VACUUM DEPOSITED OPTICAL PHASE FILTERS

by

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ABSTRACT

The advantages of an optical spatial phase filter constructed by thickness variations are put forward and a method of fabricating such a device using vacuum deposition techniques is detailed.

The design and construction of a vacuum system to produce such a device is outlined. The system comprises a vacuum chamber with a source holder for zinc sulfide, an electronically controlled shutter, an aperture, and a substrate and holder mounted on an x-y motion table driven by stepper motors. The system is controlled by a mini-computer and measurements of thickness are made by an ellipsometer controlled by the minicomputer.

Experiments conducted with the system determine the spatial resolution and closed loop control capabilities to be adequate. An analysis of the results of the tests concludes that with further refinements it seems feasible to fabricate spatial phase filters by using vacuum deposition techniques.

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INTRODUCTION

This thesis is an investigation of the practicality of producing optical phase filters using vacuum deposition techniques.

Consider an optical system consisting of two parallel planes separated by some distance. The electromagnetic field intensity in one plane is a function of the intensity in the other plane. To produce specific intensity functions in one plane from a particular intensity function in the other requires, in general, a complex valued filter to be placed between the two. An example of such a filter is a lens.

An ideal lens can be represented mathematically as a multiplicative factor of the form,[1]

$$\exp -jc(x^2+y^2) \tag{1}$$

where c is a constant and x, y are perpendicular reference axes. It is desirable to be able to produce more complicated phase functions than that of the lens. In fact, the corrections that must be made to a real lens so that it approximates the ideal more closely require a much more complex phase function.[2]

A simple form of phase filter was used by Tsujiuchi to correct lens aberrations and to produce optical systems with two focii.[3] The filters used were very simple in that they consisted only of a pattern of half wavelength retardations. Approximations were made in the calculations of the filter pattern in order to easily fabricate the devices.

Recently holographic techniques have been used to produce phase filters.[4] In the referenced work the authors used an amplitude hologram. Less than ten per cent of the signal power was deflected into the beam that has the desired altered phase.[5]

The most straightforward method of producing a pattern of phase variation would seem to be the use of a transparent material with a pattern of thickness variation. The material must have an index of refraction different from the transmission medium so that the speed of light is different in the filter. Thus the thickness variations convert to phase variations. With the aid of an index matching layer a phase filter of this type passes all of the available input signal power and is thus a significant improvement over the holographic type of filter. The thickness variation type of phase filter could conceivably be used in many applications in the field of optical information processing and spatial filtering where conventional photographic holograms are now used.

Researchers at I.B.M. have produced thickness variation phase filters which they call Kinoforms.[6] The devices are constructed by bleaching computer generated photonegatives. Bleaching removes the dark material in the negative, leaving a transparent pattern of thickness. It is pointed out that the ideal way of fabricating such devices would be to produce the thickness directly and not rely on a transformation from intensity to phase.

In this thesis an investigation is made of a method of fabricating a two dimensional device with thickness variations suitable for use as a phase filter in an optical system.

Starting with a parallel faced slab or substrate of transparent material, additional material must be added or removed to produce a thickness variation over the surface. Removal of material was not further explored, although developments in laser etching techniques make it look feasible. There are a number of methods of adding material to a substrate such as vacuum deposition, sputtering and screening. Of these, vacuum deposition seemed to be the most promising technique and was singled out for investigation.

Vacuum deposition was chosen for further study for a number of reasons. The technique has been used widely in the field of optics for various purposes such as anti-reflection films and multi-layer frequency selective filters. The materials used in vacuum deposition have been studied and are well documented.[7,8,9,10]

The following chapters describe the work performed to investigate the feasibility of fabricating phase filters by vacuum deposition techniques. Chapter I is a description of the proposed filter and the method of production. Chapter II describes the hardware designed and constructed, and the software written. Chapter III is a summary of the results and conclusions of the investigation.

CHAPTER I - BACKGROUND

A dielectric material will cause a phase change of the light transmitted through it in the following way. Consider Figure 1(a). The optical system between the two fixed reference planes z_0 and z_1 can be considered as a system with a transmission coefficient T.

$$T = \frac{(1+r_{01}r_{12}+r_{01}+r_{12})}{1+r_{01}r_{12}e^{-2j\theta_2}} e^{-j(\theta_1+\theta_2+\theta_3)} \qquad (2)$$

r_{ij} is the Fresnel reflection coefficient from medium i to medium j. The reflection coefficient for perpendicularly polarized light is

$$r_{ij} = \frac{n_i\cos\phi_i - n_j\cos\phi_j}{n_i\cos\phi_i + n_j\cos\phi_j} \qquad (3)$$

and for parallel polarization

$$r_{ij} = \frac{n_i\cos\phi_j - n_j\cos\phi_i}{n_i\cos\phi_j + n_j\cos\phi_i} \qquad (4)$$

ϕ_i and ϕ_j are defined in Figure 2. The optical path lengths θ_i's are given by

$$\theta_i = \frac{2\pi}{\lambda} n_i d_i \cos\phi_i \qquad (5)$$

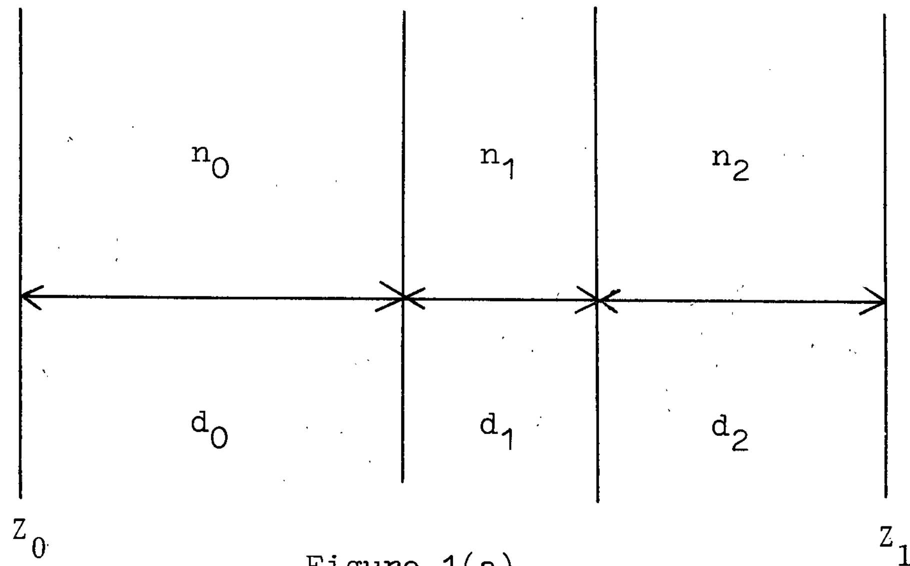

Figure 1(a)

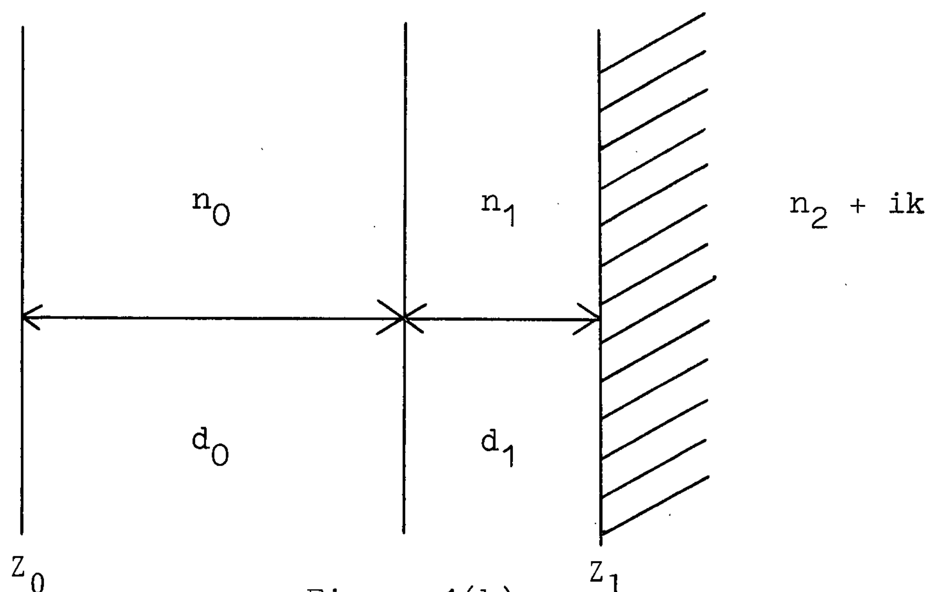

Figure 1(b)

Transmission and Reflection Optical Systems

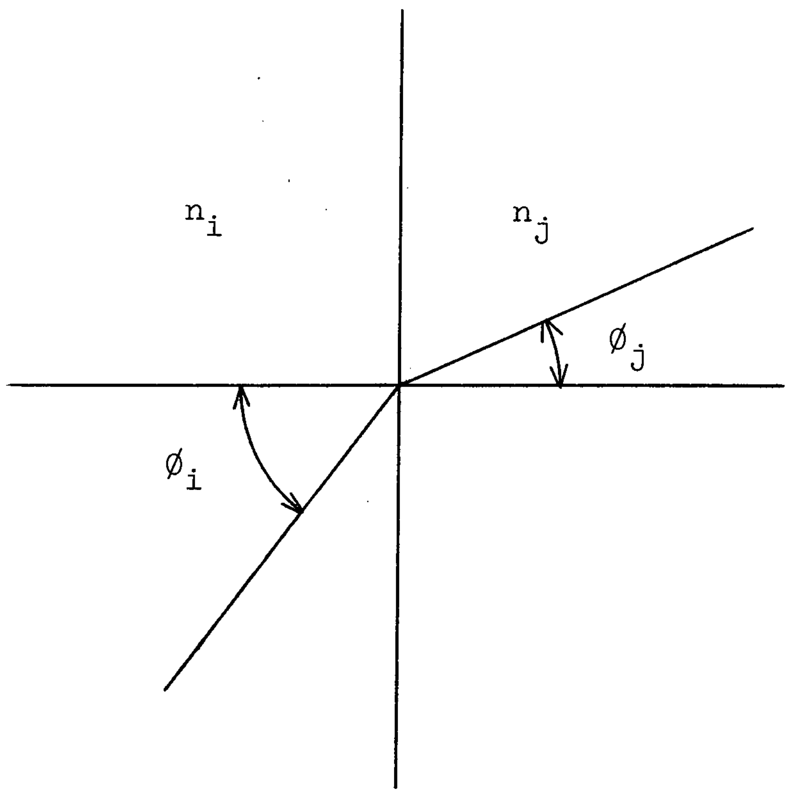

Figure 2. Angle of Incidence

where λ is the wavelength of the light, n_i is the refractive index of the i^{th} medium, and d_i is the thickness of the i^{th} medium. By varying the thickness d_1, the phase change introduced by the optical system is altered.

A similar result can be achieved by using the reflection geometry of Figure 1(b). The optical system between the two planes z_0 and z_1 can be characterized by a reflection coefficient

$$R = \frac{(1+r_{01}+r_{12}+r_{01}r_{12})(r_{01}+r_{12}e^{-j2\theta_1})}{1+r_{01}r_{12}e^{-j2\theta_1}} e^{-2j\theta_0} \qquad (6)$$

The computer program in Appendix I was used to calculate the phase changes produced by varying the thickness of the dielectric layer. The arbitrary zero of phase change was chosen to occur when the dielectric layer has zero thickness. Appendix I lists the computed change of phase due to dielectric thickness.

For the transmission geometry, the optical constants used in the equations were chosen for a film of magnesium fluoride on glass in air. For the reflection geometry, the constants used correspond to a film of zinc sulfide on an aluminum backing in air. These constants were chosen because they represent materials that have been frequently used in the field of optics.

A phase filter, being a device which alters the phase of a plane wave as a function of two dimensions, could be used in much the same manner as an interference hologram to store information and create images. This property can be demonstrated by utilizing the Fourier transformation property of a lens. A lens displays the two dimensional spatial Fourier transform of the intensity of one of its focal planes in the other focal plane. Thus, if an image is placed in the focal plane of a lens, its Fourier transform would appear in the other focal plane. The Fourier transform of a real image is in general a complex valued function.

The amplitude part of such a function can be easily constructed with a photographic transparency. If a phase filter could be constructed with the appropriate pattern of phase, one should be able to produce an image from the complex valued Fourier transform. Even without the amplitude part of the filter, it should be able to produce a reasonable image. This experiment was simulated numerically by using the Fast Fourier Transform program available on the University of British Columbia I.B.M. 360 computer system.

A two dimensional black-white image was digitized and then transformed into the spatial frequency plane. There the individual spatial frequencies were altered by normalizing each amplitude to unity while leaving the phases intact. This simulates the effect of illuminating the phase filter without amplitude compensation with a unit amplitude plane wave. The Fourier transform of the altered transform was then taken. This corresponds to the reconstruction process with a lens. Taking the Fourier transform twice, instead of taking the transform and its inverse, results in the axes being inverted.

The program written to demonstrate this effect is listed in Appendix II. The input to the program is the digitized pattern of Figure 3(a). The intensity function is spread by the amplitude normalizing. However, the bright areas, as indicated by the pattern of Figure 3(b), still show a reproduction of the original. The results of the computer experiment demonstrate the capabilities of a phase filter.

Vacuum deposition requires that the material to be deposited be heated to the vapour state and then condensed on the substrate. To produce a phase filter with vacuum techniques, involves the deposition of a varying thickness dielectric on the surface of a substrate such that the thickness is a function of the position on the surface. This involves controlling the position of deposition and also controlling the thickness of deposition.

Position of deposition can be controlled by collimating the vapour from the deposition source into a narrow beam and exposing the substrate only to that beam. The substrate must then be moved about so that the beam covers the entire surface. Use of this method restricts the spatial resolution to the fineness of the beam. An ellipsometer was available to measure the thickness of the deposited layer. The measurements from the ellipsometer could be used to determine the thickness of the layer that was currently being deposited

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Original Image

Figure 3(a)

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Second Transform

Figure 3(b)

Spatial Fourier Transform Example

and thus indicate when the layer was thick enough before proceeding to the next area.

The ellipsometer had been previously automated by connecting it to a Digital Equipment Corporation PDP 8-e minicomputer. This computer was ideally suited to control the positioning of the substrate and to control the thickness of the deposition at any one point. It would also be simple to communicate the pattern of phase required to a minicomputer since the pattern would, in all probability, be generated by a large computer.

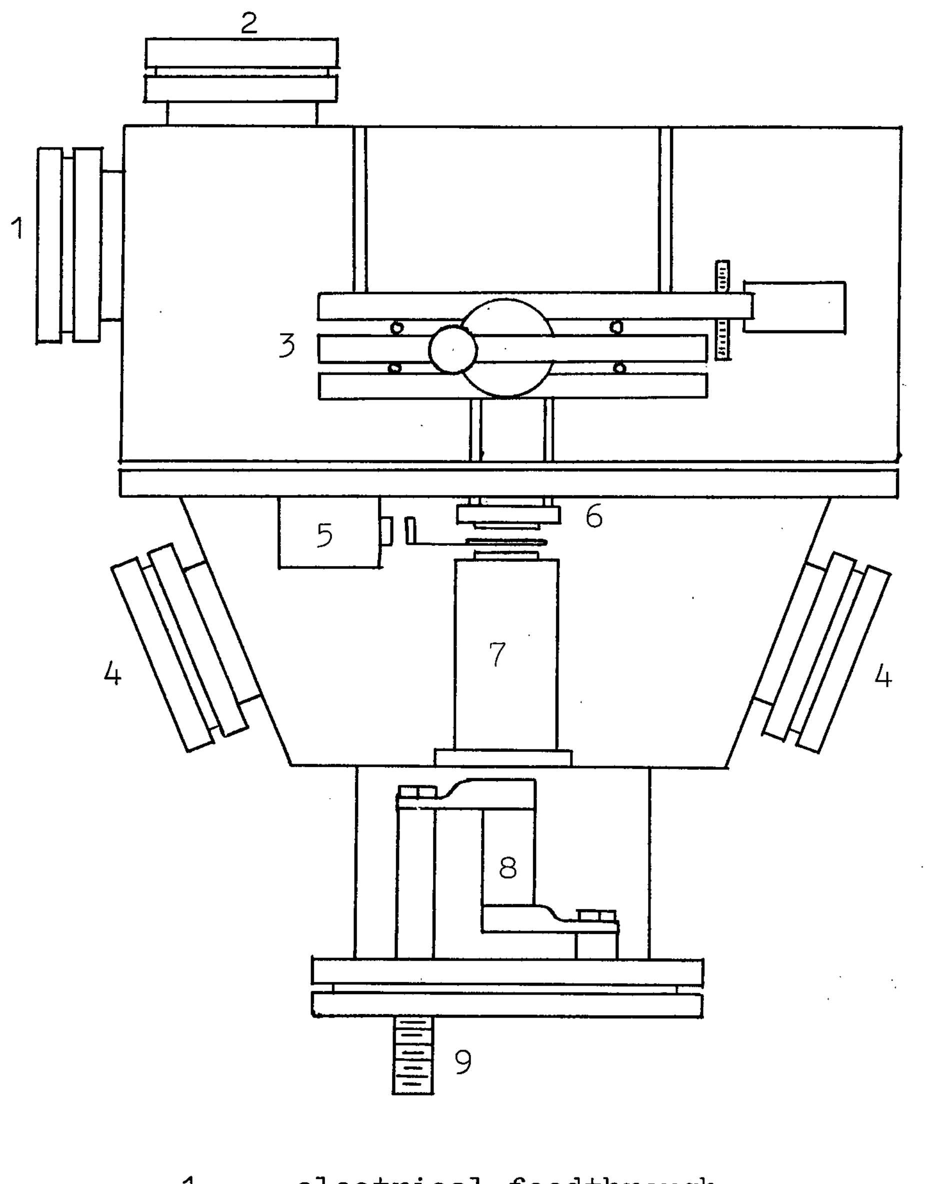
To further investigate the feasibility of producing phase filters by vacuum techniques, additional apparatus had to be designed, constructed and tested. The control strategy had also to be designed and implemented.

CHAPTER II - HARDWARE AND SOFTWARE

The technique of vacuum deposition requires a chamber equipped with a pumping system that can maintain pressures lower than 1×10^{-5} Torr. In this chamber, the source material to be deposited must be heated to a high temperature so that it vaporizes. The substrate must be held in proximity to the source so that the vapour condenses on its surface. Figure 4 is a sketch of the vacuum system designed and built to test the feasibility of producing a pattern of varying thickness deposit.

The main section of the chamber houses an x-y movement upon which the substrate is mounted. The x-y movement is driven by two stepper motors mounted within the chamber and powered from an electrical feedthrough on the side of the chamber. The rear of the chamber has a connection to the pumping system.

The front section of the chamber has angled sides and a barrel shaped nosepiece. The sides, which form a "V" with an interior angle of 140 degrees, are fitted with windows such that a light beam entering the center of one window at right angles would strike the substrate at an angle of incidence of 70 degrees and reflect out the other window. An electromagnetically operated shutter is fitted along the center line of the chamber as close to the point of intersection with the right angles to the windows as possible without interfering with the passage of light from



1 - electrical feedthrough
2 - vacuum pump connection
3 - x-y motion table and drive motors
4 - optical windows
5 - shutter
6 - substrate holder
7 - collimator
8 - source
9 - high current feedthrough

Figure 4. Vacuum Chamber Details

window to substrate to window. Between the shutter and substrate is a mask with a square aperture. The barrel of the chamber contains the source. The source is a round tantalum tube that is connected to high current electrical feedthroughs at the end of the barrel. The endpiece also contains an electrical feedthrough for the operation of the shutter. The source shutter and mask all lie along the center line of the chamber. Thus, the source is only able to deposit material on that section of the substrate visible to the source through the mask and then, only when the shutter is open. The motion of the x-y movement presents different areas of the substrate to the source.

The windows are fitted in such a way that the entire chamber can be placed between the two arms of an ellipsometer. Thus, the thickness of the area being deposited can be monitored in situ.

The chamber is constructed of helium-arc welded type 316 stainless steel. The front section separates from the main chamber to allow servicing of the substrate. The two sections are bolted together and sealed with a large "O" ring. The source and feedthroughs are mounted on a flange that is bolted to the front end of the barrel section. The entire chamber is mounted on a large aluminum plate that facilitates locating the unit on the ellipsometer.

The pumping system connected to the rear of the main chamber consists of a mechanical rotary pump for roughing from atmospheric pressures and an oil diffusion pump for higher vacuums. This arrangement of pumps is able to adequately maintain a pressure of less than 1 x 10^{-5} Torr.

The chamber and x-y movement were designed for this experiment. The construction was carried out by Mr. J. Stuber.

The ellipsometer used to monitor film thickness had been previously equipped to make measurements under control of a minicomputer. An ellipsometer is a device which measures two optical quantities called Δ and Ψ which are related to the reflection coefficients of an optical system by

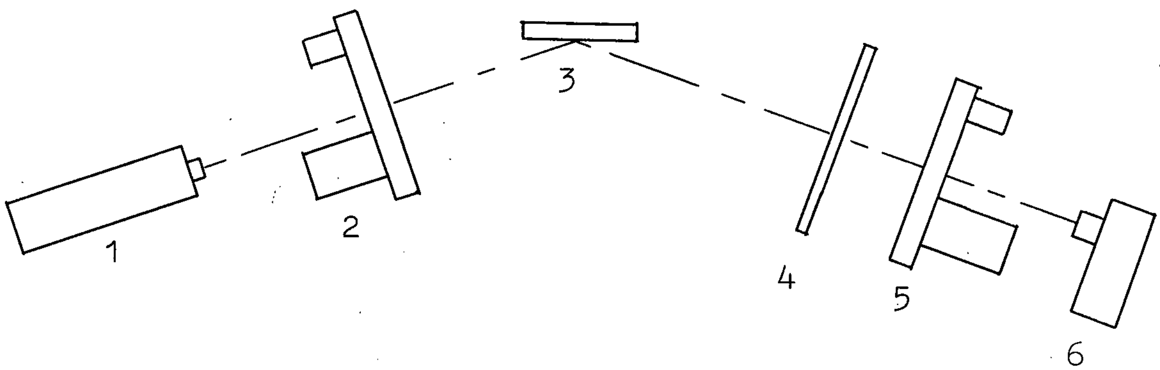
$$\tan\Psi e^{j\Delta} = \frac{R_p}{R_s} \qquad (7)$$

where R_p is the reflection coefficient for parallel polarized light and R_s is the reflection coefficient for perpendicular polarized light.

A schematic diagram of the ellipsometer is given in Figure 5. The polarizer and analyzer are polaroids and the quarter wave plate is a Soleil Babinet compensator that introduces a phase change of 90 degrees between the perpendicular and parallel polarizations of the light beam. The intensity of the light emerging from the analyzer is given by

$$I = I_0 \sin^2(\Psi + A) - \sin 2\Psi \sin^2 \tfrac{1}{2}(\Delta - \Delta') \qquad (8)$$

[1] Δ' is defined by



1 - laser light source

2 - polarizer with shaft encoder and drive motor

3 - sample

4 - quarter wave plate

5 - analyzer with shaft encoder and drive motor

6 - photomultiplier tube light detector

Figure 5. Ellipsometer Schematic

$$\tan \Delta' = \sin\delta \tan(2P-\frac{\pi}{2}) \qquad (9)$$

where δ is the retardation of the quarter wave plate, and A is the analyzer setting and P is the polarizer setting.

Making a measurement with the ellipsometer, or balancing the ellipsometer, involves determining a combination of polarizer and analyzer settings that produces a null in the light intensity emerging from the analyzer.

With the quarter wave plate set at -45° to the plane of incidence, at extinction the relations between Δ and P, and Ψ and A are:

$$\begin{array}{ll} \Delta = 90° - 2P & 135° > P > -45° \\ \Psi = A & 90° > A > 0 \end{array} \qquad (10)$$

and

$$\begin{array}{ll} \Delta = 2P - 90° & 225° > P > 45° \\ \Psi = 180° - A & 180° > A > 90° \end{array} \qquad (11)$$

A detailed list of all combinations of analyser and polarizer settings that produce a null is given by F.L. McCrackin et al.[12]

Because the signal from the photomultiplier falls to insignificant levels near a null, it was not possible to determine the position of the null directly. Fortunately, both I versus A and I versus P characteristics are symmetrical about the null point. I versus P is symmetrical provided δ is close to 90 degrees. Thus, by determining equal intensities on either side of the minimum, the position of the null can be determined as the midpoint.

Both the polarizer and analyzer are driven by stepping motors geared so that one step rotates the polaroid by 0.01 degrees. The positions of the polarizer and analyzer are measured by a shaft encoder connected to the drive gearing in each unit. The two encoders are read by a multiplexed decoder to provide a five digit BCD output which ranges from 000.00 degrees to 359.99 degrees. The analyzer shaft encoder was mounted in opposition to the scale engraved in the analyzer so that the reading from the encoder must be complimented by 360 degrees to make it compatible. The light intensity monitored by the photomultiplier is read through a multiplexed ten bit analog to digital converter.

The ellipsometer had previously been interfaced to a PDP-8e minicomputer. The shaft encoder and photomultiplier were input to the computer and the computer was able to turn the stepper motors on the analyzer and polarizer. The interface was expanded so that the computer was able to rotate the stepper motors connected to the x-y drive in the vacuum chamber. The shutter was also operated through the computer interface.

Operator communication to the system was made via an ASR-33 teletype. The teletype handler program operates the teletype under interrupt control. All input from the keyboard is put into a buffer until it is used and removed by a program requiring input. All print output is put into another buffer which the teletype handler tries to keep empty by outputting the contents on the printer. Since teletype input and output are performed on an interrupt basis, the computer is able to carry out control tasks in the background while serving the teletype.

A simple operating system was written to allow an operator to initiate control actions from the keyboard. When first started, the operating system initializes flags and counters used throughout the programs in the system. The only other function of the operating system is to check the keyboard buffer for inputs and translate these inputs into control programs to execute. Commands take the form of two truncated ASCII characters. The operating system compares inputs with a table of names it recognizes. If a match is made, the control program in the address table corresponding to the name table is executed. The control programs are all subroutines that return to the operating system when they have completed their task.

For this thesis, it was required to operate the ellipsometer and the shutter and x-y drive in the chamber. Also a higher level program was required to coordinate these controls in such a way as to produce a deposit of a required thickness. Two commands that were implemented were "set the polarizer" (SP), and "set the analyzer" (SA). Either command expected a five digit input from the keyboard that represented the position required of the analyzer or polarizer. These two programs first read the shaft encoder to determine the present position of the unit and then output the appropriate number of steps to turn the unit to the required position in the direction that required the least motion.

The two commands to move the x-direction and y-direction stepper motors on the x-y drive in the chamber were given the names MX and MY respectively. The programs associated with these commands expected inputs from keyboard to indicate direction of movement in the plane and the distance of travel. Direction was indicated by "F" and "R". An "F" meant to the right in the x-direction and up in the y-direction when looking at the chamber from the source end. "R" is the opposite of "F".

All four stepper motors, the shaft encoder multiplexer and the shutter switch were connected to device 33 in the computer interface. This device was a set of twelve flip flops, one per bit of the computer word as defined in Table 1. The IOP2 pulse from the computer output the accumulator to set the flip flops. The IOP4 pulse was used to send a pulse to the stepper motors that had their enable bit set. The pulse was steered to the clockwise or counter-clockwise input on the stepper motor controllers by the direction bit. Thus, any of the four stepper motors could be moved by first setting its enable and direction bits with an IOP2 pulse and then sending an IOP4 pulse for each step.

Once the gating for a motor had been set, a routine labelled STEP was used to output one step pulse to the motor. The motors used had a resonance at approximately 200 steps per second. To run the motors at a speed above the resonance required that they be accelerated from a stopped position.

Device 33 of Computer Interface

Bit Position	Function
0	Polarizer motor direction
1	Polarizer motor enable
2	Analyzer motor direction
3	Analyzer motor enable
4	Y-axis motor direction
5	Y-axis motor enable
6	X-axis motor direction
7	X-axis motor enable
8	Unused
9	Unused
10	Shutter control
11	Shaft encoder gate

Table 1

Since timing was generated by software, it was not convenient to run more than one motor at a time. The hardware status of device 33 was stored in a location labelled DIR. Bit 9 of DIR was used for a flag to indicate that acceleration was required. The routine STEP accelerated the motors by shortening the time between pulses from a maximum when the flag was first set to a minimum after a certain number of pulses had been sent. At this time the flag was cleared.

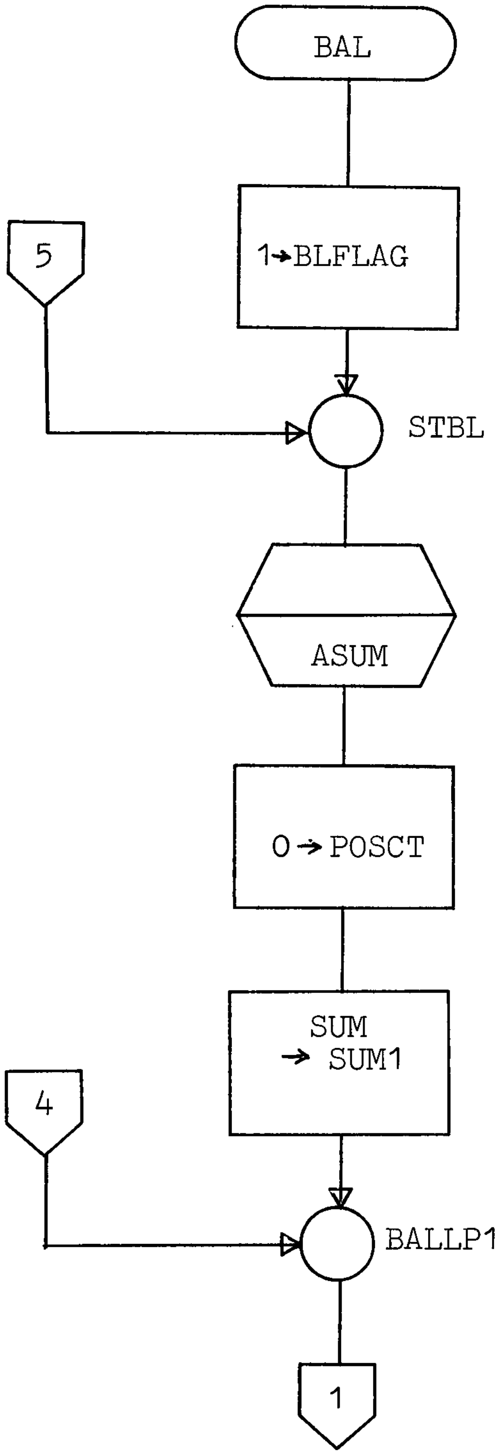
The output of the multiplexed shaft encoder was connected to device 30 in the interface. The shaft encoder was always set to read the analyzer when the analyzer motor was selected, and the polarizer, when the polarizer motor was selected. The IOP2 pulse was used to strobe the high order two BCD digits into the accumulator and the IOP4 pulse was used to strobe the three low order BCD digits. These numbers were read by a program named RDSFT and were stored in locations SHFTH and SHFTL respectively.

The output from the photomultiplier on the ellipsometer was measured by the computer with an analog to digital converter, device 32 in the interface. The program, ANALG, was responsible for reading the analog to digital converter and converting the reading into volts.

To take a reading from the ellipsometer requires that the polarizer and analyzer be positioned so that the output from the photomultiplier is a minimum. The suggested procedure is to first balance, that is, find a minimum of, the polarizer.[11] Then the analyzer is balanced. The polarizer is again balanced and finally the analyzer is balanced again. This procedure can be commanded from the keyboard with a BE input. The procedure is really a combination of the two commands BA and BP which balance the analyzer and polarizer respectively. These two routines set the gating for the appropriate stepper motors and then call upon a common routine called BALU.

The routine BAL (see Figure 6) determines the position of a minimum photomultiplier reading by finding equal intensities around a minimum. To avoid noise problems due to low signal levels, the sum of many readings is taken. First a running sum of readings is taken by moving the motor one step, reading the photomultiplier and adding the reading to the sum. The sum is taken over sixty-four steps. A second running sum is taken and compared with the first. If the second sum is larger, the motor is reversed and the routine restarted. Otherwise, the first sum is replaced by the second and the second sum is taken again and again compared with the first. A flag is set to indicate the minimum has not yet been passed. At some point the second sum will be larger than the first indicating that the minimum has been passed. Another set of readings is taken and this sum is saved as the comparison on one side of the minimum. The motor is reversed and run back two sets of readings. The next set of readings is saved, reading by reading, along with the running sum. From here on, every time the motor is stepped, the newest reading is put at the beginning of the

FLOWCHART OF SUBROUTINE BAL



ENTRY POINT.

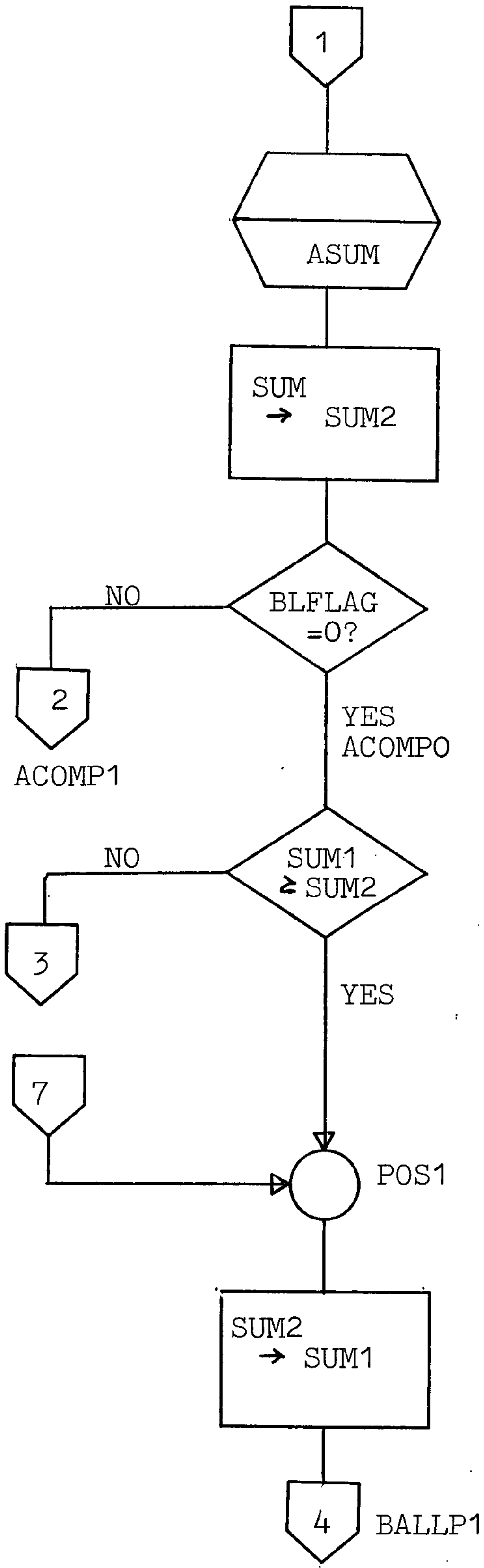
SET FLAG TO INDICATE MINIMUM NOT BEING APPROACHED.

TAKE A GROUP OF READINGS.

INITIALIZE POSITION COUNTER.

SAVE FIRST GROUP OF READINGS.

FIGURE 6



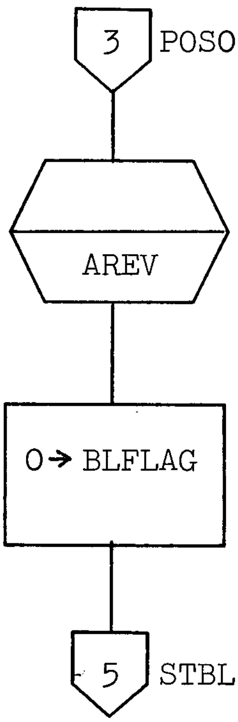
TAKE ANOTHER SET OF READINGS.

SAVE SECOND SET.

IS MINIMUM BEING APPROACHED?

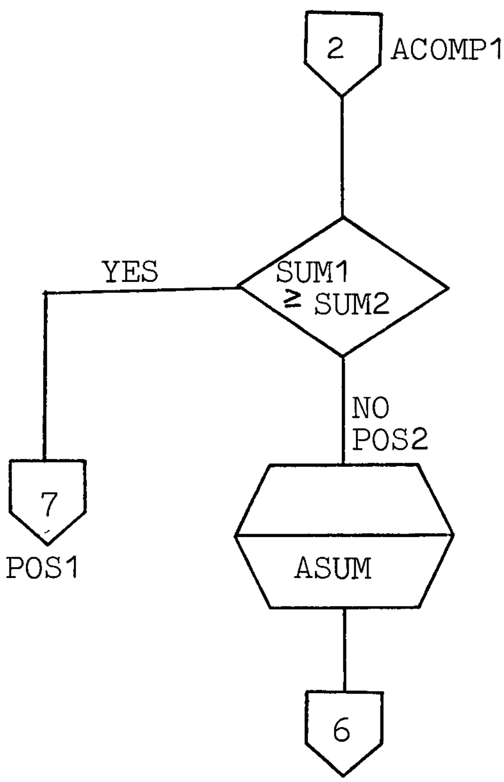
COMPARE SUCCESSIVE READINGS TO DETERMINE IF MINIMUM IS STILL BEING APPROACHED.

REPLACE FIRST READING WITH SECOND AND ITERATE.



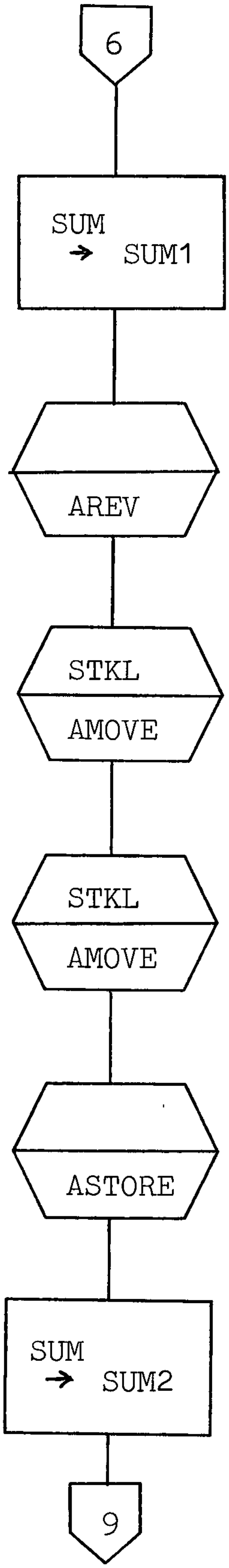
CHANGE DIRECTION
OF DRIVE MOTOR.

SET FLAG TO INDICATE
MINIMUM IS BEING
APPROACHED.



CHECK IF STILL
APPROACHING MINIMUM.

TAKE ANOTHER SET OF
READINGS TO USE FOR
COMPARISON.



SAVE COMPARISON SUM OF READINGS.

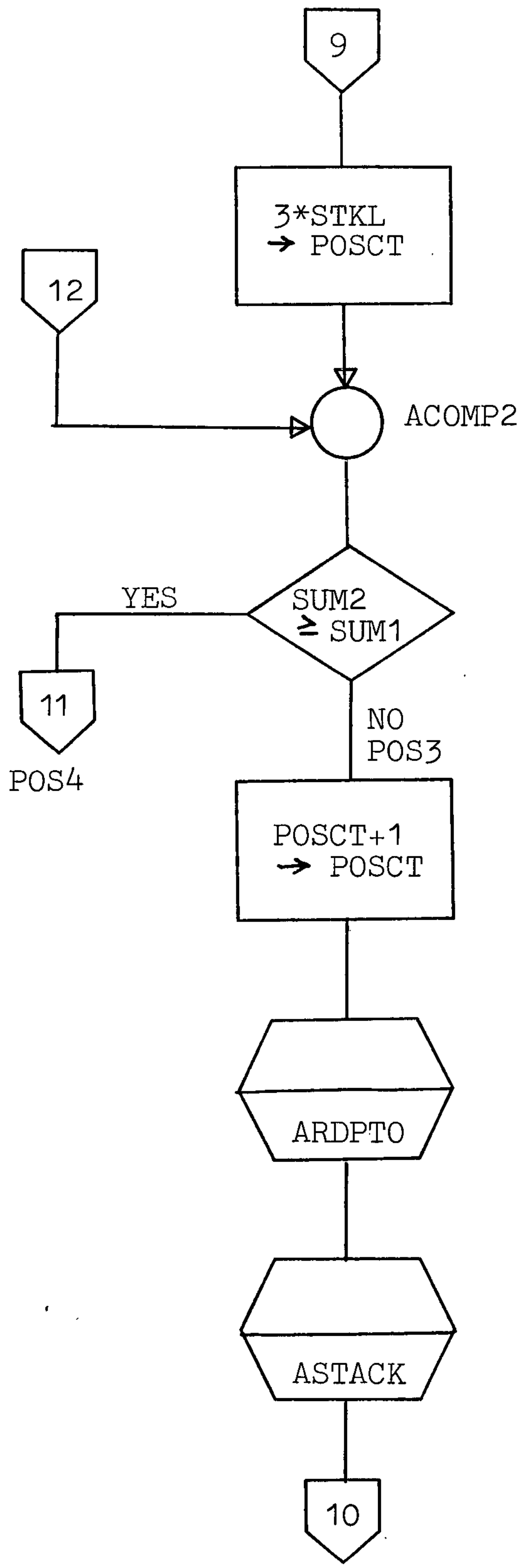
REVERSE DIRECTION OF DRIVE MOTOR.

MOVE NUMBER OF STEPS IN ONE SET OF READINGS. (STKL)

MOVE BACK A SECOND SET OF READINGS.

TAKE A SET OF READINGS AND SAVE EACH READING IN A FIRST-IN-FIRST-OUT STORE.

SAVE SUM OF ABOVE SET OF READINGS.



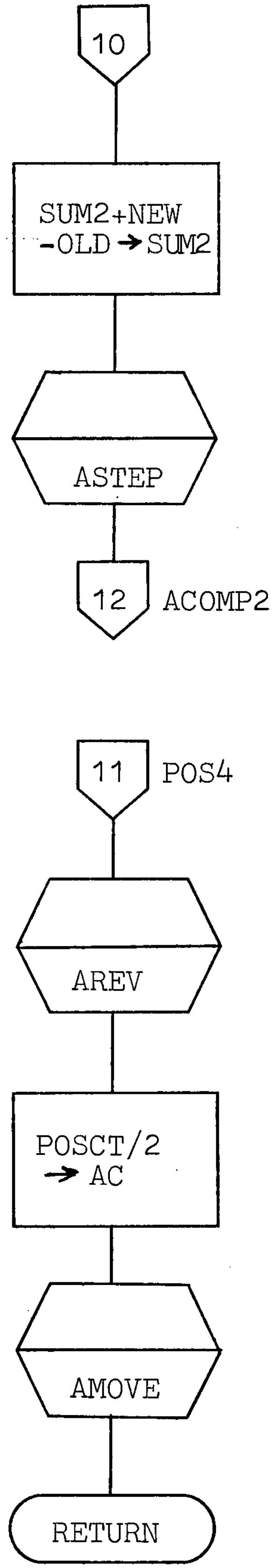
SET POSITION POINTER TO INDICATE DISTANCE MOVED FROM START OF COMPARISON SUM.

HAS EQUAL POSITION ON OPPOSITE SIDE OF MINIMUM BEEN REACHED?

ADVANCE POSITION COUNTER.

TAKE A READING.

PUT NEW READING IN STACK AND REMOVE OLDEST READING.



UPDATE SET SUM WITH NEW READING.

MOVE MOTOR TO NEXT READING AND ITERATE.

REVERSE DRIVE MOTOR DIRECTION.

DIVIDE DISTANCE BETWEEN CURRENT POSITION AND COMPARISON SUM POSITION IN HALF.

MOVE TO BALANCE POSITION.

RETURN FROM BAL SUBROUTINE.

buffer and the oldest one is removed. The running sum is also adjusted by adding on the newest reading and subtracting the oldest. This running sum is compared with the comparison sum and as soon as it is equal to or larger than the comparison sum, the position of the minimum can be determined as the midpoint of the two sums. The motor is reversed and driven to the midpoint. The analyzer and polarizer positions and photomultiplier reading at the balance point are printed on the teletype.

The shutter in the chamber could be operated from the keyboard with the two commands "open shutter" (OS), and "close shutter" (CS). These commands changed the state of a flip flop on device 33 in the interface. The shutter solenoid was energized by a power transistor driven by the flip flop.

Closed loop control of film thickness was accomplished by setting the analyzer and polarizer to the positions at which a balance would occur if the film were the correct thickness. The shutter was then opened until the photomultiplier output dropped to a minimum. The shutter was closed to stop the deposition process. This procedure was commandable from the keyboard and given the name SB, "stop on balance". For noise immunity, the SB program uses sums of readings instead of a single reading of the photomultiplier.

A typical sequence of commands that produces a deposit of a specified thickness is the following:

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MX F 001
MY F 001
SA 47.21
SP 325.54
SB
```

The MX and MY commands move the substrate to a desired position and the SA and SP commands move the analyzer and polarizer to the balance position. The SB command finally opens the shutter and closes it when a balance occurs. The distances for the MX and MY commands are in units of the mask aperture width so that adjoining areas can be reached by moving in increments of one.

The teletype input program was written so that the paper tape reader on the ASR 33 was enabled if there was room in the input buffer. Thus, the operation of the system could be controlled with commands stored on paper tape. In this way the thickness pattern of the substrate could be generated on a large computer system where it could be converted to analyzer and polarizer settings. The large computer system would then generate an ASCII paper control tape. The physical pattern could then be produced with the hardware described by reading this tape.

CHAPTER III - RESULTS AND CONCLUSIONS

To test the performance of the equipment, two experiments were conducted. The first experiment consisted of depositing material to study the deposition process and products. The second experiment was a check of the closed loop control of the system.

The substrate used was an optical glass flat, 25 x 25 millimeters. The substrate was coated with a layer of vacuum deposited aluminum to give it a reflecting surface. The substrate was transferred to the x-y movable holder in the vacuum chamber. The chamber was evacuated in preparation for deposition of zinc sulfide.

Before any depositions were made on the bare aluminum surface of the substrate, the surface was checked for uniformity. This was accomplished by moving the x-y holder so that the ellipsometer could take readings of different areas of the surface. A map of the surface uniformity is given in Table 2.

The x-y holder was then set to a corner of the substrate and the evaporation current turned on. The shutter was opened and zinc sulfide allowed to deposit through the aperture onto the substrate. The ellipsometer was used to observe the evaporation process. After a suitable thickness of zinc sulfide had been deposited, the evaporation was halted by closing the shutter. The x-y holder was then moved a distance equal to the width of the aperture,

56.85 46.18	56.69 46.18	56.50 46.16	55.76 46.21
57.03 46.19	56.82 46.19	56.59 46.15	55.85 46.24
57.41 46.17	57.30 46.18	57.00 46.21	56.57 46.20
57.76 46.11	57.56 46.17	57.42 46.10	56.85 46.27
58.88 46.03	58.64 46.03	58.01 46.05	57.17 46.08

Top - Polarizer

Bottom - Analyzer

Table 2. Scan of Aluminum Coated Substrate

1.59 millimeters. The shutter was then again opened to deposit onto an area adjacent to the first. A thickness of zinc sulfide different from the first area was then deposited on the second. The procedure was repeated for a third time to form three adjacent areas of different thicknesses.

After the third area, the shutter was closed and the x-y holder moved at right angles a distance twice the width of the aperture. At this position, a thickness of zinc sulfide was again deposited. The holder was then positioned a little beyond the edge of the last square deposited and an ellipsometer reading was taken. The holder was then moved a small distance, 47 micrometers, towards the square and another reading was taken. This process was repeated until the profile of the entire square was obtained. The holder was then positioned near the area of the three adjacent squares and a similar scan was made along the center line of the three squares. The readings are presented graphically in Figures 7, 8 and 9.

The second experiment was performed to determine the capabilities of the control system. For this experiment different areas of the same substrate were used. Suitable values of polarizer and analyzer readings were chosen from the first set of evaporations. These readings were used to produce a control tape for the second experiment. Four areas adjacent to one another were to be evaporated upon. The vacuum system was prepared and evacuated. After the

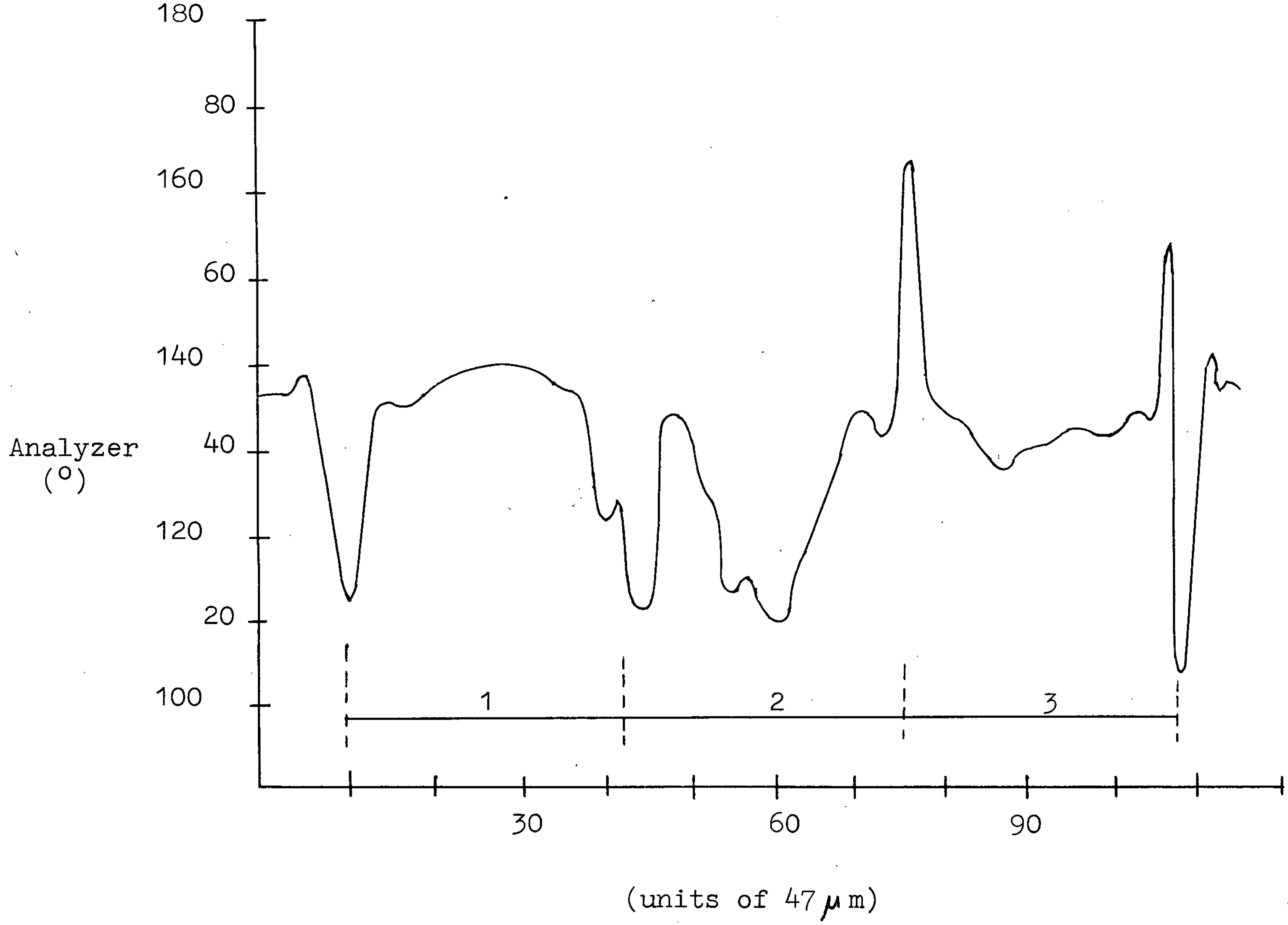

Figure 7. Analyzer Scan of Squares 1 - 3

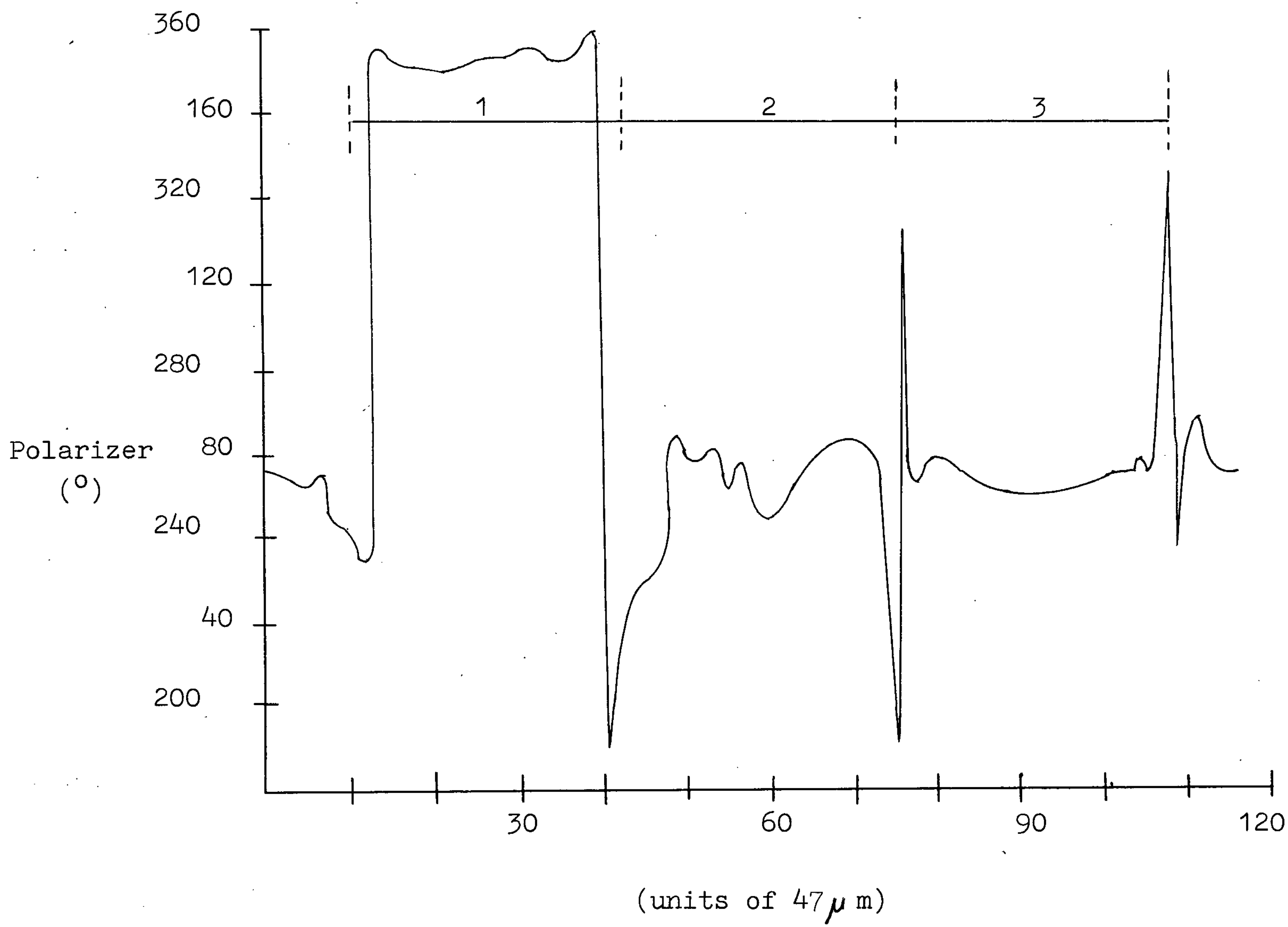

Figure 8. Polarizer Scan of Squares 1 - 3

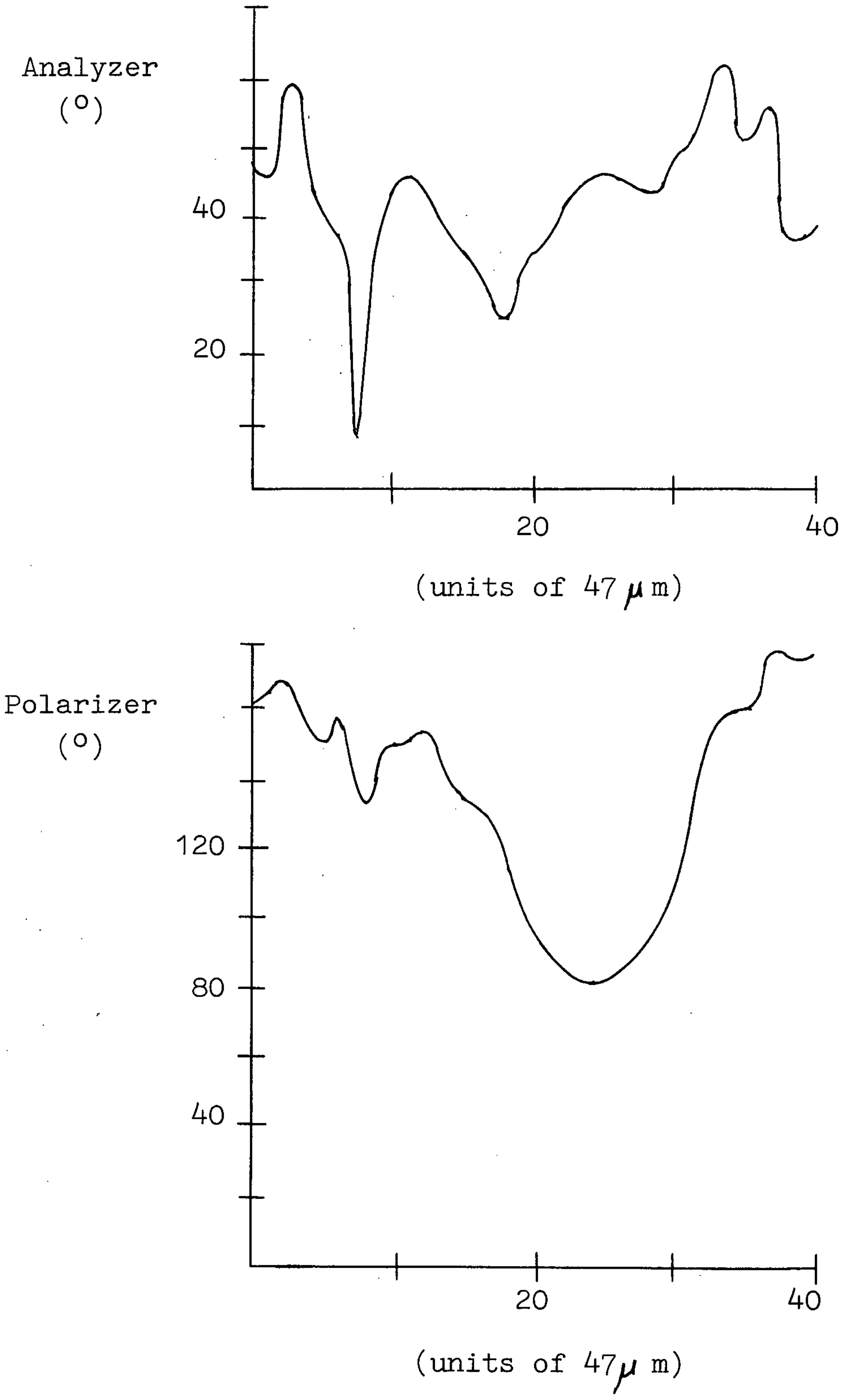

Figure 9. Polarizer and Analyzer Scan of Square 4

evaporation current was turned on, the control tape was read into the computer and the computer was allowed to control the evaporations and movements of the x-y holder. The photomultiplier reading was observed while the process was taking place.

The control system successfully found a null on the first square deposited, halted deposition and went on to the next square. On the second square, the null was very shallow and two shallow nulls were bypassed before manual intervention caused the process to proceed to the third and fourth squares. The control system again successfully detected nulls on these two areas and halted evaporation.

After the fourth square, the evaporation current was turned off and the ellipsometer was used to scan the center line of the four squares taking readings at short intervals. The scan is graphically presented in Figures 10 and 11. Finally, the holder was moved to a bare area and with the shutter open, continuous ellipsometer readings were taken. The Δ-Ψ curve from this data was plotted in Figure 12.

Using the average values of polarizer and analyzer readings from Table 2, the optical constants of the aluminum substrate, as viewed through the windows on the chamber, were determined using McCracken's program.[11] Using values for the index of zinc sulfide, the Δ-Ψ curve for the filter was calculated again using McCracken's program. This curve is presented graphically in Figure 13.

The scan of the bare aluminum substrate indicated that

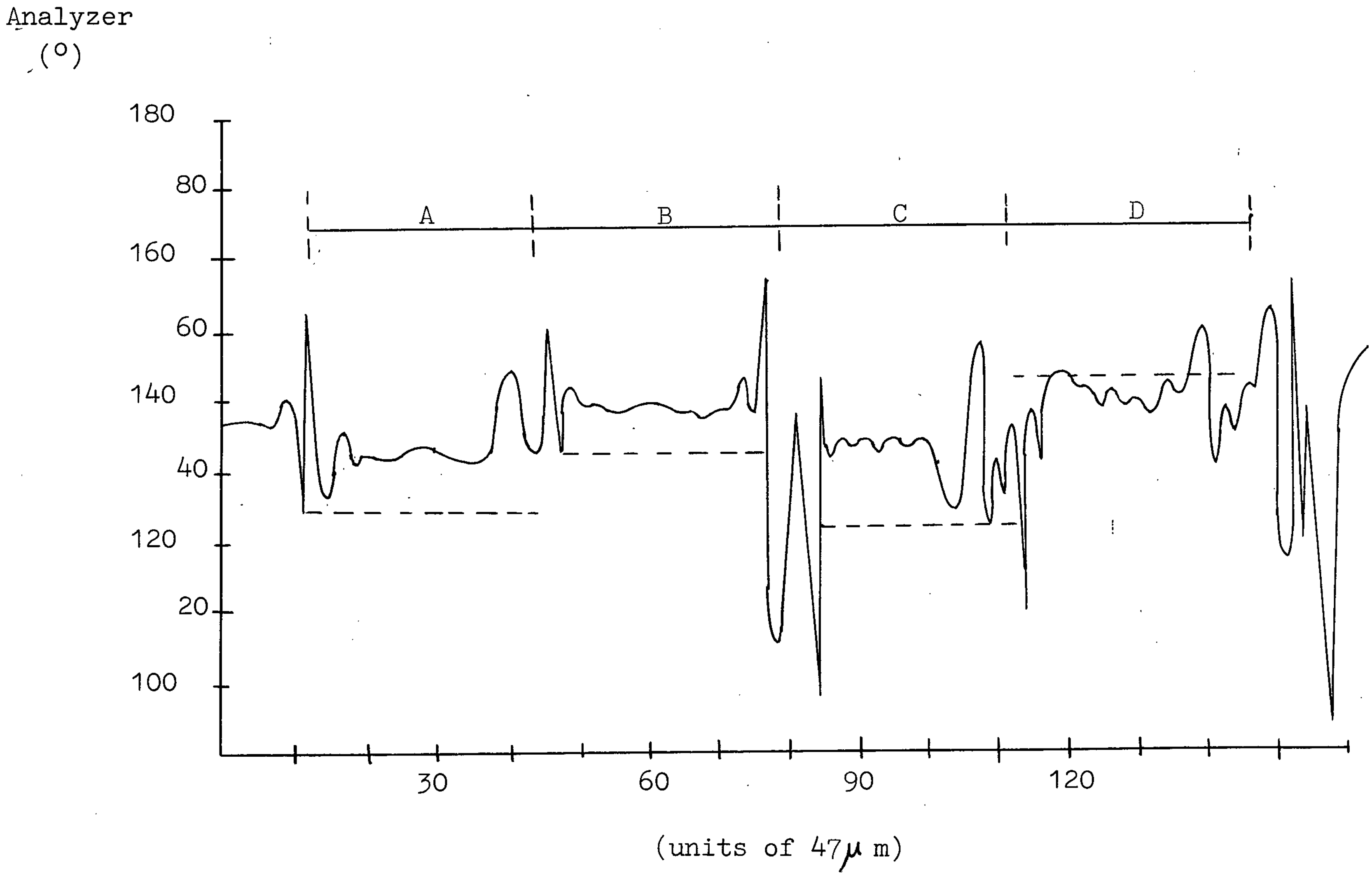

Figure 10. Analyzer Scan for Squares Deposited While on Control

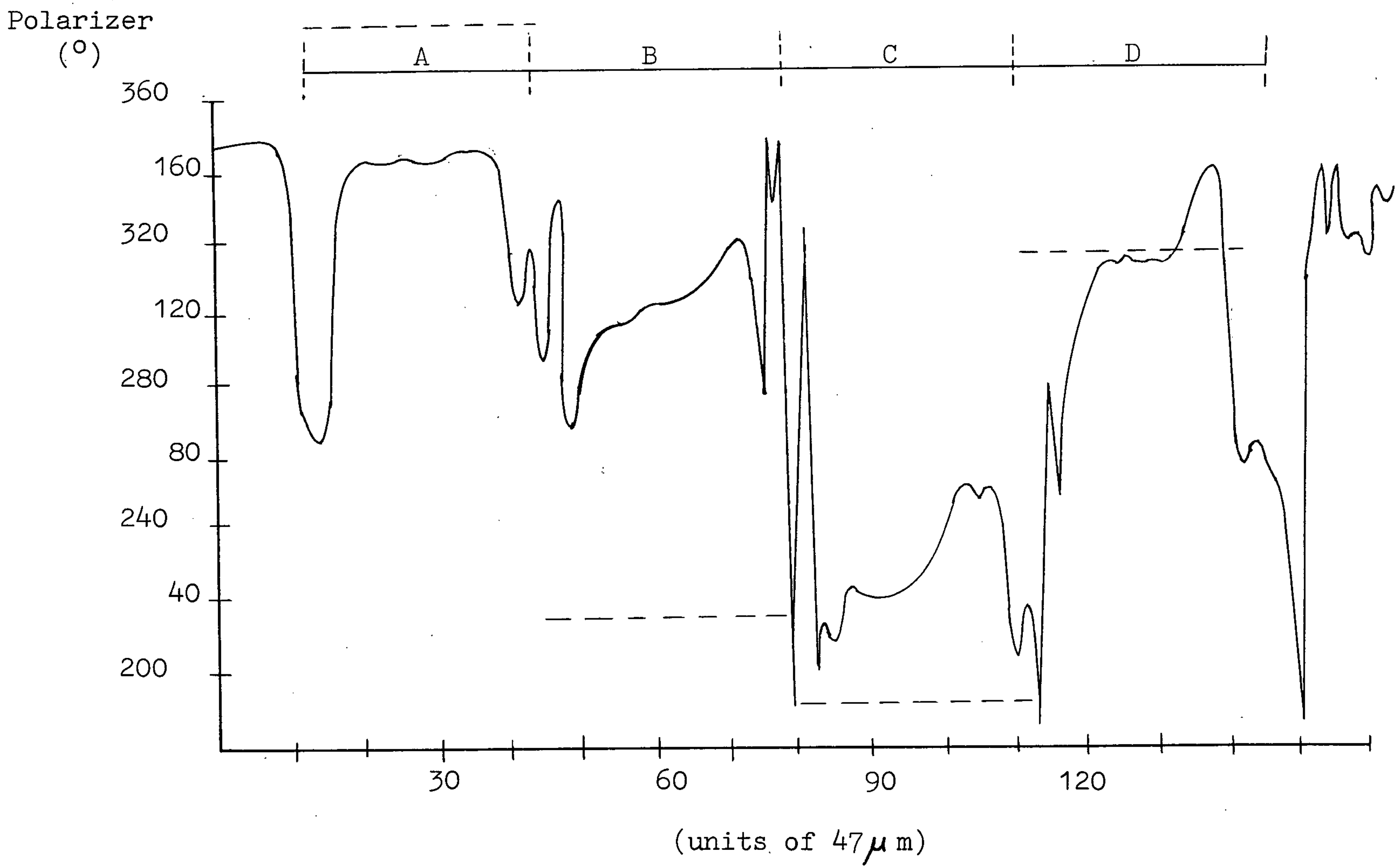

Figure 11. Polarizer Scan for Squares Deposited While on Control

the surface was uniform to an equivalent thickness of 20 angstroms of zinc sulfide as judged from the Δ-Ψ curve of Figure 13. The Δ and Ψ readings for the aluminum covered substrate, however, do not fit on the calculated curve for zinc sulfide on aluminum. The reason for this is probably that the "bare" aluminum is not really bare but has a coating of aluminum oxide which forms when aluminum is exposed to air. Therefore, the ellipsometer is actually measuring the aluminum and aluminum oxide layer as the substrate.

The results of the first experiment indicate mixed conclusions. The ellipsometer scan of the deposited squares point to nonuniform depositions and this was confirmed by visual examination of the substrate. The squares labelled 2 and 4 in Figures 7, 8 and 9 were uneven. The scan does, however, show clearly the definition of the squares. The edges of the square are defined by drastic changes in ellipsometer readings and the center sections are reasonably smooth.

The ellipsometer curve drawn from the measurements of the second experiment, Figure 12, differs from the theoretical curve for zinc sulfide on aluminum, Figure 13. Again, the most probable cause for this is the coating of aluminum oxide on the bare substrate. The index of vacuum deposited zinc sulfide films has been discovered to depend on the details of deposition such as rate of deposition, temperature and pressure.[8] These findings could also contribute to the difference.

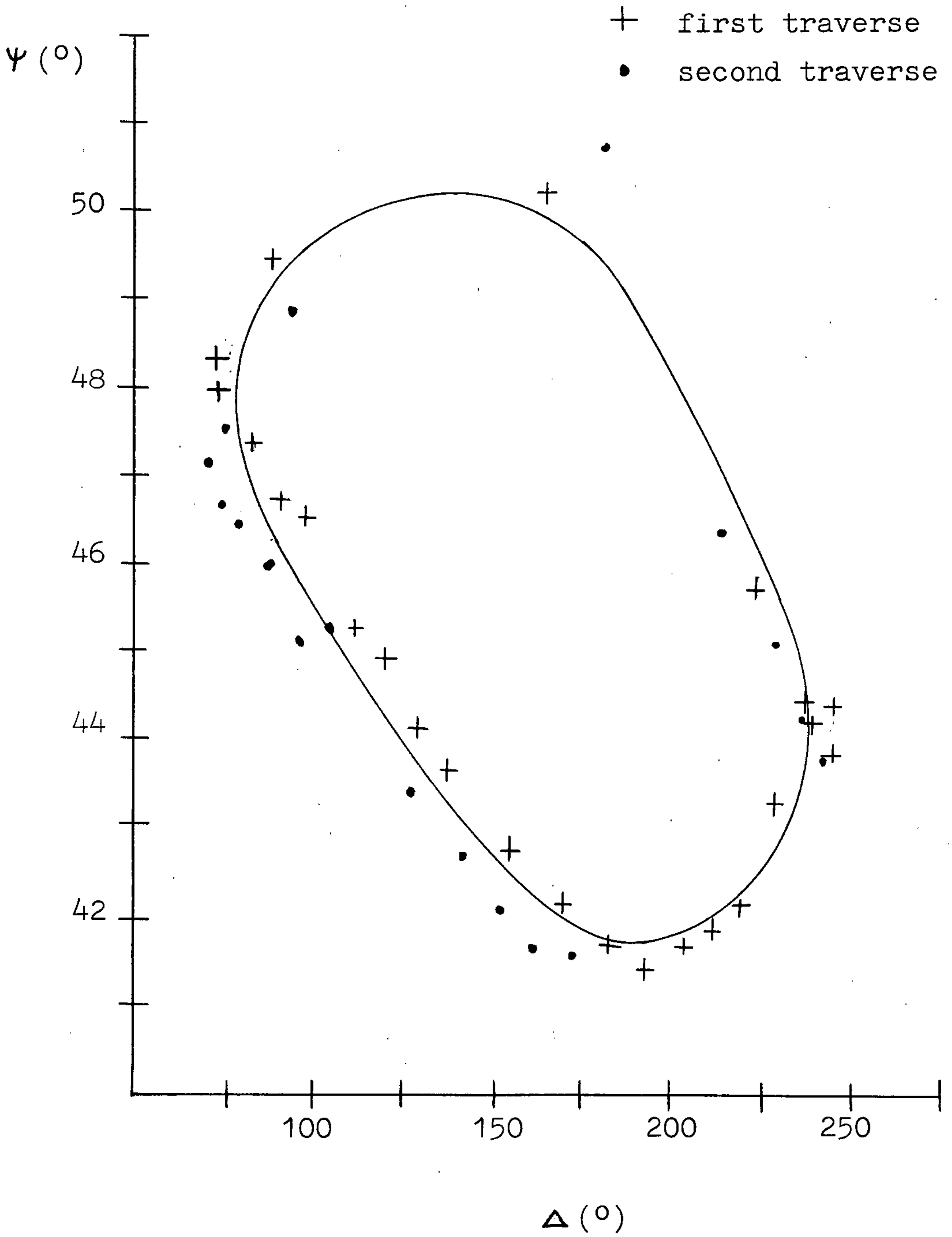

Figure 12. Δ-Ψ Plot (Experimental)

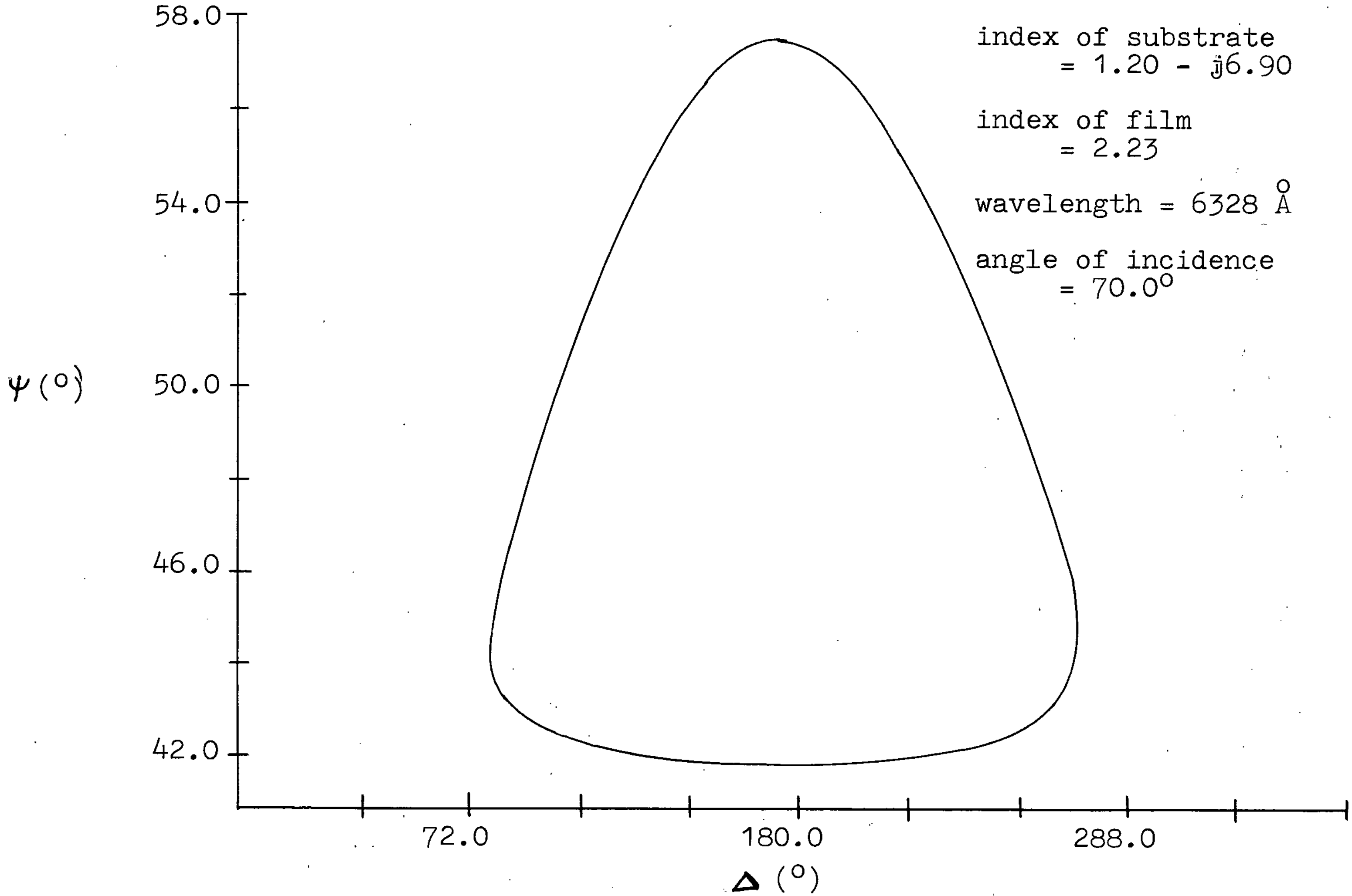

Figure 13. Δ-Ψ Plot (Calculated)

The computer control of thickness was successful to a limited extent. The actual control mechanism and algorithm performed well. The shutter was automatically closed to stop deposition after just passing the low point of a minimum from the ellipsometer readings. A poor selection process caused values of polarizer and analyzer readings to be chosen as setpoints. The chosen readings did not fall on the curve of Figure 12. The poor setpoints were evidenced by the shallow minimum in the ellipsometer output. The control system stopped deposition when it came as close as possible to the setpoints. During the deposition of the square labelled "D" in Figures 10 and 11, a sharp minimum was observed and as seen from later analysis, the control system came very close to the desired setpoints. The setpoints are shown as dotted straight lines in Figures 10 and 11.

The equipment built and experiments made have only tested the feasibility of producing phase filters with vacuum deposition techniques. To produce useful devices, the spatial resolution of the deposition system must be increased by an order of magnitude. This involves smaller apertures and closer tolerances on the positioning mechanisms. The experiments conducted have shown that the resolution used is attainable. The deposition system must be calibrated and errors introduced by the surface condition of the substrate must be accounted for. During the tests of this thesis, these factors were ignored as only relative thickness of deposit was aimed for. The control and measurement systems seem capable of the tasks required of them. Thus, if further tests to calibrate the system were made, absolute thickness variations should be achievable.

In summary, a method of fabricating optical phase filters has been investigated. Possible uses of an optical phase filter have been proposed. The hardware to fabricate such a phase filter using vacuum deposition techniques was designed and constructed. Software was written to control production of the phase filters by a digital computer. And finally, the first steps were taken to produce the devices. The difficulties encountered were not fundamental in nature and require only refinements in technique to solve.

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APPENDIX I

A Program to Calculate Phase Changes Produced by Varying Thickness

27 JAN. 76 00:00 DCO SCRC - F O R T R A N   C O M P I L E R

```
      C
      C     TO CALCULATE REFLECTION COEFFICIENT OF FOLLOWING SYSTEM
      C
      C     *              *         */
      C     *              *         */
      C     *--------------*         */
      C     *      NO      *---------*/
      C     *              *   N1    */
      C     *      DO      *         */
      C     *              *   D1    */   N2
      C     *              *         */
      C     *              *         */
      C
      C     ZO                       Z1
      C
      C
            COMPLEX CTHETA,CTHET1,CTHET2,DPO,DP1,RO1P,RO1S,R12P,R12S
            COMPLEX NO,N1,N2,PHI,R1,R2,R3,REF,CEXP,CMPLX
      C
      C
      C     INPUT PARAMETERS  D=Z1-ZO   A FIXED DISTANCE
      C                       NO,N1,N2  REFRACTIVE INDICIES
      C                       WL        WAVELENGTH OF LIGHT
      C                       DINC '    INCREMENT AT WHICH TO CAL REFL COEF
      C
            READ(5,1) NO,N1,N2,D,DINC,WL
        1   FORMAT(9E8.0)
      C
      C
      C     PRINT OUT CONSTANTS
      C
            WRITE(6,2) NO,N1,N2,WL
        2   FORMAT(1H1/,10X,6HNO = (,F5.2,1H,,F5.2,1H),
           1         /10X,6HN1 = (,F5.2,1H,,F5.2,1H),
           2         /10X,6HN2 = (,F5.2,1H,,F5.2,1H),
           3        //10X,12HWAVELENGTH =,F6.0,9HANGSTROMS,
           4      ///5X,9HTHICKNESS,10X,12HPHASE CHANGE,
           5         /5X,11H(ANGSTROMS),9X,9H(DEGREES)/)
      C
      C
            PI=3.14159265
      C
      C     INITIALIZE VARIABLES
      C
            D1=0.
            CTHETA=CMPLX(COS(0.),0.)
      C
      C
      C     CALCULATE FRESENEL COEFFICIENTS
      C
            CALL REFL(NO,N1,CTHETA,CTHET1,RO1P,RO1S)
            CALL REFL(N1,N2,CTHET1,CTHET2,R12P,R12S)
      C
      C
      C     CALCULATE DO
      C
        3   DO=D-D1
```

```
27 JAN. 76 00:00  DCO SCRC -      F O R T R A N   C O M P I L E R

C
C
C      CALCULATE OPTICAL PATH LENGTHS
C
       DPO=2.*DO*PI*NO*CTHETA/WL
       DP1=2.*PI*D1*N1*CTHET1/WL
C
C
C      CALCULATE REFLECTION COEFFICIENT
C
       R1=1.+RO1P+R12P+RO1P*R12P
       R2=RO1P+R12P*CEXP(DP1*CMPLX(0.,-2.))
       R3=1.+RO1P*R12P*CEXP(DP1*CMPLX(0.,-2.))
       REF=(R1*R2/R3)*CEXP(DPO*CMPLX(0.,-2.))
C
C
C      CALCULATE PHASE OF REFLECTION COEFFICEINT
C
       ANGLE=ATAN2(AIMAG(REF),REAL(REF))*180./PI
       IF(ANGLE.LT.0.) ANGLE=ANGLE+360.
C
C
C      PRINT RESULTS
C
       WRITE(6,4) D1,ANGLE
  4    FORMAT(5X,F10.0,8X,F10.2)
C
C
C      INCREMENT D1 AND DO CALULATIONS AGAIN
C
       D1=D1+DINC
       IF(D1.LE.D) GO TO 3
       CALL EXIT
       END
```

```
 27 JAN. 76 00:00  DCO SCRC -     F O R T R A N   C O M P I L E R

C
C     A SUBROUTINE TO CALCULATE THE PERPENDICULAR AND PARALLEL FRESNEL
C     REFLECTION COEFFICIENTS AT A BOUNDARY
C
C     INPUT PARAMETERS
C
C     N1,N2     INDICIES OF REFRACTION ON EITHER SIDE OF BOUNDARY
C     THETA     COSINE OF ANGLE OF INCIDENCE
C
C
C     OUTPUT PARAMETERS
C
C     PHI       COSINE OF ANGLE OF REFRACTION
C     RP        PERPENDICULAR REFLECTION COEFFICIENT
C     RS        PARALLEL REFLECTION COENEFFICIENT
C
C
C
      SUBROUTINE REFL(N1,N2,THETA,PHI,RP,RS)
      COMPLEX N1,N2,THETA,RS,RP,CSQRT,SI,SR,PHI
C
C
C     CALCULATE SINE OF ANGLE OF INCIDENCE
C
      SI=CSQRT(1.-THETA*THETA)
C
C
C     USE SNELL'S LAW TO CALCULATE SINE OF ANGLE OF REFRACTANCE
C
      SR=N1*SI/N2
C
C
C     CALCULATE COSINE OF ANGLE OF REFRACTANCE
C
      PHI=CSQRT(1.-SR*SR)
C
C
C     CALCULATE REFLECTION COEFFICIENTS
C
      RP=(N1*PHI-N2*THETA)/(N1*PHI+N2*THETA)
      RS=(N1*THETA-N2*PHI)/(N1*THETA+N2*PHI)
C
C
      RETURN
      END
```

N0 = (1.00, 0.00)
N1 = (2.23, 0.00)
N2 = (1.20, -6.90)

WAVELENGTH = 6238. ANGSTROMS

THICKNESS (ANGSTROMS)	PHASE CHANGE (DEGREES)
0.	356.70
20.	356.50
40.	356.23
60.	355.89
80.	355.46
100.	354.93
120.	354.29
140.	353.52
160.	352.61
180.	351.53
200.	350.27
220.	348.79
240.	347.08
260.	345.10
280.	342.82
300.	340.21
320.	337.22
340.	333.81
360.	329.93
380.	325.53
400.	320.57
420.	315.00
440.	308.80
460.	301.94
480.	294.44
500.	286.33
520.	277.71
540.	268.71
560.	259.47
580.	250.21
600.	241.10
620.	232.32
640.	224.02
660.	216.29
680.	209.19
700.	202.75
720.	196.95
740.	191.78
760.	187.18
780.	183.12
800.	179.54
820.	176.40
840.	173.65
860.	171.26
880.	169.17
900.	167.37
920.	165.81
940.	164.47
960.	163.33

980.	162. 35
1000.	161. 53
1020.	160. 85
1040.	160. 28
1060.	159. 82
1080.	159. 45
1100.	159. 15
1120.	158. 93
1140.	158. 76
1160.	158. 65
1180.	158. 57
1200.	158. 52
1220.	158. 50
1240.	158. 50
1260.	158. 50
1280.	158. 50
1300.	158. 50
1320.	158. 48
1340.	158. 45
1360.	158. 38
1380.	158. 27
1400.	158. 12
1420.	157. 92
1440.	157. 65
1460.	157. 30
1480.	156. 86
1500.	156. 33
1520.	155. 68
1540.	154. 90
1560.	153. 98
1580.	152. 89
1600.	151. 61
1620.	150. 12
1640.	148. 39
1660.	146. 39
1680.	144. 09
1700.	141. 46
1720.	138. 44
1740.	135. 00
1760.	131. 08
1780.	126. 65
1800.	121. 65
1820.	116. 04
1840.	109. 79
1860.	102. 89
1880.	95. 34
1900.	87. 20
1920.	78. 55
1940.	69. 52
1960.	60. 28
1980.	51. 02
2000.	41. 93

APPENDIX II

A Program to Calculate Fourier Transform Twice

```
27 JAN. 76 00:04  DCO SCRC -     F O R T R A N   C O M P I L E R

C
C
C       A PROGRAM TO CALCULATE A TWO DIMENSIONAL SPATIAL FOURIER
C       TRANSFORM, NORMALIZE THE TRANSFORM, AND TAKE THE
C       TRANSFORM A SECOND TIME.
C
C
        DIMENSION NA(64)    ,B(64,64),C(64),ND(2)
        COMPLEX A(64,64),AAA(64,64),CMPLX
        N=64
        ND(1)=N
        ND(2)=N
C
C
C       DEFINE BRIGHT AREAS BY *, OTHERWISE BLANK.
C
        READ(6,104) BLANK, STAR
C
C
C       INPUT A PATTERN (BRIGHT AREA = 8)
C
        DO 1 I=1,64
        READ(5,101) (NA(J),J=I,N)
 101    FORMAT(64I1)
C
C
C       INITIALIZE FIELD TO 0.
C
        DO 1 J=1,N
        A(I,J)=CMPLX(0.,0.)
C
C
C       SET BRIGHT AREAS TO 1.
C
        IF(NA(J).EQ.8) A(I,J)=CMPLX(1.,0.)
 1      CONTINUE
C
C
C       DO FIRST TRANSFORM. (EXTERNAL SUBROUTINE)
C
        CALL FOUR2(A,ND,2,-1,+1)
        AM1=0.
C
C
C       CHANGE AXES FROM -180,180 TO 0,360
C
        DO 10 I=1,N
        K=I+32
        IF(I.GT.32) K=I-32
        DO 10 J=1,N
        L=J+32
        IF(J.GT.32) L=J-32
        X=REAL(A(I,J))
        Y=AIMAG(A(I,J))
        Z=SQRT(X*X+Y*Y)
        IF(Z.GT.AM1) AM1=Z
 10      AAA(K,L)=A(I,J)
```

```
      A2=.02*AM1
      DO 50 I=1,N
      DO 50 J=1,N
C
C
C     MAKE ALL INTENSITIES 1.
C
      X=REAL(AAA(I,J))
      Y=AIMAG(AAA(I,J))
      Z=SQRT(X*X+Y*Y)
      IF(Z.EQ.0.) GO TO 49
      AAA(I,J)=AAA(I,J)/Z
49    IF(Z.LT.A2) AAA(I,J)=1.
50    CONTINUE
C
C
C     DO SECOND TRANSFORM.
C
      CALL FOUR2(AAA,ND,2,-1,+1)
      AMAX=0.
      DO 3 I=1,N
      DO 3 J=1,N
      A(I,J)=AAA(I,J)
C
C
C     DETERMINE PEAK OF INTENSITY
C
      X=REAL(A(I,J))
      Y=AIMAG(A(I,J))
      B(I,J)=SQRT(X*X+Y*Y)
      IF(B(I,J).GT.AMAX) AMAX=B(I,J)
3     CONTINUE
      WRITE(6,103) AMAX
103   FORMAT(10X,E10.3)
C
C
C     SET A LEVEL
C
      AA=.01*AMAX
104   FORMAT(2A1)
      DO 4 I=1,N
      DO 5 J=1,N
C
C
C     PRINT PICTURE MARKING ELEMENTS ABOVE LEVEL
C
      C(J)=BLANK
      IF(B(I,J).GT.AA) C(J)=STAR
5     CONTINUE
4     WRITE(6,105) (C(J),J=1,N)
105   FORMAT(2X,64A1)
      STOP
      END
```

APPENDIX III

Listing of the Software Written for the PDP-8e

```
0100  0000  SHFTH,   0                        /VARIABLES
0101  0000  SHFTL,   0
0102  0000  DVML,    0
0103  0000  DVMH,    0
0104  0000  MSDIG,   0
0105  0000  DNUMB,   0
0106  0000  ASUML,   0
0107  0000  ASUMH,   0
0110  0000  DIR,     0
0111  0100  STKL,    100
0112  7700  STKLC,   -100
0113  0000  SUMH1,   0
0114  0000  SUMH2,   0
0115  0000  SUML1,   0
0116  0000  SUML2,   0
0117  0000  STPCNT,  0
0120  1177  STSTK,   1177
0121  0000  AL,      0
0122  0000  AH,      0
0123  0000  BL,      0
0124  0000  BH,      0
0125  0000  CL,      0
0126  0000  CH,      0
0127  0003  POLCD,   3
0130  4010  ANZCD,   4010
0131  0200  M2XCD,   200
0132  0040  M2YCD,   40
0133  0000  DECL,    0
0134  0000  DECH,    0
0135  0000  DESTL,   0
0136  0000  DESTH,   0
            /
            /
                     *200
            /
            /
            /INTERRUPT SERVICE
            /
0200  3370  INTSER,  DCA ACCUM                /SAVE AC
0201  7004           RAL
0202  3371           DCA LINK                 /SAVE LINK
0203  7701           ACL
0204  3372           DCA MQSAVE               /SAVE MQ
0205  6031           KSF                      /KEYBOARD?
0206  7410           SKP
0207  5302           JMP KYBRD
0210  6041           TSF                      /TELETYPE?
0211  7410           SKP
0212  5223           JMP TELTP                /IF NEITHER
0213  7300  EXTINT,  CLA CLL                  /THEN EXIT
0214  1371           TAD LINK
0215  7110           CLL RAR                  /RESTORE LINK
0216  1372           TAD MQSAVE
0217  7421           MQL                      /RESTORE MQ
0220  1370           TAD ACCUM                /RESTORE AC
0221  6001           ION                      /TURN INT ON
0222  5400           JMP I 0                  /RETURN
            /
            /
            /TELETYPE SERVICE
            /
0223  1373  TELTP,   TAD TELCNT               /ARE THERE MORE
0224  7450           SNA                      /CHAR TO TYPE
```

```
0225  5244            JMP CTHUP         /NO
0226  7041            CIA               /YES
0227  7001            IAC
0230  7041            CIA               /DECREMENT CHAR
0231  3373            DCA TELCNT        /COUNTER
0232  1012            TAD TYPEPT        /END OF BUFFER
0233  7041            CIA               /AREA REACHED?
0234  1362            TAD ENDBUF
0235  7640            SZA CLA
0236  5241            JMP NOTEND        /NO
0237  1363            TAD STBUF         /YES,RESET TO
0240  3012            DCA TYPEPT        /START
0241  1412  NOTEND,   TAD I TYPEPT      /GET CHAR FROM
                                        /BUFFER
0242  6046            TLS               /TYPE IT
0243  5213            JMP EXTINT        /EXIT
0244  7201  CTHUP,    CLA IAC           /NO MORE CHAR
0245  3364            DCA TFLAG         /SET TFLAG
0246  6042            TCF               /CLEAR TTY FLAG
                                        /TO STOP TTY
0247  5213            JMP EXTINT        /EXIT
            /
            /
            /PUT CHAR IN BUFFER TO BE TYPED
            /
0250  0000  BUFFER,   0                 /CHAR IN AC
0251  3411            DCA I BUFPT       /PUT CHAR IN BUFF
0252  2373            ISZ TELCNT        /INCRE CHAR COUNT
0253  1373  BUFLP1,   TAD TELCNT        /CHECK FOR FULL
0254  1363            TAD STBUF         /BUFFER. WAIT
0255  7041            CIA               /IN LOOP UNTIL
0256  1362            TAD ENDBUF        /THERE IS ROOM
0257  7650            SNA CLA
0260  5253            JMP BUFLP1
0261  6002            IOF               /NOT FULL. TURN
                                        /OFF INT TO AVOID
                                        /COMPLICATIONS
0262  1011            TAD BUFPT         /CHECK FOR END
0263  7041            CIA               /OF BUFFER AREA
0264  1362            TAD ENDBUF
0265  7640            SZA CLA
0266  5271            JMP NOTEDB        /NOT END
0267  1363            TAD STBUF         /END - RESET TO
0270  3011            DCA BUFPT         /START
0271  1364  NOTEDB,   TAD TFLAG         /TEST TFLAG
0272  7640            SZA CLA           /FLAG UP - MUST
0273  5276            JMP CLTFLG        /RESTART TTY
0274  6001            ION               /NOT UP - CONTINUE
0275  5650            JMP I BUFFER      /EXIT - AC CLEAR
0276  3364  CLTFLG,   DCA TFLAG         /CLEAR TFLAG
0277  6040            SPF               /RESTART TTY BY
                                        /SETTING TTY FLAG
                                        /TO RAISE INT.
0300  6001            ION               /CONTINUE
0301  5650            JMP I BUFFER      /EXIT - AC CLEAR
            /
            /
            /KEYBOARD SERVICE
            /
0302  6034  KYBRD,    KRS               /READ KBD
0303  3413            DCA I KYBDPT      /STORE
0304  2374            ISZ KBDCNT        /INCRE CHAR COUNT
0305  1013            TAD KYBDPT        /CHECK FOR END
```

```
0306  7041           CIA             /OF BUFFER AREA
0307  1365           TAD ENDKBF      /AND RESET IF
0310  7640           SZA CLA         /AT END
0311  5314           JMP KYNEND
0312  1366           TAD STKYBF
0313  3013           DCA KYBDPT
0314  1374  KYNEND,  TAD KBDCNT      /TEST FOR FULL
0315  1366           TAD STKYBF      /BUFFER
0316  7041           CIA
0317  1365           TAD ENDKBF
0320  7650           SNA CLA
0321  5324           JMP SETKFL      /BUFFER FULL
0322  6032           KCC             /NOT FULL - SET
                                     /READER RUN
0323  5213           JMP EXTINT      /EXIT
0324  7201  SETKFL,  CLA IAC         /FULL - SET KYFLAG
0325  3367           DCA KYFLAG
0326  6030           KCF             /CLEAR KBD FLAG
                                     /DO NOT SET READER
                                     /RUN
0327  5213           JMP EXTINT      /EXIT
            /
            /
            /TO REMOVE A CHARACTER FROM KBD BUFFER
            /
0330  0000  READB,   0
0331  1374           TAD KBDCNT      /IF BUFFER IS
0332  7650           SNA CLA         /EMPTY, WAIT FOR
0333  5331           JMP .-2         /SOME INPUT
0334  6002           IOF             /INT OFF TO AVOID
                                     /COMPLICATIONS
0335  7240           CLA CMA         /DECREMENT CHAR
0336  1374           TAD KBDCNT      /COUNTER
0337  3374           DCA KBDCNT
0340  1014           TAD READPT      /CHECK FOR END OF
0341  7041           CIA             /BUFFER AND RESET
0342  1365           TAD ENDKBF      /IF AT END
0343  7640           SZA CLA
0344  5347           JMP KYND2
0345  1366           TAD STKYBF
0346  3014           DCA READPT
0347  1367  KYND2,   TAD KYFLAG      /WAS READER
0350  7640           SZA CLA         /STOPPED?
0351  5355           JMP FLAGUP      /YES
0352  1414           TAD I READPT    /NO - GET CHAR
0353  6001           ION             /LEAVE IN AC
0354  5730           JMP I READB     /EXIT
0355  3367  FLAGUP,  DCA KYFLAG      /CLEAR KYFLAG
0356  6032           KCC             /RESTART READER
0357  1414           TAD I READPT    /GET CHARACTER
0360  6001           ION             /LEAVE IN AC
0361  5730           JMP I READB     /EXIT
0362  7177  ENDBUF,  7177            /END OF OUTPUT
                                     /BUFFER
0363  6777  STBUF,   6777            /START OF OUTPUT
                                     /BUFFER
0364  0000  TFLAG,   0
0365  7377  ENDKBF,  7377            /END OF INPUT
                                     /BUFFER
0366  7177  STKYBF,  7177            /START OF INPUT
                                     /BUFFER
0367  0000  KYFLAG,  0
0370  0000  ACCUM,   0
```

```
0371  0000  LINK,    0
0372  0000  MQSAVE,  0
0373  0000  TELCNT,  0
0374  0000  KBDCNT,  0
            /
            /
                     *400
            /
            /
            /TO PRODUCE A CARRIAGE RETURN AND LINE
            /FEED
            /
0400  0000  CRLF,    0
0401  7200           CLA
0402  1215           TAD K215          /CR CHAR
0403  4454           JMS I ABUFF       /TYPE IT
0404  1214           TAD K212          /LF CHAR
0405  4454           JMS I ABUFF       /TYPE IT
0406  5600           JMP I CRLF        /EXIT - AC CLEAR
            /
            /
            /TO PRODUCE A SPACE
            /
0407  0000  SPACE,   0
0410  7200           CLA
0411  1216           TAD K240          /SPACE CHAR
0412  4454           JMS I ABUFF       /TYPE IT
0413  5607           JMP I SPACE       /EXIT - AC CLEAR
            /
0414  0212  K212,    212
0415  0215  K215,    215
0416  0240  K240,    240
            /
            /
            /TO UNPACK A WORD AND PRINT IT OUT
            /SIMILAR TO PRINT PROGRAM IN DEC MANUAL
            /
0417  0000  PRINT,   0
0420  7300           CLA CLL
0421  3301           DCA STNBR
0422  1300           TAD NUMBER
0423  7004           RAL
0424  3301           DCA STNBR
0425  1274  UNPACK,  TAD ROTNBR
0426  3305           DCA STROT
0427  1301           TAD STNBR
0430  7004           RAL
0431  2305           ISZ STROT
0432  5230           JMP .-2
0433  3301           DCA STNBR
0434  7004           RAL
0435  3374           DCA LKPRT
0436  1301           TAD STNBR
0437  0273           AND MASK
0440  1276           TAD K260
0441  4454           JMS I ABUFF
0442  1374           TAD LKPRT
0443  7110           CLL RAR
0444  2302           ISZ DIGCTR
0445  5225           JMP UNPACK
0446  5617           JMP I PRINT
            /
            /
```

```
                    /TO PRINT THE NUMBER IN THE AC AS A 3
                    /DIGIT BCD NUMBER
                    /
0447  0000  PRTDC,  0
0450  3300          DCA NUMBER       /STORE
0451  1303          TAD KC3          /SET NO OF DIGITS
0452  3302          DCA DIGCTR       /TO 3
0453  1277          TAD KC4          /SET NO OF BITS
0454  3274          DCA ROTNBR       /PER DIGIT TO 4
0455  1304          TAD MASK17       /SET UP 4 BIT MASK
0456  3273          DCA MASK
0457  4217          JMS PRINT        /USE PRINT
0460  5647          JMP I PRTDC      /EXIT - AC CLEAR
                    /
                    /
                    /TO PRINT THE NUMBER IN THE AC AS A
                    /4 DIGIT OCTAL NUMBER
                    /
0461  0000  PRTOC,  0
0462  3300          DCA NUMBER       /STORE NUMBER
0463  1277          TAD KC4          /SET NO OF DIGITS
0464  3302          DCA DIGCTR       /TO 4
0465  1303          TAD KC3          /SET NO OF BITS
0466  3274          DCA ROTNBR       /PER DIGIT TO 3
0467  1275          TAD MASK7        /SET UP A 3 BIT
0470  3273          DCA MASK         /MASK
0471  4217          JMS PRINT        /USE PRINT
0472  5661          JMP I PRTOC      /EXIT - AC CLEAR
                    /
0473  0000  MASK,   0
0474  0000  ROTNBR, 0
0475  0007  MASK7,  7
0476  0260  K260,   260
0477  7774  KC4,    -4
0500  0000  NUMBER, 0
0501  0000  STNBR,  0
0502  0000  DIGCTR, 0
0503  7775  KC3,    -3
0504  0017  MASK17, 17
0505  0000  STROT,  0
                    /
                    /
                    /TO READ THE ANALOG CHANNEL WHOSE CODE
                    /IS IN THE AC
                    /
0506  0000  ANALG,  0
0507  6323          6323             /CHANNEL SELECT
0510  6321          6321             /WAIT FOR FLAG
0511  5310          JMP .-1
0512  7300          CLA CLL
0513  6324          6324             /READ
0514  7040          CMA              /INPUT IN OPPOSITE
                                     /LOGIC
0515  4453          JMS I AMULT5     /MULT BY 5
0516  7421          MQL
0517  7701          ACL              /SPLIT RESULT INTO
0520  0340          AND MK7700       /2 WORDS
0521  7012          RTR
0522  7012          RTR              /DIVIDE HIGH WORD
0523  7012          RTR              /BY 64
0524  4453          JMS I AMULT5
0525  4453          JMS I AMULT5     /MULT BY 25
0526  3342          DCA SHIGH        /STORE
```

```
0527  7701           ACL
0530  0341           AND MK77        /GET LOW HALF
0531  4453           JMS I AMULT5
0532  4453           JMS I AMULT5    /MULT BY 25
0533  0340           AND MK7700      /DIVIDE LOW HALF
0534  7002           BSW             /BY 64
0535  1342           TAD SHIGH       /PUT HALVES BACK
0536  7010           RAR             /DIVIDE BY 2
                                     /RESULT IS TO
                                     /MULTBY (1000/1024)
0537  5706           JMP I ANALG     /EXIT - RESULT
                                     /LEFT IN AC
0540  7700  MK7700,  7700
0541  0077  MK77,    77
0542  0000  SHIGH,   0
            /
            /
            / TO INITILIZE THE POINTERS AND FLAGS
            /FOR THE OPERATING SYSTEM
            /
0543  0000  INITZE,  0
0544  7200           CLA
0545  1366           TAD KK1777      /INITILIZE
0546  3011           DCA BUFPT       /POINTERS
0547  1366           TAD KK1777
0550  3012           DCA TYPEPT
0551  1367           TAD KK2177
0552  3013           DCA KYBDPT
0553  1367           TAD KK2177
0554  3014           DCA READPT
0555  7201           CLA IAC
0556  3770           DCA I ATFLAG    /SET FLAGS
0557  7201           CLA IAC
0560  3771           DCA I AKFLAG
0561  3773           DCA I ATLCNT    /CLEAR COUNTERS
0562  3772           DCA I AKYCNT
0563  6032           KCC
0564  6001           ION             /TURN INTERRUPT ON
0565  5743           JMP I INITZE    /EXIT - AC CLEAR
            /
0566  6777  KK1777,  6777
0567  7177  KK2177,  7177
0570  0364  ATFLAG,  TFLAG
0571  0367  AKFLAG,  KYFLAG
0572  0374  AKYCNT,  KBDCNT
0573  0373  ATLCNT,  TELCNT
0574  0000  LKPRT,   0
            /
            /
                     *600
            /
            /
            /PUT OUT PULSE TO STEP MOTORS
            /
0600  0000  STEP1,   0
0601  6334           6334            /PULSE TO STEP
0602  7200           CLA
0603  1210           TAD WT          /WAIT LOOP
0604  7001           IAC
0605  7440           SZA
0606  5204           JMP .-2
0607  5600           JMP I STEP1     /EXIT - AC CLEAR
0610  6500  WT,      6500            /DELAY FOR A RATE
```

```
                                        /OF 400 STEPS/SEC
                   /
                   /
0611  0000  WAIT,    0
0612  3225           DCA ENDTIM
0613  6342           6342
0614  6341  WLP1,    6341
0615  5214           JMP .-1
0616  6344           6344
0617  7040           CMA
0620  7041           CIA
0621  1225           TAD ENDTIM
0622  7440           SZA
0623  5214           JMP WLP1
0624  5611           JMP I WAIT
0625  0000  ENDTIM,  0
            /
            /
            /READ SHAFT ENCODER
            /
0626  0000  RDSFT,   0
0627  7200           CLA
0630  6302           6302               /READ AND STORE
0631  3100           DCA SHFTH          /2 MSD
0632  6304           6304               /READ AND STORE
0633  3101           DCA SHFTL          /3 LSD
0634  5626           JMP I RDSFT        /EXIT - AC CLEAR
            /
            /
            /READ DIGITAL VOLT METER
            /
0635  0000  RDDVM,   0
0636  7300           CLA CLL
0637  6311           6311               /READ HIGH WORD
0640  0252           AND MASK40         /TEST FLAG IN
0641  7440           SZA                /BIT 6
0642  5236           JMP .-4            /WAIT FOR FLAG
0643  7200           CLA                /TO GO DOWN
0644  6301           6301               /READ AND STORE
0645  3102           DCA DVML           /LOW WORD
0646  6311           6311               /READ AND STORE
0647  0253           AND MASK37         /HIGH WORD (ONLY
0650  3103           DCA DVMH           /1 BCD CHAR)
0651  5635           JMP I RDDVM        /EXIT - AC CLEAR
0652  0040  MASK40,  40
0653  0037  MASK37,  37
            /
            /
            /TO ACCELERATE MOTORS
            /
0654  0000  STEP,    0
0655  7200           CLA
0656  1110           TAD DIR            /CHECK ACCEL FLAG
                                        /(BIT 9 OF DIR)
0657  0315           AND MSKD1
0660  7640           SZA CLA
0661  5267           JMP ACCST          /FLAG=1,START
                                        /ACCELERATION
0662  1316           TAD ACCSTP         /FLAG=0, CONTINUE
                                        /ACCELERATION
0663  7640           SZA CLA            /CHECK FOR END
                                        /OF ACCEL
0664  5302           JMP ACCNTU         /NO - CONT ACCEL
```

```
0665  4200           JMS STEP1     /YES - STEP MOTOR
0666  5654           JMP I STEP    /EXIT - AC CLEAR
0667  7001  ACCST,   IAC           /START ACCEL
0670  7440           SZA           /LET MOTOR SETTLE
0671  5267           JMP .-2
0672  1315           TAD MSKD1
0673  7040           CMA
0674  0110           AND DIR       /CLEAR FLAG IN
0675  3110           DCA DIR       /DIR TO CONTINUE
                                   /ACCELERATION
0676  1317           TAD SKC16     /SET NUMBER OF
0677  3316           DCA ACCSTP    /STEPS IN ACCEL
0700  1320           TAD WT1       /SET ORIGINAL
0701  3321           DCA WTIME     /EXTRA DELAY
0702  4200  ACCNTU,  JMS STEP1     /STEP MOTOR
0703  1321           TAD WTIME
0704  1322           TAD ACTIME    /DECREASE EXTRA
0705  3321           DCA WTIME     /DELAY TIME
0706  1321           TAD WTIME
0707  7001           IAC           /WAIT EXTRA DELAY
0710  7440           SZA
0711  5307           JMP .-2
0712  2316           ISZ ACCSTP    /INCREMENT ACCEL
                                   /COUNTER
0713  5654           JMP I STEP
0714  5654           JMP I STEP    /EXIT - AC CLEAR
0715  1000  MSKD1,   1000          /MASK FOR FLAG
0716  0000  ACCSTP,  0             /ACCEL STEP COUNT
0717  7760  SKC16,   -20           /NUMBER OF ACCEL
                                   /STEPS
0720  5700  WT1,     5700          /ORIGINAL EXTRA
                                   /DELAY
0721  0000  WTIME,   0             /TEMP STORAGE
0722  0100  ACTIME,  100           /DECREASE IN DELAY
            /
            /
            /TO COMPLIMENT ANALYZER READING BY 360.00
            /
0723  0000  ANZCP,   0
0724  7200           CLA
0725  1101           TAD SHFTL     /CONVERT LSDS
0726  4442           JMS I ADCBIN  /(SHFTL) TO BIN
0727  7041           CIA
0730  1345           TAD K1000D    /1000(DEC)-SHFTL
0731  4441           JMS I ABNBCD  /CONVERT TO BCD
0732  1105           TAD DNUMB     /PUT BCD RESULT
0733  3101           DCA SHFTL     /BACK IN SHFTL
0734  1100           TAD SHFTH     /CONVERT MSDS
0735  4442           JMS I ADCBIN  /(SHFTH) TO BIN
0736  7041           CIA
0737  1104           TAD MSDIG     /35(DEC)+CARRY
0740  1346           TAD K35D      /-SHFTH
0741  4441           JMS I ABNBCD  /CONVERT TO BCD
0742  1105           TAD DNUMB     /PUT BCD RESULT
0743  3100           DCA SHFTH     /IN SHFTH
0744  5723           JMP I ANZCP   /EXIT - AC CLEAR
0745  1750  K1000D,  1750          /1000(DEC
0746  0043  K35D,    43            /35(DEC)
            /
            /
                     *1000
            /
            /
```

```
                    /CONVERT 3 DIGIT BCD IN AC TO BINARY
                    /LEAVE RESULT IN AC
                    /
1000  0000  DCBIN,   0
1001  7421           MQL               /SAVE BCD NO.
1002  7701           ACL
1003  0225           AND MK17          /SEPARATE LSD
1004  3224           DCA OCNBR         /STORE AS BIN
1005  7701           ACL
1006  0226           AND MK360         /SEPARATE MIDDLE
1007  7112           CLL RTR           /DIGIT
1010  7012           RTR               /RIGHT JUSTIFY
1011  4230           JMS MULT10        /MULT BY 10
1012  1224           TAD OCNBR         /ADD TO BIN NO.
1013  3224           DCA OCNBR
1014  7701           ACL
1015  0227           AND MK7400        /SEPARATE MSD
1016  7106           CLL RTL           /RIGHT JUSTIFY
1017  7006           RTL
1020  7004           RAL
1021  4244           JMS MLT100        /MULT BY 100
1022  1224           TAD OCNBR         /ADD TO BIN NO.
1023  5600           JMP I DCBIN       /EXIT - BIN IN AC
1024  0000  OCNBR,   0                 /STORAGE FOR BIN
1025  0017  MK17,    17                /MASK FOR LSD
1026  0360  MK360,   360               /MASK FOR MID DIG
1027  7400  MK7400,  7400              /MASK FOR MSD
                    /
                    /
                    /MULT NO. IN AC BY 10 - LEAVE RESULT IN AC
                    /
1030  0000  MULT10,  0
1031  4234           JMS MULT5         /MULT BY 5
1032  7104           CLL RAL           /MULT BY 2
1033  5630           JMP I MULT10
                    /
                    /
                    /MULT NO. IN AC BY 5 - LEAVE RESULT IN AC
                    /
1034  0000  MULT5,   0
1035  3243           DCA MNBR          /STORE NO.
1036  1243           TAD MNBR
1037  7104           CLL RAL           /MULT BY 2
1040  7104           CLL RAL           /MULT BY 2
1041  1243           TAD MNBR          /ADD NO.
1042  5634           JMP I MULT5       /IE  5X=2X+2X+X
1043  0000  MNBR,    0                 /TEMP STORAGE
                    /
                    /
                    /MULT AC BY 100 - RESULT IN AC
                    /
1044  0000  MLT100,  0
1045  4230           JMS MULT10        /MULT BY 10
1046  4230           JMS MULT10        /MULT BY 10
1047  5644           JMP I MLT100
                    /
                    /
                    /CONVERT BIN NO. IN AC TO 4 DIGITS BCD
                    /RESULT IN MSDIG (MOST SIG DIGIT) AND
                    /DNUMB (DECIMAL NO.) - ON PAGE 0
                    /
1050  0000  BNBCD,   0
1051  3342           DCA BNBR          /STORE BIN
```

```
1052  7100            CLL
1053  3104            DCA MSDIG         /CLEAR
1054  1342            TAD BNBR
1055  1344  BNLP1,    TAD KC1000        /SUBT 1000 FROM
1056  7500            SMA               /BIN NO.
1057  5263            JMP BACK          /IF AC IS NOT NEG
1060  7430            SZL               /OR LINK=0 THEN
1061  5263            JMP BACK          /INCREMENT MSDIG
1062  5266            JMP FINISH        /AND SUBT 1000
1063  2104  BACK,     ISZ MSDIG         /AGAIN
1064  7100            CLL
1065  5255            JMP BNLP1
1066  3342  FINISH,   DCA BNBR          /IF AC IS LT 0
1067  1344            TAD KC1000        /AND L=1, THEN
1070  7041            CIA               /HAVE SUBT 1000
1071  1342            TAD BNBR          /ONCE TOO OFTEN
1072  3342            DCA BNBR          /ADD 1000 BACK ON
            /
1073  7300            CLA CLL
1074  3343            DCA DIG           /CLEAR
1075  1342            TAD BNBR
1076  1345  BNLP2,    TAD KC100         /SUBT 100 FROM BIN
1077  7500            SMA               /IF AC IS NOT NEG
1100  5302            JMP BK2           /THEN INCREMENT
1101  5304            JMP FNH2          /DIG AND SUBT
1102  2343  BK2,      ISZ DIG           /AGAIN
1103  5276            JMP BNLP2
1104  3342  FNH2,     DCA BNBR          /AC IS NEG - SAVE
1105  1343            TAD DIG           /PUT NO. OF SUBT
1106  7106            CLL RTL           /IN MSD POSITION
1107  7006            RTL               /OF DNUMB
1110  3105            DCA DNUMB
1111  1345            TAD KC100         /ADD 100 BACK
1112  7041            CIA               /TO BIN NO.
1113  1342            TAD BNBR
1114  3342            DCA BNBR
            /
1115  7300            CLA CLL
1116  3343            DCA DIG           /CLEAR
1117  1342            TAD BNBR
1120  1346  BNLP3,    TAD KC10          /SUBT 10 FROM
1121  7500            SMA               /BIN NO.  IF
1122  5324            JMP BK3           /AC IS NOT NEG
1123  5326            JMP FNH3          /INCR DIG AND
1124  2343  BK3,      ISZ DIG           /SUBT AGAIN
1125  5320            JMP BNLP3
1126  3342  FNH3,     DCA BNBR          /AC IS NEG - SAVE
1127  1343            TAD DIG           /PUT NO. OF SUBT
1130  1105            TAD DNUMB         /IN MID DIG OF
1131  7106            CLL RTL           /DNUMB
1132  7006            RTL
1133  3105            DCA DNUMB
1134  1346            TAD KC10          /ADD 10 BACK TO
1135  7041            CIA               /BIN NO.
1136  1342            TAD BNBR
1137  1105            TAD DNUMB         /PART LEFT IS LSD
1140  3105            DCA DNUMB         /OF DNUMB
1141  5650            JMP I BNBCD       /EXIT - AC CLEAR
            /
1142  0000  BNBR,     0                 /STOR FOR BIN NO.
1143  0000  DIG,      0                 /STOR FOR DIG
1144  6030  KC1000,   6030              /-1000
1145  7634  KC100,    7634              /-100
```

```
1146  7766  KC10,   7766              /-10
                /
                /
                        *1300
                /
                /
                /TO STORE A SET OF READINGS IN A STACK
                /FIXED LENGTH STACK - LATEST ADDITION
                /REPLACES EARLIEST - INPUT IN AC -
                /OUTPUT LEFT IN AC
                /
1300  0000  STACK,  0
1301  3323          DCA SVSTK1        /SAVE ADDITION
1302  1010          TAD ENDSTK
1303  7041          CIA               /CHECK FOR END OF
1304  1111          TAD STKL          /STACK AREA AND
1305  1120          TAD STSTK         /RESET TO START
1306  7440          SZA               /IF AT END
1307  5312          JMP .+3           /STACK AREA IS
1310  1120          TAD STSTK         /1200 TO 1277
1311  3010          DCA ENDSTK
1312  7200          CLA
1313  1410          TAD I ENDSTK      /REMOVE NO. FROM
1314  3324          DCA SVSTK2        /STACK AND SAVE IT
1315  1010          TAD ENDSTK
1316  3325          DCA ENDSK1        /REPLACE IT WITH
1317  1323          TAD SVSTK1        /INPUT THAT WAS
1320  3725          DCA I ENDSK1      /IN AC
1321  1324          TAD SVSTK2        /PUT NO. REMOVED
1322  5700          JMP I STACK       /IN AC - EXIT
1323  0000  SVSTK1, 0
1324  0000  SVSTK2, 0
1325  0000  ENDSK1, 0
                /
                /
                /TO READ THE PHOTOMULTIPLIER STKL NUMBER
                /OF TIMES AND KEEP A RUNNING SUM OF THE
                /READINGS STORED IN 2 WORDS, ASUMH, ASUML
                /
1326  0000  SUM,    0
1327  7200          CLA
1330  1111          TAD STKL          /SET COUNTER
1331  7041          CIA
1332  3117          DCA STPCNT
1333  3107          DCA ASUMH         /CLEAR STORAGE
1334  3106          DCA ASUML
1335  4347  LPSUM,  JMS RDPTO         /READ PHOTOMULT.
1336  7100          CLL
1337  1106          TAD ASUML         /ADD TO ASUML
1340  7430          SZL               /IF OVERFLOW
1341  2107          ISZ ASUMH         /INCRE ASUMH
1342  3106          DCA ASUML         /STORE SUM
1343  4433          JMS I ASTEP       /STEP MOTOR
1344  2117          ISZ STPCNT        /LOOP
1345  5335          JMP LPSUM
1346  5726          JMP I SUM         /EXIT - AC CLEAR
                /
                /
                /TO READ PHOTOMULTIPLIER - RESULT LEFT
                /IN AC
                /
1347  0000  RDPTO,  0
1350  7200          CLA
```

```
1351  1354            TAD PHTOCD        /SET PTM CODE
1352  4431            JMS I AANALG      /USE ANALG
1353  5747            JMP I RDPTO       /EXIT - RESUT IN
                                        /AC
1354  0017  PHTOCD,   17                /CODE FOR PTM
                                        /ANALG CHANNEL
            /
            /
                      *1400
            /
            /
            /TO REVERSE ELLIPSOMETER MOTORS
            /
1400  0000  REV,      0
1401  7200            CLA
1402  1110            TAD DIR
1403  0216            AND MSKDIR        /SEPARATE
                                        /DIRECTION BITS
1404  7040            CMA               /COMPLIMENT DIR
                                        /BITS
1405  0216            AND MSKDIR
1406  3220            DCA CHDIR         /STORE COMP DIR
                                        /BITS
1407  1110            TAD DIR
1410  0217            AND MSKDR2        /CLEAR OLD DIR
                                        /BITS AND FLAG
1411  1233            TAD FLGSET        /SET FLAG TO
                                        /ACCELERATE
1412  1220            TAD CHDIR         /SET CHANGED DIR
                                        /BITS
1413  6332            6332              /SET FLIP FLOPS
1414  3110            DCA DIR           /RESTORE IN DIR
1415  5600            JMP I REV         /EXIT - AC CLEAR
1416  0005  MSKDIR,   5                 /MASK FOR DIR
                                        /BITS
1417  6772  MSKDR2,   6772              /TO CLEAR FLAG
                                        /AND DIR BITS
1420  0000  CHDIR,    0                 /TEMP STORAGE
            /
            /
            /TO SET ACCELERATION FLAG AND FLIP FLOPS
            /FOR MOTORS
            /
1421  0000  SETM,     0
1422  3234            DCA MOTOR         /CODE FOR MOTORS
                                        /WAS IN AC
                                        /STORE IT
1423  1110            TAD DIR
1424  0232            AND MSKDR1        /DO NOT CHANGE
                                        /SWITCH FF
1425  1233            TAD FLGSET        /SET FLAG TO
                                        /START ACCEL
1426  1234            TAD MOTOR         /SET MOTOR
                                        /INFORMATION
1427  6332            6332              /SET FLIP FLOPS
1430  3110            DCA DIR           /STORE IN DIR
1431  5621            JMP I SETM        /EXIT - AC CLEAR
1432  2000  MSKDR1,   2000              /MASK FOR SWITCH
                                        /FLIP FLOP
1433  1000  FLGSET,   1000              /TO SET FLAG
1434  0000  MOTOR,    0                 /TEMP STORAGE
            /
            /
```

```
                   /TO RUN MOTORS NUMBER OF STEPS IN AC
                   /
1435   0000   MOVE,     0
1436   7041             CIA              /SET COUNTER
1437   3117             DCA STPCNT
1440   4433             JMS I ASTEP      /STEP MOTORS
1441   2117             ISZ STPCNT
1442   5240             JMP .-2          /LOOP
1443   5635             JMP I MOVE       /EXIT - AC CLEAR
                   /
                   /
                   /COMP0, COMP1, COMP2, SET ADDRESSES FOR
                   /THE JUMP IN CMPSM (FOR USE IN BAL ROUTINE)
                   /
1444   0125   COMP0,    CL               /IF SUM2 IS LESS
1445   1307             TAD APOS1        /THAN SUM1 THEN GO
1446   3305             DCA S2LTS1       /TO POS 1
1447   1306             TAD APOS0        /OTHERWISE GO TO
1450   3304             DCA S2GTS1       /POS 0
1451   5266             JMP CMPSM
                   /
                   /
1452   7200   COMP1,    CLA              /IF SUM2 IS LESS
1453   1307             TAD APOS1        /THAN SUM1 THEN
1454   3305             DCA S2LTS1       /GO TO POS 1
1455   1310             TAD APOS2        /OTHERWISE GO TO
1456   3304             DCA S2GTS1       /POS 2
1457   5266             JMP CMPSM
                   /
                   /
1460   7200   COMP2,    CLA              /IF SUM2 IS LESS
1461   1311             TAD APOS3        /THAN SUM1 THEN
1462   3305             DCA S2LTS1       /GO TO POS 3
1463   1312             TAD APOS4        /OTHERWISE GO TO
1464   3304             DCA S2GTS1       /POS 4
1465   5266             JMP CMPSM
                   /
                   /
1466   7200   CMPSM,    CLA              /TO PERFORM
1467   1115             TAD SUML1        /SUM1-SUM2 IN
1470   3121             DCA AL           /DOUBLE PRECISION
1471   1113             TAD SUMH1        /AND TEST RESULT
1472   3122             DCA AH
1473   1116             TAD SUML2
1474   3123             DCA BL
1475   1114             TAD SUMH2
1476   3124             DCA BH
1477   4447             JMS I ADPSUB     /(A-B=C)
1500   1126             TAD CH           /TEST RESULT
1501   7500             SMA
1502   5705             JMP I S2LTS1     /SUM2 LT SUM1
1503   5704             JMP I S2GTS1     /SUM2 GT SUM1
1504   0000   S2GTS1,   0                /ADDRESS SET BY
1505   0000   S2LTS1,   0                /COMP ROUTINES
1506   1622   APOS0,    POS0             /LIST OF
1507   1625   APOS1,    POS1             /ADDRESSES
1510   1633   APOS2,    POS2
1511   1660   APOS3,    POS3
1512   1713   APOS4,    POS4
                   /
                   /
                   /TO FILL STACK ORIGINALLY AND KEEP A
                   /SUM OF THE READINGS
```

```
                   /
1513  0000  STORE,    0
1514  7200            CLA
1515  1112            TAD STKLC      /SET COUNTER
1516  3117            DCA STPCNT
1517  1120            TAD STSTK      /SET START OF STACK
1520  3010            DCA ENDSTK
1521  3106            DCA ASUML      /CLEAR
1522  3107            DCA ASUMH
1523  4445  STLP1,    JMS I ARDPTO   /READ PTM
1524  7421            MQL            /STORE
1525  7701            ACL
1526  3410            DCA I ENDSTK   /STORE IN STACK
1527  7701            ACL
1530  7100            CLL
1531  1106            TAD ASUML      /ADD TO ASUML
1532  3106            DCA ASUML
1533  7430            SZL            /INCRE ASUMH
1534  2107            ISZ ASUMH      /IF OVERFLOW
1535  4433            JMS I ASTEP    /STEP MOTOR
1536  2117            ISZ STPCNT
1537  5323            JMP STLP1      /LOOP
1540  5713            JMP I STORE    /EXIT - AC CLEAR
            /
            /
            /DOUBLE PRECISION ADD   A+B=C
            /(FROM DEC MANUAL INTRODUCTION TO PROG)
            /
1541  0000  DPADD,    0
1542  7300            CLA CLL
1543  1121            TAD AL
1544  1123            TAD BL
1545  3125            DCA CL
1546  7004            RAL
1547  1122            TAD AH
1550  1124            TAD BH
1551  3126            DCA CH
1552  5741            JMP I DPADD    /EXIT - AC CLEAR
            /
            /
            /DOUBLE PRECISION SUBTRACTION A-B=C
            /(FROM DEC INTRO. TO PROG.)
            /
1553  0000  DPSUB,    0
1554  7300            CLA CLL
1555  1123            TAD BL
1556  7041            CIA
1557  1121            TAD AL
1560  3125            DCA CL
1561  7004            RAL
1562  3371            DCA KPDPS
1563  1124            TAD BH
1564  7040            CMA
1565  1122            TAD AH
1566  1371            TAD KPDPS
1567  3126            DCA CH
1570  5753            JMP I DPSUB    /EXIT - AC CLEAR
1571  0000  KPDPS,    0
            /
            /
                      *1600
            /
            /
```

```
                  /TO BALANCE THE ELLIPSOMETER
                  /
1600  0000  BAL,  0
1601  7201        CLA IAC          /SET FLAG TO
1602  3323        DCA BLFLAG       /INDICATE START
1603  4724  STBL, JMS I ASUM       /TAKE SET OF READS
1604  3321        DCA POSCT        /CLEAR POSITION
                                   /POINTER
1605  1107        TAD ASUMH
1606  3113        DCA SUMH1        /STORE READINGS
1607  1106        TAD ASUML        /IN SUM1 (HIGH
1610  3115        DCA SUML1        /AND LOW)
1611  4724  BALLP1, JMS I ASUM     /TAKE ANOTHER SET
1612  1107        TAD ASUMH
                                   /OF READINGS AND
1613  3114        DCA SUMH2        /STORE IN SUM2
1614  1106        TAD ASUML
1615  3116        DCA SUML2
1616  1323        TAD BLFLAG       /CHECK FLAG. A
1617  7440        SZA              /CLEAR FLAG
                                   /INDICATES THAT
                                   /A MINIMUM IS
                                   /BEING APPROACHED
1620  5727        JMP I ACOMP0     /COMPARE SUM1
1621  5730        JMP I ACOMP1     /AND SUM2
1622  4443  POS0, JMS I AREV       /GOING AWAY FROM
1623  3323        DCA BLFLAG       /MIN. REV MOTORS
1624  5203        JMP STBL         /CLEAR FLAG. START
                                   /OVER AGAIN
1625  7200  POS1, CLA              /GOING TOWARD A MIN
1626  1114        TAD SUMH2        /PUT SUM2 INTO
1627  3113        DCA SUMH1        /SUM1
1630  1116        TAD SUML2
1631  3115        DCA SUML1        /RETURN TO TAKE
1632  5211        JMP BALLP1       /SUM2 AGAIN
1633  4724  POS2, JMS I ASUM       /GOING AWAY FROM
                                   /MIN AFTER HAVING
                                   /PASSED THROUGH IT
                                   /TAKE A SET OF
                                   /READINGS TO BE
                                   /USED FOR
                                   /COMPARISON
1634  4443        JMS I AREV       /REV MOTORS
1635  1106        TAD ASUML        /STORE READINGS
1636  3115        DCA SUML1        /IN SUM1
1637  1107        TAD ASUMH
1640  3113        DCA SUMH1
1641  1111        TAD STKL         /MOVE BACK TWO
1642  4444        JMS I AMOVE      /SETS OF READINGS
1643  1111        TAD STKL
1644  4444        JMS I AMOVE
1645  4726        JMS I ASTORE     /STORE NEXT SET
1646  7200        CLA              /OF READINGS IN
1647  1107        TAD ASUMH        /STACK AND STORE
1650  3114        DCA SUMH2        /THE SUM IN SUM2
1651  1106        TAD ASUML
1652  3116        DCA SUML2
1653  1111        TAD STKL         /SET POSITION
1654  1111        TAD STKL         /POINTER TO NO.
1655  1111        TAD STKL         /OF STEPS TAKEN
1656  3321        DCA POSCT        /FROM COMPARISON
                                   /SUM
1657  5731        JMP I ACOMP2     /COMPARE SUM2 AND
```

```
                                        /SUM1
1660  7200  POS3,   CLA                 /HAVE NOT YET
                                        /COME TO SAME
                                        /DISTANCE FROM MIN
                                        /AS COMPARISON SUM
1661  2321          ISZ POSCT           /INCRE POS POINTER
1662  4445          JMS I ARDPTO        /TAKE A SINGLE
                                        /READING
1663  7421          MQL
1664  7701          ACL                 /STORE IT IN STACK
1665  4725          JMS I ASTACK
1666  3123          DCA BL              /SUBTRACT READING
1667  3124          DCA BH              /REMOVED FROM STACK
1670  7701          ACL                 /FROM READING PUT
1671  3121          DCA AL              /IN STACK
1672  3122          DCA AH
1673  4447          JMS I ADPSUB
1674  1125          TAD CL              /ADD RESULT TO
1675  3121          DCA AL              /SUM2
1676  1126          TAD CH
1677  3122          DCA AH
1700  1116          TAD SUML2
1701  3123          DCA BL
1702  1114          TAD SUMH2
1703  3124          DCA BH
1704  4450          JMS I ADPADD
1705  1125          TAD CL
1706  3116          DCA SUML2
1707  1126          TAD CH
1710  3114          DCA SUMH2
1711  4433          JMS I ASTEP         /MOVE MOTOR ONE
                                        /STEP
1712  5731          JMP I ACOMP2        /COMPARE SUM1
                                        /AND SUM2
                                        /IF SUM2 LT SUM1
                                        /RETURN TO POS3
1713  4443  POS4,   JMS I AREV          /OTHERWISE HAVE
                                        /FOUND BALANCE
                                        /REVERSE MOTORS
1714  7300          CLA CLL             /DRIVE TO MIDPOINT
1715  1321          TAD POSCT           /OF SUM1 AND SUM2
1716  7010          RAR
1717  4444          JMS I AMOVE
1720  5600          JMP I BAL           /EXIT - AC CLEAR
                                        /ELLIPSOMETER
                                        /UNIT LEFT AT
                                        /BALANCED POSITION
1721  0000  POSCT,  0                   /POSITION POINTER
1722  0000  HLDBL1, 0
1723  0000  BLFLAG, 0                   /BALANCE FLAG
1724  1326  ASUM,   SUM                 /ADDRESSES USED
1725  1300  ASTACK, STACK               /BY BAL ROUTINE
1726  1513  ASTORE, STORE
1727  1444  ACOMP0, COMP0
1730  1452  ACOMP1, COMP1
1731  1460  ACOMP2, COMP2
            /
            /
                    *2000
            /
            /
            /TO SET DERIRED UNIT OF ELLIPSOMETER
            /TO A REQUIRED POSITION
```

```
                     /
2000  0000  SETEL,   0
2001  4435           JMS I ARDSFT    /READ SHAFT ENCODER
2002  1365           TAD FWD         /TO DETERMINE POS
2003  7104           CLL RAL         /OF UNIT
2004  7630           SZL CLA         /DETERMINE WHETHER
                                     /ANZ OR POL IS TO
2005  4451           JMS I AANZCP    /SET.  IF ANZ
                                     /COMPLIMENT BY 360
2006  1101           TAD SHFTL
2007  3133           DCA DECL        /CONVERT POSITION
2010  1100           TAD SHFTH       /FROM BCD TO BINARY
2011  3134           DCA DECH
2012  4457           JMS I ADPDBN
2013  1125           TAD CL
2014  3101           DCA SHFTL       /STORE POS IN
2015  1126           TAD CH          /SHAFT(LOW,HIGH)
2016  3100           DCA SHFTH
2017  1135           TAD DESTL
2020  3121           DCA AL          /PERFORM
2021  1136           TAD DESTH       /(DEST-SHAFT)
2022  3122           DCA AH
2023  1101           TAD SHFTL
2024  3123           DCA BL
2025  1100           TAD SHFTH
2026  3124           DCA BH
2027  4447  SUBPT,   JMS I ADPSUB    /IS RESULT -VE,
2030  1126           TAD CH          /0, OR +VE?
2031  7640           SZA CLA
2032  5236           JMP .+4
2033  1125           TAD CL
2034  7650           SNA CLA
2035  5600           JMP I SETEL     /IF 0 THEN DONE
2036  1126           TAD CH
2037  7700           SMA CLA
2040  5260           JMP AHEAD       /IF +VE JUMP
2041  1135           TAD DESTL
2042  3123           DCA BL          /IF -VE INTER-
2043  1136           TAD DESTH       /CHANGE DEST AND
2044  3124           DCA BH          /SHAFT AND DIR
2045  1101           TAD SHFTL       /CODES (FWD FOR
2046  3121           DCA AL          /BKD AND VICE
2047  1100           TAD SHFTH       /VERSA)
2050  3122           DCA AH
2051  1366           TAD BKWD
2052  3377           DCA BHLDK
2053  1365           TAD FWD
2054  3366           DCA BKWD
2055  1377           TAD BHLDK
2056  3365           DCA FWD
2057  5227           JMP SUBPT       /DO SUBT AGAIN
2060  1126  AHEAD,   TAD CH
2061  3372           DCA DMSEH       /STORE DEST-SHAFT
2062  1125           TAD CL          /IN DMSE
2063  3371           DCA DMSEL
2064  1126           TAD CH
2065  3122           DCA AH          /PERFORM
2066  1125           TAD CL          /(DMSE-180.00)
2067  3121           DCA AL          /TO DETERMINE
2070  1373           TAD H180        /SHORTEST DIRECTION
2071  3124           DCA BH          /TO TRAVEL
2072  1374           TAD L180
2073  3123           DCA BL
```

```
2074  4447            JMS I ADPSUB
2075  1126            TAD CH
2076  7710            SPA CLA
2077  5326            JMP MVEFWD      /IF -VE OR 0
                                      /MOVE FORWARD
2100  1375            TAD H360        /IF +VE
2101  3122            DCA AH          /PERFORM
2102  1376            TAD L360        /(360.00-DMSE)
2103  3121            DCA AL
2104  1372            TAD DMSEH
2105  3124            DCA BH
2106  1371            TAD DMSEL
2107  3123            DCA BL
2110  4447            JMS I ADPSUB
2111  1366            TAD BKWD
2112  4452            JMS I ASETM     /SET MOTORS TO
2113  1126            TAD CH          /MOVE BACKWARDS
2114  7450            SNA             /MOVE 10000(OCT)
2115  5323            JMP .+6         /STEPS FOR EACH
2116  7041            CIA             /COUNT IN CH
2117  3126            DCA CH
2120  4444            JMS I AMOVE
2121  2126            ISZ CH
2122  5320            JMP .-2
2123  1125            TAD CL          /MOVE CL STEPS
2124  4444            JMS I AMOVE
2125  5600            JMP I SETEL     /EXIT - AC CLEAR
2126  1365  MVEFWD,   TAD FWD
2127  4452            JMS I ASETM     /SET MOTORS TO
2130  1372            TAD DMSEH       /MOVE FORWARD
2131  7450            SNA
2132  5340            JMP .+6         /MOVE AS ABOVE
2133  7041            CIA
2134  3372            DCA DMSEH
2135  4444            JMS I AMOVE
2136  2372            ISZ DMSEH
2137  5335            JMP .-2
2140  1371            TAD DMSEL
2141  4444            JMS I AMOVE
2142  5600            JMP I SETEL
            /
            /
            /TO SET THE ANALYZER TO THE POSITION
            /STORED IN DESTH,DESTL (A TWO WORD BINARY
            /NUMBER IN THE RANGE 0 TO 35999 DECIMAL)/
2143  0000  SETAN,    0
2144  1130            TAD ANZCD       /GET ANZ CODE
2145  4452            JMS I ASETM     /SET GATING
2146  1130            TAD ANZCD
2147  3366            DCA BKWD        /SET FWD AND BKWD
2150  1367            TAD ANZ2        /CODES TO BE USED
2151  3365            DCA FWD         /BY SETEL
2152  4200            JMS SETEL
2153  5743            JMP I SETAN     /EXIT - AC CLEAR
            /
            /
            /TO SET POLARIZER AS ABOVE
            /
2154  0000  SETPL,    0
2155  1127            TAD POLCD       /GET POL CODE
2156  4452            JMS I ASETM
2157  1127            TAD POLCD       /AS ABOVE
2160  3365            DCA FWD
```

```
2161  1370           TAD POL2
2162  3366           DCA BKWD
2163  4200           JMS SETEL
2164  5754           JMP I SETPL      /EXIT - AC CLEAR
                /
2165  0000  FWD,     0
2166  0000  BKWD,    0
2167  4014  ANZ2,    4014
2170  0002  POL2,    2
2171  0000  DMSEL,   0
2172  0000  DMSEH,   0
2173  0004  H180,    4
2174  3120  L180,    3120
2175  0010  H360,    10
2176  6240  L360,    6240
2177  0000  BHLDK,   0
                     *2200
                /
                /
                /TO CONVERT A TWO WORD BCD NUMBER TO BINARY
                /BCD IN DECH,DECL BINARY IN CH,CL
                /
2200  0000  DPDBN,   0
2201  1134           TAD DECH         /CONVERT HIGH
2202  4442           JMS I ADCBIN     /WORD TO BIN
2203  3237           DCA DPX2L
2204  3240           DCA DPX2H
2205  4245           JMS DPX2
2206  4245           JMS DPX2         /MULT BY 2X2X2=8
2207  4245           JMS DPX2
2210  1243           TAD CNT3         /SET UP TO MULT
2211  3244           DCA CNT3HD       /BY 5X5X5=125
2212  1237           TAD DPX2L
2213  3241           DCA DPX5L
2214  1240           TAD DPX2H
2215  3242           DCA DPX5H
2216  4255           JMS DPX5         /MULT BY 5
2217  1126           TAD CH
2220  3242           DCA DPX5H        /NET RESULT IS TO
2221  1125           TAD CL           /MULT DECH BY
2222  3241           DCA DPX5L        /1000(DECIMAL)
2223  2244           ISZ CNT3HD
2224  5216           JMP .-6
2225  1125           TAD CL
2226  3121           DCA AL
2227  1126           TAD CH
2230  3122           DCA AH
2231  1133           TAD DECL         /CONVERT DECL
2232  4442           JMS I ADCBIN     /TO BINARY
2233  3123           DCA BL
2234  3124           DCA BH           /ADD TO HIGH PART
2235  4450           JMS I ADPADD
2236  5600           JMP I DPDBN      /EXIT - AC CLEA
2237  0000  DPX2L,   0
2240  0000  DPX2H,   0
2241  0000  DPX5L,   0
2242  0000  DPX5H,   0
2243  7775  CNT3,    -3
2244  0000  CNT3HD,  0
                /
                /
                /DOUBLE PRECISION MULTIPLY BY 2
                /INPUT AND OUTPUT IN DPX2H,DPM2L
```

```
                /
2245  0000  DPX2,   0
2246  1237          TAD DPX2L
2247  7104          CLL RAL         /ROTATE ONE LEFT
2250  3237          DCA DPX2L
2251  1240          TAD DPX2H
2252  7004          RAL
2253  3240          DCA DPX2H
2254  5645          JMP I DPX2      /EXIT - AC CLEAR
                /
                /
                /DOUBLE PRECISION MULTIPLY BY 5
                /INPUT IN DPX5H,DPX5L  OUTPUT IN CH,CL
                /
2255  0000  DPX5,   0
2256  1241          TAD DPX5L       /SET UP TO X2
2257  3237          DCA DPX2L
2260  1242          TAD DPX5H
2261  3240          DCA DPX2H
2262  4245          JMS DPX2        /X2
2263  4245          JMS DPX2        /X2
2264  1237          TAD DPX2L
2265  3121          DCA AL          /ADD ON ORIGINAL
2266  1240          TAD DPX2H       /NUMBER
2267  3122          DCA AH
2270  1241          TAD DPX5L
2271  3123          DCA BL
2272  1242          TAD DPX5H
2273  3124          DCA BH
2274  4450          JMS I ADPADD
2275  5655          JMP I DPX5      /EXIT - AC CLEAR
                /
                /
                /TO TURN ON POWER TRANSISTOR
                /
2276  0000  ONSW,   0
2277  7200          CLA
2300  1110          TAD DIR         /CLEAR BIT 1
2301  0315          AND MK2000      /OF DIR
2302  1316          TAD MC2000      /SET BIT 1 OF DIR
2303  6332          6332            /SET GATES
2304  3110          DCA DIR         /STORE CHANGE
2305  5676          JMP I ONSW      /EXIT - AC CLEAR
                /
                /
                /TO TURN OFF POWER TRANSISTOR
                /
2306  0000  OFFSW,  0
2307  7200          CLA
2310  1110          TAD DIR         /CLEAR BIT 1
2311  0315          AND MK2000      /OF DIR
2312  6332          6332            /SET GATES
2313  3110          DCA DIR         /STORE CHANGE
2314  5706          JMP I OFFSW     /EXIT - AC CLEAR
                /
2315  5777  MK2000, 5777
2316  2000  MC2000, 2000
                /
                /
                    *2400
                /
                /
                /TO BALANCE THE POLARIZER AND TYPE
```

```
                    /OUT THE BALANCE POSITION
                    /
2400   0000   BALP,    0
2401   7200            CLA
2402   1127            TAD POLCD       /SET POL
2403   4452            JMS I ASETM     /CODE
2404   4214            JMS BALU        /USE BALU
2405   5600            JMP I BALP      /EXIT -  AC CLEAR
                    /
                    /
                    /TO BALANCE THE ANALYZER AND TYPE
                    /OUT THE BALANCE POSITION
                    /
2406   0000   BALA,    0
2407   7200            CLA
2410   1130            TAD ANZCD       /SET ANZ
2411   4452            JMS I ASETM     /CODE
2412   4214            JMS BALU        /USE BALU
2413   5606            JMP I BALA      /EXIT - AC CLEAR
                    /
                    /
                    /TO BALANCE THE UNIT SPECIFIED ABOVE
                    /
2414   0000   BALU,    0
2415   4432            JMS I ASPACE
2416   4432            JMS I ASPACE    /TYPE 2 SPACES
2417   4446            JMS I ABAL      /BALANCE
2420   1247            TAD CH1CD       /READ
2421   4431            JMS I AANALG    /PHOTOMULTIPLIER
2422   3352            DCA ESIG        /STORE READING
2423   4435            JMS I ARDSFT    /READ SHAFT ENCODER
2424   1110            TAD DIR         /IF ANZ THEN COMP
2425   7104            CLL RAL         /BY 360.00
2426   7630            SZL CLA
2427   4451            JMS I AANZCP
2430   1100            TAD SHFTH       /PRINT OUT
2431   4440            JMS I APRTDC    /SHAFT ENCODER
2432   1101            TAD SHFTL
2433   4440            JMS I APRTDC
2434   4432            JMS I ASPACE
2435   4432            JMS I ASPACE    /PRINT 3 SPACES
2436   4432            JMS I ASPACE
2437   1250            TAD CE
2440   4454            JMS I ABUFF     /TYPE ES(ERROR
2441   1251            TAD CS          /SIGNAL)
2442   4454            JMS I ABUFF
2443   4432            JMS I ASPACE    /LEAVE SPACE
2444   1352            TAD ESIG        /PRINT OUT ES
2445   4437            JMS I APRTOC
2446   5614            JMP I BALU      /EXIT - AC CLEAR
2447   0017   CH1CD,   0017
2450   0305   CE,      305
2451   0323   CS,      323
                    /
                    /
                    /TO DO A COMLETE BALANCE OF THE
                    /ELLIPSOMETER AND TYPE OUT THE RESULTS
                    /
2452   0000   BALE,    0
2453   1127            TAD POLCD       /SET POL
2454   4452            JMS I ASETM     /CODE
2455   4446            JMS I ABAL      /BALANCE POL
2456   1130            TAD ANZCD       /SET ANZ
```

```
2457  4452          JMS I ASETM     /CODE
2460  4446          JMS I ABAL      /BALANCE ANZ
2461  1127          TAD POLCD       /SET POL
2462  4452          JMS I ASETM     /CODE
2463  4446          JMS I ABAL      /BALANCE POL
2464  4432          JMS I ASPACE
2465  4432          JMS I ASPACE    /TYPE 3 SPACES
2466  4432          JMS I ASPACE
2467  4435          JMS I ARDSFT    /READ SHAFT ENCODER
2470  1344          TAD CP
2471  4454          JMS I ABUFF     /TYPE "POL
2472  1345          TAD CO
2473  4454          JMS I ABUFF
2474  1346          TAD CLC
2475  4454          JMS I ABUFF
2476  4432          JMS I ASPACE    /LEAVE A SPACE
2477  1100          TAD SHFTH
2500  4440          JMS I APRTDC    /PRINT OUT SHAFT
2501  1101          TAD SHFTL       /ENCODER (POL)
2502  4440          JMS I APRTDC
2503  4432          JMS I ASPACE
2504  4432          JMS I ASPACE    /LEAVE 3 SPACES
2505  4432          JMS I ASPACE
2506  1347          TAD CA
2507  4454          JMS I ABUFF     /TYPE "ANZ"
2510  1350          TAD CN
2511  4454          JMS I ABUFF
2512  1351          TAD CZ
2513  4454          JMS I ABUFF
2514  4432          JMS I ASPACE    /LEAVE A SPACE
2515  1130          TAD ANZCD       /SET ANZ
2516  4452          JMS I ASETM     /CODE
2517  4446          JMS I ABAL      /BALANCE ANZ
2520  1247          TAD CH1CD       /READ
2521  4431          JMS I AANALG    /PHOTOMULTIPLIER
2522  3352          DCA ESIG        /STORE
2523  4435          JMS I ARDSFT    /READ SHAFT ENCODER
2524  4451          JMS I AANZCP    /COMPLIMENT BY
2525  1100          TAD SHFTH       /360.00
2526  4440          JMS I APRTDC    /PRINT OUT SHAFT
2527  1101          TAD SHFTL       /ENCODER (ANZ)
2530  4440          JMS I APRTDC
2531  4432          JMS I ASPACE
2532  4432          JMS I ASPACE    /LEAVE 3 SPACES
2533  4432          JMS I ASPACE
2534  1250          TAD CE
2535  4454          JMS I ABUFF     /TYPE "ES"
2536  1251          TAD CS
2537  4454          JMS I ABUFF
2540  4432          JMS I ASPACE    /LEAVE SPACE
2541  1352          TAD ESIG        /TYPE OUT ES
2542  4437          JMS I APRTOC
2543  5652          JMP I BALE      /EXIT - AC CLEAR
2544  0320  CP,     320
2545  0317  CO,     317
2546  0314  CLC,    314
2547  0301  CA,     301
2550  0316  CN,     316
2551  0332  CZ,     332
2552  0000  ESIG,   0
            /
            /
                    *2600
```

```
                    /
                    /
                    /TO SET THE ANALYZER FROM THE KEYBOARD
                    /
2600    0000        SETAR,  0
2601    4432                JMS I ASPACE
2602    4432                JMS I ASPACE      /TYPE TWO SPACES
2603    4214                JMS RDFVE         /READ A 5 DIGIT
                                              /BCD NUMBER
2604    4460                JMS I ASETAN      /USE SETAN ROUTINE
2605    5600                JMP I SETAR       /EXIT - AC CLEAR
                    /
                    /
                    /TO SET THE POLARIZER FROM THE KEYBOARD
                    /
2606    0000        SETPR,  0
2607    4432                JMS I ASPACE      /TYPE TWØ SPACES
2610    4432                JMS I ASPACE
2611    4214                JMS RDFVE         /READ NUMBER
2612    4461                JMS I ASETPL      /USE SETPL
2613    5606                JMP I SETPR       /EXIT - AC CLEAR
                    /
                    /
                    /TO READ A 5 DIGIT BCD CHARACTER FROM
                    /THE KEYBOARD
                    /
2614    0000        RDFVE,  0
2615    4455                JMS I AREADB      /READ FIRST CHAR
2616    7421                MQL
2617    7701                ACL
2620    4454                JMS I ABUFF       /TYPE IT
2621    7701                ACL
2622    1300                TAD M260          /REMOVE ASKII CODE
2623    7106                CLL RTL           /ROTATE 4 BITS
2624    7006                RTL               /LEFT
2625    3134                DCA DECH          /STORE IN DECH
2626    4455                JMS I AREADB      /GET 2ND CHAR
2627    7421                MQL
2630    7701                ACL
2631    4454                JMS I ABUFF       /TYPE IT
2632    7701                ACL
2633    1300                TAD M260          /REMOVE ASKII
2634    1134                TAD DECH
2635    3134                DCA DECH          /ADD TO DECH
2636    4455                JMS I AREADB      /GET 3RD CHAR
2637    7421                MQL
2640    7701                ACL
2641    4454                JMS I ABUFF       /TYPE IT
2642    7701                ACL
2643    1300                TAD M260          /REMOVE ASKII
2644    7110                CLL RAR
2645    7012                RTR               /STORE IN HIGH
2646    7012                RTR               /ORDER 4 BITS OF
2647    3133                DCA DECL          /DECL
2650    4455                JMS I AREADB      /GET 4TH CHAR
2651    7421                MQL
2652    7701                ACL
2653    4454                JMS I ABUFF       /TYPE IT
2654    7701                ACL
2655    1300                TAD M260          /REMOVE ASKII
2656    7106                CLL RTL           /STORE IN MIDDLE
2657    7006                RTL               /4 BITS OF
2660    1133                TAD DECL          /DECL
```

```
2661  3133          DCA DECL
2662  4455          JMS I AREADB     /GET LAST CHAR
2663  7421          MQL
2664  7701          ACL
2665  4454          JMS I ABUFF      /TYPE IT
2666  7701          ACL
2667  1300          TAD M260         /REMOVE ASKII
2670  1133          TAD DECL         /STORE IN LOW
2671  3133          DCA DECL         /4 BITS OF DECL
2672  4457          JMS I ADPDBN     /CONVERT TO BIN
2673  1126          TAD CH
2674  3136          DCA DESTH        /STORE IN
2675  1125          TAD CL           /DESTINATION
2676  3135          DCA DESTL        /(DESTH,DESTL)
2677  5614          JMP I RDFVE      /EXIT - AC CLEAR
2700  7520    M260, -260
              /
              /
                    *3000
              /
              /
              /TO MOVE MOTORS FROM KYBRD
              /
3000  0000    MOTR, 0
3001  4432          JMS I ASPACE     /TYPE SPACE
3002  4455          JMS I AREADB     /GET FR CHAR
3003  7421          MQL              /SAVE
3004  7701          ACL
3005  4454          JMS I ABUFF      /TYPE FR CHAR
3006  4432          JMS I ASPACE     /TYPE SPACE
3007  1300          TAD MOTINF       /INTERROGATE XY
3010  1301          TAD MX
3011  7640          SZA CLA
3012  5231          JMP YM           /XY IS NOT X
3013  7701          ACL              /XY IS X
3014  1302          TAD MF           /INTERROGATE
                                     /FOR REV CHAR
3015  7640          SZA CLA
3016  5222          JMP MXR          /FR IS NOT F
3017  1131          TAD M2XCD        /FR IS F - SET
3020  4452          JMS I ASETM      /MOTORS X-FOR
3021  5252          JMP RUNM         /RUN MOTORS
3022  7701    MXR,  ACL              /LOAD FR CHAR
3023  1303          TAD MR           /IS IT R
3024  7640          SZA CLA
3025  5600          JMP I MOTR       /NO - EXIT
3026  1304          TAD M2XCDR       /YES - SET MOTORS
3027  4452          JMS I ASETM      /TO X-REV
3030  5252          JMP RUNM         /RUN MOTORS
3031  1300    YM,   TAD MOTINF       /IS XY CHAR Y
3032  1305          TAD MY
3033  7640          SZA CLA
3034  5600          JMP I MOTR       /NO - EXIT
3035  7701          ACL              /YES GET FR CHAR
3036  1302          TAD MF
3037  7640          SZA CLA
3040  5244          JMP MYR
3041  1132          TAD M2YCD        /  SAME FOR Y
3042  4452          JMS I ASETM      /  AS FOR X
3043  5252          JMP RUNM
3044  7701    MYR,  ACL
3045  1303          TAD MR
3046  7640          SZA CLA
```

```
3047  5600            JMP I MOTR
3050  1306            TAD M2YCDR
3051  4452            JMS I ASETM
3052  4455  RUNM,     JMS I AREADB     /READ FIRST OF
3053  1307            TAD M260M        /TWO DIGITS TO
3054  7106            CLL RTL          /DETERMINE NO
3055  7006            RTL              /OF 1/16" TO
3056  3310            DCA SIXTN        /PLATES
3057  4455            JMS I AREADB
3060  1307            TAD M260M
3061  1310            TAD SIXTN
3062  7421            MQL
3063  7701            ACL              /SAVE
3064  4432            JMS I ASPACE     /TYPE SPACE
3065  7701            ACL
3066  4440            JMS I APRTDC     /TYPE OUT MOVE-
                                       /MENT OF PLATES
3067  7701            ACL
3070  4442            JMS I ADCBIN     /CONVERT MOVE-
                                       /ENT TO BINARY
3071  7041            CIA              /SET UP COUNTER
3072  3310            DCA SIXTN
3073  1311            TAD SIXTEN
3074  4444            JMS I AMOVE      /STEP 1/16"
3075  2310            ISZ SIXTN        /STEP REQUIRED
3076  5273            JMP .-3          /NO OF 1/16"
3077  5600            JMP I MOTR       /EXIT - AC CLEAR
3100  0000  MOTINF,   0
3101  7450  MX,       -330
3102  7472  MF,       -306
3103  7456  MR,       -322
3104  0300  M2XCDR,   300
3105  7447  MY,       -331
3106  0060  M2YCDR,   60
3107  7520  M260M,    -260
3110  0000  SIXTN,    0
3111  2000  SIXTEN,   2000
3112  0330  MXC,      330
3113  0331  MYC,      331
            /
            /
            /TO MOVE X MOTOR
            /
3114  0000  MOTRX,    0
3115  7200            CLA
3116  1312            TAD MXC          /PUT "X" IN MOTOR
3117  3300            DCA MOTINF       /INFO
3120  4200            JMS MOTR         /USE MOTR ROUTINE
3121  5714            JMP I MOTRX      /RETURN
            /
            /
            /TO MOVE Y MOTOR
            /
3122  0000  MOTRY,    0
3123  7200            CLA
3124  1313            TAD MYC          /PUT "Y" IN MOTOR
3125  3300            DCA MOTINF       /INFO
3126  4200            JMS MOTR         /USE MOTR ROUTINE
3127  5722            JMP I MOTRY      /RETURN
            /
            /
                      *3200
            /
```

```
                /
                /TO OPEN SHUTTER AND WAIT FOR A BALANCE
                /
3200  0000  STOP,   0
3201  4455          JMS I AREADB     /DETERMINE NO OF
3202  3237          DCA STPNO        /BALANCES
3203  3240          DCA DNFLAG       /CLEAR FLAG
3204  4462          JMS I AONSW      /OPEN SHUTTER
3205  4243          JMS RDP4         /READ PHOTOMULT
3206  3241          DCA SM1          /STORE READINGS
3207  4243  LPSTP,  JMS RDP4         /READ AGAIN
3210  3242          DCA SM2          /SORE READINGS
3211  1242          TAD SM2
3212  7041          CIA
3213  1241          TAD SM1          /SM1-SM2
3214  7700          SMA CLA          /TEST RESULT
3215  5223          JMP UPHILL       /READS INCRESE
3216  7001          IAC              /READS DECREASE
3217  3240          DCA DNFLAG       /SET FLAG
3220  1242          TAD SM2          /REPLACE SM1
3221  3241          DCA SM1          /BY SM2
3222  5207          JMP LPSTP        /LOOP
3223  1237  UPHILL, TAD STPNO        /LAST BAL?
3224  7640          SZA CLA
3225  5231          JMP CNTST        /NO BAL AGAIN
3226  1240          TAD DNFLAG       /APPROACHING MIN?
3227  7650          SNA CLA
3230  5235          JMP ENDSTP       /FININHED
3231  3240  CNTST,  DCA DNFLAG       /CLEAR FLAG
3232  1242          TAD SM2          /REPLACE SM1 BY
3233  3241          DCA SM1          /SM2
3234  5207          JMP LPSTP        /LOOP
3235  4463  ENDSTP, JMS I AOFFSW     /CLOSE SHUTTER
3236  5600          JMP I STOP       /EXIT - AC CLEAR
3237  0000  STPNO,  0
3240  0000  DNFLAG, 0
3241  0000  SM1,    0
3242  0000  SM2,    0
                /
                /
                /TO READ AND SUM PHOTOMULT 4 TIMES
                /   (SUM LEFT IN AC)
                /
3243  0000  RDP4,   0
3244  1255          TAD M4C
3245  3254          DCA CNT4         /SET COUNTER
3246  3256          DCA SUMPTO       /CLEAR
3247  4445          JMS I ARDPTO     /READ PHOTOM
3250  1256          TAD SUMPTO       /ADD TO SUM
3251  2254          ISZ CNT4         /FOURTH TIME?
3252  5247          JMP .-3
3253  5643          JMP I RDP4       /EXIT SUM IN AC
3254  0000  CNT4,   0
3255  7774  M4C,    -4
3256  0000  SUMPTO, 0
                /
                /
                        *3400
                /
                /
                /TO ITERROGATE KEYBOARD AND DECODE
                /COMMANDS
                /
```

```
3400  4456            JMS I AINIT     /INITILIZE
3401  4430            JMS I ACRLF     /CRLF
3402  4455  STSYS,    JMS I AREADB    /READ A CHAR
3403  7421            MQL             /SAVE IT
3404  7701            ACL             /LOAD IT
3405  4454            JMS I ABUFF     /TYPE IT
3406  7701            ACL             /LOAD AGAIN
3407  1246            TAD KC300       /SUB 300
3410  7002            BSW             /BYTE SWAP
3411  3247            DCA CHARAD      /SAVE 1ST CHAR
3412  4455            JMS I AREADB    /READ 2ND CHAR
3413  7421            MQL
3414  7701            ACL
3415  4454            JMS I ABUFF     /TYPE IT
3416  7701            ACL
3417  1246            TAD KC300       /SUBT 300
3420  1247            TAD CHARAD      /PUT IN LOW BYTE
3421  3247            DCA CHARAD      /WITH 1ST CHAR
3422  1243            TAD STLST       /SET ADDRESS OF
3423  3015            DCA LSTPT       /POINTER
3424  1415            TAD I LSTPT     /GET COMPARISON
3425  7041            CIA             /WORD. NEGATE
3426  7450            SNA             /0 INDICATES END
3427  5241            JMP ENDLST      /OF LIST
3430  1247            TAD CHARAD      /COMPARE
3431  7640            SZA CLA         /IF NOT THE SAME
3432  5224            JMP .-6         /GET NEXT COMP
3433  1015            TAD LSTPT       /ADDRESS OF LOC
3434  1244            TAD ADLST       /IS SUMM
3435  3245            DCA ADSTOR      /SAVE ADDRESS
3436  1645            TAD I ADSTOR    /GET ADDRESS OF
3437  3245            DCA ADSTOR      /COMMAND, SAVE IT
3440  4645            JMS I ADSTOR    /EXECUTE COMMAND
3441  4430  ENDLST,   JMS I ACRLF     /CRLF ENDS COMMAND
3442  5202            JMP STSYS       /START OVER
3443  3677  STLST,    3677
3444  0040  ADLST,    40
3445  0000  ADSTOR,   0
3446  7500  KC300,    -300
3447  0000  CHARAD,   0
            /
            /
                      *3700
3700  0205  ABE,      0205            /CODES FOR
3701  0201  ABA,      0201            /COMPARISON
3702  0220  ABP,      0220
3703  2301  ASA,      2301
3704  2320  ASP,      2320
3705  1530  AMX,      1530
3706  1531  AMY,      1531
3707  2302  ASB,      2302
3710  1723  AOS,      1723
3711  0323  ACS,      0323
3712  0000  AEND,     0
            /
            /
                      *3740
3740  2452  BBE,      BALE            /ADDRESSES
3741  2406  BBA,      BALA            /OF SUBROUTINES
3742  2400  BBP,      BALP
3743  2600  BSA,      SETAR
3744  2606  BSP,      SETPR
3745  3114  BMX,      MOTRX
```

```
3343        3746  3122  BMY,     MOTRY
3344        3747  ØØ64  BSB,     ASTOP
3345        375Ø  2276  BOS,     ONSW
3346        3751  23Ø6  BCS,     OFFSW
3347                    /
335Ø                    /

NO ERRORS

AANALG ØØ31
AANZCP ØØ51
ABA    37Ø1
ABAL   ØØ46
ABE    37ØØ
ABNBCD ØØ41
ABP    37Ø2
ABUFF  ØØ54
ACCNTU Ø7Ø2
ACCST  Ø667
ACCSTP Ø716
ACCUM  Ø37Ø
ACL    77Ø1
ACOMPØ 1727
ACOMP1 173Ø
ACOMP2 1731
ACRLF  ØØ3Ø
ACS    3711
ACTIME Ø722
ADCBIN ØØ42
ADLST  3444
ADPADD ØØ5Ø
ADPDBN ØØ57
ADPSUB ØØ47
ADSTOR 3445
AEND   3712
AH     Ø122
AHEAD  2Ø6Ø
AINIT  ØØ56
AINTSR ØØØ2
AKFLAG Ø571
AKYCNT Ø572
AL     Ø121
AMOVE  ØØ44
AMULT5 ØØ53
AMX    37Ø5
AMY    37Ø6
ANALG  Ø5Ø6
ANZCD  Ø13Ø
ANZCP  Ø723
ANZ2   2167
AOFFSW ØØ63
AONSW  ØØ62
AOS    371Ø
APOSØ  15Ø6
APOS1  15Ø7
APOS2  151Ø
APOS3  1511
APOS4  1512
APRTDC ØØ4Ø
APRTOC ØØ37
ARDDVM ØØ36
ARDPTO ØØ45
ARDSFT ØØ35
```

AREADB	0055
AREV	0043
ASA	3703
ASB	3707
ASETAN	0060
ASETM	0052
ASETPL	0061
ASP	3704
ASPACE	0032
ASTACK	1725
ASTEP	0033
ASTOP	0064
ASTORE	1726
ASUM	1724
ASUMH	0107
ASUML	0106
ATFLAG	0570
ATLCNT	0573
AWAIT	0034
BACK	1063
BAL	1600
BALA	2406
BALE	2452
BALLP1	1611
BALP	2400
BALU	2414
BBA	3741
BBE	3740
BBP	3742
BCS	3751
BH	0124
BHLDK	2177
BKWD	2166
BK2	1102
BK3	1124
BL	0123
BLFLAG	1723
BMX	3745
BMY	3746
BNBCD	1050
BNBR	1142
BNLP1	1055
BNLP2	1076
BNLP3	1120
BOS	3750
BSA	3743
BSB	3747
BSP	3744
BSW	7002
BUFFER	0250
BUFLP1	0253
BUFPT	0011
CA	2547
CAM	7621
CE	2450
CH	0126
CHARAD	3447
CHDIR	1420
CH1CD	2447
CL	0125
CLASWP	7721
CLC	2546
CLTFLG	0276

```
CMPSM  1466
CN     2550
CNTST  3231
CNT3   2243
CNT3HD 2244
CNT4   3254
CO     2545
COMP0  1444
COMP1  1452
COMP2  1460
CP     2544
CRLF   0400
CS     2451
CTHUP  0244
CZ     2551
DCBIN  1000
DECH   0134
DECL   0133
DESTH  0136
DESTL  0135
DIG    1143
DIGCTR 0502
DIR    0110
DMSEH  2172
DMSEL  2171
DNFLAG 3240
DNUMB  0105
DPADD  1541
DPDBN  2200
DPSUB  1553
DPX2   2245
DPX2H  2240
DPX2L  2237
DPX5   2255
DPX5H  2242
DPX5L  2241
DVMH   0103
DVML   0102
ENDBUF 0362
ENDKBF 0365
ENDLST 3441
ENDSK1 1325
ENDSTK 0010
ENDSTP 3235
ENDTIM 0625
ESIG   2552
EXTINT 0213
FINISH 1066
FLAGUP 0355
FLGSET 1433
FNH2   1104
FNH3   1126
FWD    2165
HLDBL1 1722
H180   2173
H360   2175
INITZE 0543
INTRPT 0000
INTSER 0200
KBDCNT 0374
KCF    6030
KC10   1146
KC100  1145
```

KC1000	1144
KC3	0503
KC300	3446
KC4	0477
KK1777	0566
KK2177	0567
KPDPS	1571
KYBDPT	0013
KYBRD	0302
KYFLAG	0367
KYND2	0347
KYNEND	0314
K1000D	0745
K212	0414
K215	0415
K240	0416
K260	0476
K35D	0746
LINK	0371
LKPRT	0574
LPSTP	3207
LPSUM	1335
LSTPT	0015
L180	2174
L360	2176
MASK	0473
MASK17	0504
MASK37	0653
MASK40	0652
MASK7	0475
MC2000	2316
MF	3102
MK17	1025
MK2000	2315
MK360	1026
MK7400	1027
MK77	0541
MK7700	0540
MLT100	1044
MNBR	1043
MOTINF	3100
MOTOR	1434
MOTR	3000
MOTRX	3114
MOTRY	3122
MOVE	1435
MQA	7501
MQL	7421
MQSAVE	0372
MR	3103
MSDIG	0104
MSKDIR	1416
MSKDR1	1432
MSKDR2	1417
MSKD1	0715
MULT10	1030
MULT5	1034
MVEFWD	2126
MX	3101
MXC	3112
MXR	3022
MY	3105
MYC	3113

MYR	3044
M2XCD	0131
M2XCDR	3104
M2YCD	0132
M2YCDR	3106
M260	2700
M260M	3107
M4C	3255
NOTEDB	0271
NOTEND	0241
NUMBER	0500
OCNBR	1024
OFFSW	2306
ONSW	2276
PHTOCD	1354
POLCD	0127
POL2	2170
POSCT	1721
POS0	1622
POS1	1625
POS2	1633
POS3	1660
POS4	1713
PRINT	0417
PRTDC	0447
PRTOC	0461
RDDVM	0635
RDFVE	2614
RDPTO	1347
RDP4	3243
RDSFT	0626
READB	0330
READPT	0014
REV	1400
ROTNBR	0474
RUNM	3052
SETAN	2143
SETAR	2600
SETEL	2000
SETKFL	0324
SETM	1421
SETPL	2154
SETPR	2606
SHFTH	0100
SHFTL	0101
SHIGH	0542
SIXTEN	3111
SIXTN	3110
SKC16	0717
SM1	3241
SM2	3242
SPACE	0407
SPF	6040
STACK	1300
STBL	1603
STBUF	0363
STEP	0654
STEP1	0600
STKL	0111
STKLC	0112
STKYBF	0366
STLP1	1523
STLST	3443

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STNBR	Ø5Ø1
STOP	32ØØ
STORE	1513
STPCNT	Ø117
STPNO	3237
STROT	Ø5Ø5
STSTK	Ø12Ø
STSYS	34Ø2
SUBPT	2027
SUM	1326
SUMH1	Ø113
SUMH2	Ø114
SUML1	Ø115
SUML2	Ø116
SUMPTO	3256
SVSTK1	1323
SVSTK2	1324
SWP	7521
S2GTS1	15Ø4
S2LTS1	15Ø5
TELCNT	Ø373
TELTP	Ø223
TFLAG	Ø364
TYPEPT	ØØ12
UNPACK	Ø425
UPHILL	3223
WAIT	Ø611
WLP1	Ø614
WT	Ø61Ø
WTIME	Ø721
WT1	Ø72Ø
YM	3Ø31