Prediction of cut-off frequency from the maximum slope of a transmittance scan of an ideal edge

Dale E. Ewbank
PREDICTION OF CUT-OFF FREQUENCY FROM THE MAXIMUM SLOPE OF A TRANSMITTANCE SCAN OF AN IDEAL EDGE

by

Dale E. Ewbank

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

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ABSTRACT

This study has empirically shown that the maximum slope of an ideal edge scan in transmittance versus position is an excellent indicator of the cut-off frequency at which a microdensitometer system's modulation transfer function goes to zero. It was found that numerical aperture of collection objective, scanning slit width and alignment, system focus, and sampling interval are parameters which must be carefully chosen and set-up when implementing or using this slope technique to check system performance.
ACKNOWLEDGEMENTS

The author wishes to thank James Jakubowski for his time, ideas, and encouragement in helping to complete this thesis.

A very special thank you is to go to Martha Leahy for her typing assistance and for her love and patience which may have past unnoticed during the last year. I hope that she will be more than repaid in the years to come; which we shall spend together.
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INTRODUCTION

Microdensitometers are used extensively to gain information about photographic systems. They are used to digitize images which are on film or glass, and to study such parameters as granularity and modulation transfer.

When using a microdensitometer, it is necessary to know its performance characteristics. One important characteristic is the system's modulation transfer function (MTF(f)) and its limiting frequency.¹ Edge gradient analysis may be done to determine a system's MTF(f) by either of two different methods. In the conventional method, the edge scan is differentiated to give the line spread function of the system. This line spread function is then Fourier Transformed; and the modulus of this transform is the MTF(f) of the system.¹,²,³,⁴ The second way of obtaining the transfer function of a system is Tatian's method. In Tatian's method the transfer function of the system is calculated by a trigonometric series whose coefficients are proportional to the sampled values of the edge response. The series is also modified by added terms to take into account the known asymptotic behavior of the edge response.⁵

For a diffraction limited optical system with a circular aperture, the frequency at which the transfer function goes to zero is predictable. This limiting frequency (f₀) is:
\[ f_o = \frac{2 \cdot NA}{\lambda}, \]

where NA is the numerical aperture of the collection system, and \( \lambda \) is the wavelength of radiation.\(^6\),\(^7\)

Many microdensitometers are designed to work at the diffraction limit of their microscope objective.\(^8\) Thus the frequency at which the transfer function of the system goes to zero is predictable from this objective's numerical aperture. The conventional method and Tatian's method of edge gradient analysis are two ways of checking the system's MTF(f), and also estimating the system's cut-off frequency. Both of these require computation which is usually done on a computer.

Swing suggests that the maximum slope of a scan of an ideal edge in transmittance versus position is equal to the cut-off frequency of the system.\(^9\) This would be a good check on the system and only requires minimal calculations.

For the diffraction limited case on a normalized frequency scale, the line spread function of the system \( l(x) \) can be modeled using one dimensional analysis as:

\[ l(x) = f_o \text{sinc}^2(f_0x). \]

The function has area of unity. The Fourier Transform of the line spread function \( L(f) \) is:

\[ L(f) = \text{tri}(\frac{f}{f_o}). \]
Thus the modulation transfer function of the system \( \text{MTF}(f) \) is (Figure 1):

\[
\text{MTF}(f) = \left| \text{tri} \left( \frac{f}{f_o} \right) \right|.
\]

The modulation transfer function goes to zero as its argument goes to one;

\[
\left| \text{MTF}(f) \right| = \left| \text{tri} \left( \frac{f}{f_o} \right) \right| = 0, \quad f = f_o
\]

Therefore, the limiting frequency is \( f_o \) for the line spread given.

The scan of an ideal edge with a finite slit on the above optical system \((e(x))\) can be mathematically represented as a convolution of the line spread \((f_o \text{sinc}^2(f_o x))\) with the edge \((\text{step}(x))\) and the slit \((-\frac{1}{a} \text{rect}(-\frac{x}{a}))\).

\[
e(x) = f_o \text{sinc}^2(f_o x) \ast \text{step}(x) \ast \frac{1}{a} \text{rect}(-\frac{x}{a}).
\]

If the slit is made very small so as to appear as a delta function to the system;

\[
\lim_{a \to 0} \frac{1}{a} \text{rect}(-\frac{x}{a}) = \delta(x).
\]

The edge response \((e_1(x))\) becomes:

\[
e_1(x) = f_o \text{sinc}^2(f_o x) \ast \text{step}(x) \ast \delta(x).
\]

Since \(f(x) \ast \delta(x) = f(x);\) the edge response \((e_1(x))\) is the convolution:
Figure 1. Comparison of modeled MTF(f) to the theoretical diffraction limited MTF(f). The cut-off frequency is $f_0$. 
\[ e_1(x) = f_o \text{sinc}^2(f_o x) \ast \text{step}(x) \]

The derivative of this convolution is equal to the slope of the edge scan. Knowing:

\[ \frac{d}{dx}(f(x) \ast g(x)) = f(x) \ast \frac{d(g(x))}{dx}; \]

the derivative of the edge response \((e_1'(x))\) can be written as:

\[ e_1'(x) = f_o \text{sinc}^2(f_o x) \ast \delta(x). \]

Thus the slope is equal to:

\[ e_1'(x) = f_o \text{sinc}^2(f_o x), \]

and the maximum slope is at \(x=0\).

\[ e_1'(0) = f_o \text{sinc}(f_o x) \bigg|_{x=0} = f_o \]

The maximum slope \((f_o)\) yields the same results as the limiting frequency \((f_o)\) for the line spread function.

Using the maximum slope to indicate the cut-off frequency for an optical system will be a quick and easy check on system performance. The transmittance values of a scan can easily be plotted and the maximum slope drawn. The slope then only needs to be normalized to reflect the value of the cut-off frequency, (Figure 2).

The objectives of this study were to empirically show
whether the maximum slope of an ideal edge scan is equal to the cut-off frequency of the system as predicted by the modulation transfer function and by the numerical aperture (for diffraction limited system), and show the limitations of implementing and using this technique to check system performance.

Figure 2. Example plot of transmittance versus position for an edge scan.

\[ \text{normalized slope} = \left( \frac{\Delta t}{\Delta x} \right) \left( \frac{1}{t_{\text{max}} - t_{\text{min}}} \right) \]
EXPERIMENTAL

The determination of the cut-off frequency using the numerical aperture of the system is straightforward. The limiting frequency, \( f_o \), is related to the numerical aperture (NA) and the wavelength \( (\lambda) \) of radiation:

\[
f_o = \frac{2(NA)}{\lambda}.
\]

Since the work was done with incoherent radiation, the radiation was broadband; and a median wavelength of .500 micrometers was used for the microdensitometer system.

Determining the cut-off frequency from the MTF(f) is more involved. The MTF(f) can be determined using an edge gradient analysis (conventional or Tatian's method). An ideal edge is scanned in transmittance versus position on the system, and the edge response function is transformed to give the system MTF(f). The cut-off frequency is where the MTF(f) goes to zero.

Tatian's method of edge gradient analysis was used to obtain the MTF(f)s of the edge scans because it proved easier to use and to be influenced less by system noise in the data. When using the conventional edge gradient analysis method, the effect of noise is to introduce a random error and a positive bias to the modulation transfer function.\(^{12}\)

The maximum slope of the edge scans was evaluated graphically by plotting the transmittance values versus relative position for the region of the scan near the edge.
The maximum slope can then be drawn for the edge response. The normalized slope is calculated from the slope \( \frac{\Delta t}{\Delta x} \) and the minimum and maximum transmittances \( t_{\text{min}} \) and \( t_{\text{max}} \).

\[
\text{maximum slope} = \frac{\Delta t}{\Delta x} \\
\text{normalized slope} = \left( \frac{\Delta t}{\Delta x} \right) \left( \frac{1}{t_{\text{max}} - t_{\text{min}}} \right)
\]

The MTF(f)s calculated by Tatian's method do not go identically to zero, because of noise in the discrete data. Therefore these MTF(f)s are visually matched to the theoretical MTF(f) for a diffraction limited system of known cut-off frequency \( f_o \), (Figure 1). \(^{10}\)

\[
\text{theoretical MTF(f)} = \frac{\pi}{2} \left( \cos^{-1}\left( \frac{f}{f_o} \right) - \frac{f}{f_o} \sqrt{1 - \left( \frac{f}{f_o} \right)^2} \right)
\]

The image scanning was done on a PDS microdensitometer using incoherent irradiation. \(^{13}\) The scans were run of an NBS edge \(^{14}\) to give transmittance versus position. The smallest sampling interval during scanning is 1 \( \mu \text{m} \) on the PDS. This sampling interval sets the maximum frequency for which the transform can be calculated. This is the folding frequency \( f_{\text{max}} \) for the interval \( \Delta x \):

\[
f_{\text{max}} = \frac{1}{2 \Delta x}
\]

Therefore the frequencies which could be evaluated were less than 500 cycles/mm.
\[ f_{\text{max}} = \frac{1}{2(0.001 \text{mm})} = 500 \text{ cycles/mm} \]

The efflux objective of the PDS needed to have a cut-off of less than 500 cycles/mm. Assuming a mean wavelength of .5 mm for the radiation. Numerical apertures of .10 and .08 were used, having theoretical cut-off frequencies shown.

\[ f_o = \frac{2(\text{NA})}{\lambda} \]
\[ f_o = \frac{2(.10)}{.5} = 400 \text{ cycles/mm} \]
\[ f_o = \frac{2(.08)}{.5} = 320 \text{ cycles/mm} \]

Scans were run of the NBS edge in transmittance versus position on the PDS microdensitometer. Multiple focus positions (at 10 um steps from best visual focus) were used to obtain a focus series for each of the microdensitometer set-ups in table 1.

<table>
<thead>
<tr>
<th>Set-up</th>
<th>A</th>
<th>B</th>
</tr>
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<tbody>
<tr>
<td>Efflux objective</td>
<td>.10 NA &quot;4X&quot; Zeiss</td>
<td>.08 NA &quot;2.5X&quot; Zeiss</td>
</tr>
<tr>
<td>Efflux ocular</td>
<td>10X Zeiss</td>
<td>6.3X special</td>
</tr>
<tr>
<td>detected area</td>
<td>.17um X .145 mm</td>
<td>.49um X .439mm</td>
</tr>
<tr>
<td>system magnification</td>
<td>45.1X</td>
<td>15.4X</td>
</tr>
<tr>
<td>image scanning</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>sampling interval</td>
<td>1 um</td>
<td>1 um</td>
</tr>
<tr>
<td>focus series</td>
<td>yes</td>
<td>yes</td>
</tr>
</tbody>
</table>

Table 1: PDS microdensitometer set-ups used in data collection.
Data from the PDS microdensitometer scans is stored on magnetic tape. The records on the magnetic tape are read and converted using the programs in Appendix A. The final output of these programs is a plot of transmittance versus position for the region of the scan around the edge. (Figure 3)

The plot is then hand smoothed to eliminate the noise in the tails. Then the discrete data points are transformed using a program (EGA, Appendix B) on the Apple II computer. The program uses Tatian's method to calculate the transfer function of the system. The cut-off frequency was then determined by matching the $MTF(f)$ with theoretical $MTF(f)$s of known cut-off frequencies.

The maximum slope is drawn on the plot at the center of the edge scan. (Figure 4) This maximum slope is then normalized by the range of transmittance ($t_{\text{max}} - t_{\text{min}}$) to give the normalized slope which relates to the cut-off frequency.
Figure 4. Edge response for scan with .10 NA objective.
RESULTS

The plot in Figure 4 shows the transmittance values from one of the scans from a focus series done with a .10 NA. The maximum slope is .047; when this is normalized by $1/(t_{\text{max}} - t_{\text{min}})$ the value is .181. The normalized slope is .181 $\text{um}^{-1}$; this is 181 cycles/mm in frequency. The transform of the discrete data from Figure 4 is shown in Figure 5. This transfer function has the same form as the theoretical $\text{MTF}(f)$ with a cut-off frequency of 181 cycles/mm (Figure 5) down to approximately 30%.

The plot in Figure 6 shows the transmittance values from one of the scans from a focus series done with a .08 NA. The maximum slope is .024; when this is normalized by $1/(t_{\text{max}} - t_{\text{min}})$ the value is .071. The normalized slope is .071 $\text{um}^{-1}$; this is 71 cycles/mm frequency. The transform of the discrete data from Figure 6 is shown in Figure 7. This transfer function has the same form as the theoretical $\text{MTF}(f)$ with a cut-off frequency of 71 cycles/mm (Figure 7) down to approximately 20%.

In both of these cases it is seen that the normalized slope is a very good indicator of the cut-off frequency at which the $\text{MTF}(f)$ of the microdensitometer system does go to zero. It is also apparent that both the slope method and Tatian's method are not good indicators of the cut-off frequency as calculated from the numerical aperture. Possible reasons why the microdensitometer system is not diffraction
Figure 5. Comparison of MTF(f) for edge scan with .10 NA to theoretical MTF(f) with a cut-off of 181 cycles/mm.
Figure 6. Edge response for scan with .08 NA objective.
Figure 7. Comparison of MTF(f) for edge scan with .08 NA to theoretical MTF(f) with a cut-off of 71 cycles/mm.
limited are:

1) The objective is not used at the proper tube length and magnification.

2) The microdensitometer is not focused on the object.

3) The scanning slit is not aligned with the edge.

These reasons for which the microdensitometer would not be a diffraction limited system were investigated using the .08 numerical aperture objective. The objective tube length and tube length at which it was used were checked. They were close enough to only give a 2.3% change in magnification in conjunction with a 6.3X ocular. This would only have a very slight effect on the MTF(f) of the system.

Microdensitometer scans were done with a through focus series at 10 um increments. The change in edge profiles was only slight as compared with the predicted rise or drop in MTF(f) do to defocus for an optical path difference of \( \frac{\lambda}{2} \) or more.\textsuperscript{13,14}

The transfer function of a misaligned slit (\( T_{\text{skew}}(f) \)) is:

\[
T_{\text{skew}}(f) = \frac{\sin(\pi L \theta f)}{\pi L \theta f},
\]

where \( L \) is the slit length and \( \theta \) is the angle of misalignment.\textsuperscript{15}

In order for the transfer function, \( T_{\text{skew}}(f) \), to not
limit the system cut-off ; the angle of misalignment ($\theta$) must be less than:

$$\theta \leq \frac{1}{f_o L},$$

where $f_o$ is the maximum frequency to be transferred and $L$ is slit length.

When using a .08 NA with a detected area of .49 um X .439 mm; the misalignment must be less than .0071 radians or .41 degrees. The slit length can be shortened to increase the angle tolerance, but then the signal to noise for the system goes down. Even with a 100 um slit length, the slit must be aligned to within 1.8 degrees. This is a difficult task, and the slit alignment (misalignment) is believed to be the reason for which the microdensitometer system is not diffraction limited.
CONCLUSIONS

The maximum slope of a normalized scan of an ideal edge is an excellent indicator of the cut-off frequency at which the system's $MTF(f)$ goes to zero. When some factor (i.e. defocus, slit misalignment) causes the $MTF(f)$ to cut-off lower than the diffraction limit of the system, the maximum slope of an ideal edge scan predicts the $MTF(f)$ of the system to 30 percent modulation or less.

The difficulties of verifying the slope technique for the diffraction limited case are:

1) using a low numerical aperture objective
2) setting up the objective at the proper tube length and magnification
3) setting microdensitometer focus
4) aligning detector slit with ideal edge (skew)
5) using a slit width small enough to give good modulation out to cut-off of the objective
6) using sampling interval small enough to allow calculation of the cut-off frequency.

The slope technique proved to be an excellent check on microdensitometer performance. Knowing the slope technique works even when the microdensitometer system is not diffraction limited, it is reasonable to assume that this method
does provide a quick check of system performance for high
numerical aperture objectives.

For the future, it would be of value to continue the
empirical investigation to determine the conditions under
which low numerical aperture objectives can be made to work
at their diffraction limit. Also a study using high numerical
aperture objectives could lead to a better understanding of
system capabilities and could indicate the limiting compo-
nents of the system.
REFERENCES


8. Ibid., p. 331.

9. R.E.Swing, per personal conversation with J. Jakubowski, information to be published at a later date by Swing.


APPENDIX A

C***************************************************************************
C
3.000 C* DAL IS A FORTRAN PROGRAM WHICH READS THE INFORMATION
C
4.000 C* FROM A DEBLOCKED FILE OF PDS DATA. THE FILE SHOULD
C
5.000 C* BE IN TWO BYTE RECORDS. THE OUTPUT OF THIS PROGRAM IS A
C
6.000 C* FILE WHICH CAN BE READ BY FORTAL AND BE PLOTTED ON THE
C
7.000 C* ZETA FLOTTOR. TO RUN THIS PROGRAM USE THE FOLLOWING
C
8.000 C* COMMANDS:
C
9.000 C*
10.000 C* !FORT DAL OVER $
11.000 C* EXT. FORTRAN IV, VERSION F02
12.000 C* OPTIONS >NS
13.000 C*
14.000 C* !SET F:100/SOURCEFILE;IN
15.000 C* !SET F:106/OUTPUTFILE;OUT
16.000 C*
17.000 C* !RUN $
18.000 C*
19.000 C*
20.000 C***************************************************************************

21.000 C

22.000 C

23.000 C**************** CHANGES IN LINES 37 AND 38 ****************
24.000 C*

25.000 C* N = ( THE NUMBER OF DATA PIONTS IN EACH SCAN )
26.000 C* ZZ = ( THE NUMBER OF SCANS IN THE FILE )

27.000 C*

28.000 C***************************************************************************

29.000 C

30.000 C

31.000 C

32.000 C IMPLICIT INTEGER(A-Z)
33.000 DIMENSION BUF(2144), TBL(256), OUT(83), Y(1024)
34.000 REAL Y, T1, T2
35.000 C

36.000 C

37.000 N = 128
38.000 ZZ = 19
39.000 N2P96 = N*2 +96
40.000 C

41.000 C

42.000 DATA TBL(32)/' /
43.000 DATA TBL(160)/' /
44.000 DATA TBL(171)/' +'/
45.000 DATA TBL(173)/' -'/
46.000 DATA TBL(174)/' '/
47.000 DATA TBL(175)/' '/
48.000 DATA (TBL(I), I=176,185)/' 0', '1', '2', '3', '4', '5', '6', '7', '8', '9'/
49.000 *' 1', '2', '3', '4', '5', '6', '7', '8', '9'/
50.000 DATA TBL(192)/' @'/

*

WRITE(108,1) 1 FORMAT(IX,'  DAL IS RUNNING****')

DO 999 Z=1,ZZ

READ(100,2 END=50, ERR=60) (BUF(I), X=1,N2P96)

2 FORMAT(2A1)

DO 10 I=1,N2P96

BUF(I)=ISL(BUF(I), -24)

10 CONTINUE

IF (.NOT.((BUF(I) .EQ. 63) .AND. (BUF(2) .EQ. 63))) GOTO 70

DO 20 I=3,81,2

C= BUF(I)*64+BUF(I+1)

20 OUT(I) = TBL(C)

DO 30 I=1,N

Y(I)=(FLOAT(BUF(I*2+95)*64+BUF(I*2+96)))/4000.0

30 CONTINUE

DO 40 I=1,N-1

T1 = ABS( Y(I+1) - Y(I) )

IF (T1 .LT. T2) GOTO 40

T2 = T1

INDEX = I

40 CONTINUE

INDEX = INDEX - 15

INDEXP = INDEX +30

WRITE (108,3) ((OUT(X), X=3,81,2), INDEX, T2 )

WRITE (106,3) ((OUT(X), X=3,81,2), INDEX, T2 )

3 FORMAT (IX,40R1,IS,F10.4)
101.000 C
102.000 WRITE (106,4) (Y(I), I=INDEX,INDEXP)
103.000 4 FORMAT (16F8.4)
104.000 C
105.000 C
106.000 999 CONTINUE
107.000 50 STOP
108.000 C
109.000 C
110.000 60 WRITE (108,61)
111.000 61 FORMAT(' ERROR IN READ')
112.000 STOP
113.000 C
114.000 C
115.000 70 WRITE (108,71)
116.000 71 FORMAT(' BAD RECORD')
117.000 GOTO 999
118.000 C
119.000 C
120.000 END

*
PLOTDAL IS A FORTRAN PROGRAM TO PLOT THE DATA SET IN A
FILE BY DAL. THIS PROGRAM MUST BE COMPILE AND THEN RUN
ON BATCH WITH A CARD DECK. TO COMPILE THIS PROGRAM USE
THESE COMMANDS:

!FORT PLOTDAL OVER DFLOT
EXT. FORTRAN IV, VERSION F02
OPTIONS >NS

WHEN THE SYSTEM COMES BACK WITH A ! THE PROGRAM IS
COMPiled IN DFLOT. IT CAN BE RUN ON BATCH WITH A DECK OF
CARDS WHICH HAVE THE FOLLOWING COMMANDS:

!JOB ACCOUNTNUMBER(NAME),7.NAME
!LIMIT (TIME,1),(CORE,24),(LO,50)
!ASSIGN F:100,(FILE,SOURCEFILE),(IN),(SAVE)
!LYNX DFLOT;.ROMLIB1
!RUN
!EOD

INTEgER FILE(10), NX(2), NY(2)
REAL  X(33), Y(33), DX(1), DY(1)
N= 31
ZZ = 19

DX(1) = 1.0/3.0
NX(1) = 30
NX(2) = 0
DY(1) = .2
NY(1) = 40
NY(2) = 0
51.000 C
52.000 C
53.000 DO 99 M=1,ZZ
54.000 C
55.000 C
56.000 READ (100,5) FILE
57.000 5 FORMAT (10A4)
58.000 C
59.000 C
60.000 READ (100,10) (Y(I),I=1,N)
61.000 10 FORMAT (16F8.4)
62.000 C
63.000 C
64.000 DO 20 I=1,N
65.000 X(I)= FLOAT(I)-1.0
66.000 20 CONTINUE
67.000 C
68.000 C
69.000 C
70.000 X(N+1)= 0.0
71.000 X(N+2)= 3.0
72.000 Y(N+1)= 0.0
73.000 Y(N+2)= .05
74.000 C
75.000 C
76.000 C
77.000 CALL BEGPT (3,11)
78.000 C
79.000 CALL AXIS(.5,.5,'X DISTANCE',-10,10,5,0,0,X(N+1),X(N+2),0)
80.000 CALL AXIS(.5,.5,FILE,40,8.5,90.0,Y(N+1),Y(N+2),3)
81.000 C
82.000 CALL GRID(.5,.5,DX,NX,DY,NY)
83.000 C
84.000 CALL PLOT(.5,.5,-3)
85.000 C
86.000 CALL LINE(X,Y,N,1,0,2)
87.000 C
88.000 CALL FINPT
89.000 C
90.000 C
91.000 99 CONTINUE
92.000 C
93.000 C
94.000 STOP
95.000 END

*
1 DIM E(100),MG(75),PH(75),FR(75),L(100)
2 REM THIS PG Will COMPUTE MTF VALUES FROM THE EDGE GRADIENT DATA
3 HOMe : VTab 2: PRINT "DETERMINATION OF MTF FROM" : PRINT "THE EDGE TRACE ANALYSIS"
4 FOR I = 1 TO 500: NEXT : PRINT : PRINT "DATA INPUT"; PRINT
5 PRINT "TYPE K FOR INPUT FROM THE KEYBOARD": PRINT "TYPE D FOR INPUT FROM THE DISC": PRINT "INPUT V$"
6 IF V$ = "K" THEN 20
7 HOMe : VTab 2: PRINT "DATA FILE NAME": PRINT "NM$"
8 A$ = CHR$(4): PRINT A$;"OPEN"NM$: PRINT A$;"READ"NM$
9 INPUT IP
10 FOR I = 1 TO IP
11 INPUT E(I)
12 NEXT
13 PRINT A$;"CLOSE"NM$
14 GOTO 71
15 HOME : VTab 2: PRINT "ENTER YOUR EDGE DATA STARTING WITH": PRINT "THE SMALLEST VALUE AND ENDING WITH": PRINT "THE LARGEST"
16 REMEMBER YOU MUST HAVE": PRINT "AN ODD NUMBER OF POINTS!"
17 HOME : VTab 2: PRINT "NUMBER OF DATA POINTS?": IP
18 HOME : PRINT "ENTER YOUR DATA."
19 FOR I = 1 TO IP
20 VTab 4: PRINT SPC(35): VTab 4: HTAB 1: PRINT "ENTER POINT (";I;")": PRINT E(I)
21 NEXT
22 INPUT "WISH TO STORE THE DATA": V$
23 IF V$ = "N" THEN 71
24 HOME : VTab 2: PRINT "DATA FILE NAME": NM$
25 A$ = CHR$(4): PRINT A$;"OPEN"NM$: PRINT A$;"WRITE"NM$
26 PRINT IP
27 FOR I = 1 TO IP: PRINT E(I): NEXT
28 PRINT A$;"CLOSE"NM$
29 MIN = E(I)
30 DI = E(IP) - E(1)
31 FOR I = 1 TO IP
32 E(I) = (E(I) - MIN) / DI
33 NEXT
34 HOME : VTab 2: HTAB 3: PRINT "INPUT THE DISTANCE BETWEEN": INPUT " POINTS IN M.M.";EP
35 HOME : VTab 2: HTAB 3: PRINT "ENTER": VTab 4: INPUT "FREQUENCY START ";FS: VTab 5: INPUT "FREQUENCY END ";FE: VTab 8: INPUT "FREQUENCY INCREMENT ";FD: HOME : VTab 1: PRINT "FREQUENCY ": PRINT "MODULUS ": PRINT "PHASE"
36 N = INT (IP / 2);F1 = 3.1415927;N1 = N + 1
37 C = 0
38 FOR F = FS TO FE STEP FD
39 IF F # 1 / (2 * EF) THEN 503
40 C = C + 1:FR(C) = F
41 T1 = 0:T2 = E(N1):ARG = 2 * PI * EP * F
42 FOR I = 1 TO N
43 T1 = T1 + (E(N1) + I) - E(N1 - I)) * SIN (F * ARG):T2 = T2 + (E(N1 + I) + E(N1 - I)) * COS (ARG * I): NEXT
44 T1 = T1 * ARG:T2 = T2 * ARG;A2 = ARG / 2;S0 = SIN (A2) / A2
45 T1 = T1 + COS ((N + .5) * ARG) / S0
46 T2 = T2 - SIN ((N + .5) * ARG) / S0
47 MAG = SQR (T1 * T1 + T2 * T2):MG(C) = INT (MAG * 1000) / 1000
48 1000 GOSUB 400
210 PHI = 360 * PHI / (2 * PI)  
215 PH(C) = INT (PHI * 100) / 100  
217 PRINT F, MG(C), PH(C)  
220 NEXT F  
230 GOTO 503  
400 IF T1 = 0 THEN 404  
401 IF T1 ≠ 0 THEN PHI = ATN (T2 / T1); RETURN  
402 IF T2 ≠ 0 THEN PHI = ATN (T2 / T1) + PI; RETURN  
403 PHI = ATN (T2 / T1) - PI; RETURN  
404 IF T2 ≠ 0 THEN PHI = PI / 2; RETURN  
405 IF T2 = 0 THEN PHI = - PI / 2; RETURN  
406 PHI = 0; RETURN  
500 VTAB 20  
503 PRINT "PLEASE ANSWER Y FOR YES---N FOR NO"; FOR V = 1 TO 2000; NEXT  
504 INPUT "DO YOU WANT TO RETURN TO THE CURRENT PROBLEM?"; Q$  
505 IF Q$ = "Y" THEN 90  
550 HOME: VTAB 10; HTAB 2; PRINT "TYPE .P. FOR PLOT ROUTINE"; PRINT  
575 HTAB 7: PRINT ".E. TO END:"; INPUT V$  
600 IF V$ = "E" THEN 4100  
625 HOME: VTAB 2; PRINT "DO YOU WANT TO PLOT THE EDGE TRACE?"; INPUT V$  
650 IF V$ = "N" THEN 785  
670 XI = INT (2700 / IP) / 10  
675 X = 0; Y = 0  
700 HGR: HCOLOR= 7  
725 FOR I = 1 TO IP: Y = 159 - (159 * E(I)); HPLT X,Y  
730 X = X + XI; NEXT: X = 0; Y = 0  
775 GOSUB 2500  
780 VTAB 22; PRINT "DO YOU WANT A PRINT-OUT"; INPUT V$  
782 IF V$ = "Y" THEN 785  
784 AS$ = CHR$(4); PRINT AS$; "SAVE EDGE, A8192, L8192"  
785 TEXT: HOME: VTAB 2; PRINT "DO YOU WANT TO PLOT THE"; PRINT "SPREAD FUNCTION"; INPUT V$  
788 IF V$ = "N" THEN 1480  
790 FOR I = 1 TO (IP - 1)  
791 L(I) = (E(I + 1) - E(I)) / EP  
793 IF L(I), HI THEN 795  
794 HI = L(I)  
795 NEXT  
796 XI = INT (1590 / HI) / 10  
797 HGR: HCOLOR=7; FOR I = 1 TO IP  
798 Y = 159 - (YI * L(I)); HPLT X,Y  
800 X = X + XI; NEXT: X = 0; Y = 0  
805 GOSUB 2500
810 VTAB 22: PRINT "DO YOU WANT A PRINT-OUT";: INPUT V$
815 IF V$ = "N" THEN 1480
820 A$ = CHR$(4): PRINT A$;"BSAVE SPREAD, A8192,L8192"
1480 TEXT : HOME : VTAB 2: PRINT "DO YOU WANT TO PLOT THE"; PRINT "TRANSFER FUNCTION";: INPUT V$
1490 IF V$ = "N" THEN 2500
1495 HGR : HCOLOR = 7
1496 LET XI = INT (2700 / C) / 10
1500 FOR I = 1 TO C
1505 REM TR TO 1750
1700 Y = 159 - (159 * MG(I))
1750 X = X + XI
1800 HPLT X,Y
1825 NEXT
1850 GOSUB 2500
1900 VTAB 22: PRINT "DO YOU WANT A PRINT-OUT";: INPUT V$
2000 IF V$ = "N" THEN 2210
2200 A$ = CHR$(4): PRINT A$;"BSAVE TRANSFER, A8192,L8192"
2210 PR# 1
2215 PRINT "FREQUENCY","MODULUS","PHASE"
2220 FOR I = 1 TO C
2230 PRINT FR(I),MG(I),PH(I)
2240 NEXT
2250 PR# 0
2400 GOTO 3200
2500 P = 1:Q = 9
2600 FOR I = 1 TO 27
2700 HPLT P,159 TO Q,159: P = P + 10: Q = Q + 10
2800 NEXT
2900 U = 1:V = 15: FOR I = 1 TO 10
3000 HPLT 0,U TO 0,V
3100 U = U + 16: V = V + 16
3150 NEXT : RETURN
3200 TEXT : HOME : VTAB 12: PRINT "TO PLOT FOLLOW THE INSTRUCTIONS"; FOR V = 1 TO 2000: NEXT : PRINT : PRINT
3400 HTAB 4: PRINT "1) REPLACE THE DISK WITH THE": HTAB 7: PRINT ".HI-RES PLOT. DISK": PRINT
3500 HTAB 4: PRINT "2) TYPE .RUN HI-RES PLOTTER."": PRINT
3600 HTAB 4: PRINT "3) HIT RETURN KEY TILL YOU SEE": HTAB 7: PRINT ",PICTURE TO BE LOADED."
3700 PRINT : HTAB 4: PRINT "4) NOW INSERT THE ORIGINAL DISK BACK": PRINT
3800 HTAB 4: PRINT "5) TYPE THE TITLE OF YOUR PLOT": HTAB 7: PRINT "EDGE/SPREAD/TRANSFER": PRINT
3900 HTAB 4: PRINT "6) HIT RETURN TILL YOU SEE THE PLOT": HTAB 7: PRINT "ON THE SCREEN": PRINT
4000 PRINT : PRINT : PRINT "NOW YOU ARE ON YOUR OWN!": PRINT
4100 HTAB 13: PRINT "BYE! SEE YOU LATER!!!": END
CALL - 936
PRINT "THE HI-RESOLUTION PLOTTING ROUTINES"
PRINT "ON THIS DISK REQUIRE THAT ANY PICTURES"
PRINT "TO BE PLOTTED FIRST BE SAVED AS BINARY"
PRINT "FILES. A PICTURE IS SAVED TO DISK FROM"
PRINT "PAGE1 BY BSAVE, PIC#, A8192, LB192 OR FROM"
PRINT "PAGE2 BY BSAVE, PIC#, A16284, LB192"
PRINT "WHERE PIC# IS YOUR PICTURE FILE NAME."
PRINT "AFTER SELECTION OF PICTURE AND OPTIONS"
PRINT "THE PROGRAM LOADS THE PICTURE FILE INTO"
PRINT "HI-RES GRAPHICS PAGE ONE (8192-16383)"
PRINT "IT IS EXPECTED THAT THE PRINTER WILL BE""ATTACHED TO A SERIAL INTERFACE CARD IN ""SLOT 01, WITH THE DIP SWITCHES SET TO""PRINT " 1 2 3 4 5 6 7"
PRINT " 0 0"
PRINT " N N N O 0 0 0"
PRINT " F F F F F"
PRINT " F F F F F"
PRINT "FOR 300 BAUD, TO SET OUTPUT AT 1200 BAUD"
PRINT "CHANGE LINE 3500 TO POK 1145, 16"
VTAB 24; INPUT "HIT RETURN TO CONTINUE "; Q$
CALL - 936
PRINT "THERE ARE ALREADY TWO PICTURES ON THIS"
PRINT "DISK FROM THE APPLE BANK PROGRAMS THAT"
PRINT "CAN BE USED FOR EXPERIMENTATION."
PRINT "THE LONGER FORM OF PROMPTING AVAILABLE"
PRINT "IN THE PROGRAM WILL PROVIDE ADDITIONAL"
PRINT "ASSISTANCE IF MORE INFORMATION ON THE"
PRINT "OPTIONS IS REQUIRED."
D$ = "": PRINT : PRINT
PRINT "TO END PRESS , Q , RETURN": PRINT
INPUT "TO PLOT A PICTURE PRESS ,RETURN": PQ$: IF PQ$ = "" THEN PRINT D$"RUN PLOT"
END
10000 REM PURCHASING THIS DISK
10001 REM CONVEYS A LICENSE TO
10002 REM USE THE PLOT ROUTINES
10003 REM HEREIN WITH A SINGLE
10004 REM APPLE SYSTEM ONLY
10005 REM ANY UNAUTHORIZED
10006 REM TRANSFER OR COPYING
10007 REM IS EXPRESSLY FORBIDDEN
10008 REM ALL RIGHTS RESERVED
10009 REM APR 1980
10010 REM PLOTWARE
10011 REM PO BOX 9514
10012 REM ROCHESTER NY 14604
100  GOTO 1250
150  FOR TH = 0 TO 2: FOR OC = 0 TO 7: FOR LI = 0 TO 7: A = ST + LI * 1024 + OC * 128 + TH * 40
250  IF NOT PEEK (30) THEN 700
300  LS = PEEK (24):SS = PEEK (25): IF LS = 0 THEN 500
350  POKE 9,L; CALL 843
400  PRINT "A:LS = LS - 1: IF LS & 0 THEN 400
450  POKE 9,H; CALL 843
500  IF SS = S THEN 600
550  PRINT "A:SS = SS - 1: GOTO 500
600  PRINT H$: CALL 821
650  GOTO 250
700  PRINT : NEXT LI; NEXT OC; NEXT TH
1000 PR# 0: POKE -16301,0: VBAB 24;G$ = "":;H$ = ""
1050 PRINT "DO YOU WISH TO PRINT ANOTHER": PRINT
1100 INPUT "PICTURE AT THIS TIME? ":;MP$
1150 IF MP$ = "" AND MP$, "" THEN 1350
1200 TEXT : CALL - 936: END
1250 REM INITIAL ENTRY
1300 D$ = "": PRINT D$;"LOAD PLOT.CODE":;LF = 1
1350 TEXT : CALL - 936: VBAB 4; IF NOT LF THEN 1850
1400 PRINT "THERE ARE SEVERAL OPTIONS THAT MAY": PRINT "BE SELECTED FOR THE GRAPHICS PLOT": PRINT
1450 PRINT "YOU WILL BE GIVEN QUESTIONS TO ANSWER": PRINT "BUT THE SECOND CHOICE FOR EACH QUESTION"
1500 PRINT "IS CALLED THE DEFAULT MODE AND MAY BE": PRINT "SELECTED BY PRESSING ONLY THE RETURN"
1550 PRINT "KEY IN RESPONSE TO EACH QUESTION": PRINT "LONG FORM PROMPTING QUESTIONS OFFER"
1600 PRINT "SOME ASSISTANCE IN UNDERSTANDING THE": PRINT "PLOTING OPTIONS": PRINT
1650 PRINT "LONG OR SHORT FORM PROMPTING (L OR S) ";PQ$
1700 LF = 0: IF PQ$ = "$L THEN LF = 1
1750 IF NOT LF THEN 1850
1800 PRINT D$;"CATALOG": PRINT
1850 IF "PICTURE TO BE LOADED ";G$1900 IF NOT LF THEN 2150
1950 CALL - 936: VBAB 4; PRINT "PICTURES MAY BE PLOTTED IN": PRINT "YOUR CHOICE OF TWO SIZES": PRINT
2000 PRINT "SMALL SCALE PICTURES ARE APPROXIMATELY": PRINT ",4 INCHES BY 5 INCHES IN SIZE AND ": PRINT "ARE PLOTTED USING THE
2050 PRINT "LARGE PICTURES ARE 7 BY 10 AND ANOTHER": PRINT "OPTION ALLOWS SELECTION OF THE"
2100 PRINT "CHARACTER TO BE USED FOR PLOTTING": PRINT "THE ASTERISK ( ) IS THE DEFAULT MODE": PRINT
2150 INPUT "PICTURE TO BE LARGE OR SMALL (L OR S) ";S$
2200 H$ = "": IF S$ = "L" THEN 2350
2250 INPUT "CHARACTER TO BE USED FOR PLOTTING ";H$
2300 IF H$ = "" THEN H$ = ""
2350 IF NOT LF THEN 2650
2400 CALL - 936: VTAB 3
2450 PRINT "THERE ARE TWO PLOTTING MODES": PRINT "POINT FOR POINT AND REVERSED": PRINT
2500 PRINT "REVERSED MODE IS TO BE SELECTED": PRINT "WHEN A BRIGHT SPOT ON THE VIDEO SCREEN"
2550 PRINT "REPRESENTS A CLEAR AREA ON THE PAPER": PRINT "POINT-FOR-POINT IS SUITED FOR"
2600 PRINT "LINE GRAPHICS AND IS THE DEFAULT MODE": PRINT
2650 INPUT "REVERSED OR POINT-FOR-POINT (R OR P) "; TS$
2700 CALL - 936: VTAB 4: HMI = 2: VMI = 1: IF $S$, "$L" THEN 2800
2750 S$ = "$L": HMI = 5: VMI = 2
2800 IF TS$, "$R" THEN 2900
2850 TS$ = "$R": POKE 785, 56: POKE 788, 144: GOTO 2900
2900 POKE 785, 24: POKE 788, 176
2950 IF $S$, "$L" THEN PRINT "SCALE: SMALL"
3000 IF $S$, "$L" THEN PRINT "SCALE: LARGE"
3050 PRINT: IF TS$, "$R" THEN PRINT "PLOTTING IS POINT-FOR-POINT"
3100 IF TS$, "$R" THEN PRINT "PLOTTING IS REVERSED"
3150 PRINT: PRINT "CHARACTER USED FOR PLOTTING IS ( "; $H$; " )"
3200 PRINT: PRINT "PLOT TO BE LOADED IS "; $G$: VTAB 22
3250 INPUT "ARE ALL OPTIONS CORRECT? "; OK$: IF OK$, "$N" OR OK$ = "$N" THEN 1000
3300 GR: POKE -16297, 0: POKE -16302, 0
3350 PRINT D$: "BLOAD"; $G$; "A$2000"
3400 PR$: 1: PRINT "$";
3450 POKE 1785, 0: REM NO EXTRA CR.S
3500 REM POKE E1145, 16 FOR 1200
3550 PRINT: PRINT : SS = 0: LS = 0: ST = 8192
3600 H = HMI + 1: L = HMI * 16 + 1
3650 POKE 8, 30: POKE 9, (VMI + 1): CALL 843
3700 POKE 8, 31: POKE 9, H: CALL 843
3750 GOTO 150
10000 REM PURCHASING THIS DISK
10001 REM CONVEYS A LICENSE TO
10002 REM USE THE PLOT ROUTINES
10003 REM HEREIN WITH A SINGLE
10004 REM APPLE SYSTEM ONLY
10005 REM ANY UNAUTHORIZED
10006 REM TRANSFER OR COPYING
10007 REM IS EXPRESSLY FORBIDDEN
10008 REM ALL RIGHTS RESERVED
10009 REM MAR 1980
10010 REM DAVID C WESTHOP
10015 REM 45 ROUND TRAIL DR
10020 REM PITTSFORD NY 14534
VITA

Dale E. Ewbank is currently an undergraduate student in Photographic Science and Instrumentation at the Rochester Institute of Technology and is anticipating his B.S. degree in May, 1982. He was raised in Orlando, Florida and attended Colonial High School. He received a Fuji Award Scholarship while at R.I.T. After graduation and his wedding with Martha Leahy in July, 1982, he will be employed by American Microsystems Inc., in Santa Clara, California.