THE WAVELENGTH DEPENDENCE OF THE MODULATION TRANSFER FUNCTION OF THE ATMOSPHERE

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THESIS

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by

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of the
Modulation Transfer Function
of the Atmosphere

by

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ABSTRACT

An apparatus was designed and constructed to measure the modulation transfer function of the atmospheric medium as a function of wavelength of light. The modulation transfer function (MTF) in this case was considered to be the ratio of the modulation of an optical target at a fixed range to the modulation at a range short enough so that atmospheric attenuation was negligible.

Modulation measurements were made using a telescope which focused the image of the target on a slit. The image was mechanically scanned across the slit by a rotating mirror, and the intensity at the slit was measured by a photodetector.

The preliminary results indicated a linear decrease in modulation of 0.1 per 1000Å.

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I. INTRODUCTION

With the increasing complexity of optical systems in recent years, it has become necessary to find a general figure of merit by which to compare them. By viewing the object of interest as an input, and the image formed as an output, it has become common practice to use the theory of the transfer function as the descriptive link between the two.

Generally speaking, the quality of an image formed by an optical system is a function of three things: 1. The total abberation in the ray optics design of the system, 2. The (inherent) diffraction caused by the wave nature of light, and 3. Manufacturing inaccuracies. In the case where manufacturing and abberation effects can be considered negligible, the system is said to be diffraction limited. The diffraction limited case is the closest to ideal that can be reached. The observable effect of diffraction is a reduction in contrast which increases with the spatial frequency of the target.

When dealing with the intensity distribution of a periodic target, an important comparative parameter is the modulation, defined as the difference between the maximum and minimum signal amplitude divided by the sum of the two. This parameter is the ratio of (twice) the amplitude variation to (twice) the average intensity.

In the most common usage, the plot of modulation versus the spatial frequency of the target (cycles per distance on the target) is called the modulation transfer function (MTF) curve. Since this is normalized to 1.0 at zero cycles, it will be defined in this paper as the ratio of the modulation at a fixed distance to the modulation at approximately

zero distance for a fixed spatial frequency at a particular wavelength of received light. Since the atmosphere is the common medium of propagation for most optical systems, it is necessary for both prediction and evaluation of system performance that an understanding of its characteristics be applied to MTF calculations.

A. THEORY OF MTF FOR A DIFFRACTION LIMITED SYSTEM

The response of an optical system is determined for basic patterns, such as points, lines, or edges. The responses to these patterns are called the point, line and edge spread functions respectively. For responses to complex objects, such as periodic targets, the optical transfer function is used if both amplitude and phase are of concern, and the MTF if amplitude only is desired. Since any object may be considered a collection of points, there is a connection between the point spread function and the transfer functions.

The point spread function is the normalized diffraction pattern formed by a point object. It is usually plotted as illuminance as a function of distance in the image plane.

Once the point spread functions for a sensor system are known, the illuminance of any object can be obtained by summing the point spread functions of the target object. This process can be represented by a convolution integral. As a general example, consider an object plane (x_1) and an image plane (x_2). Let the function $O(x_1)$ and the spread function $S(x_2)$ define an object. The illuminance of the image, $I(x_1)$, is given by the convolution of the object functions:

$$I(x_1) = \int_{-\infty}^{\infty} S(x_2) O(x_1 - x_2) dx_2$$

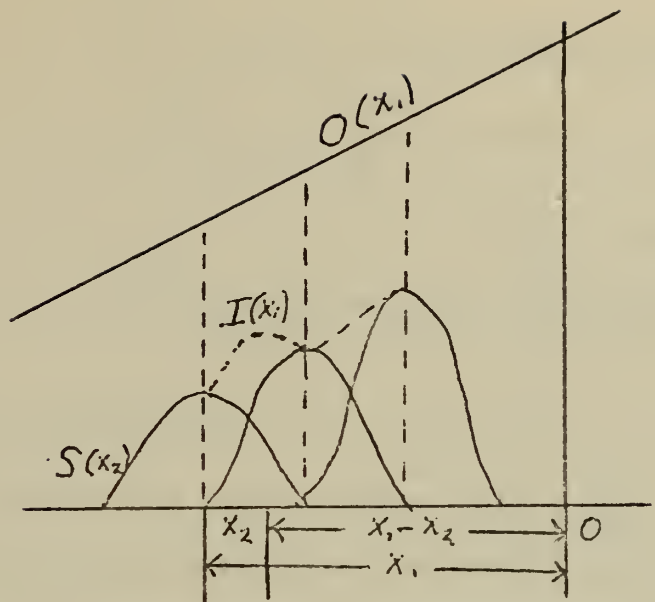


Figure 1. Illustration of convolution process.

Figure 1 shows the convolution of an object function and a spread function to produce an image function. The image function does not exactly reproduce the object because only three points in the image function are illustrated. The appearance of the argument $(x_1 - x_2)$ implies that one function is translated or scanned along the other function so that each point in the object is traced through the system to the image, and the spread function is then scanned over the image point.

For a linear system, the response due to a number of inputs is the product of the transfer functions of each. In an optical system, the mathematical foundation is the Fourier transform:

$$G(w) = \int_{-\infty}^{\infty} g(x)\exp(-iwx)dx$$

In any real system, the spatial variable is usually at least two-dimensional. Taking the Fourier transform of both sides of the convolution integral,

$$I(w) = \iint_{-\infty}^{\infty} S(x_2)O(x_1-x_2)\exp(-iwx_1)dx_2dx_1$$

$$= \int_{-\infty}^{\infty} S(x_2)dx_2 \int_{-\infty}^{\infty} O(x_1-x_2)\exp(-iwx_1)dx_1$$

$$= \int_{-\infty}^{\infty} S(x_2)dx_2 \int_{-\infty}^{\infty} O(u)\exp(-iwu)\exp(-iwx_2)du$$

where $u = x_1-x_2$

$$= \int_{-\infty}^{\infty} S(x_2)\exp(-iwx_2)dx_2 \int_{-\infty}^{\infty} O(u)\exp(-iwu)du$$

So that $I(w) = S(w)O(w)$.

The spread function can then be written $S(w) = \frac{I(w)}{O(w)}$. When normalized, the Fourier transform of the spread function is the optical transfer function.

$$OTF(w) = \frac{\int_{-\infty}^{\infty} S(x)\exp(-iwx)dx}{\int_{-\infty}^{\infty} S(x)dx}$$

The MTF as a function of $k = \frac{w}{2\pi}$, can be obtained by:

$$MTF(k) = \left| OTF(\frac{w}{2\pi}) \right|$$

It should be pointed out here that k is the spatial frequency in lines per distance, and that w is therefore a spatial angular frequency, in radians per distance. Recalling that

$$\exp(-iwx) = \exp(-i2\pi kx) = \cos(2\pi kx)-i\sin(2\pi kx),$$

$$MTF(k) = \frac{\left| \int_{-\infty}^{\infty} S(x)\cos(2\pi kx)dx - i\int_{-\infty}^{\infty} S(x)\sin(2\pi kx)dx \right|}{\left| \int_{-\infty}^{\infty} S(x)dx \right|}.$$

The numerator is the vectorial sum of the cosine and sine Fourier transforms of S(x).

As an example of the calculation of the MTF of a spread function, consider a function defined as:

$$S(x) = \begin{cases} 1, & \frac{-a}{2} < x < \frac{a}{2} \\ 0, & \text{elsewhere} \end{cases}$$

This might represent the spread functon of a scanning spot of diameter a with spatial frequency $\frac{1}{a}$. Since the spread function is symmetrical,

$$\int_{-a/2}^{a/2} S(x)\sin(2\pi kx)dx = 0 \text{ for all } k$$

$$\int_{-a/2}^{a/2} S(x)\cos(2\pi kx)dx = 2\int_{-a/2}^{a/2} \cos(2\pi kx)dx$$

$$= 2\left[\frac{\sin(2\pi kx)}{2\pi k}\right]_0^{a/2}$$

$$= \frac{\sin(\pi ka)}{\pi k}$$

The denominator, $\int_{-a/2}^{a/2} S(x)dx = a$, so that

$$MTF(k) = \left|\frac{\sin(\pi ka)}{\pi ka}\right|$$

It can be seen that the MTF vanishes at integer multiples of $\frac{1}{a}$.

The existence of the MTF beyond its cutoff frequency of $\frac{1}{a}$ is referred to as spurious or false resolution. This can be explained by considering a bar chart of lines and spaces of width a. If the scanning spot of diameter a is positioned so that the center of the spot traces the edge of each successive line, the output of each scan will be the same because each will scan the same amount of line and space. If the spatial frequency is increased, the lines and spaces become narrower, and therefore closer together. In this case, the amount of line and space covered each scan varies from

nearly all line to the opposite, and the varying output looks like resolution, although no useful information can be obtained from it.

In the case of a diffraction limited lens, the spread function is the pattern consisting of the central Airy disk surrounded by progressively fainter rings. The MTF is the Fourier transform of this diffraction pattern. Consider the general case of Fraunhofer diffraction of a circular aperture. Figure 2 illustrates the coordinates used.

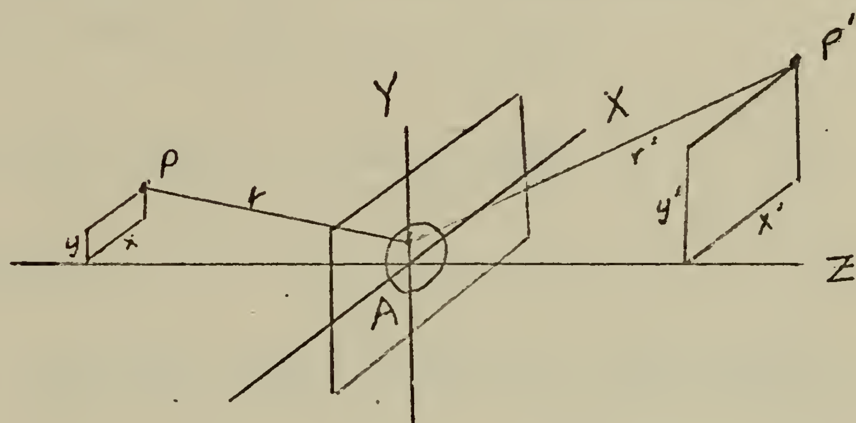


Figure 2. Fraunhofer diffraction of a circular aperture.

It is desired to find the illumination at a point P' due to a source at point P after the radiation has passed through an aperture A. The amplitude of P' is found by summing all the contributions from the area elements in A.

$$U(P') = C' \int U(X,Y) \frac{\exp(ikr')}{r'} dA = C_o C' \int \frac{\exp(ik(r+r'))dA}{rr'}$$

Because kr is large, the numerator changes rapidly with r, while the denominator changes slowly over the range of integration, so long as $rr' >> X_{max}, Y_{max}$.

$$r = [(x-X)^2 + (y-Y)^2 + Z^2]^{1/2}$$

$$= r_o\left(1 + \frac{X^2 + Y^2 - 2xX - 2yY}{r_o^2}\right)^{1/2}$$

$$\simeq r_o - \frac{xX + yY}{r_o} + \frac{X^2 + Y^2}{2r_o} - \frac{(xX + yY)^2}{2r_o^3}$$

A similar expression can be obtained for r'. In these expressions, r_o and r'_o are the distances from the origin to P and P' respectively. Now let l and m be the first two direction cosines for P and l' and m' be those for P'. These cosines may be written:

$$l = \frac{-x}{r_o}, \quad m = \frac{-y}{r_o}, \quad l' = \frac{x'}{r'_o}, \quad m' = \frac{y'}{r'_o}.$$

Substituting,

$$U(P') = C\exp(ik(r_o + r'_o)) \iint_A \exp\Big[ik((l - l')X + (m-m')Y$$

$$- \frac{1}{2}\Big[\left(\frac{1}{r_o} + \frac{1}{r'_o}\right)(X^2 + Y^2) - \frac{(lX+mY)^2}{r_o} - \frac{(l'X + m'Y)^2}{r'_o}\Big]\Big] dXdY$$

In the case where $|r_o|, |r'_o| \gg \frac{(X^2 + Y^2)}{\lambda}$ max, the terms in the second bracket may be neglected. This is the Fraunhofer diffraction approximation. The amplitude expression may be simplified to:

$$U(\Delta l,\Delta m) = C\iint_A \exp[ik(X\Delta l + Y\Delta m)]dXdY$$

Assuming the aperture does not transmit perfectly, and calling its transmittance T(X,Y),

$$U(\Delta l,\Delta m) = C\iint_{-\infty}^{\infty} T(X,Y)\exp(ik(X\Delta l + Y\Delta m))dXdY$$

The amplitude of the diffracted wave is the two-dimensional Fourier transform of the aperture transmittance, provided the aperture coordinates are measured in units of $\frac{1}{k} = \frac{\lambda}{2\pi}$. Using the Fraunhofer

approximation, the linear coordinates may be written, $x = r'_o \Delta l$, $y = r'_o \Delta m$

$$U(x,y) = C \iint_{\infty}^{\infty} T(X,Y) \exp\left(\frac{ik}{r'_o}(xX + yY)\right) dX dY$$

Consider a circular aperture of radius a. In order to integrate in polar coordinates, we substitute

$$X = R\cos\theta, \quad Y = R\sin\theta$$

$$x = r\cos\phi, \quad y = r\sin\phi$$

$$dA = R dR d\theta, \quad f = r'_o$$

$$U = c \int_0^a R \int_0^{2\pi} \exp\left[\frac{ikrR}{f}(\cos\theta\cos\phi + \sin\theta\sin\phi)\right] d\theta dR$$

$$U = c \int_0^a R \int_0^{2\pi} \exp\left(\frac{ikrR}{f} \cos(\theta - \phi)\right) d\theta dR$$

Recall that $\int_0^{2\pi} \exp(ix\cos\alpha) d\alpha = 2\pi J_o(x)$, where $J_o(x)$ is the zero order Bessel function. Since the integrand is periodic, we may add any finite amount to both limits simultaneously without changing the value, so that $U = 2\pi c \int_0^a R J_o\left(\frac{krR}{f}\right) dR$. The recurrence relation for Bessel functions states that

$$\frac{d}{dx}\left(x^{n+1} J_{n+1}(x)\right) = x^{n+1} J_n(x), \text{ so that}$$

$$\int x J_o(x) dx = x J_1(x)$$

$$U = (\pi a^2 c) \frac{2 J_1\left(\frac{kra}{f}\right)}{\frac{kra}{f}}$$

The irradiance is the square of the amplitude, or

$$I = \left[\frac{2J_1\left(\frac{kra}{f}\right)}{\frac{kra}{f}} \right]^2 I_o, \text{ where } I_o = \frac{AP}{\lambda^2 f^2}$$

A = aperture area, P = total power

The corresponding distribution is called an Airy pattern, and the area enclosed by the first minimum is an Airy disk. The diameter of the disk turns out to be approximately $1.22 \frac{\lambda}{\sin\alpha'}$, where α' is the apex half angle of the cone converging on the image point.

To determine the amplitude spread function, consider Figure 3.

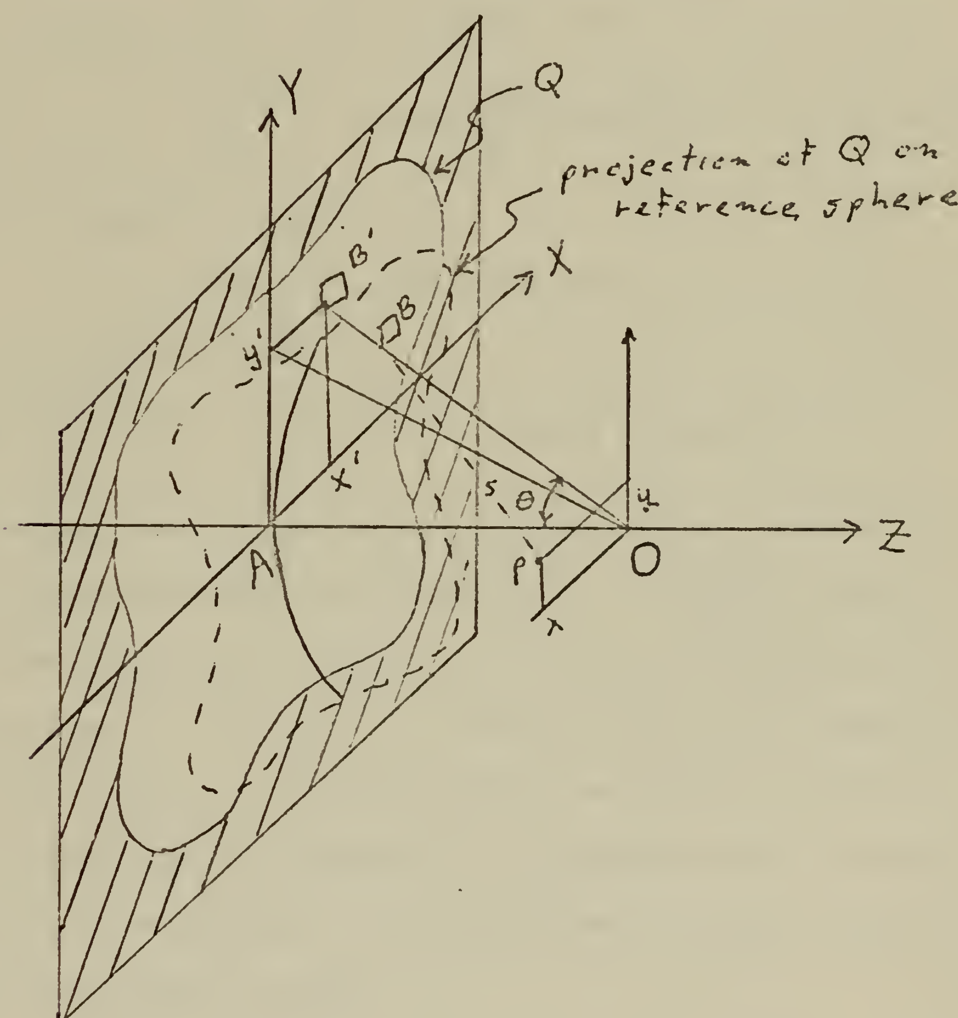


Figure 3. Derivation of lens spread function.

The spherical wavefront of radius R has its vertex, A, at the center of an aperture, Q, which can be considered the exit pupil of a diffraction limited lens. P(x,y) is a point in the image plane. The amplitude of the wave at P is obtained by integrating from all the area elements dx'dy' over the wavefront. For each point B'(x',y') in the aperture, a projection is made to a point B(x',y') on the wavefront. A wavefront area ds corresponds to each dx'dy'. The projection is made such that $\frac{ds}{dx'dy'} = \cos^3\theta$. The amplitude U_o at P can be obtained by integrating over the area elements at Q.

$$U_o(x,y) = \iint_Q [E\exp(iks)\cos^3\theta \, dx'dy']^{1/2}$$

$$\approx \left(\frac{\Phi}{S_Q}\right)^{1/2} \exp(ikR) \iint_Q \exp\left[\left(\frac{-ik}{R}\right)(xx' + yy')\right] dx'dy'$$

E = aperture illumination

Φ = total energy flux in the aperture

S_Q = aperture area

Assumptions: $\frac{x}{R}, \frac{y}{R} << 1$; $\cos\theta \approx 1$; uniform illumination.

The integral above is the Fourier transform of the aperture function. For a circular aperture this becomes $U_o(r) = \frac{2J_1(krA)}{krA}$, where $k = \frac{2\pi}{\lambda_o}$, λ_o is the wavelength in vacuum. A is a numerical representation of the aperture, and $r = (x^2 + y^2)^{1/2}$. Note that this is the square root of the Airy function. A pupil function can be defined, $V(x',y') = T(x',y')\exp(ik\nu(x',y'))$, where T is the amplitude and ν the phase deviation in the aperture. Writing the amplitude spread function in terms of the pupil function,

$$U(x,y) = \frac{\iint_{-\infty}^{\infty} V(x',y')\exp\left[\frac{-ik}{R}(xx' + yy')\right]dx'dy'}{\iint_{-\infty}^{\infty} V(x',y')dx'dy'}$$

The amplitude spread function is, then, the inverse Fourier transform of the pupil function.

To obtain the transfer function of a lens, it is necessary to take the Fourier transform of the spread function. New variables are defined; $\nu'_x = \frac{x'}{\lambda R}$, and $\nu'_y = \frac{y'}{\lambda R}$, so that

$$U(x,y) = C \iint_{-\infty}^{\infty} V'(\nu'_x,\nu'_y)\exp[-i(x\nu'_x + y\nu'_y)]\, d\nu_x d\nu_y$$

$$C = \frac{\lambda^2 R^2}{\iint_{-\infty}^{\infty} V(x',y')dx'dy'}$$

This is the inverse Fourier transform of V', the pupil function, written in the new variables. For an incoherent object, the transfer function is the Fourier transform of the intensity spread function,

$$T(\nu_x,\nu_y) = \frac{\mathcal{F}[E(x,y)]}{\mathcal{F}_o[E(x,y)]}, \quad \text{where } E(x,y) = \left|U(x,y)\right|^2$$

$$E(x,y) = C\,[\mathcal{F}^{-1}(V')]\,[\mathcal{F}^{-1}(V')]^*$$

Applying the convolution theorem of the Fourier transform,

$$T(\nu_x,\nu_y) = \frac{C\mathcal{F}\{[\mathcal{F}^{-1}(V')]\,[\mathcal{F}^{-1}(V')]^*\}}{\mathcal{F}_o[E]}$$

$$= \frac{C\{V' * \mathcal{F}[\mathcal{F}^{-1}(V')]^*\}}{\mathcal{F}_o[E]}, \text{ but}$$

$$\mathcal{F}[\{\mathcal{F}^{-1}[V(x)]\}^* = V^*(-x)$$

Thus the convolution changes to correlation,

$$T(\nu_x,\nu_y) = \frac{C(V' \odot V'^*)}{\mathcal{F}_o(E)}, \text{ where } f(x) \odot g(x) = \int_{-\infty}^{\infty} f(x')g(x'-x)dx'.$$

The denominator, $\mathcal{F}_o(E) = V' \odot V'^* \Big|(0,0) = \Phi T$, the total flux through the aperture. When normalized, $T(\nu_x,\nu_y) = \frac{V' \odot V'^*}{\Phi_T}$, which represents

the value of $V_1V_2^*$ integrated over the common area when two figures of identical cross section are displaced by ν_x, ν_y. Taking the example of Figure 4, where two circular apertures are shown, the MTF = $\frac{\text{common area}}{\text{total area}}$.

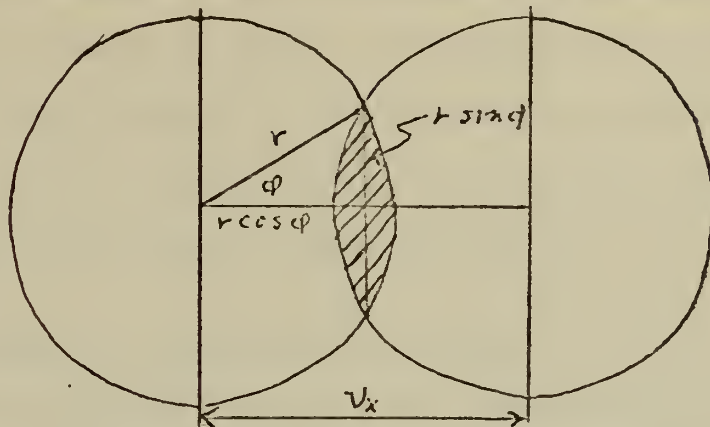


Figure 4. Correlation of two identical circular apertures.

From Figure 4 it can be seen that $r\cos\phi = \frac{\nu_x}{2}$, so that $\cos\phi = \frac{\nu_x}{2r} = \frac{\nu_x}{D}$.

The common area is given by $2[\frac{2\phi\pi r^2}{2\pi} - (r\sin\phi)(r\cos\phi)] = 2r^2(\phi - \sin\phi\cos\phi)$

$$\text{MTF} = \frac{2}{\pi}(\phi - \sin\phi\cos\phi)$$

If the maximum spatial frequency is k_o, then the normalized spatial frequency $= \frac{k}{k_o} = \frac{\nu_x}{D} = \cos\phi$, and $\sin\phi$ is equal to $(1-\cos^2\phi)^{1/2}$.

$$\text{MTF} = \frac{2}{\pi}\left[\cos^{-1}\left(\frac{k}{k_o}\right) - \frac{k}{k_o}\left(1 - \left(\frac{k}{k_o}\right)^2\right)^{1/2}\right]$$

This is the Fourier transform of $\left[\frac{2J_1(\pi k_o x)}{\pi k_o x}\right]^2$, the Airy pattern, so that the MTF is that of a diffraction limited lens. The interesting point is that the MTF is the convolution of the aperture with itself.

B. THEORY OF THE EXPERIMENT

The wavelength dependence of the MTF of the atmosphere was to be obtained by optically scanning a 4' x 6' bar chart made of alternating black and white strips. Each strip was ten centimeters wide, with a resulting spatial frequency of five lines per meter. The angular scan

provided by a rotating mirror was a total of 0.0038 radians, and was interrupted by a mechanical chopper at the rate of 29 chops per second to provide a reference zero. The chopper and rotating mirror were constructed as shown in Figure 5. The wavelength of the received light was to be varied through the visible and into the infrared, and the modulation observed and referenced to the modulation obtained at essentially zero distance to yield the MTF.

C. EVOLUTION OF THE EXPERIMENTAL APPARATUS

The block diagram of Figure 6 was a common factor throughout the research effort, but several modifications were made to the optics in an effort to improve signal amplitude and accessibility of the slit for visual target monitoring.

The initial optical arrangement was as shown in Figure 7, using the monochromator section of a Perkin-Elmer Model 13 infrared spectrophotometer. In this arrangement, the light passed through the entrance slit, was dispersed by the prism, passed through an array of mirrors and slits, and was finally reflected up through an aperture in the cover of the monochromator to a silicon photocell by mirror M6. The detector circuit was as shown schematically in Figure 8, except that the rectifier diode had not yet been added. Wavelength scanning was achieved by changing the angle of M2 to cover the entire prism dispersion pattern.

A problem was discovered with this arrangement in that the losses suffered by the light in passing through 9 mirrors (including two in the telescope), through the prism twice, and into the detector were so great that the signal amplitude out of the detector was too low to be observed above the noise on the Tektronix 451 oscilloscope. The

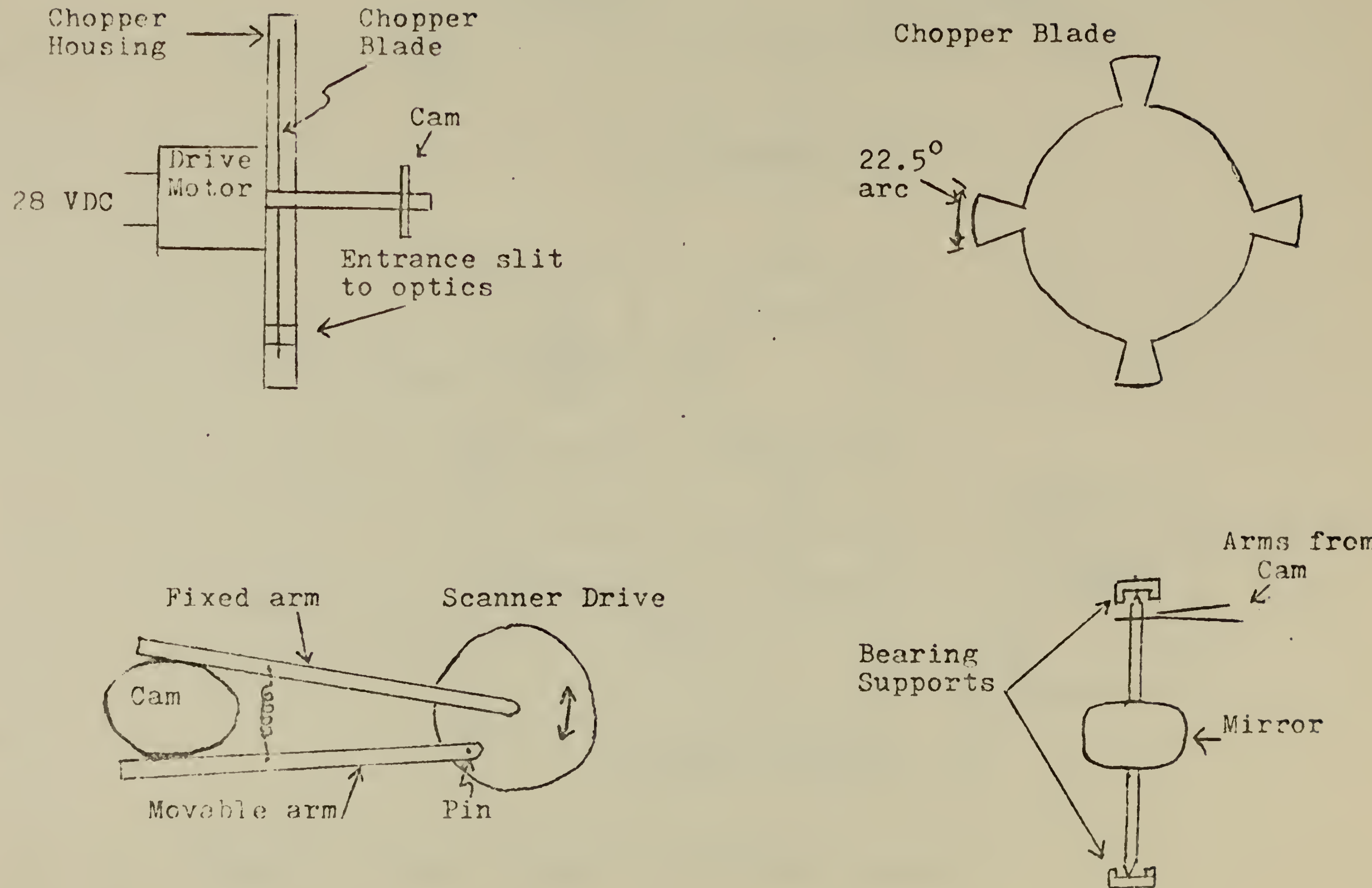


Figure 5. Chopper and Scanner Mechanisms.

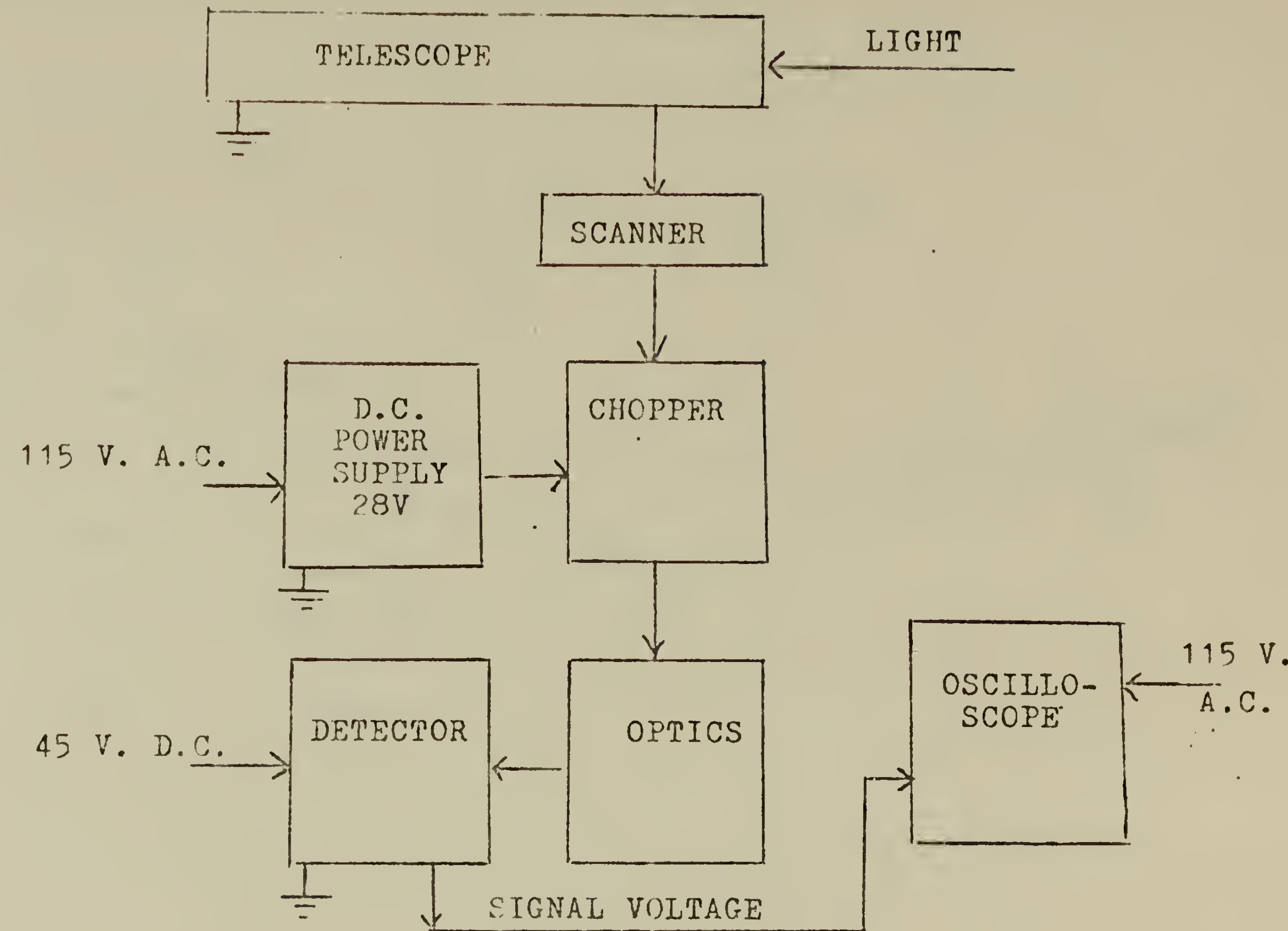


Figure 6. Block Diagram of Detection System.

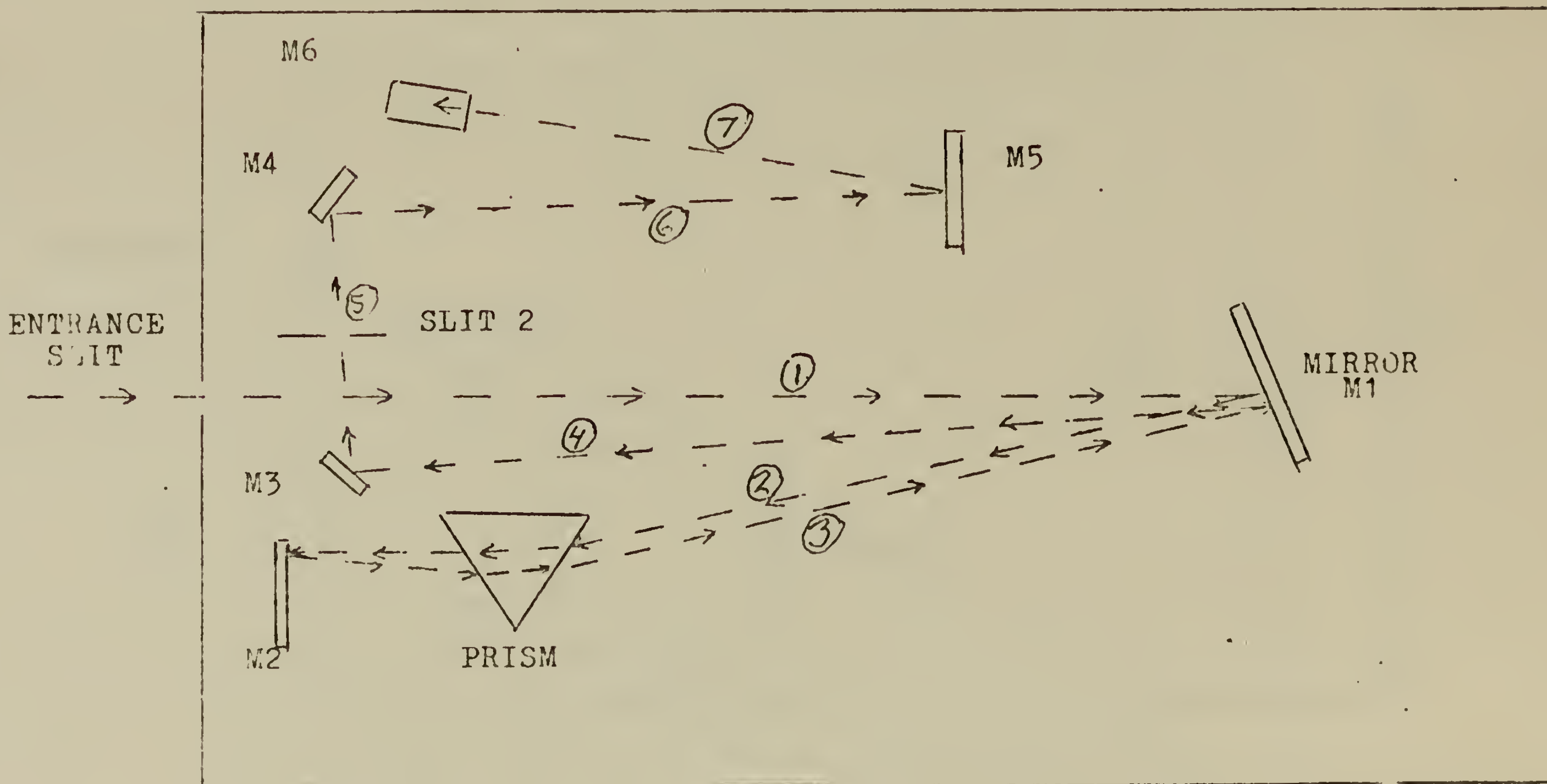


Figure 7. Initial Optical Arrangement.

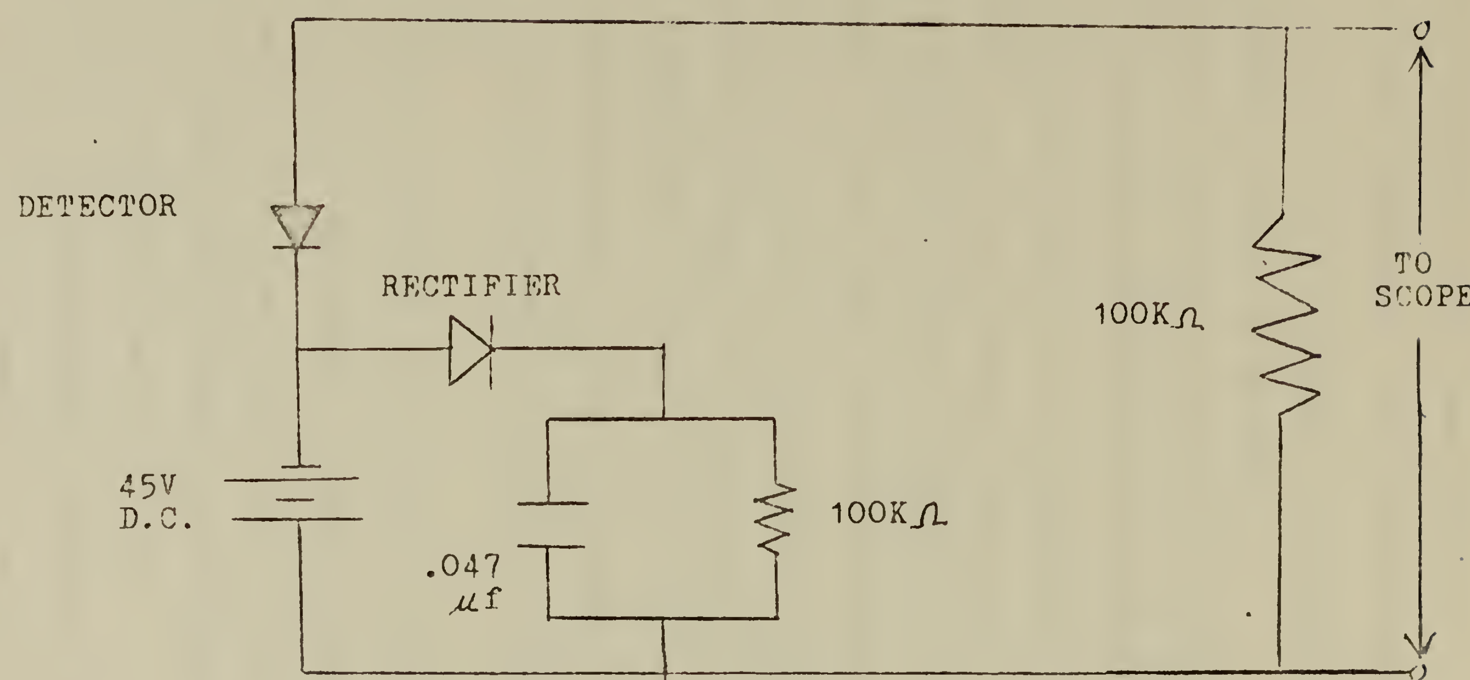


Figure 8. Detector Circuit Schematic.

first effort to improve this situation was to shift from a Type E Low Level Differential AC Preamp plug-in scope module (which had a lower range of 50 microvolts per cm) to a type 1A7 High Gain Differential Amplifier (with a lower range of 10 microvolts per cm). This was still unsuccessful. With the entrance slit full open at 2 mm, the white bars on the target were visible on the scope, but the black bars were lost in the noise.

The next modification was to bypass the monochromator entirely, and place the detector directly behind the entrance slit. This gave detectable signal amplitude, but a problem of overshoot on the scope coupled with capacitive discharge through the detector circuit produced a negative response of approximately the same amplitude as the signal. At this point, it was decided that at least part of the problem could be solved by dealing with the capacitor. The value of the capacitor was changed twice, ending with .047 microfarads. It was also observed at this time that the photocell output as observed on the scope was overshooting in the negative sense on each chop, either as a result of the internal oscilloscope or detector circuit characteristics.

By partial dismantling of the system, it was possible to determine visually that the chop on each cycle was occurring while the image of the target had been swept past the slit, which implied that there was only background present when the chop occurred. This problem was corrected by rotating the cam on its shaft.

At this point in the research, an attempt was made to change detectors from the silicon photocell to an InSb photovoltaic, liquid nitrogen cooled detector manufactured by Barnes Engineering. In order

to accommodate the detector, shown in Figure 9, the optics were rearranged as shown in Figure 10. The documents pertaining to the detector failed to show the associated circuitry required, and, as a result, no useful data were obtained from it. An attempt was made to take the output directly from the detector to the scope, since it operated at zero volt bias and had low maximum current and voltage ratings, but no signal was observed.

In order to alleviate the capacitor discharge problem, the rectifier and resistor were added to the detector circuit so that any discharge would occur through the internal circuit vice through the output.

Since phone calls and local efforts were unsuccessful in getting results from the InSb detector, the silicon photocell was reinstalled using the optics as shown in Figure 10. Wavelength variation was achieved through the use of interference filters. The results obtained will be presented in Section II of this paper.

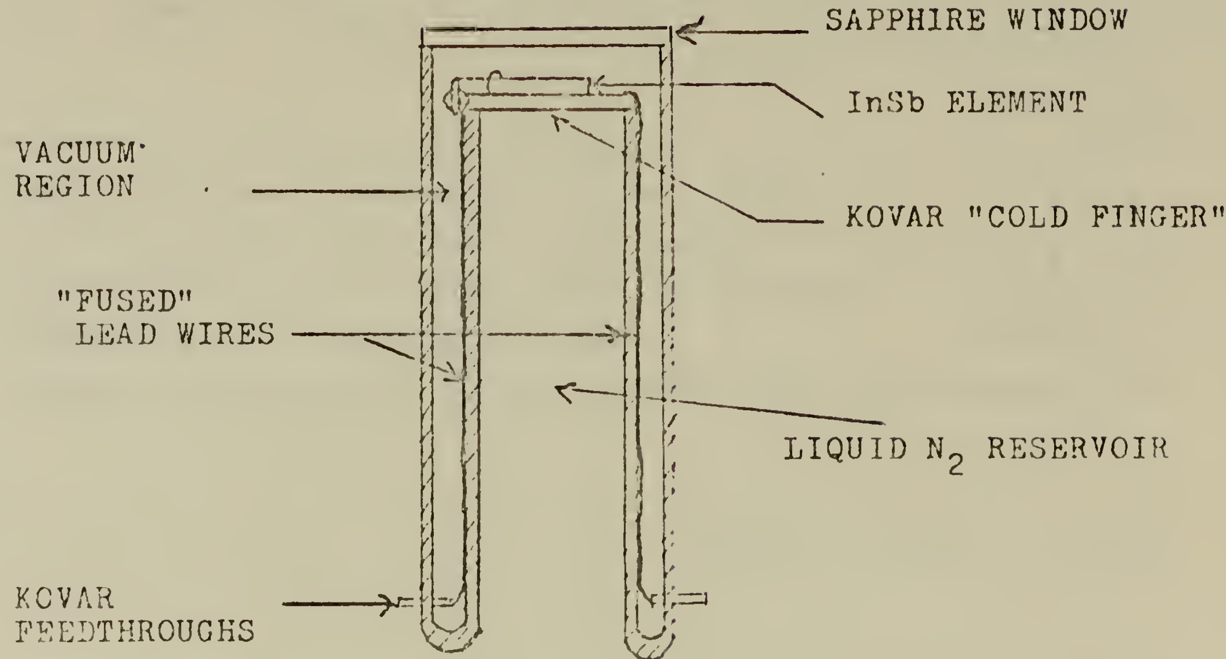
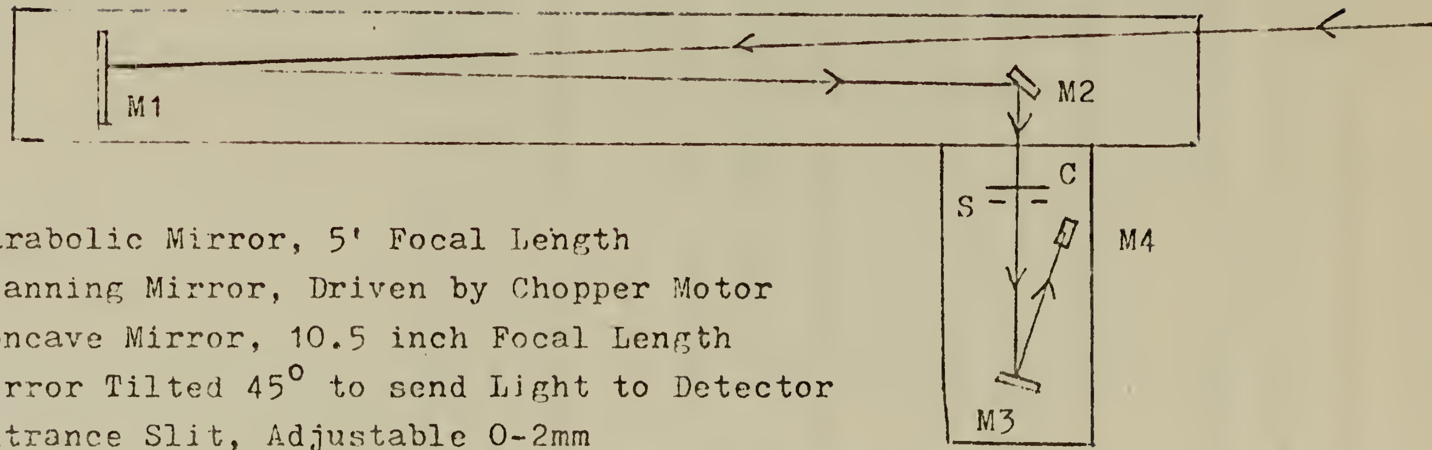


Figure 9. InSb Detector.



M1: Parabolic Mirror, 5' Focal Length

M2: Scanning Mirror, Driven by Chopper Motor

M3: Concave Mirror, 10.5 inch Focal Length

M4: Mirror Tilted 45^{o} to send Light to Detector

S: Entrance Slit, Adjustable 0-2mm

C: Chopper, Mechanically Driven Slotted Disk (See Figure 5.)

Scale: 1 inch = 1 foot

Figure 10. Path of Light through Telescope and Optics.

II. RESULTS OF THE EXPERIMENT

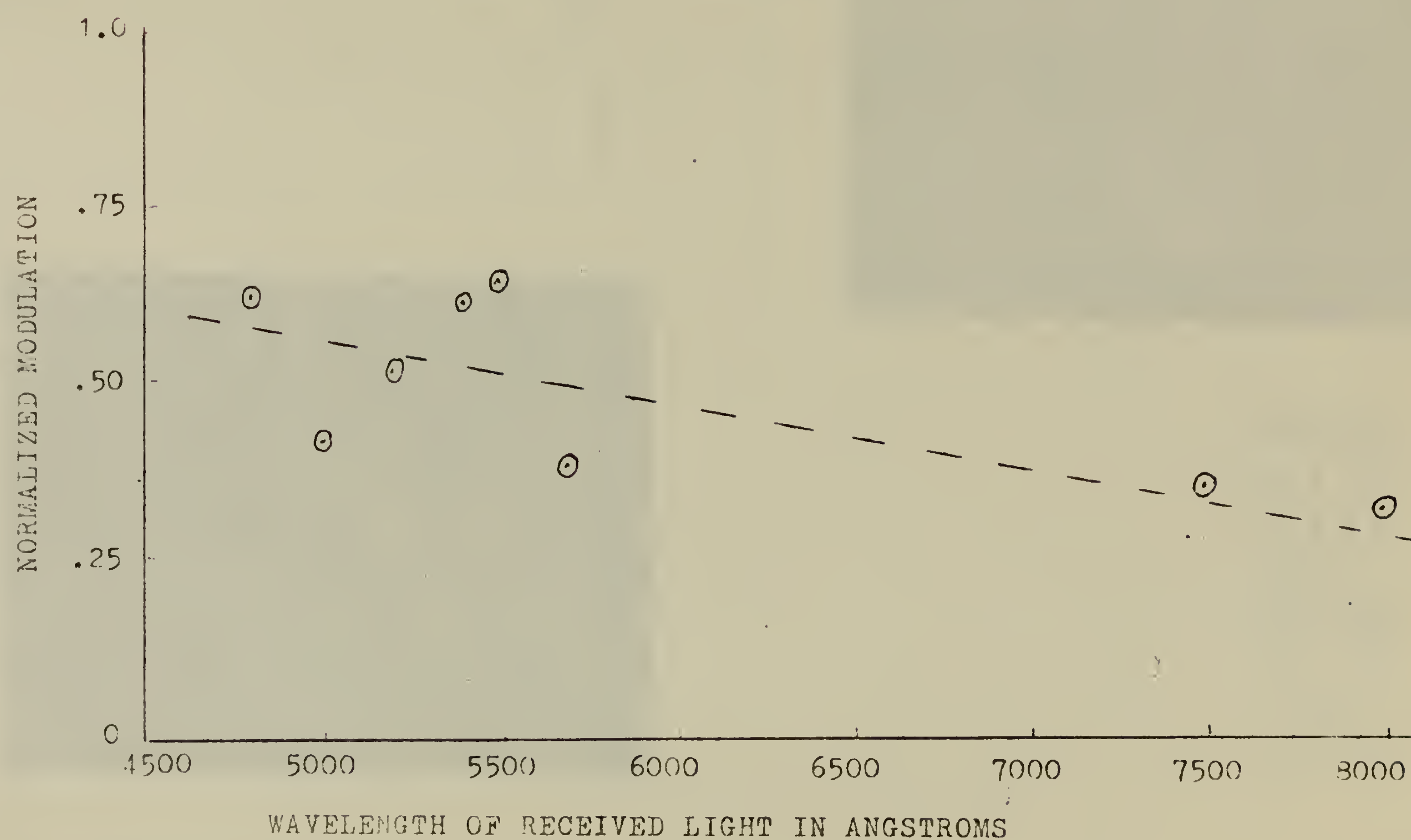
The following data were obtained using a target illumination of approximately 200 watts per square meter by incandescent light, a chopping frequency of 29 per second, and essentially zero attenuation due to distance.

The reference modulation of the target based on 46 measurements at distances between 20 and 120 meters was 0.647 $\pm$ .011. This should be normalized to 1.0 in dealing with future data. Graph 1 is a plot of modulation versus wavelength at zero range. The reliability of this graph is questionable since the interference filters used were of varying transmittance. In order to resolve this problem, a set of matched, high transmittance filters should be used. It is expected that the trend of this graph will reverse to some extent at the higher wavelengths, using an infrared detector at greater range, due to the infrared window of the atmosphere.

Figure 11 shows scope photographs of typical signal presentations.

GRAPH 1

MODULATION VS WAVELENGTH AT ZERO RANGE



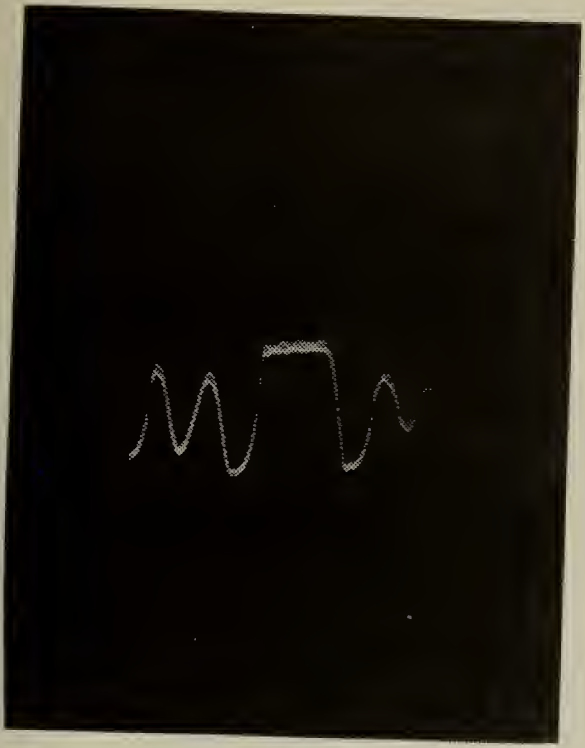


Figure 11a. Typical oscilloscope presentation. Highest amplitude is white bar, double peaks are black, and chop is between.

Figure 11b. Expanded scope trace.

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13. ABSTRACT

An apparatus was designed and constructed to measure the modulation transfer function of the atmospheric medium as a function of wavelength of light. The modulation transfer function (MTF) in this case was considered to be the ratio of the modulation of an optical target at a fixed range to the modulation at a range short enough so that atmospheric attenuation was negligible.

Modulation measurements were made using a telescope which focused the image of the target on a slit. The image was mechanically scanned across the slit by a rotating mirror, and the intensity at the slit was measured by a photodetector.

The preliminary results indicated a linear decrease in modulation of 0.1 per 1000Å.

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