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(NASA-CR-169717) A MICROPROCESSOR-BASED ONE
DIMENSIONAL OPTICAL DATA PROCESSOR FOR
SPATIAL FREQUENCY ANALYSIS Final Technical
Report, No. 1979 - Aug. 1982 (Arkansas
Univ.) 70 p HC A04/MF A01

N83-16199

Unclas
02395

CSSL 20F G3/74

**A MICROPROCESSOR-BASED
ONE DIMENSIONAL
OPTICAL DATA PROCESSOR
FOR SPATIAL FREQUENCY ANALYSIS**



Final Technical Report

by

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November 1979 - August 1982

**NASA Research Grant NGL-04-001-007
Supplement No. 17**

for

**Nephelometer Evaluation for Measurement of
Cloud Parameters in Earth and Planetary Atmospheres**

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submitted by

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A MICROPROCESSOR-BASED ONE DIMENSIONAL
OPTICAL DATA PROCESSOR FOR SPATIAL
FREQUENCY ANALYSIS

by

R. L. Collier and G. S. Ballard

I. INTRODUCTION

Over the past few years there has been led to a general interest in the detection and characterization of aerosol particles with diameters of the order of a few micrometers. Conventional methods of sample collection such as filtering and weighing are not effective with particles of this size. Recently, classification of particles by use of laser instrumentation has become a valuable investigative method. This is actually a branch of a field of study known as Optical Information Processing. This subject has been studied for many years and, since the discovery of the laser, has undergone a revival in the area of pattern recognition, particle sizing, and spatial frequency analysis.

In 1973, Wankum demonstrated what he referred to as a general purpose spatial frequency analyzer.⁸ This instrument was based on a unique application of the basics of Fourier optics to the problem of sample analysis by investigation of the sample's diffraction pattern. In his design, the detector and transform

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lens are mounted on an arm that rotates about the sample. In 1975, McKean used a variation of this instrument in his investigation of the resolution of photographic emulsions.⁵ Since that time, different forms of the analyzer have been used in a number of other studies. In each case, the spectrum analyzer was adapted as necessary to the specific research in progress.

Several problems existed with the earlier versions of the analyzer. One such problem was the physical discontinuity of the optical axis. The light source and collimating optics were located in one room while the sample, collection optics, and detector were located in another room. The two parts of the system were placed on separate tables of different heights and stability. While intended to protect the analyzer's detector from stray light, this arrangement made the optical system virtually impossible to align and keep aligned.

In spatial frequency analysis it is necessary to determine the intensity of scattered light as a function of scattering angle. Wankum used a time base strip chart recorder to identify the angle for any given intensity measurement. McKean modified the system to accept a Sine Potentiometer that was connected to a shaft through the center of the rotation axis of the arm carrying the transform lens and detector. The output was a function of the sine of the arm angle, which was used to drive an x-y recorder directly. Both of these approaches suffered from a lack of repeatability. It was also difficult to locate the arm at a

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specific angle with any degree of accuracy.

The third problem area was the lack of a general purpose data acquisition system. Each time the system was adapted to a new research project the data system was also altered. Each of these data systems was primarily analog in nature and required close attention by the operator during the sample scan.

Other problems, while not considered as important as the ones already discussed, were identified. The rotating arm was limited to a scan range of ± 75 degrees. This was due both to the construction of the sample mounting system and to the limits of the angle measuring process. Also, the spatial frequency spectrum of weakly scattering particles was difficult to obtain because a low power laser was used as a light source.

The purpose of this work is to take the concept of the spatial frequency analyzer and to develop an instrument readily usable for a wide variety of potential applications. To this end, each of the problem areas mentioned above have been addressed with special emphasis on the following areas:

- (1) Stability and ease of alignment
- (2) Development of a general purpose digital data acquisition system
- (3) Increasing the angular range of the instrument to include backscatter measurements
- (4) Ability to change light sources if a different wavelength or power is desired.
- (5) Control of stray light

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II. BACKGROUND INFORMATION

The function of the optical data processor is to define the spatial frequency structure of a given sample. When a coherent beam of radiation is passed through a sample, be it a slit, a straight fiber, a circular aperture, a grating, or a sphere, radiation will be scattered in the forward and backward direction in such a manner that it will constructively and destructively interfere to form a pattern unique to the sample. If the observation point and the source of radiation are effectively at infinite distances from the sample causing the pattern, then the phenomenon is known as Fraunhofer or Far Field diffraction. Several authors offer extremely good explanations of this phenomenon.^{1,4}

The diffraction pattern in the Fraunhofer region is given by the Fourier transform of the amplitude distribution of the sample.² Shulman, in his work on optical data processors, demonstrated a method that utilized the fact that a positive lens produces at its back focal plane the Fourier transform of an input located at its front focal plane.⁶ If the distribution pattern just past the sample is focused by a positive lens on a detector, then the detector will measure the Fraunhofer diffraction pattern directly. A simple system is shown in Figure 1. One problem exists with a system of this type. The size of the lens limits the amount of the diffraction pattern that can be seen. Often

important information on the structure of the sample is present only in the higher spatial frequency regions of the diffraction pattern. This information would be lost due to truncation of the pattern by the limited size of the lens. Also, the effects of common lens aberrations such as distortion, coma, spherical aberration, and astigmatism must be considered. Illumination of the entire lens tends to maximize these effects.

The Fourier transform of the input signal, or sample scattering, contains x, y, and z components. In general, the z component of the transform is considered to lie directly on the optical axis and is dropped from theoretical consideration. The x and y components are then presented in the plane perpendicular to the axis. The majority of optical data processors investigate either the x or y components of the Fourier transform. Considering only the x direction, the spatial frequency component of the Fourier transform is given as:

$$g(x) = \frac{\sin \theta}{\lambda} \quad (1)$$

where λ is the wavelength of radiation incident on the sample and θ is the angle from the optical axis.⁸ The spatial frequency limits for any instrument can be calculated with Equation 1 as long as both the wavelength of radiation and the angular limits of the system are known.

In 1973 Wankum demonstrated a technique that essentially

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eliminated the problem of lens truncation.⁸ The transform lens and detector were mounted on a rotating arm. The sample point was located at the center of rotation of the arm. A laser beam incident on the sample created an intensity distribution in space that was scanned by the transform lens and detector mounted on the rotating arm. A pinhole placed at the focal point of the lens served to limit that portion of the diffraction pattern reaching the detector to radiation scattered at a specific angle $\theta + \alpha$. θ is the angle of the rotating arm relative to the optical axis and α is determined by:

$$\alpha = \text{Arctan} \left(\frac{r}{f} \right) \quad (2)$$

where r is the radius of the pinhole and f is the focal length of the lens. The spatial frequency response of this system is then limited by the wavelength of the laser used and the angular travel limits of the rotating arm rather than the diameter of the transform lens. As the arm was rotated through the sample spectrum only those rays parallel to the optical axis of the lens were focused on the pinhole, eliminating all off-axis lens aberrations.

In recent years a great deal of work has been centered on the use of spatial frequency analysis in the evaluation of the resolution of photographic emulsions by measurement of a quantity known as the Modulation Transfer Function (MTF). Dainty,³ in his

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work on image science, offers a good treatment of the applications of the MTF to optical data processing. In 1975, McKean utilized a variation of the system developed by Wankum to measure the MTF of an edge imaged on a photographic plate.⁵ While he introduced changes such as an automatic angle measuring device and specific signal processing electronics, the major change introduced by McKean was in the handling of background noise due to the photographic emulsion substrate and stray light. His procedure was to first take a scan with just the substrate in the sample beam and then subtract this background on a point by point basis from his subsequent data scan of the edge image. This proved valuable in separating sample signal from noise in the case of samples mounted on backgrounds that are extremely good scatterers.

III. EXPERIMENTAL SETUP

The instrument described by this research represents a rather radical departure from the design of optical data processors that one normally encounters.⁷ As illustrated in Figure 2, the sample and beam path are held stationary while the lens collection system and detector rotate in a circle around the sample. The instrument essentially maps the Fraunhofer diffraction pattern as it is presented in space in a plane containing the optical axis. Wankum presents a mathematical treatment of the theory of operation of this instrument in his thesis.⁸

Throughout the development of this instrument two factors, the control of stray light and instrument alignment stability, surfaced as the major concerns in any portion of the system design. It is obvious as to why the control of stray light is important. In an electronic system, the most frequent problem that the designer encounters is noise. The same holds true for optical systems except that the noise, often referred to as stray light, is optical in nature. Stray light is any radiation incident on the detector, with sufficient strength to cause a signal, that does not come from the sample along the optical axis being examined. The presence of stray light affects every phase of the data gathering process. This is due primarily to the fact that the detector has no way of distinguishing the difference between stray light and legitimate data. The researcher is left

with two alternatives; to shield the detector and the system from every possible source of stray light, or to accept its presence and attempt to subtract it in some manner from the final data.

In the design of the optical data processor for this research a mixture of the two alternatives was effected. In every facet of the project design the control of stray light was one of the primary considerations. This accounts for the amount of shielding and the number of apertures present in the system. Figures 3 and 4 illustrate the extent of this carefully placed equipment. However, shielding and apertures do not solve the problem completely. Any residual stray light is measured by obtaining a scan without a sample present. The purpose of this is to establish a background against which the actual data would be taken. The data collection system, to be discussed in section E, has the capability of subtracting this background from subsequent data scans.

Less obvious to the observer, however, is the need for instrument alignment stability and the preservation of the optical axis. In order to properly evaluate the diffraction pattern of a sample, the sample must be located over the center of rotation of the arm. The path of the incident laser beam defines the optical axis of the system and must be contained in the plane traversed by the detector. These conditions must be identical for all sample runs. This is necessary in order for the instrument to be used for comparing diffraction characteristics of several different

samples. Frequent alignment of the optical system would be time consuming and a possible source of error.

The actual optical data processor is composed of several major subcomponents. Figures 3 and 4 depict the location of the subcomponents with respect to the entire system. Each component will be discussed separately.

A. Rotating Arm and Drive System

An Ealing Corporation Model 22-950 Lathe Bed Optical Bench serves as the major support component of the optical data processor. Mounted on one end of the bench is the rotating arm platform base plate. The base plate is made of 1.9 centimeter (cm) thick aluminum and is 60 cm square. The center of the base plate is drilled to accept a 2.2 cm diameter hollow tube threaded on one end. Centered on this hole and also mounted to the base plate is a 10 cm bearing race. The bearing is mounted in a 30 cm diameter plate that functions as the rotation point for the arm. The 2.2 cm diameter tube is passed through this rotation plate as it sits on the bearing race. A locknut under the base plate holds the rotator in place. The platform itself is an 86 cm diameter circle of 1.27 cm aluminum with a cutout in the center to accommodate the rotator. This platform is bolted to the base plate and provides the track for the drive mechanism. The arm, a 76.2 cm long piece of 7.62 cm wide channel aluminum, is fastened to the rotator plate at one end and supported by the arm drive mechanism

at the other. An optical bench railing designed to accept the Ealing Optical Carrier Model 22-958 with x and y axis adjustment is fastened to this arm. Once assembled, the rotating arm assembly describes a circle 106 cm in diameter. See Figures 3 and 4.

The drive mechanism is a Hurst 110 VAC 4 RPM Model PC-DA reversible drive motor with magnetic clutch. The motor is connected by a series of gears to a drive wheel attached to the rotating arm. The motor and gearing arrangement can be manually lifted from contact with the drive wheel so that the arm can be moved freely by hand. A diagram of the motor control panel is shown in Figure 5. The drive motor control panel is located at the data collection station and connected by cable to the drive motor. This drive arrangement provides a scan speed of 0.2813 degrees per second.

As indicated previously, the sample producing the diffraction pattern must be held at the center of rotation of the arm while the scan is being made. The sample holder support, as shown in Figure 3, is an optical bench supported at one end. The other end is suspended over the center of rotation of the arm. The optical bench accepts the same mounts as the rest of the system. The construction of the assembly is such that it does not flex under the weight of the sample mount. The sample holder support is bolted to the arm base plate as shown in Figure 3.

In earlier versions of the instrument, the travel of the

rotating arm was limited by the design of the sample holder support to ± 90 degrees. The support was redesigned to allow scattering to be measured at angles of up to ± 160 degrees from the incident radiation.

Once the sample holder support is in place, two types of sample holders are used. The sample holder shown in Figure 6a is designed to hold samples mounted on standard glass microscope slides. In addition it will hold any other sample material that is of the same size as a microscope slide. The three point contact system of the slide holder can be removed from the rest of the mount and then, because of the three point contact design, be replaced back in its original position with a high degree of precision.

The sample holder shown in Figure 6b is designed for use with slits, fibers and gratings where the diffraction pattern must be aligned to the desired plane of observation. The micrometer can be disengaged and the sample moved as desired in a complete circle.

B. Angle Measuring Equipment

Perhaps the most important aspect of this project is the way in which the angle of the arm is measured. Angular measurements must be repeatable, accurate, and offer good resolution.

One method consisted of placing a stainless steel shaft through the center of rotation of the arm and coupling it to a

Beckman Model NL 5713 Sine Cosine Helipot. When a voltage is applied across the potentiometer it presents the position of the arm as an analog voltage. This voltage is related to the sine of the angle by

$$V_{out} = \text{Sin } (\theta) V_{supply} \quad (3)$$

where θ is the angle of the arm measured from the optical axis and V_{supply} is the voltage applied to the potentiometer. Figure 7 is a plot of the cosine of arm angle versus the sine of arm angle as produced by the Beckman Sine Cosine Helipot. The output of the sine pot is not linear. The data being plotted as a function of the arm position is compressed as the arm approaches 90 degrees, resulting in a loss of detail at extreme angles.

A BEI Model 86 CGL shaft position encoder has also been used as an angle measuring device. This encoder, by means of a specially patterned disc and a light source, divides a circle into one thousand separate parts and presents a three digit number in Binary Coded Decimal (BCD) for each part. The resolution of the angle measuring system is 0.36 degrees per encoder position. The encoder internal resolution is 165 arcsec RMS absolute position. The encoder requires a specialized power supply. The voltage requirements are: +5 Vdc at 495 mA, +7.6 Vdc at 810 mA and -5.5 Vdc at 96 mA. Tolerances on all voltages are \pm 5 percent. An advantage of the encoder is that its digital output is linear with

respect to arm position, eliminating the compression of data measured at large angles. See Figure 8.

The final system chosen for the optical data processor is a marriage of the Helipot and encoder. This arrangement is shown in Figure 9. The encoder, because of its linear output and accuracy, is used as the main sensing device. The data from the encoder is gathered by a microcomputer and stored for use. In order to reduce the problem of backlash, an anti-backlash type Bellows coupling available from Winfred M. Berg Inc. is used to couple the encoder shaft to the shaft from the rotating arm assembly. This arrangement insures accuracy and good repeatability for all angle measurements. The backlash of the stainless steel shaft is considered to be negligible.

As shown in Figure 9, the Helipot is connected to the encoder by means of a timing belt and pulleys. The belt is 0.3 cm wide polyester cord and the pulleys are low profile aluminum alloy 0.80 degrees pitch grooved pulleys 3.9 cm in diameter. The pulley ratio is one to one. The Helipot is powered by ± 10 Vdc from a variable power supply. The outputs of the two angle measuring devices are matched as shown in Table I. The power supply for the encoder is built around a Calnex Model 7248 microprocessor power supply which produces +12 Vdc at 1 A, -12 Vdc at 200 mA, +5 Vdc at 6 A, and -5 Vdc at 100 mA. The circuit shown in Figure 10 is used to produce the necessary voltages with the appropriate current limits for the encoder.

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TABLE I
Angle Measuring Equipment Outputs

Arm Angle (Degrees)	Encoder Position (BCD)	Helipot	
		Sine (Vdc)	Cosine (Vdc)
0	000	0	+10
-90	250	-10	0
180	500	0	-10
+90	700	+10	0

The tandem combination of the encoder and Helipot is used primarily for the convenience of the system operator. The digital output of the encoder must be collected and processed by a computer and then matched with the output of the detector before a plot of Scattering Intensity versus Angle can be produced. While this is the most accurate way of handling the data, it requires completion of an entire run before the data can be examined. Therefore, if a problem such as a misalignment of the sample or the failure of the light detector arises, it would not be noticed until the entire procedure was completed.

The output of the Helipot is an analog voltage that can be used directly to drive the x axis of an x-y recorder. If the output signal of the detector is placed on the y axis of the recorder, a plot of the data will be produced as it is being taken. This serves as an excellent indicator as to whether or not the total system is functioning properly. If a problem is indicated the data run can be stopped, the problem corrected, and the data run restarted.

C. Lasers

The optical data processor has been designed so that different radiation sources can be easily substituted if power or wavelength requirements so dictate. Four separate lasers are used. Table II lists the lasers currently available, along with the wavelength and rated power of each.

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The Model 120 laser is the primary light source for the instrument. Mounted permanently on the main optical bench of the system, it is used both for data and to establish the optical axis of the processor for alignment purposes. See Figure 4.

If different intensities or wavelengths are required, then one of the other three alternate lasers can be used. The LD-60 is a small Gallium Arsenide diode laser. It can be mounted on the main optical bench of the system directly in front of the Model 120 alignment laser and is aligned directly with the optical axis. See Figure 4.

The other two lasers used with the system cannot be mounted on the optical bench of the instrument because of their size. They are mounted outside the room housing the data processor. The beam from either of these lasers is passed through a port in the wall and directed at a point just in front of the Model 120 alignment laser. This beam path is perpendicular to the optical axis of the system.

The alignment platform shown in Figure 11 is used to align the incoming beam with the optical axis of the instrument. It is placed on the optical bench in front of the Model 120 laser. See Figure 4. The alignment platform consists of a mirror to reflect the beam 90 degrees to the optical axis. An Oriel Model 6650 Laser Beam Aligner is used for the final matching of the incoming beam to the optical axis. Located just after the aligner is a filter holder which can accommodate up to four neutral density

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TABLE II

Lasers Used in the Optical Data Processor

laser	Type	Wavelength (nm)	Rated Power
Spectra Physics Model 120	cw HeNe	632.8	5 mw
Spectra Physics Model 125	cw HeNe	632.8	50 mw
Spectra Physics Model 162A	cw Argon Ion	488.0	25 mw
Laser Diode Inc. Model LD-60	Pulsed GaAs Diode	905	3.1 watts peak

filters. These are used to attenuate the beam incident on the sample if necessary.

This arrangement would appear to reintroduce the problem of axis discontinuity that existed with earlier versions of this system. With the present design, however, the system is aligned by using the Model 120 laser as a reference. Any other alternate radiation source, regardless of its physical location, is aligned with the permanent optical axis of the system without adjusting or disturbing any component of the optical data processor. At any time, the alternate light source can be removed and the system alignment verified with the Model 120 laser.

D. Intensity Data Collection System

Once a diffraction pattern has been produced by passing the laser beam through a sample located at the center of rotation of the arm, it is necessary to collect and accurately measure the intensity of that scattered radiation. As indicated, the rotating arm is outfitted with an optical bench rail that accepts the standard optical mount for the system. Utilizing this railing and mounts, the components of the intensity data collection system are arranged on the arm as shown in Figure 12. These components are a front optical mask with 1.27 cm aperture, a lens in a three point holder, and a photomultiplier with an 800 micrometer pinhole as an entry aperture.

The front optical mask is not designed to be a limiting

aperture in the system. Its purpose is to shield the lens and detector from spurious light signals. With many samples most of the incident laser beam is transmitted by the sample. As the movable arm scans the diffraction pattern close to the optical axis, the lens and lens mount will pass through this beam. The edge of the lens or the lens mount scatters light as it passes through the transmitted beam, causing rather intense light levels to reach the detector. These levels would be great enough to override the diffraction pattern signal present.

A large, flat, aluminum mask was first used to cover the entire lens mount system. The aperture diameter of 1.27 cm was chosen arbitrarily. This opening was larger than the 4 millimeter diameter of the incident beam and would not serve as a limiting aperture on the system. Also, this aperture was small enough to allow the arm to scan within three degrees of the zero axis before edge scattering occurred.

The addition of this mask did not totally eliminate the problem of these stray light signals. While it removed the high intensity signals caused by the edge of the lens and the lens mount, a signal of lesser intensity was introduced when the beam slipped off the edge of the mask. This noise occurred further out in the scan and was small enough that it usually did not overwhelm the scattering pattern signal.

Figure 13a shows the final shape of the front optical mask. In this top view of the mask, it is evident that the shape is no

longer flat. The edges of the mask are swept back so that the edge is well past the location of the lens mount on the rotating arm. As the beam slips off the edge of this mask the scattering is not seen by the detector.

The lens used is an uncoated double convex lens 10 cm in diameter. Its focal length is 23 cm. This lens can be used with any of the three laser wavelengths available for this system. The lens is positioned on the arm so that, as discussed previously, it functions as a Fourier transform lens. The front optical mask is positioned so that only the center portion of the lens is used. Since this is the region of least curvature, the spherical aberration of the lens will be minimized.

An 800 micrometer diameter pinhole is mounted on the photomultiplier case so that it is centered approximately 2.50 cm from the viewing window of the tube. This area is sealed against stray radiation so that the only light entrance to the photomultiplier is the pinhole. In previous systems the pinhole was usually mounted several centimeters from the photomultiplier tube with no means provided for blocking stray light. This led to the possibility that light could reach the photomultiplier without being focused through the pinhole.

The 800 micrometer pinhole determines the acceptance angle of the instrument's light detector. Ideally the only radiation that should reach the detector is that traveling parallel with the optical axis of the rotating arm. In practice, some off axis

radiation will also be focused into the collection pinhole. From Equation 2, the amount of angular deviation from the optical axis is controlled by the size of the pinhole and the focal length of the lens. For this system, a pinhole radius of 400 micrometers and a lens focal length of 23 cm, the acceptance angle α is ± 0.1 degrees. See Figure 13b.

The detector used is a Hamamatsu Model 928 side view photomultiplier tube. This tube has a multialkali coated cathode and a spectral response of 185 to 930 nanometers. Power for the photomultiplier tube is supplied by a Hewlett Packard Model 6516A high voltage power supply. The voltage for the tube is varied from 0 to -1000 Vdc, depending on the sensitivity required. The response of the photomultiplier is linear over this range of supply voltages.

The photomultiplier tube produces a current output that is directly related to the amount of radiation incident on the cathode of the tube. In the case of the Model 928 the maximum output is 100 A. This output current must be converted to a voltage before it can be used as an input to an analog-to-digital converter. Because of the range of the analog-to-digital converter used, it was required that the 0 to 100 A output of the photomultiplier tube be presented to the analog-to-digital converter as a 0 to 10 Vdc input. The circuit used to make this conversion is shown in Figure 14. Utilizing the MC1741SCP Operational Amplifier with a 15 volt per microsecond rise time,

this circuit contains a current-to-voltage converter, an amplification stage, and a buffer. It should be noted that the current-to-voltage conversion and amplification could be done with one operational amplifier. However, this can lead to considerable electronic noise due to the larger resistors that would be required. The circuit is designed so that 0.03 μ A of output current will correspond to 2.89 mV of output voltage. The detector sensitivity is controlled by varying the voltage applied to the photomultiplier tube. This enables the processor to take data over a large dynamic range of intensities.

E. Data Collection System

The heart of the data collection system, shown in Figure 15, is a KIM-1 6502 based microprocessor with 12 kilobytes of additional memory. This board provides the data storage and program control for the acquisition of the light intensity and angle data. However, these data inputs cannot be fed directly into the microcomputer. They must pass through certain interface and conversion circuits to be present in the correct form for storage.

As indicated previously, the output of the encoder is three digit BCD. This means that 12 unique bits of binary code are presented for each angular position of the movable arm. The outputs of the encoder are hardwired to the two input-output ports, PortA and PortB, of the KIM-1. The 4 bits of data that

make up the most significant digit of the encoder BCD output are placed on PBO-PB3 of PortB with the most significant bit on PBO. The last two digits of the encoder output are placed on PA0-PA7 of PortA with the least significant bit placed on PA7. The reason for the reverse order of the bit string presented to PortA will be covered in the explanation of the program operation in Section F. The output of the encoder is also routed to a display board that presents a three digit LED display of the current arm position to the instrument operator.

The output of the intensity detector is a DC voltage. This voltage must be converted to binary form for storage by the microprocessor. The device used to do this is an analog-to-digital (A/D) converter. The A/D converter chosen is the Analog Device's AD574 diagramed in Figure 16. It is a 12 bit converter with a 25 microsecond conversion time. A 12 bit A/D converter can subdivide a 10 Vdc input into 4095 increments of 2.44 mV each, while an 8 bit converter subdivides the same input into only 255 increments of 39 mV each. If input changes on the order of 5 mV are to be detected, a 12 bit converter must be used.

Internal to the AD574 is the necessary circuitry to interface its 12 bit output to the 8 bit data buss of the KIM-1. The data is presented in two bytes. One byte contains the eight most significant bits of the 12 bit string. The other byte contains the four least significant bits trailed by zeros. The order of presentation to the data buss of the KIM-1 is under software

control of the operating program.

The analog data system is basically the same one that has been used in past variations of the instrument. The output of the sine potentiometer is placed on the x axis of a Hewlett Packard Model 7044B x-y recorder. The output of the detector can be placed on the y axis of the recorder so that a direct x-y plot of the data can be obtained.

F. Program

Control of the data collection system is executed by a program written for the KIM-1 microprocessor. The system's sole function is to collect data and store it for transfer to cassette tape. Appendix 1 contains a flowchart and listing for the program.

The concept of the program operation is simple. Each time the encoder indicates a new position, a measurement of the intensity of scattered light at that point will be taken and stored in microprocessor memory. An examination of the 12 bit string produced by the encoder indicates that the least significant bit (LSB) of the string alternates between 1 and 0 with each position change. The KIM-1 operating system contains an instruction called the BIT instruction that provides a method of easily testing for a one bit change. As indicated previously, the LSB of the 12 bit encoder data string is hardwired to PA7 of PortA of the KIM-1. This places the LSB in bit 7 of the data from the

port. When the BIT instruction is executed, the value of bit 7 of the memory location referenced is loaded into the negative flag (N) of the processor status register. Since this bit alternates from 0 to 1 with every position change of the encoder, it indicates to the microprocessor that the encoder has transitioned to a new angle position.

Since the optical data processor is designed to record an intensity data point for every position increment of the encoder, only the starting angle position of the arm is stored in memory. When the Intensity versus Angle plot is constructed, the angles will be calculated and matched to the appropriate intensity values by a minicomputer. The change of the LSB from 1 to 0 or vice versa is used as a signal to the microprocessor to service the A/D converter for a new intensity value.

The intensity data and angle data should be taken simultaneously for every point on the diffraction pattern. However, an examination of the program shows that the time delay between the detection of the bit transition and the signal to the A/D to start conversion would be approximately 13 microseconds. Considering the 0.2813 degrees per second scanning speed of the arm and the fact that a spatially variant, rather than a time variant, signal is being measured, this delay will have no measurable effect on the accuracy of the intensity data. Further, this delay remains constant for each measurement throughout the entire data collection process.

Once the intensity data has been collected and stored in memory, it is recorded on cassette tape for transfer to an Interdata Model 7/32 Minicomputer. Transfer of the data is accomplished by the use of a 6502 based SYM microprocessor that has been permanently interfaced to the minicomputer. Software that controls the data flow from the SYM to the minicomputer at a rate selected by the user is available. This allows the data transfer program to be easily adapted to virtually any format of data.

Appendix 2 contains a flow chart and listing of the Fortran program utilized to process the data from the spatial frequency analyzer. The function of this program is to take the intensity data and pair it with the appropriate angle. This is passed to the file utilized by the plotting program of the minicomputer. A plot of scattered light Intensity versus Angle can then be produced. The Fortran program also contains the capability of correction for background light as was discussed in the section on control of stray light.

IV. WORK PERFORMED

To verify the operation of the optical data processor developed by this research, a two-part procedure was used. First the operation of the microprocessor controlled data collection system was tested by inputting the cosine output of the angle intensity measuring system Helipot to the A/D converter. The movable arm was then scanned from 0 to 90 degrees with the output of the Helipot acting as the input of the data collection system. Figure 8 is a plot of this input signal. Superimposed on this curve is a plot of the actual cosine of the arm angle multiplied by ten. The two curves are virtually identical, indicating that the data collection system is functioning properly.

The second test of the optical data processor was to demonstrate that it does, in fact, accurately record diffraction patterns. To do this, two samples were selected whose diffraction patterns are well known. These samples, a 25 micrometer diameter pinhole and a 39.37 line pairs per millimeter series of multiple slits, have patterns that can be verified by calculation. A third sample, a microscope slide coated with 1.091 micrometer diameter Polystyrene Latex Spheres (PLS), was used to demonstrate background correction.

A. 25 Micrometer Diameter Pinhole

The maxima and minima of the diffraction pattern of a

circular aperture can be located using the equation

$$\sin \theta = \frac{n\lambda}{d} \quad (4)$$

where λ is the wavelength of radiation incident on the aperture, d is the diameter of the aperture and θ is the angular separation of the bright and dark rings of the diffraction pattern from the optical axis. The value of n is obtained in terms of Bessel Functions of order unity.⁴

Table III contains the calculated values of θ for the first four maxima and minima of the diffraction pattern of the 25 micrometer diameter pinhole assuming incident radiation with a wavelength of 632.8 nanometers. Also contained in this table are the corresponding angles taken from the plot in Figure 17, produced by the optical data processor using a Helium Neon (HeNe) laser as the light source.

The last column of Table III contains the apparent diameter of the pinhole calculated from Equation 4, substituting the values for θ obtained from Figure 17 and using 632.8 nanometers as the wavelength of illumination. The average apparent diameter of the pinhole was calculated to be 24.95 micrometers. This agrees quite well with the given size of the pinhole.

The diffraction pattern of the pinhole was scanned on both sides of the optical axis. Figure 17 shows the symmetry of this pattern. The relative intensities of the recorded maxima agree

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TABLE III

Calculated versus Measured Angles for the Diffraction Pattern of a
25 Micrometer Pinhole Produced by a HeNe Laser Operating
at 632.8 Nanometers

RING	n	Calculated Angle (degrees)	Measured Angle (degrees)	Apparent Pinhole Diameter (micrometers)
First Minimum	1.220	1.77	1.80	24.56
Second Maximum	1.635	2.37	2.43	24.42
Second Minimum	2.233	3.24	3.20	25.31
Third Maximum	2.679	3.89	3.97	24.48
Third Minimum	3.238	4.70	4.66	25.24
Fourth Maximum	3.699	5.37	5.29	25.41
Fourth Minimum	4.241	6.16	6.11	25.20

quite well with theory.

B. Series of Multiple Slits

The diffraction pattern of a sample consisting of a series of alternating light and dark lines on a glass plate is described by

$$n\lambda = d \sin\theta \quad n = 1, 2, 3, \dots \quad (5)$$

where n is the diffraction order, λ is the wavelength of radiation incident on the sample, θ is the angle from the optical axis to a maximum of the spectrum, and d is the width of a pair of lines.

The sample used for this test has a spatial frequency of 39.37 line pairs per millimeter, with a d of 0.0254 millimeters. Figure 18 is the recorded spectrum of this sample using a HeNe laser as the radiation source. In Table IV the calculated angles of the first twelve maxima of the sample diffraction pattern are compared with the corresponding measured values. The agreement of the measured angles with the calculated angle is extremely good for this sample. If the width of the slits was exactly $1/2 d$ then the sample would represent an optical square wave and all of the even diffraction orders would be missing.

C. 1.091 Micrometer Diameter Polystyrene Latex Spheres

The optical data processor has the capability of subtracting a noisy background from the desired diffraction pattern. To

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TABLE IV

Calculated versus Measured Angles for the Diffraction Pattern of a
39.37 Line Pairs Per Millimeter Series of Multiple Slits
with λ equal to 632.8 Nanometers

n	Calculated (degrees)	Measured (degrees)
1	1.43	1.46
2	2.86	2.88
3	4.29	4.37
4	5.72	5.75
5	7.16	7.17
6	8.60	8.63
7	10.04	10.05
8	11.50	Missing
9	12.96	12.96
10	14.43	14.38
11	15.90	15.87
12	17.40	Missing

illustrate this, a sample was prepared by precipitating 1.091 micrometer PLS on a clean glass microscope slide using a TSI Model 3100 Electrostatic Aerosol sampler. The slide was placed in the sample holder of the optical data processor and the diffraction pattern was measured. The plot shown in Figure 19 consists of the diffraction pattern of the PLS plus scattering from the glass slide. The slide was then cleaned of all PLS particles and replaced on the sample holder. Figure 20 shows the measured scatter from the clean glass slide alone. The instrument parameters for both scans were identical.

The Fortran program for processing the optical data has the capability of subtracting the background signal of Figure 20 from the spectrum in Figure 19. The result, shown in Figure 21, is a plot of the diffraction pattern of the PLS alone. The sharp peaks observed at 26 and 35 degrees are the results of dust particles drifting through the incident laser beam when recording the sample spectrum.

V. CONCLUSIONS

An optical data processor was constructed that exhibits a high degree of accuracy in measuring the spatial frequency spectrum of known samples. The microprocessor based data system functioned as a reliable collector of intensity versus angle data. Problems with early versions of the instrument, such as stray light control, system alignment, and angle measurement, have been addressed and effectively solved by a redesign of the entire system.

The capabilities of the instrument have been extended by the addition of appropriate optics to allow the use of different wavelengths of laser radiation and by increasing the travel limits of the rotating arm to ± 160 degrees.

Data acquisition, storage, and plotting is handled totally by computer. This allows the researcher a free hand in the manipulation of data acquired by this instrument. One example of this, the subtraction of background scattering from a known diffraction pattern, was demonstrated by this work.

ACKNOWLEDGEMENT

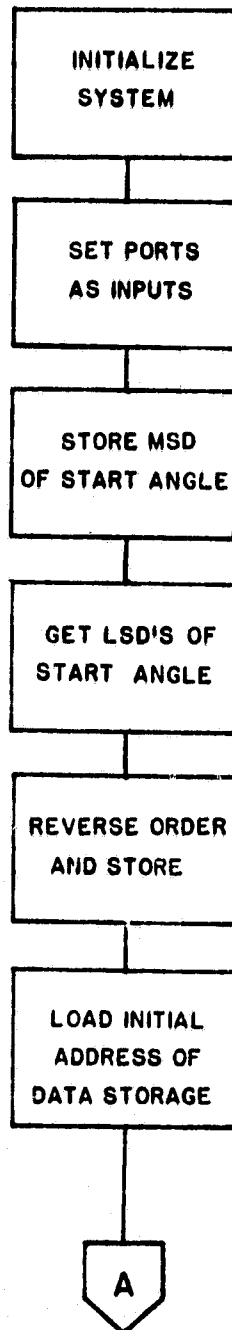
This research was supported by NASA Grant Number NGL 04-001-007.

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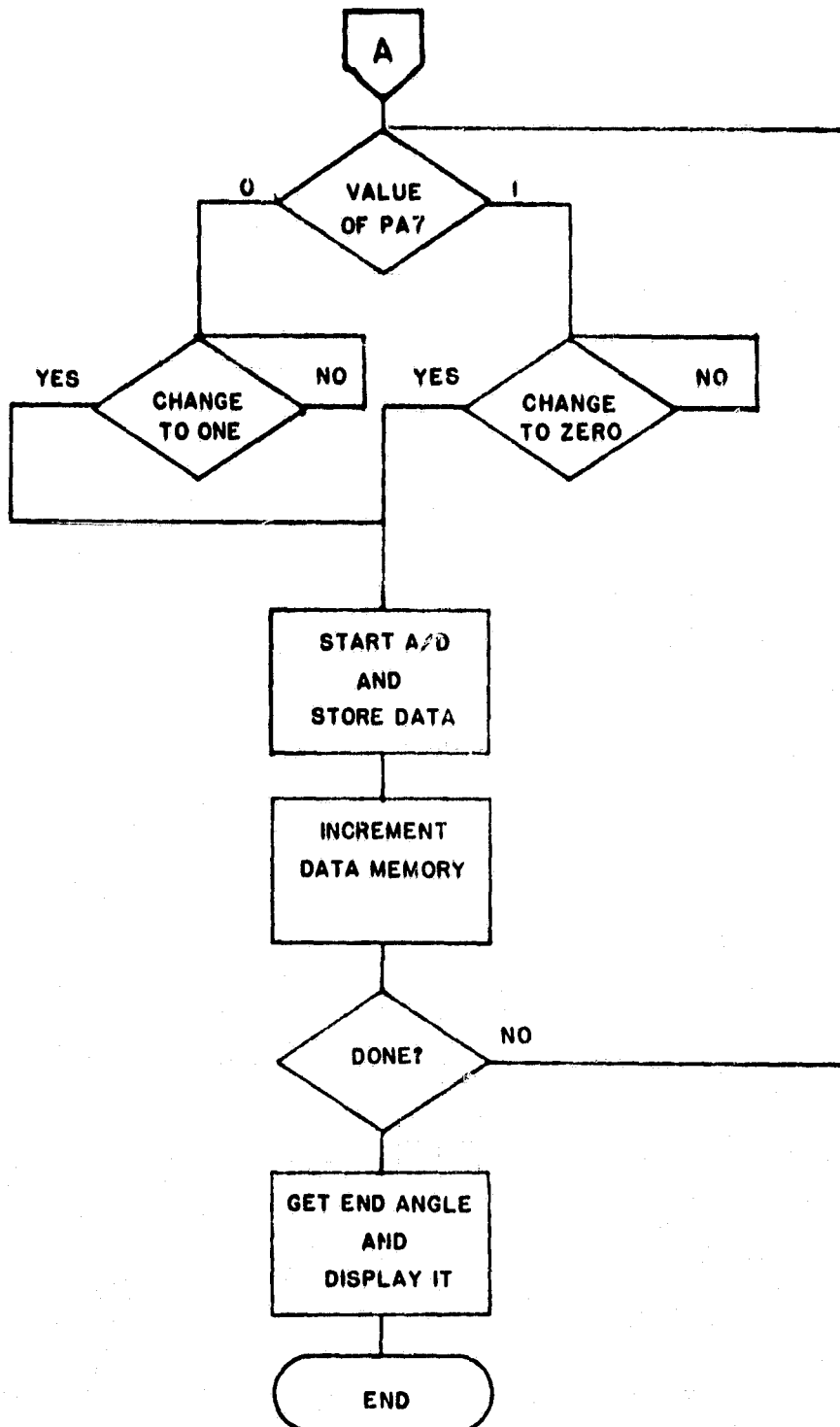
APPENDIX I

A. FLOWCHART OF KIM PROGRAM



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B. PROGRAM LISTING

: THIS PROGRAM CONTROLS THE ACQUISITION AND STORAGE OF DATA
: FOR THE OPTICAL DATA PROCESSOR. SPECIAL MEMORY
: LOCATIONS ARE AS FOLLOWS.
:
: 0000 ENTER NUMBER OF DATA POINTS
: 0001 ENTER 0 IF LESS THAN FF POINTS DESIRED
: 0200 START ADDRESS OF THE PROGRAM
: 2000,2001 START ANGLE IS STORED HERE
: 2002 NUMBER OF DATA POINTS
: 2003 XMULT
: 2004,2005 ENTER DATA SCAN ID NUMBER
: 2006,2007 NOT USED
: 2008 START OF DATA STORAGE MEMORY
:
CLD :CLEAR DECIMAL COUNTER
NOP
LDA 00 SET UP STOP KEY
STA 17FA
LDA 1C
STA 17FB
NOP
NOP
LDA 00 SET UP PORTS AS INPUTS
STA 1701
LDA 00
STA 1703
LDX 00 ZERO THE INCREMENT COUNTER
NOP
NOP
LDA 1702 GET THE MOST SIGNIFICANT DIGIT
STA 2000 AND STORE IT
LDA 1700 GET THE LEAST SIGNIFICANT DIGITS OF THE ANGLE
NEXT LDY 08 SET UP LOOP COUNTER
ROR
ROL 2001 REVERSE THE ORDER OF THE BITS AND STORE
DEY DECREMENT THE LOOP COUNTER
BNE NEXT CONTINUE THE LOOP UNTIL THE COUNTER IS ZERO
JMP 02C0 GO TO A SECTION OF CODE THAT SETS THE START OF DATA MEMORY
: THIS SECTION OF CODE LOOKS FOR THE TRANSITION OF PA7
: FROM 1 TO 0 OR VICE VERSA
:
AGAIN BIT 1700 IDENTIFY PA7 AS BEING
BMI CHECK1 EITHER 1 OR 0
JMP CHECK2

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CHECK1 BIT 1700 PA7 IS ONE, THIS GROUP LOOKS FOR THE CHANGE TO ZERO
BPL DATA WHEN THE CHANGE IS SEEN THE PROGRAM GOES TO TAKE A DATA
JMP CHECK1 POINT
NOP
NOP

CHECK2 BIT 1700 THIS SECTION LOOKS FOR THE CHANGE FROM 0 TO 1
BNI DATA
JMP CHECK2
NOP
NOP

: THIS SECTION CONTROLS THE A/D AND STORES THE DATA

DATA STA 1002 START CONVERSION
LDY OF SET UP DELAY FOR A/D CONVERSION TIME
DELAY DEY

BNE DELAY
LDA 1002 GET MSB'S OF DATA
ADDR1 STA 2002 AND STORE THEN
LDA 1001 GET LSB OF DATA

ADDR2 STA 2003 AND STORE IT
CLC CLEAR CARRY

: THIS SECTION INCREMENTS THE MEMORY FOR THE NEXT DATA POINT
: TO BE STORED

LDA ADDR1+1
ADC 02
STA ADDR1+1
LDA ADDR1+2
ADC 00
STA ADDR1+2
CLC
LDA ADDR2+1
ADC 01
STA ADDR2+1
LDA ADDR2+2
ADC 00
STA ADDR2+2
CLC
NOP
NOP
INX

CPX 0000 SEE IF THE DATA RUN IS COMPLETE
BEQ CHECK SEE IF MORE THAN 256 DATA POINTS ARE TO BE TAKEN
JMP AGAIN GO BACK AND LOOK FOR THE NEXT POSITION CHANGE

:
: THIS SECTION LOOKS AT XHULT AND DETERMINES IF MORE
: THAN 256 DATA POINTS ARE TO BE TAKEN

CHECK LDA 0001
CMP 00
BEQ DONE IF XHULT IS 0 THEN GO TO THE END OF THE PROGRAM

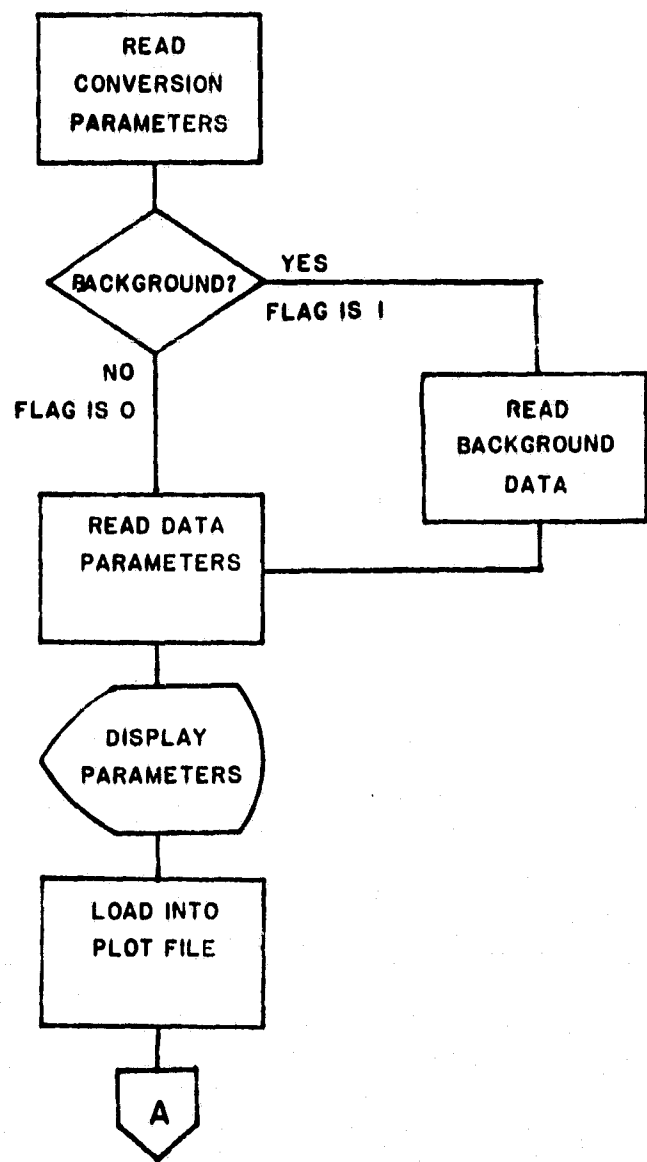
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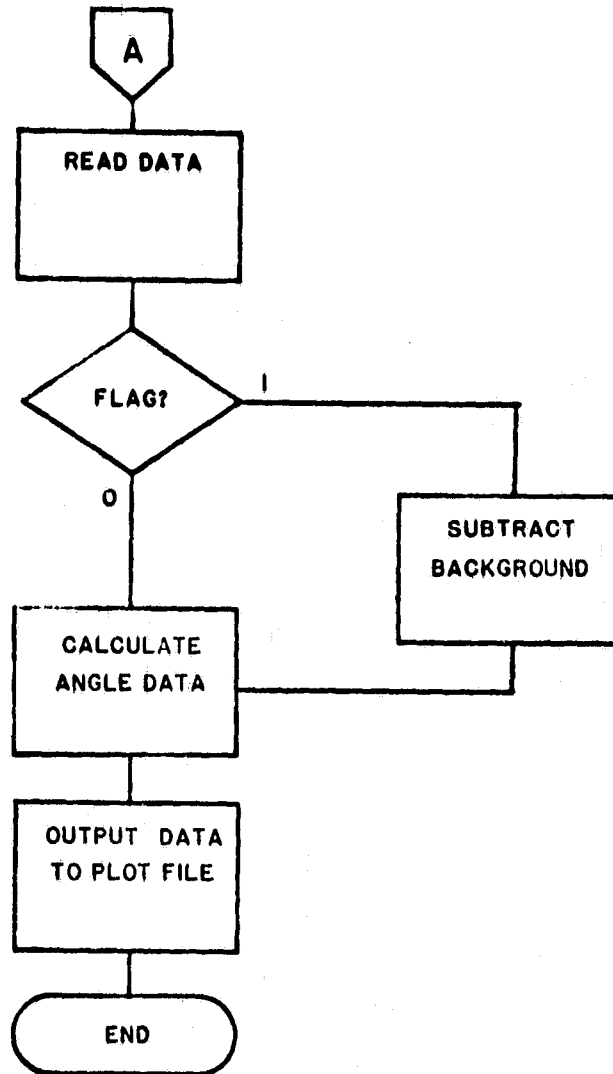
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```
SBC 1
STA 0001
LDX 00 START THE PROGRAM OVER AGAIN UNTIL XMULT DOES EQUAL 0
JMP AGAIN
:
: THIS IS THE END ROUTINE OF THE PROGRAM. IT STORES
: THE END ANGLE AND DISPLAYS IT.
:
DONE LDA 1702 GET THE MSB OF THE END ANGLE
      STA 00FB
      LDA 1700 GET THE LSB'S
      LDY 08 REVERSE AND STORE THE ANGLE
      STILL ROR
          ROL 00FA
          DEY
          BNE STILL
          LDA 00
          STA 00F9
      END JSR SCANDS
          JMP END
          NOP
: THIS SECTION STORES THE PARAMETERS TO BE PASSED TO THE
: MINICOMPUTER
:
: IT ALSO RESETS THE DATA MEMORY AT THE START OF
: EACH DATA RUN
:
      LDA 08
      STA 025B
      LDA 09
      STA 0261
      LDA 20
      STA 025C
      LDA 20
      STA 0262
      LDA 0000
      STA 2002
      LDA 0001
      STA 2003
      INC 0000
      JMP 0231
```

APPENDIX 2

A. FLOWCHART OF FORTRAN PROGRAM





B. PROGRAM LISTING

```
DIMENSION D(21),F(10),AMP(255),POS(255),BAMP(255)
INTEGER TITLE(5),XCNT,XMULT,RNUM,STANG,IDAT(255),IBACK(255),FLAG
INTEGER XMIN,XMAX,YMIN,YMAX,A(5),B(5)
C THIS PROGRAM READS DATA TRANSFERED FROM A CASSETTE TAPE
C PREPARED BY THE OPTICAL DATA PROCESSOR AND PREPARES
C THAT DATA ACCORDING TO INSTRUCTIONS IN THE PROGRAM FOR
C PLOTTING. THE DATA HAS BEEN TRANSFERED USING THE
C READSYN COMMAND TO DATA.SCT OR BACK.SCT IF BACKGROUND
C CORRECTION IS TO BE PERFORMED.
C
C
C THE FIRST 8 BYTES OF DATA CONTAIN THE START ANGLE OF THE
C SCAN (STANG), THE NUMBER OF DATA POINTS (XCNT), A
C MULTIPLIER (XMULT), AND A DATA RUN IDENTIFIER. 2 BYTES ARE
C NOT USED, THE REST OF THE FILE CONTAINS INTENSITY DATA
C TRANSFERED 8 BYTES AT A TIME.
C
C LOGICAL UNIT ASSIGNMENTS ARE AS FOLLOWS:
C 1,DATA.SCT
C 2,CHLT.SCT
C 3,BACK.SCT
C 5,CONSOLE
C
WRITE(5,500)
C INFORMATION IS INPUT TO ALLOW THE COMPUTER TO CALCULATE
C THE VOLTAGE CONVERSION FACTOR FOR THE A/D CONVERTER
C DATA
500  FORMAT('ENTER NO. OF BITS AND VOLTAGE SPAN')
CALL READ(5,D,F,80,3,K)
DECODE(D,F) NBIT,VSPAN
CONFAC=VSPAN/(2**NBIT)
WRITE(5,510)
C THE PROGRAM HAS THE CAPABILITY OF SUBTRACTING BACKGROUND
C DATA FROM THE DATA TO BE PLOTTED.
510  FORMAT('BACKGROUND CORRECTION?')
READ(5,103)INPC
103  FORMAT(I A1)
IF(INPC.EQ.'N') GO TO 1000
C THIS SECTION READS THE BACKGROUND DIFFRACTION DATA FROM
C BACK.SCT FILE AND LOADS ARRAY BAMP(K). THIS SECTION IS
C BYPASSED IF NO BACKGROUND CORRECTION IS DESIRED.
FLAG=1
READ(3,10)STANG,XCNT,XMULT,RNUM
IF(XMULT.NE.0)XCNT=(XCNT*XMULT)
```

```

READ(3,20)(IDAT(I),I=1,XCNT)
DO 27 K=1,XCNT
27  BAMP(K)=CONFAC*IDAT(K)
    GO TO 5000
1000 FLAG=0
C THIS SECTION READS THE DIFFRACTION PATTERN DATA TO BE
C PLOTTED AND LOADS IT INTO IDAT(K). THE START ANGLE
C (STANG) OF THE DATA SCAN IS ALSO CALCULATED.
5000 READ(1,10)STANG,XCNT,XMULT,RNUM
    10  FORMAT(1X,I3,Z2,Z2,Z4)
        IF(STANG.LT.500)STANG=(0-STANG)
        IF(STANG.LE.0)GO TO 2000
        STANG=(1000-STANG)
2000 IF(XMULT.NE.0)XCNT=(XCNT*XMULT)
C THIS SECTION OUTPUTS PERTINENT DATA TO THE OPERATOR
C AS TO WHAT SET OF DATA IS BEING PROCESSED
WRITE(5,520)RNUM
520  FORMAT('DATA RUN',I4)
WRITE(5,530)STANG
530  FORMAT('START POSITION',I4)
WRITE(5,540)XCNT
540  FORMAT('NUMBER OF DATA POINTS',I4)
C THIS SECTION SETS UP THE DATA TO BE PASSED TO THE
C CHLT.SCT FILE UTILIZED BY THE PLOT PROGRAM
C OF THE MINICOMPUTER.
WRITE(2,4)
4    FORMAT(' 1 1 0 1 1 1 0')
WRITE(5,600)
600  FORMAT('X-AXIS MIN AND MAX')
CALL READ (5,D,F,80,3,K)
DECODE (D,F) XMIN,XMAX
WRITE(2,40)XMIN,XMAX
WRITE(5,610)
610  FORMAT('Y-AXIS MIN AND MAX')
CALL READ (5,D,F,80,3,K)
DECODE (D,F) YMIN,YMAX
WRITE(2,40)YMIN,YMAX
40   FORMAT(2I5)
WRITE(2,5)
5    FORMAT(' ARM POSITION(DEGREES)')
WRITE(2,6)
6    FORMAT(' INTENSITY(VOLTS)')
WRITE(2,7)XCNT
7    FORMAT(13,' 0 0')
WRITE(5,100)
C THE OPERATOR INPUTS THE TITLE OF THE PLOT.

```

```
100  FORMAT('TITLE OF PLOT?')
      READ(5,8)TITLE
8     FORMAT(5A4)
      WRITE(2,9)TITLE
9     FORMAT(5A4)
C DATA FROM THE OPTICAL DATA PROCESSOR IS READ FROM THE
C DATA.SCT FILE
15    READ(1,20)(IDAT(I),I=1,XCNT)
      WRITE(3,20)(IDAT(I),I=1,XCNT)
20    FORMAT(4(Z3,1X))
      DO 21 K=1,XCNT
21    AMP(K)=CONFAC*IDAT(K)
C IF THERE IS TO BE A BACKGROUND CORRECTION OF THE DATA
C IT WILL BE DONE AT THIS POINT
      IF(FLAG.EQ.0)GO TO 3000
      DO 26 K=1,XCNT
      AMP(K)=AMP(K)-BAMP(K)
      IF(AMP(K).LT.0.)AMP(K)=0
C AMP(K) CONTAINS THE INTENSITY DATA TO BE PLOTTED.
26    CONTINUE
3000  DO 25 K=1,XCNT
C POS(K) IS LOADED WITH THE ANGLE DATA FOR THE PLOT.
25    POS(K)=(STANG+K)*.36
C THE INTENSITY AND ANGLE DATA IS NOW PASSED TO
C CHLT.SCT WHICH HAS BEEN DESIGNATED AS LOGICAL
C UNIT 2.
      WRITE(2,22)(POS(I),I=1,XCNT)
      WRITE(2,23)(AMP(I),I=1,XCNT)
23    FORMAT(10F7.3)
22    FORMAT(10F7.2)
      WRITE(5,16)
C THE DATA IS NOW READY TO BE PLOTTED.
16    FORMAT('RUN SPIN TO PLOT THE DATA')
      END
```

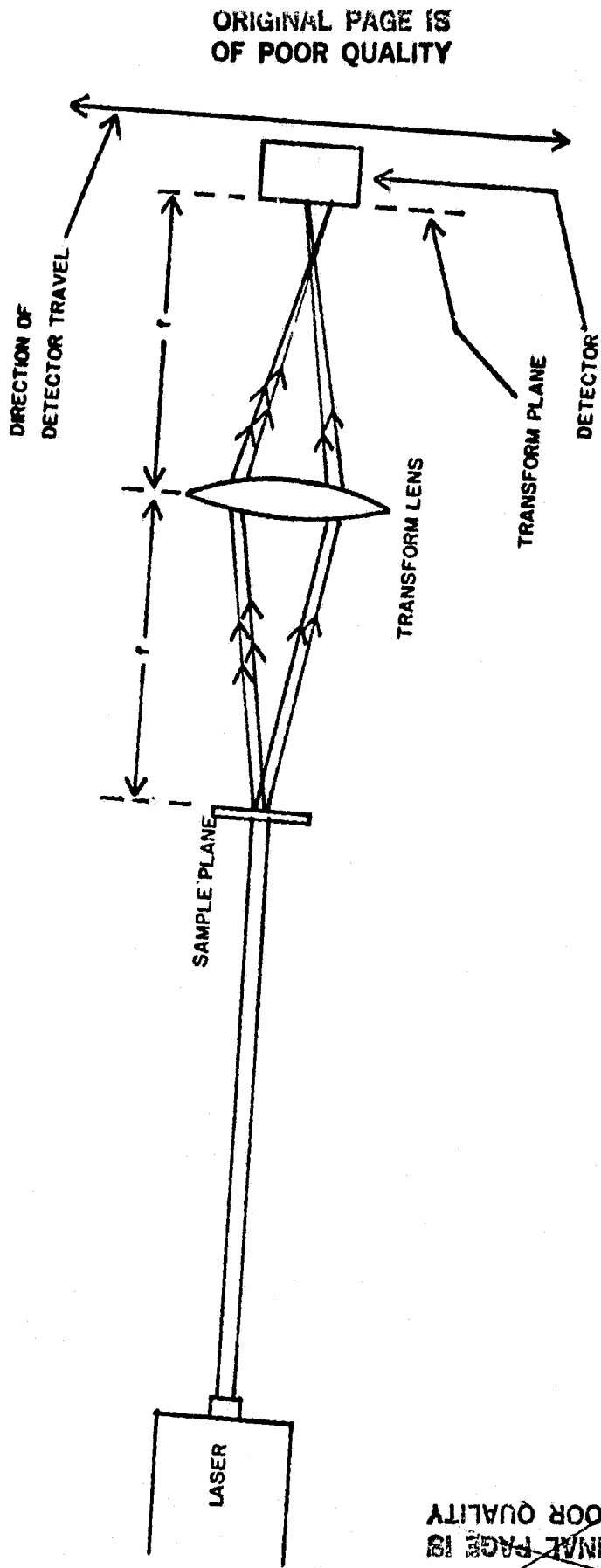


Figure 1
A Simple System for Spatial Frequency Analysis

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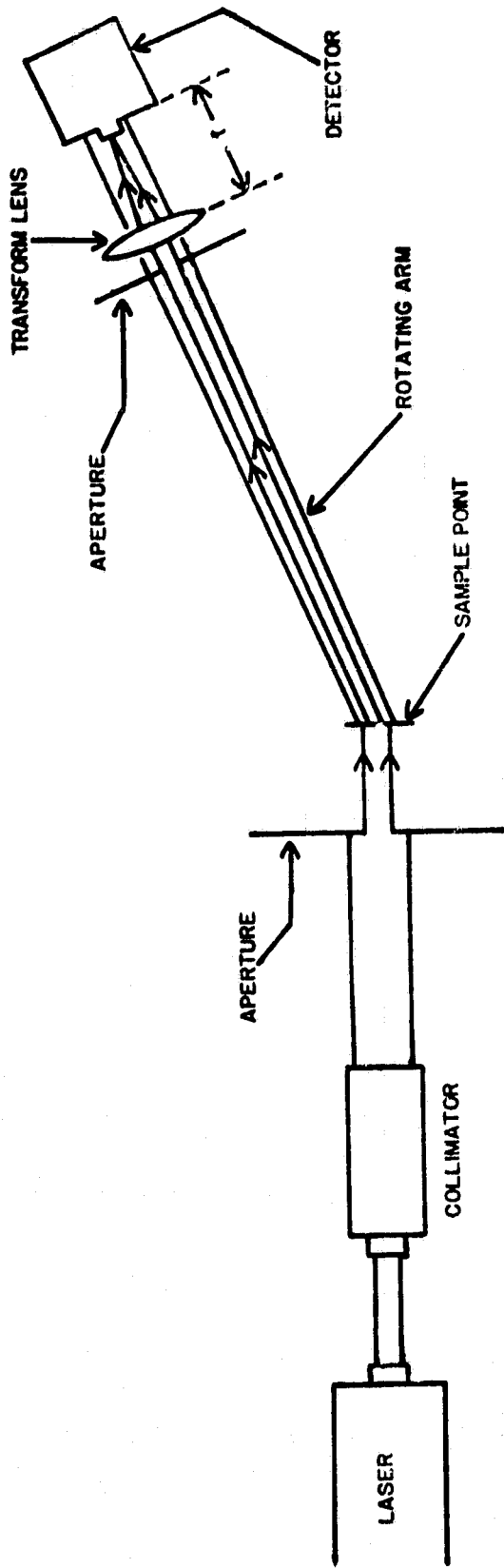


Figure 2
A Rotating Arm Spatial Frequency Analyzer

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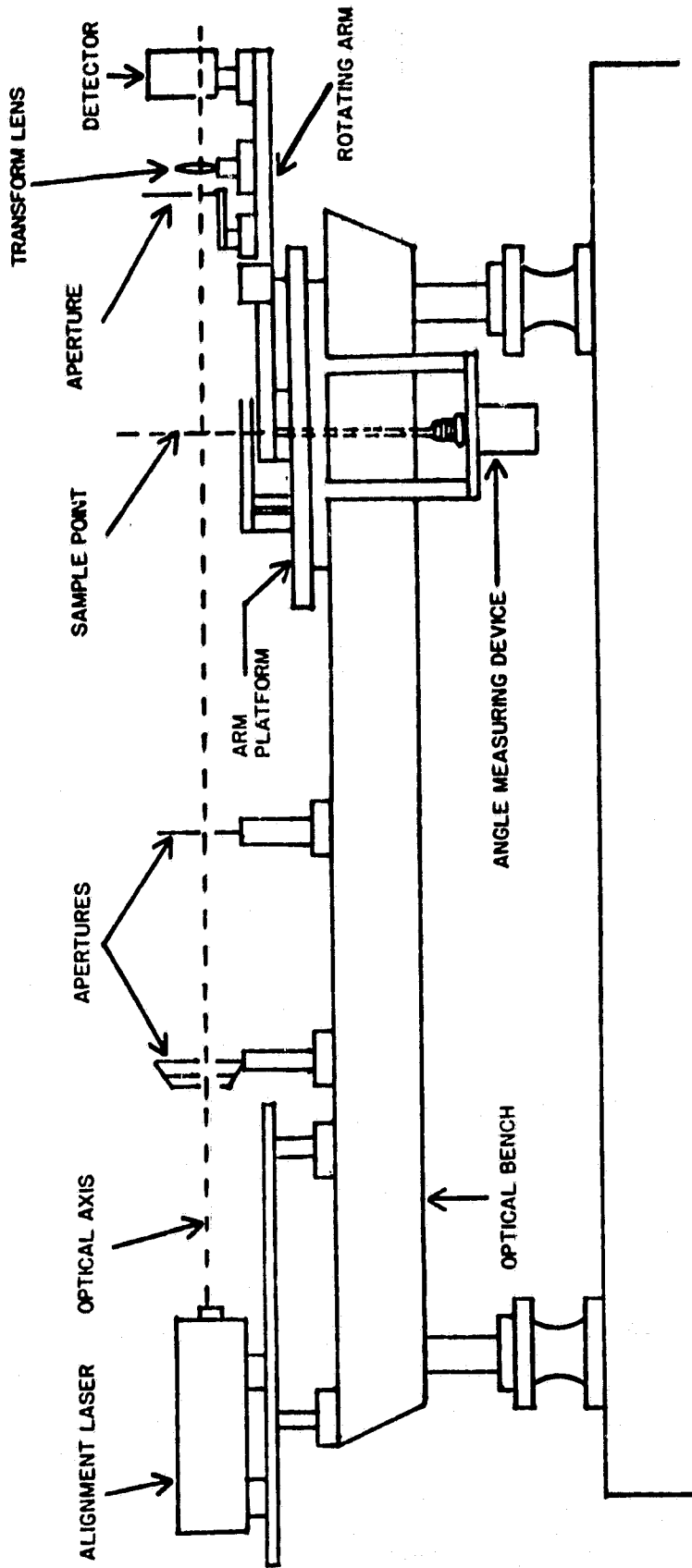


Figure 3
Side View of the Optical Data Processor

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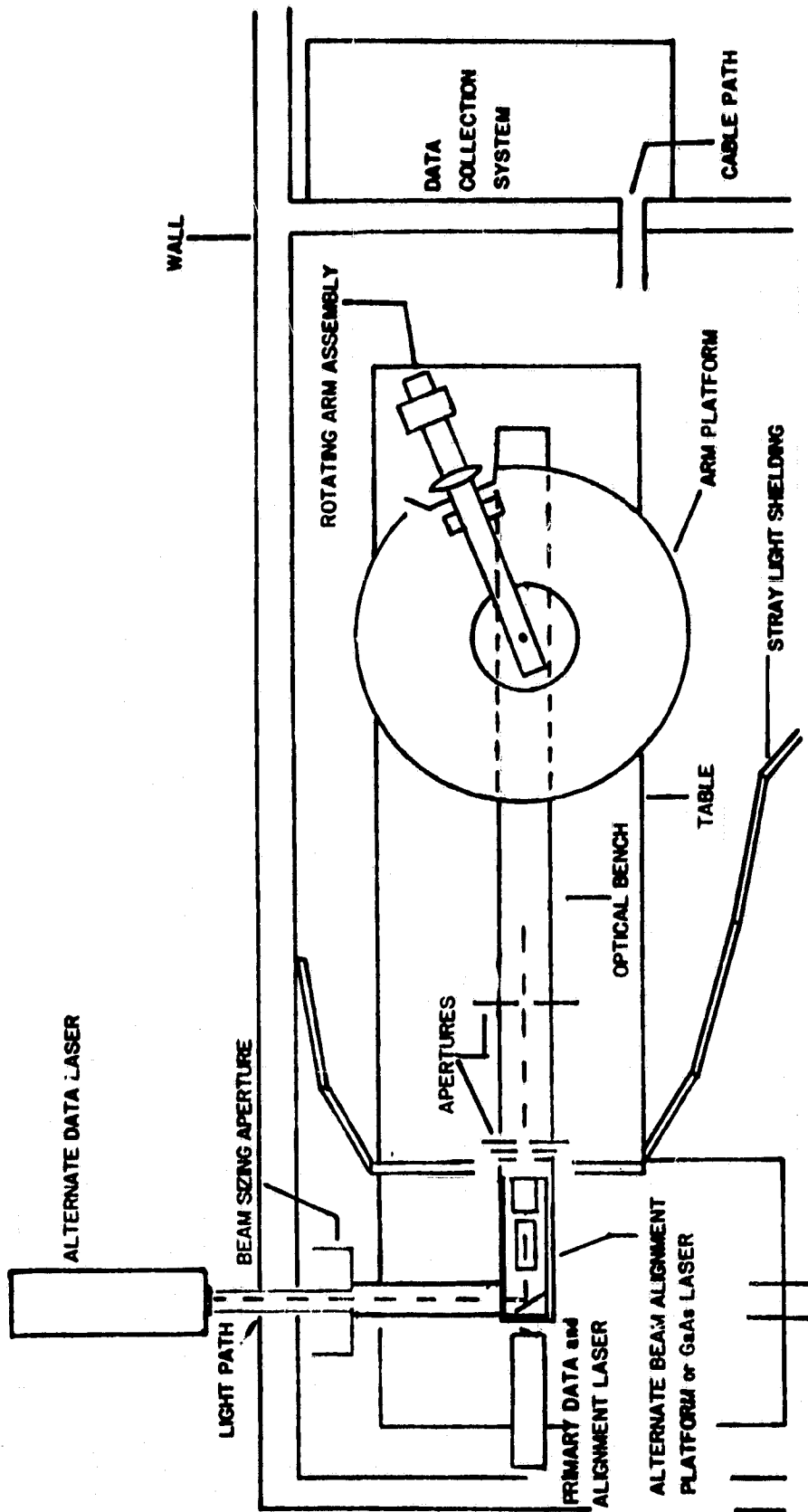


Figure 4
Top View of the Optical Data Processor

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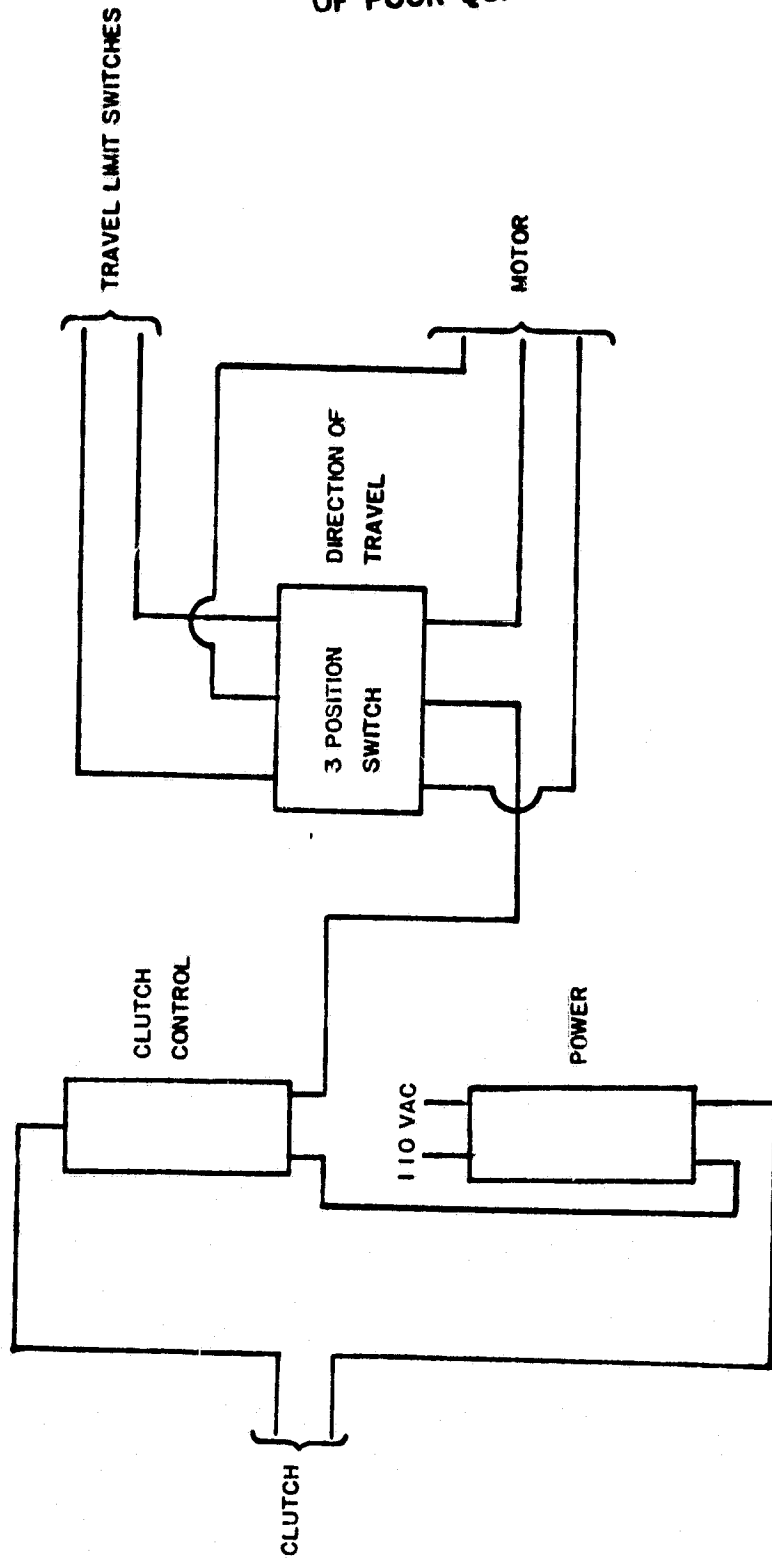


Figure 5
Motor Drive Control Panel

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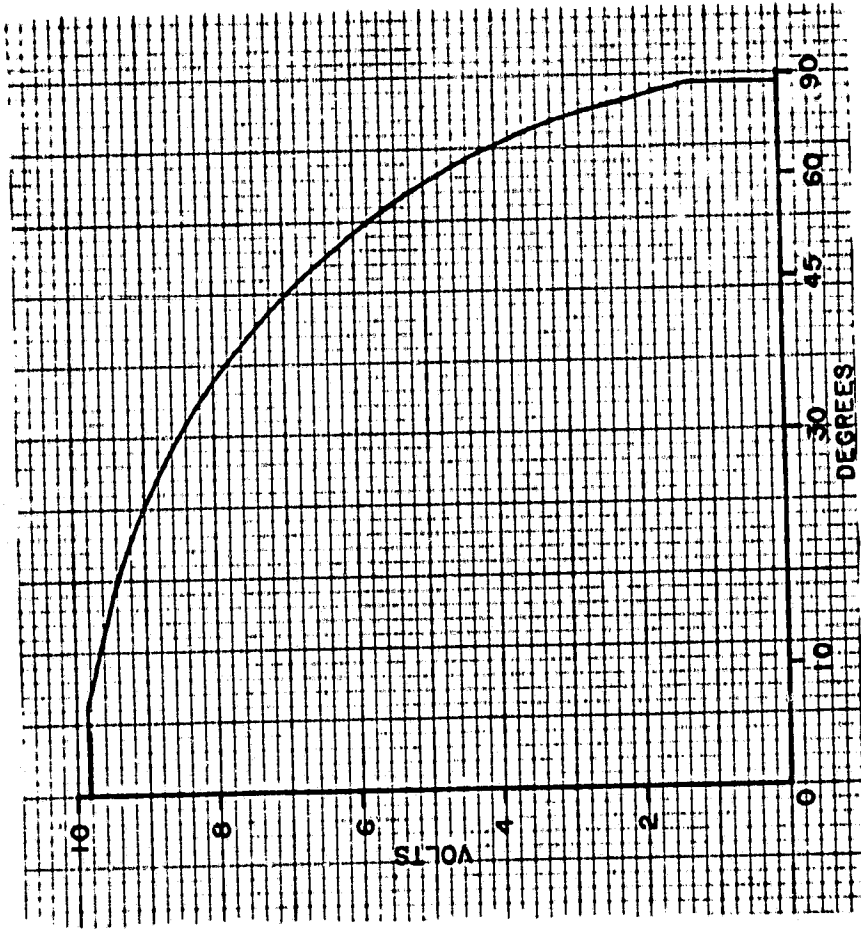


Figure 7.
Cosine Output of Helipot Versus Sine Output

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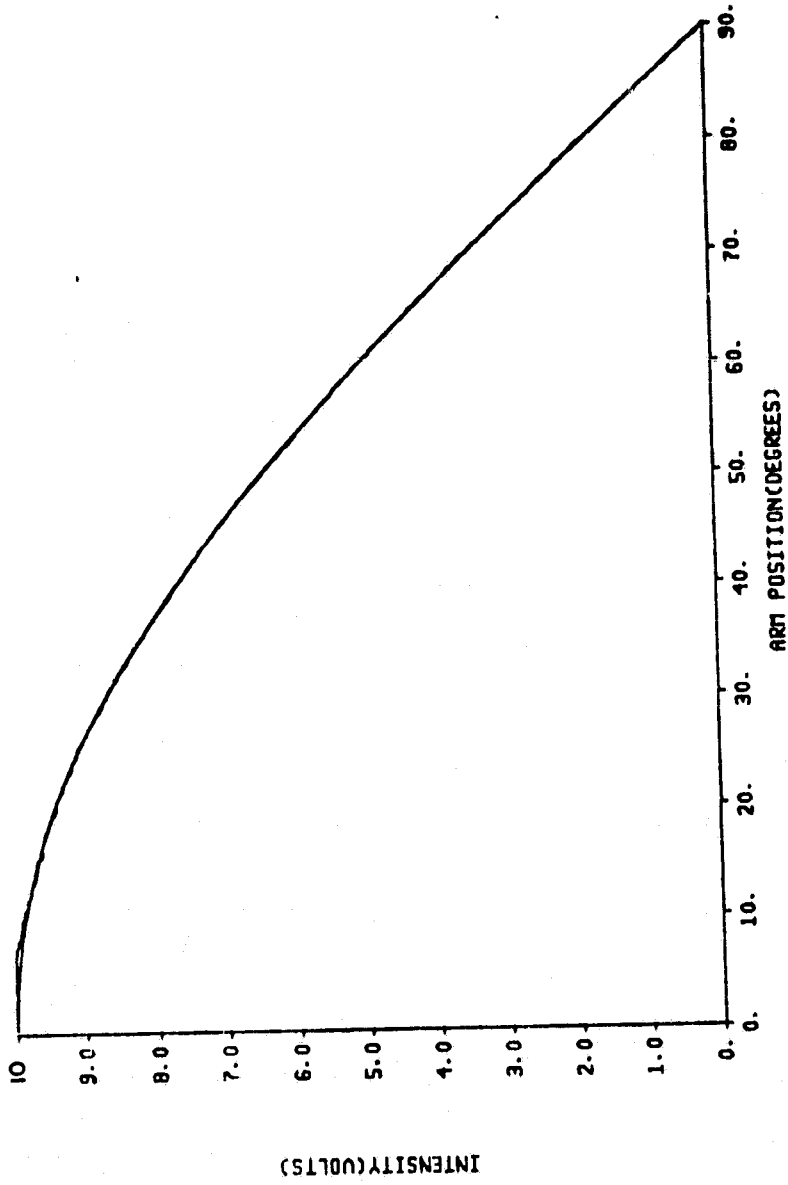


Figure 8
Cosine Output of Helipot Versus Encoder Position

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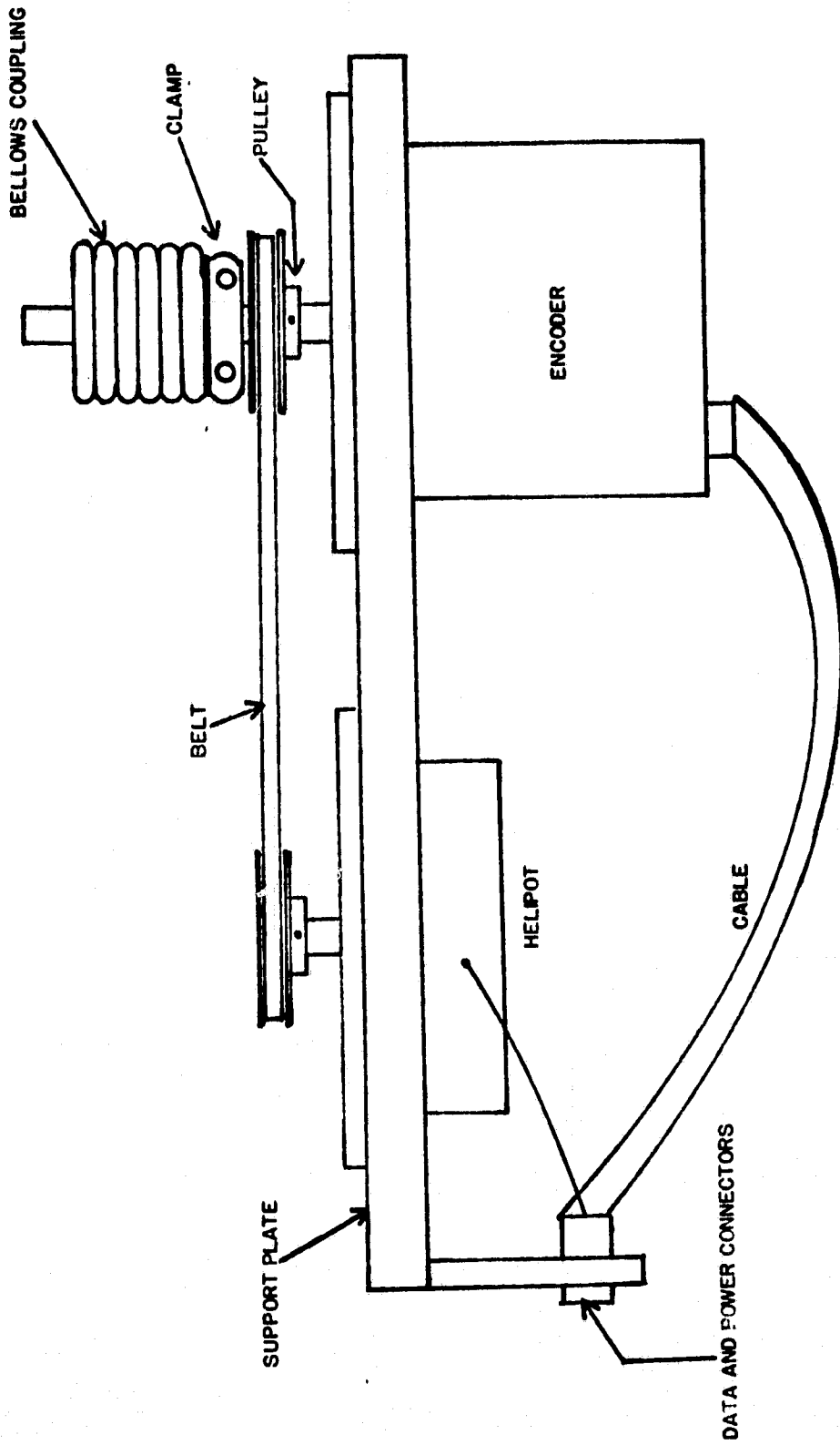


Figure 9
Angle Measuring Equipment

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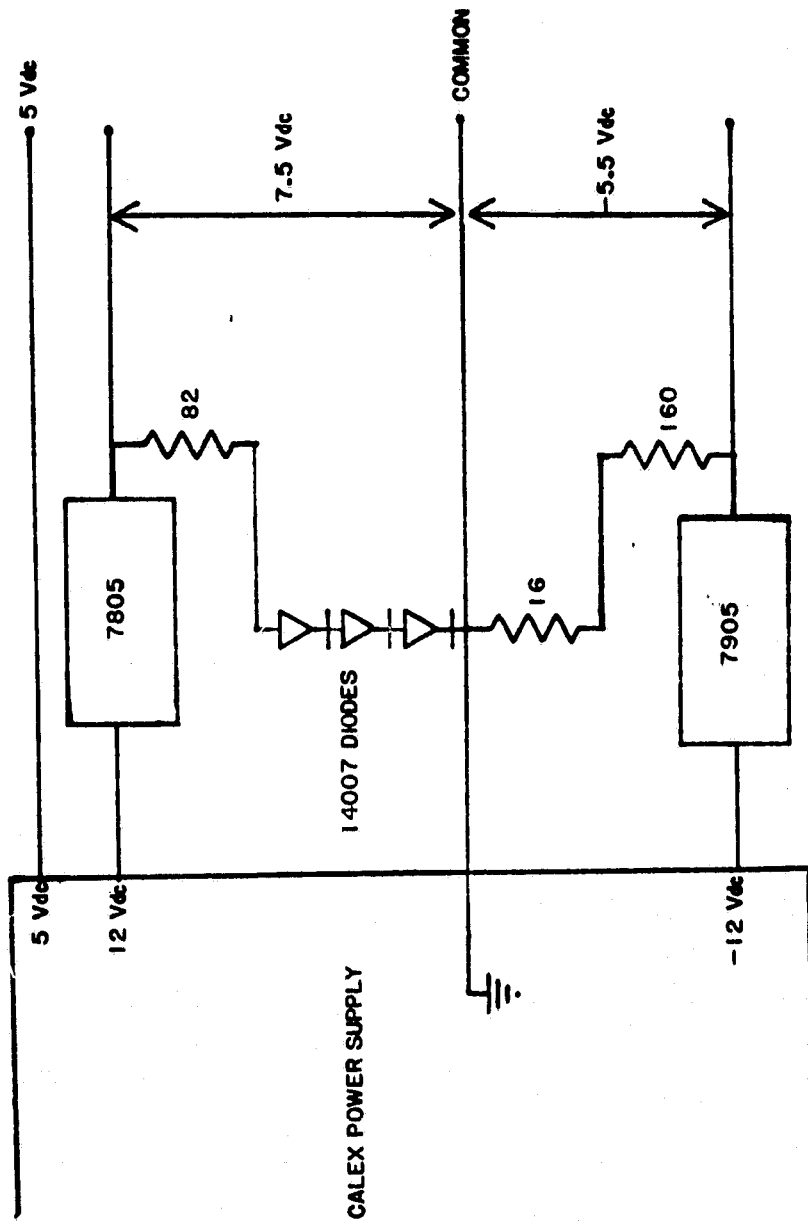


Figure 10
Encoder Power Supply

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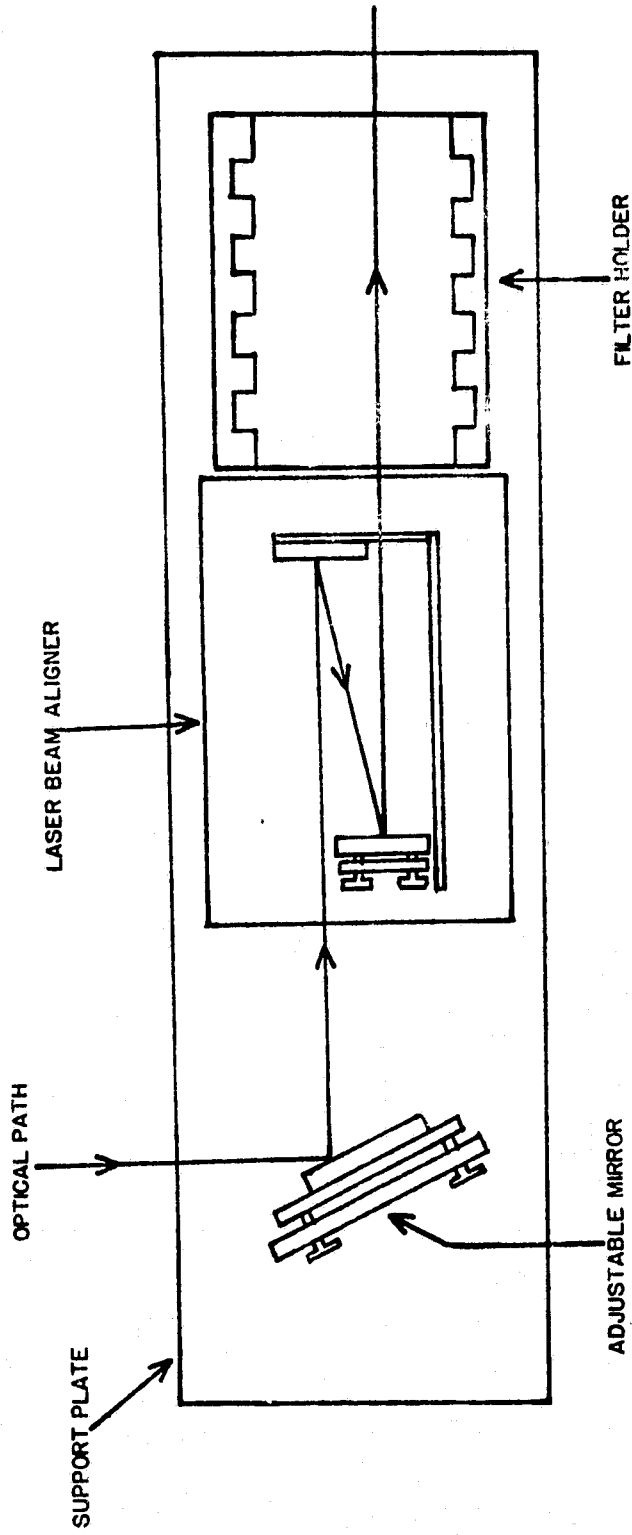


Figure 11
Alignment Platform for Alternate Laser Beam

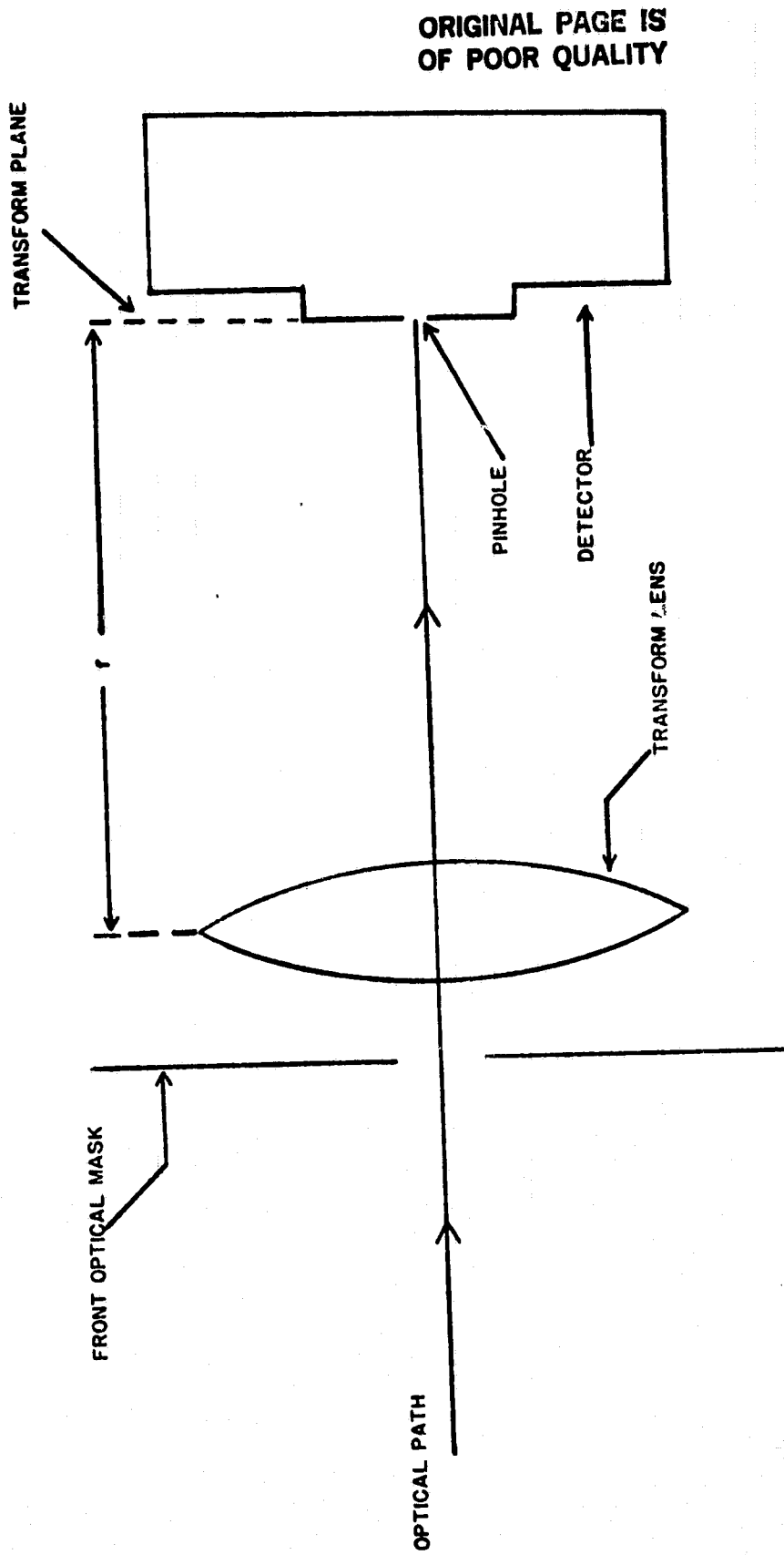
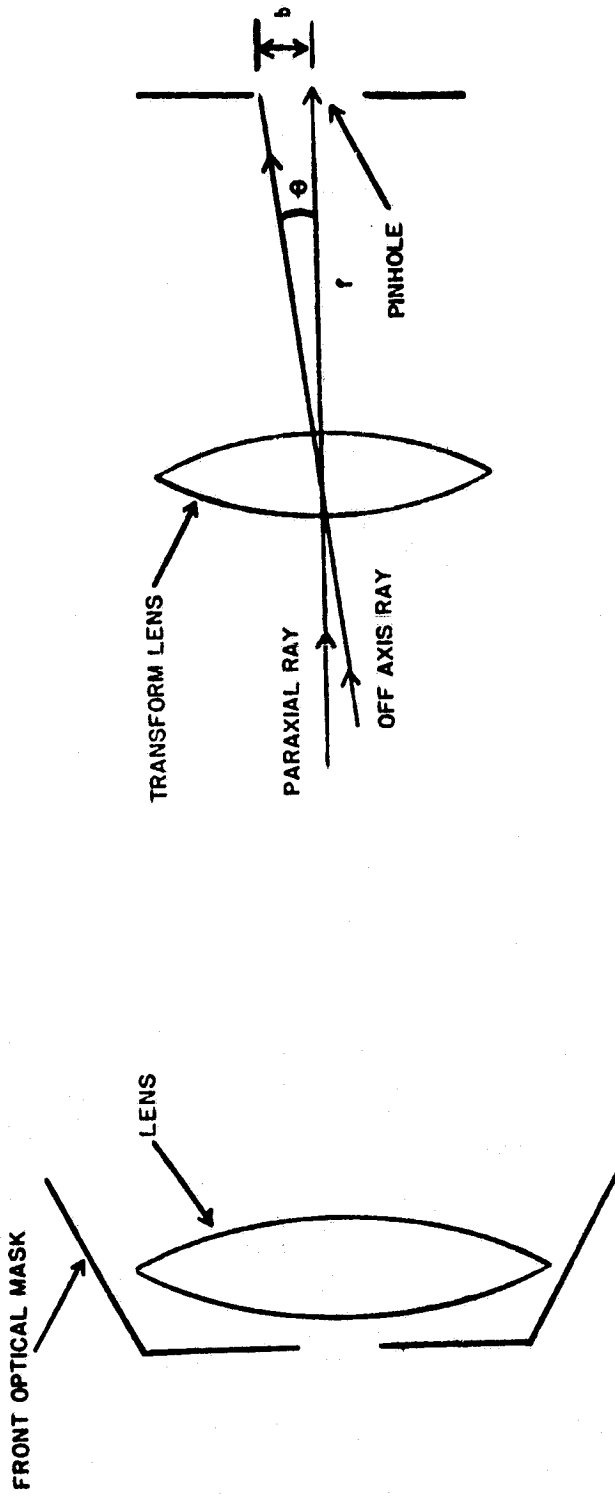


Figure 12
Intensity Data Collection System

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B. Acceptance Angle of the Optical System

A. Top View of the Front Optical Mask

Figure 13

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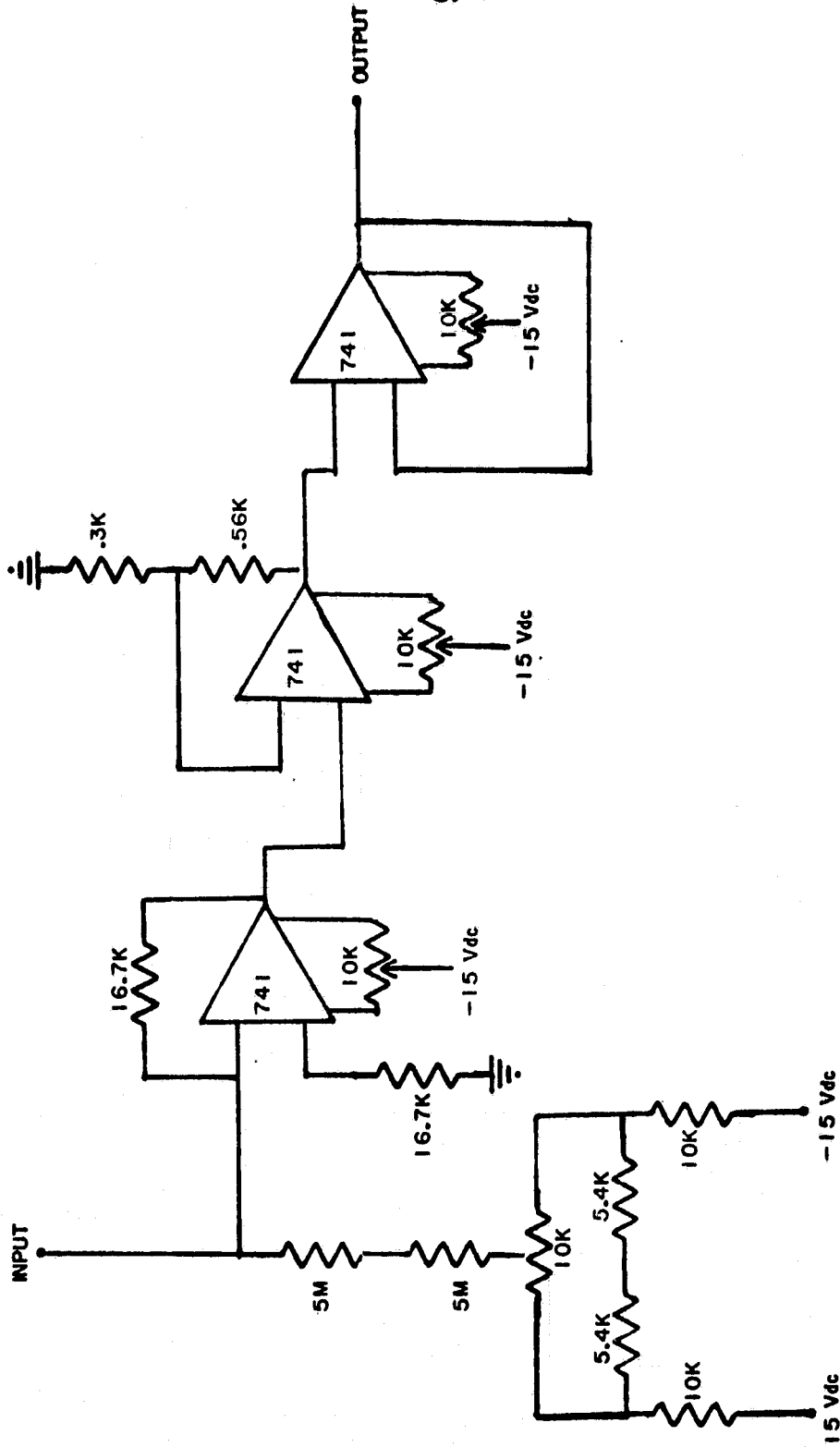


Figure 14
Photomultiplier Signal Processing Circuit

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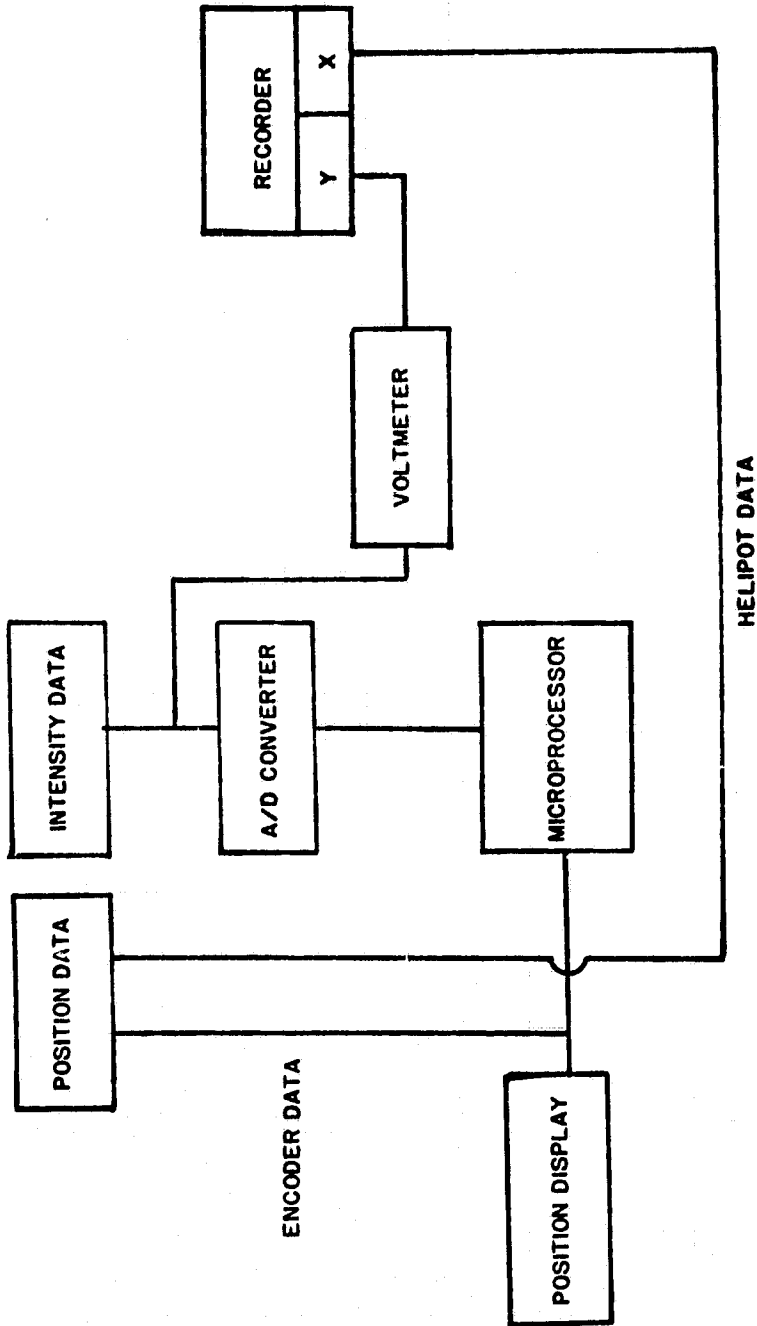


Figure 15
Block Diagram of the Data Collection System

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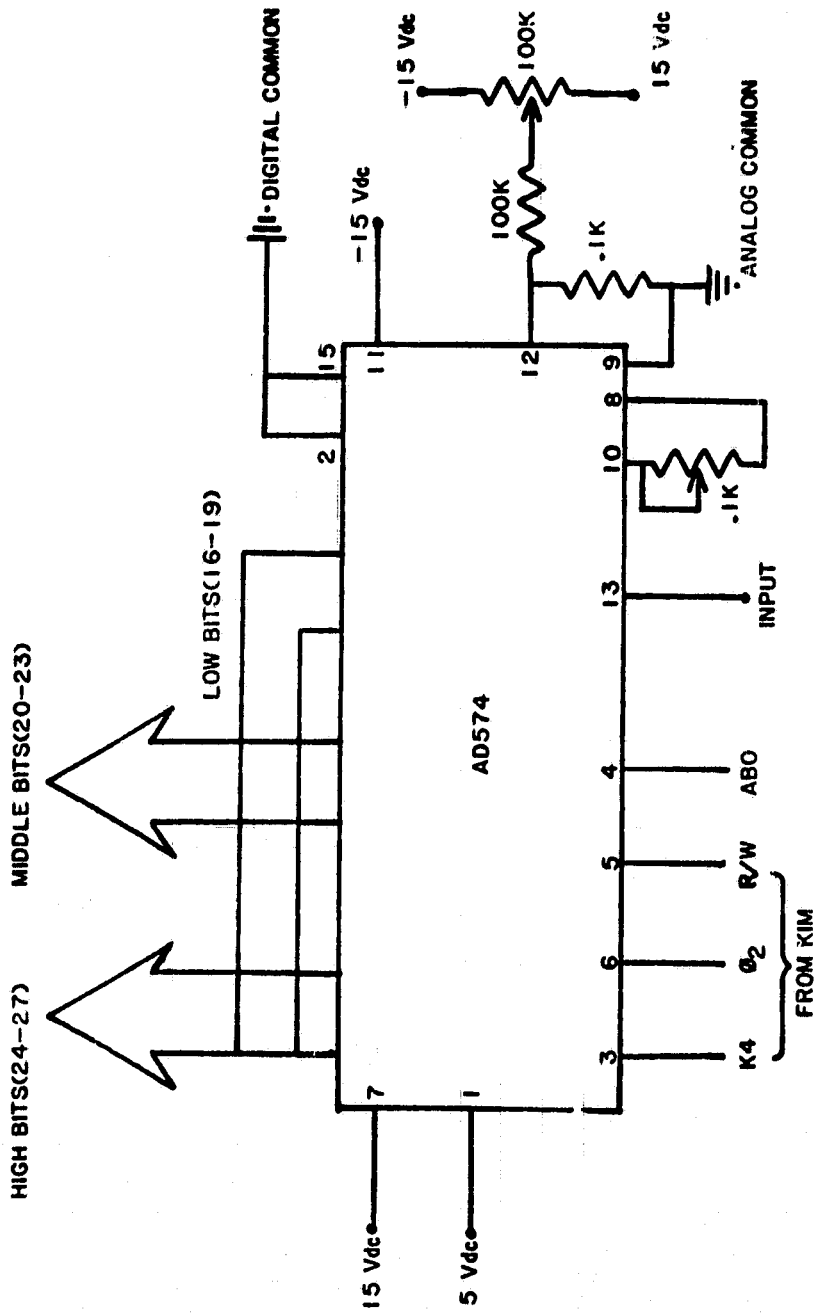


Figure 16
Circuit Diagram of the AD574 A/D Converter

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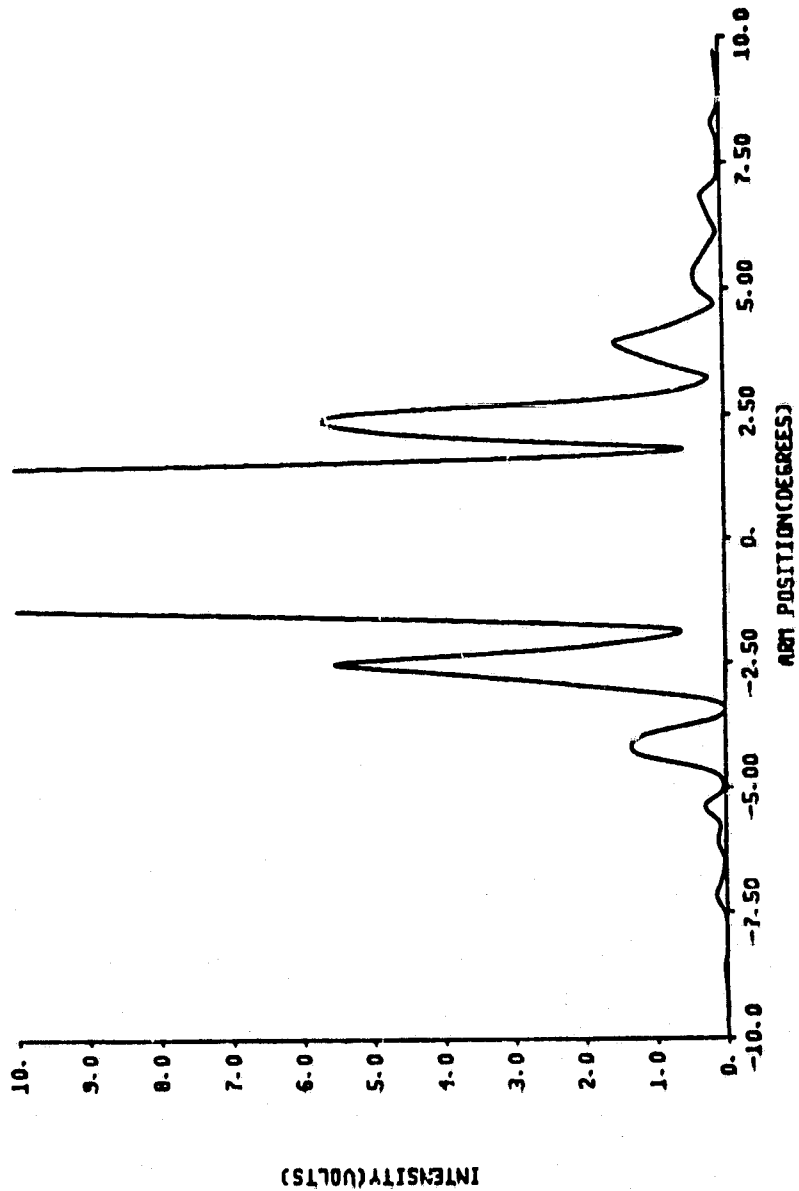


Figure 17

Diffraction Pattern of a 25 Micrometer Diameter Pinhole

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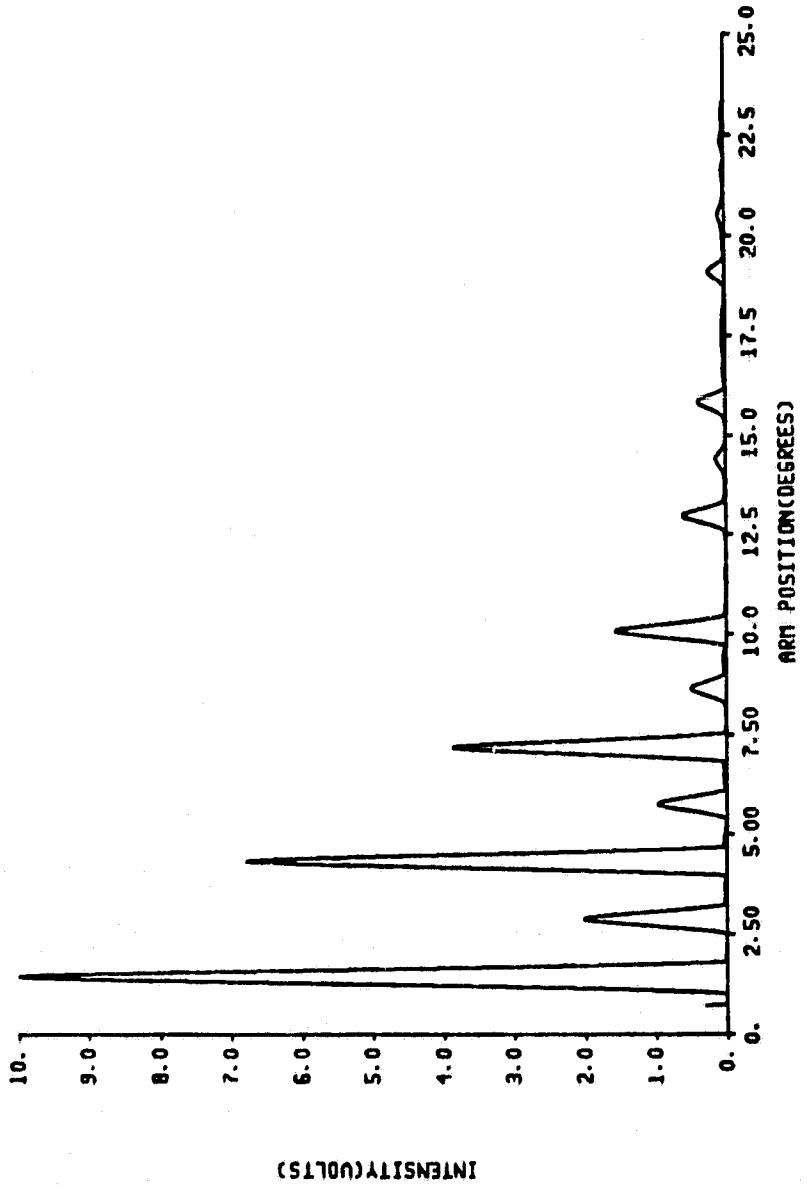


Figure 18
Multiple Slit Diffraction Pattern

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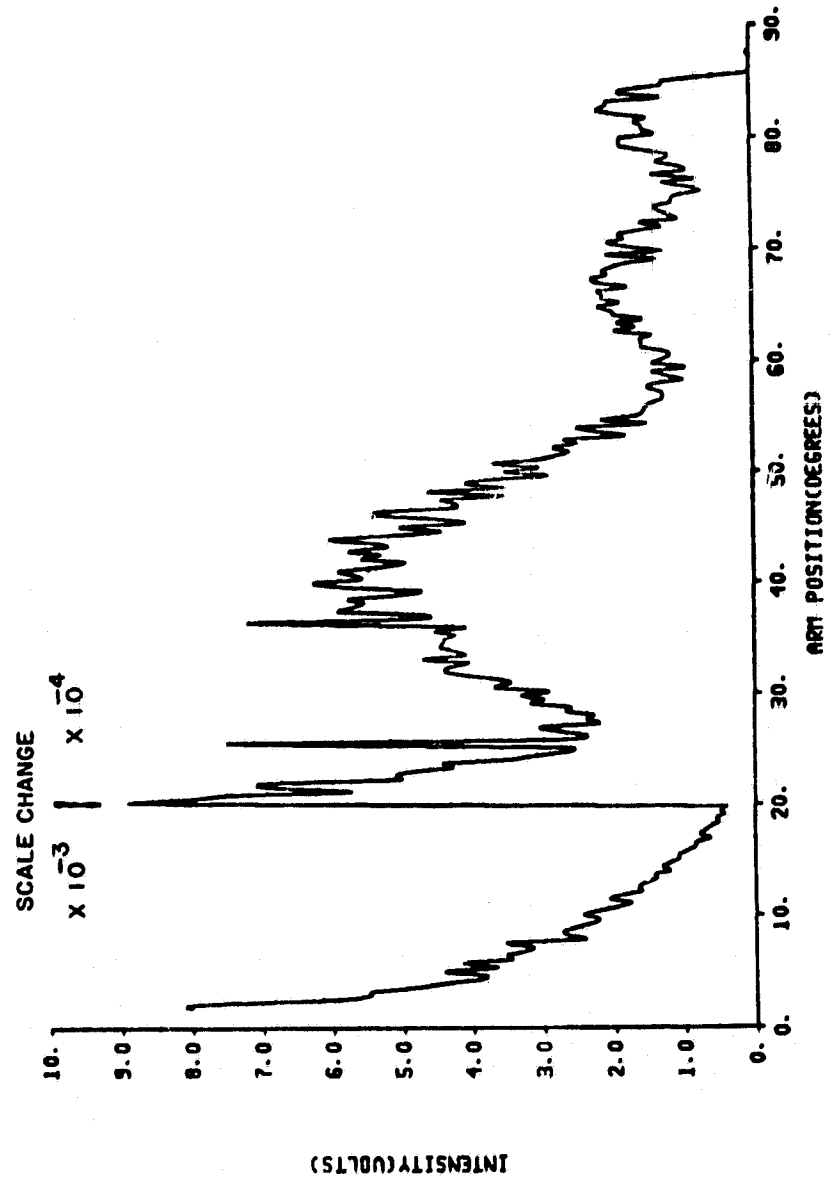


Figure 19

Diffraction Pattern of 1.091 Micrometer Diameter PLS on a Glass Slide

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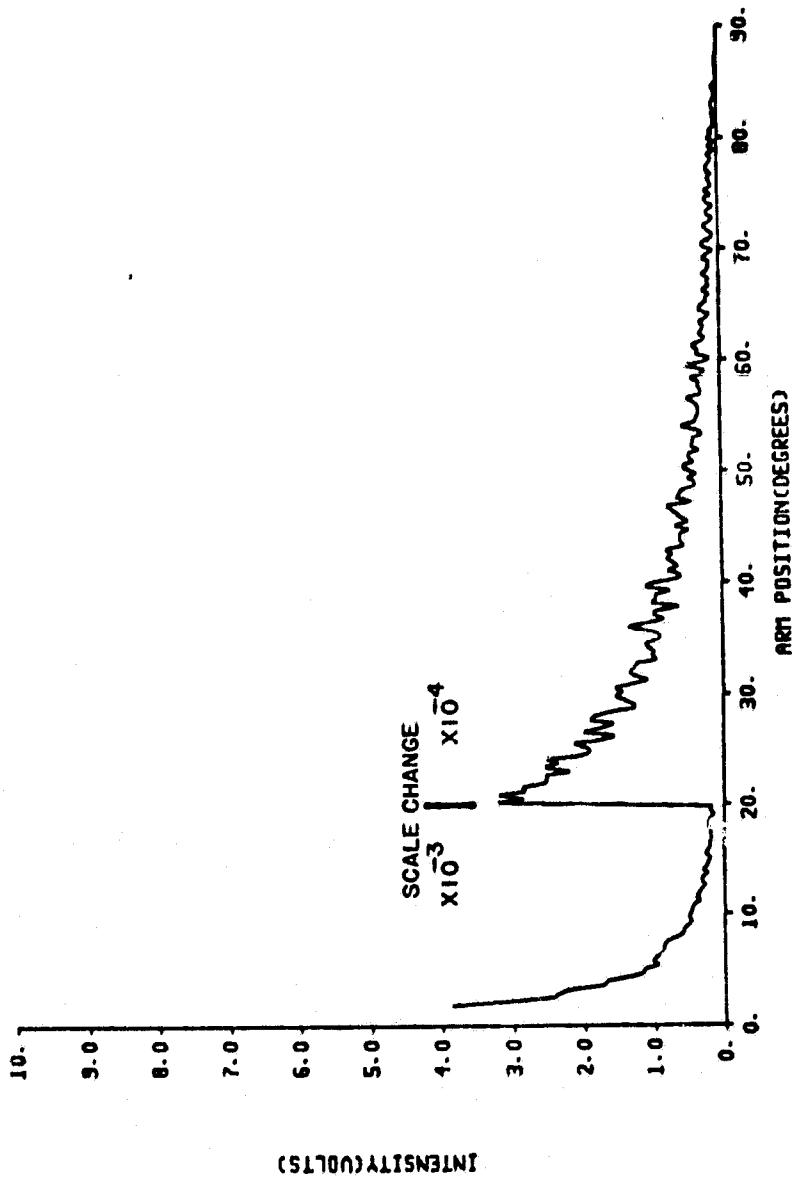


Figure 20
Diffraction Pattern of a Clean Glass Slide

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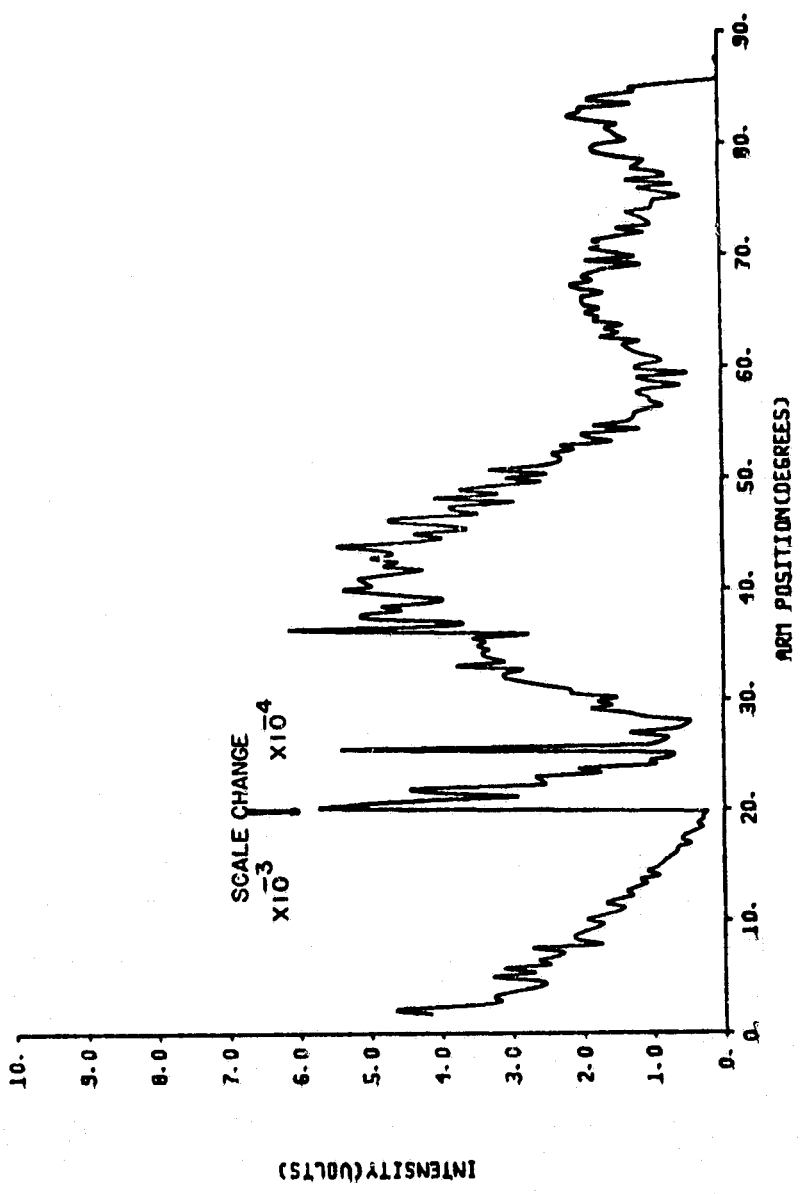


Figure 2 I

Background Compensated Diffraction for 1.09 μ Micrometer Diameter PLS