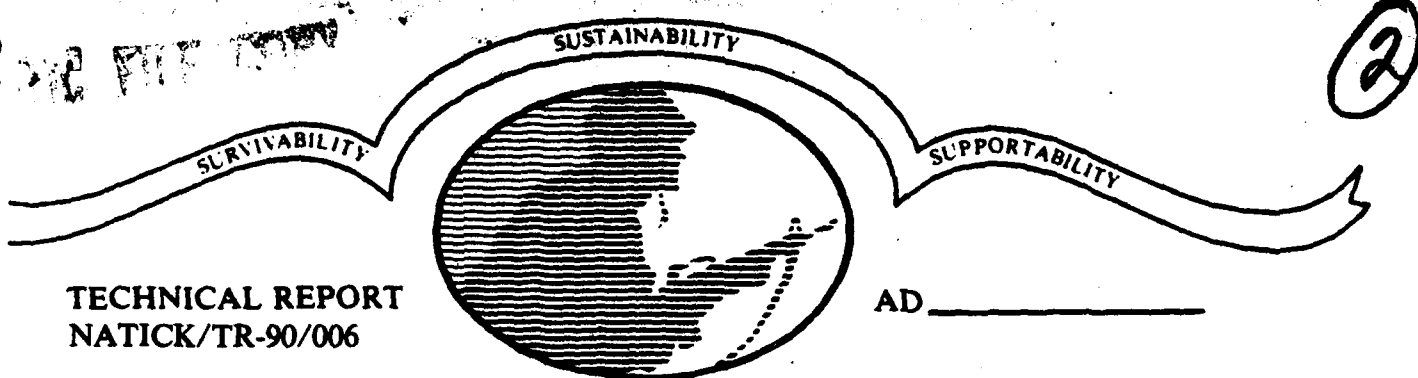


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COLOR MATCHING SPANNING THE VISIBLE AND NEAR-INFRARED: USE OF THE CUBIC SPLINE FUNCTION IN INTERPOLATION

BY

R. A. PROSSER
G. ARRUDA

NOVEMBER 1989

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19. ABSTRACT (Continue on reverse if necessary and identify by block number) The colorimetric and spectrophotometric procedures for color matching are compared, and the advantages of each discussed. It is shown that the spectrophotometric procedure can provide a good spectral match across the visible and near infrared. An empirical investigation showed that the Saunderson correction is useful for color matching on textiles, and that the Kubelka-Munk equation appears to be accurate within our current experimental error.					
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SUMMARY

The research reported had two important objectives:

1. Practical: The creation of a color-matching formulation algorithm and associated computer program which covers the 400-900 nanometer (nm) spectral range, and provides formulations which comply with camouflage specifications over the stated range.
2. Theoretical: Modification of the Kubelka-Munk equation to provide improved color matches to standards.

In the past, a military item was well camouflaged if it was visually inconspicuous. Surveillance techniques utilizing photographic film and electro-optical instrumentation are sensitive not only in the visible range from 400 to 700 nm but also in the near infrared (N-IR), 700 to about 900 nm. If there is a substantial spectral mismatch between an object and its terrain background anywhere between 400 and 900 nm, these devices can make the item readily discernible. Since the conventional theory used in color formulation prediction (matching of tristimulus values) applies only to the visible range, another concept (matching reflectance spectra) which theoretically covers the entire range from 400 to 900 nm was employed, and a computer program based thereon written. The results were excellent. They showed that a close spectral match to a target reflectance curve could be obtained over the entire 400-900 nm range, frequently resulting in an improved visual color match.

It has been reported in the literature that the reason that precise color matches are generally not obtainable, especially for dark samples, is because of assumptions made in the derivation of the Kubelka-Munk equation. Consequently, numerous modifications of the equation (and the Saunderson correction for reflectance, as well) were tried. Additional computer programs designed to search out the source(s) of the error(s) were written. However, consistent predictions for many known formulations were not obtainable. The reason may be that the current experimental error is much larger than any errors in the equation(s).



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PREFACE

The primary objective of this study was the development of a computer program that provides colorant formulations based on the best spectral match obtainable from a set of dyes to the spectral reflectance curve of the standard. This program permits the inclusion of the near infrared, which is beyond the range of the usual colorimetric (tristimulus) formulation procedures, in textile camouflage specifications.

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COLOR-MATCHING SPANNING THE VISIBLE AND NEAR-IR: USE OF THE CUBIC SPLINE FUNCTION IN INTERPOLATION

INTRODUCTION

In the past, an item of military materiel was considered to be well camouflaged if it blended visually into its surroundings. Among other things, this blending required that the colors of the item have minimum contrast with the colors in the background. Suitable colors were then selected and matching colorant formulations obtained. Surveillance techniques utilizing photographic film and electro-optical instrumentation are sensitive not only in the visible range of 400 to 700 nm, but also in the near infrared (N-IR), 700 to about 900 nm. Although an item may be visually detectable only with difficulty, if its reflectance over any region of the visible or N-IR is substantially different from the terrain elements of its surroundings, currently fielded detectors can make the item readily discernible, especially at night. When attempting to obtain a dye formulation for a textile substrate that both matches the color of a terrain element and has similar spectral reflectance characteristics in the N-IR, the conventional mathematical procedure for match prediction developed by Stearns and Allen¹⁻³ cannot be used, because that procedure is limited to the visible range.

The object of this report is to show how dye formulations can be calculated to meet the camouflage requirements of both the visual and N-IR ranges. The results of this study are applicable to dyes, not pigments.

Two approaches to color-matching were considered. In one the tristimulus values of the standard are matched; and in the other, the spectral reflectance curve of the standard is matched. In either case a data bank of dye reflectance values is required. To create a data bank, a group of dyes is chosen that covers the desired color gamut, has acceptable colorfastness properties, and is appropriate to the substrate of interest. Each dye is applied to the substrate at several different concentrations. Reflectance values of these dyed swatches and the mock-dyed sample (see EQUIPMENT AND PROCEDURE below) are then measured on a spectrophotometer and stored in the computer. The levelness of the dyeing is always a factor; all reflectance values were therefore determined 10 times and averaged. Both procedures are discussed to show specifically why the colorimetric approach cannot be used for "color-matching" in the N-IR, and why a spectral matching method is required.

COLORIMETRIC APPROACH

The first procedure is based on tristimulus values obtained using the weighted ordinate method. A full description is given by Stearns.¹ This method has a definite advantage in that the color of the standard, under given lighting conditions, can be matched by many combinations of dyes, even though they differ from the set used in dyeing the standard. Consequently, it is probably used in most, if not all, commercial color-matching computer programs. For the purposes of this study, the weighted ordinate method has the following disadvantages:

1. It is limited to the visible range, since the standard observer and illuminant functions are defined only from 360 to 830 nm, and most

spectrometers and colorimeters operate from 400 to 700 nm. Consequently, an acceptable match to the reflectance curve of the standard in the N-IR by the trial dyeing is fortuitous.

2. A visually acceptable color match may have a high degree of metamerism. A pair of colored objects having different spectral reflectance curves but the same tristimulus values for one illuminant is said to be metameric. Commercial color-matching programs handle this problem by computing the degree of metamerism expected from a given calculated formulation, and displaying only those formulations with a metameric index below a minimum value. If there is a substantial spectral difference between the standard and the trial dyeing at certain wavelengths, then sensors that are sensitive at these wavelengths could distinguish between the two.

THE MATCHING OF SPECTRAL REFLECTANCE CURVES

A spectral match to a terrain element across the visible and N-IR will improve camouflage. This can be accomplished by devising a procedure which will generate colorant formulations that enable the item to blend with its background across any spectral range, assuming that the Kubelka-Munk equation,

$$K/S = (1-R)^2/2R$$

or other additive function holds.⁴ In this equation, K is the absorption coefficient, S is the scattering coefficient, and R is the reflectance at a given wavelength. Using such formulations to color fabric, the field item should be distinguishable from its background only with difficulty by the eye, photographic film, or electro-optical instrumentation, specifically, image intensifier devices such as the Starlight Scope.

In this procedure all combinations of all the dyes in the dye bank are chosen two at a time, and then three at a time, for comparison with the standard. The standard may be a reflectance curve for a terrain element, or an average of several elements obtained from field experiments. Assuming the computer program is trying to match the standard using three dyes at a time, the procedure is as follows:

1. A particular combination of three dyes and the appropriate mock-dyed sample are chosen from the dye data bank.

2. The Saunderson correction (see below) for surface and internal reflectance is applied to the spectral reflectance values of the dyes and the mock-dyed sample.

3. The corrected reflectance values are converted to K/S values using the Kubelka-Munk equation.

4. The K/S value of the mock dyed sample is subtracted from the K/S value of the selected data bank dyes and the standard at each wavelength. This accounts for the color of the greige goods.

5. Using the cubic-spline function, a relationship is obtained between the K/S values and the concentrations at each wavelength.⁵

6. By iteration, the K/S values of the three dyes are summed until a close match (least squares criterion) to the K/S values of the standard is obtained. The corresponding concentrations are noted.

7. This procedure is repeated with other sets of three dyes and then with the various sets of four dyes, if desired. The set which provides the closest match (least metamerism) over the entire wavelength range is chosen for the first trial dyeing. Metamerism is defined, for this study, as the sum of the absolute values, of the percent difference between the calculated and standard K/S values at each wavelength, over the wavelength range specified. A flow chart is given in Fig. 1.

8. A first trial dyeing is prepared. A set of reflectance readings, and L^* , a^* , and b^* are obtained.⁶ If the dyes used to dye the standard are included in the data bank, and the nature of the substrate has not changed, a precise spectral match is obtainable. This is usually not the case. Many dyes previously used on textile substrates are no longer available because of Occupational Safety and Health Agency (OSHA) or environmental concerns. Also the spectral characteristics of naturally occurring terrain elements may not be precisely duplicated with organic colorants. If the match between the first trial dyeing and the standard is not satisfactory, an empirical correction is applied. To correct (at least partially) for a spectral mismatch, the reflectance spectra for the standard and the trial dyeing are compared. Suppose that at 500 nm the reflectance value of the standard is 15.0% whereas the value for the trial dyeing is 14.0%. A mathematical "standard" is then created, which compensates for the low reflectance value of the trial dyeing by assigning a reflectance value of 16.0% to the "standard". The reflectance values for the "standard" at other wavelengths are obtained similarly. A second formulation based on the new set of "standard" reflectances is then calculated. The second trial dyeing usually results in an improved match with a CIELAB* color difference, ΔE^* , of 2 or less.

Spectrometric curve matching has the advantage that a rather precise spectral match can be, and frequently is, obtained.⁸ This matching results in very low metamerism, making the match practically independent of both lighting conditions and observers/detectors. It has disadvantages in that a larger dye-bank is required to provide the variety of dyes needed to obtain an acceptable match, as well as requiring a much longer run time in the computer.

Use of a large data bank has an advantage. If there are 21 dyes in the data bank, one has 210 two-dye, 1330 three-dye, and 5985 four-dye combinations possible. Although 5985 combinations may seem excessive, there have been instances where there were less than 30 possible formulations of which only two were acceptable. (All other formulations for that standard had at least one dye with a calculated negative concentration, causing them to be discarded.)

Of course, using a limited number of carefully selected dyes from the data bank can reduce the number of combinations and consequent computer run time. This option is available. Alternatively, one can initially include all of the dyes in the dye-bank, and use a statistical approach. The first cycle usually results in negative concentrations for several dyes; these are eliminated. The cycle is repeated until all of the dyes with negative concentrations have been removed. Dyes with minor concentrations are included only if they pass a

statistical test. This procedure has the advantage that computer run time is considerably shortened, especially in those cases where there are thousands of combinations possible. (Although one would expect the dye selection for the final formulation to be independent of the procedure, in the two cases tested the statistical procedure provided formulations which were decidedly inferior to the best calculated by the combinatorial procedure.) The dyes with negative concentrations can be eliminated in one cycle using the Simplex procedure as shown by Ohta and Urabe.

Steps 2, 3, and 5 of the spectrophotometric approach will now be discussed in more detail to provide clarification.

Step 2. Saunderson correction: One of the problems is the correction for surface (specular) reflectance and internal (body) reflectance. A rigorous mathematical treatment including both surface and internal reflectance is very difficult¹⁰ due to the rod-like structure of the filaments of synthetic yarns. Consequently, the Saunderson correction (although derived for a plane surface)

$$R = (R^{\circ} - k_1)/(1 - k_1 - k_2 + k_2 R^{\circ})$$

was used.¹¹ R° is the observed reflectance, k_1 is the specular reflectance coefficient, k_2 is the diffuse internal reflectance coefficient, and R is the corrected reflectance. According to Stearns, as long as the reflectance is above five percent, the surface reflectance can be ignored. However, for dark standards, such as the brown and dark green camouflage colors, the spectral reflectance is frequently well below five percent at many wavelengths. Surface reflectance can be estimated by preparing a series of dyeings at increasing concentrations of dye until the minimum reflectance value becomes relatively constant. This value is often taken as the effective surface reflectance. Alternatively, both k_1 and k_2 can be estimated empirically.

Step 3. Additive functions: The additive function used was the Kubelka-Munk equation. An alternate function by Mudgett and Richards may be better, especially for plane surfaces, but was not used because 1) its implementation requires a substantial computer program, which would considerably lengthen the already long run time, and 2) the fabric surface is far from being planar.¹²

Step 5. Interpolation: The problem is one of obtaining a function that relates the K/S values to the concentrations and that accurately represents the K/S values between concentration points. Finding such a function proved to be difficult because of the unequal spacing of the abscissas, such as 0.1, 0.5, 1.0, and 2.0 percent, and the requirement that the curve pass through the origin. Several ways were tried:

1. a polynomial fit to the points,
2. least-squares,
3. a cubic-spline function.

The first method, although quite attractive since the plot goes through all the data points, has the disadvantage that the plot may "meander" between

them, a known polynomial behavior. Computer plots of a set of data showed this meandering to be true in many cases. Consequently, this approach was not used.

The least squares procedure was unacceptable also. It is frequently used because the plot is "well-behaved" between points, although it never passes through them. When one has numerous data points, a high degree polynomial can be used permitting the plot to reasonably conform to the general trend of the data points. In this case we have only five points. Initially a spot check of the curves obtained using a function of the form,

$$K/S = aC + bC^2 + cC^3$$

where a, b, and c are coefficients, and C is the concentration, revealed good behavior. However, an actual dyeing using this relationship was not very successful. A careful examination of all of the computer plots, four dyes at 16 wavelengths each, showed many plots in which points at concentrations of 0.1 and 0.5 percent were slightly "out of line" resulting in considerable excursions of the plots between the points at the higher concentrations, thereby causing inaccurate interpolation.

The cubic-spline function offers both advantages; it passes through the data points, and is "well-behaved" between them permitting reasonably accurate interpolation. A cubic-spline function is constructed from a set of cubic polynomials. Each cubic passes through only two adjacent points. In this case, since we have four points plus the origin, there will be four cubic equations. Each cubic joins its neighbor at a data point. At these points the values of the functions and the first derivatives of the two curves are mathematically forced to be identical so that the juncture of the two cubic plots is smooth. Thus, although four different curves are involved, the spline function passes exactly through each point; and, since the polynomial is of low degree and the slopes are specified at the data points, the function is "well-behaved" between them. The main disadvantage with this approach is that one never knows in advance which of the cubic equations is applicable because the dye concentration required could fall in any of the four intervals. This difficulty is overcome by iteration, and is the main reason for the long run time. Minor disadvantages are: the slopes at the end points must be arbitrarily set; there is a comparatively large number of parameters involved (four parameters for each cubic); the actual curve between points may not be a cubic; and occasionally the algorithm fails to converge.

AN EMPIRICAL INVESTIGATION

In calculating a formulation using the spectrophotometric approach, one tries to match the reflectance curve of the standard from 400 to 900 nm at 10 nm intervals. Thus 51 points are involved. However, in the weighted ordinate method, only three values, the tristimulus values, are matched. It was felt that the additional precision provided by the former procedure might make it possible to find an empirical correction for the problem of dark samples.

The Kubelka-Munk function is reputed to hold better for standards at moderate levels of lightness than for very dark standards. This behavior is

probably because of an assumption made in its derivation, and is interpreted to mean that for very dark standards, the sum of the K/S values of the dyes used to dye a standard is significantly different from the K/S value of the standard obtained, at most wavelengths. At a given wavelength, the sum of the K/S values of the known dyes at the known concentrations should be consistently greater or less than the K/S value of the standard. The difference can be diminished by using the transformation,

$$R = a/(R^o)^4 + b/(R^o)^5$$

where R is the corrected reflectance, R^o is the observed reflectance, and "a" and "b" are adjustable parameters. Only low reflectance values (less than 5%) are substantially changed. For a standard for which the dyes and their concentrations were known, values of a and b could be determined that gave a much improved formulation. The same values of a and b, however, provided much poorer formulations in many of the 42 cases where the formulations were also known. Many modifications of the Kubelka-Munk equation were tried with the same result. Additional computer programs designed to locate the source(s) of the errors were written without success. This fact strongly indicates that the currently held belief (hypothesis) that the Kubelka-Munk relation does not hold for dark standards may not be warranted. It was felt that if the error in the Kubelka-Munk equation was the dominant error, then one of the numerous mathematical modifications tried would have substantially reduced the formulation error in all cases. By trial and error, the best values found for the surface and internal reflectances in the Saunderson equation were roughly 0.0002 for k_1 and 0.43 for k_2 .

EQUIPMENT AND PROCEDURE

The Hunter D54P spectrophotometer was used to obtain reflectance values in the visible range. Reflectance readings in the N-IR were taken on a Diano/Hardy II. A UNIVAC 1106 computer was used for the calculations.

The dyeing procedure is as follows: The dye stock solution for the individual dyeings was prepared by using one gram of dyestuff to one liter distilled water. The dyestuff was weighed in a 40 mL beaker on an analytical balance to within one milligram. Approximately 10 mL distilled hot water was added to the beaker. The dye was stirred into a paste with a glass stirring rod, then transferred to a 200 mL beaker. More hot water was added and all lumps and particles were broken up and dissolved. Additional distilled water was then added to fill a 1000 mL volumetric flask to the mark. Ten grams of spun nylon 6,6 fabric were dyed in a bath ratio of 45:1 (water to fiber).

The equipment used for dyeing was a Renigal Dye Control Press-66. This equipment provides a steady increase of the dye-bath temperature and also accurate dyeing times. All samples dyed with acid dyes were brought to a boil in 45 minutes, boiled for one hour, and then cooled and rinsed. The pH was controlled by adding three percent (of the weight of the fiber) of ammonium sulfate in all dyeings. Various percentages of a wetting agent were used. To obtain a mock-dyed sample, the above procedure was repeated without the dye.

RESULTS

Formulating a match depends not only on the computer program but also on the number and variety of colors available. To remove this latter dependence, since the number of dyes covering the visible and N-IR in our data bank is not very extensive at this time, three standards were prepared using dyes in the data bank. The three standards were very close in color to the brown, light green, and dark green of the Standard Woodland Pattern, Nyco Twill. They were then matched over the visible and N-IR using the domestic (DOM) computer color-matching program, and over the visible range using a commercial (COM) computer program. Both programs selected the set of dyes used in the preparation of each standard for the formulation. For a given standard the formulations differed substantially in the amounts of the dyes to be used. Dyeings were then prepared; the results are shown in Table 1 (D65 and 10° observer) and Figs. 2-7.

Table 1. Comparison of Colorimetric Values Obtained from Domestic and Commercial Computer Color-matching Programs, with the standards.

	X	Y	Z	ΔL^*	Δa^*	Δb^*	ΔE^*
Standard-Brown	6.55	6.47	5.65				
DOM, Vis & N-IR	6.88	6.74	5.80	0.64	0.57	0.07	0.86
COM, Vis	7.13	7.02	6.32	1.29	0.36	-1.03	1.69
Standard-Light Green	9.81	9.84	6.48				
DOM, Vis & N-IR	9.88	9.88	6.33	0.06	0.25	0.74	0.78
COM, Vis	10.18	10.14	6.66	0.53	0.59	0.22	0.82
Standard-Dark Green	4.40	4.85	4.38				
DOM, Vis & N-IR	4.24	4.63	4.15	-0.64	0.50	0.11	0.82
COM, Vis	4.10	4.43	3.94	-1.25	1.15	0.24	1.72

The main criterion is the ΔE^* value. The smaller this value, the better the color-match between the trial dyeing and the standard. As is apparent, the domestic computer program provides ΔE^* values that are less than the ΔE^* of the commercial program, i.e., a smaller color difference. This relationship has usually been the case. Frequently the ΔE^* value for the domestic program is about half that of the commercial program.

Comparison of Figs. 2 and 3, Figs. 4 and 5, and Figs. 6 and 7 shows that the matches in the N-IR are better for the domestic program in two of the three cases. The fact that the commercial computer program provides acceptable matches in the N-IR is to be expected, in these cases, since the dyes selected for the trial dyeings were those used to dye the standard.

When dealing with color standards where the formulation is unknown, one would not expect the matches to be as accurate as those given above. This

expectation is shown by a comparison of Figs. 2 to 7 with Figs. 8 to 10, which are spectral plots of some Tan standards (solid lines) and the corresponding first trial dyeings (dotted lines). (In the latter case, Figs. 8-10, the trial samples were printed. The calculations were based on printed primaries.)

Besides the paucity of primaries there are the usual problems brought about by the passage of time, such as use of different dye batches and variations in the properties of the substrate. Generally, however, the dotted lines conform to the shape of the corresponding solid lines from 400 to 900 nm in all cases. The colorimetric data (D65 and 10° observer) are given in Table 2.

Table 2. Colorimetric Values for the Tan Standards and Domestic Matches

	X	Y	Z	ΔL^*	Δa^*	Δb^*	ΔE^*
Tan 104, STD	24.53	25.64	19.46				
DOM	23.53	24.25	18.30	1.35	-1.46	0.05	1.99
Tan 105, STD	16.57	16.93	11.63				
DOM	16.83	17.10	12.04	-0.21	-0.60	0.74	0.98
Tan 106, STD	42.77	44.62	37.43				
DOM	42.13	43.66	36.22	0.64	-0.85	-0.43	1.14

CONCLUSIONS

It has been shown that the spectrophotometric procedure can provide color-matches in the visible range which are of accuracy comparable to those provided by the colorimetric procedure, and also a good spectral match in the N-IR.

It was found that a closer formulation was obtained in about 65% of the cases when the Saunderson correction was included in the calculations.

No modification of the Kubelka-Munk equation or transformation that could consistently give substantially improved formulations was found, indicating that the equation is accurate within the current experimental error.

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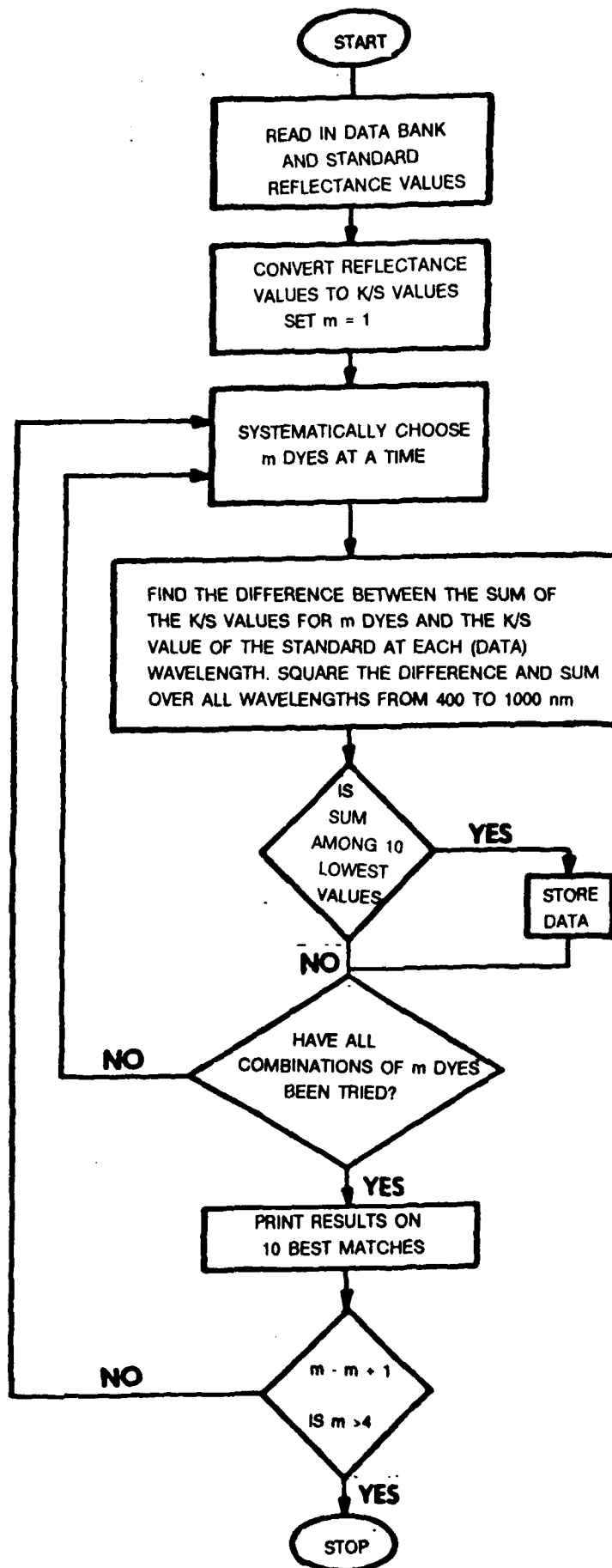


Figure 1. Flow chart for color matching using the spectrophotometric approach.

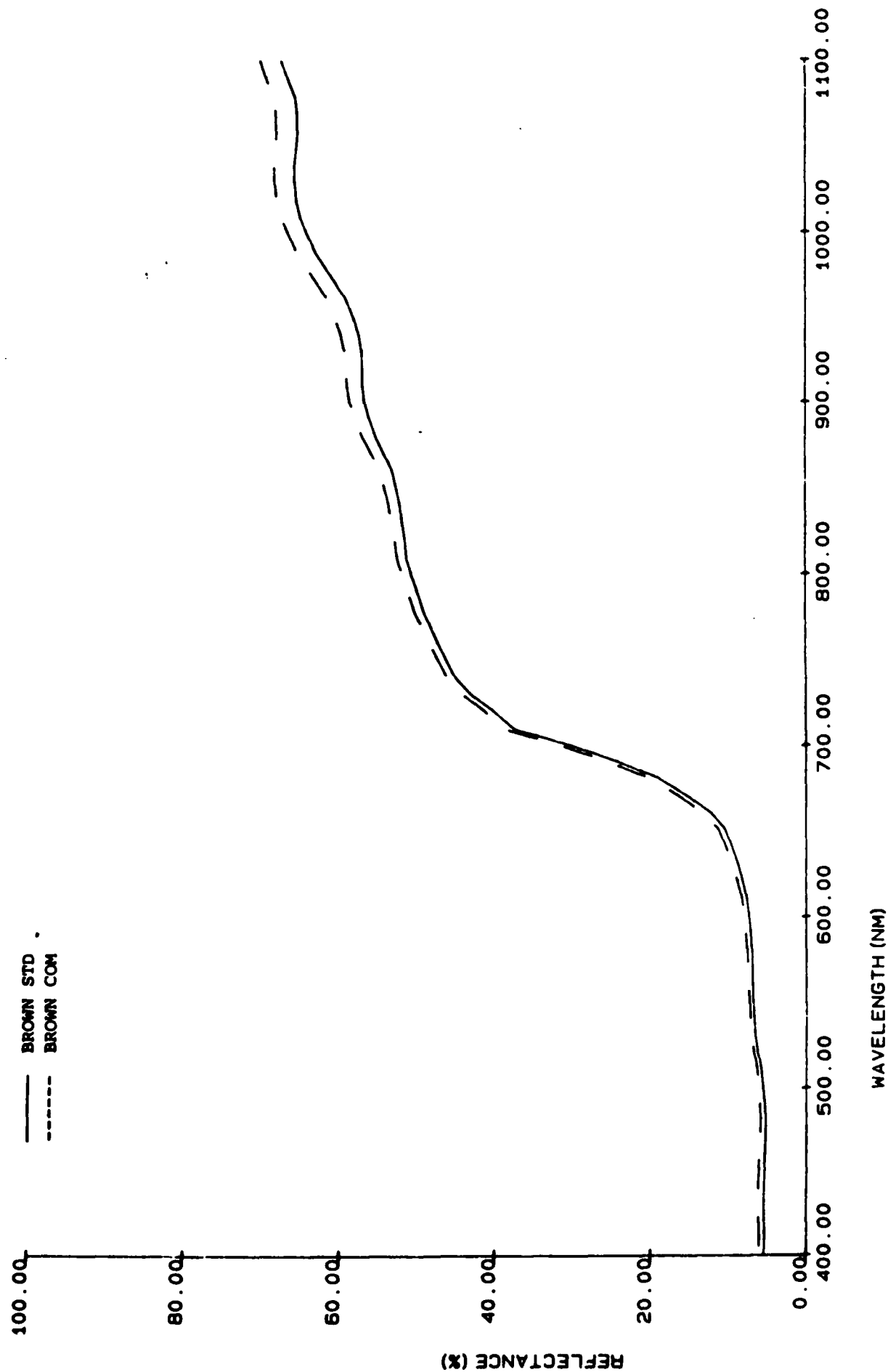


Figure 2. Brown. Solid line: Standard. Dashed line: Match obtained using the commercial color-matching computer program.

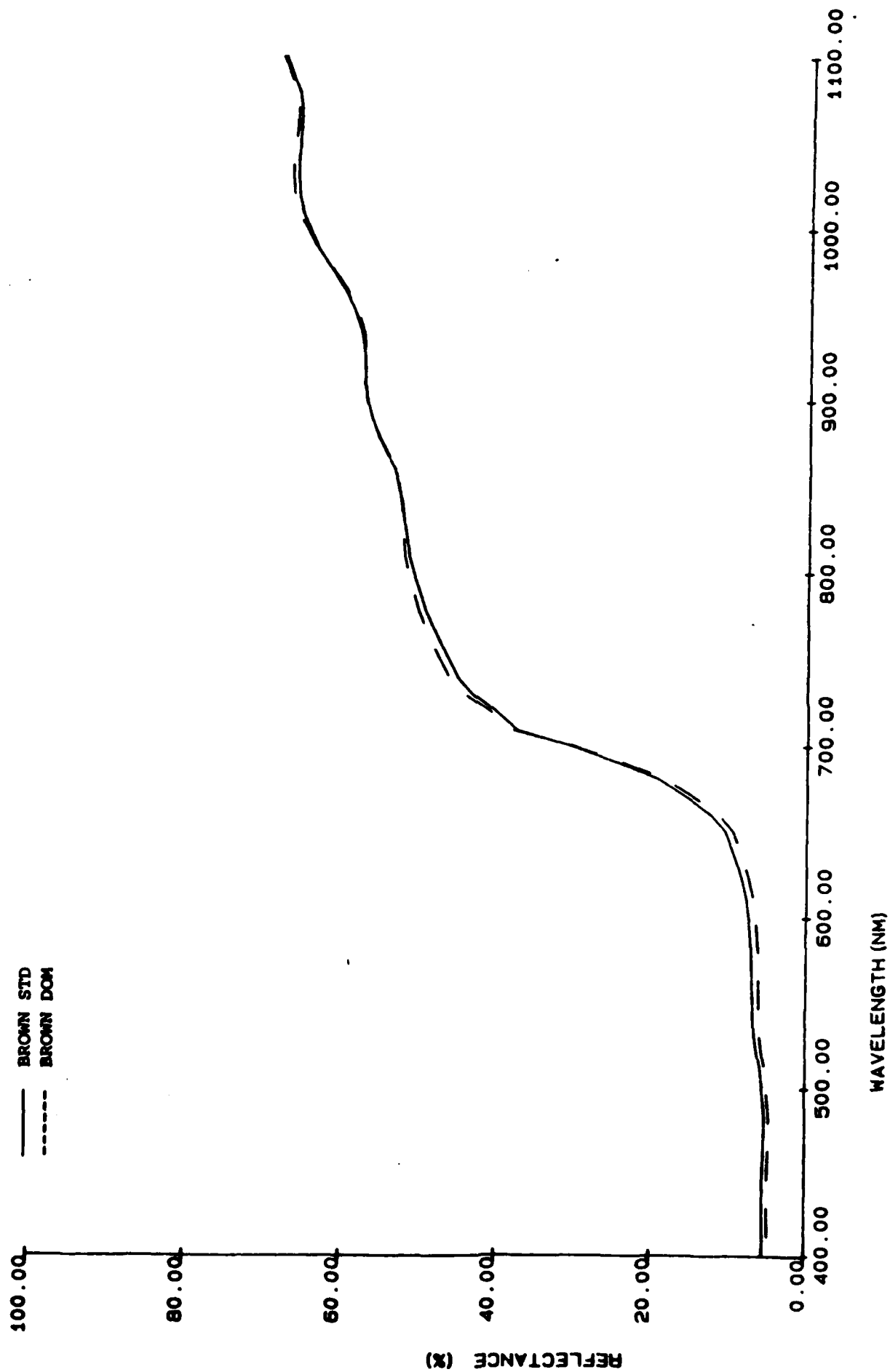


Figure 3. Brown. Solid line: Standard. Dashed line: Match obtained using the domestic color-matching computer program.

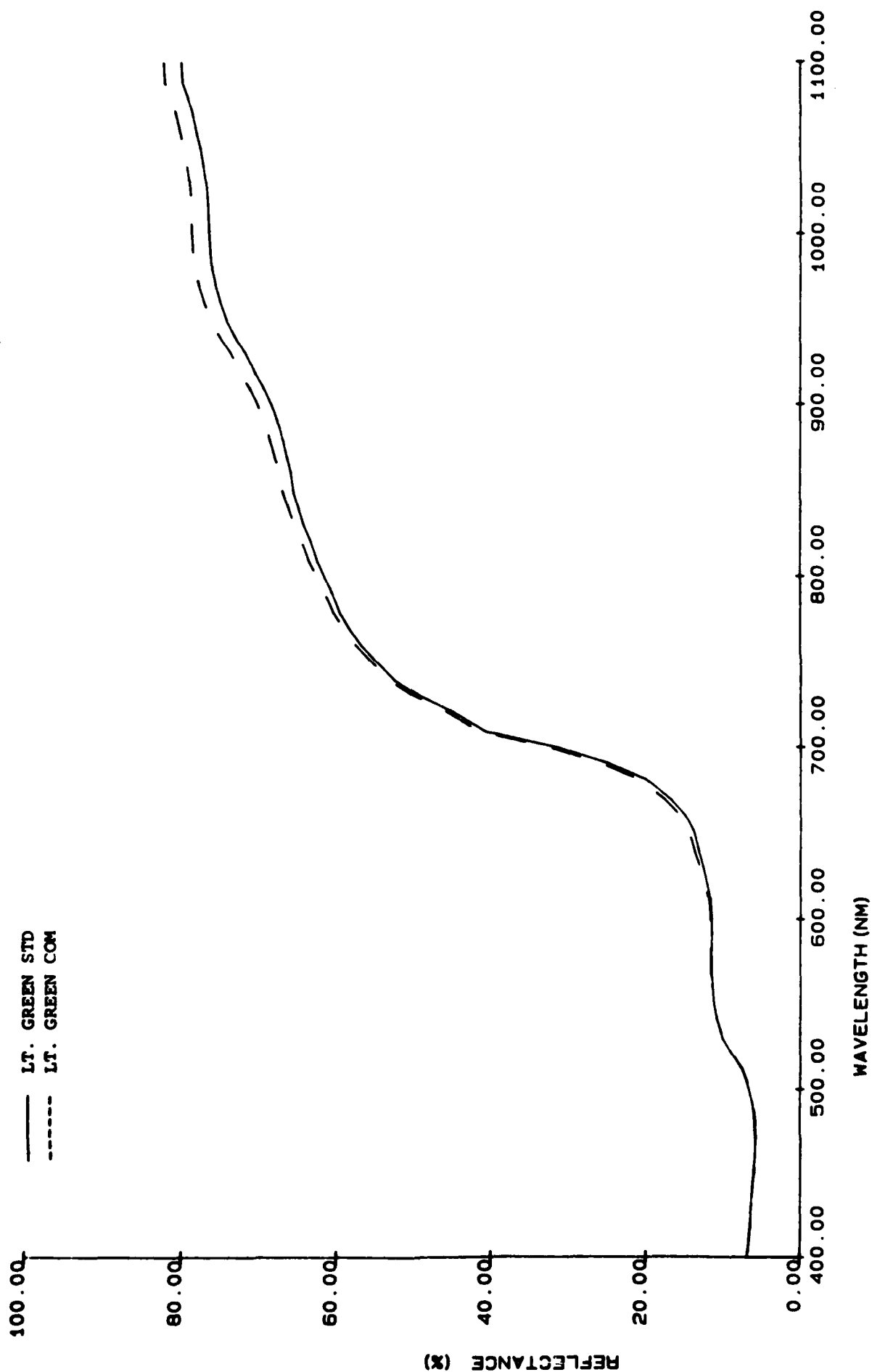


Figure 4. Light Green. Solid line: Standard. Dashed line: Match obtained using the commercial color-matching computer program.

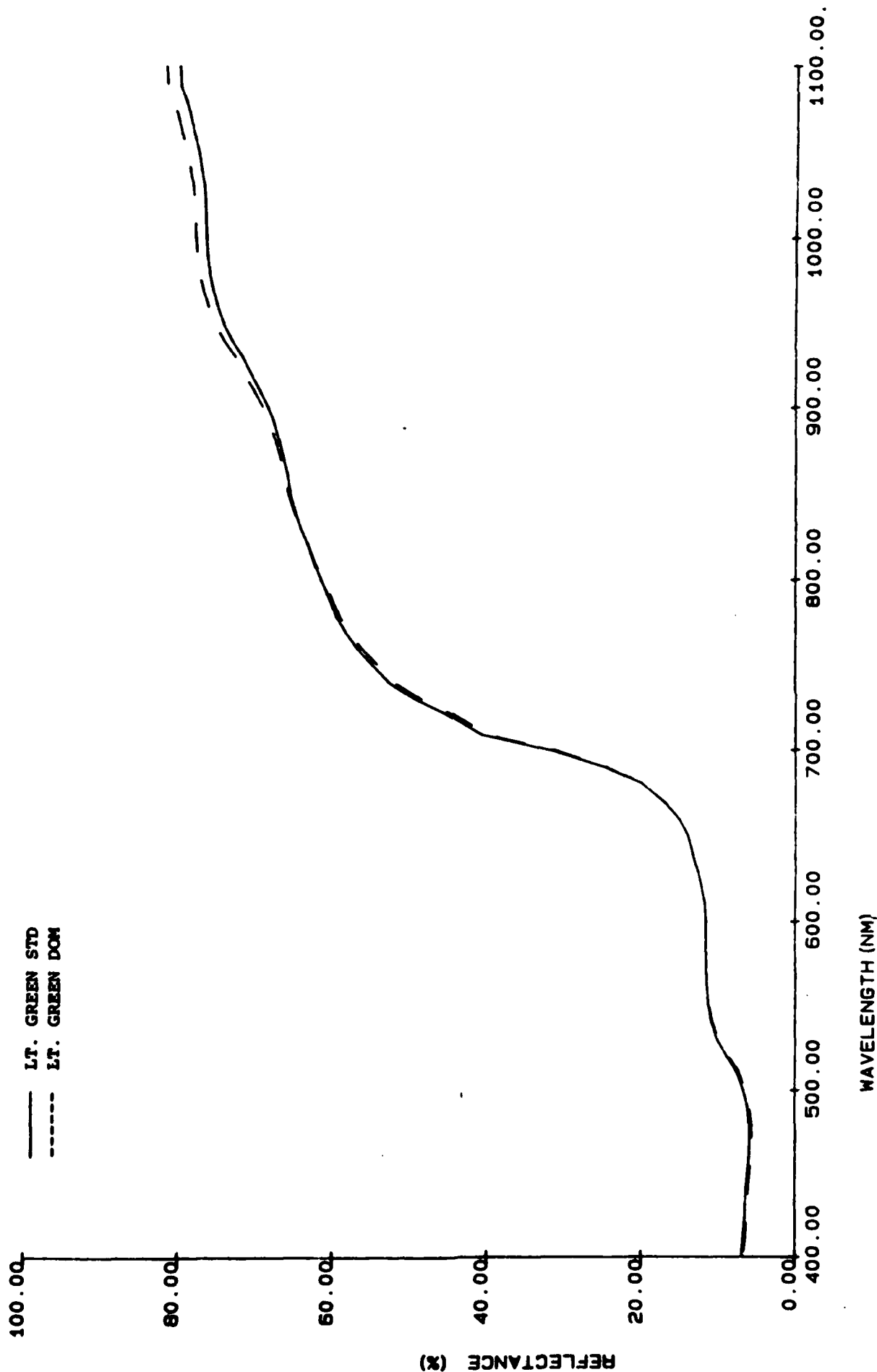


Figure 5. Light Green. Solid line: Standard. Dashed line: Match obtained using the domestic color-matching computer program.

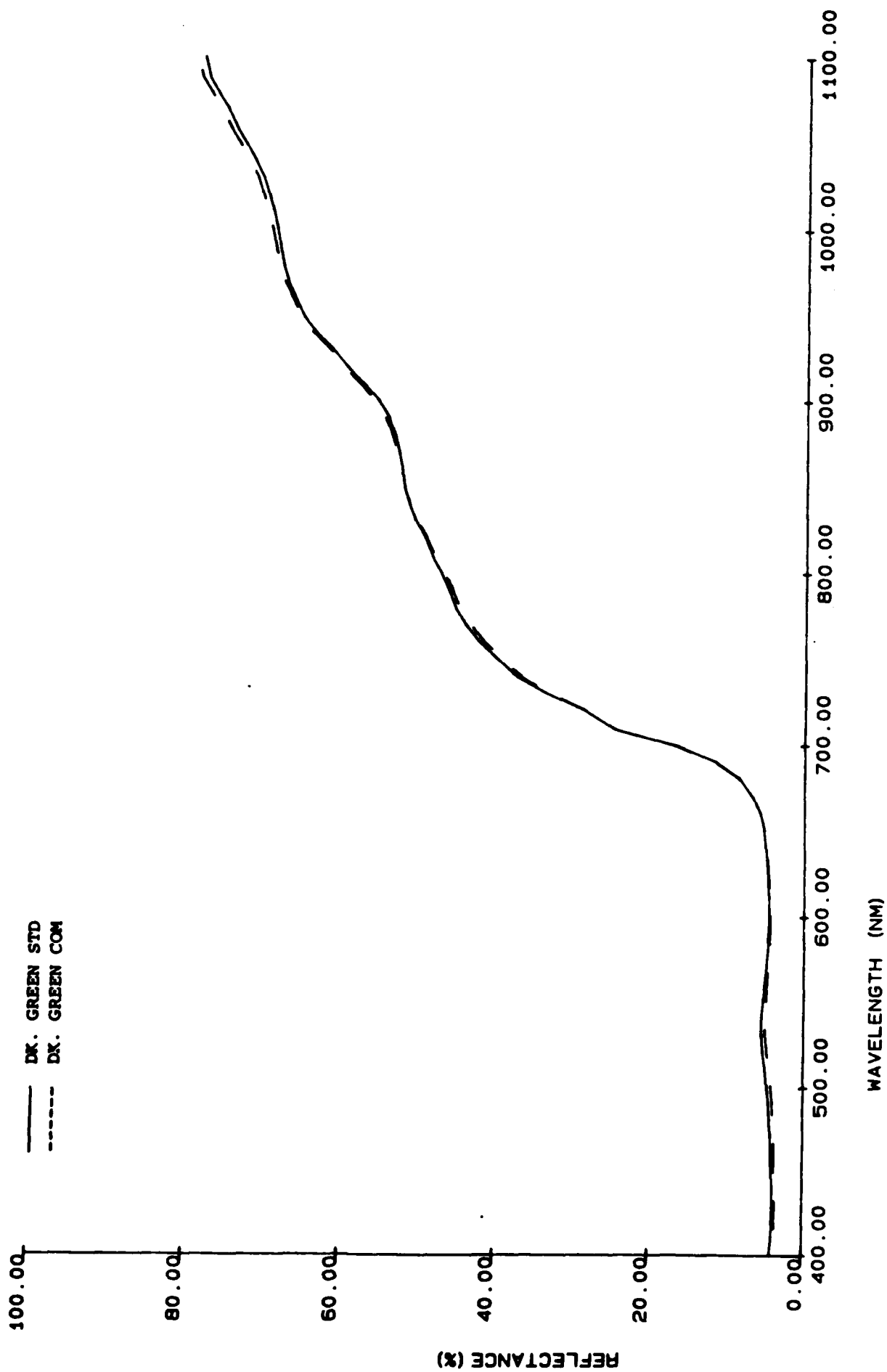


Figure 6. Dark Green. Solid line: Standard. Dashed line: Match obtained using the commercial color-matching computer program.

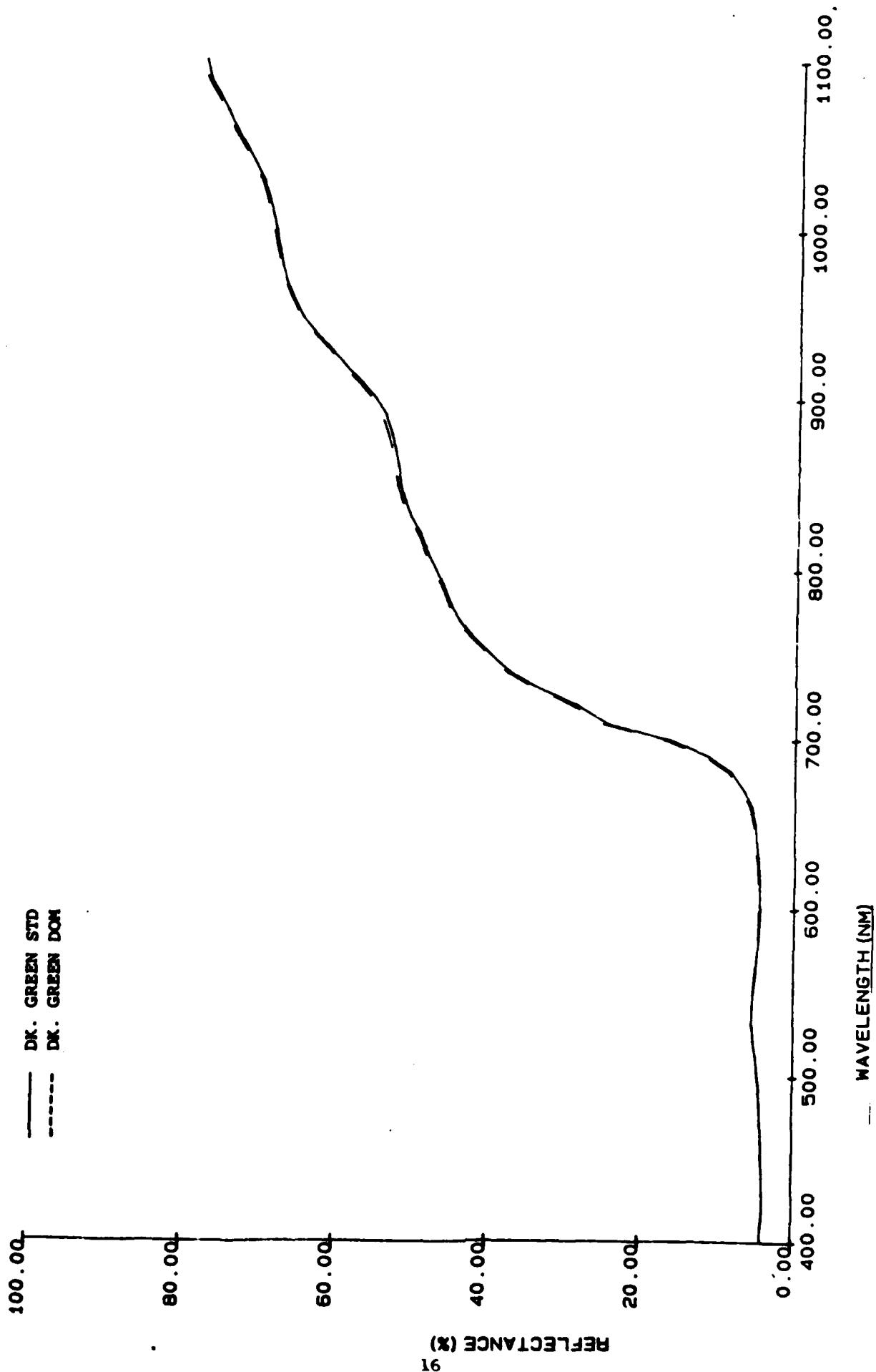


Figure 7. Dark Green. Solid line: Standard. Dashed line: Match obtained using the domestic color-matching computer program.

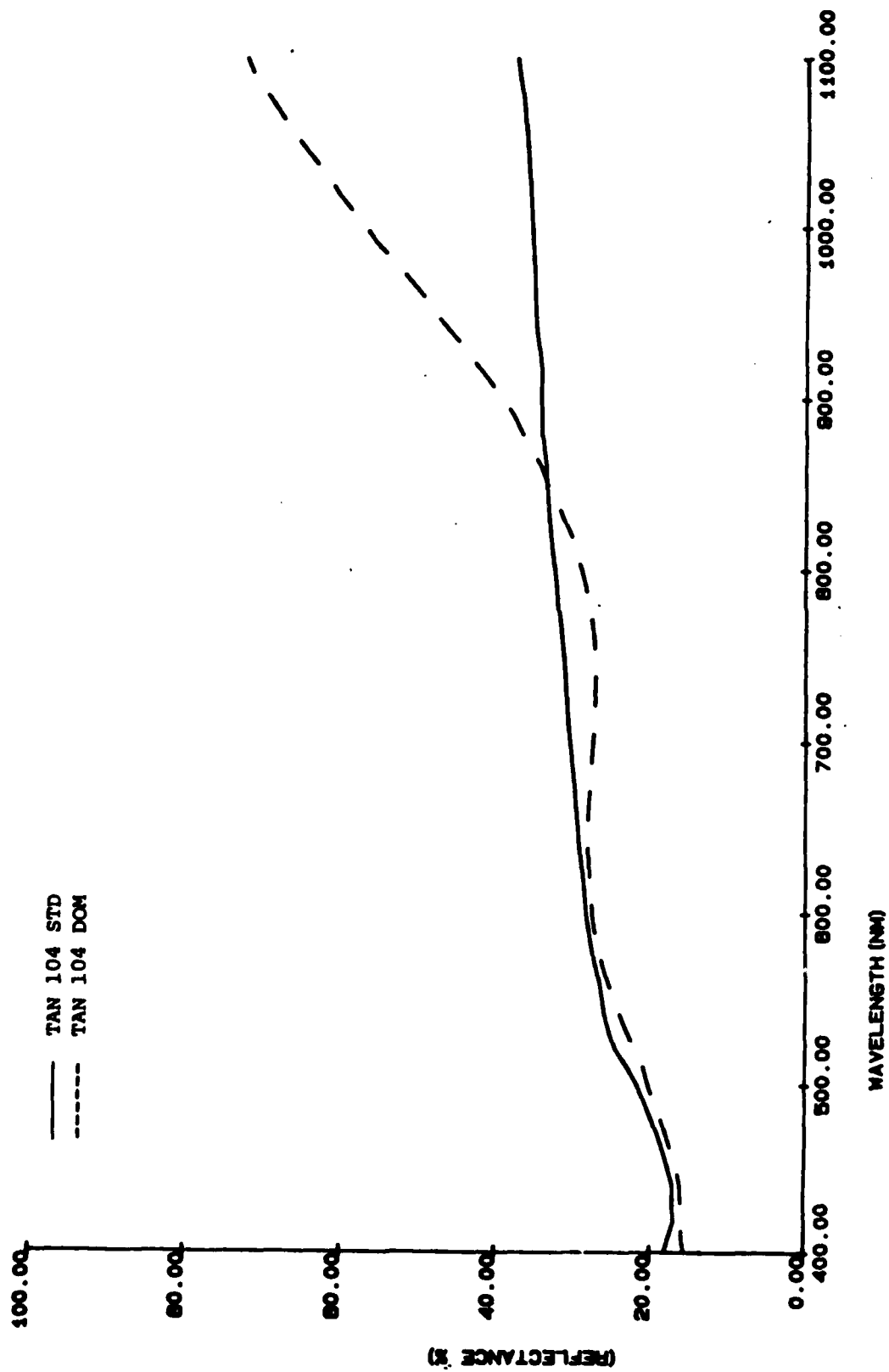


Figure 8. Tan 104, Standard (formulation unknown) and spectrometric match (400-900 nm)

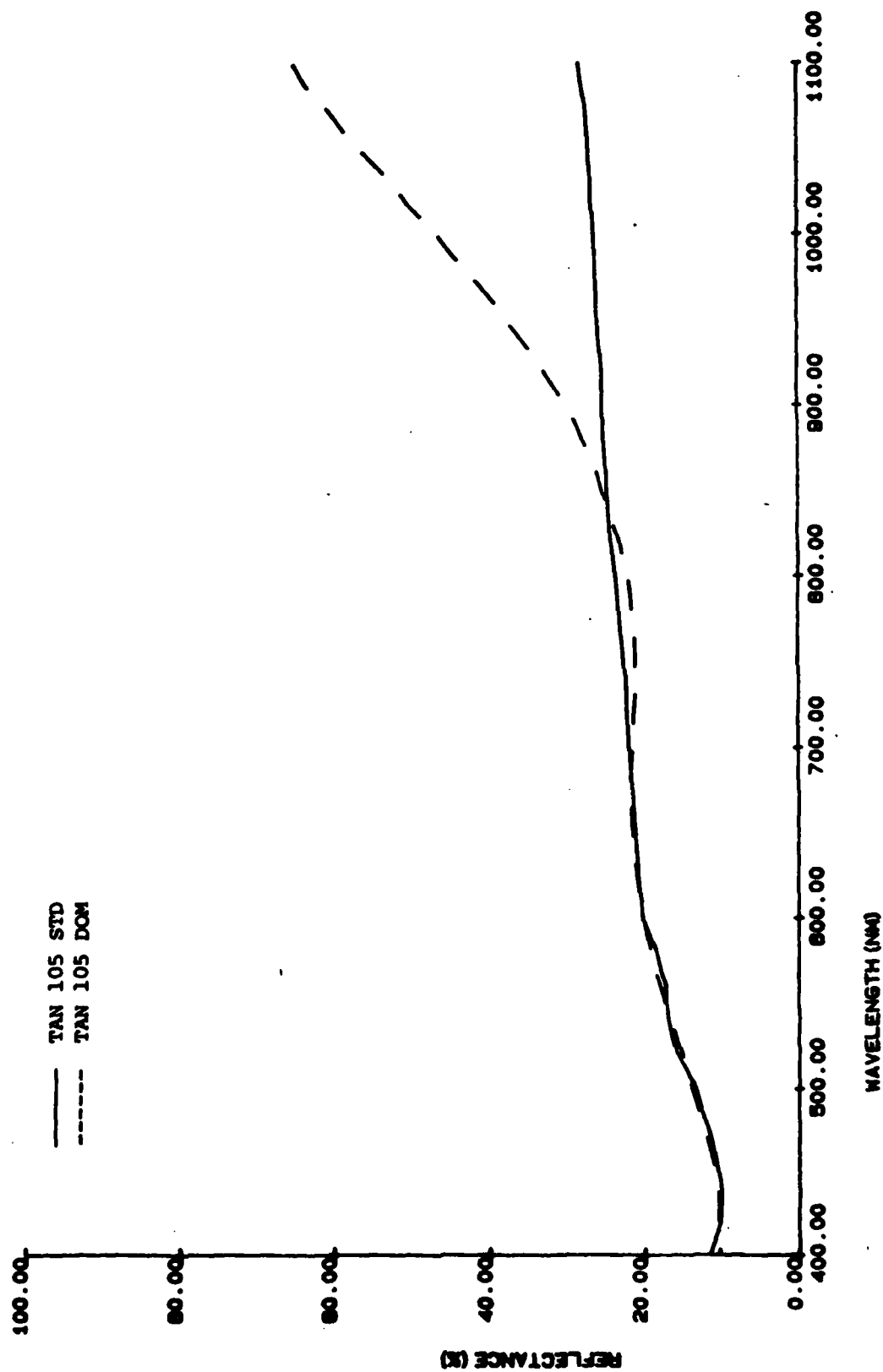


Figure 9. Tan 105, Standard (formulation unknown) and spectrometric match (400-900 nm).

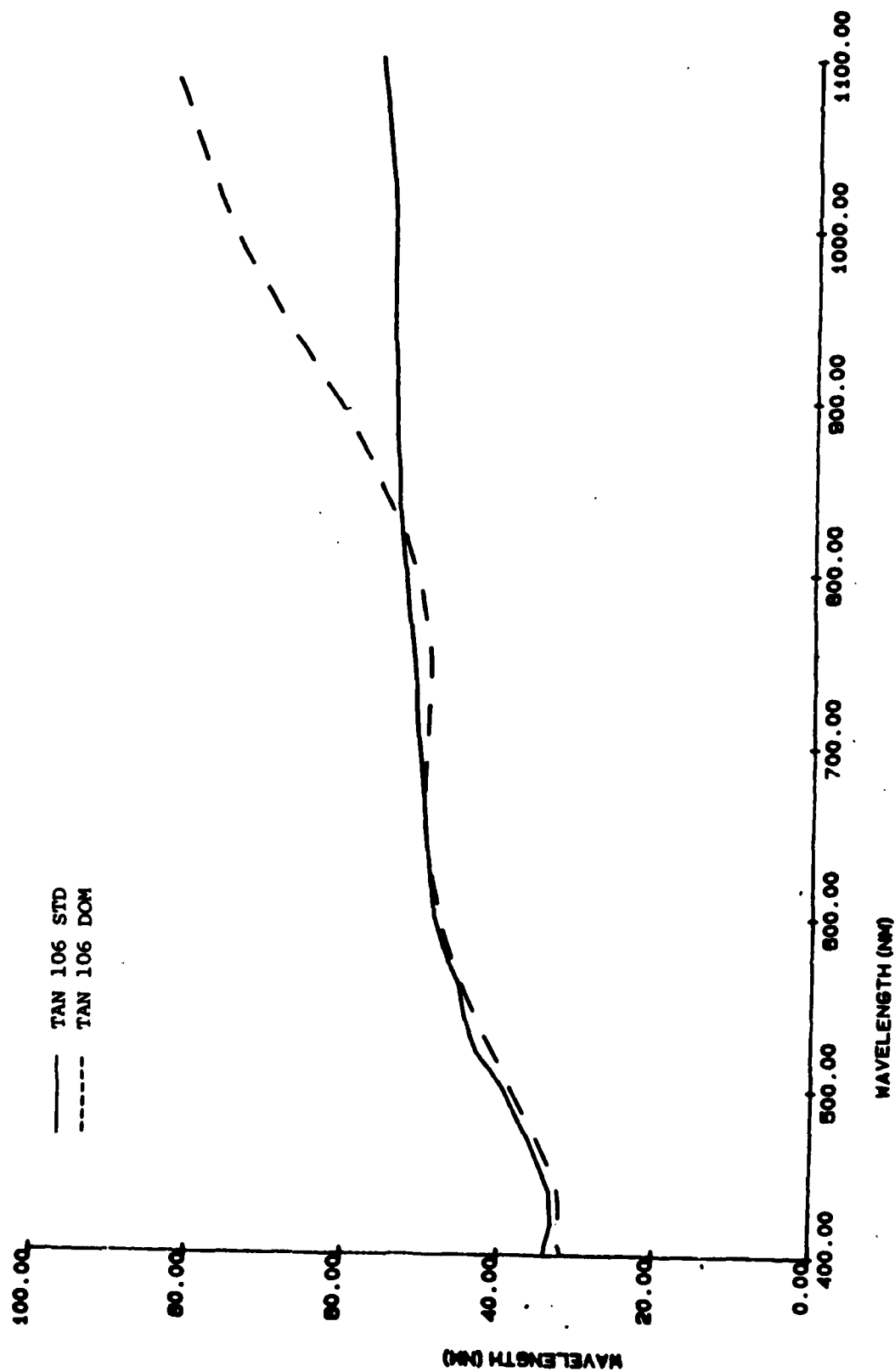


Figure 10. Tan 106, Standard (formulation unknown) and spectrometric match (400-900 nm).