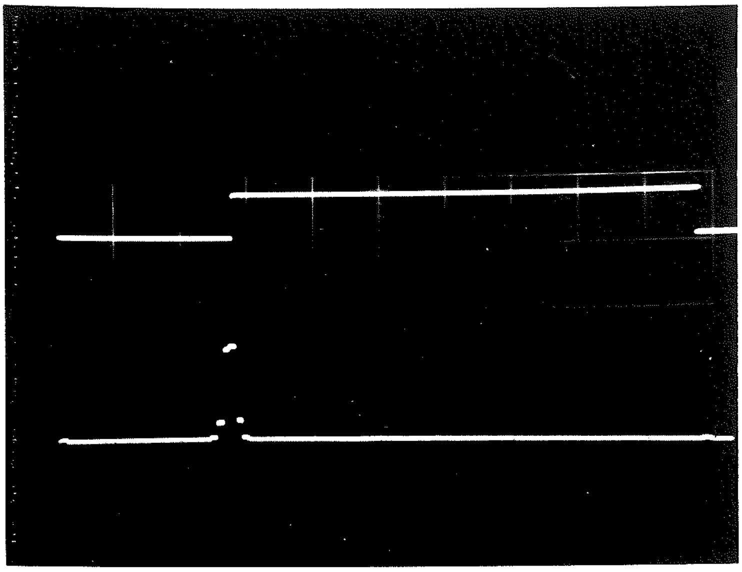


Figure 5.14: Linear spectrum of a 26.5Hz sinusoid weighted by a Hanning window

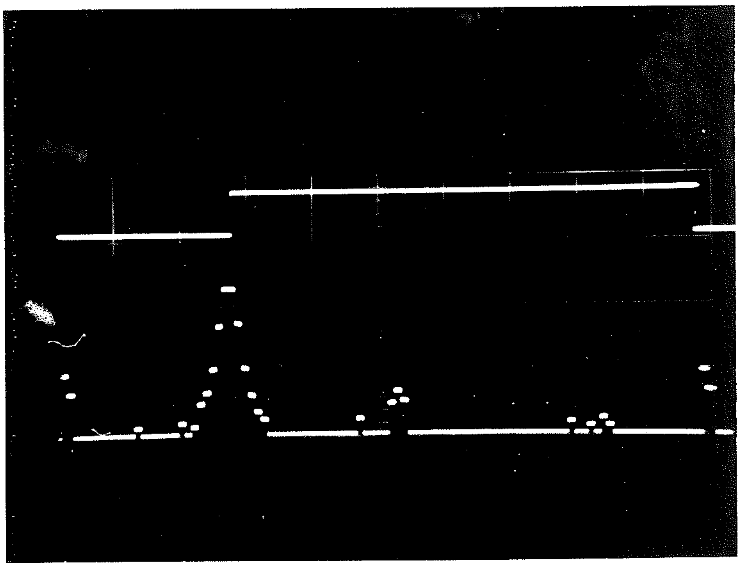


Figure 5.15: Logarithmic spectrum of a 26.5Hz sinusoid weighted by a Hanning window

Figure 5.16 shows a 27 Hz square wave sampled at 256 samples/ second. The slight overshoot seen on the waveform is due to the step response of the elliptic low pass input filters. Figures 5.17 and 5.18 show the spectrum of this signal on a linear and logarithmic amplitude scale respectively. A perfect square wave has only odd harmonics whereas a 2nd harmonic is apparent. This is probably due to the poor waveshape produced by this particular oscillator.

Figures 5.19 to 5.21 show the sampled square wave operated on by a modified Bingham window and its spectrum and this is again repeated in figures 5.22 to 5.24 using a Hanning Window. The same features appear as for a sinusoid except that there are larger harmonics.

Figure 5.25 shows the spectrum on a logarithmic amplitude scale of a 27 Hz square wave with no window employed and the sample rate doubled. Since the sampling time is halved the output frequency components are even integers ie. 0, 2, 4, ..., 200 Hz. Hence the 27 Hz fundamental and the odd harmonics are half-way between output frequency components and so exhibit large side-lobes whereas the even harmonics have negligible side-lobes due to the fact that they each correspond closely to an output frequency component.

Figure 5.26 is included to show simply that a waveform is more easily 'recognizable' when it is sampled at a rate much greater than its fundamental frequency component.

Figures 5.27 to 5.29 are given to illustrate the veracity of the FFT routine. A test input array is set up which has the properties :

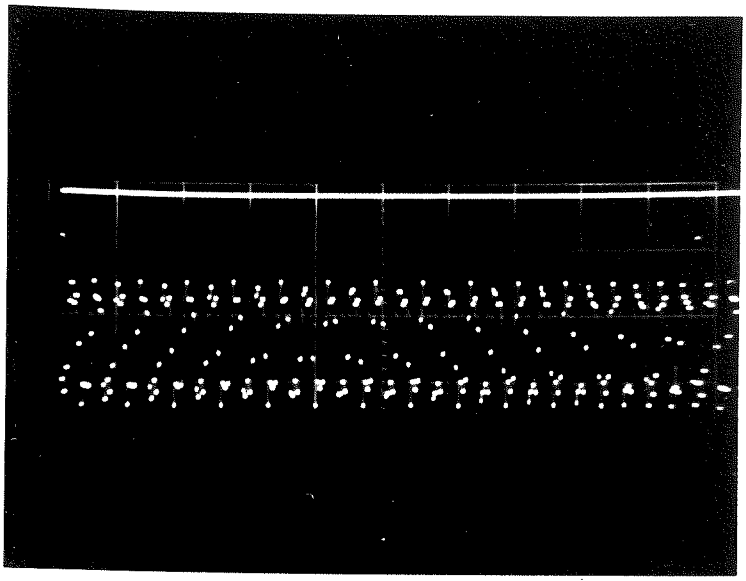


Figure 5.16:

27Hz square wave sampled at 256 samples/sec. No windowing.

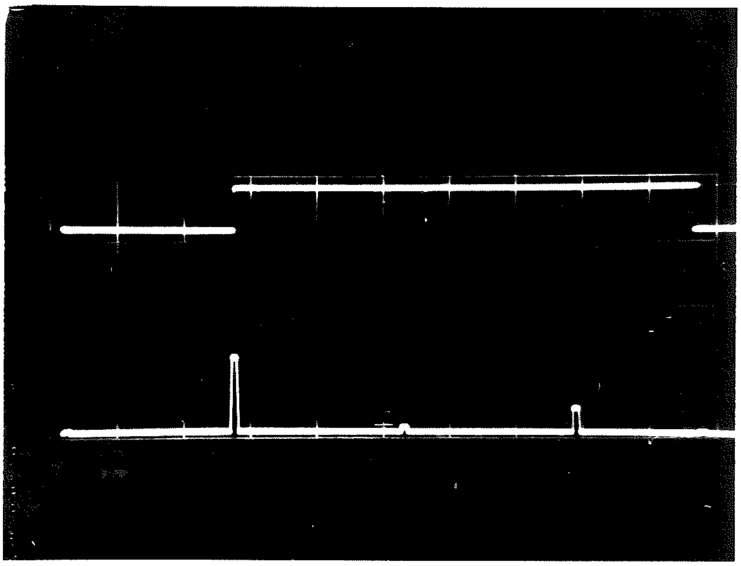


Figure 5.17:

Spectrum of sampled signal on a linear scale

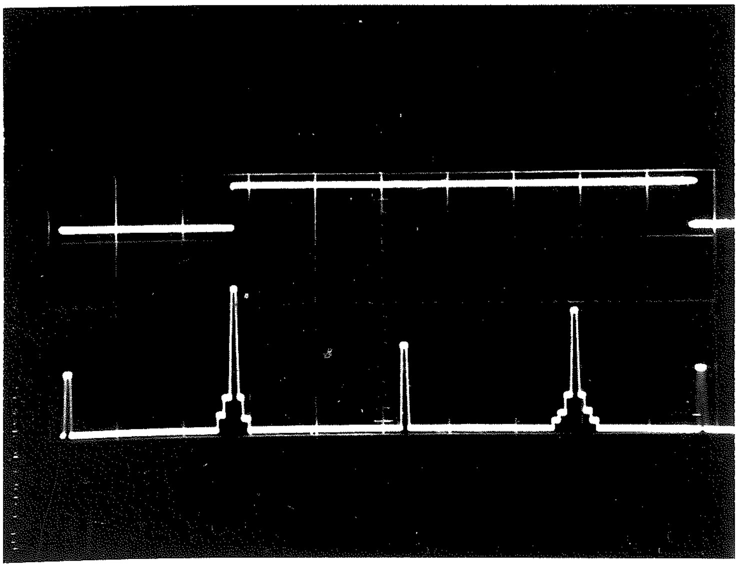


Figure 5.18:

Spectrum of sampled signal on a logarithmic scale

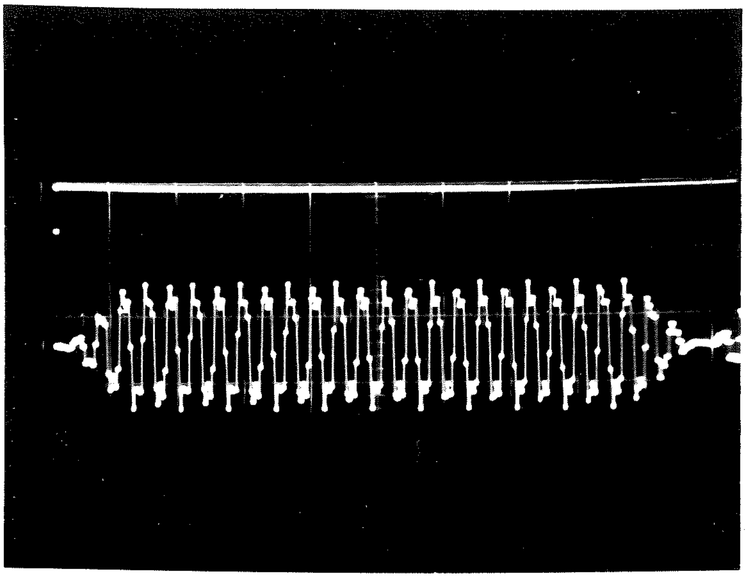


Figure 5.19:

27Hz square wave weighted by a modified Bingham window

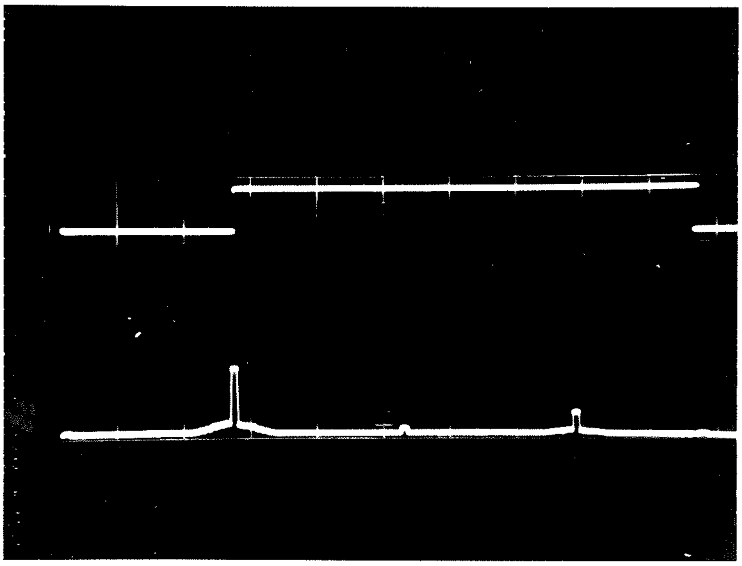


Figure 5.20:

Spectrum of sampled signal on a linear scale

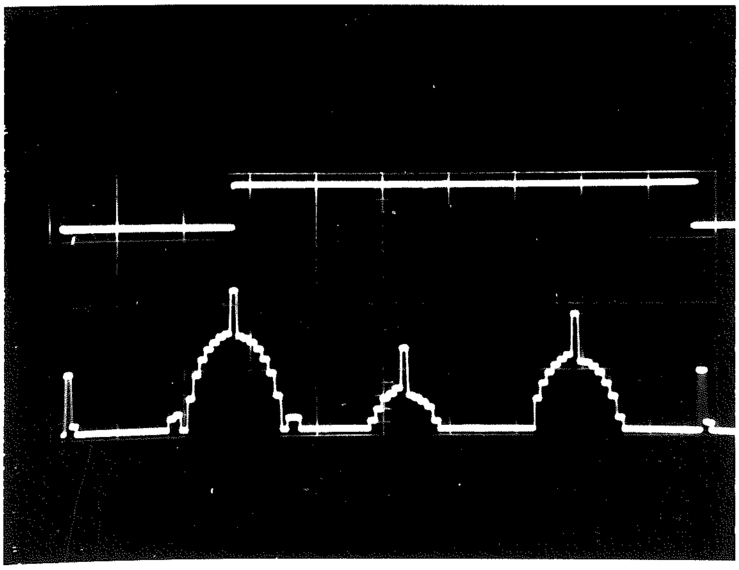


Figure 5.21:

Spectrum of sampled signal on a logarithmic scale

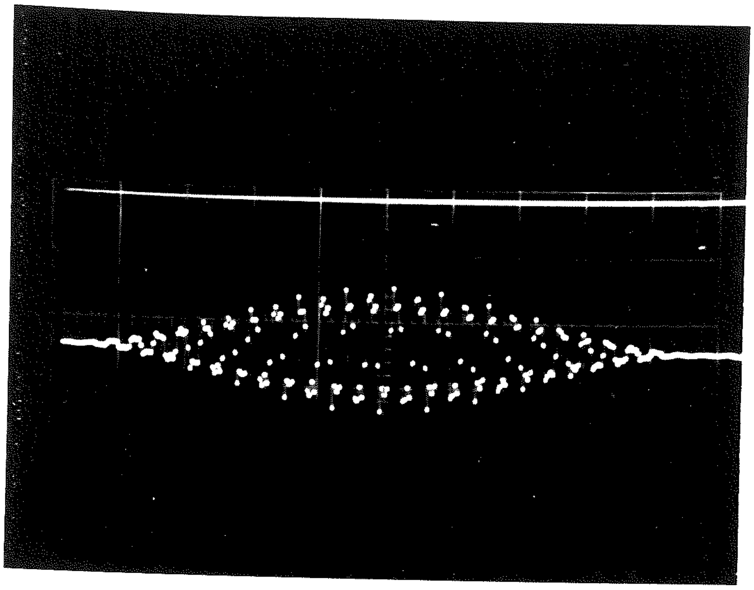


Figure 5.22:

27Hz square wave modified by a Hanning window

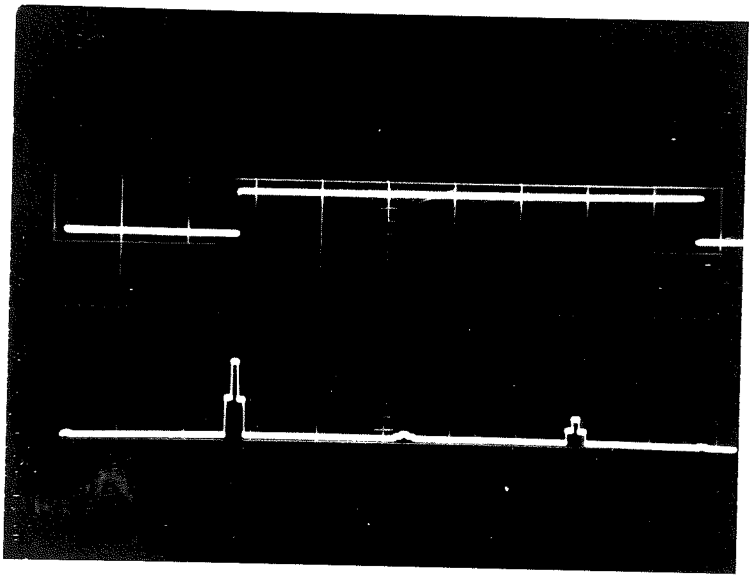


Figure 5.23:

Spectrum of sampled signal on a linear scale

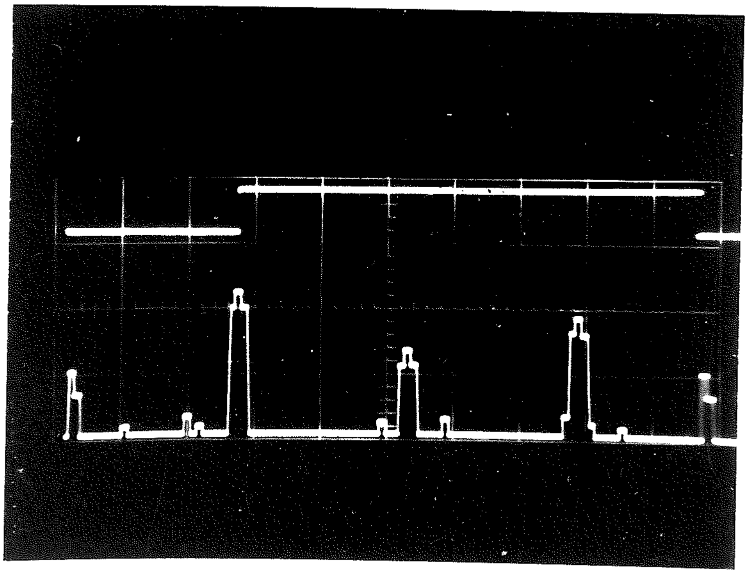


Figure 5.24:

Spectrum of sampled signal on a logarithmic scale

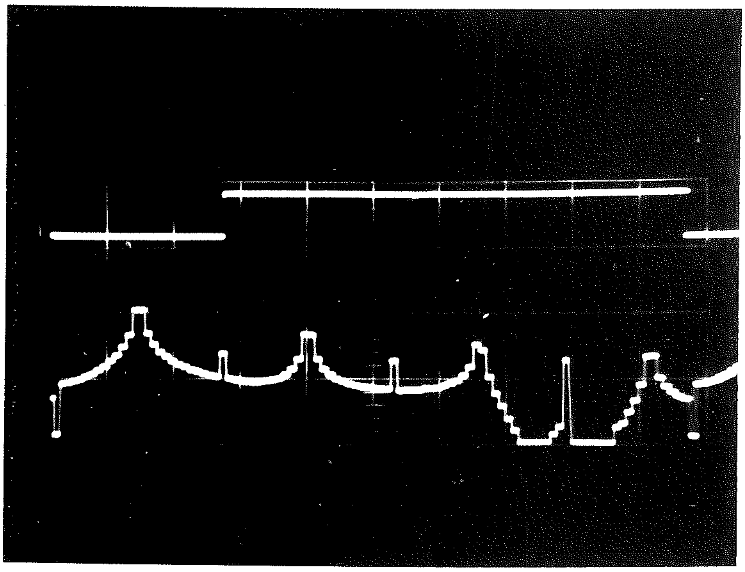


Figure 5.25: Spectrum of a 27Hz square wave sampled at 512 samples/sec. Logarithmic scale.

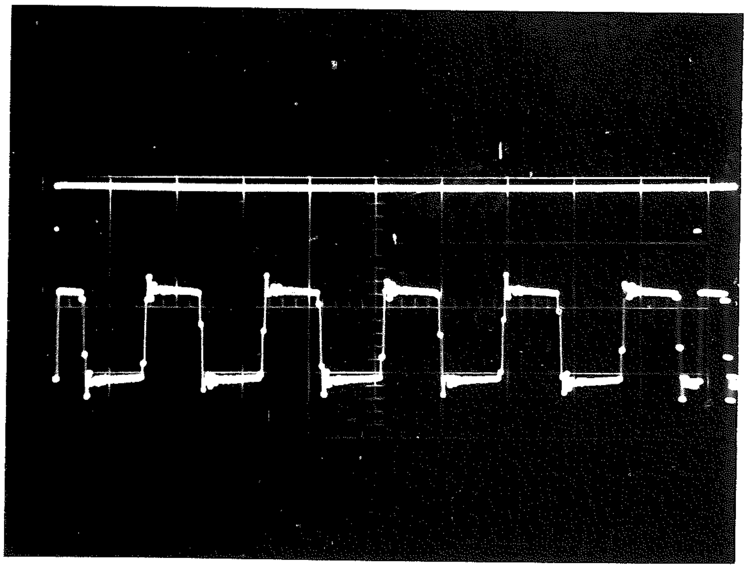


Figure 5.26: 27Hz square wave sampled at 1.28kHz

$$X_K = \begin{cases} 1 & \text{for } k = 0\ldots(N/2-1) \\ 0 & \text{for } k = N/2\ldots(N-1) \end{cases}$$

In Appendix 3 it is shown that :

$Xo = 0.5$

$Xn = 0$ for n even

$Xn = (1 - j\cos(\Pi n/N)/\sin(\Pi n/N))/N$ for n odd

Figure 5.27 shows the input array X_k and figures 5.28 and 5.29 show the imaginary part of X_n

$$\mathrm{Im}\ (Xn) = \begin{cases} 0 & \text{for } n = 0 \\ 0 & \text{for } n \text{ even} \\ -(1/N).\cos(\Pi n/N)/\sin(\Pi n/N) & \end{cases}$$

For $n << N/2$

$\mathrm{Im}\ (Xn) \propto 1/n$

From figure 5.28 it can be seen that only odd frequency components occur and that their amplitudes successively decrease at a $1/n$ rate.

$$\begin{aligned} \mathrm{Im}\ (X(N-n)) &= -(1/N)\cos(\Pi(N-n)/N)/\sin(\Pi(N-n)/N) \\ &= (1/N)\cos(\Pi n/N)/\sin(\Pi n/N) \\ &= -\mathrm{Im}\ (Xn) \end{aligned}$$

ie. the imaginary part of Xn is odd about the $n = N/2$ axis which can be seen from figure 5.29.

Figures 5.30 to 5.34 are included to illustrate the effect of spectral averaging. The input signal consists of some constant frequency components which are mixed with noise. In figure 5.30 the spectrum is fairly meaningless but as the number of accumulations increases the nature of the spectral content of the input signal can be ascertained more accurately. From figure 5.34, which is obtained by averaging 64 spectra, it can be seen that there are several fixed frequency components amidst a background of noise which is substantially 'white' over the measured frequency range.

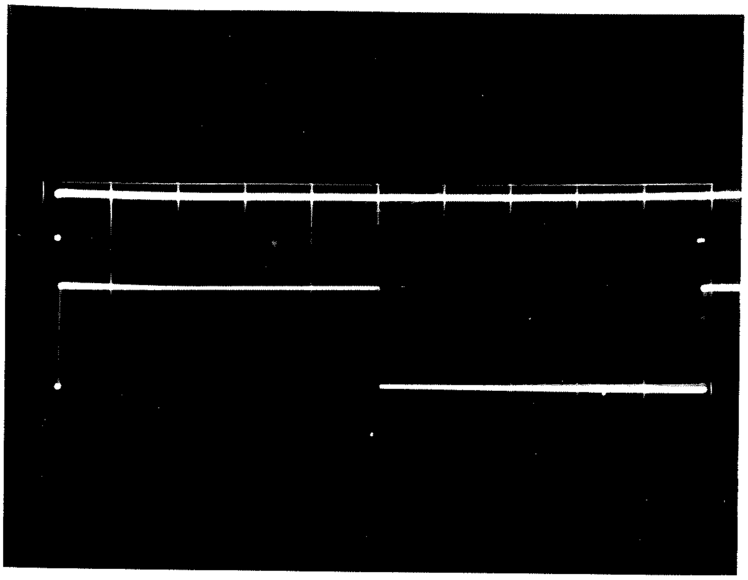


Figure 5.27:

Step function

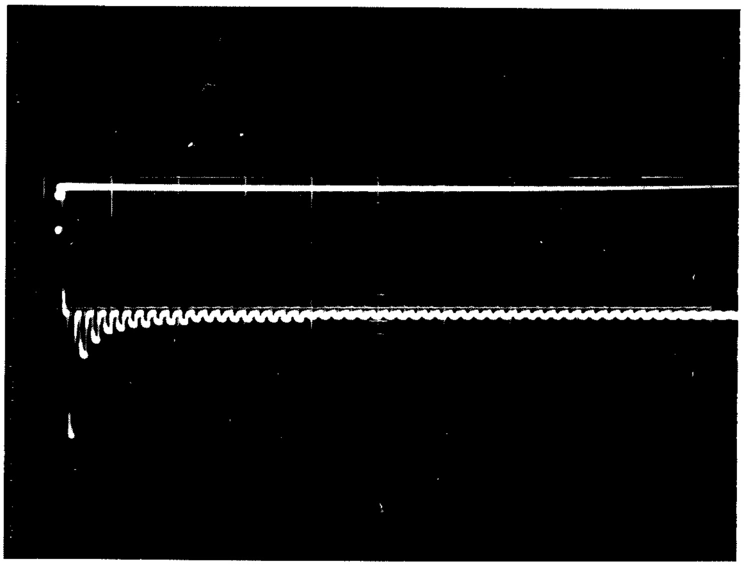


Figure 5.28:

Imaginary part of DFT of step function

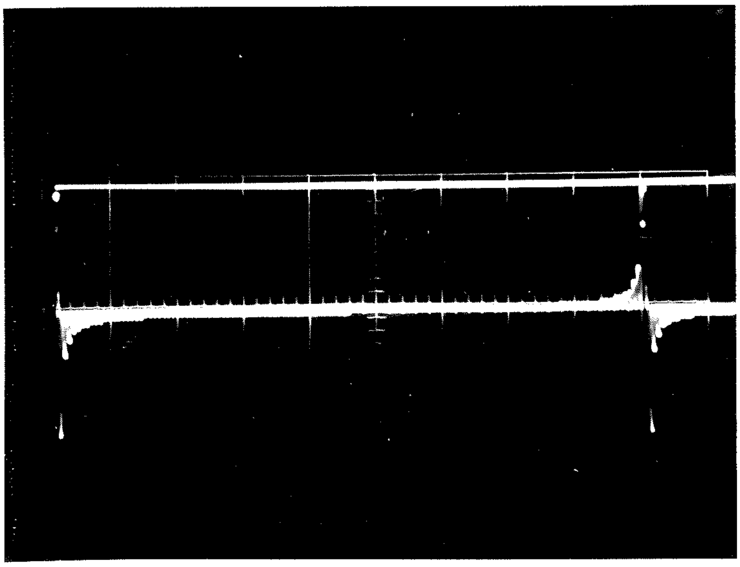


Figure 5.29:

Imaginary part of DFT on an expanded scale

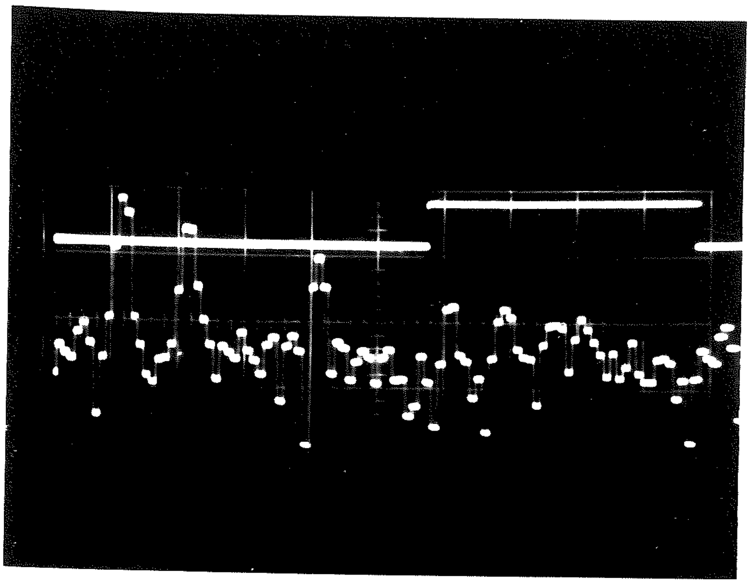


Figure 5.30:

Signal plus noise
one accumulation
logarithmic scale

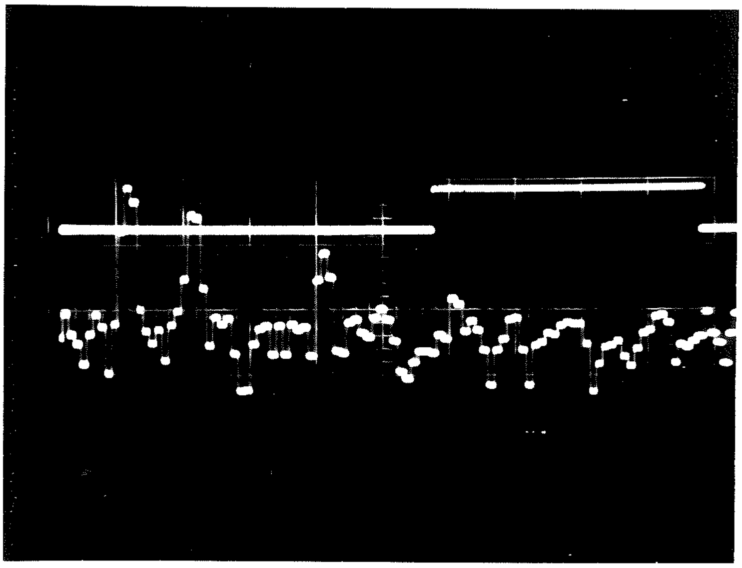


Figure 5.31:

Two accumulations

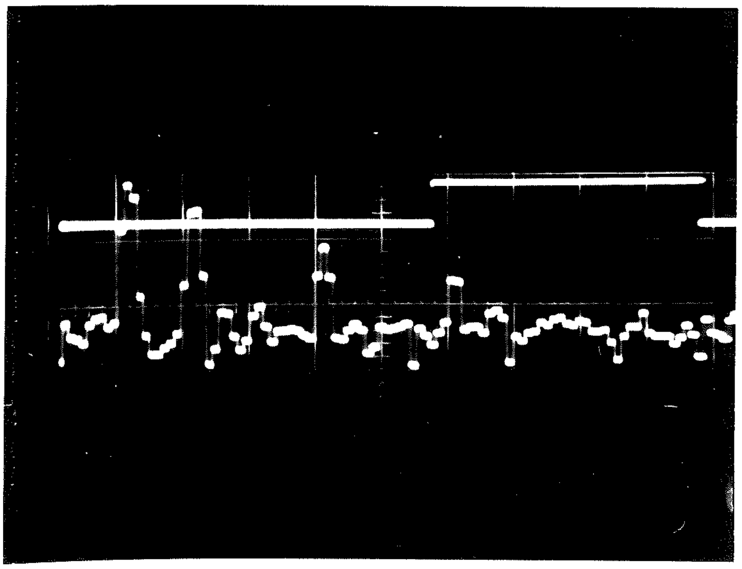


Figure 5.32:

Four
accumulations

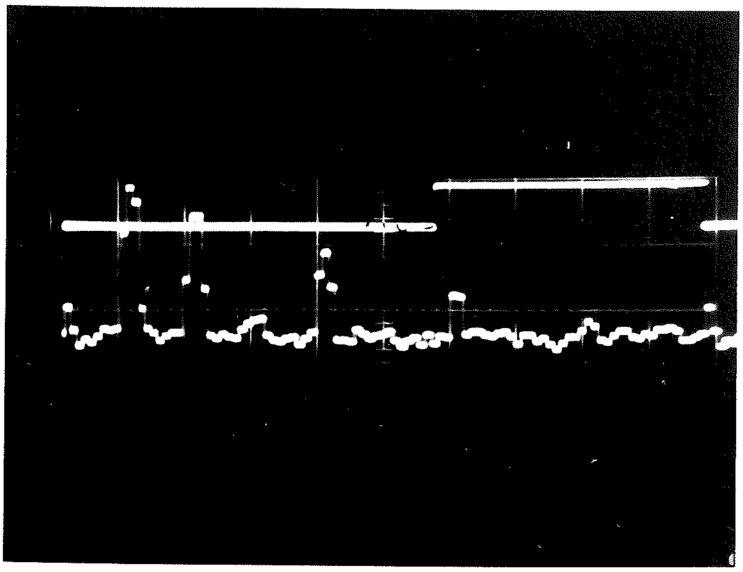


Figure 5.33:

Sixteen accumulations

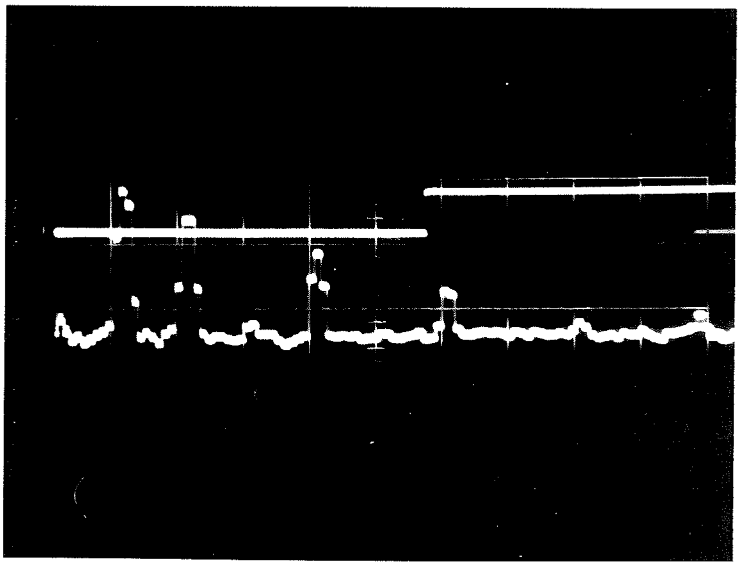


Figure 5.34:

Sixty four accumulations

6. CONCLUSION

From the previous chapters it can be seen that sophisticated fourier techniques, previously only used on large computers, are now able to be incorporated in relatively cheap and small micro-computer systems. The analyser presented is fairly crude when compared with the measurement capability or extra features of an instrument such as Hewlett Packard's Model 3582A Spectrum Analyser outlined in reference [1], however its performance could be improved further with only minor hardware additions as follows :

(a) Improvement in Frequency Resolution

The present analyser performs a 256 point DFT. A 1024 point DFT could be easily implemented by adding an extra 3072 (3K) words of RAM and making only minor alterations to the existing software. This would improve resolution by a factor of 4 which would greatly enhance the instrument's usefulness.

(b) Digital Display of Amplitude

At present a digital display of frequency is provided which is used in conjunction with the cursor control. The same display circuitry could be used to display amplitude in db or millivolts by the addition of 1 switch and an extra subroutine.

(c) Flat-top Window

From figures 2.8, 2.10 and 2.12 from chapter 2 it can be seen that there is substantial variation in amplitude of the spectrum of the existing window functions over the range $(-\frac{1}{2T}, \frac{1}{2T})$ where T is the sampling time. The implication of this is that a sinusoid with frequency in between 2 output frequency points will be reduced in amplitude on the output of the spectrum.

This is a serious limitation to the measurement of the amplitudes of the spectral components.

The problem can be overcome, however, by the use of a 'flat-top' window as described in [2]. This function has a substantially flat spectrum over the range $(-\frac{1}{2T}, \frac{1}{2T})$ which would allow accurate amplitude measurements to be made. A suggested 'flat-top' window function is :

$$w(t) = 1.0 + 1.86 \cos 2\pi t + 0.86 \cos 4\pi t \qquad -\tfrac{1}{2} \leq t \leq \tfrac{1}{2}.$$

(d) An Additional Input

If additional circuitry were added so that two input signals could be examined at the same time then the analyser could perform other useful tasks such as cross-correlation or the determination of the transfer function of an input-output port (eg. a filter).

In conclusion, there is wide scope to the applications for which an instrument such as this can be used. The limits would often be determined by the requirements of the user and the time invested in generating software.

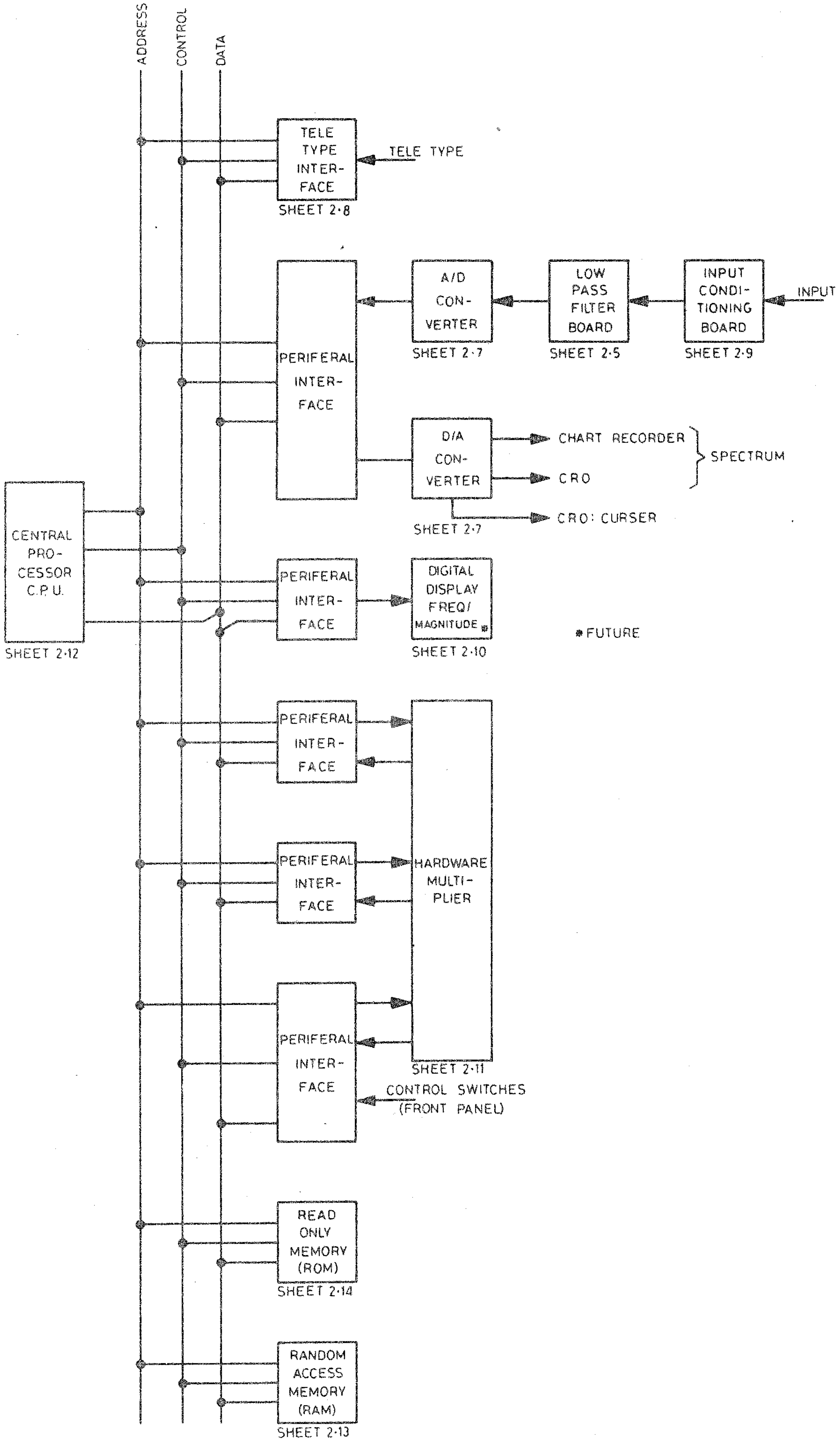
Reference

[1] "A High-Resolution, Low-Frequency Spectrum Analyser" by Nixon A. Pendergrass and John S. Farnbach, Hewlett-Packard Journal, July 1978.

[2] "Window Functions for Spectrum Analysis" by Roger G. Cox, Hewlett-Packard Journal, July 1978.

APPENDIX 1

DETAILED CIRCUIT DIAGRAMS



BLOCK DIAGRAM

SPECTRUM ANALYSER

THE ELECTRICITY TRUST OF SOUTH AUSTRALIA

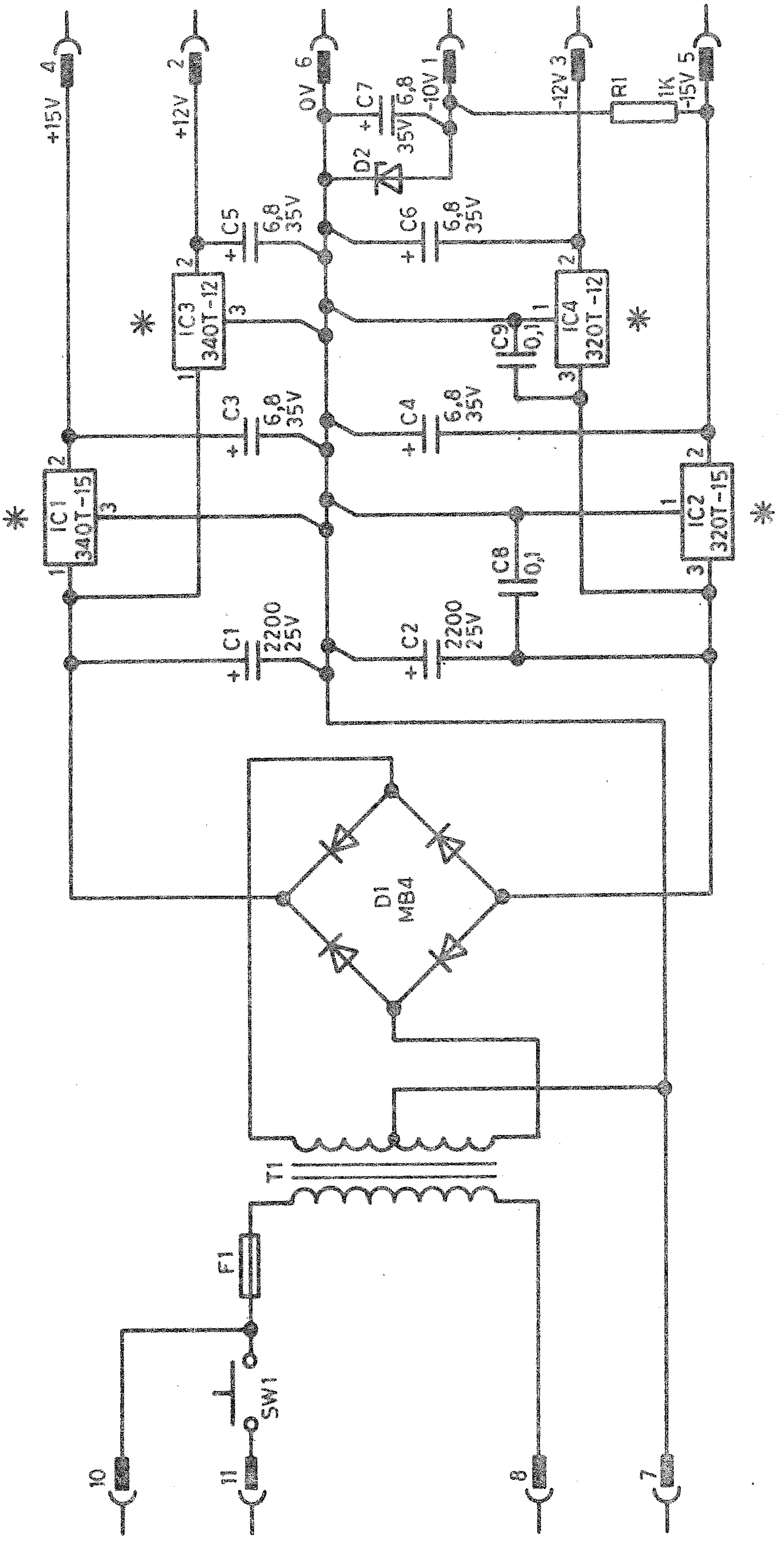
D.M. TURNER

24.5.79

A.O. T0344

T0344 SHEET 2·2

A4-T0344 SHEET 2·3·1

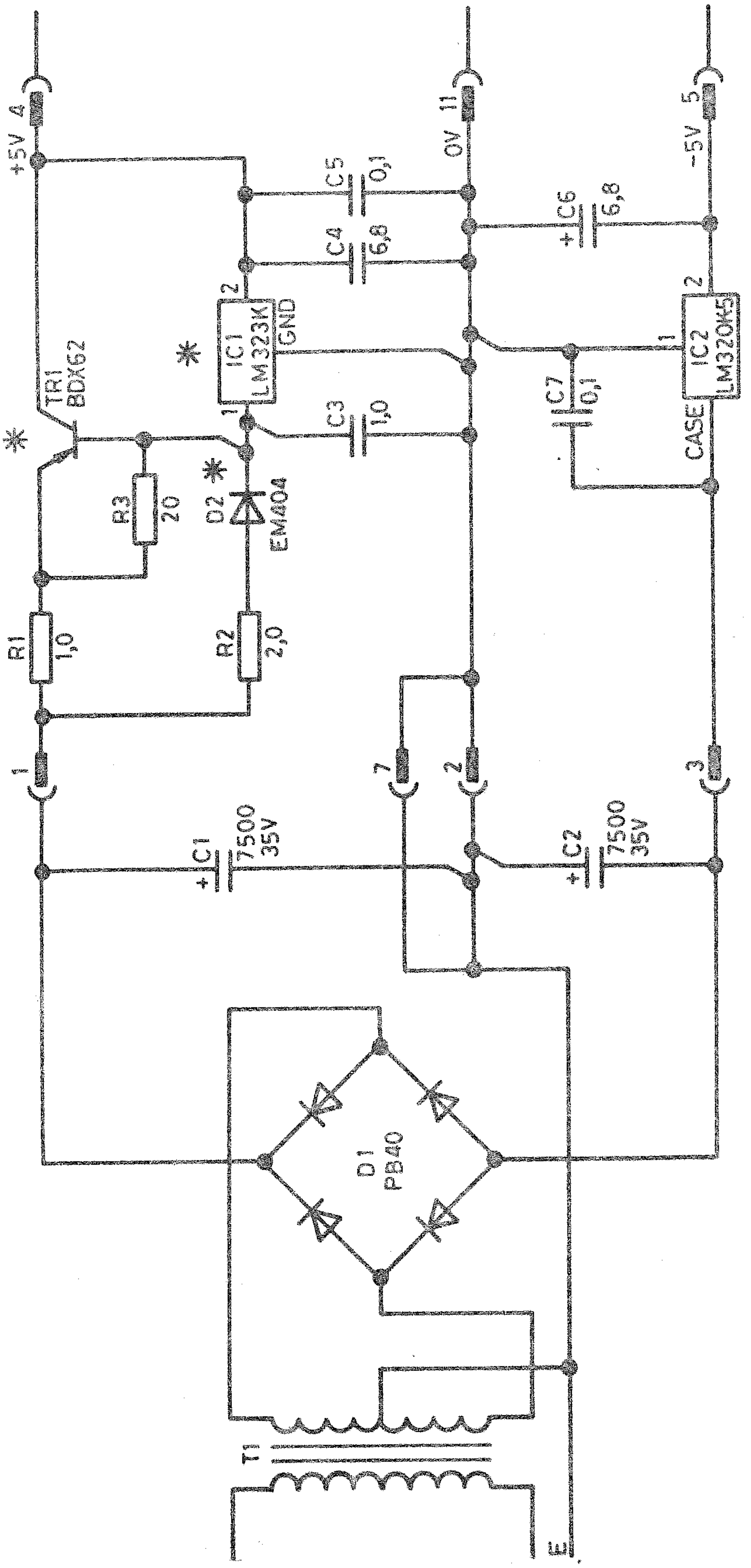


* MOUNTED ON HEATSINKS

SPECTRUM ANALYSER POWER SUPPLY BOARD 1

DRN		7/5/79	THE ELECTRICITY TRUST OF SOUTH AUSTRALIA	SCALE	OP3
CKD	D.M.TURNER	25-5-79	INSTRUMENTATION T.E.P	A4-T0344 SHEET 2·3·1	
INSP		25-5-79			
AUTH	J. Lindsay	29-5-79			

A4-T0344 SHEET 2·4·1



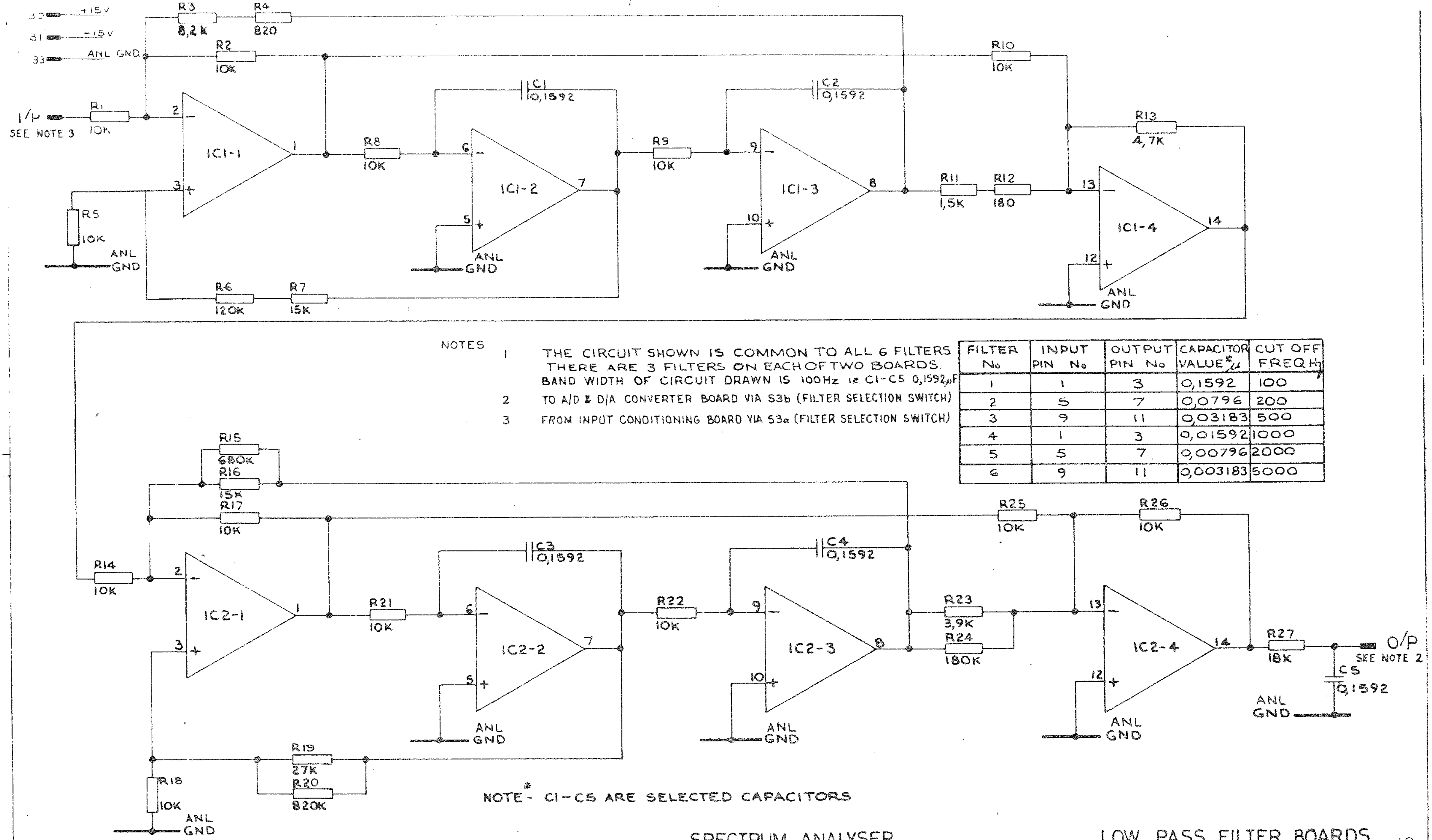
CAPACITORS C3,4,5 & THE GROUND CONNECTIONS OF IC1 & IC2 TO HAVE A SINGLE POINT GROUND CONNECTION.

* MOUNTED ON COMMON HEAT SINK

D1 & T1 ARE MOUNTED BEHIND THE SWITCH PANEL

SPECTRUM ANALYSER POWER SUPPLY BOARD 2

DRN		24/4/79	THE ELECTRICITY TRUST OF SOUTH AUSTRALIA	SCALE	OP3
CKD	D.M.TURNER	25.5.79	INSTRUMENTATION T.E.P.	A4-T0344 SHEET 2·4·1	
INSP		25.5.79			
AUTH		25.5.79			



NOTES

1 THE CIRCUIT SHOWN IS COMMON TO ALL 6 FILTERS THERE ARE 3 FILTERS ON EACH OF TWO BOARDS. BAND WIDTH OF CIRCUIT DRAWN IS 100Hz ie. C1-C5 0,1592μF

2 TO A/D & D/A CONVERTER BOARD VIA S3b (FILTER SELECTION SWITCH)

3 FROM INPUT CONDITIONING BOARD VIA S3a (FILTER SELECTION SWITCH)

FILTER No	INPUT PIN No	OUTPUT PIN No	CAPACITOR VALUE* μ	CUT OFF FREQ Hz
1	1	3	0,1592	100
2	5	7	0,0796	200
3	9	11	0,03183	500
4	1	3	0,01592	1000
5	5	7	0,00796	2000
6	9	11	0,003183	5000

NOTE* - C1-C5 ARE SELECTED CAPACITORS

SPECTRUM ANALYSER

LOW PASS FILTER BOARDS

26

REF.	DETAIL OF REVISION	RVD	KD	APD	DATE

D.M.TURNER 26-4-79
KD 3/5/79
NSP 25-5-79
AUTH 28-5-79

THE ELECTRICITY TRUST OF SOUTH AUSTRALIA

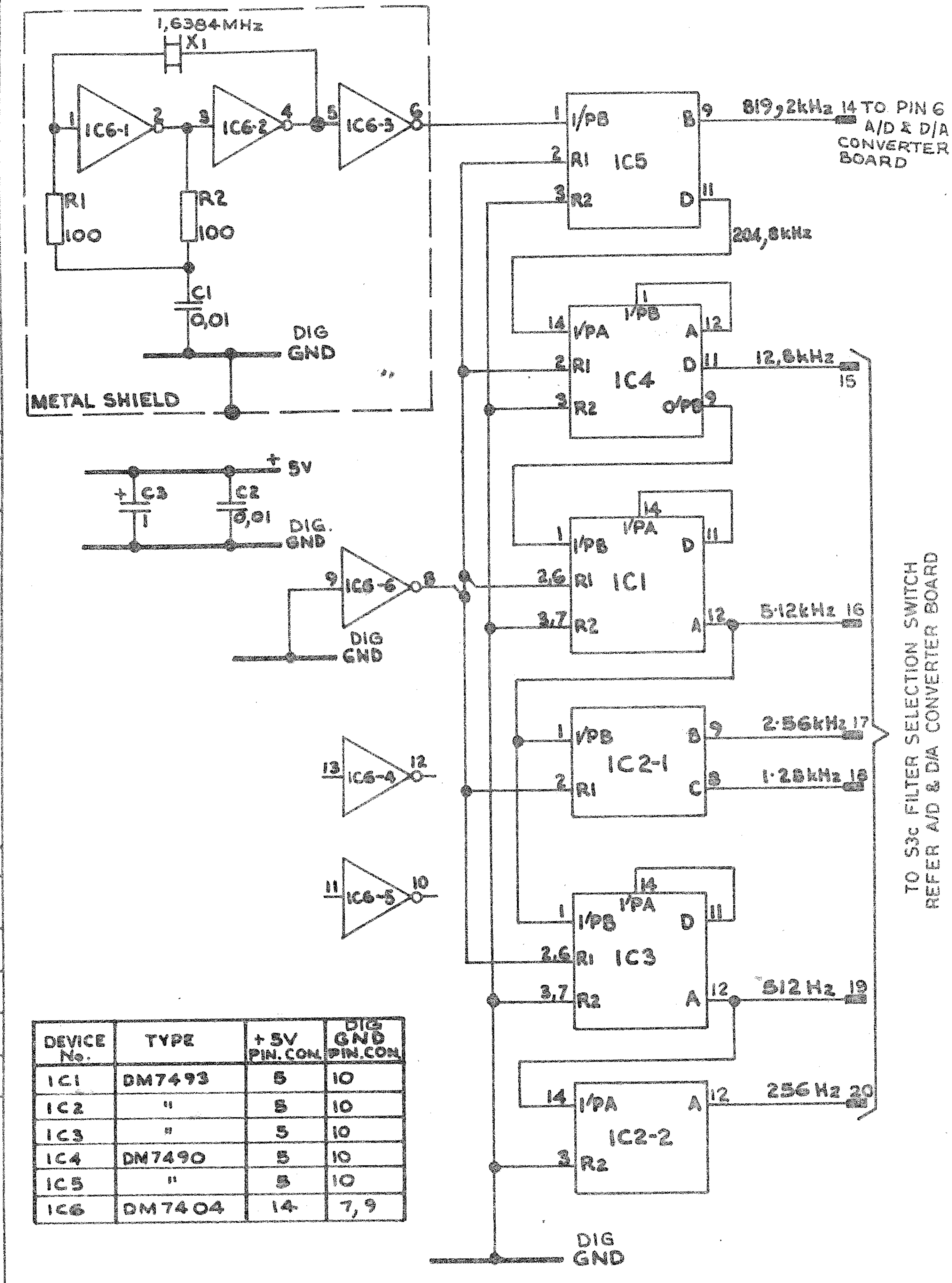
INSTRUMENTATION T.E.P.

SCALE

A3 T0344

SHEET 2.5.1

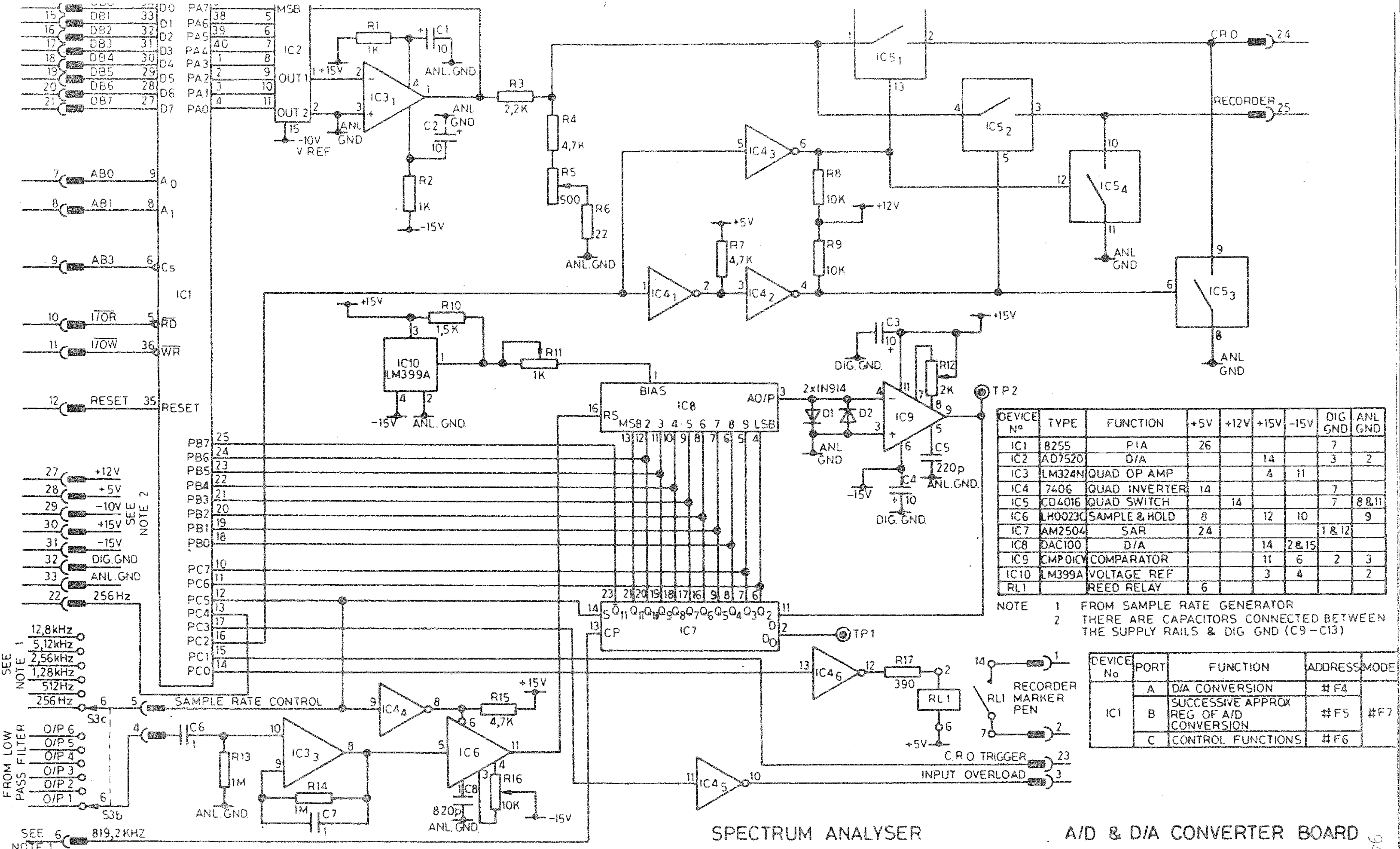
A4-T0344 SHT 2.6.1



DEVICE No.	TYPE	+5V PIN.CON.	DIG GND PIN.CON.
IC1	DM7493	5	10
IC2	"	5	10
IC3	"	5	10
IC4	DM7490	5	10
IC5	"	5	10
IC6	DM7404	14	7, 9

SPECTRUM ANALYSER SAMPLE RATE GENERATOR

DRN	D.M.TURNER	26-4-79	THE ELECTRICITY TRUST OF SOUTH AUSTRALIA	SCALE	OP3
CKD		3/5/79	INSTRUMENTATION T.E.P.	A4-T0344 SHEET 2.6.1	
INSP		25·5·79			
AUTH		28·5·79			



DEVICE N°	TYPE	FUNCTION	+5V	+12V	+15V	-15V	DIG GND	ANL GND
IC1	8255	PIA	26				7	
IC2	AD7520	D/A			14		3	2
IC3	LM324N	QUAD OP AMP			4	11		
IC4	7406	QUAD INVERTER	14				7	
IC5	CD4016	QUAD SWITCH		14			7	8 & 11
IC6	LH0023C	SAMPLE & HOLD	8		12	10		9
IC7	AM2504	SAR	24				1 & 12	
IC8	DAC100	D/A			14	2 & 15		
IC9	CMP01CY	COMPARATOR			11	6	2	3
IC10	LM399A	VOLTAGE REF			3	4		2
RL1		REED RELAY	6					

NOTE 1 FROM SAMPLE RATE GENERATOR
2 THERE ARE CAPACITORS CONNECTED BETWEEN THE SUPPLY RAILS & DIG GND (C9 – C13)

DEVICE No	PORT	FUNCTION	ADDRESS	MODE
IC1	A	D/A CONVERSION	#F4	#F7
	B	SUCCESSIVE APPROX REG OF A/D CONVERSION	#F5	
	C	CONTROL FUNCTIONS	#F6	

SPECTRUM ANALYSER A/D & D/A CONVERTER BOARD

94

THE ELECTRICITY TRUST OF SOUTH AUSTRALIA

D.M.TURNER 25-5-79
25-5-79
25-5-79

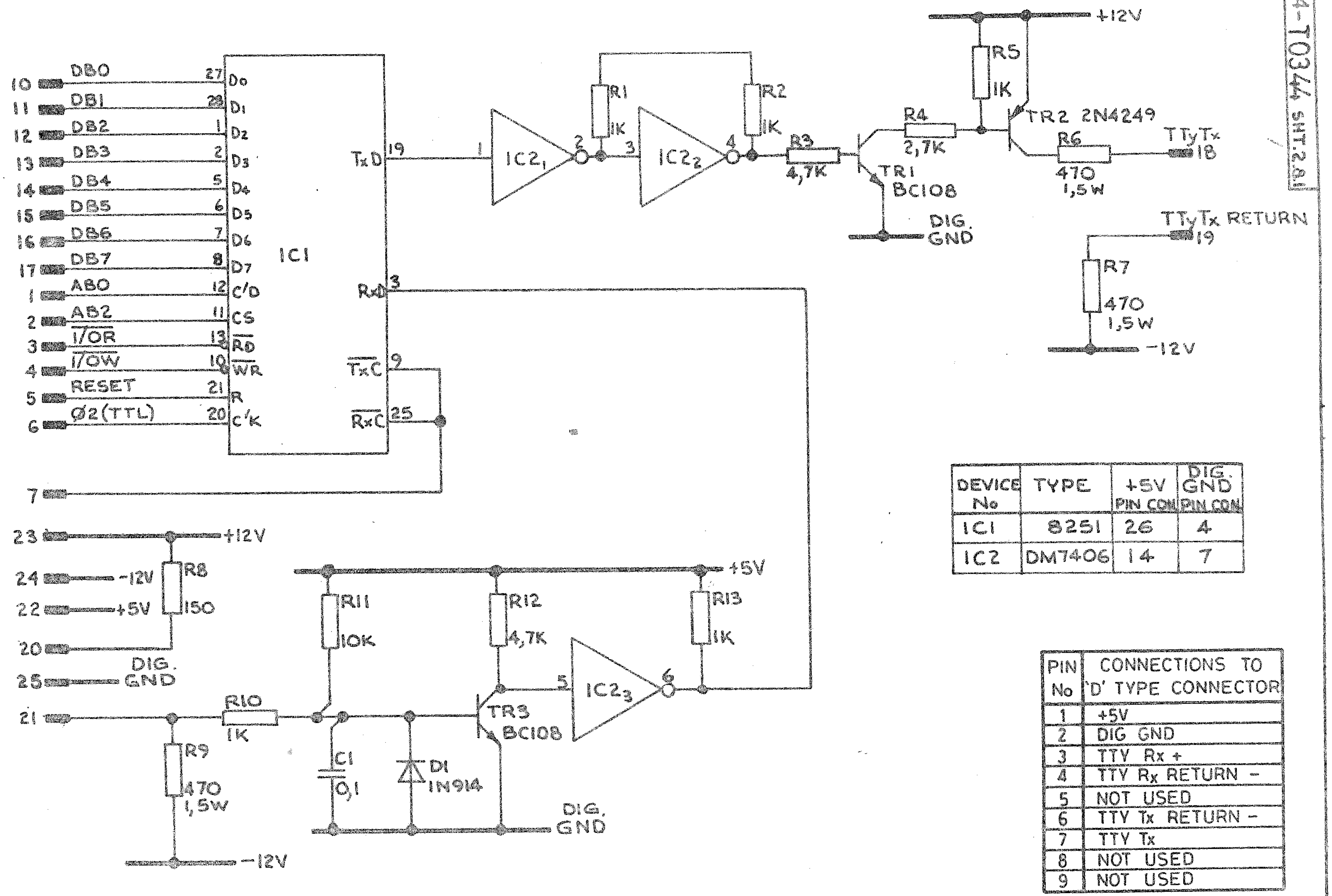
INSTRUMENTATION T.E.P.

A3 T0344
SHEET 2·7·1

REF.

DATE

A4-T0344 SHT 2.8.1



DEVICE No	TYPE	+5V PIN CON	DIG. GND PIN CON
IC1	8251	26	4
IC2	DM7406	14	7

PIN No	CONNECTIONS TO 'D' TYPE CONNECTOR
1	+5V
2	DIG GND
3	TTY Rx +
4	TTY Rx RETURN -
5	NOT USED
6	TTY Tx RETURN -
7	TTY Tx
8	NOT USED
9	NOT USED

SPECTRUM ANALYSER

TELE TYPE INTERFACE

DRN D.M.TURNER
CKD
INSP
AUTH

THE ELECTRICITY TRUST OF SOUTH AUSTRALIA

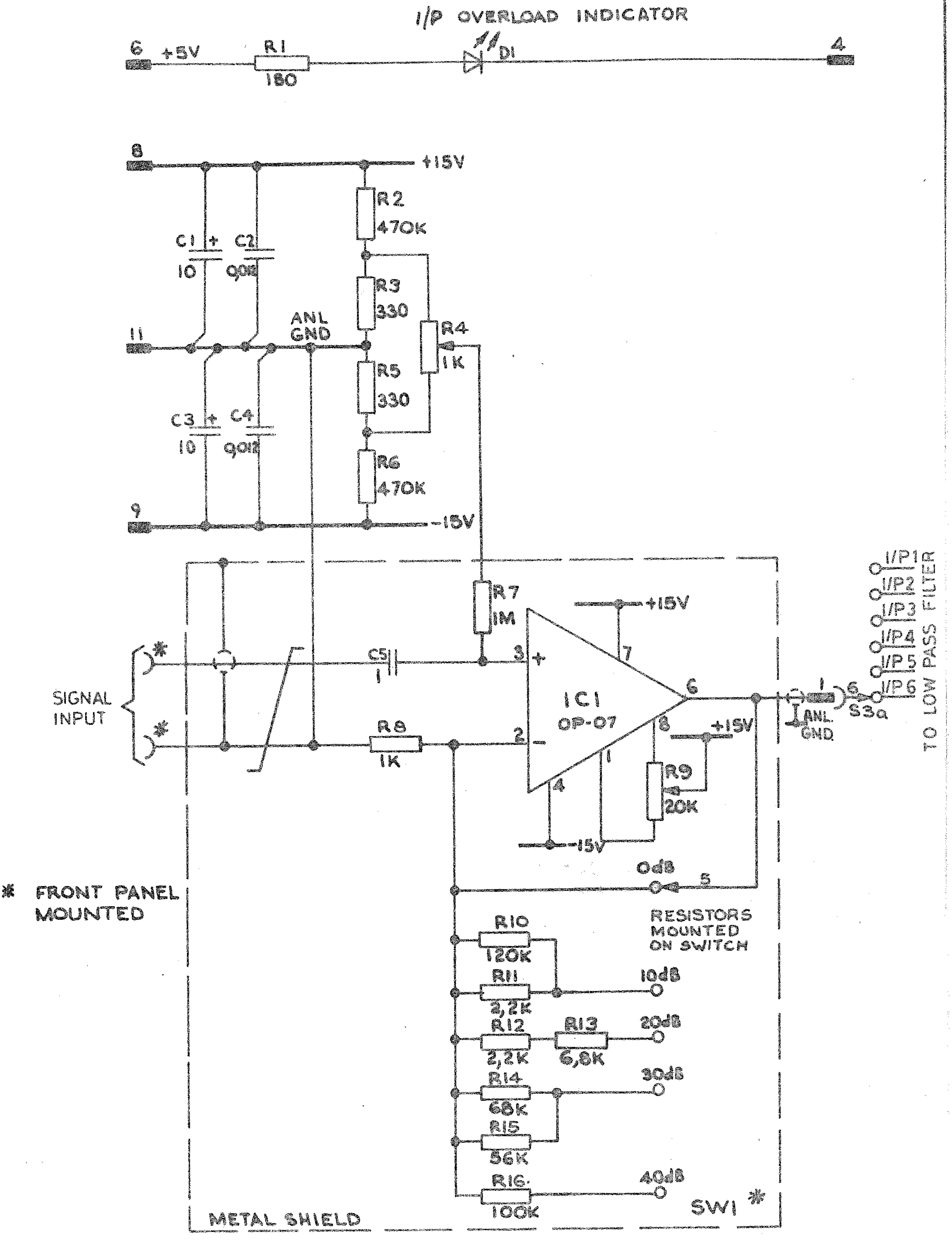
INSTRUMENTATION T.E.P.

SCALE

OP3

A4-T0344
SHEET 2.8.1

A4- T0344 SHT.2.9.1



SPECTRUM ANALYSER INPUT CONDITIONING BOARD

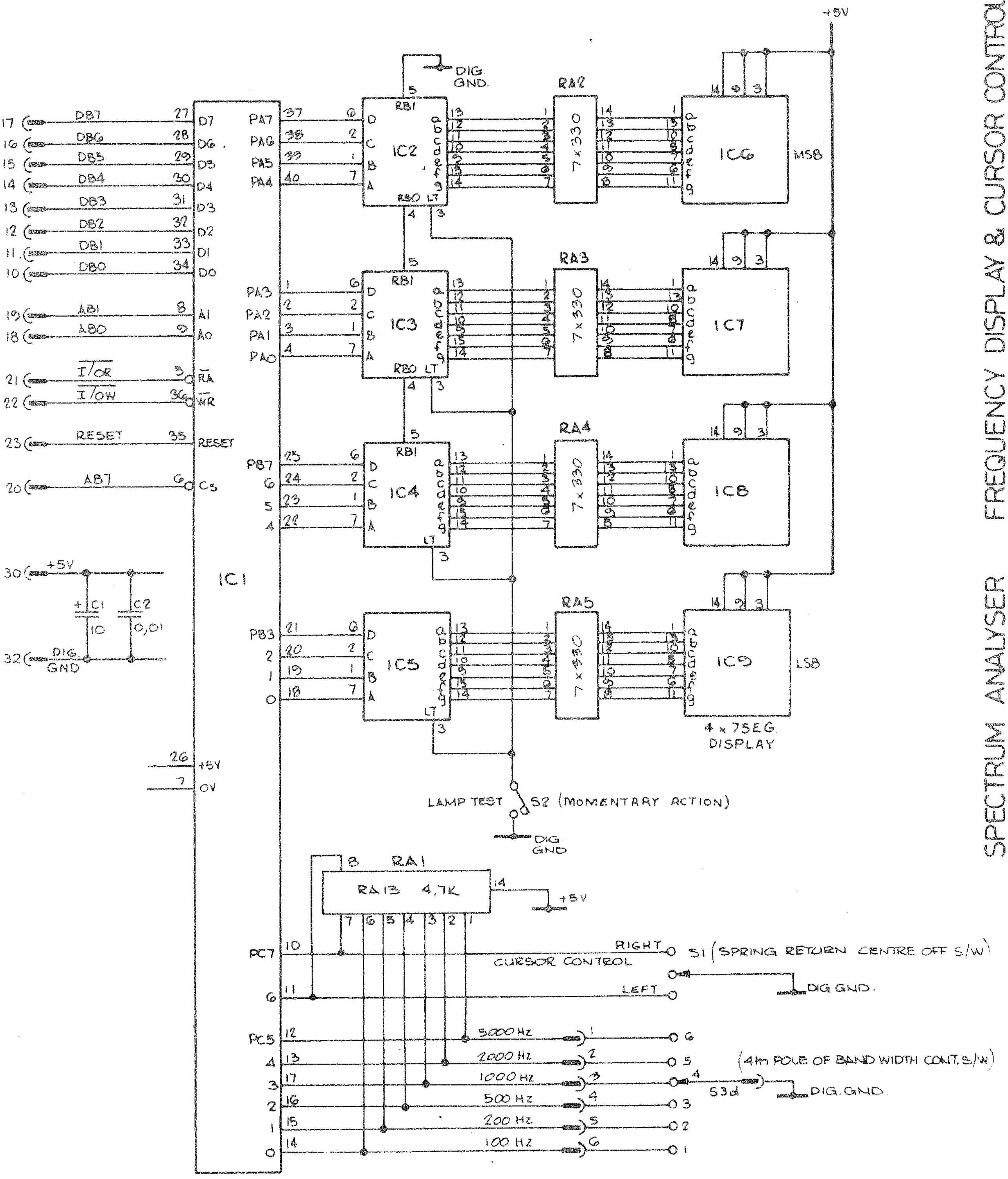
DRN	D.M.TURNER	24-4-79	THE ELECTRICITY TRUST OF SOUTH AUSTRALIA	SCALE	OP3
CKD		3/5/79	INSTRUMENTATION T.E.P.	A4-T0344 SHEET 2.9.1	
INSP		25.5.79			
AUTH		28.5.79			

SPECTRUM ANALYSER FREQUENCY DISPLAY & CURSOR CONTROL BOARD

THE ELECTRICITY TRUST OF SOUTH AUSTRALIA

INSTRUMENTATION T.F.D

A3 T0344

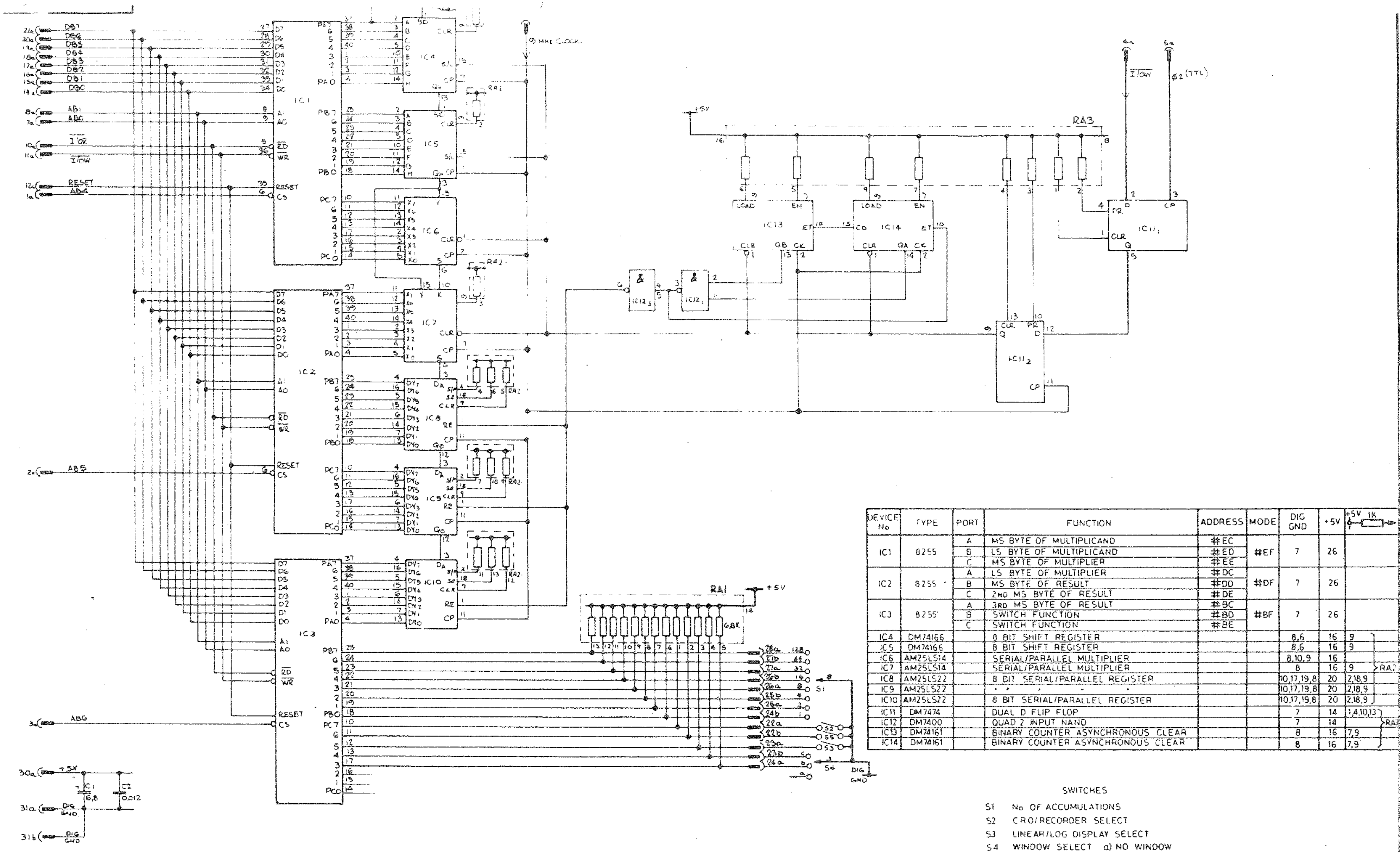


DEVICE No	TYPE	PORT	ADDRESS	MODE	+5V	DIG GND
IC1	8255	A	#07CH		26	7
		B	#07DH			
		C	#07EH			
				#07FH		
IC2-5	7446				16	8
IC6-9	DL707				3,9,14	–

K. Warland 1.5.79

7/5/79

25.5.79



DEVICE No	TYPE	PORT	FUNCTION	ADDRESS	MODE	DIG GND	+5V	+5V 1K
IC1	8255	A	MS BYTE OF MULTIPLICAND	#EC	#EF	7	26	
		B	LS BYTE OF MULTIPLICAND	#ED				
		C	MS BYTE OF MULTIPLIER	#EE				
IC2	8255	A	LS BYTE OF MULTIPLIER	#DC	#DF	7	26	
		B	MS BYTE OF RESULT	#DD				
		C	2ND MS BYTE OF RESULT	#DE				
IC3	8255	A	3RD MS BYTE OF RESULT	#BC	#BF	7	26	
		B	SWITCH FUNCTION	#BD				
		C	SWITCH FUNCTION	#BE				
IC4	DM74166		8 BIT SHIFT REGISTER			8,6	16	9 RA2
IC5	DM74166		8 BIT SHIFT REGISTER			8,6	16	9
IC6	AM25LS14		SERIAL/PARALLEL MULTIPLIER			8,10,9	16	
IC7	AM25LS14		SERIAL/PARALLEL MULTIPLIER			8	16	9
IC8	AM25LS22		8 BIT SERIAL/PARALLEL REGISTER			10,17,19,8	20	2,18,9
IC9	AM25LS22		" " " "			10,17,19,8	20	2,18,9
IC10	AM25LS22		8 BIT SERIAL/PARALLEL REGISTER			10,17,19,8	20	2,18,9
IC11	DM7474		DUAL D FLIP FLOP			7	14	1,4,10,13 RA3
IC12	DM7400		QUAD 2 INPUT NAND			7	14	
IC13	DM74161		BINARY COUNTER ASYNCHRONOUS CLEAR			8	16	7,9
IC14	DM74161		BINARY COUNTER ASYNCHRONOUS CLEAR			8	16	7,9

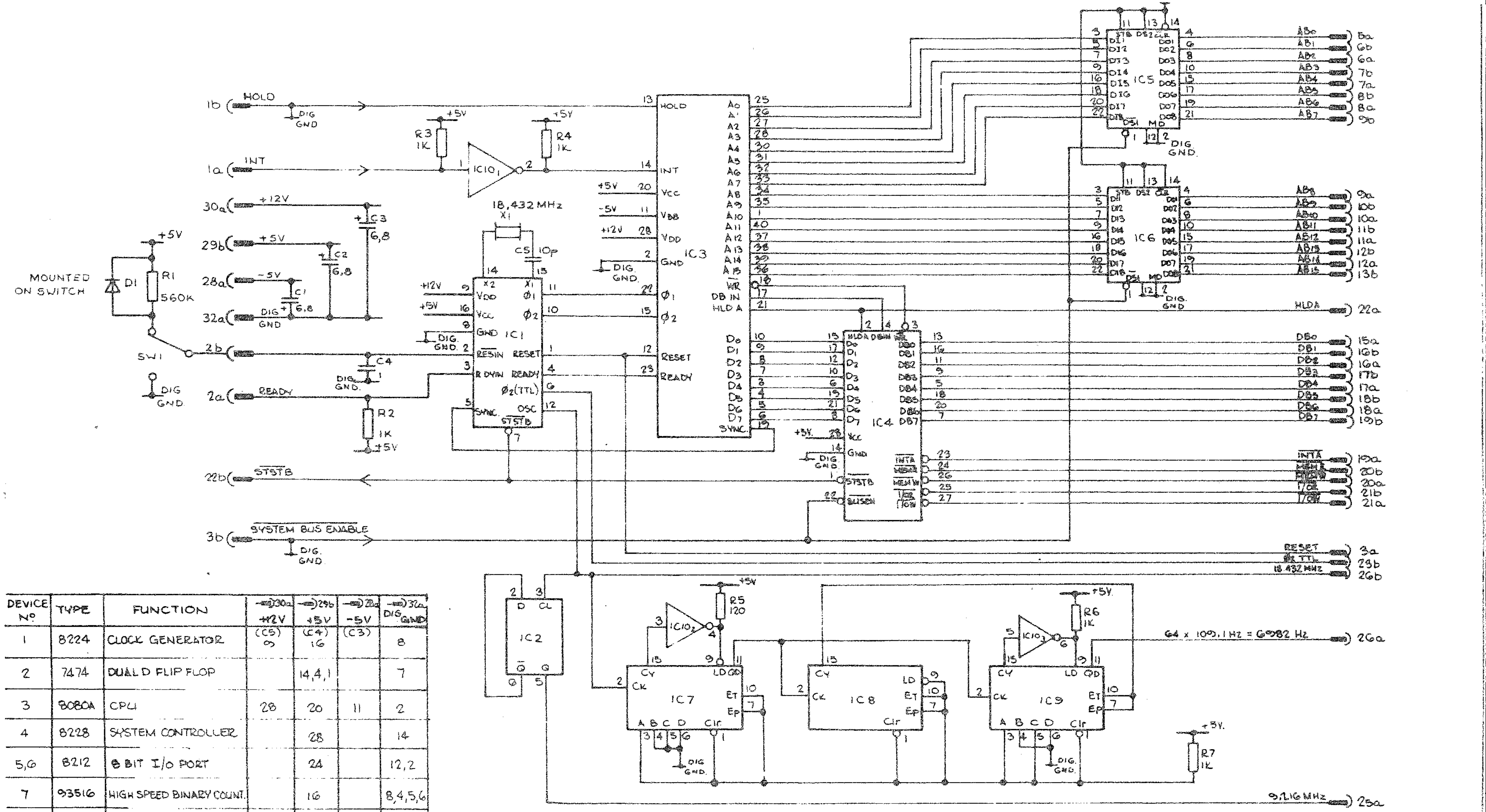
SWITCHES

S1 No OF ACCUMULATIONS
S2 CRO/RECORDER SELECT
S3 LINEAR/LOG DISPLAY SELECT
S4 WINDOW SELECT a) NO WINDOW
b) BINGHAM WINDOW
c) HANNING WINDOW
S5 SPARE (TO BE MAGNETUDE/FREQ. SELECT)

SPECTRUM ANALYSER HARDWARE MULTIPLIER

DRN	S.K Warburton	8.5.79	THE ELECTRICITY TRUST OF [illegible] TH AUSTRALIA	SCALE OP3
CKD	G.J Rolat	7/5/79	INSTRUMENTATION T.E.P.	A2 - T0344
NSP		25.5.79		SHEET 2·11·1
AUTH		25.5.79		

REV	DETAILS OF REVISION	RVD	CKD	APD	DATE



DEVICE Nº	TYPE	FUNCTION	30a +12V	29b +5V	28a -5V	32a DIG GND
1	8224	CLOCK GENERATOR	(C5) 9	(C4) 16	(C3)	8
2	7474	DUAL D FLIP FLOP		14,4,1		7
3	8080A	CPU	28	20	11	2
4	8228	SYSTEM CONTROLLER		28		14
5,6	8212	8 BIT I/O PORT		24		12,2
7	93S16	HIGH SPEED BINARY COUNT.		16		8,4,5,6
8	74161-9316	BINARY COUNTER		16		8
9	74161-9316	BINARY COUNTER		16		8,4,6
10	7406	HEX. INVERTER		14		7

SPECTRUM ANALYSER C.P.U. BOARD

S.K. Warburton 2.5.79
7/5/79
25.5.79
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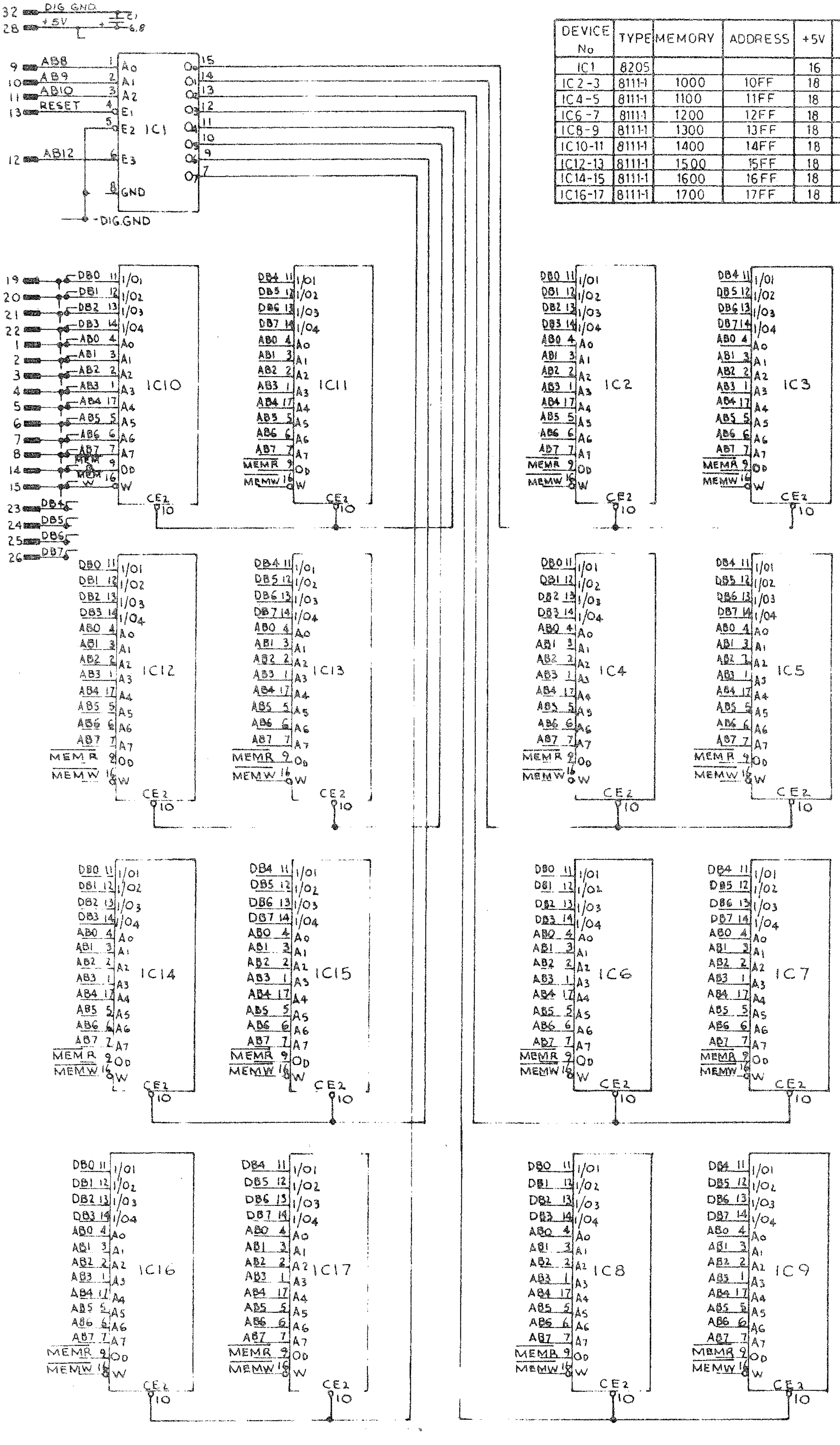
A3 T0344
SHEET 2.12.1

DEVICE No	TYPE	MEMORY	ADDRESS	+5V	DIG GND
IC1	8205			16	8,5
IC 2-3	8111-1	1000	10FF	18	8,15
IC 4-5	8111-1	1100	11FF	18	8,15
IC 6-7	8111-1	1200	12FF	18	8,15
IC 8-9	8111-1	1300	13FF	18	8,15
IC 10-11	8111-1	1400	14FF	18	8,15
IC 12-13	8111-1	1500	15FF	18	8,15
IC 14-15	8111-1	1600	16FF	18	8,15
IC 16-17	8111-1	1700	17FF	18	8,15



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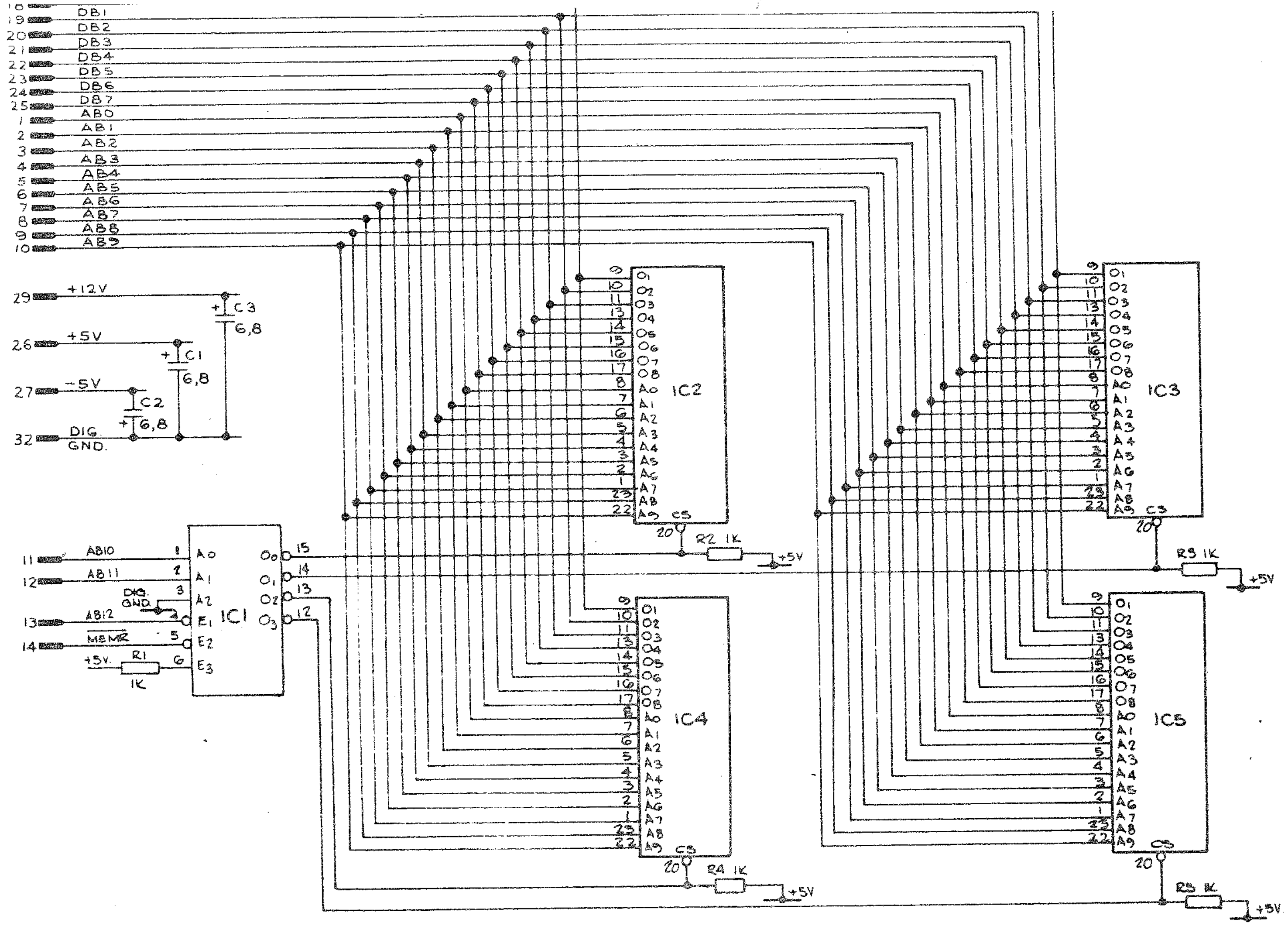
INSTRUMENTATION T.E.P.

A3 T0344
SHEET 2.13.1

D.M.TURNER 1·5·79
25·5·79

DATE
APD



DEVICE No	TYPE	FUNCTION	MEMORY	ADDRESS	+12V	+5V	-5V	DIG GND
IC1	8205	BINARY 1 OF 8 DECODER			(C3)	(C1) 16	(C2)	8,3
IC2	8708	1K x 8 BIT EPROM	0000	03FF	19	24	21	12,18
IC3	8708	1K x 8 BIT EPROM	0400	07FF	19	24	21	12,18
IC4	8708	1K x 8 BIT EPROM	0800	0BFF	19	24	21	12,18
IC5	8708	1K x 8 BIT EPROM	0C00	0FFF	19	24	21	12,18

SPECTRUM ANALYSER R.O.M. BOARD

S.K.Warburton 1.5.79
3/5/79
25.5.79
28 . 79

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A3 T0344
SHEET. 2.14.1

APPENDIX 2

LISTING OF ASSEMBLY AND MACHINE CODE

```
0200             B0       SET     0200H
02F5             LIN      SET     02F5H
0400             *C       SET     0400H
0484             LOG      SET     0484H
051A             OUTU     SET     051AH
0598             REC      SET     0598H
0000                      ORG     0000H
0000    3E8A     BEGIN:   MVI     A,8AH
0002    D3F7              OUT     0F7H
0004    3E80              MVI     A,80H
0006    D3EF              OUT     0EFH
0008    3E88              MVI     A,88H
000A    D3DF              OUT     0DFH
000C    3E89              MVI     A,89H
000E    D37F              OUT     7FH
0010    3E9B              MVI     A,9BH
0012    D3BF              OUT     0BFH     ;SET MODE OF PIA CHIPS
0014    31BF13            LXI     SP,13BFH;SET STACK POINTER
0017    210010            LXI     H,1000H
001A    0600              MVI     B,0
001C    3E13              MVI     A,13H
001E    70       ZERO:    MOV     M,B
001F    23                INX     H
0020    BC                CMP     H
0021    C21E00            JNZ     ZERO     ;(1000-12FF)=0
0024    DBBD              IN      0BDH     ; READ ACCUMULATION SELECTOR SWITCH
0026    2F                CMA
0027    32FE13            STA     13FEH    ;VARIABLE
002A    0602              MVI     B,2
002C    04       SOT:     INR     B
002D    17                RAL
002E    D22C00            JNC     SOT
0031    78                MOV     A,B
0032    32FF13            STA     13FFH    ;(13FF)=2+LOG2(256/NO.ACC)
0035    DBBE              IN      0BEH
0037    E618              ANI     18H
0039    32FD13            STA     13FDH    ;WINDOW SELECTION
```

```
003C   DB7E            IN     7EH      ; READ FREQUENCY SELECTOR SWITCH
003F   2F              CMA             ; AND CALCULATE MULTIPLICATION FACTOR
003F   E63F            ANI    3FH      ; SELECT 6 LS BITS
0041   0601            MVI    B,1
0043   1F              RAR
0044   DA6100          JC     MF
0047   0602            MVI    B,2
0049   1F              RAR
004A   DA6100          JC     MF
004D   0605            MVI    B,5
004F   1F              RAR
0050   DA6100          JC     MF
0053   060A            MVI    B,10
0055   1F              RAR
0056   DA6100          JC     MF
0059   0614            MVI    B,20
005B   1F              RAR
005C   DA6100          JC     MF
005F   0632            MVI    B,50
0061   78      MF:     MOV    A,B
0062   32F813          STA    13F8H
0065   CDDF00  ACCUM:  CALL   START
0068   00              NOP
0069   3AFD13          LDA    13FDH
006C   FE08            CPI    8H
006E   CC3001          CZ     HANN0    ;IS HANNING WINDOW SELECTED?
0071   3AFD13          LDA    13FDH
0074   FE10            CPI    10H
0076   CC6201          CZ     HAMM0    ;IS PARTIAL WINDOWING SELECTED?
0079   00              NOP
007A   CDB801          CALL   SHUF0    ;SHUFFLE DATA
007D   CD0002          CALL   B0       ;CALCULATE FOURIER COEFFICIENTS
0080   00              NOP
0081   CD0004          CALL   WC       ; CORRECT AMPLITUDE AND ACCUMULATE
0084   00              NOP
0085   DBBE            IN     0BEH
0087   17              RAL
```

```
0089   D2A600            JNC     SKIP     ;CRO SELECTED?
008B   DBBE              IN      0BEH
008D   E620              ANI     20H
008F   CCB404            CZ      LOG      ;LOG SELECTED?
0092   DBBE              IN      0BEH
0094   E620              ANI     20H
0096   C4F502            CNZ     LIN      ;LINEAR SELECTED?
0099   CD1A05            CALL    OUT0     ;DISPLAY ON CRO FOR .5S
009C   CD1A05            CALL    OUT0
009F   CD1A05            CALL    OUT0
00A2   CD1A05            CALL    OUT0
00A5   00                NOP
00A6   3AFE13    SKIP:   LDA     13FEH
00A9   3D                DCR     A
00AA   32FE13            STA     13FEH    ;A=A-1
00AD   C26500            JNZ     ACCUM    ;IF(A.NE.0)GOTO ACCUM
00B0   DBBE      REAP:   IN      0BEH
00B2   E620              ANI     20H
00B4   32FC13            STA     13FCH    ;LOG-LIN IN 13FCH
00B7   CCB404            CZ      LOG      ;LOG SELECTED?
00BA   DBBE              IN      0BEH
00BC   E620              ANI     20H
00BE   C4F502            CNZ     LIN      ;LINEAR SELECTED?
00C1   DBBE              IN      0BEH
00C3   17                RAL
00C4   D29805            JNC     REC      ;RECORDER SELECTED?
00C7   CD1A05    CROR:   CALL    OUT0     ;DISPLAY ON CRO FOR 0.125 SECS.
00CA   DBBE              IN      0BEH
00CC   17                RAL
00CD   D2B000            JNC     REAP     ;RECORDER SELECTED?
00D0   DBBE              IN      0BEH
00D2   E620              ANI     20H
00D4   47                MOV     B,A
00D5   3AFC13            LDA     13FCH
00D8   B8                CMP     B
00D9   CAC700            JZ      CROR     ;LOG-LINEAR UNCHANGED?
00DC   C3B000            JMP     REAP
```

```
00DF    210014   START:  LXI     H,1400H ; A/D CONVERSION
00E2    DBF6     A0:     IN      0F6H    ; SYNCHRONISE BEFORE STARTING
00E4    E620             ANI     20H
00E6    C2E200           JNZ     A0
00E9    DBF6     A1:     IN      0F6H
00EB    E620             ANI     20H
00ED    CAE900           JZ      A1      ;PC5=0?
00F0    00               NOP
00F1    00               NOP
00F2    DBF5             IN      0F5H
00F4    77               MOV     M,A     ;(M)=PORT A
00F5    24               INR     H       ;H=15H
00F6    DBF6             IN      0F6H
00F8    E6C0             ANI     0C0H
00FA    77               MOV     M,A     ;MS 2 BITS SELECTED
00FB    25               DCR     H       ;H=14H
00FC    2C               INR     L       ;L=L+1
00FD    CA0A01           JZ      A3
0100    DBF6     A2:     IN      0F6H
0102    E620             ANI     20H
0104    CAE900           JZ      A1      ;PC5=0?
0107    C30001           JMP     A2
010A    210016   A3:     LXI     H,1600H ;H=16H,L=0
010D    0600             MVI     B,0
010F    70       A4:     MOV     M,B
0110    23               INX     H
0111    3E18             MVI     A,18H
0113    BC               CMP     H
0114    C20F01           JNZ     A4      ;H.NE.18H?
0117    2614             MVI     H,14H   ;CHECK INPUT DATA FOR OVERLOAD
0119    067F             MVI     B,7FH
011B    0E80             MVI     C,80H
011D    7E       A5:     MOV     A,M
011E    B8               CMP     B
011F    CA2801           JZ      A6
0122    B9               CMP     C
0123    CA2801           JZ      A6
```

```
0126   2C                  INR    L
0127   C21D01              JNZ    A5
012A   C9                  RET
012B   3E08     A6:        MVI    A,8
012D   D3F6                OUT    0F6H
012F   76                  HLT
0130   16C0     HANN0:     MVI    D,0C0H    ;D=0C0H
0132   1E00                MVI    E,0       ;E=0
0134   2606     HANN1:     MVI    H,6       ;H=6
0136   6A                  MOV    L,D
0137   7E                  MOV    A,M
0138   D3EC                OUT    0ECH
013A   24                  INR    H         ;H=7
013B   7E                  MOV    A,M
013C   D3ED                OUT    0EDH       ;MULTIPLICAND= (1/2)SIN(D)
013E   2614                MVI    H,14H     ;H=14H
0140   6B                  MOV    L,E
0141   7E                  MOV    A,M
0142   47                  MOV    B,A
0143   D3EE                OUT    0EEH
0145   24                  INR    H         ;H=15H
0146   7E                  MOV    A,M
0147   4F                  MOV    C,A
0148   D3DC                OUT    0DCH       ;MULTIPLIER=XRE
014A   78                  MOV    A,B
014B   FE80                CPI    80H
014D   3F                  CMC
014E   1F                  RAR
014F   47                  MOV    B,A
0150   79                  MOV    A,C
0151   1F                  RAR
0152   4F                  MOV    C,A       ;(BC)=XRE/2
0153   DBDE                IN     0DEH       ;2ND MS RESULT
0155   81                  ADD    C
0156   71                  MOV    M,C
0157   25                  DCR    H         ;H=14H
0158   DBDD                IN     0DDH       ;MS RESULT
```

```
015A   88                 ADC   B
015B   77                 MOV   M,A       ;XRE=(XRE+SIN(D))/2
015C   14                 INR   D         ;D=D+1
015D   1C                 INR   E         ;E=E+1
015E   C23401             JNZ   HANN1     ;E.NE.0?
0161   C9                 RET
0162   16C0      HAMM0:   MVI   D,0C0H     ;D=0C0H
0164   1E00               MVI   E,0       ;E=0
0166   2606      HAMM1:   MVI   H,6       ;H=6
0168   6A                 MOV   L,D
0169   7E                 MOV   A,M
016A   D3EC               OUT   0ECH
016C   24                 INR   H         ;H=7
016D   7E                 MOV   A,M
016E   D3ED               OUT   0EDH       ;MULTIPLICAND=(1/2)SIN(D)
0170   2614               MVI   H,14H
0172   6B                 MOV   L,E
0173   7E                 MOV   A,M
0174   47                 MOV   B,A
0175   D3EE               OUT   0EEH
0177   24                 INR   H         ;H=15H
0178   7E                 MOV   A,M
0179   4F                 MOV   C,A
017A   D3DC               OUT   0DCH       ;MULTIPLIER=XRE
017C   78                 MOV   A,B
017D   FE80               CPI   80H
017F   3F                 CMC
0180   1F                 RAR
0181   47                 MOV   B,A
0182   79                 MOV   A,C
0183   1F                 RAR
0184   4F                 MOV   C,A       ;(BC)=XRE/2
0185   DBDE               IN    0DEH       ;2ND MS RESULT
0187   81                 ADD   C
0188   77                 MOV   M,A
0189   25                 DCR   H         ;H=14H
018A   DBDD               IN    0DDH       ;MS RESULT
```

```
018C    88                  ADC     B
018D    77                  MOV     M,A      ;(HE)=((HE)+SIN(D))/2
018E    97                  SUB     A
018F    93                  SUB     E
0190    6F                  MOV     L,A      ;L=-E
0191    7E                  MOV     A,M
0192    47                  MOV     B,A
0193    D3EE                OUT     0EEH      ;MS MULTIPLIER
0195    24                  INR     H        ;H=15H
0196    7E                  MOV     A,M
0197    4F                  MOV     C,A
0198    D30C                OUT     0DCH      ;LS MULTIPLIER
019A    78                  MOV     A,B
019B    FE80                CPI     80H
019D    3F                  CMC
019E    1F                  RAR
019F    47                  MOV     B,A
01A0    79                  MOV     A,C
01A1    1F                  RAR
01A2    4F                  MOV     C,A      ;(BC) ARE HALVED
01A3    DBDE                IN      0DEH      ;2ND MS RESULT
01A5    81                  ADD     C
01A6    77                  MOV     M,A
01A7    25                  DCR     H        ;H=14H
01A8    DBDD                IN      0DDH      ;MS RESULT
01AA    88                  ADC     B
01AB    77                  MOV     M,A
01AC    7A                  MOV     A,D
01AD    C604                ADI     04H
01AF    57                  MOV     D,A      ;D=D+4
01B0    1C                  INR     E
01B1    7B                  MOV     A,E
01B2    FE20                CPI     20H
01B4    C26601              JNZ     HAMM1    ;E.NE.20H?
01B7    C9                  RET
01B8    210114    SHUF0:    LXI     H,1401H ;H=14H,L=1
01BB    55        SHUF1:    MOV     D,L      ;D=L
```

```
 01BC   1E08              MVI     E,8H     ;E=8
 01BE   7A       SHUF2:   MOV     A,D
 01BF   07                RLC
 01C0   57                MOV     D,A      ;ROLL D LEFT
 01C1   78                MOV     A,B
 01C2   1F                RAR
 01C3   47                MOV     B,A      ;ROLL B RIGHT THRU CARRY
 01C4   1D                DCR     E        ;E=E-1
 01C5   C2BF01            JNZ     SHUF2    ;E.NE.0?
 01C8   7D                MOV     A,L
 01C9   B8                CMP     B
 01CA   D2DD01            JNC     SHUF3    ;L.GTE.B?
 01CD   56                MOV     D,M
 01CE   4D                MOV     C,L
 01CF   68                MOV     L,B
 01D0   5E                MOV     E,M
 01D1   72                MOV     M,D
 01D2   69                MOV     L,C
 01D3   73                MOV     M,E      ;(HL) AND (HB) ARE SWAPPED
 01D4   24                INR     H        ;H=15H
 01D5   56                MOV     D,M
 01D6   4D                MOV     C,L
 01D7   68                MOV     L,B
 01D8   5E                MOV     E,M
 01D9   72                MOV     M,D
 01DA   69                MOV     L,C
 01DB   73                MOV     M,E      ;(HL) AND (HB) ARE SWAPPED
 01DC   25                DCR     H        ;H=14H
 01DD   2C       SHUF3:   INR     L        ;L=L+1
 01DE   C2AB01            JNZ     SHUF1    ;L.NE.0?
 01E1   C9                RET
NO PROGRAM ERRORS
 * 01
 A        0007      A0      00E2      A1      00E9      A2      0100
 A3       010A      A4      010F      A5      0110      A6      012B
 ACCUM    0065      B       0000      B0      0200      BEGIN   0000 *
 C        0001      CROR    00C7      D       0002      E       0003
```

```
H       0004     HAMM0  0162     HAMM1  0166     HANN0  0130
HANN1   0134     L      0005     LIN    02F5     LOG    0484
M       0006     MF     0061     OUT0   051A     PSW    0006
REAP    0080     REC    0598     SHUF0  01B8     SHUF1  01BB
SHUF2   01BF     SHUF3  0100     SKIP   00A6     SOT    002C
SP      0006     START  000F     WC     0400     ZERO   001E
```

```
0200                          ORG     200H
0200    010180    B0:         LXI     B,8001H ;B=80H,C=1
0203    2E00      B1:         MVI     L,0     ;L=0
0205    55        B2:         MOV     D,L     ;D=L
0206    1E00                  MVI     E,0     ;E=0
0208    E5        B3:         PUSH    H       ;SAVE L IN STACK
0209    2606                  MVI     H,6
020B    6B                    MOV     L,E
020C    7E                    MOV     A,M
020D    D3EC                  OUT     0ECH
020F    24                    INR     H       ;H=7
0210    7E                    MOV     A,M
0211    D3ED                  OUT     0EDH     ;SIN(E) MULTIPLICAND PORT
0213    7D                    MOV     A,L
0214    C640                  ADI     40H
0216    6F                    MOV     L,A
0217    7E                    MOV     A,M
0218    32C113                STA     13C1H   ;LS BYTE OF COS(E) AT 13C1H
021B    25                    DCR     H       ;H=6
021C    7E                    MOV     A,M
021D    32C013                STA     13C0H   ;MS BYTE OF COS(E) AT 13C0H
0220    E1                    POP     H       ;RECOVER L FROM STACK
0221    2614                  MVI     H,14H   ;H=14H
0223    7D                    MOV     A,L
0224    81                    ADD     C
0225    6F                    MOV     L,A     ;L=L+C
0226    7E                    MOV     A,M
0227    32C213                STA     13C2H   ;MS BYTE OF A(L+C) AT 13C2H
022A    D3EE                  OUT     0EEH
022C    24                    INR     H
022D    7E                    MOV     A,M
022E    32C313                STA     13C3H   ;LS BYTE OF A(L+C) AT 13C3H
0231    D3DC                  OUT     0DCH     ;AL+C IN MULTIPLIER PORT
0233    24                    INR     H       ;H=16H
0234    7E                    MOV     A,M
0235    32C413                STA     13C4H   ;MS BYTE OF BL+C AT 13C4H
0238    24                    INR     H       ;H=17H
```

```
0239   7E         MOV   A,M
023A   32C513     STA   13C5H   ;LS BYTE OF BL+C AT 13C5H
023D   7D         MOV   A,L
023E   91         SUB   C
023F   6F         MOV   L,A     ;L IS RESTORED
0240   2614       MVI   H,14H
0242   7E         MOV   A,M
0243   FE80       CPI   80H
0245   3F         CMC
0246   1F         RAR
0247   32CA13     STA   13CAH   ;MS BYTE OF AL/2 AT 13CAH
024A   24         INR   H       ;H=15H
024B   7E         MOV   A,M
024C   1F         RAR
024D   32CB13     STA   13CBH   ;LS BYTE OF AL/2 AT 13CBH
0250   24         INR   H       ;H=16H
0251   7E         MOV   A,M
0252   FE80       CPI   80H
0254   3F         CMC
0255   1F         RAR
0256   32CC13     STA   13CCH   ;MS BYTE OF BL/2 AT 13CCH
0259   24         INR   H       ;H=17H
025A   7E         MOV   A,M
025B   1F         RAR
025C   32CD13     STA   13CDH   ;LS BYTE OF BL/2 AT 13CDH
025F   79         MOV   A,C
0260   32CE13     STA   13CEH   ;C STORED AT 13CEH
0263   C5         PUSH  B
0264   D5         PUSH  D       ;SAVE VARIABLES
0265   DBDE       IN    0DEH
0267   4F         MOV   C,A
0268   DBDD       IN    0DDH
026A   47         MOV   B,A     ;BC=0.5AL+CSIN(E)
026B   3AC413     LDA   13C4H
026E   D3EE       OUT   0EEH
0270   3AC513     LDA   13C5H
0273   D3DC       OUT   0DCH     ;BL+C IN MULTIPLIER
```

```
0275    DBDE                IN      0DEH
0277    5F                  MOV     E,A
0278    DBDD                IN      0DDH
027A    57                  MOV     D,A       ;DE=0.5BL+CSIN(E)
027B    3AC013              LDA     13C0H
027E    D3EC                OUT     0ECH
0280    3AC113              LDA     13C1H
0283    D3ED                OUT     0EDH
0285    DBDE                IN      0DEH
0287    91                  SUB     C
0288    4F                  MOV     C,A
0289    DBDD                IN      0DDH
028B    98                  SBB     B
028C    47                  MOV     B,A       ;BC=(BL+CCOS(E)-AL+CSIN(E))/2
028D    3AC213              LDA     13C2H
0290    D3EE                OUT     0EEH
0292    3AC313              LDA     13C3H
0295    D3DC                OUT     0DCH
0297    DBDE                IN      0DEH
0299    83                  ADD     E
029A    5F                  MOV     E,A
029B    DBDD                IN      0DDH
029D    8A                  ADC     D
029E    57                  MOV     D,A       ;DE=(AL+CCOS(E)+BL+CSIN(E))/2
029F    2615                MVI     H,15H
02A1    3ACB13              LDA     13CBH
02A4    83                  ADD     E
02A5    77                  MOV     M,A
02A6    25                  DCR     H         ;H=14H
02A7    3ACA13              LDA     13CAH
02AA    8A                  ADC     D
02AB    77                  MOV     M,A       ;AL=(AL+(AL+CCOS(E)+BL+CSIN(E)))/2
02AC    2617                MVI     H,17H
02AE    3ACD13              LDA     13CDH
02B1    81                  ADD     C
02B2    77                  MOV     M,A
02B3    25                  DCR     H         ;H=16H
```

```
02B4    3ACC13              LDA     13CCH
02B7    88                  ADC     B
02B8    77                  MOV     M,A     ;BL=(BL+(BL+CCOS(E)-AL+CSIN(E)))/2
02B9    3ACE13              LDA     13CEH   ;VARIABLE C IS RECOVERED
02BC    85                  ADD     L
02BD    6F                  MOV     L,A     ;L=L+C
02BE    24                  INR     H       ;H=17H
02BF    3ACD13              LDA     13CDH
02C2    91                  SUB     C
02C3    77                  MOV     M,A
02C4    25                  DCR     H       ;H=16H
02C5    3ACC13              LDA     13CCH
02C8    98                  SBB     B
02C9    77                  MOV     M,A     ;BL+C=(BL-(BL+CCOS(E)-AL+CSIN(E)))/2
02CA    25                  DCR     H       ;H=15H
02CB    3ACB13              LDA     13CBH
02CE    93                  SUB     E
02CF    77                  MOV     M,A
02D0    25                  DCR     H       ;H=14H
02D1    3ACA13              LDA     13CAH
02D4    9A                  SBB     D
02D5    77                  MOV     M,A     ;AL+C=(AL-(AL+CCOS(E)+BL+CSIN(E)))/2
02D6    D1                  POP     D
02D7    C1                  POP     B       ;RECOVER VARIABLES FROM STACK
02D8    7D                  MOV     A,L
02D9    91                  SUB     C
02DA    6F                  MOV     L,A
02DB    2C                  INR     L       ;L=L+1
02DC    78                  MOV     A,B
02DD    83                  ADD     E
02DE    5F                  MOV     E,A     ;E=E+B
02DF    79                  MOV     A,C
02E0    82                  ADD     D
02E1    BD                  CMP     L
02E2    C20802              JNZ     B3      ;L.NE.(D+C)?
02E5    79                  MOV     A,C
02E6    85                  ADD     L
```

```
02E7    6F                  MOV     L,A      ;L=L+C
02E8    C20502              JNZ     B2       ;L.NE.0?
02EB    78                  MOV     A,B
02EC    0F                  RRC
02ED    47                  MOV     B,A      ;B=B/2
02EE    79                  MOV     A,C
02EF    87                  ADD     A
02F0    4F                  MOV     C,A      ;C=2C
02F1    C20302              JNZ     B1       ;C.NE.0?
02F4    C9                  RET
02F5    2E00       LIN:     MVI     L,0      ;L=0
02F7    3EAA                MVI     A,0AAH
02F9    D3ED                OUT     0EDH
02FB    3E6B                MVI     A,6BH
02FD    D3EC                OUT     0ECH     ;MULT FACTOR IN MULTIPLICAND
02FF    E5         SQRT:    PUSH    H
0300    2610                MVI     H,10H
0302    7E                  MOV     A,M
0303    D3EE                OUT     0EEH
0305    24                  INR     H        ;H=11H
0306    7E                  MOV     A,M
0307    D3DC                OUT     0DCH     ;PSD IN MULTIPLIER
0309    DBDD                IN      0DDH
030B    57                  MOV     D,A
030C    DBDE                IN      0DEH
030E    5F                  MOV     E,A
030F    DBDC                IN      0DCH
0311    47                  MOV     B,A      ;DEB=RESULT
0312    0E02                MVI     C,2      ;C=2
0314    78         PREMH:   MOV     A,B
0315    87                  ADD     A
0316    47                  MOV     B,A
0317    7B                  MOV     A,E
0318    8F                  ADC     A
0319    5F                  MOV     E,A
031A    7A                  MOV     A,D
031B    8F                  ADC     A
```

```
031C    57                  MOV     D,A     ;DER=2*DER
031D    0D                  DCR     C       ;C=C-1
031F    C21403              JNZ     PREMA   ;C.NE.0?
0321    3E08                MVI     A,8H
0323    32C013              STA     13C0H   ;S=8
0326    97                  SUB     A
0327    32C113              STA     13C1H   ;T=0
032A    67                  MOV     H,A
032B    6F                  MOV     L,A     ;HL=0
032C    010100              LXI     B,1     ;U=BC=1
032F    3AC113     SQRT1:   LDA     13C1H
0332    87                  ADD     A
0333    32C113              STA     13C1H   ;T=2T
0336    7B                  MOV     A,E
0337    87                  ADD     A
0338    5F                  MOV     E,A
0339    7A                  MOV     A,D
033A    8F                  ADC     A
033B    57                  MOV     D,A
033C    7D                  MOV     A,L
033D    8F                  ADC     A
033E    6F                  MOV     L,A
033F    7C                  MOV     A,H
0340    8F                  ADC     A
0341    67                  MOV     H,A
0342    7B                  MOV     A,E
0343    87                  ADD     A
0344    5F                  MOV     E,A
0345    7A                  MOV     A,D
0346    8F                  ADC     A
0347    57                  MOV     D,A
0348    7D                  MOV     A,L
0349    8F                  ADC     A
034A    6F                  MOV     L,A
034B    7C                  MOV     A,H
034C    8F                  ADC     A
034D    67                  MOV     H,A     ;R=4R
```

```
 034E  7D               MOV   A,L
 034F  91               SUB   C
 0350  7C               MOV   A,H
 0351  98               SBB   B
 0352  FA6403           JM    SORT2    ;BC.GT.HL?OR U.GT.R?
 0355  7D               MOV   A,L
 0356  91               SUB   C
 0357  6F               MOV   L,A
 0358  7C               MOV   A,H
 0359  98               SBB   B
 035A  67               MOV   H,A      ;R=R-U
 035B  3AC113           LDA   13C1H
 035E  3C               INR   A
 035F  32C113           STA   13C1H    ;T=T+1
 0362  03               INX   B
 0363  03               INX   B        ;U=U+2
 0364  79       SORT2:  MOV   A,C
 0365  87               ADD   A
 0366  4F               MOV   C,A
 0367  78               MOV   A,B
 0368  8F               ADC   A
 0369  47               MOV   B,A
 036A  0B               DCX   B        ;U=2U-1
 036B  3AC013           LDA   13C0H
 036E  3D               DCR   A
 036F  32C013           STA   13C0H    ;S=S-1
 0372  C22F03           JNZ   SORT1    ;S.NE.0?
 0375  3AC113           LDA   13C1H
 0378  E1               POP   H
 0379  2613             MVI   H,13H
 037B  77               MOV   M,A      ;STORE T AT 13L
 037C  2C               INR   L        ;L=L+1
 037D  7D               MOV   A,L
 037E  FE80             CPI   80H
 0380  C2FF02           JNZ   SORT     ;L.NE.80H?
 0383  C9               RET
NO PROGRAM ERRORS
```

```
* 01
A       0007        B       0000        B0      0200 *     B1      0203
B2      0205        B3      0208        C       0001       D       0002
E       0003        H       0004        L       0005       LIN     02F5 *
M       0006        PREM8   0314        PSW     0006       SP      0006
SQRT    02FF        SQRT1   032F        SQRT2   0364
```

```
0400                     ORG     400H
0400   3AFD13   WC:      LDA     13FDH    ; AMPLITUDE CORRECTION DUE TO WINDOWS
0403   FE18              CPI     18H
0405   CA5C04            JZ      ACRE0    ; NO WINDOW SELECTED ?
0408   FE08              CPI     8
040A   CA4604            JZ      WH       ; HANNING WINDOW SELECTED ?
040D   2F00              MVI     L,0      ; NO-BINGHAM WINDOW
040F   3E49              MVI     A,49H    ; MULTIPLICAND=2/7*256**2
0411   D3EC              OUT     0ECH
0413   3E25              MVI     A,25H
0415   D3ED              OUT     0EDH
0417   2618     WH:      MVI     H,18H
0419   25       WB1:     DCR     H
041A   7E                MOV     A,M
041B   D3DC              OUT     0DCH
041D   25                DCR     H
041E   7E                MOV     A,M
041F   D3EE              OUT     0EEH
0421   DBDD              IN      0DDH
0423   47                MOV     B,A
0424   DBDE              IN      0DEH
0426   4F                MOV     C,A
0427   DBBC              IN      0BCH
0429   57                MOV     D,A      ; BC=2/7*X(L)
042A   1E02              MVI     E,2
042C   7A       WB2:     MOV     A,D
042D   87                ADD     A
042E   57                MOV     D,A
042F   79                MOV     A,C
0430   8F                ADC     A
0431   4F                MOV     C,A
0432   78                MOV     A,B
0433   88                ADC     B
0434   47                MOV     B,A      ; BCD=2*BCD
0435   1D                DCR     E
0436   C22C04            JNZ     WB2
0439   7C                MOV     A,H
```

```
043A    FE14                CPI     14H
043C    C21904              JNZ     WH1     ; H=14H?
043F    2D                  DCR     L
0440    C21704              JNZ     WS      ; L.NE0?
0443    C35C04              JMP     ACRE0
0446    2E00       WH:      MVI     L,0
0448    2618       WH1:     MVI     H,18H
044A    25         WH2:     DCR     H
044B    7E                  MOV     A,M
044C    87                  ADD     A
044D    77                  MOV     M,A
044E    25                  DCR     H
044F    7E                  MOV     A,M
0450    8F                  ADC     A
0451    77                  MOV     M,A     ; X(L)=2*X(L)
0452    7C                  MOV     A,H
0453    FE14                CPI     14H
0455    C24A04              JNZ     WH2
0458    2D                  DCR     L
0459    C24804              JNZ     WH1
045C    2E00       ACRE0:   MVI     L,0
045E    2614       ACRE1:   MVI     H,14H
0460    7E                  MOV     A,M
0461    D3EC                OUT     0ECH
0463    D3EE                OUT     0EEH
0465    24                  INR     H       ;H=15H
0466    7E                  MOV     A,M
0467    D3ED                OUT     0EDH
0469    D3DC                OUT     0DCH
046B    DBDD                IN      0DDH
046D    4F                  MOV     C,A
046E    DBDE                IN      0DEH
0470    57                  MOV     D,A
0471    DBDC                IN      0DCH
0473    5F                  MOV     E,A     ;CDE=AL*AL
0474    24                  INR     H       ;H=16H
0475    7E                  MOV     A,M
```

```
0476    D3EC                OUT     0ECH
0478    D3EE                OUT     0EEH
047A    24                  INR     H          ;H=17H
047B    7E                  MOV     A,M
047C    D3ED                OUT     0EDH
047E    D3DC                OUT     0DCH
0480    DBBC                IN      0BCH
0482    83                  ADD     E
0483    5F                  MOV     E,A
0484    DBDE                IN      0DEH
0486    8A                  ADC     D
0487    57                  MOV     D,A
0488    DBDD                IN      0DDH
048A    89                  ADC     C
048B    4F                  MOV     C,A        ;CDE=AL*AL+BL*BL
048C    3AFF13              LDA     13FFH
048F    67                  MOV     H,A        ;H=(13FFH)
0490    0600                MVI     B,0
0492    7B          ACRE2:  MOV     A,E
0493    87                  ADD     A
0494    5F                  MOV     E,A
0495    7A                  MOV     A,D
0496    8F                  ADC     A
0497    57                  MOV     D,A
0498    79                  MOV     A,C
0499    8F                  ADC     A
049A    4F                  MOV     C,A
049B    78                  MOV     A,B
049C    8F                  ADC     A
049D    47                  MOV     B,A        ;BCDE=2*BCDE
049E    25                  DCR     H
049F    C29204              JNZ     ACRE2      ;H.NE.0?
04A2    2612                MVI     H,12H
04A4    7A                  MOV     A,D
04A5    86                  ADD     M
04A6    77                  MOV     M,A
04A7    25                  DCR     H          ;H=11H
```

```
04A8   79                MOV    A,C
04A9   8E                ADC    M
04AA   77                MOV    M,A
04AB   25                DCR    H       ;H=10H
04AC   78                MOV    A,B
04AD   8E                ADC    M
04AE   77                MOV    M,A     ;R=R+BCD
04AF   2C                INR    L
04B0   C25E04            JNZ    ACRE1   ;L.NE.0?
04B3   C9                RET
04B4   2E00      LOG:    MVI    L,0     ;L=0
04B6   2610      LOG0:   MVI    H,10H   ;H=10H
04B8   46                MOV    B,M
04B9   24                INR    H       ;H=11H
04BA   4E                MOV    C,M
04BB   24                INR    H       ;H=12H
04BC   56                MOV    D,M     ;BCD=ACC RESULT
04BD   1E02              MVI    E,210   ;E=210
04BF   7A        LOG1:   MOV    A,D
04C0   87                ADD    A
04C1   57                MOV    D,A
04C2   79                MOV    A,C
04C3   8F                ADC    A
04C4   4F                MOV    C,A
04C5   78                MOV    A,B
04C6   8F                ADC    A
04C7   47                MOV    B,A     ;SHIFT BCD LEFT
04C8   DAD904            JC     LOG2    ;CARRY SET?
04CB   7B                MOV    A,E
04CC   DE0A              SBI    0AH
04CE   5F                MOV    E,A     ;E=E-10
04CF   FEF6              CPI    0F6H
04D1   C2BF04            JNZ    LOG1    ;E.NE.-10?
04D4   1E00              MVI    E,0     ;E=0
04D6   C30F05            JMP    LOG3
04D9   FE12      LOG2:   CPI    12H
04DB   DA0F05            JC     LOG3    ;B.LTE.12H?
```

```
04DE   1C                  INR    E
04DF   FE26                CPI    26H
04E1   DA0F05              JC     LOG3     ;B.LTE.26H?
04E4   1C                  INR    E
04E5   FE3B                CPI    3BH
04E7   DA0F05              JC     LOG3     ;B.LTE.3BH?
04EA   1C                  INR    E
04EB   FE52                CPI    52H
04ED   DA0F05              JC     LOG3     ;B.LTE.52H?
04F0   1C                  INR    E
04F1   FE6A                CPI    6AH
04F3   DA0F05              JC     LOG3     ;B.LTE.6AH?
04F6   1C                  INR    E
04F7   FE84                CPI    84H
04F9   DA0F05              JC     LOG3     ;B.LTE.84H?
04FC   1C                  INR    E
04FD   FEA0                CPI    0A0H
04FF   DA0F05              JC     LOG3     ;B.LTE.0A0H?
0502   1C                  INR    E
0503   FEBE                CPI    0BEH
0505   DA0F05              JC     LOG3     ;B.LTE.0BEH?
0508   1C                  INR    E
0509   FEDE                CPI    0DEH
050B   DA0F05              JC     LOG3     ;B.LTE.0DEH?
050E   1C                  INR    E
050F   2613       LOG3:    MVI    H,13H    ;H=13H
0511   73                  MOV    M,E
0512   2C                  INR    L
0513   3E80                MVI    A,80H
0515   BD                  CMP    L
0516   C28604              JNZ    LOG0
0519   C9                  RET
051A   3AFA13     OUT0:    LDA    13FAH    ; CRO TRIGGER CONTROL
051D   6F                  MOV    L,A
051E   DB7E                IN     7EH      ; READ UP-DOWN SWITCH
0520   17                  RAL
0521   DA2805              JC     DCHK
```

```
0524    2C                 INR     L
0525    C32D05             JMP     RCHK
0528    17        DCHK:    RAL
0529    DA2D05             JC      RCHK
052C    2D                 DCR     L
052D    7D        RCHK:    MOV     A,L
052E    FEFF               CPI     0FFH
0530    C23805             JNZ     RCH1
0533    3E64               MVI     A,100
0535    C33E05             JMP     RCH2
0538    FE65      RCH1:    CPI     101
053A    DA3E05             JC      RCH2
053D    97                 SUB     A
053E    32FA13    RCH2:    STA     13FAH
0541    D3EC               OUT     0ECH     ; MS BYTE OF MULTIPLICAND
0543    3AFB13             LDA     13FBH
0546    D3EE               OUT     0EEH     ; MS BYTE OF MULTIPLIER
0548    97                 SUB     A
0549    D3ED               OUT     0EDH     ; LS BYTE OF MULTIPLICAND
054B    D3DC               OUT     0DCH     ; LS BYTE OF MULTIPLIER
054D    DBDD               IN      0DDH     ; MS BYTE OF RESULT
054F    47                 MOV     B,A
0550    DBDE               IN      0DEH     ; 2ND MS BYTE OF RESULT
0552    4F                 MOV     C,A
0553    110000             LXI     D,0      ; CONVERSION FROM HEXADECIMAL
0556    2610               MVI     H,16     ; TO DECIMAL
0558    79        L1:      MOV     A,C
0559    17                 RAL
055A    4F                 MOV     C,A
055B    78                 MOV     A,B
055C    17                 RAL
055D    47                 MOV     B,A      ; CARRY = MS BIT OF BC
055E    7B                 MOV     A,E
055F    8B                 ADC     E        ; E = 2E + CARRY
0560    27                 DAA              ; CONVERT TO DECIMAL
0561    5F                 MOV     E,A
0562    7A                 MOV     A,D
```

```
0563    8A                 ADC     D
0564    27                 DAA
0565    57                 MOV     D,A      ; D = 2D + CARRY
0566    25                 DCR     H
0567    C25805             JNZ     L1
056A    7B                 MOV     A,E      ; TO DIGITAL FREQUENCY DISPLAY
056B    D37D               OUT     7DH
056D    7A                 MOV     A,D
056E    D37C               OUT     7CH
0570    2613      OUTPU:   MVI     H,13H    ; DISPLAY SPECTRUM ON CRO
0572    0618               MVI     B,24     ; DURATION = 1/8 SEC APPROX.
0574    3E02               MVI     A,2
0576    D3F6               OUT     0F6H     ; PC1 = 1
0578    05        OUT1:    DCR     B
0579    C8                 RZ                 ; RETURN TO MAIN PROGRAM ?
057A    97                 SUB     A
057B    D3F6               OUT     0F6H     ; TRIGGER CRO
057D    6F                 MOV     L,A      ;L=0
057E    7E        OUT2:    MOV     A,M
057F    D3F4               OUT     0F4H     ; FREQUENCY COMPONENT TO CRO
0581    3AF413             LDA     13F4H    ; FREQUENCY REFERENCE
0584    57                 MOV     D,A
0585    7D                 MOV     A,L
0586    BA                 CMP     D        ; CARRY SET IF D.GT.L
0587    3F                 CMC              ; CARRY SET IF FR.LE.F
0588    3E00               MVI     A,0
058A    17                 RAL
058B    17                 RAL              ; CARRY IS MOVED TO BIT NO. 1
058C    D3F6               OUT     0F6H     ; POSITIVE EDGE INDICATES FREQUENCY
058E    2C                 INR     L
058F    7D                 MOV     A,L
0590    FE65               CPI     101
0592    CA7805             JZ      OUT1     ; END OF FREQUENCY SCAN ?
0595    C37E05             JMP     OUT2     ; NO. DISPLAY ANOTHER SPECTRAL POINT
0598    210013    REC:     LXI     H,1300H ; RECORDER OUTPUT SUBROUTINE
059B    1E00               MVI     E,0      ; E IS MARKER PEN CONTROLLER
059D    1600      REC0:    MVI     D,0      ; 1 SECOND TIMER
```

```
059F   DBF6      TEST:    IN     0F6H
05A1   E610               ANI    10H      ;SELECT PC4
05A3   48                 MOV    C,B      ; FORMER IN C
05A4   47                 MOV    B,A      ; LATTER IN C
05A5   B9                 CMP    C
05A6   D29F05             JNC    TEST     ; DETECT NEGATIVE TRANSITION OF 256HZ
05A9   14                 INR    D
05AA   C29F05             JNZ    TEST     ; 1 SECOND DELAY ELAPSED?
05AD   3E04               MVI    A,4
05AF   D3F6               OUT    0F6H     ; SET MARKER TO 0
05B1   7E                 MOV    A,M
05B2   D3F4               OUT    0F4H     ; DATA TO D/A
05B4   7B                 MOV    A,E
05B5   BD                 CMP    L
05B6   CCC405             CZ     MARK     ; IS MARKER REQUIRED?
05B9   2C                 INR    L
05BA   7D                 MOV    A,L
05BB   FE65               CPI    101
05BD   C29D05             JNZ    RECO     ; L.NE.101 ?
05C0   97                 SUB    A
05C1   D3F6               OUT    0F6H     ; ZERO O/P AND MARKER REALEASE
05C3   76                 HLT
05C4   C60A      MARK:    ADI    10
05C6   5F                 MOV    E,A      ; E=E+10
05C7   3E05               MVI    A,5
05C9   D3F6               OUT    0F6H     ; ENERGISE MARKER PEN
05CB   C9                 RET
05CC   2E00      ENT:     MVI    L,0      ;TEST STAIRCASE
05CE   75        ENT1:    MOV    M,L
05CF   2C                 INR    L
05D0   C2CE05             JNZ    ENT1
05D3   CF                 RST    1
05D4   2E00      AD80:    MVI    L,0      ;TEST ADD 80H
05D6   7E        AD801:   MOV    A,M
05D7   C680               ADI    80H
05D9   77                 MOV    M,A
05DA   2C                 INR    L
```

```
 05DB   C20605            JNZ     AD801
 05DE   00                NOP
 05DF   7E        TOUT:   MOV     A,M       ;TEST OUTPUT
 05E0   D3F4              OUT     0F4H
 05E2   2C                INR     L
 05E3   00                NOP
 05E4   00                NOP
 05E5   00                NOP
 05E6   00                NOP
 05E7   00                NOP
 05E8   00                NOP
 05E9   C2DF05            JNZ     TOUT
 05EC   97                SUB     A
 05ED   D3F6              OUT     0F6H
 05EF   3E02              MVI     A,02H
 05F1   D3F6              OUT     0F6H
 05F3   C3DF05            JMP     TOUT
 05F6   2E00      ENTA:   MVI     L,0       ;TEST,ENTER CONSTANT DATA
 05F8   77        ENTA1:  MOV     M,A
 05F9   2C                INR     L
 05FA   C2F805            JNZ     ENTA1
 05FD   CF                RST     1
NO PROGRAM ERRORS
 * 01
 A       0007       ACRE0  045C       ACRE1  045E       ACRE2  0492
 AD80    0504 *     AD801  0506       B      0000       C      0001
 D       0002       DCHA   0526       E      0003       ENT    05CC *
 ENT1    05C6       ENTA   05F6 *     ENTA1  05F8       H      0004
 L       0005       L1     0558       LOG    0484 *     LOG0   0486
 LOG1    048F       LOG2   04D9       LOG3   050F       M      0006
 MARK    05C4       OUT0   051A *     OUT1   0578       OUT2   057E
 OUTPU   0570 *     PSW    0006       RCH1   0538       RCH2   053E
 RCHK    052D       REC    059A *     REC0   059D       SP     0006
 TEST    059F       TOUT   05DF       WB     0417       WB1    0419
 WB2     042C       WC     0400 *     WH     0446       WH1    0448
 WH2     044A
```

```
0600                          ORG     600H
0600    00                    DB      00H
0601    03                    DB      03H
0602    06                    DB      06H
0603    09                    DB      09H
0604    0C                    DB      0CH
0605    0F                    DB      0FH
0606    12                    DB      12H
0607    15                    DB      15H
0608    18                    DB      18H
0609    1C                    DB      1CH
060A    1F                    DB      1FH
060B    22                    DB      22H
060C    25                    DB      25H
060D    28                    DB      28H
060E    2B                    DB      2BH
060F    2E                    DB      2EH
0610    30                    DB      30H
0611    33                    DB      33H
0612    36                    DB      36H
0613    39                    DB      39H
0614    3C                    DB      3CH
0615    3F                    DB      3FH
0616    41                    DB      41H
0617    44                    DB      44H
0618    47                    DB      47H
0619    49                    DB      49H
061A    4C                    DB      4CH
061B    4E                    DB      4EH
061C    51                    DB      51H
061D    53                    DB      53H
061E    55                    DB      55H
061F    58                    DB      58H
0620    5A                    DB      5AH
0621    5C                    DB      5CH
0622    5E                    DB      5EH
0623    60                    DB      60H
```

```
0624    62                                  DB              62H
0625    64                                  DB              64H
0626    66                                  DB              66H
0627    68                                  DB              68H
0628    6A                                  DB              6AH
0629    6C                                  DB              6CH
062A    6D                                  DB              6DH
062B    6F                                  DB              6FH
062C    70                                  DB              70H
062D    72                                  DB              72H
062E    73                                  DB              73H
062F    75                                  DB              75H
0630    76                                  DB              76H
0631    77                                  DB              77H
0632    78                                  DB              78H
0633    79                                  DB              79H
0634    7A                                  DB              7AH
0635    7B                                  DB              7BH
0636    7C                                  DB              7CH
0637    7C                                  DB              7CH
0638    7D                                  DB              7DH
0639    7E                                  DB              7EH
063A    7E                                  DB              7EH
063B    7F                                  DB              7FH
063C    7F                                  DB              7FH
063D    7F                                  DB              7FH
063E    7F                                  DB              7FH
063F    7F                                  DB              7FH
0640    7F                                  DB              7FH
0641    7F                                  DB              7FH
0642    7F                                  DB              7FH
0643    7F                                  DB              7FH
0644    7F                                  DB              7FH
0645    7F                                  DB              7FH
0646    7E                                  DB              7EH
0647    7E                                  DB              7EH
0648    7D                                  DB              7DH
```

```
0649    7C                 DB        7CH
064A    7C                 DB        7CH
064B    7B                 DB        7BH
064C    7A                 DB        7AH
064D    79                 DB        79H
064E    78                 DB        78H
064F    77                 DB        77H
0650    76                 DB        76H
0651    75                 DB        75H
0652    73                 DB        73H
0653    72                 DB        72H
0654    70                 DB        70H
0655    6F                 DB        6FH
0656    6D                 DB        6DH
0657    6C                 DB        6CH
0658    6A                 DB        6AH
0659    68                 DB        68H
065A    66                 DB        66H
065B    64                 DB        64H
065C    62                 DB        62H
065D    60                 DB        60H
065E    5E                 DB        5EH
065F    5C                 DB        5CH
0660    5A                 DB        5AH
0661    58                 DB        58H
0662    55                 DB        55H
0663    53                 DB        53H
0664    51                 DB        51H
0665    4E                 DB        4EH
0666    4C                 DB        4CH
0667    49                 DB        49H
0668    47                 DB        47H
0669    44                 DB        44H
066A    41                 DB        41H
066B    3F                 DB        3FH
066C    3C                 DB        3CH
066D    39                 DB        39H
```

```
066E    36                  DB        36H
066F    33                  DB        33H
0670    30                  DB        30H
0671    2E                  DB        2EH
0672    2B                  DB        2BH
0673    28                  DB        28H
0674    25                  DB        25H
0675    22                  DB        22H
0676    1F                  DB        1FH
0677    1C                  DB        1CH
0678    18                  DB        18H
0679    15                  DB        15H
067A    12                  DB        12H
067B    0F                  DB        0FH
067C    0C                  DB        0CH
067D    09                  DB        09H
067E    06                  DB        06H
067F    03                  DB        03H
0680    00                  DB        00H
0681    FC                  DB        0FCH
0682    F9                  DB        0F9H
0683    F6                  DB        0F6H
0684    F3                  DB        0F3H
0685    F0                  DB        0F0H
0686    ED                  DB        0EDH
0687    EA                  DB        0EAH
0688    E7                  DB        0E7H
0689    E3                  DB        0E3H
068A    E0                  DB        0E0H
068B    DD                  DB        0DDH
068C    DA                  DB        0DAH
068D    D7                  DB        0D7H
068E    D4                  DB        0D4H
068F    D1                  DB        0D1H
0690    CF                  DB        0CFH
0691    CC                  DB        0CCH
0692    C9                  DB        0C9H
```

```
0693   C6                    DB       0C6H
0694   C3                    DB       0C3H
0695   C0                    DB       0C0H
0696   BE                    DB       0BEH
0697   BB                    DB       0BBH
0698   B8                    DB       0B8H
0699   B6                    DB       0B6H
069A   B3                    DB       0B3H
069B   B1                    DB       0B1H
069C   AE                    DB       0AEH
069D   AC                    DB       0ACH
069E   AA                    DB       0AAH
069F   A7                    DB       0A7H
06A0   A5                    DB       0A5H
06A1   A3                    DB       0A3H
06A2   A1                    DB       0A1H
06A3   9F                    DB       9FH
06A4   9D                    DB       9DH
06A5   9B                    DB       9BH
06A6   99                    DB       99H
06A7   97                    DB       97H
06A8   95                    DB       95H
06A9   93                    DB       93H
06AA   92                    DB       92H
06AB   90                    DB       90H
06AC   8F                    DB       8FH
06AD   8D                    DB       8DH
06AE   8C                    DB       8CH
06AF   8A                    DB       8AH
06B0   89                    DB       89H
06B1   88                    DB       88H
06B2   87                    DB       87H
06B3   86                    DB       86H
06B4   85                    DB       85H
06B5   84                    DB       84H
06B6   83                    DB       83H
06B7   83                    DB       83H
```

```
06B8    82                  DB        82H
06B9    81                  DB        81H
06BA    81                  DB        81H
06BB    80                  DB        80H
06BC    80                  DB        80H
06BD    80                  DB        80H
06BE    80                  DB        80H
06BF    80                  DB        80H
06C0    80                  DB        80H
06C1    80                  DB        80H
06C2    80                  DB        80H
06C3    80                  DB        80H
06C4    80                  DB        80H
06C5    80                  DB        80H
06C6    81                  DB        81H
06C7    81                  DB        81H
06C8    82                  DB        82H
06C9    83                  DB        83H
06CA    83                  DB        83H
06CB    84                  DB        84H
06CC    85                  DB        85H
06CD    86                  DB        86H
06CE    87                  DB        87H
06CF    88                  DB        88H
06D0    89                  DB        89H
06D1    8A                  DB        8AH
06D2    8C                  DB        8CH
06D3    8D                  DB        8DH
06D4    8F                  DB        8FH
06D5    90                  DB        90H
06D6    92                  DB        92H
06D7    93                  DB        93H
06D8    95                  DB        95H
06D9    97                  DB        97H
06DA    99                  DB        99H
06DB    9B                  DB        9BH
06DC    9D                  DB        9DH
```

```
06DD    9F                  DB          9FH
06DE    A1                  DB          0A1H
06DF    A3                  DB          0A3H
06E0    A5                  DB          0A5H
06E1    A7                  DB          0A7H
06E2    AA                  DB          0AAH
06E3    AC                  DB          0ACH
06E4    AE                  DB          0AEH
06E5    B1                  DB          0B1H
06E6    B3                  DB          0B3H
06E7    B6                  DB          0B6H
06E8    B8                  DB          0B8H
06E9    BB                  DB          0BBH
06EA    BE                  DB          0BEH
06EB    C0                  DB          0C0H
06EC    C3                  DB          0C3H
06ED    C6                  DB          0C6H
06EE    C9                  DB          0C9H
06EF    CC                  DB          0CCH
06F0    CF                  DB          0CFH
06F1    D1                  DB          0D1H
06F2    D4                  DB          0D4H
06F3    D7                  DB          0D7H
06F4    DA                  DB          0DAH
06F5    DD                  DB          0DDH
06F6    E0                  DB          0E0H
06F7    E3                  DB          0E3H
06F8    E7                  DB          0E7H
06F9    EA                  DB          0EAH
06FA    ED                  DB          0EDH
06FB    F0                  DB          0F0H
06FC    F3                  DB          0F3H
06FD    F6                  DB          0F6H
06FE    F9                  DB          0F9H
06FF    FC                  DB          0FCH
0700    00                  DB          00H
0701    24                  DB          24H
```

```
0702    48                  DB        48H
0703    6B                  DB        6BH
0704    8C                  DB        8CH
0705    A8                  DB        0A8H
0706    C8                  DB        0C8H
0707    E2                  DB        0E2H
0708    F9                  DB        0F9H
0709    0C                  DB        0CH
070A    1A                  DB        1AH
070B    24                  DB        24H
070C    28                  DB        28H
070D    27                  DB        27H
070E    1F                  DB        1FH
070F    11                  DB        11H
0710    FC                  DB        0FCH
0711    DF                  DB        0DFH
0712    BA                  DB        0BAH
0713    8D                  DB        8DH
0714    57                  DB        57H
0715    17                  DB        17H
0716    CE                  DB        0CEH
0717    7B                  DB        7BH
0718    1D                  DB        1DH
0719    B4                  DB        0B4H
071A    40                  DB        40H
071B    C0                  DB        0C0H
071C    34                  DB        34H
071D    9B                  DB        9BH
071E    F6                  DB        0F6H
071F    43                  DB        43H
0720    82                  DB        82H
0721    B4                  DB        0B4H
0722    D7                  DB        0D7H
0723    EC                  DB        0ECH
0724    F2                  DB        0F2H
0725    E9                  DB        0E9H
0726    D0                  DB        0D0H
```

```
0727   A7                 DB        0A7H
0728   6F                 DB        6EH
0729   24                 DB        24H
072A   CA                 DB        0CAH
072B   5F                 DB        5FH
072C   E3                 DB        0E3H
072D   55                 DB        55H
072E   86                 DB        086H
072F   05                 DB        05H
0730   42                 DB        42H
0731   6C                 DB        6CH
0732   85                 DB        85H
0733   8A                 DB        8AH
0734   7D                 DB        7DH
0735   5D                 DB        5DH
0736   2A                 DB        2AH
0737   E4                 DB        0E4H
0738   8A                 DB        8AH
0739   1E                 DB        1EH
073A   9D                 DB        9DH
073B   0A                 DB        0AH
073C   62                 DB        62H
073D   A7                 DB        0A7H
073E   D9                 DB        0D9H
073F   F6                 DB        0F6H
0740   FF                 DB        0FFH
0741   F6                 DB        0F6H
0742   D9                 DB        0D9H
0743   A7                 DB        0A7H
0744   62                 DB        62H
0745   0A                 DB        0AH
0746   9D                 DB        9DH
0747   1E                 DB        1EH
0748   8A                 DB        8AH
0749   E4                 DB        0E4H
074A   2A                 DB        2AH
074B   5D                 DB        5DH
```

```
074C    7D                DB        7DH
074D    8A                DB        8AH
074E    65                DB        65H
074F    6C                DB        6CH
0750    42                DB        42H
0751    05                DB        05H
0752    B6                DB        0B6H
0753    55                DB        55H
0754    E3                DB        0E3H
0755    5F                DB        5FH
0756    CA                DB        0CAH
0757    24                DB        24H
0758    6E                DB        6EH
0759    A7                DB        0A7H
075A    D0                DB        0D0H
075B    E9                DB        0E9H
075C    F2                DB        0F2H
075D    EC                DB        0ECH
075E    D7                DB        0D7H
075F    B4                DB        0B4H
0760    82                DB        82H
0761    43                DB        43H
0762    F6                DB        0F6H
0763    9B                DB        9BH
0764    34                DB        34H
0765    C0                DB        0C0H
0766    40                DB        40H
0767    B4                DB        0B4H
0768    1D                DB        1DH
0769    74                DB        74H
076A    CE                DB        0CEH
076B    17                DB        17H
076C    57                DB        57H
076D    8D                DB        8DH
076E    BA                DB        0BAH
076F    DF                DB        0DFH
0770    FC                DB        0FCH
```

```
0771   11                 DB       11H
0772   1F                 DB       1FH
0773   27                 DB       27H
0774   28                 DB       28H
0775   24                 DB       24H
0776   1A                 DB       1AH
0777   0C                 DB       0CH
0778   F9                 DB       0F9H
0779   E2                 DB       0E2H
077A   C8                 DB       0C8H
077B   A8                 DB       0A8H
077C   8C                 DB       8CH
077D   68                 DB       68H
077E   48                 DB       48H
077F   24                 DB       24H
0780   00                 DB       00H
0781   DC                 DB       0DCH
0782   B8                 DB       0B8H
0783   95                 DB       95H
0784   74                 DB       74H
0785   55                 DB       55H
0786   38                 DB       38H
0787   1E                 DB       1EH
0788   07                 DB       07H
0789   F4                 DB       0F4H
078A   E6                 DB       0E6H
078B   DC                 DB       0DCH
078C   D8                 DB       0D8H
078D   D9                 DB       0D9H
078E   E1                 DB       0E1H
078F   EF                 DB       0EFH
0790   04                 DB       04H
0791   21                 DB       21H
0792   46                 DB       46H
0793   73                 DB       73H
0794   A9                 DB       0A9H
0795   E9                 DB       0E9H
```

```
0796    32                  DB        32H
0797    85                  DB        85H
0798    E3                  DB        0E3H
0799    4C                  DB        4CH
079A    C0                  DB        0C0H
079B    40                  DB        40H
079C    CC                  DB        0CCH
079D    65                  DB        65H
079E    0A                  DB        0AH
079F    8D                  DB        08DH
07A0    7E                  DB        7EH
07A1    4C                  DB        4CH
07A2    29                  DB        29H
07A3    14                  DB        14H
07A4    0E                  DB        0EH
07A5    17                  DB        17H
07A6    30                  DB        30H
07A7    59                  DB        59H
07A8    92                  DB        92H
07A9    DC                  DB        0DCH
07AA    36                  DB        36H
07AB    A1                  DB        0A1H
07AC    1D                  DB        1DH
07AD    AB                  DB        0ABH
07AE    4A                  DB        4AH
07AF    FB                  DB        0FBH
07B0    BF                  DB        0BFH
07B1    94                  DB        94H
07B2    7B                  DB        7BH
07B3    76                  DB        76H
07B4    83                  DB        83H
07B5    A3                  DB        0A3H
07B6    D6                  DB        0D6H
07B7    1C                  DB        1CH
07B8    76                  DB        76H
07B9    E2                  DB        0F2H
07BA    63                  DB        63H
```

```
07BB    F6                DB        0F6H
07BC    9E                DB        9EH
07BD    59                DB        59H
07BE    27                DB        27H
07BF    0A                DB        0AH
07C0    01                DB        01H
07C1    0A                DB        0AH
07C2    27                DB        27H
07C3    59                DB        59H
07C4    9E                DB        9EH
07C5    F6                DB        0F6H
07C6    63                DB        63H
07C7    E2                DB        0E2H
07C8    76                DB        76H
07C9    1C                DB        1CH
07CA    D6                DB        0D6H
07CB    A3                DB        0A3H
07CC    83                DB        83H
07CD    76                DB        76H
07CE    78                DB        78H
07CF    94                DB        94H
07D0    BE                DB        0BEH
07D1    F8                DB        0F8H
07D2    4A                DB        4AH
07D3    AB                DB        0ABH
07D4    1D                DB        1DH
07D5    A1                DB        0A1H
07D6    36                DB        36H
07D7    DC                DB        0DCH
07D8    92                DB        92H
07D9    59                DB        59H
07DA    30                DB        30H
07DB    17                DB        17H
07DC    0E                DB        0EH
07DD    14                DB        14H
07DE    29                DB        29H
07DF    4C                DB        4CH
```

```
  07E0   7E               DB      7EH
  07E1   BD               DB      0BDH
  07E2   0A               DB      0AH
  07E3   65               DB      65H
  07E4   CC               DB      0CCH
  07E5   40               DB      40H
  07E6   C0               DB      0C0H
  07E7   4C               DB      4CH
  07E8   E3               DB      0E3H
  07E9   85               DB      85H
  07EA   32               DB      32H
  07EB   E9               DB      0E9H
  07EC   A9               DB      0A9H
  07ED   73               DB      73H
  07EE   46               DB      46H
  07EF   21               DB      21H
  07F0   04               DB      04H
  07F1   EF               DB      0EFH
  07F2   E1               DB      0E1H
  07F3   D9               DB      0D9H
  07F4   D8               DB      0D8H
  07F5   DC               DB      0DCH
  07F6   E6               DB      0E6H
  07F7   F4               DB      0F4H
  07F8   07               DB      07H
  07F9   1E               DB      1EH
  07FA   38               DB      38H
  07FB   55               DB      55H
  07FC   74               DB      74H
  07FD   95               DB      95H
  07FE   58               DB      058H
  07FF   DC               DB      0DCH
NO PROGRAM ERRORS
 * 01
 A        0007      B       0000       C       0001       D       0002
 E        0003      H       0004       L       0005       M       0006
 PSW      0006      SP      0006
```

APPENDIX 3

THE DFT OF THE STEP FUNCTION

The DFT as used in the spectrum analyser is defined as :

$$Xn = (1/N) \sum_{k=0}^{N-1} x_k \exp(-j2\pi nk/N)$$

Consider the input signal with the following properties :

$$x_k = \begin{cases} 1 & \text{for } k = 0\ldots(N/2-1) \\ 0 & \text{for } k = (N/2)\ldots(N-1) \end{cases}$$

$$\therefore \quad Xn = (1/N) \sum_{k=0}^{(N/2-1)} \exp(-j\pi nk/N)$$

$$\therefore \quad Xo = (1/N) \sum_{k=0}^{(N/2-1)} 1 = (1/N).(N/2)$$

$$\therefore \quad Xo = 0.5$$

for $n > 0$

$$Xn = (1 - \exp(-j\pi n))/(1 - \exp(-j2\pi n/N))/N$$

If n is even $\exp(-j\pi n) = 1$

$$\therefore \quad Xn = 0$$

If n is odd $\exp(-j\pi n) = -1$

$$\therefore \quad Xn = (2/N)/(1 - \exp(-j2\pi n/N))$$

$$= \frac{(2/N)}{\exp(-j\pi n/N)(\exp(j\pi n/N) - \exp(-j\pi n/N))}$$

$$= (-j/N \quad \exp(j\pi n/N)/ \sin(\pi n/N)$$

$$\therefore \quad Xn = (1/N) - j\,(1/N) \cos(\pi n/N)/ \sin(\pi n/N)$$

for odd n