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Generation of sinusoidal test images by incoherent spatial filtering

Joel Gray

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GENERATION OF SINUSOIDAL TEST IMAGES
BY INCOHERENT SPATIAL FILTERING

By

Joel E. Gray

A thesis submitted in partial fulfillment of the requirements for the degree of Bachelor of Science in the School of Photographic Arts and Sciences College of Graphic Arts and Photography Rochester Institute of Technology

June 1970

Thesis Advisor: Professor John F. Carson
ACKNOWLEDGMENTS

I would like to personally thank Professor John F. Carson and Dr. G.W. Schumann for their suggestion of this project and their continued advice and encouragement. My appreciation is also extended to Mr. Frank Scott of the Perkin Elmer Corporation for his list of references and encouragement.

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GENERATION OF SINUSOIDAL TEST IMAGES
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An Abstract
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ABSTRACT

Most methods used for determining the modulation transfer function of a photographic film require that a sinusoidal intensity distribution object be imaged on the film and the resultant effective exposure modulation compared to the object modulation. This paper describes the investigation of the feasibility of generating a sinusoidal intensity distribution from a crenelate pattern by incoherent spatial filtering using non-monochromatic radiation.

Using a Kodak Ektar Enlarging Lens (focal length of 100 mm.) at f/8 it has been found that images may be spatially filtered up to 30 cycles/mm while maintaining a modulation of 62% in white light (tungsten illumination). At this frequency the third harmonic is about 10% of the D.C. level in white light and approaching 13% in blue (Wratten Filter #47) radiation. The magnitude of the third harmonic appears to limit the range of this system from 5 to 30 cycles/mm if the user can tolerate a 10% third harmonic. At frequencies lower than 30 cycles/mm the third harmonic was considerably less.
The average energy required in the object plane for this particular type of system is 70 lumens/cm$^2$-steradian. All work on this project was carried out using a General Electric DVY, 120 volt Quartzline lamp as a source and Kodak Panatomic X film (ASA 40).
INTRODUCTION
INTRODUCTION

In the history of photographic systems many methods have been devised to determine the performance of an optical system. In the past two decades the most of the work has been centered around the optical transfer function, composed of the modulation transfer function and the phase transfer function.\(^1\),\(^2\) One of the basic requirements for evaluating the transfer function of a system is that an object of a sinusoidal intensity distribution with a known modulation be imaged by the system. The reason for the choice of a sinusoidal intensity distribution target lies in the fact that no matter how badly a lens images an incoherently illuminated sinusoidal pattern, in the isoplanatic region of the lens, the image remains sinusoidal with changes occurring only in the phase and contrast.\(^3\) Work has been attempted using square wave distributions but the computation involved limits the application of this approach.\(^4\)

The major difficulty in testing a system under the transfer function approach is the generation of the sinusoidal intensity distributions such that the exposure and spectral distribution corresponds to those under which the system will be used. In 1956, Kapany devised an integrating sphere
technique which utilizes a square wave as the original target, converting it into a sine wave. This system requires precision gearing and movements to assure optimum quality. Lamberts reported a system used by Eastman Kodak and now widely accepted by the industry which utilizes variable area targets and cylindrical lenses to generate a sinusoidal output. The major disadvantage of Lamberts' system is its complexity. A modified Twyman-Green interferometer has been used to generate variable frequency sine wave patterns but this system requires at least quasi-monochromatic radiation. Other techniques, sometimes referred to as image smearing, have been used with more or less success. If any of the above systems are used to generate an intermediate image on film which in turn is exposed on the test film there is a tendency to introduce harmonic distortion due to the intermediate film-exposure step required.

The use of lasers and Ronchi rulings with modern optical data process techniques suggests spatial filtering techniques to produce the sinusoidal distribution but this requires coherent, monochromatic illumination—very much unlike most test systems applications.

Some attempts have been made at spatial filtering with incoherent, non-monochromatic radiation yielding encouraging results. If this approach were pursued it
should be possible to produce a device where by sinusoidal intensity distributions of various frequencies could be produced from square waves which are easy and inexpensive to produce while spectral distributions of energy could be matched to the test system application.

In this research project an attempt was made to determine if incoherent spatial filtering was indeed a feasible method for generating sinusoidal distributions. Investigations were carried out under limited conditions allowing for the testing of frequencies up to 30 cycles/mm with a spectral distribution of 3200 K (General Electric DVY, 120 volt, Quartzline lamp). These lower frequencies are of particular interest in the graphic arts and television industries as systems in their areas of interest work with lower frequency content images.
THEORETICAL BACKGROUND
THEORETICAL BACKGROUND

The frequency spectrum of the Ronchi ruling can be best described by the Fourier series for a periodic square wave (the one dimensional case). The object pattern is in general described by

\[ f(x) = a_0 + a_1 \sin x + a_3 \sin 3x + a_5 \sin 5x + \ldots \]

A lens can be used to filter the object pattern and allow only that energy representing the first two terms to pass through the system. In this case the image will consist of a sinusoidal image of the lowest frequency (fundamental harmonic) present in the original object taking into account any magnification of the system. The image could then be described by

\[ f_1(x) = a_0 + a_1 \sin Mx \]

Basic formulae are derived by Goodman to determine the cut-off frequency of an optical system (see Figure 3). Since these equations assume that the determinations are being made in the exit pupil of the system an immediate modification of the equations was necessary as the spatial filter could only be placed about 2 cm. from the exit pupil.
In order to determine the slit width required to filter out the unwanted higher harmonics in the image it is necessary to know the cut-off frequency required. Assuming that there are only odd harmonics present in the image (this assumption was confirmed in the experimental work) the cut-off frequency, \( f_o \), should be three times the image frequency, \( f_i \), (see Figure 3) allowing none of the third harmonic to enter the image area.

As a starting point the following equation was used:

\[
L \frac{f_o}{F \lambda} = \frac{L}{F \lambda}
\]

where

- \( f_o = \) cut-off frequency in cycles/mm
- \( L = \) the slit width required
- \( F = \) Focal length of the system
- \( \lambda = \) the wavelength of radiation used.

Since the radiation to be used is broad band in nature one wavelength must be chosen and used for all calculations. Since the shorter wavelengths (blue light) will require a narrower slit width than any other wave length for any one specified frequency the wavelength of \( \lambda = \) micro-meters was chosen. If all calculations are made at this wave length and the higher harmonics are eliminated in the blue light
then one can be assured that the higher harmonics will not be present in the longer wavelengths.

A test series was run at 5 cycles/mm using various slit widths (from .8 mm to 1.8 mm with the calculated width of 1.2 mm). As can be seen from Table 1 a ratio of third harmonic to the D.C. level will be less than .10 for a width of 1.1 mm or less.

<table>
<thead>
<tr>
<th>SLIT WIDTH vs HARMONIC RATIOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slit width (mm)</td>
</tr>
<tr>
<td>0.80</td>
</tr>
<tr>
<td>1.00</td>
</tr>
<tr>
<td>1.10</td>
</tr>
<tr>
<td>1.20</td>
</tr>
<tr>
<td>1.50</td>
</tr>
<tr>
<td>1.80</td>
</tr>
</tbody>
</table>

**TABLE 1**

Slit width compared to harmonic ratios for 5 cycle/mm image frequency in white light.

In addition the modulation of white light and blue light were compared for these slit widths. If the slit were to become quite narrow the modulation of the longer wavelengths would be reduced. The image at all wave lengths in the spectrum should have approximately the same modulation. As can be seen from Table 2 the slit width of 1.1 mm offers the least
difference in modulation for blue, red, and white light for this particular system and geometry. Hence, 1.1 mm was chosen as the slit width for 5 cycles/mm.

### MODULATION FOR VARIOUS COLORS

<table>
<thead>
<tr>
<th>Slit Width (mm)</th>
<th>Blue Light Modulation</th>
<th>Red Light Modulation</th>
<th>White Light Modulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.80</td>
<td>0.723</td>
<td></td>
<td>0.694</td>
</tr>
<tr>
<td>1.00</td>
<td>0.813</td>
<td>0.750</td>
<td>0.791</td>
</tr>
<tr>
<td>1.10</td>
<td>0.806</td>
<td>0.812</td>
<td>0.832</td>
</tr>
<tr>
<td>1.20</td>
<td>0.773</td>
<td>0.812</td>
<td>0.835</td>
</tr>
<tr>
<td>1.50</td>
<td>0.828</td>
<td></td>
<td>0.860</td>
</tr>
<tr>
<td>1.80</td>
<td>0.875</td>
<td></td>
<td>0.871</td>
</tr>
</tbody>
</table>

**TABLE 2**

Modulation compared with slit width for various "colors" of light. (Broad band filters)

Using this information it is possible to derive an equation for the slit width at this frequency and apply it to the determination of slit widths for higher frequencies due to the linearity of the system. This derivation yields

\[ L = 5.5f_1 F \lambda. \]

Applying this formula indicates a slit width of 6.6 mm is required to filter the higher harmonics for a 30 cycle/mm image. This width is getting quite large and is approaching the size of the pupil itself and hence may well become a limiting parameter.
BASIC OPTICAL SYSTEM
BASIC OPTICAL SYSTEM

The basic optical system used in experimentation (see Figures 1 and 2) consists of a source which is diffused by frosted glass, the object (a Ronchi ruling), an Ektar Enlarging Lens used at f/8 and a magnification of 0.40, a spatial filter consisting of a slit in opaque material, a microscope objective and a Pentax camera body for recording the filtered image.

The filtered image falls just in front of the microscope objective. The purpose of this objective is to enlarge the image for recording on Panatomic X film. This enlargement keeps the imaging frequency on the film very low to avoid the possibility of introducing harmonic distortion from the film and to reduce the modulation effects from the film itself. Most of the tests were carried out with the frequency in the film plane lower than 1 cycle/mm.

Light Source

The light source used in the experimentation was a Kodak "Sun Gun", with a G.E. DVY Quartzline lamp. The spectral quality of this source is comparable to the ideal
3200 K source. A DVY lamp is a Quartzline type source normally used for making home movies.

Due to the excessive heat output of this source it was necessary to use a heat absorber before the frosted glass. Even so, the source could be operated for only a few minutes without overheating the surrounding optical bench fixtures. This source was extremely inefficient, however, as most of the radiation was projected into the laboratory with a cone of about 5° actually reaching the Ronchi ruling and of that, only 2° of a cone was used to illuminate the area of the ruling that was imaged.

It has been estimated that when filtering an image of 5 cycles/mm and exposing this image on Panatomic X film (ASA 40) the source must be such that the frosted glass directly behind the Ronchi ruling must have an average radiance of 70 lumens/cm²-steradian. With the proper condensor optics this should be easy to obtain with more efficiency than the present source allows.

The frosted glass diffuses the source and assures that the illumination is even over the portion of the object target required for the system. A medium coarse frosted glass was used.

Ronchi Ruling

The objects that are to be imaged and subsequently filtered must be of a high quality and must consist of a
series of opaque and clear bars or lines on an appropriate substratum. Such object targets are usually referred to as Ronchi rulings. It is not necessary for the dark portions of these rulings to be completely opaque but the higher the contrast of the object, the higher the contrast and hence modulation of the image. The edges of the lines of the rulings should be sharp as any imperfections will add harmonic distortion to the system. The periodicity should be constant with exactly half of the period being the opaque portion of the ruling and the other half being the clear portion.

The Ronchi rulings used in this experimentation were purchased from Edmund Scientific. Three frequencies were used and subsequently reduced in the optical system to give the required frequencies. The Ronchi ruling frequencies used were 11.8, 3.9, and 1.9 cycles/mm.

**Ektar Lens**

The lens used in this optical system was a Kodak Ektar Enlarging Lens, f/4.5, 100 mm focal length. This lens was chosen for its flatness of field and good degree of color correction noted in preliminary testing. Throughout the experimentation this lens was operated at an aperture of f/8 since at this setting the amount of color and diffraction were minimized. The lens was aligned to the optical system using Boys' points alignment. The conjugates
were chosen such that the magnification would be 0.40. The three frequency targets would thus give image frequencies of 5, 10, and 30 cycles/mm.

**Spatial Filter**

The spatial filter is a Spindler and Hoyer adjustable slit. This was used for the two lower frequencies but was not adequate to filter the higher frequency as a slit width of 6.6 mm was required. This was accomplished by the use of two razor blades.

**Microscope**

The microscope shown in Figure 1 consists of a 10X objective and the microscope tube only. The eyepiece was removed as the degree of magnification did not require its use. The purpose of the microscope here is just to magnify the filtered image and project it onto the film plane in the camera body. Normally the image plane and film plane would be one and the same and located slightly in front of the microscope objective.

**Camera Body and Optical Bench**

The Honeywell Pentax camera body was used merely as a roll film holder and film plane on which to image the enlarged distributions. The complete system was based on a three meter I-beam construction optical bench (Tech Ops Manufacture).
EXPERIMENTAL WORK
EXPERIMENTAL WORK

Preliminary Investigations

The basic optical system was aligned using Boys' points alignment technique along with point sources and alignment targets.

Since the system with the spatial filter in place has a low numerical aperture it was thought that the depth of focus should be no problem. To assure this two points, one on either side of visual focus (without the spatial filter) were noted. A focus series was run with the spatial filter in place yielding the results in Table 3.

MODULATION vs FOCAL POSITION

<table>
<thead>
<tr>
<th>Relative Focal Position (0.001 inch)</th>
<th>Per Cent Modulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>86.5</td>
</tr>
<tr>
<td>6</td>
<td>86.7</td>
</tr>
<tr>
<td>7</td>
<td>85.5</td>
</tr>
<tr>
<td>10</td>
<td>86.5</td>
</tr>
<tr>
<td>13</td>
<td>89.5</td>
</tr>
</tbody>
</table>

TABLE 3
Modulation variance with change in focal position for white light, 5 cycles/mm image.
At relative positions 5 and 13 the image was visually out of focus without the filter so that the high value of 89.5% may be attributed to experimental error. It can be seen that the change in focal position does not adversely effect the modulation of the system with the spatial filter in place when the slit is small. This is in agreement with the Rayleigh criterion for the limit on focus.  

Checks were made to determine modulation differences with various colors of light. All work in this project done with different distributions of radiation was accomplished using the following filters:

<table>
<thead>
<tr>
<th>Wratten Filter Number</th>
<th>&quot;Color&quot; of Radiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>red</td>
</tr>
<tr>
<td>58</td>
<td>green</td>
</tr>
<tr>
<td>47</td>
<td>blue</td>
</tr>
</tbody>
</table>

**TABLE 4**

Wratten filters used in experimentation.

In some preliminary tests these filters were narrow band enough to indicate focus shifts in the optics (without the spatial filter) due to residual color. Definite shifts in modulation were noted due to the color (using one frequency and one slit width). Hence, it was necessary to investigate color problems when measuring the performance of the system.
Since it was decided to image the sinusoidal distributions on film and evaluate them after tracing on a microdensitometer and working back through the film curve to obtain exposure from the density values a method was needed to perform the required interpolation. A computer program was developed to take inputs of density along a sinusoidal trace and return the actual exposure values for each density point and also determine the modulation and perform a Fourier Analysis of the data to detect the presence of unwanted higher harmonics. The complete description of this program is included under "Data Analysis" and a copy of the program is included in the "Appendix" of this report.

**Concluding Work**

All of the exposures were made on the basic optical system using Panatomic X film enlarging the filtered images with a 10X microscope objective to avoid image modulation due to the film. The film was processed in DK-50 developer at 75° for three minutes, using intermittent agitation in a small tank. Each roll of film processed included a sensitometric strip and was processed immediately after exposing both the images and the sensi-strip. Exposure times ranged from 1 second with white light to 16 seconds for blue light with filters being placed between the source and the Ronchi rulings.
These exposure times are not consistent with most modulation transfer function testing applications. Normally the user wishes to use exposures consistent with those found in actual applications situations, i.e., less than one second. It should be pointed out that these exposures were made after the original filtered image was enlarged by a 10X objective and hence if the film were placed in the true image plane the exposures would be of the correct order of magnitude. It was determined that to properly expose Panatomic X film to the filtered image a source system of 70 lumens/cm²-steradian would be required. This energy could be supplied by condensor optics and a projection lamp.

The final phase of the evaluation required that the three selected frequencies of 5, 10, and 30 cycles/mm be filtered, imaged and evaluated to determine the modulation and harmonic component ratios (See Table 5). The evaluations were performed using blue and white light. Any decrease in the modulation of white light relative to the blue would indicate that the fundamental harmonic energy distribution of the longer wavelengths was starting to be filtered out. Any high harmonic ratios (greater than 10 to 15%) in the blue light would indicate that higher order harmonics are passing through the system and would degrade the final image (and possibly reduce the modulation of both blue and white light images).
<table>
<thead>
<tr>
<th>Frequency (cy/mm)</th>
<th>$a_1/a_0$</th>
<th>$a_3/a_0$</th>
<th>$a_5/a_0$</th>
<th>Modulation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>White Light</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1.029</td>
<td>0.058</td>
<td>0.008</td>
<td>0.774</td>
</tr>
<tr>
<td>10</td>
<td>1.130</td>
<td>0.005</td>
<td>0.016</td>
<td>0.830</td>
</tr>
<tr>
<td>30</td>
<td>1.090</td>
<td>0.109</td>
<td>0.006</td>
<td>0.620</td>
</tr>
<tr>
<td><strong>Blue Light</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1.083</td>
<td>0.109</td>
<td>0.036</td>
<td>0.802</td>
</tr>
<tr>
<td>10</td>
<td>1.200</td>
<td>0.102</td>
<td>0.011</td>
<td>0.845</td>
</tr>
<tr>
<td>30</td>
<td>1.187</td>
<td>0.128</td>
<td>0.001</td>
<td>0.602</td>
</tr>
</tbody>
</table>

**TABLE 5**

Harmonic ratios and modulation as related to slit width for white and blue light.
DATA ANALYSIS
DATA ANALYSIS

After exposing and processing the images were traced on the Joyce Loebl microdensitometer using slit widths less than 1/20 of the period and scan ratios such that one period was traced over 10 cm. For each process batch one sensitometric strip was traced using the same microdensitometer configuration. This was necessary to supply a reference so that interpolation would allow the determination of actual exposures and hence avoid the logarithmic nature of the density traced. A very large slit height was used to integrate out excessive noise (the height was approximately 10 times the width).

After plotting, the relative densities were read and recorded for computer analysis. Approximately 25 points were read per period to assure a smooth output curve and a good accuracy in the Fourier Analysis.

The relative density values were fed to the program included in the "Appendix" and executed on R.I.T.'s IBM 1800 system. The relative densities were read in for several periods (usually 3 or 4) and averaged. The relative density values from the H and D curves are read in along with the corresponding log exposure values giving rise to these densities. A
Lagrangean interpolation\textsuperscript{16} is performed on the sinusoidal input densities to determine the log exposure causing each density at the evaluated points. The relative log exposures are then converted to relative exposures, the modulation is determined, and the exposures are normalized to the maximum exposure in the group. A comparison array is generated for plotting and visual comparison and a Fourier Analysis\textsuperscript{19} is performed to determine the magnitude of the harmonics present.

Execution time for the average set of data is just over one minute.
ERROR ANALYSIS
ERROR ANALYSIS

During the preliminary work a systems error analysis was carried out. Three exposures were made on different dates using different emulsion batches, processed using the standard process but on different dates and traced on the microdensitometer on different dates. The modulation and harmonics were determined using the computer program included in the "Appendix".

With these three samples the standard deviation for the system was determined to be less than 1% for the harmonics and less than .50% for the modulation. Since the system was assumed to be under good control at this point further statistical analysis was not used.
CONCLUSIONS
CONCLUSIONS

As shown in Table 5 the modulation of the image can be maintained above 60% at 30 cycles/mm. The proposed standards for modulation transfer function testing of films require a modulation of 35%. It can thus be concluded that the generation of sinusoidal intensity distributions by incoherent spatial filtering using crenelate patterns for the systems object is indeed feasible for the range of frequencies tested (5 to 30 cycles/mm) on the system described in this thesis.
RECOMMENDATIONS
RECOMMENDATIONS

It is the opinion of this writer that this project should be carried on and that a device should be developed for the generation of sinusoidal intensity distributions by incoherent spatial filtering. This image generator should be compact and relatively simple to operate. The spectral distribution could be changed using various Wratten filters. Distributions of higher frequencies could be produced by reducing the filtered images by a zoom lens optical system.

Care should be taken at higher frequencies to assure a good depth of field so that slight shifts in the film position does not modify the generated image. The final image should have a modulation of $35\% \pm 5\%$ as suggested by the " Proposed National Standard Method for Determining the Photographic Modulation Transfer Function of Photographic Film" (PH 2-33/4).

The following questions or problems are thus proposed for future investigation:

1. Investigate, using higher grade optics, the possibility of generating the sinusoidal distributions at even higher frequencies without resorting to zoom lens systems.
2. Investigate methods for reducing the modulation of the image in the film plane so that the conditions proposed by the standard may be met. Whatever method is used the modulation should be continuously variable from zero to the maximum obtainable from the filtered image. A good source of information on this subject would be the Ealing Corporation as they make a variable modulation test target (Ealing DL Variable Modulation Test Target).

3. Determine a method of measuring (or predicting from calculations) the modulation in the image plane knowing the parameters of the system so that the input modulation may be known (or possibly pre-set) in testing photographic film.

4. Further develop the system such that it might fit in a housing similar to the Kodak 101 sensitometer and be operated just as easily.
FIGURE 2

SCHEMATIC DRAWING OF BASIC OPTICAL SYSTEM
FIGURE 3

Cut-off Frequency and MTF of a Diffraction Limited System.
Note: $f_0 = 3f_1$
INTERPOLATION AND PROXIES ANALYSIS PROGRAM -- JE GRAY

1000 FORMAT (1X, 8E14.6)
WRITE (3, 8001)

8001 FORMAT (///, 'AVERAGE INPUT DENSITIES', /)
WRITE (3, 1000) (XX(I), I = 1, L)

C C READING VALUES FROM THE H AND...
C X(LGRN) IS THE DENSITY
C Y(LGRN) IS THE LOG EXPOSURE

READ (1, 20) (X(I), I = 1, LGRN)
READ (1, 20) (Y(I), I = 1, LGRN)
WRITE (3, 8002)

8002 FORMAT (///, 'H AND I INPUT -- RELATIVE DENSITIES', /)
WRITE (3, 1000) (X(I), I = 1, LGRN)
WRITE (3, 8003)

8003 FORMAT (///, 'H AND J INPUT -- RELATIVE LOG EXPOSURE', /)
WRITE (3, 1000) (Y(I), I = 1, LGRN)

C C LANGUAGE INTERPOLATION STARTS HERE
C INTERPOLATED VALUES ARE STORED IN YY(LGRN)

CALL CLOCK (TIME)
TIME = NTIME/1000.
WRITE (3, 333) TIME

333 FORMAT (1X, 'TIME IS ', F7.3)
DO 120 II = 1, L
YY(II) = 0.
DO 120 I = 1, LGRN
CD = 1.
CJ = 1.
DO 110 J = 1, LGRN
IF (I-J) .GT. 105, 110, 105
105 CN = (XX(I) - X(J))*CN
CD = (XX(I) - X(J))*CD
110 CONTINUE
120 YY(II) = (CN/CD)*YY(I) & YY(II)
130 END DO
WRITE (3, 2222) P1, N2, N3
WRITE (3, 8004)

8004 FORMAT (///, 'INTERPOLATED RELATIVE LOG EXPOSURE VALUES', /)
CALL CLOCK (TIME)
TIME = NTIME/1000.
WRITE (3, 333) TIME
WRITE (3, 1000)(YY(I), I = 1, L)

C C CONVERT RELATIVE LOG EXPOSURE TO EXPOSURE
C
DO 140 I = 1, L
YY(I) = 10.*YY(I)
WRITE (3, 2005)
140 END DO

8005 FORMAT (///, 'INTERPOLATED RELATIVE EXPOSURE VALUES', /)
WRITE (3, 1000) (YY(I), I = 1, L)

C C SEARCH FOR MAX AND MIN
INTERPOLATION AND FOURIER ANALYSIS PROGRAM - 1.5 MAY

YMIN = YY(I)
YMAX = YY(I)
DO 240 I = 2, L

IF (YMIN - YY(I)) 220, 220, 210

210 YMIN = YY(I)

220 IF (YMAX - YY(I)) 230, 230, 240

230 YMAX = YY(I)

240 CONTINUE

C DETERMINE MODULATION (TRFNC)

TRFNC = (YMAX - YMIN) / (YMAX + YMIN)
WRITE (3, 222) N2, N3
WRITE (3, 1500) YMIN, YMAX, TRFNC

1500 FORMAT(1X, 'YMIN = ', E14.6, ' YMAX = ', E14.6, ' TRFNC = ', E14.6)

C NORMALIZE

YMAX = YMAX - YMIN
DO 280 I = 1, L

280 YY(I) = (YY(I) - YMIN) / YMAX

C GENERATE THE COMPARISON ARRAY

PI2 = 2*3.141593
DO 400 I = 1, L

400 A(I) = (COS((I-1)*PI2) + 1)/2
WRITE (3, 4006)

4006 FORMAT (1X, 'COS VALUES', 4X, 'EXPERIMENT', 2X, 'COS VALUES')
WRITE (3, 2000) (/I(I), YY(I), I = 1, L)

2000 FORMAT (1X, 10X, 1X, 20X, 1X, 4X, 1X, 1X, 20X, 1X)

CALL CLOCK (TIME)
TIME = TIME/1000.
WRITE (3, 333) TIME

C BEGIN FOURIER ANALYSIS

L2 = L/2 USING INTEGER DIVISION

NPER = ORDER OF HARMONICS TO BE OUTPUT

NPER MUST BE LESS THAN OR EQUAL TO L2

L2 = L/2
NPER = 3
CALL FORIT (A, L2, NPER, XX, X, IER)
CALL FORIT (YY, L2, NPER, Y, MAX, IER)
NPER = NPER * 1
CALL CLOCK (TIME)
TIME = TIME/1000.
WRITE (3, 333) TIME
WRITE (3, 2222) XX, Y2, -3
RITE (3, 2000)

3000 FORMAT (1X, 'FOURIER COEFFICIENTS')
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WRITE (3, 3010)
3010 FORMAT (4X, 'COS COEF...ACTUAL', 5X, 'EXPERIM TAL', 10X, 'STDEV')
WRITE (3, 3020) (XX(I), Y(I), X(I), E(I), I = 1, nFREQ)
3020 FORMAT (8X, 2E15.6, 15X, 2E15.6)
9000 CONTINUE
CALL EXIT
END
BIBLIOGRAPHY


VITA

Mr. Gray was born in Carlisle, Pennsylvania, on August 14, 1943, attended York, Pennsylvania secondary schools and York Catholic High School before commencing studies at Franklin and Marshall College, Lancaster, Pennsylvania. In October, 1963, he entered the United States Air Force and worked in Precision Photographic Processing, quality control and testing both in the United States and overseas. During the academic year 1967-68 the necessary courses were completed at the University of Maryland, enabling him to enter the Rochester Institute of Technology as a third year student. During the summer of 1969, he worked for Rank Taylor Hobson, Limited, Leicester, England as an optical design/development engineering assistant.

The writer will graduate from the Rochester Institute of Technology in June, 1970, with a Bachelor of Science degree in Photographic Science and Instrumentation. He has been elected a member of Phi Kappa Phi honor fraternity and will graduate with highest honors. In September, 1970 he will enter the University of Arizona and do graduate work at the Optical Sciences Center.