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AFAMRL-TR-85-029



**PRODUCING DESIRED COLOR STIMULI WITH
TRICHROMATORS: A TUTORIAL ON TECHNIQUE**

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*VISUAL DISPLAY SYSTEMS BRANCH
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FEBRUARY 1985

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FOR THE COMMANDER



CHARLES BATES, JR.
Director, Human Engineering Division
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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified		1b. RESTRICTIVE MARKINGS	
2a. SECURITY CLASSIFICATION AUTHORITY		3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for Public Release; distribution is unlimited.	
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE			
4. PERFORMING ORGANIZATION REPORT NUMBER(S) AFAMRL-TR-85-029		5. MONITORING ORGANIZATION REPORT NUMBER(S)	
6a. NAME OF PERFORMING ORGANIZATION Air Force Aerospace Medical Research Laboratory		6b. OFFICE SYMBOL (If applicable) AFAMRL/HEA	
7a. NAME OF MONITORING ORGANIZATION		7b. ADDRESS (City, State and ZIP Code)	
8a. NAME OF FUNDING/SPONSORING ORGANIZATION		8b. OFFICE SYMBOL (If applicable)	
9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER		10. SOURCE OF FUNDING NOS.	
8c. ADDRESS (City, State and ZIP Code) Wright-Patterson AFB OH 45433-6573		PROGRAM ELEMENT NO. 62202F	
		PROJECT NO. 7184	
		TASK NO. 11	
		WORK UNIT NO. 49	
11. TITLE (Include Security Classification) PRODUCING DESIRED COLOR STIMULI WITH TRICHROMATORS: A TUTORIAL ON TECHNIQUE (U)			
12. PERSONAL AUTHOR(S) GREENE, FRANCES A.			
13a. TYPE OF REPORT		13b. TIME COVERED FROM _____ TO _____	
14. DATE OF REPORT (Yr., Mo., Day) February 1985		15. PAGE COUNT	
16. SUPPLEMENTARY NOTATION			
17. COSATI CODES		18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)	
FIELD	GROUP	SUB. GR.	
19. ABSTRACT (Continue on reverse if necessary and identify by block number) A summary of the theory of color mixing when using a trichromator system is presented. The derivation of needed formulae to compute any desired chromaticity coordinates and corresponding luminance requirements is given. A numerical example is provided which demonstrates the application of the formulae.			
20. DISTRIBUTION/AVAILABILITY OF ABSTRACT UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS ☐		21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED	
22a. NAME OF RESPONSIBLE INDIVIDUAL Frances A. Greene		22b. TELEPHONE NUMBER (Include Area Code) (513) 255-8896	
		22c. OFFICE SYMBOL AFAMRL/HEA	

PREFACE

The theory of color mixing described herein was developed and used during a cooperative research program between the Air Force Aerospace Medical Research Laboratory, Human Engineering Division, Visual Display Systems Branch and the Human Factors Group, Royal Aircraft Establishment, Farnborough, England.

The author is a member of the Visual Display Systems Branch and was assigned to the Royal Aircraft Establishment under NATO Working Party 61 of the Aircrew Standardization and Coordinating Committee (ASCC) from December 1982 - July 1984. The research effort was funded by the European Office of Aerospace Research and Development under AFOSR Grant 83-0085. The author's participation was under work unit 71841144.

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PRODUCING DESIRED COLOR STIMULI WITH TRICHROMATORS: A TUTORIAL ON TECHNIQUE

1. SUMMARY

This report summarizes the theory of color mixing when using a trichromator system. The four-channel colorimeter system described is of a generic nature. The derivation of formulae needed to compute chromaticity coordinates and luminance requirements are presented. A numerical example is provided which demonstrates the application of the formulae.

2. INTRODUCTION

The need sometimes arises in laboratory experimentation to produce stimuli of precise chromaticity and luminance. The need this author has encountered involves color matching experiments, where two stimuli are generated that must be matched along one dimension (either dominant wavelength, excitation purity, or luminance). In the author's case, the two stimuli formed a bipartite field (Greene & Laycock, 1984). One-half of the matching field was set by the experimenter to be a predetermined and fixed chromaticity and luminance. The subject adjusted the other half of the bipartite field for a match in one of the above mentioned dimensions.

To produce the two stimuli for color-matching, a trichromator system is described which mixes the appropriate wavelengths in proper luminance proportions to generate the bipartite field. Although this report describes a generic colorimeter, it is representative of ones currently existing in laboratories in the Crew Systems Effectiveness Branch, Air Force Aerospace Medical Research Laboratory (AFAMRL/HEF), Wright-Patterson Air Force Base, Ohio, and in the Human Factors Group, Royal Aircraft Establishment, Farnborough, England.

3. TRICHROMATOR DESCRIPTION

To generate stimuli for color-matching experiments, a trichromator system was chosen by this author to produce light sources of different wavelengths for mixing. Depending upon how much luminance is required of the stimuli, the light source for the trichromator system can either be a single source divided among the three monochromators, or multiple light sources, one for each of the three monochromators.

Because of the exact nature of the mathematical equations used in the calculation of wavelengths, it is desirable to have monochromators whose selectable wavelengths are accurate to 0.1 nm. Otherwise, the mixing of wavelengths will result in less than desired precision in resultant chromaticity coordinates.

With a trichromator, monochromatic light from the three monochromators is combined through four optical channels in such a way as to produce two stimuli. In order to do this, one of the monochromators is fixed at an anchor wavelength, usually in the longer wavelengths of the visible spectrum (i.e., 600+ nm). The light from the anchor wavelength is split in half by use of a beam-splitter, forming two channels. Light from one of the other two monochromators is combined with one channel of the anchor wavelength, in exact quantities of luminance from each, to produce one stimulus of a precise chromaticity. In the same way, the third monochromator combines monochromatic light of a specific luminance with the other channel of the anchor wavelength to produce a second stimulus, again of a required chromaticity.

Figure 1 shows diagrammatically the trichromator system presently configured at the Royal Aircraft Establishment. The four optical channels are labelled for ease of understanding. In this example, light from channels 2 and 4 form the anchor wavelength channels. The monochromator in channels 2 and 4 is always set at the anchor wavelength. The light output from channels 1 and 2 is mixed to form the chromaticity, of a controlled luminance, required for one of the stimuli. Similarly, the output from channels 3 and 4 is combined to produce the chromaticity of the second stimulus, again at a precise luminance level. This combination of light outputs is shown in Figure 1. The AFAMRL trichromator system is nearly identical.

4. COLOR MIXING

The tristimulus values resulting from the mixture of two or more lights are the sums of the lights' individual tristimulus values. For a mixture consisting of only two lights, the point representing the chromaticity of the mixture is located on the straight line connecting the points representing the chromaticities of the two lights on one of the Commission Internationale de l'Eclairage (CIE) chromaticity diagrams (Graham, 1965, pp. 270-294). Any of the CIE chromaticity diagrams may be used for the purposes described herein, but the present discussion will deal only with the 1931 CIE diagram, as it is the most familiar. It is this fact of color mixing which describes the basis for the theory of the trichromator system. On the straight line drawn between two points on the spectrum locus of the 1931 CIE diagram lie all the chromaticity coordinates achievable by the mixture of these two lights.

There are three steps this author went through to use the trichromator system for color mixing. The first was to select the anchor wavelength for mixing. It was the author's desire to produce stimuli at a fairly high luminance level - 2000 cd/m². It was this consideration, coupled with the desire to examine dominant wavelengths in the longer end of the visible spectrum (640 nm), which influenced the choice of the anchor wavelength. The luminance calibration of the light output from the monochromator in channels 2/4 revealed the need for an anchor wavelength of 650 nm for the particular color-matching experiment of interest.

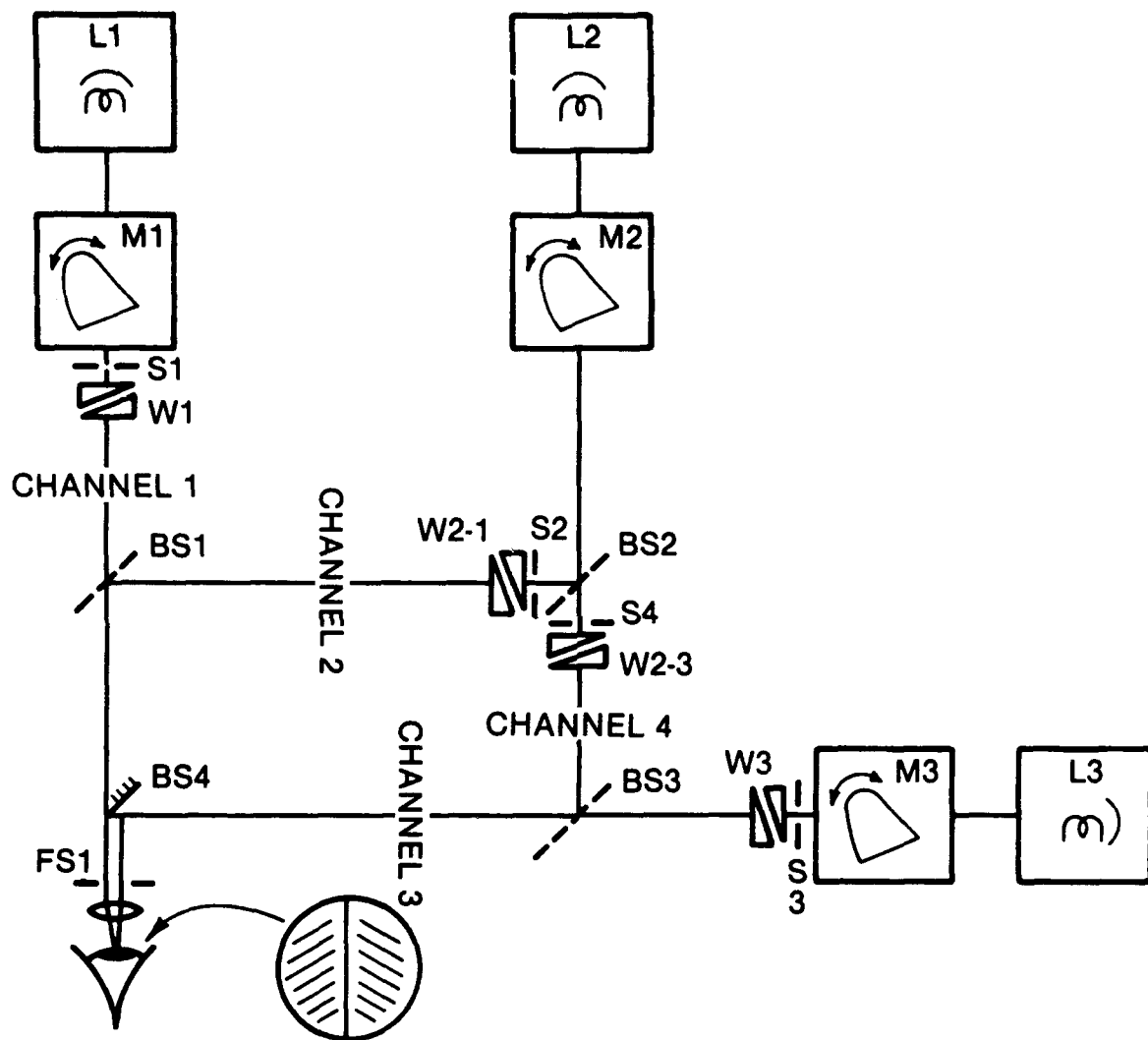


Figure 1. Optical Representation of the Trichrinator Hardware.

The second step was to calculate the variable wavelength for mixture with the anchor wavelength. This variable wavelength determination is dependent upon what stimulus chromaticity required.

The third step was to calculate the luminance proportions of the anchor and variable wavelengths required to produce a given stimulus chromaticity at a precise luminance. The next two sections describe the calculations required to achieve steps 2 and 3. The anchor wavelength setting can vary depending upon the experimental conditions under investigation.

4.1 Computation of Variable Wavelength

Figure 2 illustrates the mixing of wavelengths within a chromaticity diagram. Point "A" on the diagram shows the location on the spectrum locus of the chosen anchor wavelength, 650 nm in this example. Point "B" represents the desired chromaticity within the diagram. In order to determine which wavelength must be combined with the anchor wavelength to produce the desired chromaticity, the following procedure is used. A straight line is drawn from the anchor wavelength on the spectrum locus (Point "A") through the desired point within the chromaticity diagram (Point "B"), and extended to where the line intersects the spectrum locus, 493 nm in this example (Point "C"). The dominant wavelength represented by Point "C" is what is required for mixing with the anchor wavelength to produce the desired chromaticity.

It is possible to produce any desired chromaticity within the diagram by the combination of two dominant wavelength sources with appropriate luminance contributions from each source. The mixture of the two wavelengths in appropriate quantities determines what stimulus chromaticity is produced. In this case, the appropriate quantities of monochromatic light to be mixed are expressed in terms of luminance of each wavelength. The calculation of the amounts of luminance required at each wavelength is discussed in a later section.

The graphical method described above is not only tedious, but also does not yield exact answers. To circumvent this, a mathematical solution may be implemented on a digital computer.

Trigonometry is used to compute a table of angles, θ , formed when drawing a line from the anchor wavelength to every point on the spectrum locus at one-nanometer intervals. The chromaticity coordinates of points on the spectrum locus are provided at one-nanometer intervals in texts such as Wyszecki and Stiles, 1982, pp. 725-735. Figure 3 illustrates this trigonometric solution. Figure 4 shows graphically the determination of θ (referenced to an anchor wavelength of 650 nm) for a specific example - 490 nm.

A copy of a FORTRAN program written to determine θ angles is found in Appendix A. From this FORTRAN program, once the anchor wavelength has been selected and its chromaticity coordinates entered, a table of θ s is compiled for each one-nanometer point around the

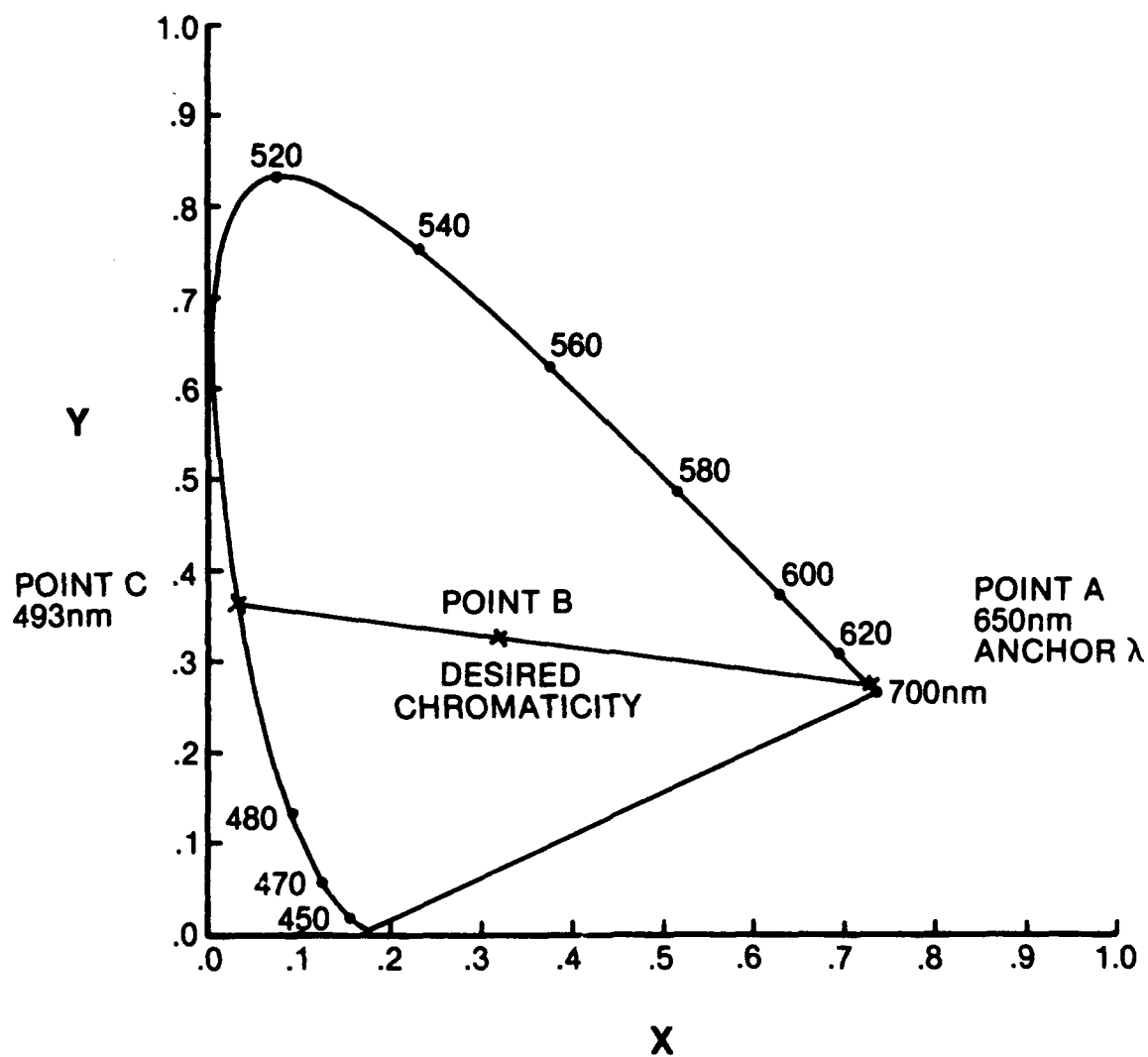


Figure 2. Trichromator Operation in 1931 CIE Chromaticity Space.

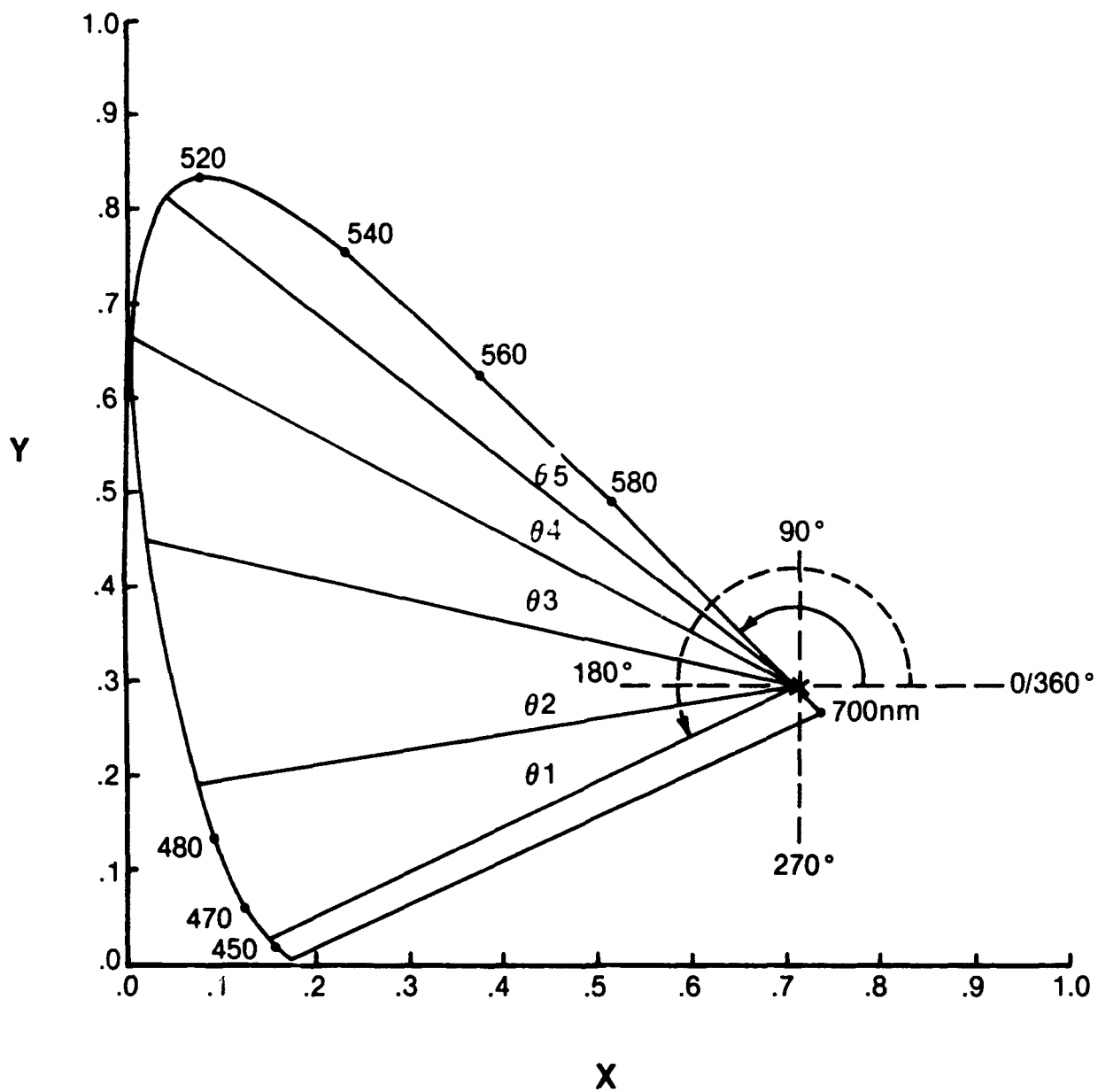


Figure 3. New Axis Coordinate Grid for Determination of Theta Angle.

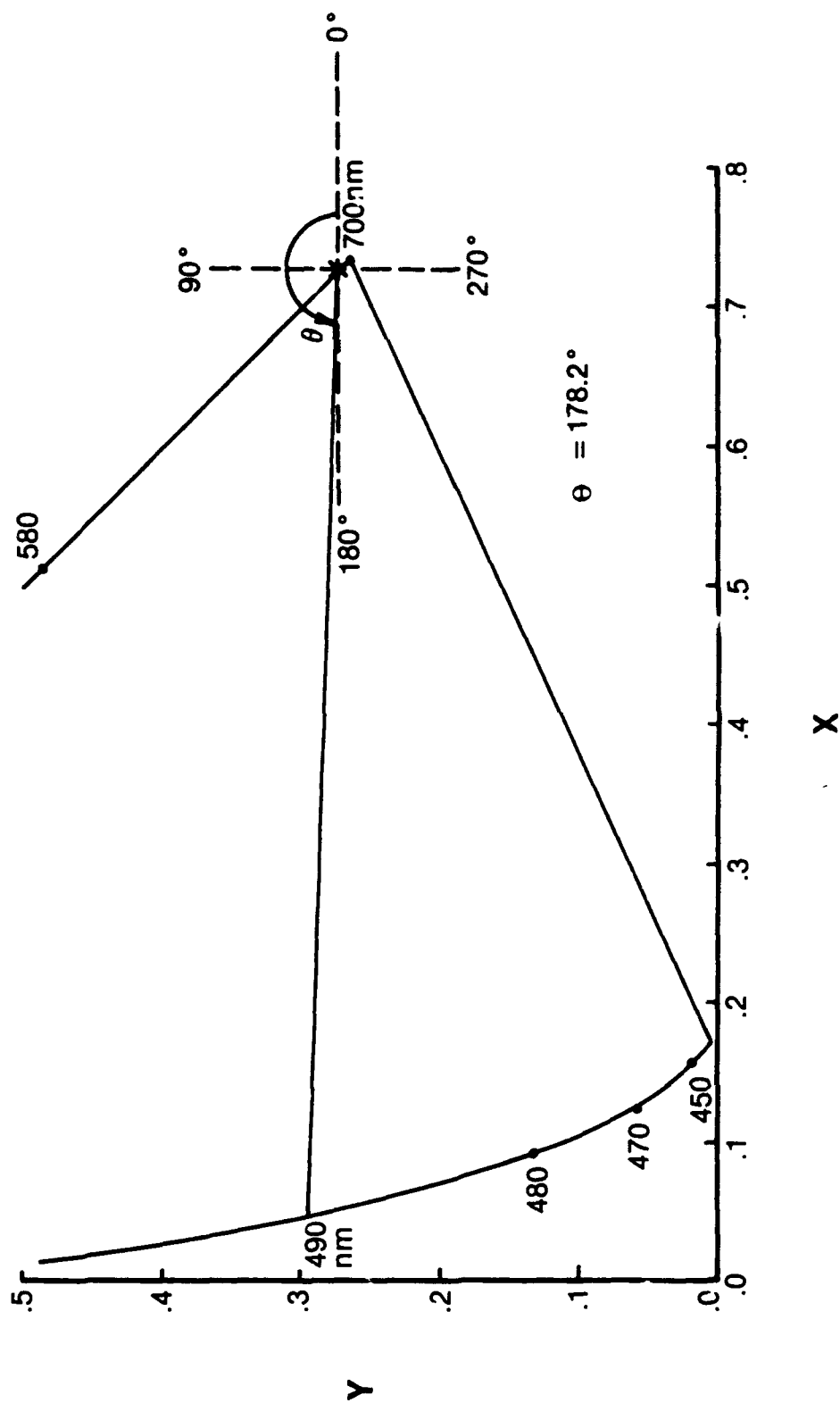


Figure 4. Example of use of Trigonometric Solution to Theta Angle.

spectrum locus (360-830 nm), referenced to the anchor wavelength. A compilation of thetas for an anchor wavelength of 650 nm is shown in Appendix B.

For the sake of convenience, this tabulated set of thetas is stored on a computer as a data file. A second computer program then can be written to search through the table of thetas to find the closest integer wavelengths, and then perform the necessary linear interpolation to arrive at the exact wavelength needed for mixing. A copy of a BASIC program written to achieve this purpose is found in Appendix C.

This section has summarized a mathematical solution to the problem of determining the wavelength required for mixing with an anchor wavelength to achieve a desired stimulus chromaticity. The next section describes a procedure for determining the luminances which are required to produce the desired chromaticity at a specific luminance.

4.2 Luminance Calculations

With the trichromator system, the luminance contributions from the three monochromators is controlled by a series of calibrated neutral density wedges. The author's practice has been to store this luminance calibration data on a computer as a data file.

The typical situation the researcher generally faces is one of trying to produce a specified chromaticity at a controlled luminance level. Once the anchor wavelength is chosen, two more steps remain. The first is to determine the variable dominant wavelength to produce the desired point on the chromaticity diagram. This step was outlined above in Section 4.1. The second step is to calculate the luminances required for the two dominant wavelengths to arrive at the needed luminance level.

In order to accomplish these two steps, the following equations are provided and were derived from Hunt (1975).

Given that:

$$x_3 = \frac{\left[\left(\frac{x_1}{y_1}\right) \times L_1\right] + \left[\left(\frac{x_2}{y_2}\right) \times L_2\right]}{\left(\frac{L_1}{y_1}\right) + \left(\frac{L_2}{y_2}\right)} \quad (1)$$

$$y_3 = \frac{(L_1 + L_2)}{\left(\frac{L_1}{y_1}\right) + \left(\frac{L_2}{y_2}\right)} \quad (2)$$

$$\text{and that } L_1 + L_2 = L_3 \quad (3)$$

where:

(X1,Y1) = CIE chromaticity coordinates for monochromator
1 wavelength setting (channel 1),

(X2,Y2) = CIE chromaticity coordinates for the anchor
wavelength setting (channel 2),

(X3,Y3) = CIE chromaticity coordinates for the desired
point inside chromaticity space,

L1 = luminance from channel 1,

L2 = luminance from channel 2,

and L3 = luminance of point of desired chromaticity.

Algebraic manipulation of the above equations results in the
equations for the luminance necessary from each monochromator. The
results of the algebraic manipulations are as follows:

$$L1 = ((-d / (c-d)) \times L3) \quad (4)$$

$$\text{and } L2 = ((c / (c-d)) \times L3) \quad (5)$$

where:

$$c = ((Y3-Y1) / Y1)$$

$$\text{and } d = ((Y3-Y2) / Y2)$$

5. EXAMPLE

It may be helpful to see a computational example using the above
derived formulae. For this example, it is desired to produce a stimulus
whose chromaticity coordinates are $x = 0.2$, $y = 0.7$ at a luminance of
500 cd/m².

The anchor wavelength for this example is 650 nm ($x = 0.72599$,
 $y = 0.27401$). The first task is to draw a straight line from the 650 nm
point on the spectrum locus of the 1931 CIE diagram, through the desired
chromaticity ($x = 0.2$, $y = 0.7$). Figure 5 illustrates this step.

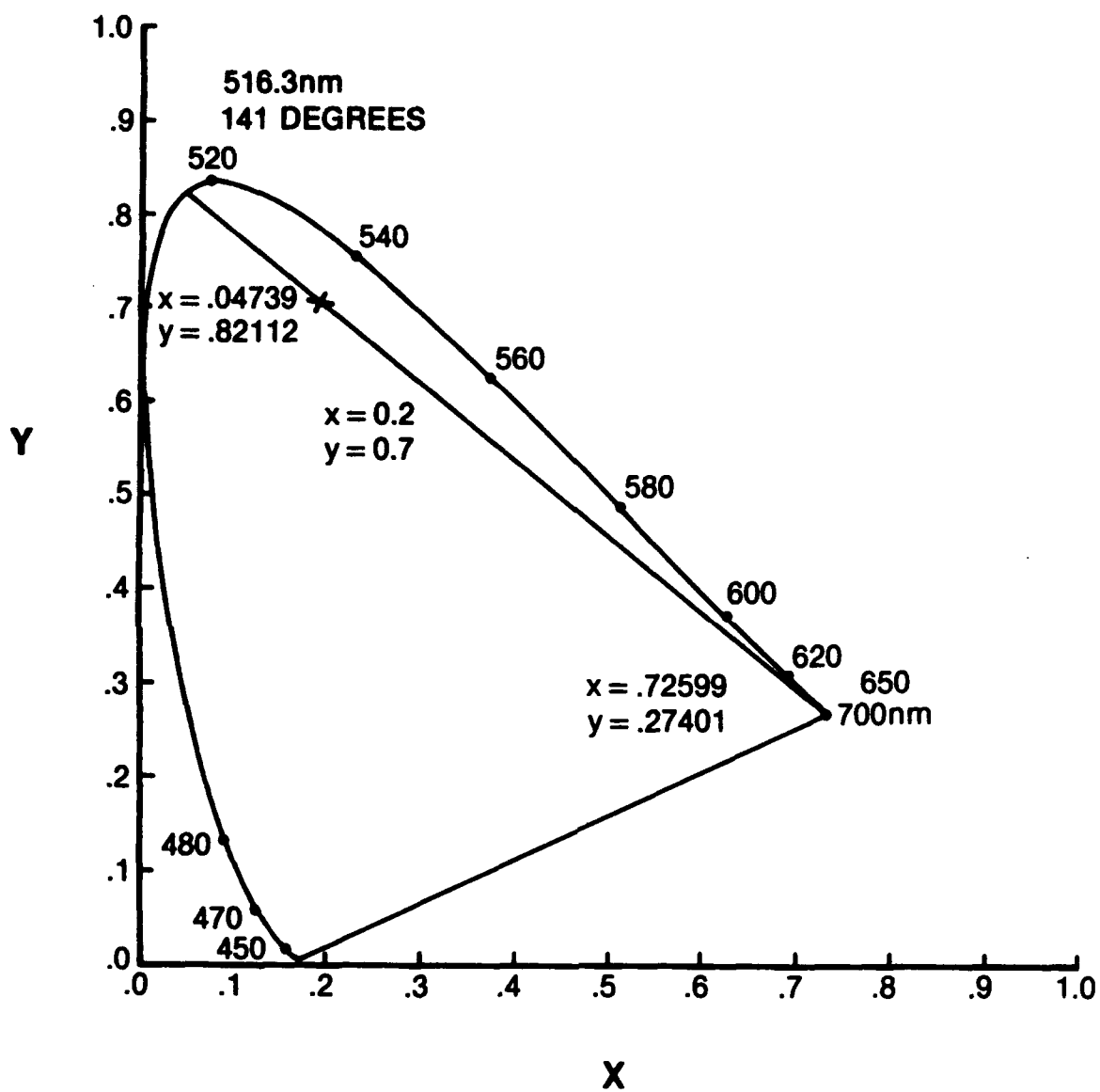


Figure 5. Finding Theta Angle and Spectrum Locus Intersection for Numerical Example.

The next task is to calculate the resulting theta angle. To avoid the ruler-and-protractor approach, the aforementioned computer programs were used to determine the theta angle of 140.997 degrees. Examining the data table of theta angles provided in Appendix B reveals the required monochromator setting needed for mixture with 650 nm is between 516 and 517 nanometers (between 141.3 and 140.7 degrees). A simple linear interpolation is performed to find the monochromator setting needed for mixture with the anchor wavelength. This calculation produces a wavelength of 516.3 nm.

Equations 4 and 5 define the luminance requirements from each of the two dominant wavelengths in order to produce the required stimulus at a given luminance level. In this example, the desired chromaticity of $x = 0.2$, $y = 0.7$ is to have a luminance of 500 cd/m^2 .

Upon examining these equations, it can be seen that the variables needed for input are the (x,y) chromaticity coordinates for the following: anchor wavelength, variable wavelength setting for mixture with the anchor wavelength, and desired chromaticity within the 1931 CIE diagram. At this point, two of the three pairs of chromaticity coordinates are known - the anchor wavelength and the chromaticity of the desired point within the chromaticity diagram.

A linear interpolation must be performed on the x and y coordinates (between the chromaticity coordinates for 516 and 517 nm) to obtain the final pair of coordinates for the equations. Linear interpolation produces the resultant coordinates: $x = 0.04739$, $y = 0.82112$.

To use Equations 4 and 5, we define our variables as follows: let X_1 , Y_1 be the coordinates of the variable monochromator in channel 1, $X_1 = 0.04739$, $Y_1 = 0.82112$, (516.3 nm in this example). Let X_2 , Y_2 be the coordinates of the anchor wavelength, $X_2 = 0.72599$, $Y_2 = 0.27401$, (650 nm in this example). Let X_3 , Y_3 be the coordinates of the desired chromaticity, $X_3 = 0.2$, $Y_3 = 0.7$.

Substituting values into Equation 4 we have:

$$L_1 = \frac{\frac{-(0.7 - 0.27401)}{0.27401} \times 500}{\frac{0.7 - 0.82112}{0.82112} - \frac{0.7 - 0.27401}{0.27401}} \quad (6)$$

Solving Equation 6, we find that L_1 , the luminance contribution at 516.3 nm, is 456.8 cd/m^2 . Thus, via Equation 3, the luminance required at 650 nm (L_2) is 43.2 cd/m^2 .

6. CONCLUSION

The numerical example worked in Section 5 is for producing one stimulus of a required chromaticity at a desired luminance level. The identical procedure would be followed to determine the other dominant wavelength needed to mix with the anchor wavelength to produce a second stimulus. In the same fashion as above, the luminance contributions would also be determined.

The theory of color mixing using a tri-stimulus colorimeter to produce two stimuli of known chromaticity and desired luminance has been presented. The derivation of the required formulae involve a simple algebraic manipulation of a set of equations. Since this manipulation has not heretofore been published in the literature, it is hoped that the sharing of this basic information will prove useful.

[illegible]

GIVEN AN "ANCHOR" POINT, DRAW A CHORD TO EACH OF 471 POINTS ON 1931 CIE CHROMATICITY DIAGRAM, MEASURING ANGLES ACCORDING TO THE FOLLOWING CONVENTION:

90

180 ++ 0

270

INPUT 471 PAIRS OF (X,Y) COORDINATES DEFINING CHROMATICITY
LOCUS FROM DISK FILE

INPUT X,Y COORDINATES OF ANCHOR POINT

COMPUTE ANGLES

```
DO 100 I = 1, 471
```

IF Y(I) =YA , COMPUTE THETA DIFFERENTLY

```
IF ( Y(I) .EQ. YA ) GO TO 20
```

FOUR POSSIBLE CASES:

$XA \geq XI$	$YA > YI$
$XA \geq XI$	$YA < YI$
$XA < XI$	$YA < YI$
$XA < XI$	$YA > YI$

COMPUTE THETA AND ADJUST IT ACCORDINGLY

$$\text{THETA} = \text{ATAN2} \left(\text{XA} - \text{X(I)}, \text{YA} - \text{Y(I)} \right) * \text{Q}$$

```
IF ( YA .LT. YI ) THETA = THETA + 180.  
IF ( XA .LT. XI .AND. YA .GT. YI ) THETA = THETA + 360.  
GO TO 60
```

```

C      20      IF ( X(I) - XA ) 30, 40, 50
C
C      30      THETA = 90.
C              GO TO 60
C
C      40      (ANCHOR POINT AND LOCUS POINT ARE IDENTICAL: SET THETA = 0)
C              THETA = 0.
C              GO TO 100
C
C      50      THETA = 270.
C
C      60      PERFORM FINAL MAPPING OF THETA
C              THETA = 270. - THETA
C              IF ( THETA .LT. 0. ) THETA = THETA + 360.
C              IF ( THETA .GT. 360. ) THETA = THETA - 360.
C
C      100     ANGLE(I) = THETA
C
C      110     SAVE RESULTS IN FILE
C
C              OPEN (UNIT=1, NAME='LTHETA.DAT', TYPE='NEW', ACCESS='SEQUENTIAL')
C              DO 105 I = 1, 471
C              105     WRITE (1,110) I+359, ANGLE(I), X(I), Y(I)
C              110     FORMAT (1X, I5, 3X, F5.1, 2(3X, F7.5))
C              CLOSE(UNIT=1)
C              STOP
C              END

```

ANCHOR POINT = (.72599,.27401) Appendix B - Wavelength by theta angle, referenced to 650 nm.

LAMBDA	THETA	X	Y	LAMBDA	THETA	X	Y	LAMBDA	THETA	X	Y
360	206.0	.17556	.00529	415	205.9	.17209	.00483	470	199.8	.12412	.05780
361	206.0	.17548	.00529	416	205.9	.17198	.00486	471	199.3	.12147	.06259
362	206.0	.17540	.00528	417	205.9	.17187	.00489	472	198.8	.11870	.06783
363	206.0	.17532	.00527	418	205.9	.17174	.00494	473	198.2	.11581	.07358
364	206.0	.17524	.00526	419	205.9	.17159	.00501	474	197.6	.11278	.07989
365	206.0	.17516	.00526	420	205.9	.17141	.00510	475	196.9	.10960	.08684
366	206.0	.17509	.00525	421	205.9	.17121	.00521	476	196.2	.10626	.09449
367	206.0	.17501	.00524	422	205.8	.17099	.00533	477	195.4	.10278	.10286
368	206.0	.17494	.00523	423	205.8	.17077	.00547	478	194.5	.09913	.11201
369	206.0	.17488	.00522	424	205.8	.17054	.00562	479	193.6	.09531	.12194
370	206.0	.17482	.00522	425	205.8	.17030	.00579	480	192.6	.09129	.13270
371	206.0	.17477	.00523	426	205.7	.17005	.00597	481	191.5	.08708	.14432
372	206.0	.17472	.00524	427	205.7	.16978	.00618	482	190.3	.08268	.15687
373	206.0	.17466	.00524	428	205.7	.16950	.00640	483	189.1	.07812	.17042
374	206.0	.17459	.00522	429	205.7	.16920	.00664	484	187.8	.07344	.18503
375	206.0	.17451	.00518	430	205.6	.16888	.00690	485	186.4	.06871	.20072
376	206.0	.17441	.00513	431	205.6	.16853	.00718	486	184.9	.06399	.21747
377	206.0	.17431	.00507	432	205.5	.16815	.00749	487	183.3	.05932	.23525
378	206.0	.17422	.00502	433	205.5	.16775	.00782	488	181.7	.05467	.25409
379	206.0	.17416	.00498	434	205.4	.16733	.00817	489	180.0	.05003	.27400
380	206.0	.17411	.00496	435	205.4	.16690	.00855	490	178.2	.04539	.29498
381	206.0	.17409	.00496	436	205.3	.16645	.00896	491	176.4	.04076	.31698
382	206.0	.17407	.00497	437	205.3	.16598	.00940	492	174.5	.03620	.33990
383	206.0	.17406	.00498	438	205.2	.16548	.00987	493	172.6	.03176	.36360
384	206.0	.17404	.00498	439	205.2	.16496	.01035	494	170.7	.02749	.38792
385	206.0	.17401	.00498	440	205.1	.16441	.01086	495	168.8	.02346	.41270
386	206.0	.17397	.00497	441	205.0	.16383	.01138	496	166.9	.01970	.43776
387	206.0	.17393	.00494	442	205.0	.16321	.01194	497	165.1	.01627	.46295
388	206.0	.17389	.00493	443	204.9	.16255	.01252	498	163.3	.01318	.48821
389	206.0	.17384	.00492	444	204.8	.16185	.01314	499	161.5	.01048	.51340
390	206.0	.17380	.00492	445	204.7	.16111	.01379	500	159.8	.00817	.53842
391	206.0	.17376	.00492	446	204.6	.16031	.01449	501	158.1	.00628	.56307
392	206.0	.17370	.00494	447	204.6	.15947	.01523	502	156.5	.00487	.58712
393	206.0	.17366	.00494	448	204.4	.15857	.01602	503	155.0	.00398	.61045
394	206.0	.17361	.00494	449	204.3	.15763	.01684	504	153.6	.00364	.63301
395	206.0	.17356	.00492	450	204.2	.15664	.01771	505	152.2	.00386	.65482
396	206.0	.17351	.00490	451	204.1	.15560	.01861	506	150.9	.00464	.67590
397	206.0	.17347	.00486	452	204.0	.15452	.01956	507	149.6	.00601	.69612
398	206.0	.17342	.00484	453	203.9	.15340	.02055	508	148.4	.00799	.71534
399	206.0	.17338	.00481	454	203.7	.15222	.02161	509	147.3	.01060	.73341
400	206.0	.17334	.00480	455	203.6	.15099	.02274	510	146.2	.01387	.75019
401	206.0	.17329	.00479	456	203.5	.14969	.02395	511	145.2	.01777	.76561
402	206.0	.17324	.00478	457	203.3	.14834	.02525	512	144.3	.02224	.77963
403	206.0	.17317	.00478	458	203.1	.14693	.02663	513	143.4	.02727	.79211
404	206.0	.17310	.00477	459	203.0	.14547	.02812	514	142.7	.03282	.80293
405	206.0	.17302	.00478	460	202.8	.14396	.02970	515	141.9	.03885	.81202
406	206.0	.17293	.00478	461	202.6	.14241	.03139	516	141.3	.04533	.81939
407	206.0	.17284	.00479	462	202.4	.14080	.03321	517	140.7	.05218	.82516
408	205.9	.17275	.00480	463	202.1	.13912	.03520	518	140.2	.05932	.82943
409	205.9	.17266	.00480	464	201.9	.13737	.03740	519	139.7	.06672	.83227
410	205.9	.17258	.00480	465	201.6	.13550	.03988	520	139.3	.07430	.83380
411	205.9	.17249	.00480	466	201.3	.13351	.04269	521	139.0	.08205	.83409
412	205.9	.17239	.00480	467	201.0	.13137	.04588	522	138.7	.08994	.83329
413	205.9	.17230	.00480	468	200.6	.12909	.04945	523	138.4	.09794	.83159
414	205.9	.17219	.00482	469	200.2	.12666	.05343	524	138.2	.10602	.82718

LAMBDA	THETA	X	Y	LAMBDA	THETA	X	Y	LAMBDA	THETA	X	Y	LAMBDA	THETA	X	Y
580	135.1	51249	48659	635	135.1	71403	28593	690	315.0	73439	26561	745	315.0	73469	26531
581	135.1	51907	48003	636	135.1	71512	28484	691	315.0	73444	26556	746	315.0	73469	26531
582	135.1	52540	47353	637	135.1	71616	28380	692	315.0	73448	26552	747	315.0	73469	26531
583	135.1	53207	46709	638	135.1	71716	28281	693	315.0	73452	26548	748	315.0	73469	26531
584	135.1	53846	46073	639	135.1	71812	28185	694	315.0	73456	26544	749	315.0	73469	26531
585	135.1	54479	45443	640	135.1	71903	28094	695	315.0	73459	26541	750	315.0	73469	26531
586	135.1	55103	44823	641	135.1	71991	28006	696	315.0	73462	26538	751	315.0	73469	26531
587	135.1	55719	44210	642	135.2	72075	27922	697	315.0	73465	26535	752	315.0	73469	26531
588	135.1	56327	43606	643	135.2	72155	27842	698	315.0	73467	26533	753	315.0	73469	26531
589	135.1	56926	43010	644	135.2	72232	27766	699	315.0	73469	26531	754	315.0	73469	26531
590	135.1	57515	42423	645	135.2	72303	27695	700	315.0	73469	26531	755	315.0	73469	26531
591	135.1	58094	41846	646	135.3	72370	27628	701	315.0	73469	26531	756	315.0	73469	26531
592	135.1	58665	41276	647	135.2	72433	27566	702	315.0	73469	26531	757	315.0	73469	26531
593	135.1	59222	40719	648	135.3	72491	27508	703	315.0	73469	26531	758	315.0	73469	26531
594	135.1	59766	40176	649	135.0	72547	27453	704	315.0	73469	26531	759	315.0	73469	26531
595	135.1	60293	39650	650	0.0	72599	27401	705	315.0	73469	26531	760	315.0	73469	26531
596	135.1	60803	39141	651	315.0	72649	27351	706	315.0	73469	26531	761	315.0	73469	26531
597	135.1	61298	38648	652	315.0	72698	27302	707	315.0	73469	26531	762	315.0	73469	26531
598	135.1	61778	38171	653	315.0	72743	27257	708	315.0	73469	26531	763	315.0	73469	26531
599	135.1	62246	37705	654	315.0	72786	27214	709	315.0	73469	26531	764	315.0	73469	26531
600	135.1	62704	37249	655	315.0	72827	27173	710	315.0	73469	26531	765	315.0	73469	26531
601	135.1	63152	36803	656	315.0	72866	27134	711	315.0	73469	26531	766	315.0	73469	26531
602	135.1	63590	36367	657	315.0	72902	27098	712	315.0	73469	26531	767	315.0	73469	26531
603	135.1	64016	35943	658	315.0	72936	27064	713	315.0	73469	26531	768	315.0	73469	26531
604	135.1	64427	35533	659	315.0	72968	27032	714	315.0	73469	26531	769	315.0	73469	26531
605	135.1	64823	35140	660	315.0	72997	27003	715	315.0	73469	26531	770	315.0	73469	26531
606	135.1	65203	34763	661	315.0	73023	26977	716	315.0	73469	26531	771	315.0	73469	26531
607	135.1	65567	34402	662	315.0	73047	26953	717	315.0	73469	26531	772	315.0	73469	26531
608	135.1	65917	34055	663	315.0	73069	26931	718	315.0	73469	26531	773	315.0	73469	26531
609	135.1	66253	33722	664	315.0	73090	26910	719	315.0	73469	26531	774	315.0	73469	26531
610	135.1	66576	33401	665	315.0	73109	26891	720	315.0	73469	26531	775	315.0	73469	26531
611	135.1	66887	33092	666	315.0	73128	26872	721	315.0	73469	26531	776	315.0	73469	26531
612	135.1	67186	32795	667	315.0	73147	26853	722	315.0	73469	26531	777	315.0	73469	26531
613	135.1	67472	32509	668	315.0	73165	26835	723	315.0	73469	26531	778	315.0	73469	26531
614	135.1	67746	32236	669	315.0	73183	26817	724	315.0	73469	26531	779	315.0	73469	26531
615	135.1	68008	31975	670	315.0	73199	26801	725	315.0	73469	26531	780	315.0	73469	26531
616	135.1	68258	31725	671	315.0	73215	26785	726	315.0	73469	26531	781	315.0	73469	26531
617	135.1	68497	31486	672	315.0	73230	26770	727	315.0	73469	26531	782	315.0	73469	26531
618	135.1	68725	31259	673	315.0	73244	26756	728	315.0	73469	26531	783	315.0	73469	26531
619	135.1	68943	31041	674	315.0	73258	26742	729	315.0	73469	26531	784	315.0	73469	26531
620	135.1	69151	30834	675	315.0	73272	26728	730	315.0	73469	26531	785	315.0	73469	26531
621	135.1	69349	30637	676	315.0	73286	26714	731	315.0	73469	26531	786	315.0	73469	26531
622	135.1	69539	30448	677	315.0	73300	26700	732	315.0	73469	26531	787	315.0	73469	26531
623	135.1	69721	30267	678	315.0	73314	26686	733	315.0	73469	26531	788	315.0	73469	26531
624	135.1	69894	30095	679	315.0	73328	26672	734	315.0	73469	26531	789	315.0	73469	26531
625	135.1	70061	29930	680	315.0	73342	26658	735	315.0	73469	26531	790	315.0	73469	26531
626	135.1	70219	29773	681	315.0	73355	26645	736	315.0	73469	26531	791	315.0	73469	26531
627	135.1	70371	29622	682	315.0	73368	26632	737	315.0	73469	26531	792	315.0	73469	26531
628	135.1	70516	29477	683	315.0	73381	26619	738	315.0	73469	26531	793	315.0	73469	26531
629	135.1	70656	29338	684	315.0	73394	26606	739	315.0	73469	26531	794	315.0	73469	26531
630	135.1	70792	29203	685	315.0	73405	26595	740	315.0	73469	26531	795	315.0	73469	26531
631	135.1	70923	29072	686	315.0	73414	26586	741	315.0	73469	26531	796	315.0	73469	26531
632	135.1	71050	28945	687	315.0	73422	26578	742	315.0	73469	26531	797	315.0	73469	26531
633	135.1	71173	28823	688	315.0	73429	26571	743	315.0	73469	26531	798	315.0	73469	26531
634	135.1	71290	28706	689	315.0	73434	26566	744	315.0	73469	26531	799	315.0	73469	26531

LAMBDA	THETA	X	Y	LAMBDA	THETA	X	Y	LAMBDA	THETA	X	Y
800	315.0	.73469	.26531								
801	315.0	.73469	.26531								
802	315.0	.73469	.26531								
803	315.0	.73469	.26531								
804	315.0	.73469	.26531								
805	315.0	.73469	.26531								
806	315.0	.73469	.26531								
807	315.0	.73469	.26531								
808	315.0	.73469	.26531								
809	315.0	.73469	.26531								
810	315.0	.73469	.26531								
811	315.0	.73469	.26531								
812	315.0	.73469	.26531								
813	315.0	.73469	.26531								
814	315.0	.73469	.26531								
815	315.0	.73469	.26531								
816	315.0	.73469	.26531								
817	315.0	.73469	.26531								
818	315.0	.73469	.26531								
819	315.0	.73469	.26531								
820	315.0	.73469	.26531								
821	315.0	.73469	.26531								
822	315.0	.73469	.26531								
823	315.0	.73469	.26531								
824	315.0	.73469	.26531								
825	315.0	.73469	.26531								
826	315.0	.73469	.26531								
827	315.0	.73469	.26531								
828	315.0	.73469	.26531								
829	315.0	.73469	.26531								
830	315.0	.73469	.26531								

Appendix C - BASIC Program to Calculate Wavelength Needed for Mixing
with Anchor Wavelength to Produce Desired Pair of Chromaticity Coordinates.

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10 REM THIS PROGRAM CALCULATES WAVELENGTH NEEDED FOR MIXING, ITS X,Y
15 REM COORDINATES ON THE SPECTRUM
20 REM LOCUS AND X,Y COORDINATES FOR THE DESIRED CHROMATICITY
40 REM ACHROMATIC POINT IS SET AT D65
60 REM IF YOU WANT TO CHANGE IT, ALTER THE U',V' COORDINATES IN LINE 80
80 LET X0=.1978 LET Y0=.4683
90 LET Q=57.2958
100 PRINT "ENTER X COORDINATE OF REQUIRED DOMINANT WAVELENGTH;"INPUT X1
110 PRINT "ENTER Y COORDINATE OF REQUIRED DOMINANT WAVELENGTH;"INPUT Y1
120 PRINT "ENTER THE FILE NAME YOU WANT THIS DATA STORED IN "INPUT IS$
130 REM CONVERTS 1931 CIE to 1976 UCS
140 LET X=4*X1/(-2*X1+12*Y1+3)
150 LET Y=9*Y1/(-2*X1+12*Y1+3)
160 IF (X-X0)<>0GOTO 200
170 A=90
180 IF (Y-Y0)>0GOTO 280
190 A=270GOTO 280
200 L=(X-X0)/(Y-Y0)
210 A=ATN(L)*Q
220 IF A>0GOTO 250
230 IF X>X0GOTO 270
240 A=90-AGOTO 280
250 IF (X-X0)>0GOTO 275
260 IF (Y-Y0)>0GOTO 280
270 A=270-AGOTO 280
275 LET A=90-A
300 REM X9, Y9 ARE X, Y COORDINATES FOR TEST FIELD
310 PRINT "WHAT IS X COORDINATE OF DESIRED COLOR?"INPUT X9
320 PRINT "WHAT IS Y COORDINATE OF DESIRED COLOR?"INPUT Y9
380 REM SETS MONOCHROMATOR 2 AT ANCHOR OF 655NM
390 LET X2=.72827/LET Y2=.27173
410 REM CALCULATES LENGTH OF R2 FROM 655 NM(MONOCHROMATOR) TO TEST POINT
420 IF (X9-X2)<>0GOTO 460
430 A2=90
440 IF (Y9-Y2)>0GOTO 550
450 A2=270GOTO 550
460 L9=(X9-X2)/(Y9-Y2)
470 A2=ATN(L9)*Q
480 REM A2 IS THETA FOR DESIRED CHROMATICITY POINT
490 IF A2>0GOTO 520
500 IF X9>X2GOTO 540
510 A2=90-A2GOTO 550
520 IF (X9-X2)>0GOTO 545
530 IF (Y9-Y2)>0GOTO 550

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540 A2=278-A2 GO TO 550
545 LET A2=90-A2
550 OPEN "DXO:LTHETA.DAT" FOR INPUT AS FILE VF1
560 OPEN I$ FOR OUTPUT AS FILE VF2
570 FOR N=1 TO 451
580 LET T2=VF1((4*N)-2)
590 IF A2>T2GO>TO 660
600 IF A2=T2GO TO 620
610 NEXT N
620 LET L4=VF1((4*N)-3)
630 LET X3=VF1((4*N)-1)
640 LET Y3=VF1(4*N)
650 GO TO 850
660 LET T1=VF1((4*N)-6)
670 REM FINDS ONE THETA ABOVE T2 AND STORES IT AS T1
680 LET L2=VF1((4*N)-3)
690 REM L2 IS WAVELENGTH ASSOCIATED WITH THETA
700 LET L1=VF1((4*N)-7)
710 REM L1 IS WAVELENGTH ASSOCIATED WITH THETA ABOVE
720 REM LINEAR INTERPOLATION FOLLOWS FOR LAMBDA AND X AND Y COORDS
730 L3=(T2-A2)*(L2-L1)/(T2-T1)
740 REM L3 IS AMOUNT TO CHANGE L2 BY TO RECEIVE REQUIRED LAMBDA
750 L4=(L2-L3)
760 REM L4 IS LAMBDA ASSOCIATED WITH WAVELENGTH NEEDED FOR MIXING WITH ANCHOR
770 LET X8=VF1((4*N)-1)
780 LET Y8=VF1(4*N)
790 LET X7=VF1((4*N)-5)
800 LET Y7=VF1((4*N)-4)
810 LET X4=(T1-A2)*(X7-X8)/(T1-T2)
820 LET X3=(X7-X4)
830 LET Y4=(T1-A2)*(Y7-Y8)/(T1-T2)
840 LET Y3=(Y7-Y4)
850 PRINT "MONOCHROMATOR WAVELENGTH FOR MIXING IS"L4
880 PRINT "X,Y FOR MONOCHROMATOR ARE "X3,Y3
882 PRINT "X,Y FOR DESIRED CHROMATICITY ARE"X9,Y9
885 PRINT "U',V' COORDINATES FOR DESIRED CHROMATICITY ARE"X6,Y6
890 LET VF2(1)=X3
900 LET VF2(2)=Y3
910 LET VF2(3)=L4
920 LET VF2(4)=X9
930 LET VF2(5)=Y9
940 END

```


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