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GENERATION OF UNIFORM CHROMATICITY SCALE IMAGERY FROM LANDSAT DATA

Job Order 73-743

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LYNDON B. JOHNSON SPACE CENTER
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16 Abstract

A method used for generating uniform chromaticity scale (UCS) imagery from Landsat data is presented. An algorithm that utilizes the (L*, a*, b*) UCS transformation is developed and some UCS color film products are generated.

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1. INTRODUCTION

This paper documents a method used for generating uniform chromaticity scale imagery from Landsat data. A previous study (ref. 1) was made to map multichannel Landsat data into color space using a maximal chromatic expansion method. This study extends the work of reference 1 to the utilization of a uniform chromaticity scale (UCS) in the form of color film products.

Familiarity on the part of the reader with standard colorimetric nomenclature is assumed; references 2 and 3 are recommended for the novice.

The motivation behind generating UCS imagery from Landsat data is uniform, controlled perceptibility of color difference caused by differences in Landsat data vectors. One can move a certain distance around any color center before noticing the difference between the color center and the translated point. The distance one can move depends on the direction of the motion and on the location of the color center itself. The generally ellipsoidal surface surrounding the color center is one step in perceptibility from the color center. The nonlinear transformation to a UCS space is such that the ellipsoids become spheres with the same radius at all color centers. In this circumstance, the color difference is simply the length of the straight line connecting the points whose color difference is desired.

One of these transformations was used to generate the UCS imagery from the Landsat data reported herein. A description of this transformation is given in section 2. Formulation of the algorithm used for generating UCS imagery is presented in section 3. Conclusions and recommendations of this study can be found in section 4.

2. DESCRIPTION OF THE UCS TRANSFORMATION USED IN THIS STUDY

The (L*, a*, b*) UCS transformation (ref. 4) was used in this report. In a UCS space, a Euclidean metric is proportional (approximately) to perceptibility of color difference. (See reference 2 for a description of some color-difference formulas and a more thorough exposition of the subject.) The (L*, a*, b*) transformation was adopted by the International Illumination Committee [(IIC); better known as the Commission Internationale de l'Eclairage (CIE)].

Let X, Y, and Z be the tristimulus values; the UCS space is generated from the tristimulus values as follows:

$$L^* = 25\left(100\frac{Y}{Y_0}\right)^{1/3} - 16 \quad ; \quad 1 \leq Y \leq 100 \tag{1}$$

$$a^* = 500\left[\left(\frac{X}{X_0}\right)^{1/3} - \left(\frac{Y}{Y_0}\right)^{1/3}\right] \tag{2}$$

$$b^* = 200\left[\left(\frac{Y}{Y_0}\right)^{1/3} - \left(\frac{Z}{Z_0}\right)^{1/3}\right] \tag{3}$$

where X_0, Y_0, and Z_0 define the color of the nominally white object-color stimulus; i.e., the illumination spectrum, taken here as that of the light table illuminating the transparencies. The L* coordinate may be thought of as the lightness or brightness of a color, a* as the green/magenta balance, and b* as the yellow/blue balance.

Slices of the (L*, a*, b*) space (at constant values of a*) that are accessible to the color gun cube of the production film converter (PFC) were generated. Plots of some of those slices are shown in figure 1 for a* values of -10, -5, 0, 5, and 10. In these plots, an edge marked B = 0 indicates that the blue gun count of the PFC is zero at that edge. An edge marked R = 1 indicates that the red gun count of the PFC is 255 at that edge. A point in the enclosed area of any of the plots in figure 1 corresponds to red (R), blue (B), and green (G) PFC gun counts between 0 and 255. A PFC

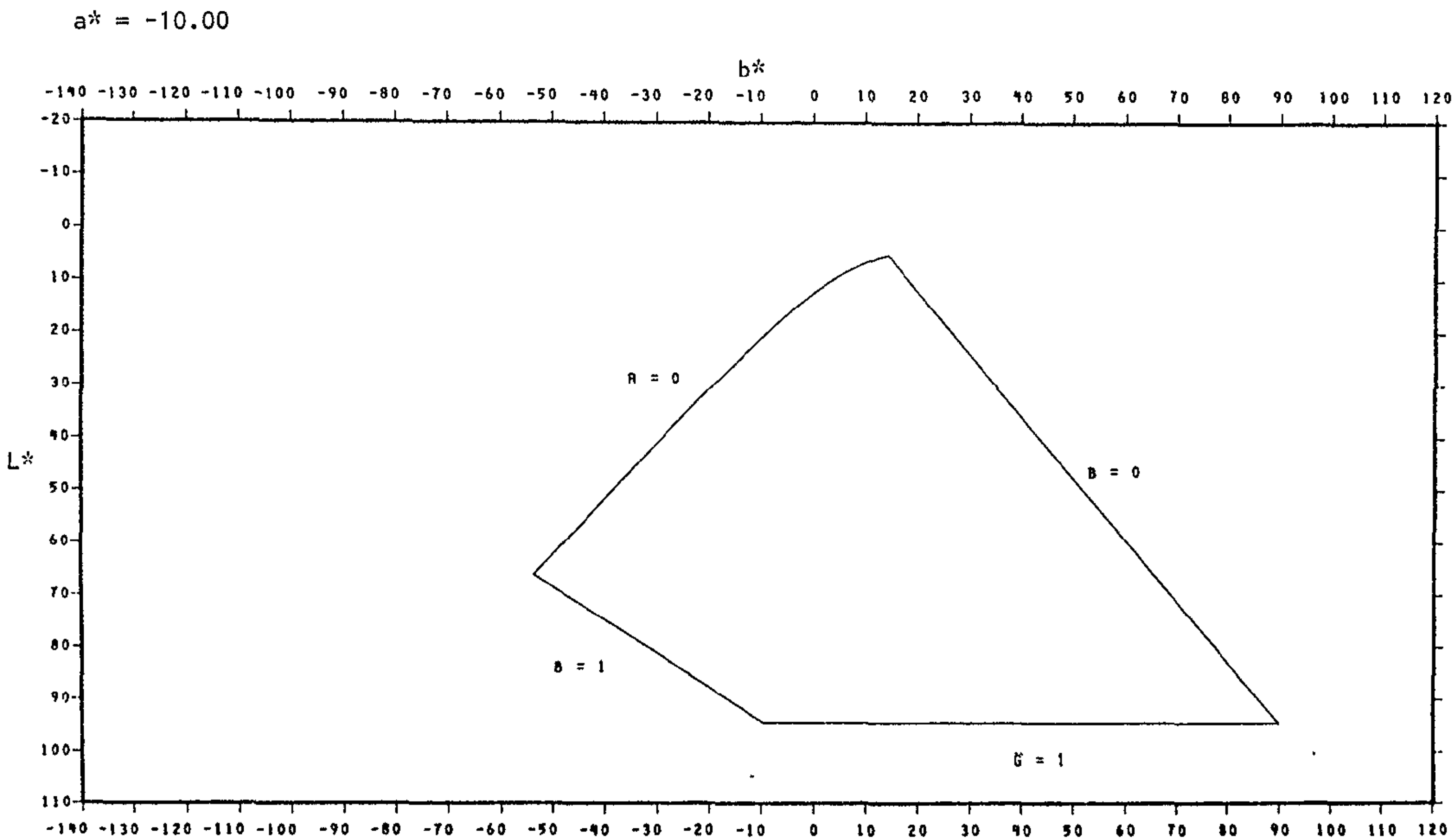
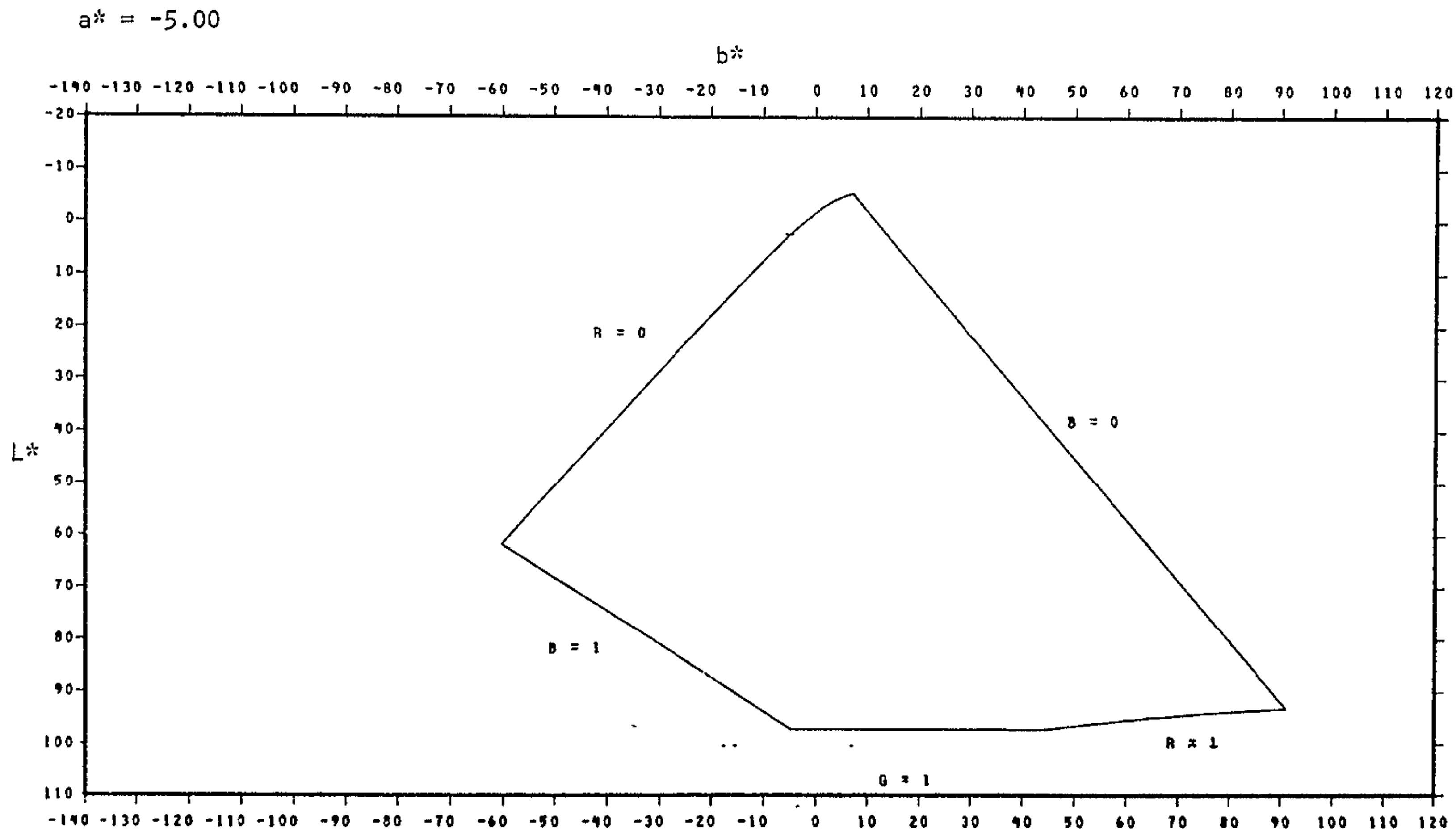


Figure 1.— Slices of the (L*, a*, b*) space at constant values of a* that are accessible to the color gun cube of the PFC.



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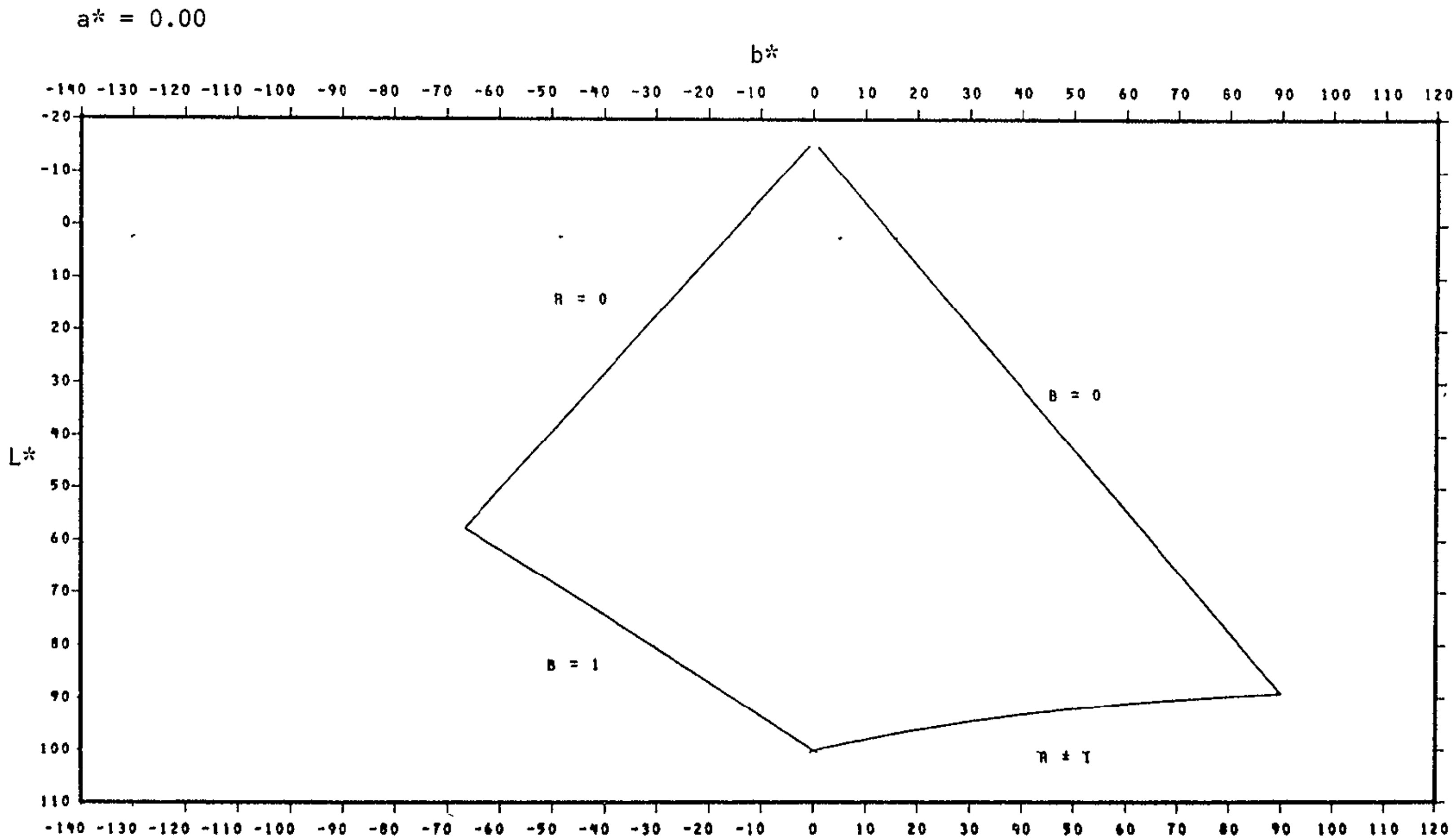

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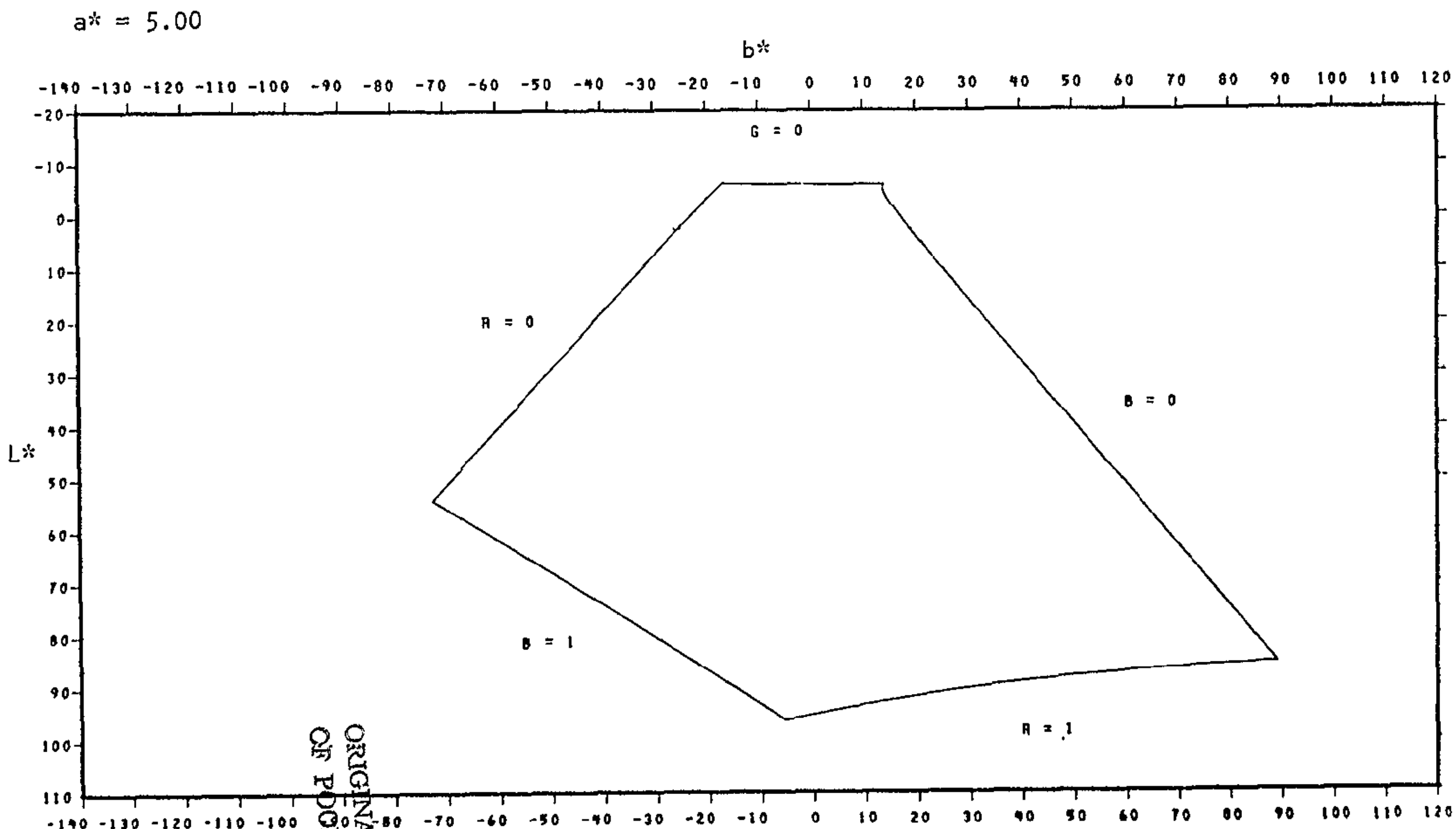

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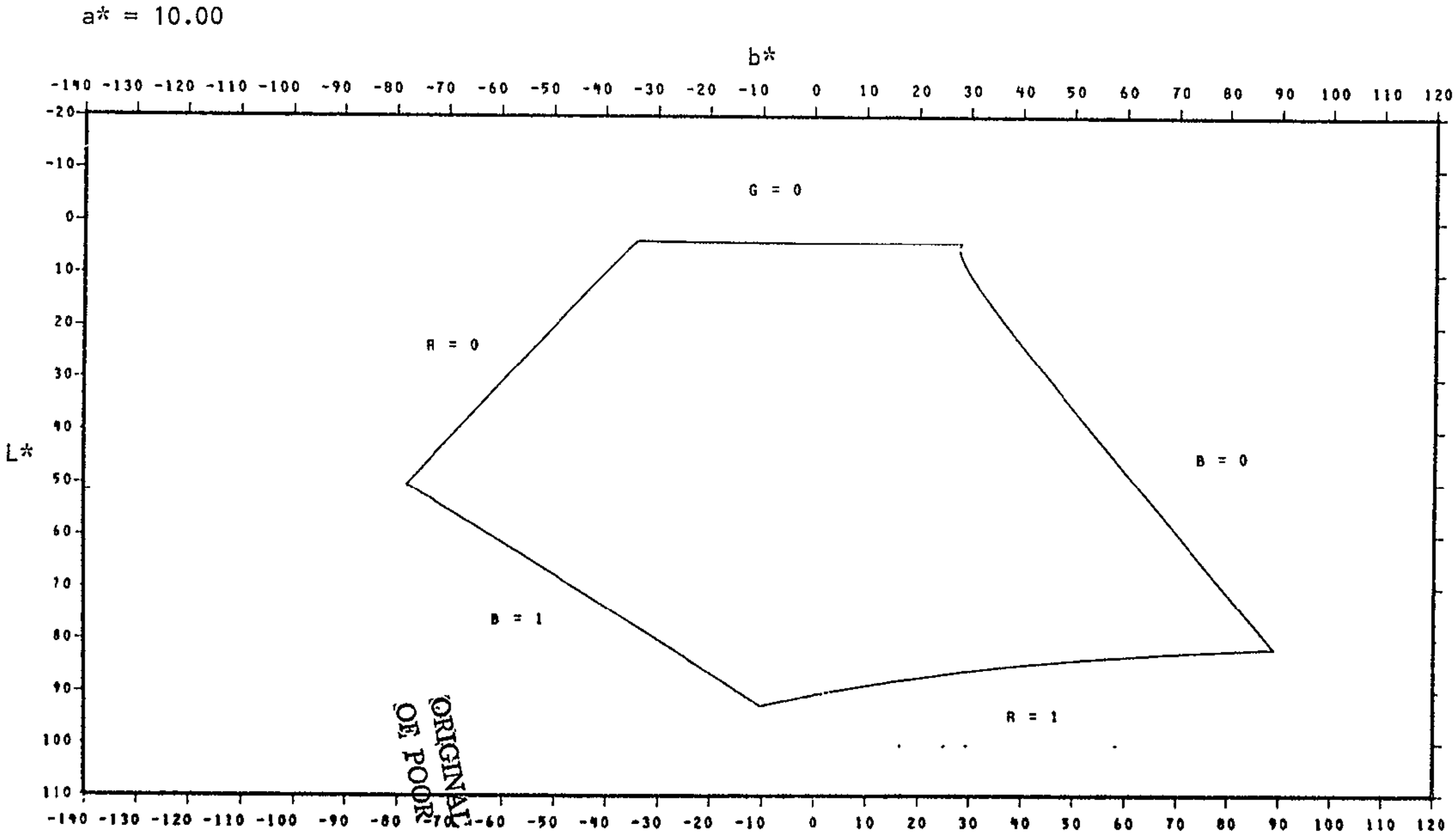


Figure 1.— Concluded.

product of the (L*, a*, b*) space, sliced at a* = 10, is shown in figure 2. Formulas used for calculating gun counts in figure 2 can be found in section 3.

Other UCS transformations exist in the literature (refs. 5, 6). These transformations might be considered in later research. The (L*, a*, b*) space was chosen over those discussed in references 5 and 6 for the following reasons.

a. The (L*, a*, b*) space has been adopted by the CIE as the principal approximation to a true UCS for the object-color solid.

b. Inversion from the (L*, a*, b*) UCS approximation into the CIE (x, y, Y) system is mathematically tractable. According to MacAdam (ref. 7), the ($\mathcal{L}$, j, g) system (ref. 5) is philosophically preferable to the (L*, a*, b*) system for this application. However, there are some considerations, such as the incorporation of Semmelroth's (ref. 8) crispening factor, that create difficulties in using the ($\mathcal{L}$, j, g) system.

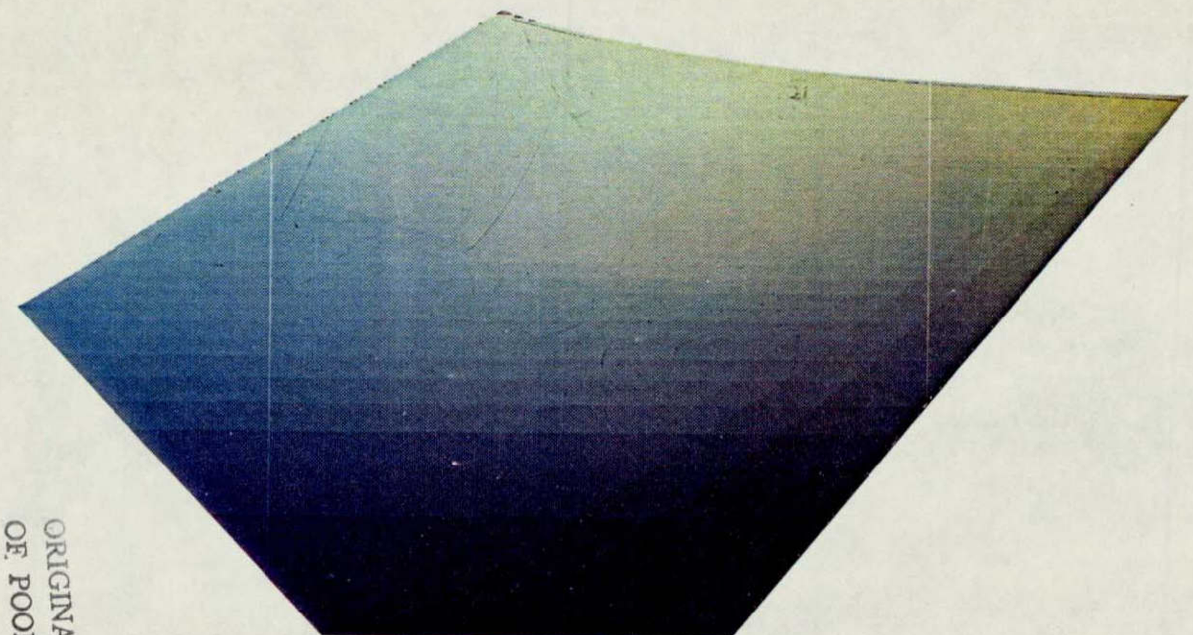


Figure 2.— A PFC product of the (L*, a*, b*) space sliced at a* = 10.

3. FORMULATION OF THE UCS ALGORITHM

In generating UCS imagery, the light table and film parameters are taken into account. The transformation from PFC counts to transmission (wavelength dependent) is regarded as stable. The primary colors considered in this study are red (R), green (G), and blue (B). This section is divided into three parts. The first part deals with calculating the primaries of light table and film chromaticities. The second part deals with fitting a prototype Landsat data structure into the (L*, a*, b*) UCS space. The third part presents the algorithm that generates color gun counts from (L*, a*, b*) values for PFC product along with four UCS images of a Large Area Crop Inventory Experiment (LACIE) segment.

3.1 COLORIMETRIC DESCRIPTION OF THE TRANSPARENCY GENERATION PROCESS

The PFC images a cathode-ray tube (CRT) through color filtration onto color reversal film, which is then developed. The CRT display is controlled by numerical input; for each color, the film density is very nearly linear with respect to input counts. The counts-to-density relationship is carefully maintained in exposing and developing the film, and the relationship is herein regarded as stable.

An approximation is made that the manner of addition of sequential images can be expressed in the form

$$X = \sum_i X_i \tag{4}$$

where X is the first tristimulus value and i is an index for the red, green, and blue PFC primaries. This also exists for Y and Z assuming that the film system produces the same final result as would be obtained by separation images projectively added. The approach avoids certain real-world problems such as masking (ref. 9). (The matter is further discussed in reference 10.) More elegant mathematics are available; therefore, a follow-on study to investigate the effect of more highly precise work is proposed.

Measurements of the spectral radiance of the light table and of the wavelength-dependent transmission of film patches from full activation of each primary in the PFC were made. These measurements were reduced to the CIE chromaticity coordinates of the four sources.

Parameter	x	y
Light table	0.3684	0.4131
Red	.5529	.4458
Green	.3603	.5730
Blue	.1919	.1540

Under the usual definition (ref. 4) for the reference white, Y, for the light table, was taken to be 100. By requiring that the primaries be added at full activation to give the light table's own illumination, one finds that the tristimulus values for the primaries (fully activated) and for the light table are

$$\begin{pmatrix} X_0 & X_R & X_G & X_B \\ Y_0 & Y_R & Y_G & Y_B \\ Z_0 & Z_R & Z_G & Z_B \end{pmatrix} = \begin{pmatrix} 89.18 & 39.74 & 35.90 & 13.53 \\ 100.00 & 32.04 & 57.09 & 10.86 \\ 52.89 & .09343 & 6.646 & 46.13 \end{pmatrix} \tag{5}$$

The activation a_i of the *ith* primary is defined as the ratio of the transmission (measured straddling the peak wavelength) at a given input to the transmission produced by full activation. The tristimulus values produced by the vector activation $\underline{a}$ are then

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} X_R & X_G & X_B \\ Y_R & Y_G & Y_B \\ Z_R & Z_G & Z_B \end{pmatrix} \begin{pmatrix} a_R \\ a_G \\ a_B \end{pmatrix} \tag{6}$$

with the 3-by-3 matrix elements taken from equation (5). Conversely, to produce a given tristimulus value vector, the activation vector

$$\begin{pmatrix} a_R \\ a_G \\ a_B \end{pmatrix} = \frac{1}{100} \begin{pmatrix} 4.966 & -3.037 & -0.7418 \\ -2.864 & 3.552 & .003732 \\ .4025 & -.5056 & 2.169 \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \qquad (7)$$

is required. The details of the counts-to-activation relationship derive from the definition

$$D = -\log_{10} \tau \qquad (8)$$

of the relationship between density, D, and transmission, τ. As mentioned earlier, the density is essentially linear with respect to input counts; therefore, the relationship is fully determined from the following table.

	Red		Green		Blue	
Counts	0	255	0	255	0	255
Density	2.52	0.753	2.182	0.306	2.513	0.694

With all the above information, one can pass in either direction between a primary-counts vector and a tristimulus values vector.

3.2 FITTING LANDSAT DATA SPACE INTO THE UCS SPACE

Two multitemporal LACIE segments were used to generate scatter plots. The Landsat data in each unitemporal segment were rotated using the Kauth transformation (ref. 11) with a bias. The Kauth brightness K_b, Kauth greenness K_g, and Kauth yellowness K_y biases were taken to be 0, 30, and 53 counts, respectively. The scatter plots of Landsat data in the (K_b, K_g) space for segments 1618 and 1645 are shown in figure 3. Figure 4 shows scatter plots of the data in the (K_b, K_y) space. The scatter plots in figure 3 were used to produce an overall Landsat (K_b, K_g) data space scatter envelope. This data space scatter envelope contains the raw K_b and K_g counts; i.e., the bias was removed and was fitted into the (L*, b*) UCS space as shown in figure 5. The UCS space, sliced at a* = 10 (figure 2), was used because it had the best shape and was near-centrally located.

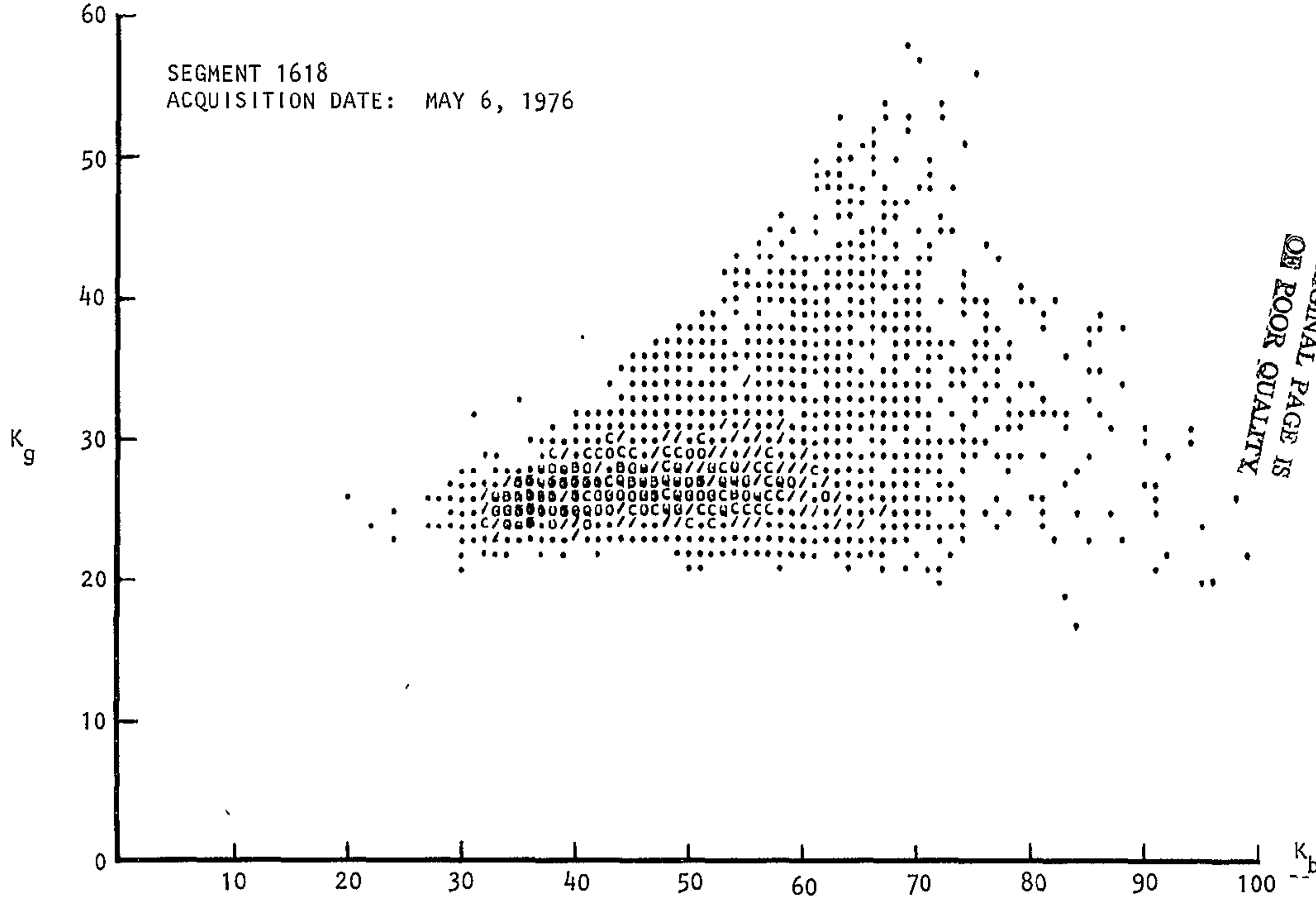
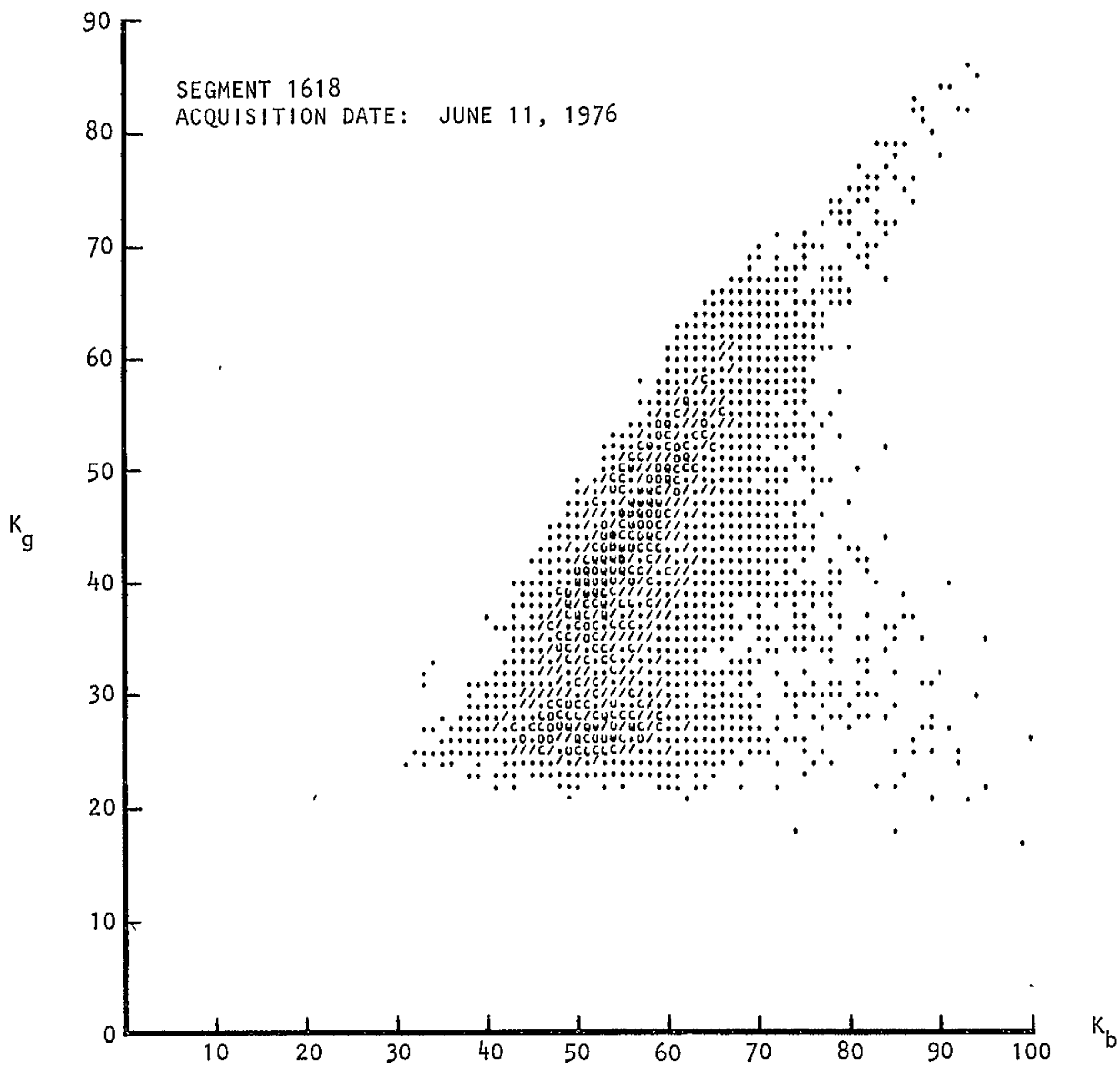


Figure 3.— Scatter plots of Landsat data in the (K_b, K_g) space for LACIE segments 1618 and 1645.



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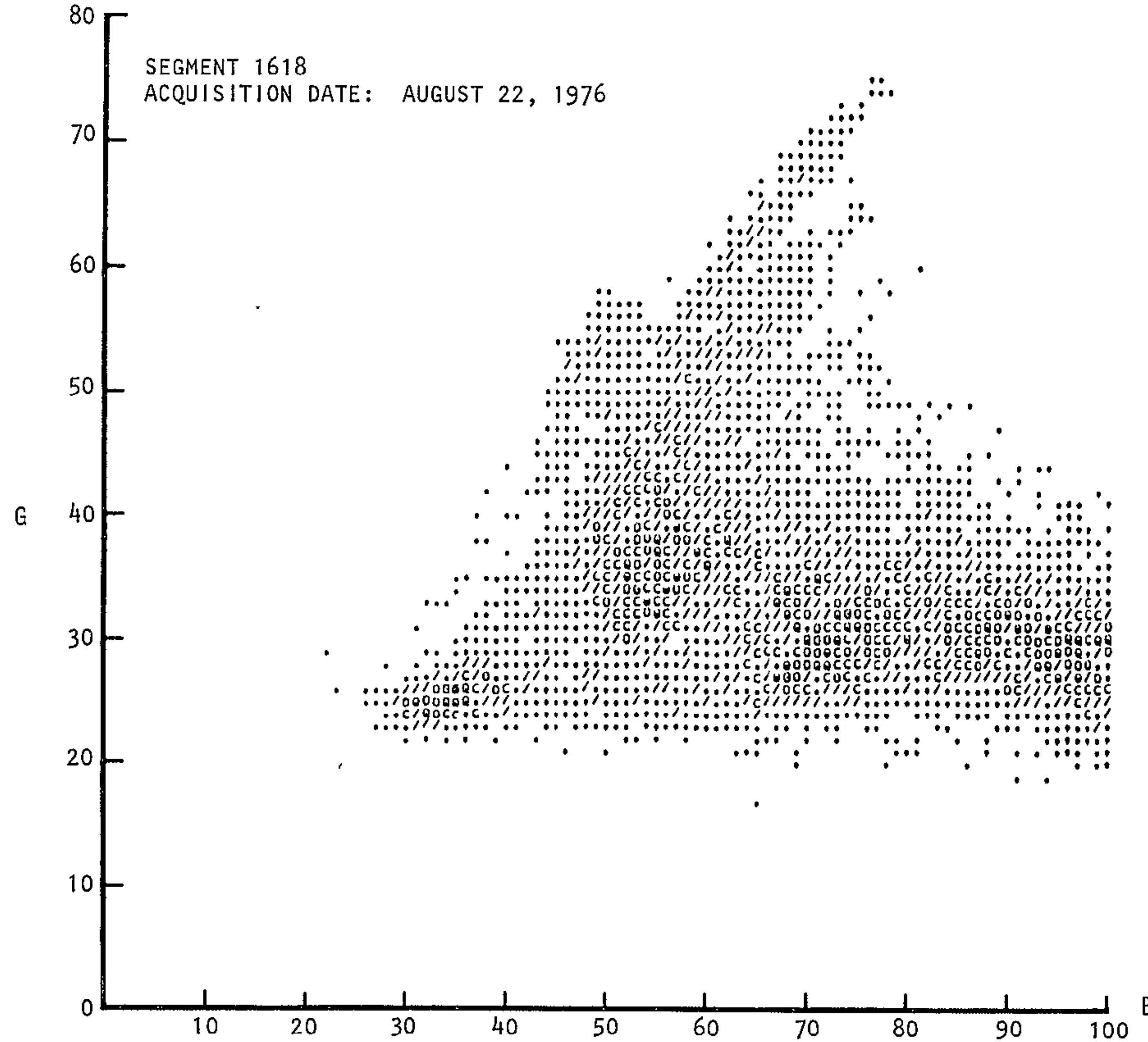

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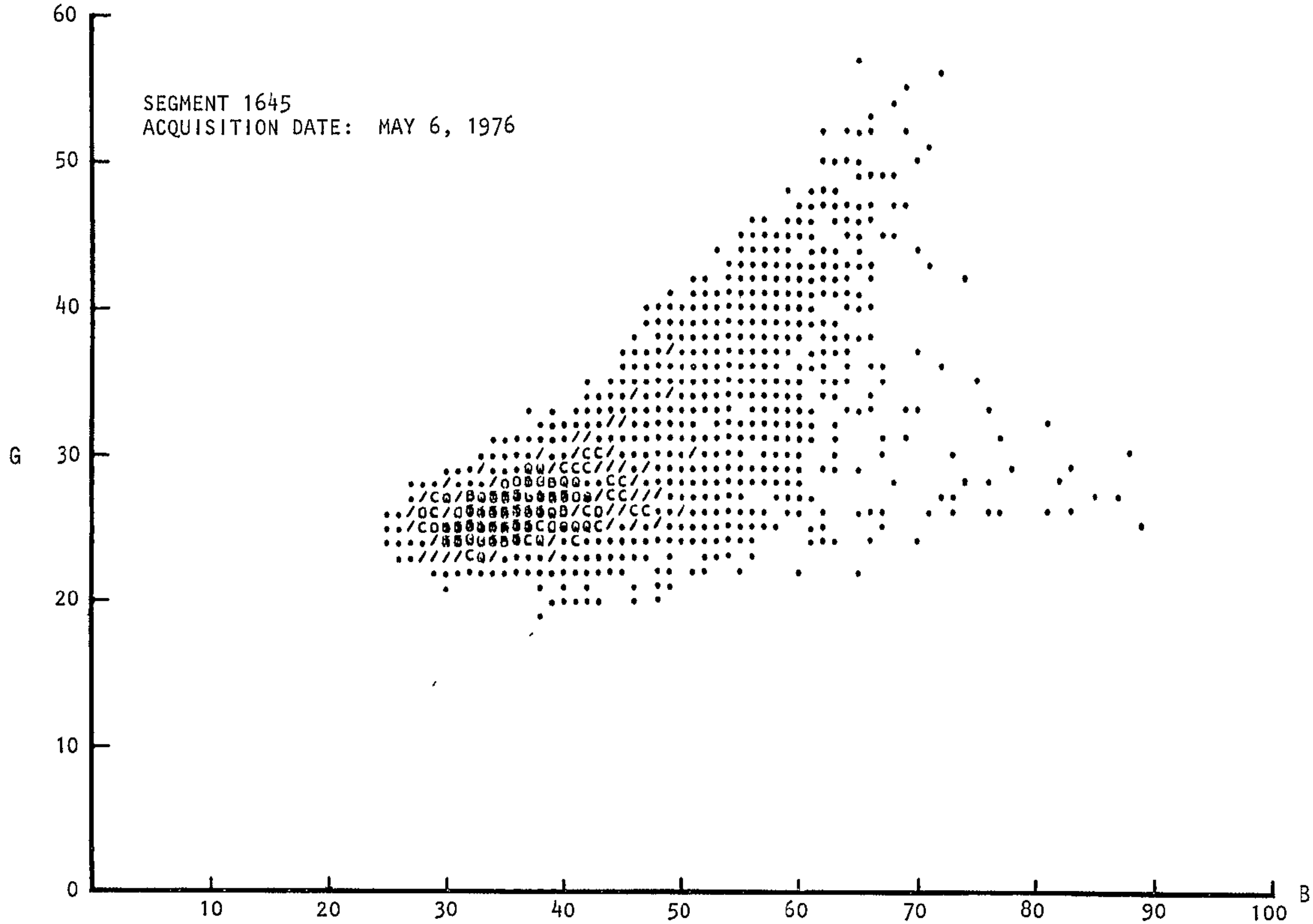

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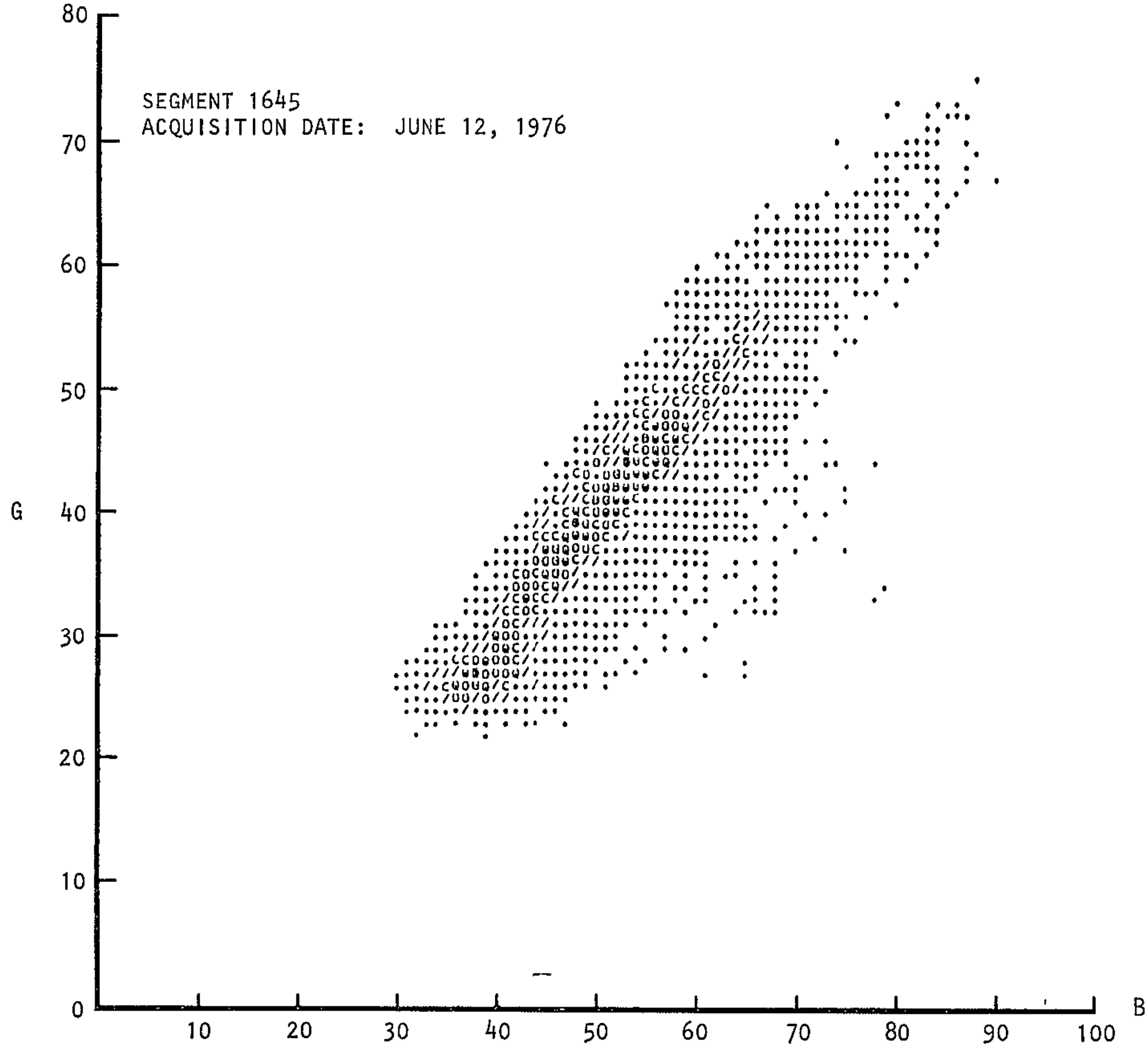

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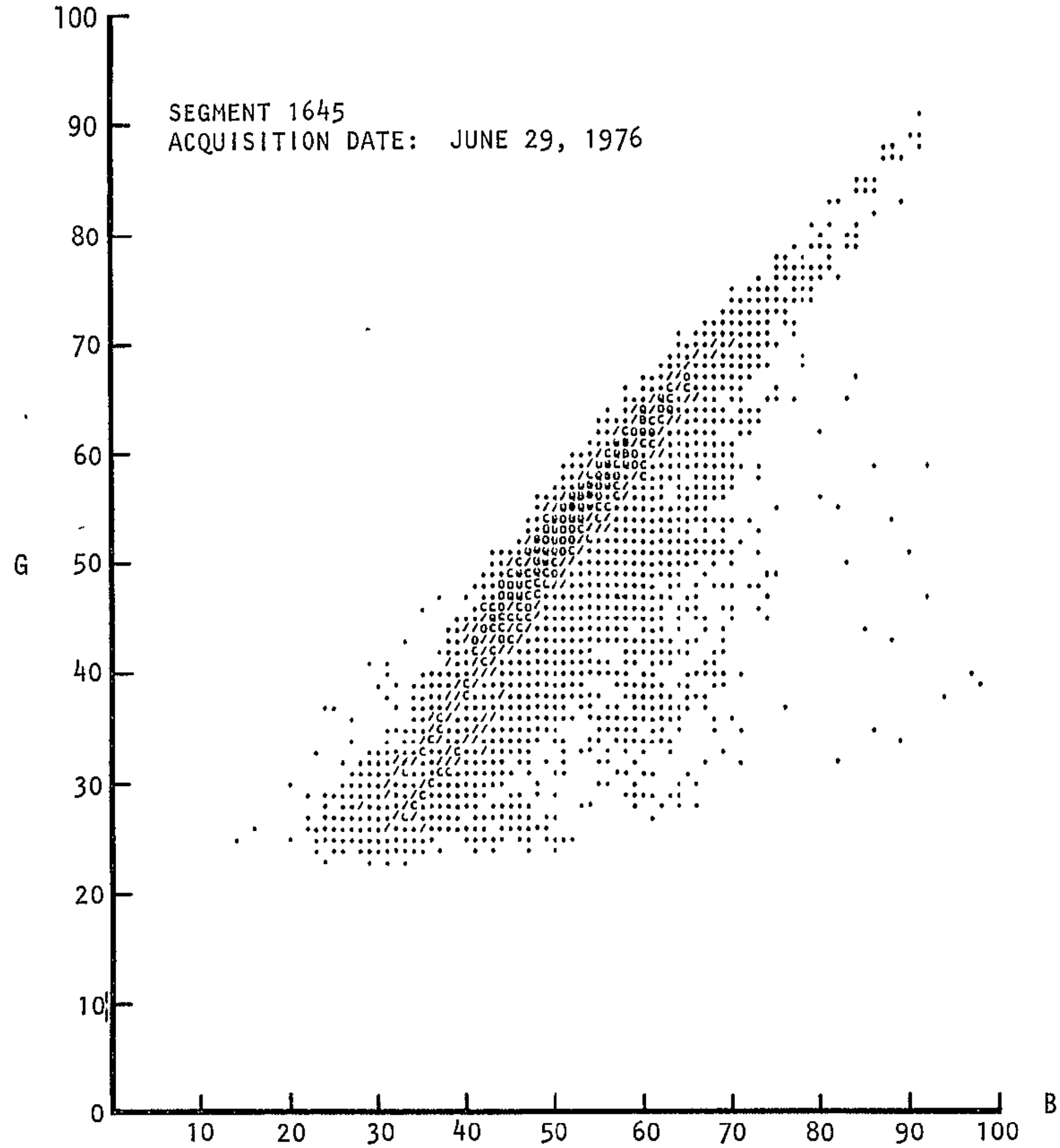

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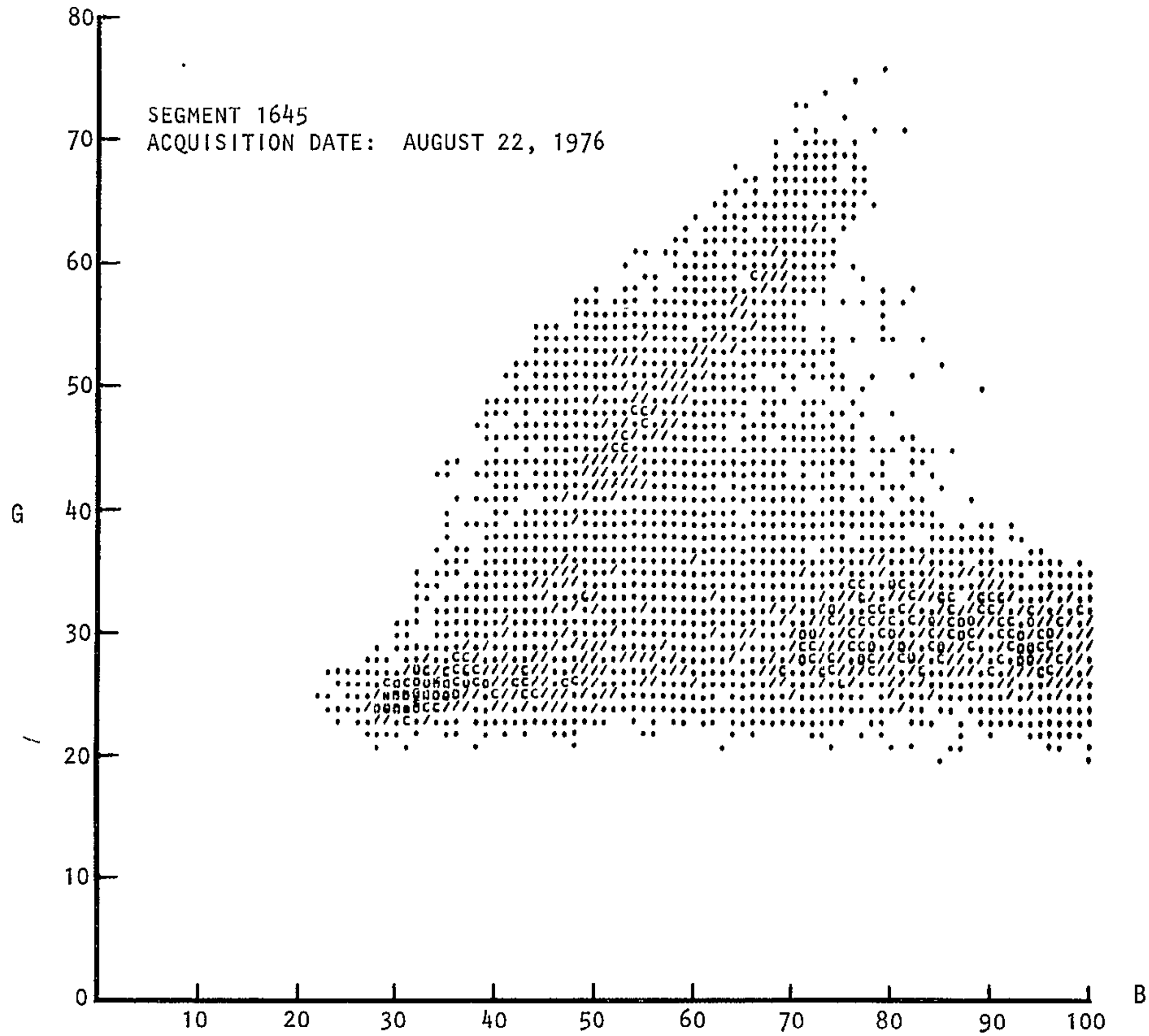

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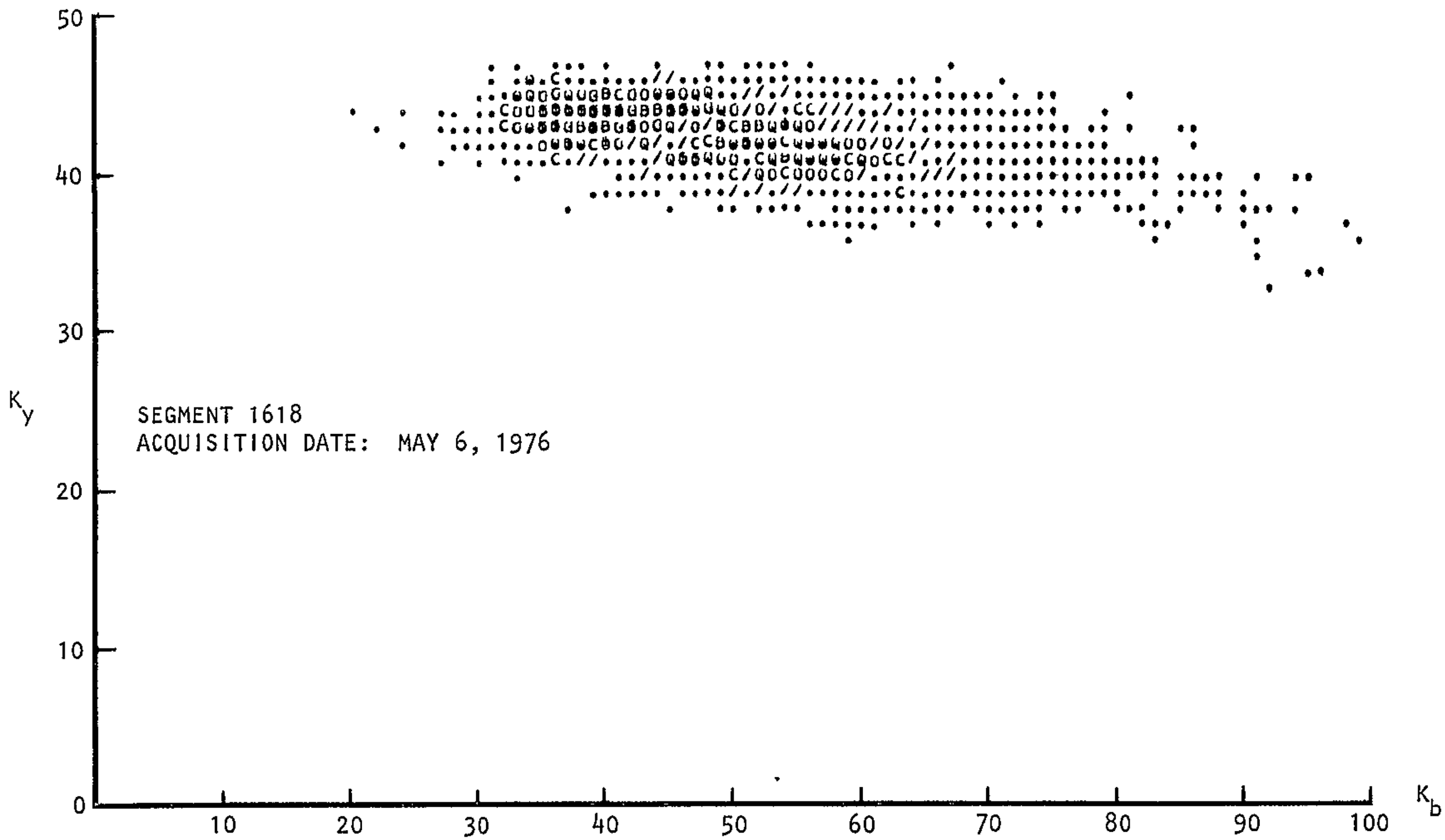
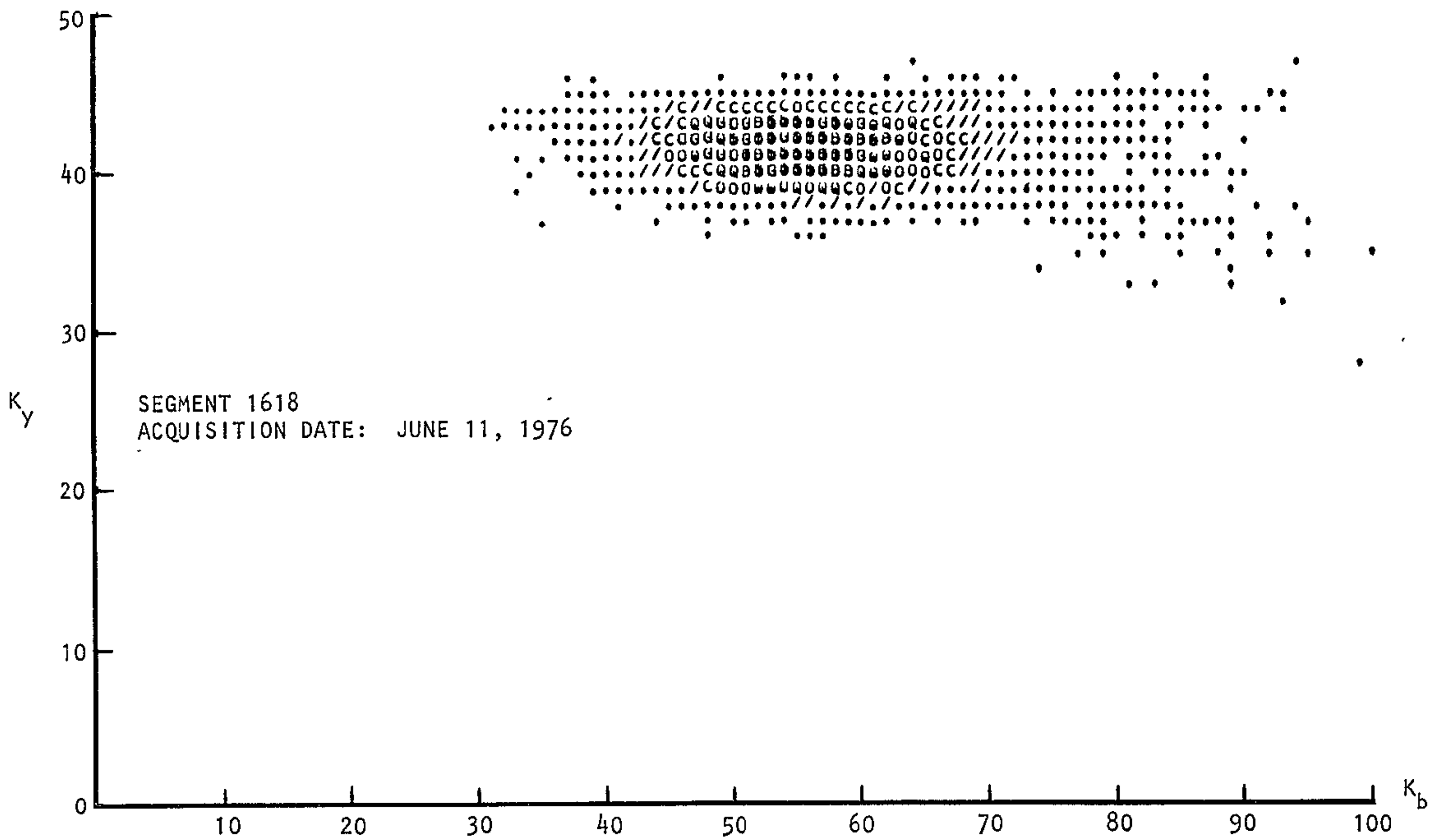


Figure 4.— Scatter plots of Landsat data in the (K_b, K_y) space for LACIE segments 1618 and 1645.



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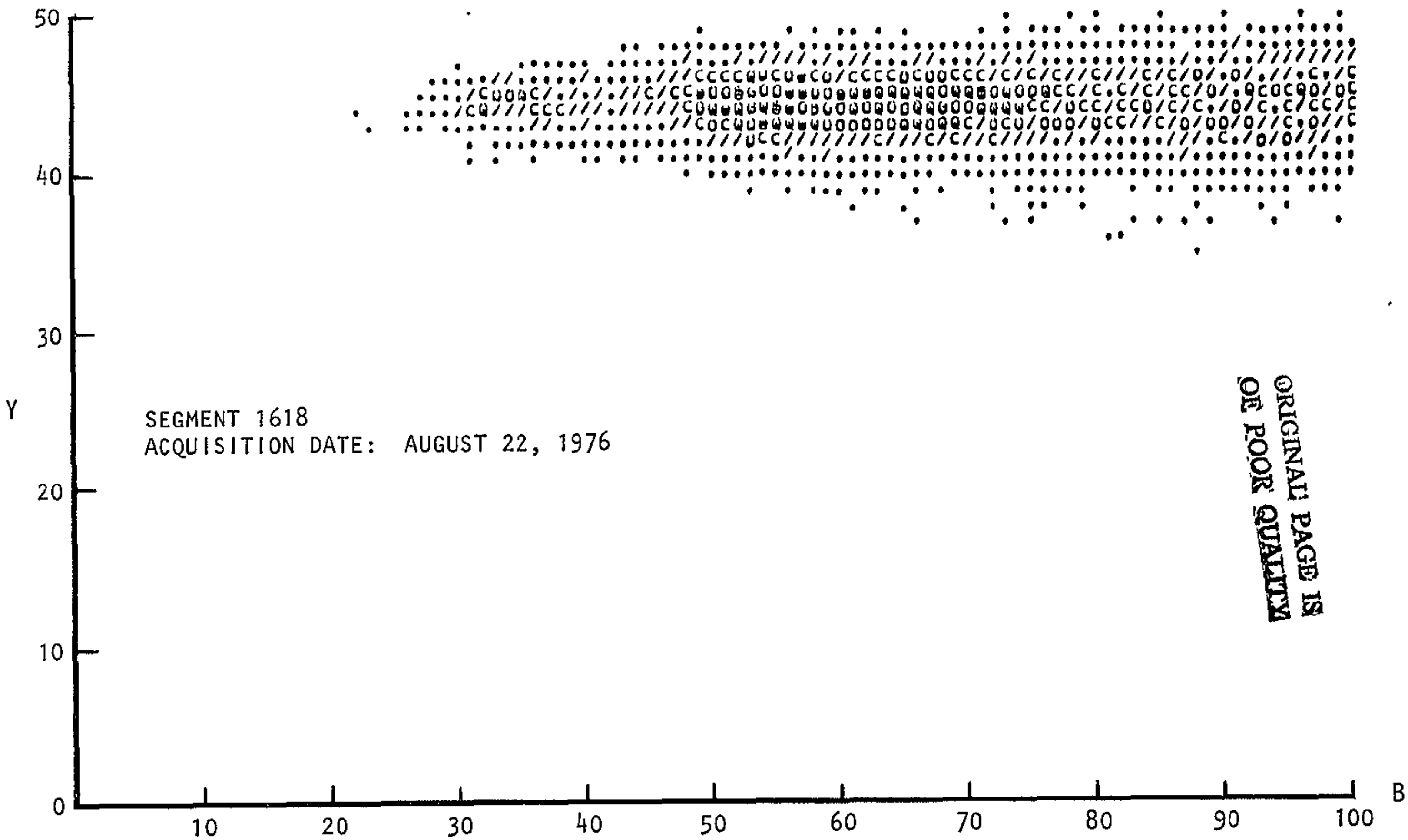

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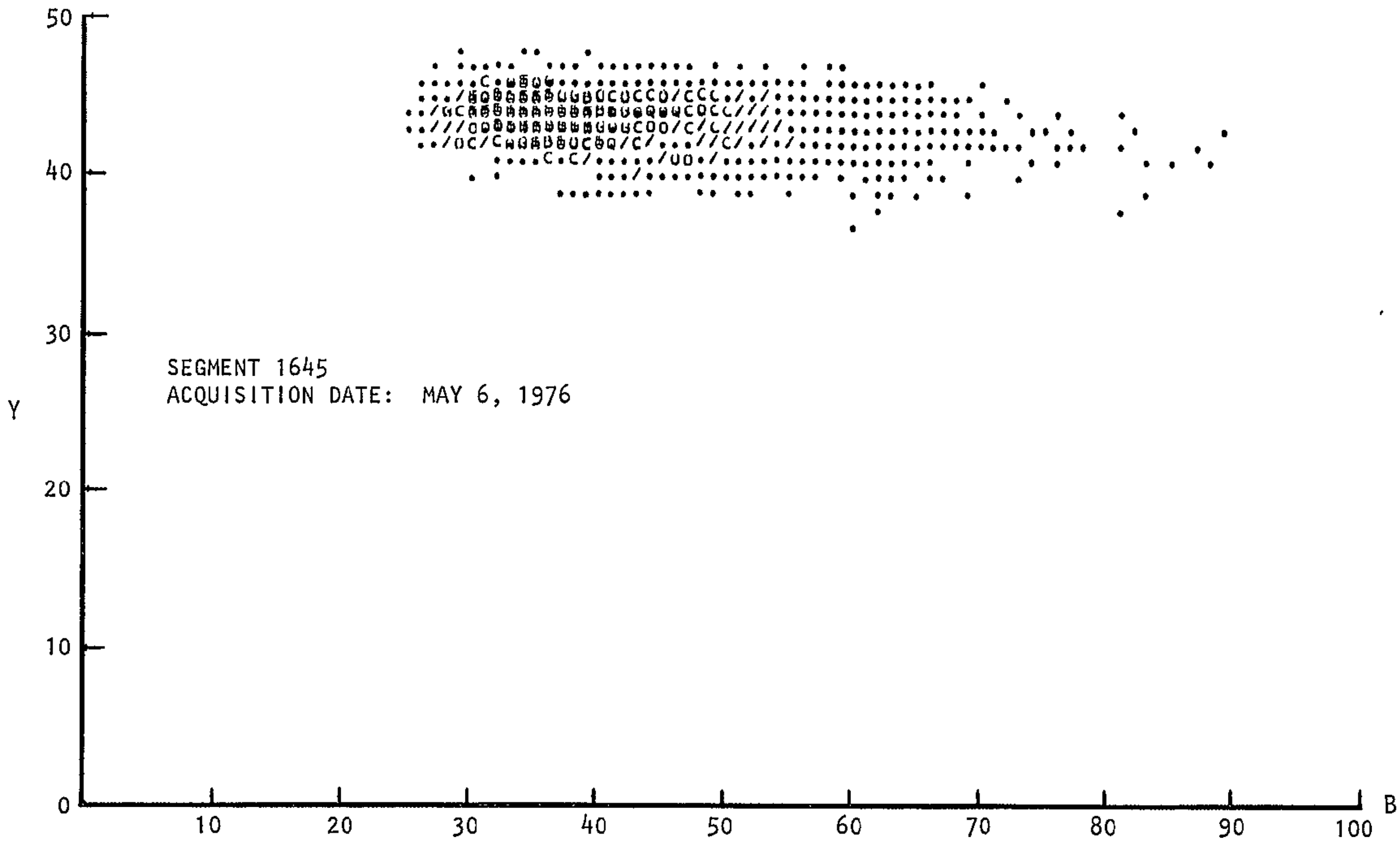

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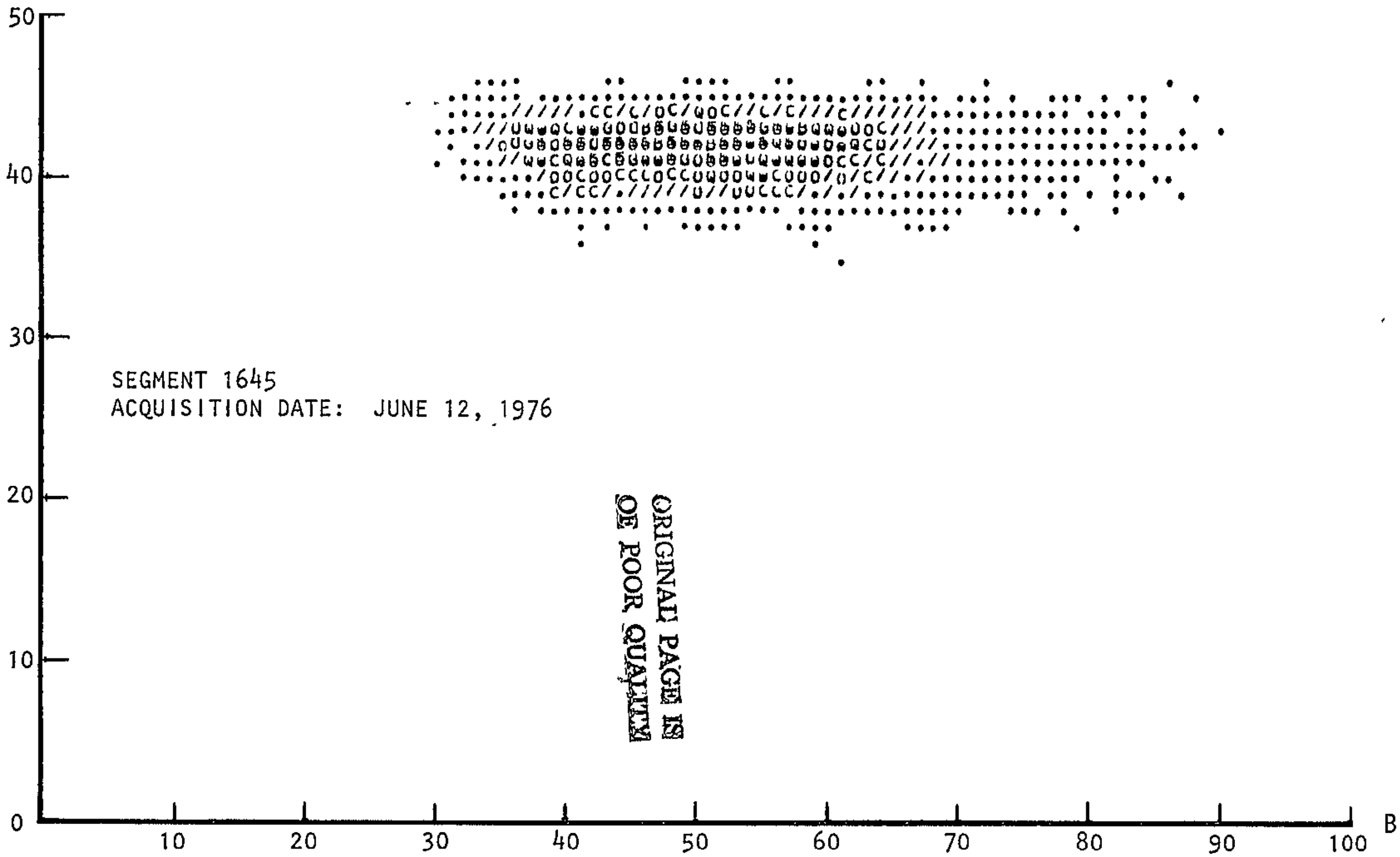

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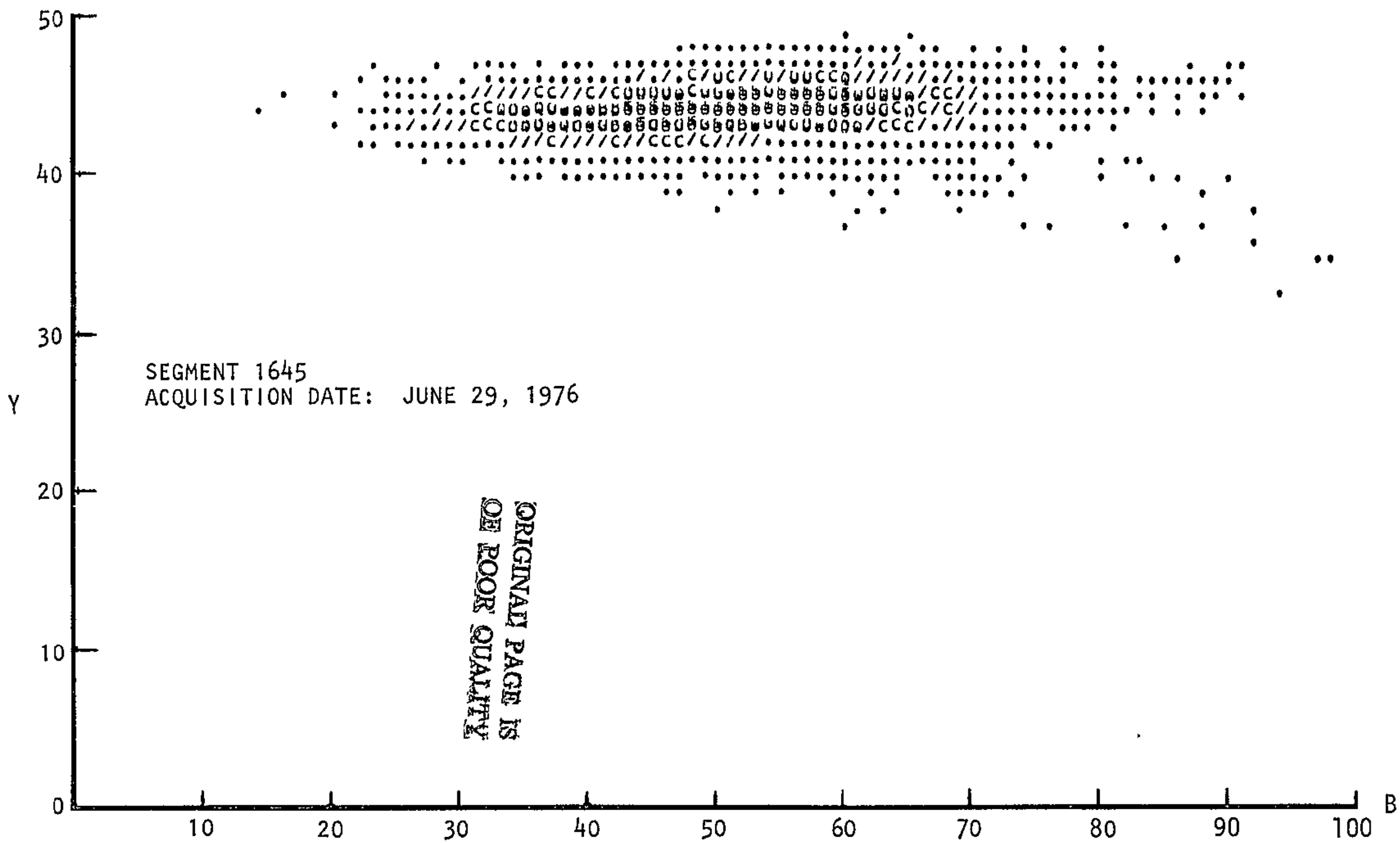

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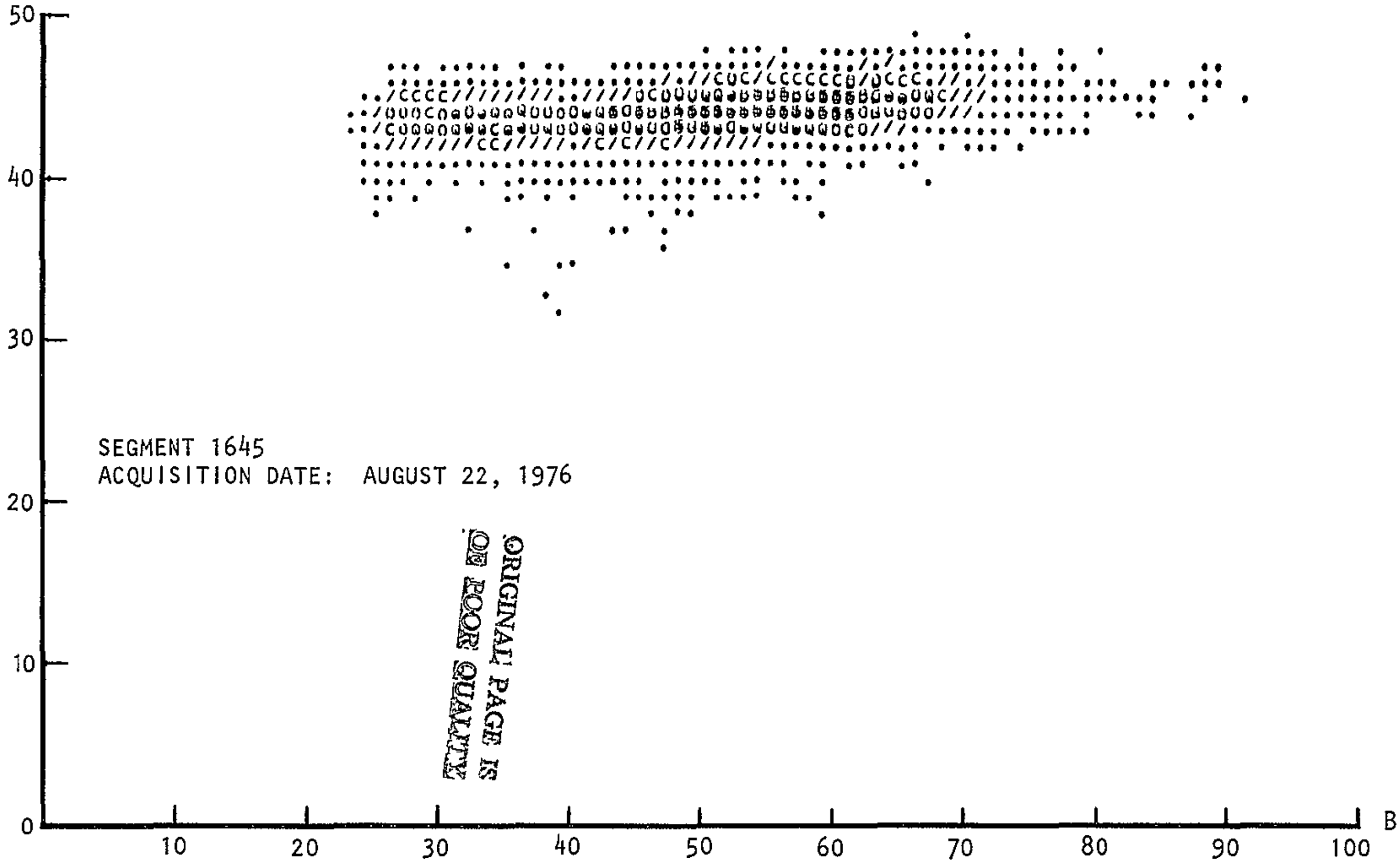

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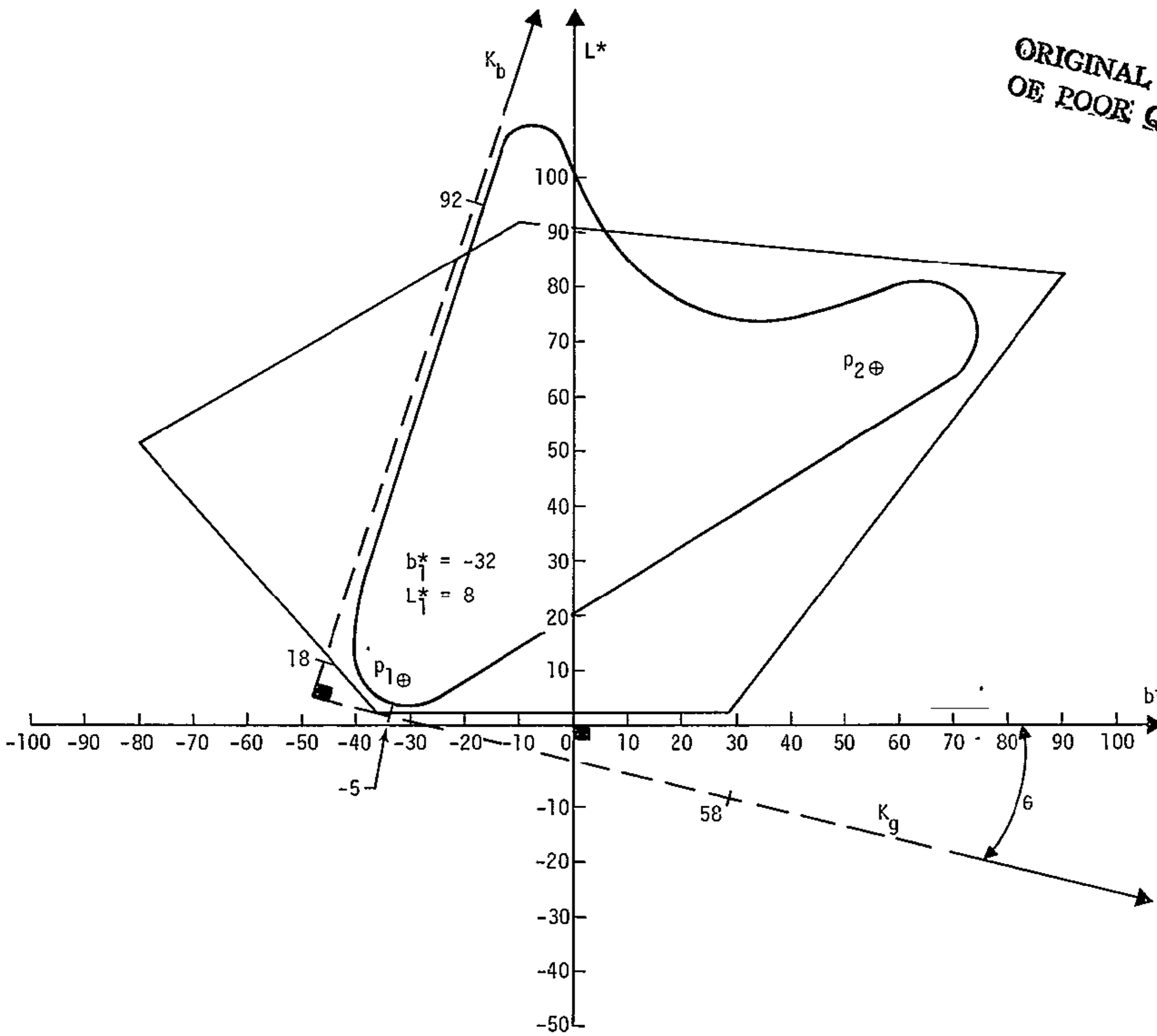

Figure 5.— Fitting Landsat (K_b, K_g) data space scatter envelope into the (L^*, b^*) UCS space sliced at $a^* = 10$.

The Landsat K_y is taken parallel to the a* dimension of the UCS space. Using figure 5 and analyzing K_g and K_b into two components along b* and L* yields:

$$L^* = S(K_g \sin\theta + K_b \cos\theta) + A_3 \quad (9)$$

$$b^* = S(K_g \cos\theta - K_b \sin\theta) + A_6 \quad (10)$$

where S is a scale factor, and A_3 and A_6 are biases. The two points p_1 and p_2 shown in figure 5 were used to calculate θ, S, A_3, and A_6 in equations (9) and (10). Let $\eta = \sin\theta$; substituting p_1 and p_2 into equations (9) and (10) yields:

$$(L_1^* - L_2^*) = S\eta\left(K_{g_1} - K_{g_2}\right) + S\sqrt{1 - \eta^2}\left(K_{b_1} - K_{b_2}\right) \quad (11)$$

$$(b_1^* - b_2^*) = S\sqrt{1 - \eta^2}\left(K_{g_1} - K_{g_2}\right) + S\eta\left(K_{b_2} - K_{b_1}\right) \quad (12)$$

Using equations (11) and (12), θ is given by:

$$\theta = \tan^{-1}\left(\frac{\eta}{\sqrt{1 - \eta^2}}\right) = \tan^{-1}\left[\frac{\left(L_1^* - L_2^*\right)\left(K_{g_1} - K_{g_2}\right) - \left(b_1^* - b_2^*\right)\left(K_{b_1} - K_{b_2}\right)}{\left(b_1^* - b_2^*\right)\left(K_{g_1} - K_{g_2}\right) + \left(L_1^* - L_2^*\right)\left(K_{b_1} - K_{b_2}\right)}\right] \quad (13)$$

The scale factor S and the biases A_3 and A_6 are given by:

$$S = \frac{L_1^* - L_2^*}{\sin\theta\left(K_{g_1} - K_{g_2}\right) + \cos\theta\left(K_{b_1} - K_{b_2}\right)} \quad (14)$$

$$A_3 = L_1^* - S\left(K_{g_1} \sin\theta + K_{b_1} \cos\theta\right) \quad (15)$$

$$A_6 = b_1^* + S\left(K_{b_1} \sin\theta - K_{g_1} \cos\theta\right) \quad (16)$$

The a* dimension of the UCS space is given by:

$$a^* = A_7 + S(K_y) \quad (17)$$

where A_7 is a bias factor. The overall scatter plot of figure 4 shows that the data center is at raw K_y of -8 counts. This center should correspond to a* of 10 where the UCS space was sliced to fit the Landsat data as shown in figure 5. Hence, A_7 is given by:

$$A_7 = 10 + 8S \tag{18}$$

Let

$$\begin{pmatrix} A_1 & A_2 \\ A_4 & A_5 \end{pmatrix} = S\begin{pmatrix} \sin\theta & \cos\theta \\ \cos\theta & -\sin\theta \end{pmatrix} \tag{19}$$

then, fitting Landsat (K_b, K_g, K_y) data space into the UCS space is achieved through the following affine transformation:

$$\underline{u} = F\underline{e} + \underline{\delta} \tag{20}$$

where

$\underline{u}$ = a column vector of L*, b*, and a*

$\underline{e} = [K_g\ K_b\ K_y]'$, and $\underline{e}'$ is the transpose of $\underline{e}$.

$\underline{\delta} = [A_3\ A_6\ A_7]'$

The matrix F is defined as:

$$F = \begin{pmatrix} A_1 & A_2 & 0 \\ A_4 & A_5 & 0 \\ 0 & 0 & S \end{pmatrix} \tag{21}$$

Using the numerical values of p_1 and p_2 of figure 5, F and $\underline{\delta}$ are computed to be:

$$F = \begin{pmatrix} -0.3012 & 1.0267 & 0 \\ 1.0267 & .3012 & 0 \\ 0 & 0 & 1.0670 \end{pmatrix} \tag{22}$$

$$\underline{\delta} = \begin{pmatrix} -11.594 \\ -32.288 \\ 18.560 \end{pmatrix} \tag{23}$$

3.3 ALGORITHM THAT GENERATES COLOR GUN COUNTS FROM (L*, a*, b*) PICTURE ELEMENT (PIXEL) VALUES FOR PFC PRODUCT

It was shown in section 3.2 that given the $\underline{e}$ vector for a picture element (pixel) in a Landsat scene, the L*, b*, and a* values for that pixel were computed according to equation (20). The tristimulus values X, Y, and Z for a pixel are computed from the pixel's L*, b*, and a* values by inverting equations (1) through (3) as follows:

$$Y = Y_0 \frac{(L^* + 16)^3}{1562500} \tag{24}$$

$$X = X_0 \left[\frac{a^*}{500} + \left(\frac{Y}{Y_0} \right)^{1/3} \right]^3 \tag{25}$$

$$Z = Z_0 \left[\left(\frac{Y}{Y_0} \right)^{1/3} - \frac{b^*}{200} \right]^3 \tag{26}$$

Let a_i, where i = R, G, and B primaries, be activations proportional to the tristimulus values. They are proportional to radiance and, hence, to film transmission τ. Film transmission and optical density D are related by:

$$\left. \begin{array}{c} \tau = 10^{-D} \\ \text{or} \\ D = -\log_{10} \tau \end{array} \right\} \tag{27}$$

The activations a_i $(0 \le a_i \le 1)$ are produced from the tristimulus values of a pixel's color according to the following:

$$\underline{a} = T^{-1} \underline{t} \tag{28}$$

where

$\underline{a} = [a_R \; a_G \; a_B]'$

$\underline{t} = [X \; Y \; Z]'$

$$T = \begin{pmatrix} 39.74 & 35.90 & 13.53 \\ 32.04 & 57.09 & 10.86 \\ .09343 & 6.646 & 46.13 \end{pmatrix}$$

The film transmission and the pixel's activations are linearly related by:

$$\tau_i = \tau_{i,min} + a_i(\tau_{i,max} - \tau_{i,min}) \quad ; \quad i = R, G, \text{ and } B \qquad (29)$$

where $\tau_{i,min}$ and $\tau_{i,max}$ were measured and found to be:

$$\left.\begin{array}{lll} \tau_{R,max} = 0.1762202 \; ; & \tau_{R,min} = 0.0030142 \; ; & \tau_{G,max} = 0.4933794 \; ; \\ \tau_{G,min} = 0.0065697 \; ; & \tau_{B,max} = 0.2020853 \; ; & \tau_{B,min} = 0.0030685 \end{array}\right\} \qquad (30)$$

Let

$$\left.\begin{array}{l} D_{i,max} = -\log_{10} \tau_{i,min} \\ \Delta D_i = \log_{10}(\tau_{i,max}/\tau_{i,min}) \end{array}\right\} i = R, G, \text{ and } B \qquad (31)$$

then the color gun counts C_i, i = R, G, and B of the PFC for the pixel, are given by:

$$C_i = \left(\log_{10} \tau_i + D_{i,max}\right)\left(\frac{255}{\Delta D_i}\right) \quad ; \quad i = R, G, \text{ and } B \qquad (32)$$

Equations (20), (24), (25), (26), (28), (29), and (32) constitute an algorithm for generating UCS imagery from Landsat data. These equations were used to produce the UCS color film products shown in figure 6 for LACIE segment 1618. Figure 6 shows four images of segment 1618, corresponding to four multitemporal acquisitions and covering all the biological stages of small grains. Figure 3, with figure 5, provides an interpretive key for the images in figure 6; i.e., small-grains fields in biostage 1 appear to have a blue color (low greenness

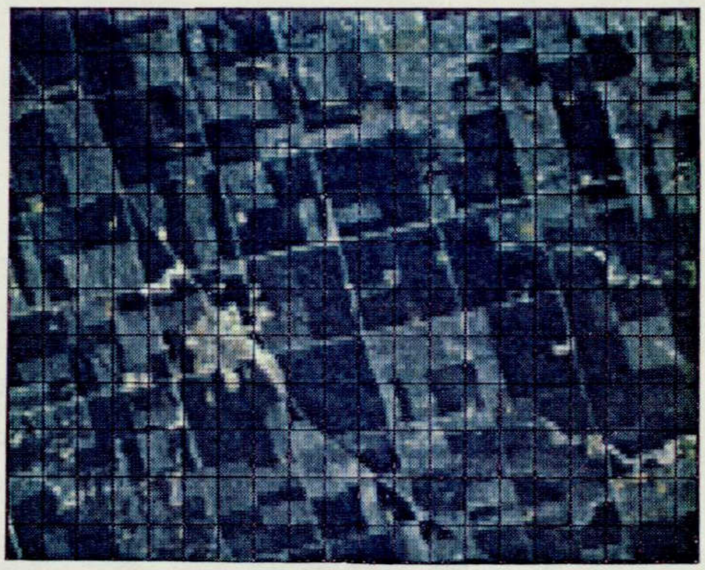

Figure 6.— UCS Film product of LACIE segment 1618.
Acquisition date: May 6, 1976.

Figure 6.— Continued. Acquisition date: June 17, 1976.

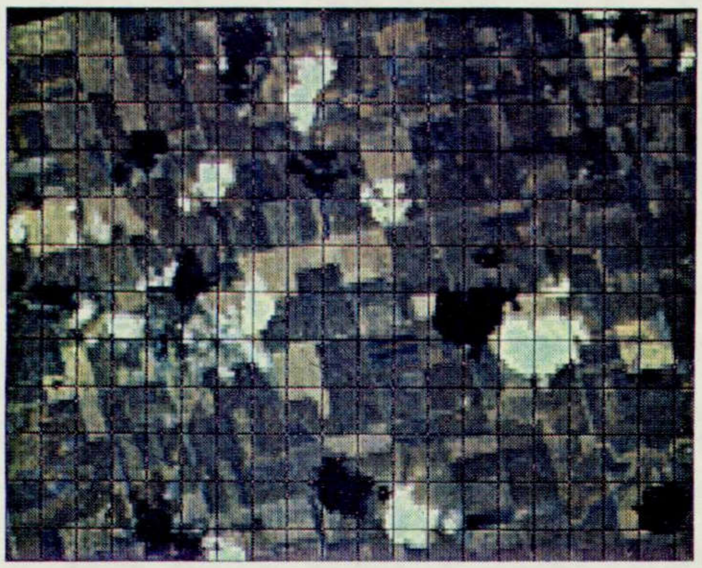

Figure 6.— Continued. Acquisition date: July 17, 1976.

Figure 6.— Concluded. Acquisition date: Aug. 22, 1976.

value K_{g_1}) while they change from light yellow orange $\left(K_{g_2} > K_{g_1}\right)$ to a darker yellow orange $\left(K_{g_3} > K_{g_2}\right)$ in going from biostage 2 to 3. In biostage 4 $\left(K_{g_4} < K_{g_3}\right)$, the small-grains fields appear to have a pinkish color. This is in agreement with how the data were fit into the UCS space as shown in figure 5 and given by equations (9), (10), and (17). The pinkish cast shows an increase in the Kauth yellow component; K_y is scaled toward positive a*, which is in the general direction of the PFC red gun.

4. CONCLUSIONS AND RECOMMENDATIONS

An algorithm for generating uniform chromaticity scale imagery from Landsat data has been presented. A computer program was written to implement the algorithm, and UCS film products were generated. The colors in the film and their temporal change are consistent with what was expected for the particular scaling of Kauth components into the (L*, a*, b*) color space. The UCS film product has yet to be put to the practical test of competing with previous transformations. In that competition (to be done outside the purview of this report), the philosophically satisfying notion of transforming Landsat data so that a one-count difference is equally perceptible at all locations in data space will be tested.

The authors recommend that analyst-interpreters (AI's) test the UCS imagery using a variety of LACIE segments. Preliminary examination indicates that the UCS product offers the possibilities of the following.

a. A single film product that will supplant two film products in current use.

b. Improved visibility of data differences in regions in data space which are critical to crop identification.

c. An analytic route to the determination of data-space transformations that will be optimal for particular discrimination problems. For example, in another project, the transformation has been used to display water bodies in Landsat data, with encouraging results.

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