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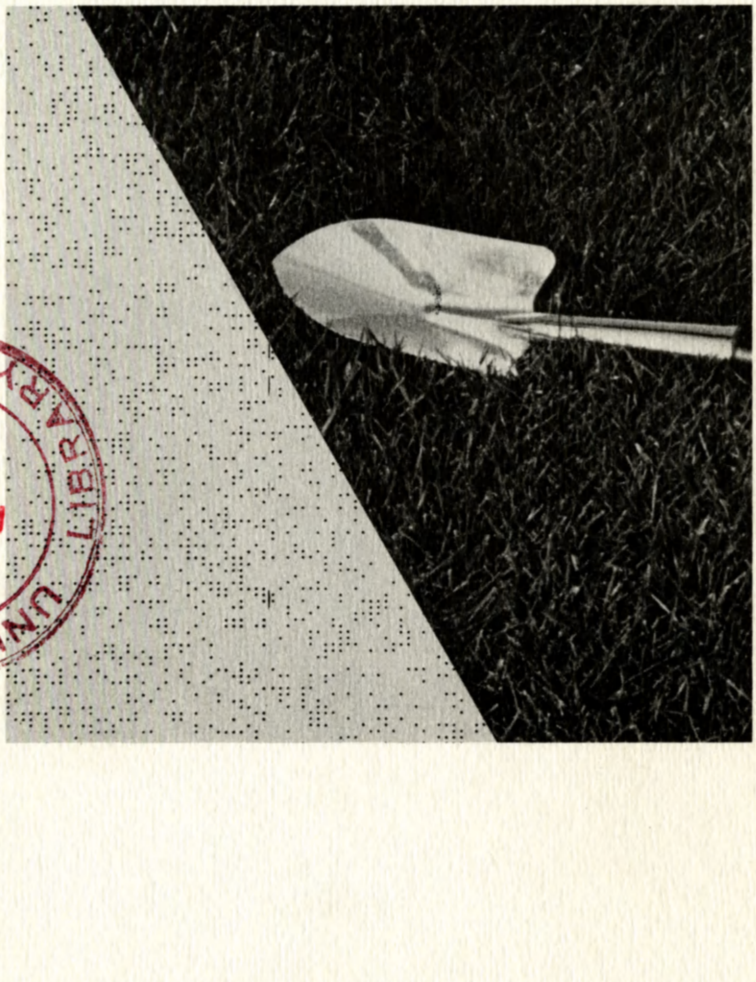

A New Retinal Model and its Application
to the Computer Analysis of Aerial Photographs

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FOREWORD

This technical report is adapted from a thesis submitted in partial fulfillment of requirements for the degree of Master of Science in Optical Sciences at the University of Arizona.

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ABSTRACT

In order to find a new and more economical method for the computer detection of object outlines in aerial photographs, the human visual system is considered. This leads to the concept of the human retina as a matrix of light receptors and permits the development of a three-stage retinal process. The first stage consists of the registering of the intensity distribution of the image. The second and third stages consist of operations that are analogous to the mathematical calculations of the first and second derivatives. This process is applied to the retinal matrix in a line-by-line method in two orthogonal directions.

This retinal model is tested experimentally and applied successfully to two photographs. The computer program that generates and performs the retinal three-stage process does so with a minimum of computer decisions, resulting in a highly efficient use of computer time. The successful application of this retinal model and its inherent economy of operation demonstrate its potential usefulness in the computer analysis of aerial photographs.

CONTENTS

INTRODUCTION

One of the fertile areas for research today is computer analysis of aerial photographs. Aerial photographs are being taken of almost every locality on earth, and now, with the success of our space efforts, photographs are also being taken of the other planets and of the moon. All of these photographs, whether taken from an airplane or other vehicle, need to be viewed, sorted, and analyzed by trained photointerpreters. This process is tedious and time consuming, and it is in this area that computer systems are being designed to aid the photointerpreter.

The task of photointerpretation by computer is a complicated one, and many approaches are taken. However, all of these approaches appear to have a common basis. All concern themselves with a method of selecting a particular density level in a predetermined spot size or area on a negative, and then they perform a search pattern, looking for adjacent areas of like density levels. Once such a composite area is obtained, geometrical edges are fitted to it and some method of computer recognition of the object is attempted.

This type of approach is quite complex. The computer must be told which density level to start with, or it must be programmed with some method to choose the correct density level. Next, a method of selecting a composite area must be programmed into the computer. The search pattern for this can be a simple geometric pattern such as a spiral, a complicated random pattern that requires the computer to make entropy measurements that affect its search direction, or a sophisticated method that allows the computer to generate its own stochastic parameters. Finally, an outline of the suspect object must be determined before object recognition can be obtained.

It is the purpose of the present research to take a different, more simplistic approach to selecting the outline of a given object. This psychophysical approach is based on a new model for the retinal system that easily and unambiguously determines the outlines of images that it views. It is therefore hoped that this will make a significant contribution to the field of computer analysis of aerial photographs.

THE MYSTERIOUS HUMAN VISUAL SYSTEM

The greatest visual detector and most sophisticated and highly reliable visual system ever designed is the human visual system. Yet man can take no credit for its design, and he is frequently forced to admit that he does not understand exactly how it works.

It is true that the eye has been studied, measured, and documented time and time again. We can speak quite confidently of its components. We can describe how the cornea gives most of the power to the visual system and how the crystalline lens accommodates for distance. We can write equations, cite figures, and draw graphs that appear to pin down our knowledge of the Seidel aberrations of the eye. We can take pride in our knowledge of photopic and scotopic vision and how we have isolated the actual receptors that play a part in the dual nature of the retina. But—and it is a big "but"—no one can speak with confidence as to how the visual system handles the image that rests on the retinal receptors. We are often tempted to satisfy ourselves with merely stating that the image is projected onto the retina—and we have vision. Yet, it is on the retina that the real perception begins to take place.

We find it quite easy to simply test the eye and measure its accuracy. A small amount of satisfaction can be obtained in testing for acuity and determining modulation transfer functions. However, instead of answering questions, these tests and measurements pose more questions. We find that acuity depends not only on the individual tested but also on the particular test used. It appears that there are as many different acuity limits as there are acuity tests, indicating that there is a mechanism here that we know very little about. Visual illusions point to the reality that a complicated system does exist and that this system can in fact become confused.

It is unfortunate that most people think of the eye in terms only of the simplified analogy of the camera. The retina is considered to perform a role identical to that of a photographic emulsion, which merely registers the image. This image is then somehow mysteriously observed by the mind's "eye." We are left with the concept of a little man sitting in our mind viewing the back of the retina as we would view a television screen. However, no one bothers to explain how this little man sees and how his visual system operates.

It is only recently that a true investigation of possible models of visual systems could be made. The availability of high-speed computers has enabled us to use a new approach to this age-old problem of how man sees. Any new knowledge of the possible retinal processes that result in discernible viewing would certainly be of use in the design of a computer system that could hope to perform functions similar to those accomplished by the human visual system.

A PROPOSED PSYCHOPHYSICAL MODEL

In our psychophysical approach we are concerned primarily with the image that is formed on the retina and how the retina reacts to it. For purposes of this study we shall consider the retina to be an array of receptors arranged in evenly spaced rows and columns (Fig. 1). We shall assume that the receptors have identical spectral sensitivity distributions and that they send out signals that represent the intensity of the image light that they sample. We shall assume also that the receptors are connected to a neural network so that they can be sampled in sequence in two orthogonal directions. We can describe the direction of movement of the nerve impulses by using a modified Cartesian system in which the positive x direction goes from left to right but, contrary to the normal convention, the positive y direction goes from top to bottom.

This nerve network is not complex, and it enables us to manipulate the intensity information produced by the receptors in two directions across the image. It may be contested that this network gives an unnatural horizontal and vertical structure to the image. However, the only basis for judging this structure to be unnatural is the obvious absence of the numerous, complex receptor interconnections that actually exist in the retina. The human visual system actually does view the world through a horizontal-vertical framework. (The disbeliever is asked to consider the standard horizontal-vertical illusions (Luckiesh, 1922, pp. 44-47; Underwood, 1966, pp. 68-98); these illu-

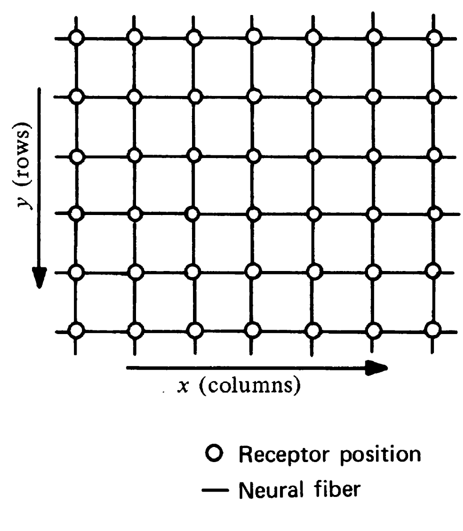


Fig. 1. The proposed retinal receptor array and neural network.

sions demonstrate that not only is there a horizontal-vertical structure to the human visual system but there is also a compression of the vertical axis.)

We shall analyze our image by considering the intensity readings in each row and each column individually. We will, therefore, be investigating the image in a line-by-line method, either vertically or horizontally, in much the same way that an image is scanned by a television system.

One question we wish to answer is whether the eye uses intensity levels alone to build up the perceived image. This would necessitate a complex process that would be analogous to the density level analysis mentioned in the Introduction. It would appear that such a complicated process would not be used by the human eye because the eye continuously analyzes and processes images almost instantaneously with remarkable accuracy. We would, therefore, assume that the eye uses the least complex system feasible.

If we assume that the human visual system evolved from the simplest type of visual system—that is, one receptor measuring light and dark—then we would assume that its processing system is the one that would have evolved most naturally. In other words, the evolution of the eye would have progressed according to Darwin's theory of natural selection. This evolution would have begun with a primeval eye consisting of a simple lens system and a simple receptor with a single neural fiber connecting it to the brain. It would have been similar to the eye of *Quadrata copilia* (Gregory, 1966, pp. 28-33), a microscopic copepod that exists today. As the organism evolved from its microscopic state to a higher form of life, it would have required a more sophisticated visual system. The easiest way to accommodate this requirement would have been to add more receptors and consequently more nerve fibers to connect the receptors with the brain. To correlate data between the receptors, nerve fibers would be developed between the individual receptors, linking them together so that each became an integral part of a neural network that resembled a matrix array. This, of course, is the model of the retina that we are proposing.

It is the author's contention that the human visual system perceives a scene by registering the data input by all of the rows and columns of its visual matrix simultaneously. It performs this function in three stages. The first stage consists of registering the intensity readings from each receptor. This gives the visual system the intensity range and is valuable for making fine adjustments of the iris. This stage also establishes the tonal quality of the image. In the second stage, the differences in intensity from receptor to receptor are registered. This provides the visual system with the general structure of the image. In the third stage, the rate of change of the intensity differences between receptors is registered. This supplies the system with the fine structure of the image and enables the eye to select object boundaries.

It should be obvious to the reader that we are proposing that the visual system actually performs first and second derivative calculations in the second and third stages, respectively. Because of the neural structure of the human retina, it is not unreasonable to assume that these three stages are performed nearly simultaneously in the retina itself. The results are then processed almost immediately at a higher level in the visual system. It is our task now to demonstrate experimentally that such a model and theory are feasible.

THE EXPERIMENTAL VISUAL SYSTEM

Equipment

To test our model, some equipment was necessary. To perform the task of image formation we used a Honeywell Pentax 35-mm camera and Kodak Tri-X film. The Optical Sciences Center's digital image analyzer (Baker, Burke, and Frieden, 1970, pp. 4-18) was used to simulate our receptor matrix. For scanning the image, we used a spot size of 80 μm and a separation of 15 μm between each sample (Fig. 2). Each time the scanner registered a reading it simulated the action of an individual receptor. After scanning 120 spots in each of 120 rows, the digital image analyzer generated data that represented the information that a matrix of 14,400 receptors would have collected instantaneously while looking at a visual scene.

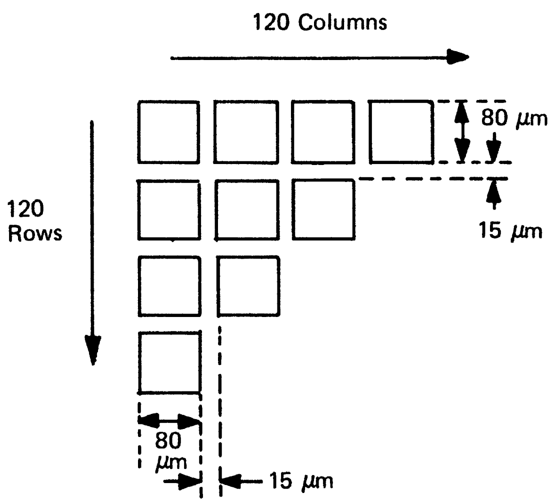


Fig. 2. The experimental receptor matrix.

Our model visual system uses the image formed by the photographic negative to simulate the image that is formed on the retina. The digital image analyzer measures the light that passes through the negative, thereby measuring the intensity of the light that forms the image on the retina. Having no evidence to the contrary, we assume that each receptor in the human retina measures intensities on a linear scale, and we will use such a scale in our measurements. Our scale will be a relative one, and we can set it up in any fashion to suit our purposes as long as we maintain its linearity. At first it would appear to be convenient to select a scale ranging from 0 to 10. However, we do not know how fine a distinction in intensities the visual system has to make in perceiving an object and we want enough significant figures in our data to enable us to make such a distinction. We will be manipulating large matrices of numbers in our program and we will be performing numerous arithmetic operations, and we do not want to lose any information due to round-off errors or overflow situations. After much consideration, we decide to use 1000 units for each of 10 intensity level steps. This will allow us enough significant figures to make fine distinctions, and at the same time it is manageable enough not to cause overflow problems. Our scale therefore reads from 0 to 10,000.

The intensity measurements were recorded on magnetic tape and then processed on the University of Arizona's CDC 6400 computer. The computer output consisted of tables of data (Appendix A) and a matrix mosaic (Figs. 5 and 12) that revealed how this method enabled our visual system to pick out the edges of objects. The mosaic consisted of 120 rows and 120 columns of characters, each signifying data produced by each individual receptor.

Since the image field that we scanned was a square field, we tried to make the output matrix square also. However, the spacing that separates lines in the computer printout is not equal to the spacing that separates the characters in each line. Consequently, the vertical axis of the output matrix is slightly compressed with respect to the horizontal axis. This might be construed as a fortuitous accident since the resultant matrix mimics the horizontal-vertical illusion referred to on pages 3-4.

Resolution

At this time the question of the resolution capabilities of our equipment should be discussed. It may be assumed that, since our retinal matrix consists of 120 receptors per row, we should be able to resolve 120 elements per row or 14,400 elements per picture. Also, we would expect that the smallest resolvable elemental size would be that of one of our receptors. The receptor can register the total light incident on it but cannot distinguish the size of the element that gives it light. It does not know whether the source it is sampling is an extended source covering an area larger than it samples or an area smaller than it samples. We are required, therefore, to assume that the smallest element that our system could resolve would be limited by the size of our receptor's effective collection area. However, the receptor's inability to distinguish size indicates that our estimate of the number of resolvable elements may be too optimistic. Consider a row of elements that we undertake to resolve. If the elements are the size of the effective area of our receptors and if they are lined up properly, we would expect that they would be resolved (Fig. 3a). In the extreme case the elements to be resolved are lined up so that they overlap the receptors (Fig. 3b). In this situation, the output signal indicates that six receptors are sampling a light source and, since these receptors are adjacent to each other, the visual system would assume that a line segment is being sampled. Because the energy of the light that is sampled is spread over six receptors instead of only three, the output energy per receptor is also less than in the original example. We should not become discouraged, however, since this is an unusual occurrence and will not be encountered frequently. It merely indicates that our effective resolution is reduced by some factor. We can determine this factor by experimentally testing objects and visual scenes that we would anticipate our system to encounter. However, because our system is quite similar to that of a television system, we shall make use of the resolution factor that the television industry has found to be realistic (Fink, 1952, p. 27); that is, we will assume that our effective resolution is 70% of the number of receptors we have in each row. That allows us 84 effective resolution elements per row and 84 per column.

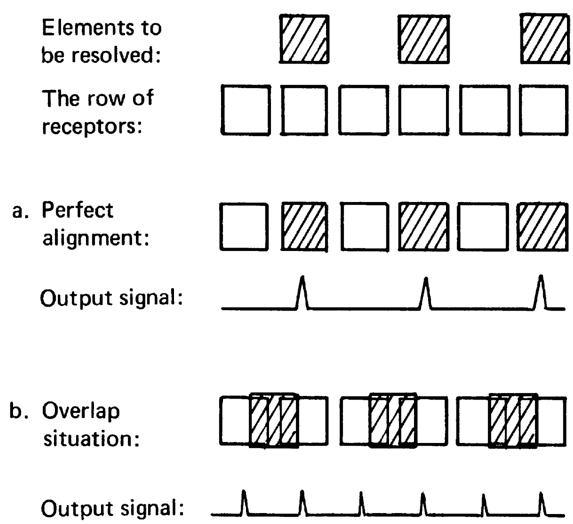


Fig. 3. Receptor resolution limitations.
a. The ideal case where the elements are resolved.
b. The extreme case where the elements are not resolved.

Computer Discrimination Process

It was necessary to write a FORTRAN program to utilize our data and to test our three-stage retinal theory. Appendix B is a copy of this program.

After reading the magnetic tape, the computer analyzes the data from each receptor and codes it into major intensity steps. These intensity steps are then printed out in matrix form on two sheets of computer paper, which are then affixed together to give the complete output matrix. This matrix represents the entire picture. (Figs. 5 and 12 are truncated versions of such representations.)

In the next stage, the computer calculates the gradient values in the x direction. Since these gradient values represent the difference in intensities between each pair of receptors, calculations result in 119 gradient values per row. We can plot these values and graphically illustrate how the intensity varies over this row, but unfortunately it would not be of much use to the computer. What is needed is a discrimination process that will pick *extreme* gradients in each row, in the hope that these extreme gradients will indicate where the edges of an object are imaged.

In searching for a discriminator that would be unique for each row and that would also be intimately related to the individual intensity values, we recall the standard deviation (Baird, 1962, p. 24), a parameter that most of us are familiar with. We know that if we measure a certain quantity a number of times, our result will be a series of measurements. We can then take an average of these measurements to give us what we consider the best estimate of the correct value of that quantity. The standard deviation, then, gives us a measurement of the uncertainty of our best estimate. We shall define a parameter that mimics the standard deviation but that possesses an important distinction: Whereas the standard deviation is conventionally applied to many measurements of a single quantity, our parameter will be applied to quantities derived from single readings of many receptors. We shall call our parameter of discrimination the SDEV discriminator. The term may be awkward, but it is convenient as a variable name when used in a computer program. We define SDEV as

$$\text{SDEV} = \left(\sum (x_i - \bar{x})^2/n\right)^{1/2},$$

where

n = the number of gradient values per row
x_i = the individual gradient values
$\bar{x}$ = $\sum x_i/n$.

This parameter fulfills our requirements since it is intimately related to the individual values and also uniquely determined for each row. The computer calculates the SDEV discriminator for each row and then goes through the row searching for positions where the differences between the average value and the actual value exceed the value of the SDEV discriminator. The computer denotes such a position by printing a point on our output matrix. It performs this function for each row. The object is therefore outlined by a series of dots on the output matrix (see Figs. 7 and 13). This entire process is then repeated for the y direction.

In the final stage the computer calculates the gradient-of-the-gradient values in each row. The SDEV discriminator is then calculated for the gradient-of-the-gradient values in each row and the discriminator process is performed as in the second stage (Figs. 9 and 14). This, of course, is also repeated for the y direction (Fig. 9) and completes our actual experimental system. Testing of selected objects and images, using the above-described procedure, will determine the validity of this approach.

THE ARTIFICIAL TEST OBJECT AND ITS IMAGE

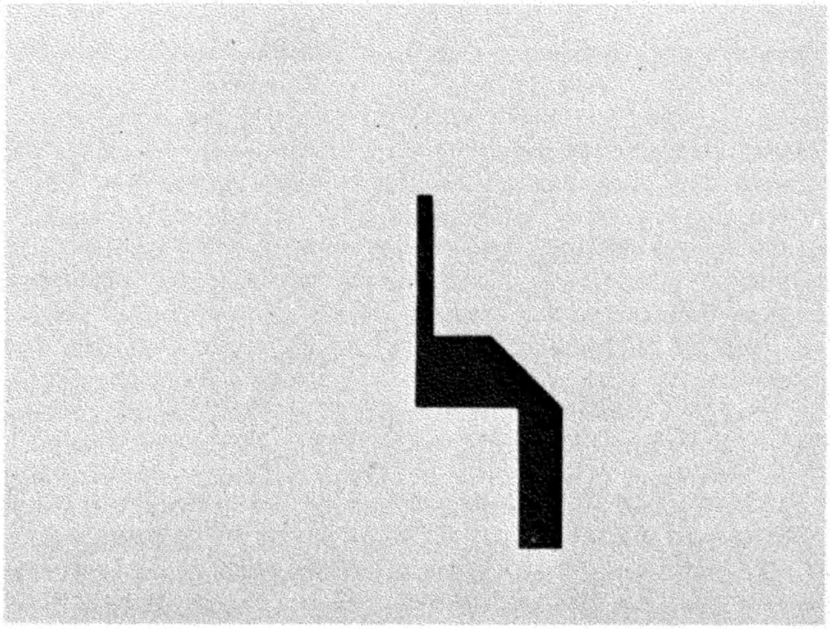
A carefully designed object (Fig. 4) was used to test our system. This black object was photographed on a white background. For all boundaries except one, horizontal and vertical lines were used in order to test the alignment of the scanning device. The one diagonal boundary was used to demonstrate that our analyses in the x and the y directions would also pick out boundaries that are not aligned perpendicular to our direction of analysis.

We first instructed the computer to print a matrix output of the intensity levels that made up the image (Fig. 5). The background is easily discernible and is coded as 1; the object itself ranges from 2 to 7. This range demonstrates that, although the object appears to be uniform, there is considerable variation in the actual intensity distribution. To better understand the situation, we have selected rows 50, 70, and 90 for special consideration. These sample the top, middle, and bottom sections of the object, respectively.

The graph of the intensity distribution (Fig. 6) shows that in row 50 the object definitely stands out above the background. The simple spike would seem to indicate that we are at the resolution limit of our system. In row 70 we see a relatively flat region at the top that extends over 14 receptors, indicating that we are at a thicker region of the object. Note that there is significant variation over this region. In row 90, a smaller flat region denotes a narrower section of the object than in row 70. In all three of these distributions we see that the background is flat except for slight, almost unnoticeable fluctuations.

If we now use the gradient procedure, we find that we can indeed pick out the object. Figure 7 is the result from the x-direction gradient procedure. As we would expect, the vertical and diagonal boundaries of the object have been selected. However, there is some confusion as to the exact position of the boundary. Let us refer to Fig. 8, the graphs of the gradient values for rows 50, 70, and 90, to see exactly what the situation is.

In all three rows in Fig. 8 we see two prominent spikes, one positive and one negative, indicating the left and right sides of the object. We see that if we use the largest positive value and the largest negative value, we can effectively pick out single boundaries. This, however, would require us to add a subprogram to our gradient procedure. Once the gradient procedure has selected the multiple boundaries, it will become the job of the subprogram to go to these boundaries and choose single



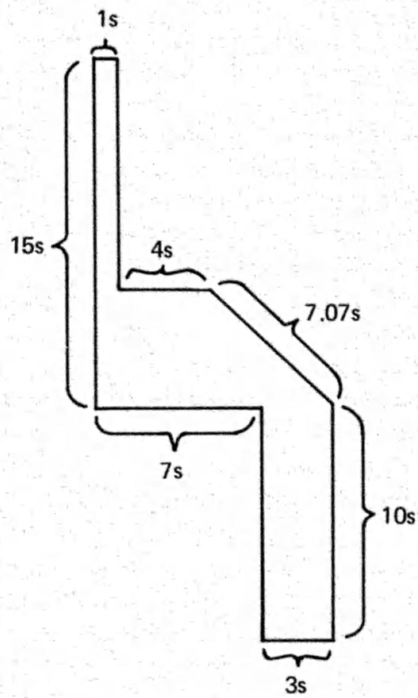


Fig. 4. The test object (above) and the proportions used (below).

COLUMNS

ROWS	50										60										70										80				
40	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
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	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	6	7	7	7	7	7	3	1	1	1	1	1	1
	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	6	7	7	7	7	7	3	1	1	1	1	1	1
80	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	6	7	7	7	7	7	3	1	1	1	1	1	1
	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	6	7	7	7	7	7	3	1	1	1	1	1	1
	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	6	7	7	7	7	7	3	1	1	1	1	1	1
	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	5	7	7	7	7	7	3	1	1	1	1	1	1
	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	5	7	7	7	7	7	3	1	1	1	1	1	1
	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	5	7	7	7	7	7	3	1	1	1	1	1	1
	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	5	7	7	7	7	7	3	1	1	1	1	1	1
	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	5	7	7	7	7	7	3	1	1	1	1	1	1
	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	5	7	7	7	7	7	3	1	1	1	1	1	1
	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	5	7	7	7	7	7	3	1	1	1	1	1	1
90	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	5	7	7	7	7	7	3	1	1	1	1	1	1
	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	5	7	7	7	7	7	3	1	1	1	1	1	1
	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	5	7	7	7	7	7	3	1	1	1	1	1	1
	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	5	7	7	7	7	7	3	1	1	1	1	1	1
	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	5	7	7	7	7	7	3	1	1	1	1	1	1
	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	5	6	6	6	6	6	3	1	1	1	1	1	1
	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	1	1	1	1	1	1	1
	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Fig. 5. Portion of test object intensity distribution.

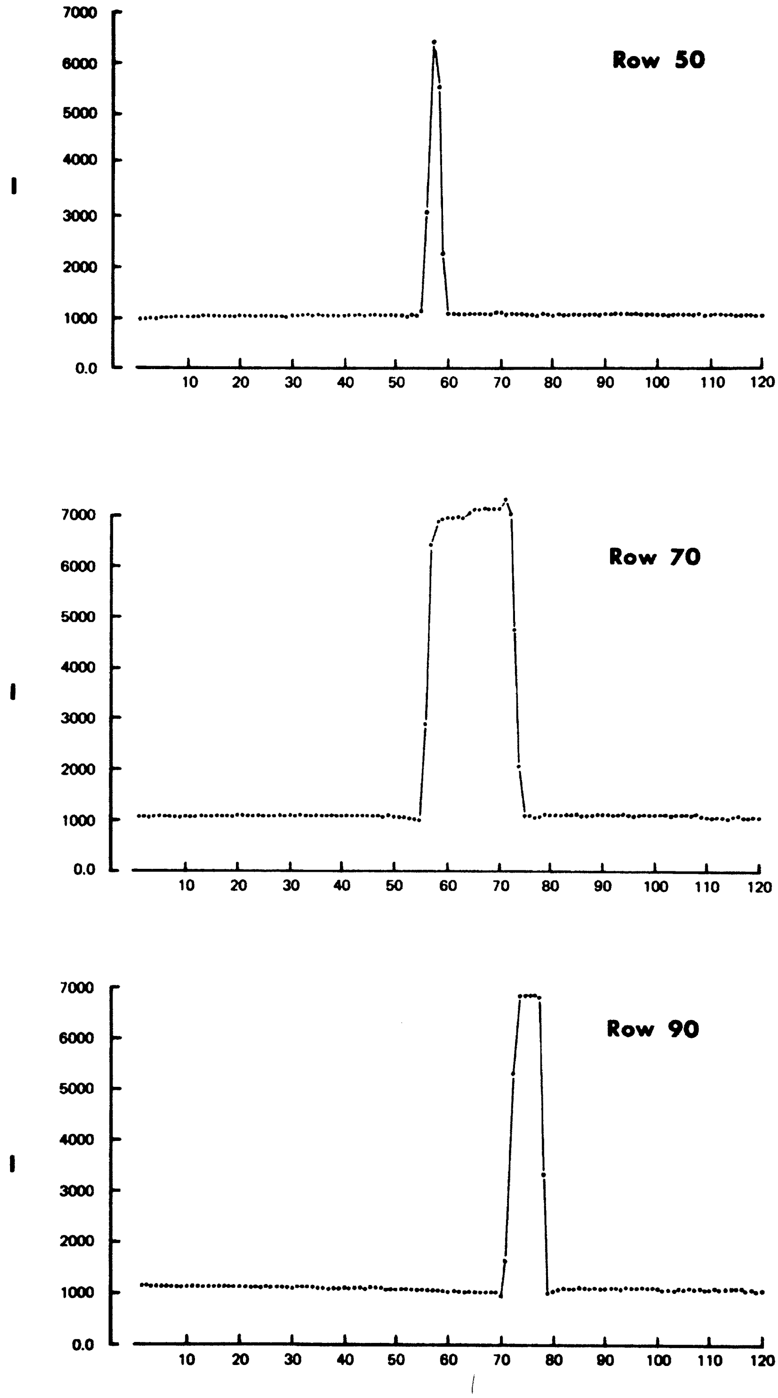

Fig. 6. Intensity distributions, rows 50, 70, and 90.

boundaries that are represented by the extreme values of the gradient spikes. This would be an effective method for selecting boundaries, but we would prefer a more accurate method at this time and would hope that the gradient-of-the-gradient analysis would provide this for us.

The computer output for the x-direction gradient-of-the-gradient procedure (Fig. 9) shows that we have again defined our object, but we still have multiple boundaries. The same situation exists for the y-direction procedure. At this time, we might feel slightly disheartened. However, if we check the plotted values for rows 50, 70, and 90 (Fig. 10), we note something significant: In each row, the boundary of the object can be selected by referring to the point where the graph intersects zero. The set of four spikes indicates the presence of an object, and the zero point denotes where the row intersects the edges of the object. This gives us an uncomplicated and unambiguous method of selecting the outline of an object. This is the type of process we would expect the eye to perform. All we need, then, is to add a subroutine to our gradient-of-the-gradient procedure that would direct the computer to the multiple boundaries that were selected by this procedure. The computer would then position the final boundary at the zero points.

We have offered sufficient evidence to demonstrate that we have a feasible method for selecting objects in a photographic negative, and we have proved that our retinal theory is acceptable. We must now demonstrate that it also works for more complex visual scenes.

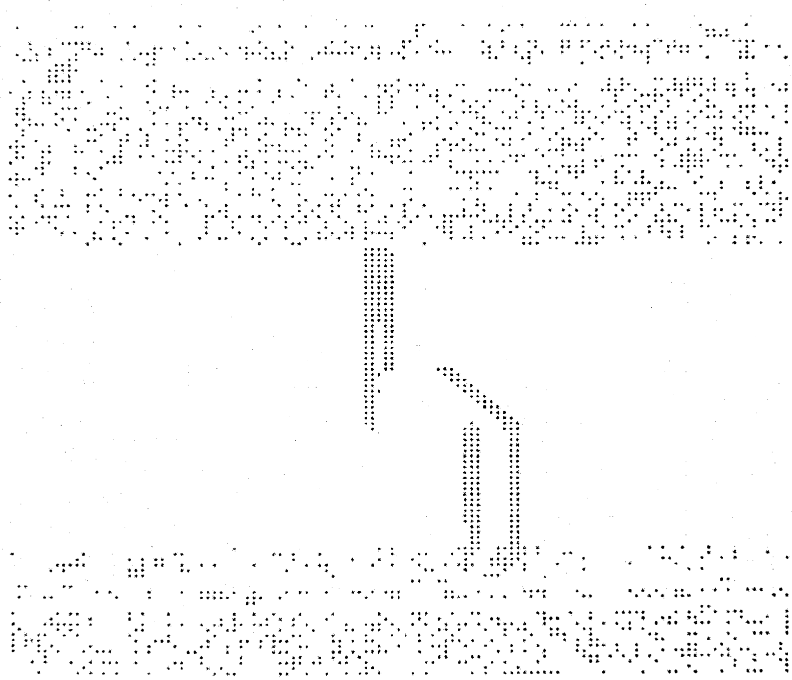

Fig. 7. Results of the x-direction gradient procedure for the test object.

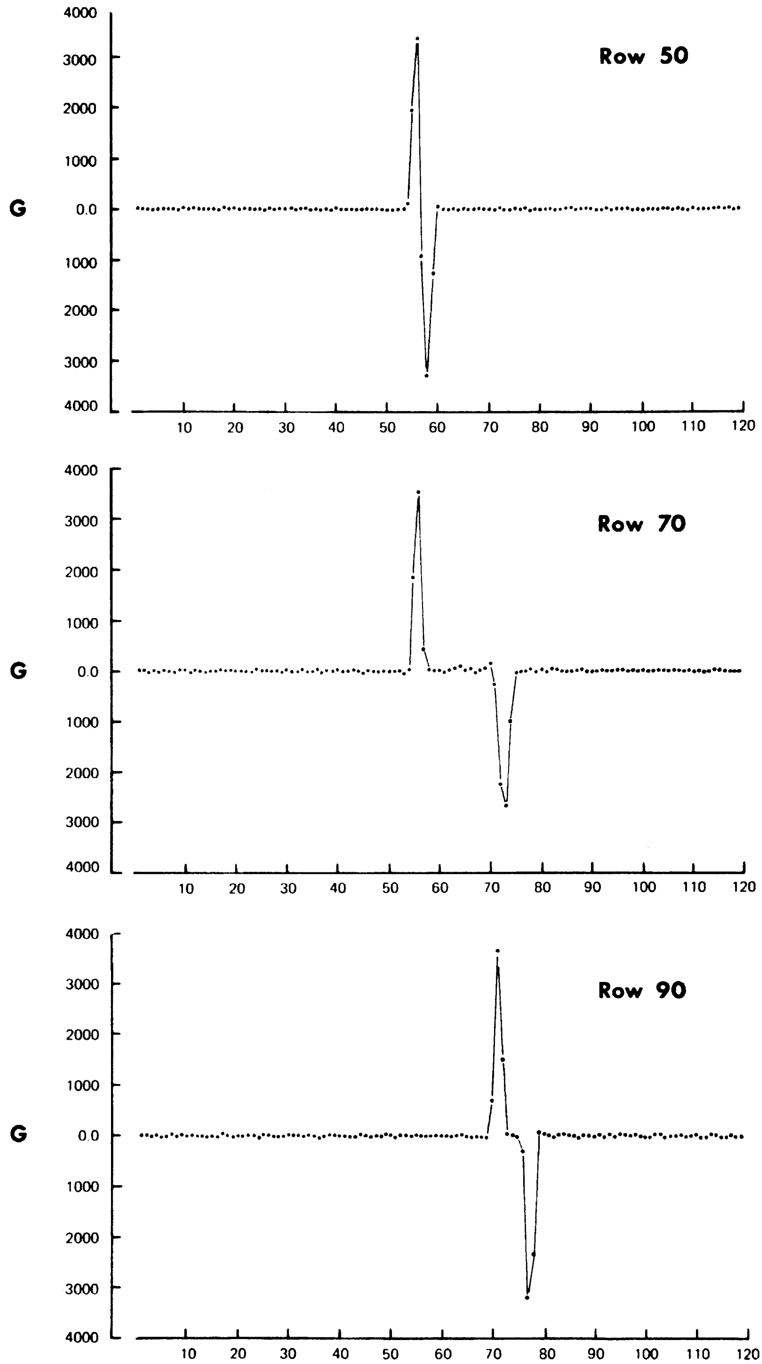

Fig. 8. Gradient values, rows 50, 70, and 90.

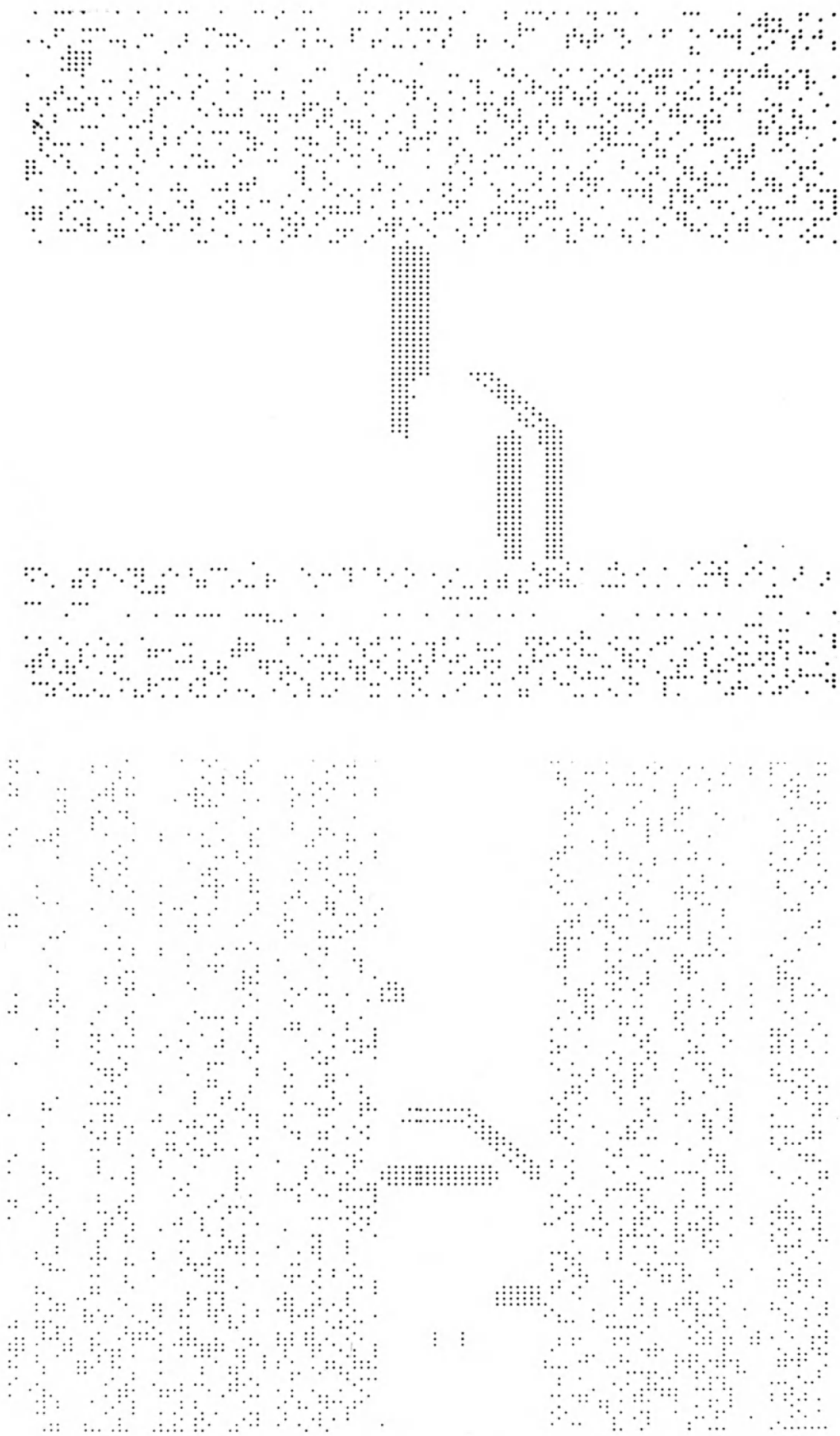

Fig. 9. Results of the x- and y-direction gradient-of-the-gradient procedure for the test object: x direction (above) and y direction (below).

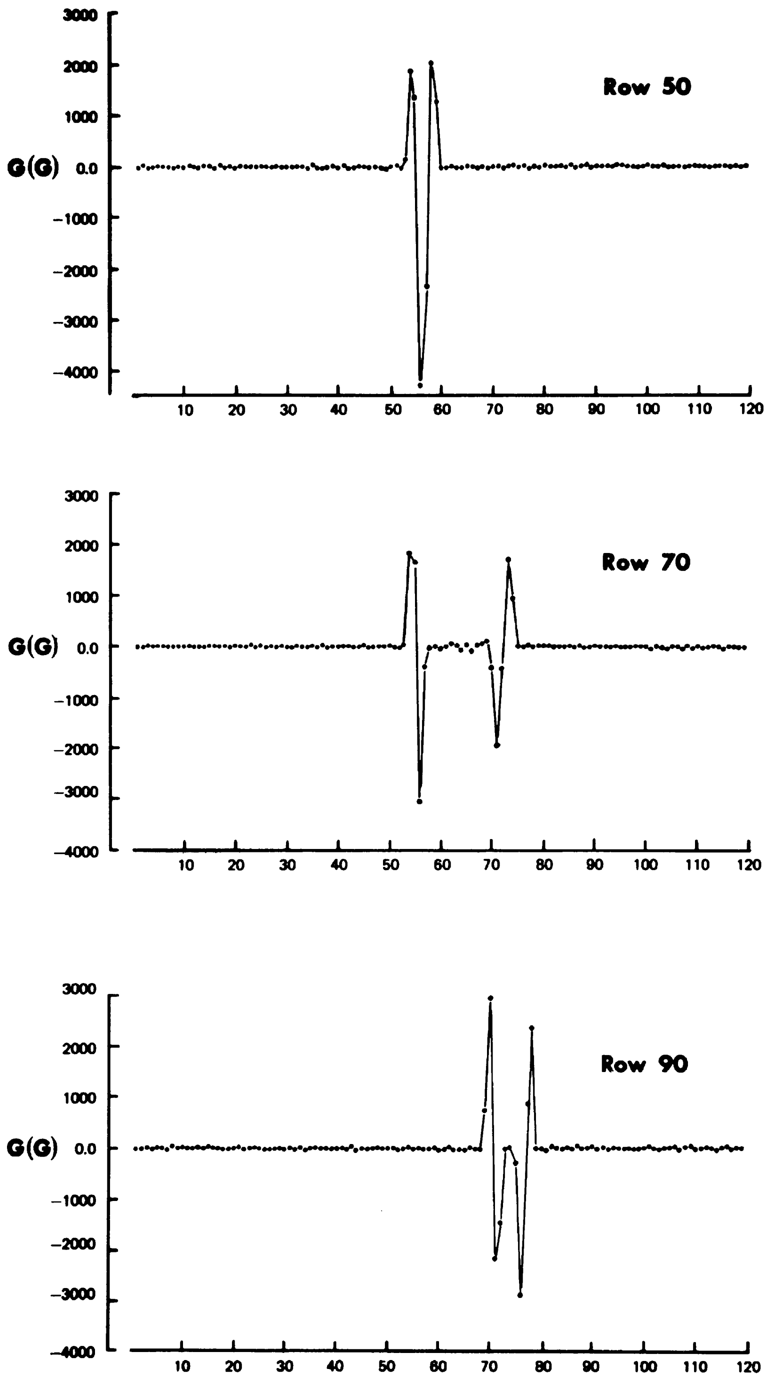

Fig. 10. Gradient-of-the-gradient values, rows 50, 70, and 90.

A REAL OBJECT SITUATION

We now turn our attention to a more complicated visual scene (Fig. 11): a chrome spade resting on a grass lawn. Armed with the confidence that we gained from our success in the previous experiment, we allow our model visual system to operate on this scene.

First, we check the intensity level output (Fig. 12) and find that we really do have a difficult situation here. Without some previous knowledge of its physical appearance, it is impossible to pick out and recognize the object.

Fig. 11. Photograph of real object.

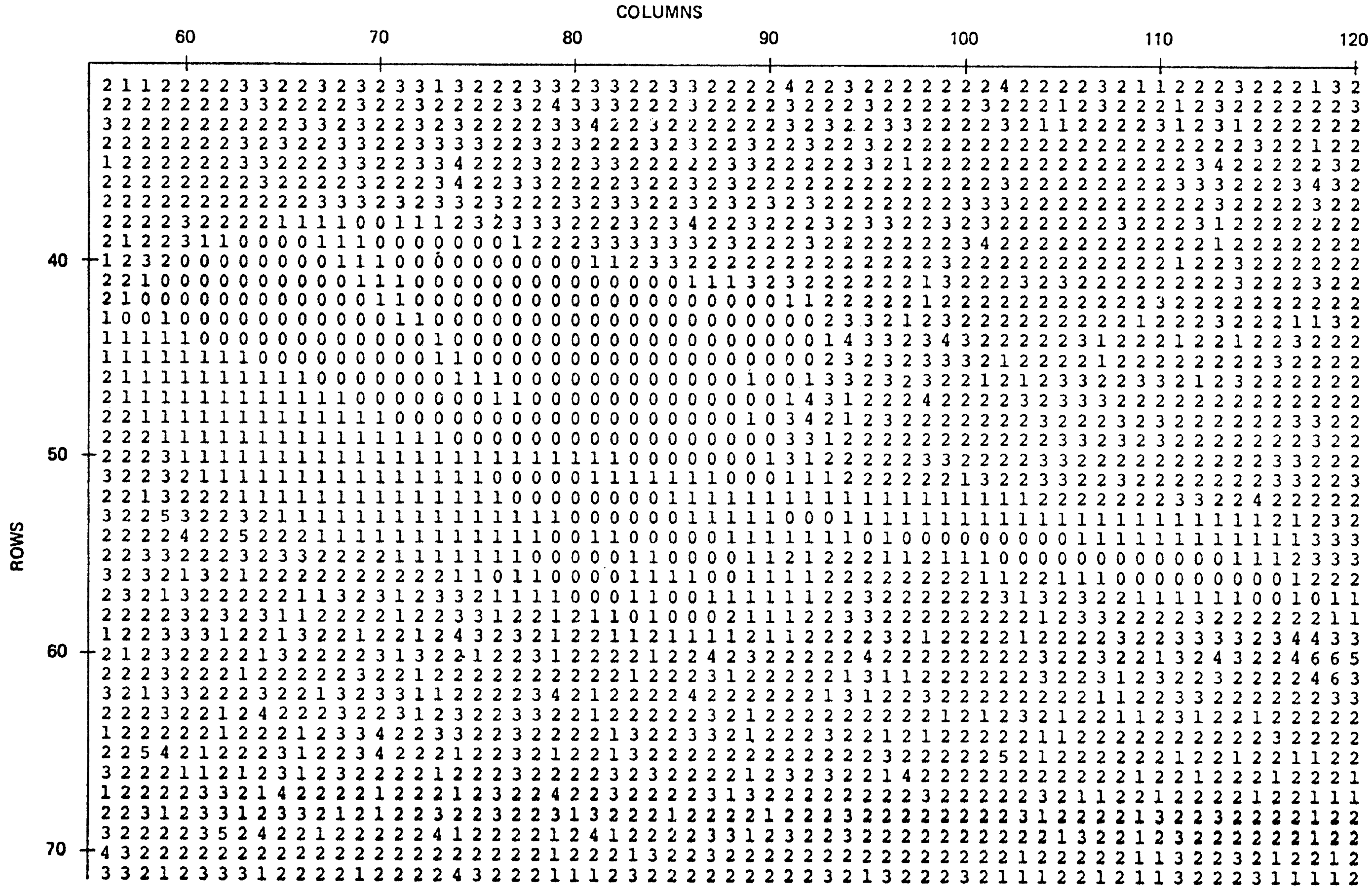

Fig. 12. Portion of real object intensity distribution.

Let us proceed now to see what the gradient procedure will produce (Fig. 13). We find that the object appears as a hole in a rather noisy background. The output of the gradient-of-the-gradient procedure (Fig. 14) shows the same situation.

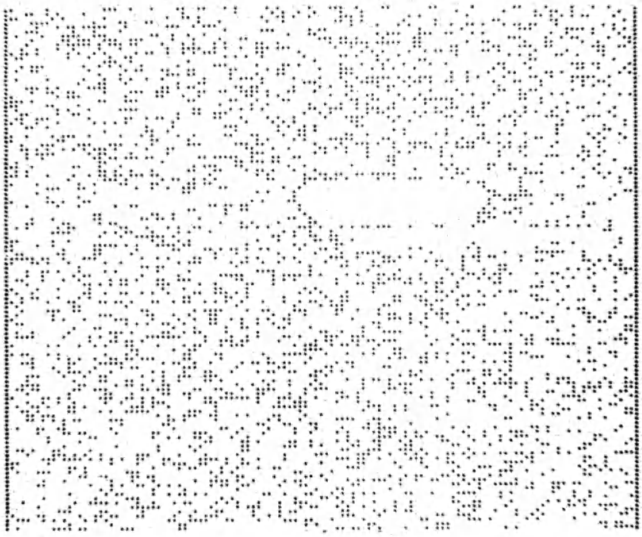

Fig. 13. Results of the x-direction gradient procedure for the real object.

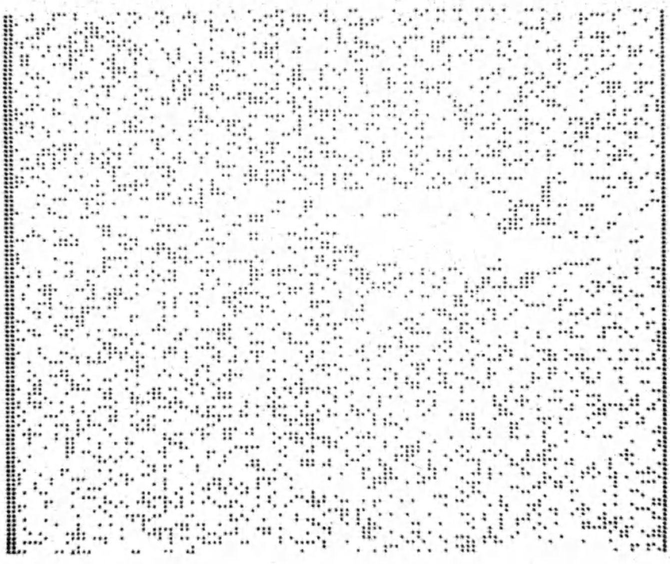

Fig. 14. Results of the x-direction gradient-of-the-gradient procedure for the real object.

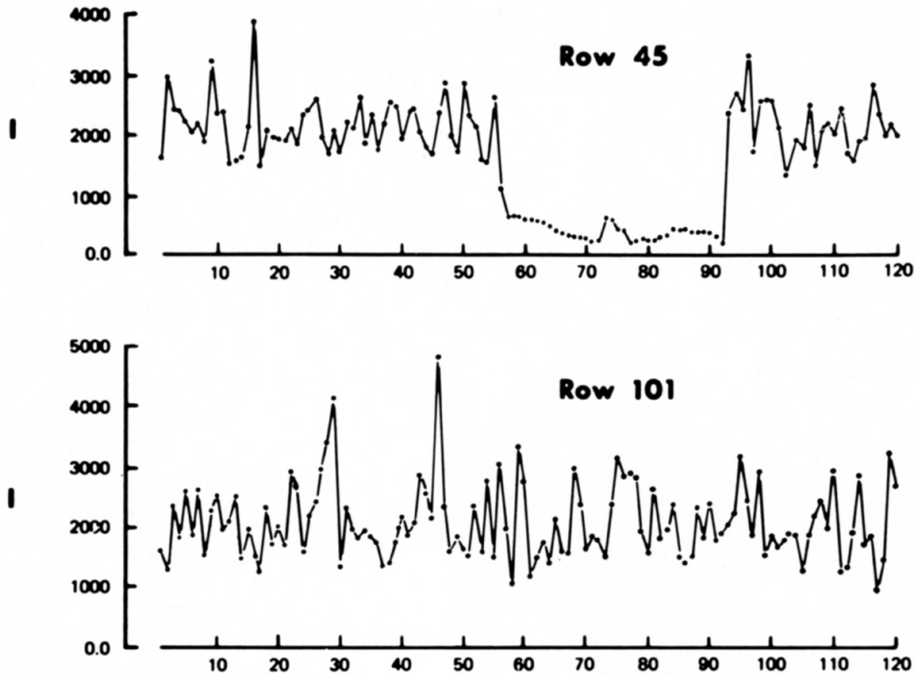

Fig. 15. Real object intensity distributions, rows 45 and 101.

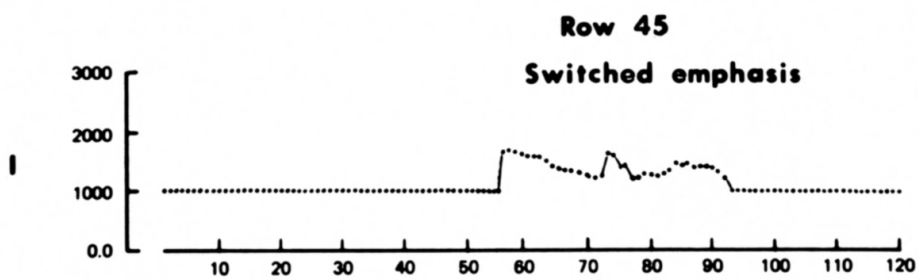

Fig. 16. Real object intensity distribution, row 45, for the switched visual emphasis.

The problem is that the computer has attempted to outline the blades of grass, and since the individual blades of grass are unresolvable, the result is a textured background. If we refer to the intensity values in row 45 (Fig. 15), we can see why the computer concentrated on the grass. The grass has a higher intensity level than the spade. To emphasize this fact, we can compare row 45 with row 101, which is at the bottom of our visual field where there is only grass. We observe that the grass background appears to be always at an intensity level of 1000 units or higher. The intensity level of the spade does indeed differ from the background, but in a negative way, being less than 1000. What we need to do is to switch the attention of our visual system from the noisy background to the spade. We can do this by instructing the computer to ascribe an intensity value of 1000 scale units to those intensities that have a value of 1000 scale units or more, and to *add* 1000 scale units to those intensities that are less than 1000 scale units. In our new intensity plot for row 45 (Fig. 16), the spade predominates and the background is retained as a constant signal. If we now apply the gradient-of-the-gradient procedure, we see that we have indeed found our object (Fig. 17).

The manner in which we switched the attention of our model visual system from the grass background to the spade is similar to a method that our own visual system uses. Looking at the photograph (Fig. 11), we see both the spade and the grass background. If we focus our attention on the grass, we see the individual blades of grass but not the details of the spade. If we then concentrate on the spade, we no longer perceive the grass as being composed of individual blades of grass but as a textured background. In other words, the signal of the grass background has been suppressed. The eye, because of foveal acuity, goes through such a process continuously but we never notice it since it is a natural function of our visual system.

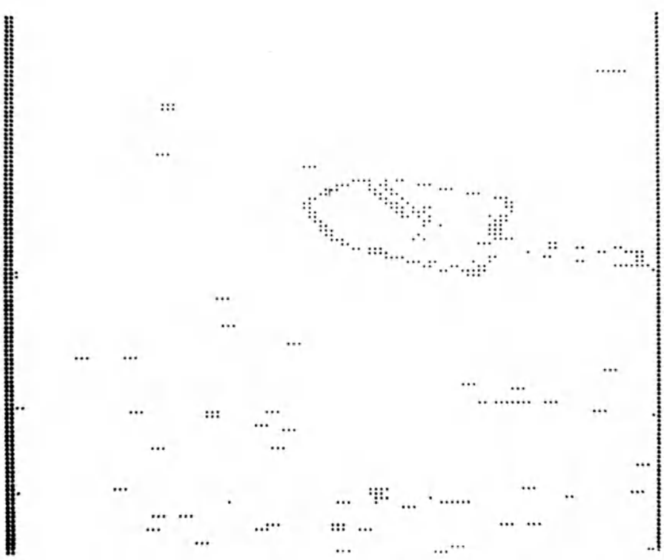

Fig. 17. Results of the x-direction gradient-of-the-gradient procedure for the real object with switched visual emphasis.

POSSIBLE APPLICATIONS

We have developed an acceptable three-stage retinal model based on psychophysical principles and have shown its validity experimentally by using equipment currently available at the University of Arizona. In the course of investigating our theory, we were also able to demonstrate a new method that can be used for selecting objects in aerial photographs. This method is a line-by-line process and needs to be applied in only two orthogonal directions. This process was completely derived from our retinal model and consequently is quite economical in its operation, requiring only a minimum of computer decision. This is significant since such a process is capable of high-speed object detection with remarkable accuracy. We can therefore say that we have indeed made a significant contribution to the area of computer analysis of aerial photographs.

It should not be assumed, however, that the procedures developed here are limited to aerial photography. The gradient-of-the-gradient procedure is extremely sensitive to changes in intensities and could very easily find application in areas where visual monitoring systems are now in use. One of the areas that has caused considerable concern to manufacturers of photographic emulsions is how to correctly evaluate color image formation in these emulsions. Using our system, a test object such as a color strip could be photographed, and then the image could be evaluated by selecting certain rows to be investigated. For each row, a graph of the density, gradient, and gradient-of-the-gradient values would be constructed. These would be repeated for each wavelength desired. We would then have an effective method of determining how well a given dye or dye combination contributes to the over-all formation of the color image.

In the area of psychophysics, our model visual system has unlimited uses. It first should be rigorously tested to determine how many similarities it actually has to the human visual system. Then a systematic study could be made to check out various theories of vision and also the many peculiarities of human vision. By use of different filters for the scanning device, theories of color vision can be investigated quite simply.

We can easily see that our model visual system is versatile in its applications. Our line of investigation has been fruitful in that we have not only successfully applied a new theory to the field of computer analysis of aerial photographs, but we have also developed an experimental model of the human visual system that appears to have unlimited applications.

APPENDIX A

COMPUTER TABULAR DATA

The following pages contain tables of data generated by the retinal computer program for use in this study. The data are arranged, in order, from left to right and from top to bottom.

Test Object Intensity Data

Row 50

992.00	998.00	1002.00	1008.00	1010.00
1010.00	1013.00	1020.00	1023.00	1013.00
1014.00	1016.00	1026.00	1029.00	1022.00
1020.00	1026.00	1020.00	1038.00	1040.00
1047.00	1034.00	1028.00	1036.00	1034.00
1030.00	1030.00	1036.00	1034.00	1040.00
1045.00	1050.00	1044.00	1046.00	1059.00
1043.00	1056.00	1057.00	1050.00	1044.00
1060.00	1059.00	1065.00	1063.00	1060.00
1060.00	1061.00	1056.00	1056.00	1054.00
1046.00	1039.00	1053.00	1039.00	1143.00
3092.00	6478.00	5564.00	2276.00	1027.00
1060.00	1062.00	1056.00	1059.00	1060.00
1060.00	1063.00	1066.00	1064.00	1067.00
1059.00	1053.00	1062.00	1060.00	1058.00
1060.00	1060.00	1072.00	1059.00	1060.00
1059.00	1062.00	1064.00	1059.00	1058.00
1060.00	1066.00	1062.00	1059.00	1070.00
1077.00	1074.00	1071.00	1080.00	1062.00
1058.00	1068.00	1080.00	1085.00	1074.00
1062.00	1063.00	1068.00	1065.00	1070.00
1074.00	1066.00	1070.00	1066.00	1056.00
1064.00	1062.00	1058.00	1052.00	1052.00
1059.00	1060.00	1053.00	1049.00	1044.00

Row 70

1056.00	1064.00	1075.00	1074.00	1078.00
1072.00	1068.00	1066.00	1060.00	1069.00
1080.00	1077.00	1083.00	1084.00	1075.00
1068.00	1066.00	1070.00	1073.00	1085.00
1090.00	1090.00	1080.00	1072.00	1082.00
1084.00	1095.00	1094.00	1090.00	1082.00
1095.00	1090.00	1085.00	1092.00	1084.00
1082.00	1088.00	1078.00	1090.00	1092.00
1097.00	1094.00	1091.00	1094.00	1088.00
1085.00	1090.00	1088.00	1080.00	1071.00
1064.00	1065.00	1056.00	1035.00	1047.00
2896.00	6434.00	6900.00	6944.00	6960.00
6984.00	6978.00	6984.00	7051.00	7126.00
7134.00	7172.00	7140.00	7145.00	7192.00
7348.00	7055.00	4810.00	2111.00	1112.00
1092.00	1086.00	1082.00	1112.00	1109.00
1106.00	1100.00	1113.00	1115.00	1110.00
1098.00	1096.00	1099.00	1119.00	1120.00
1110.00	1108.00	1114.00	1112.00	1100.00
1104.00	1110.00	1105.00	1104.00	1106.00
1114.00	1119.00	1102.00	1108.00	1113.00
1108.00	1106.00	1112.00	1097.00	1097.00
1080.00	1086.00	1084.00	1079.00	1083.00
1099.00	1088.00	1079.00	1076.00	1074.00

Row 90

1116.00	1116.00	1120.00	1117.00	1122.00
1115.00	1120.00	1127.00	1114.00	1122.00
1124.00	1120.00	1119.00	1116.00	1114.00
1106.00	1111.00	1134.00	1134.00	1122.00
1119.00	1117.00	1114.00	1120.00	1111.00
1120.00	1128.00	1116.00	1105.00	1105.00
1116.00	1124.00	1132.00	1116.00	1120.00
1110.00	1100.00	1104.00	1113.00	1118.00
1110.00	1109.00	1108.00	1104.00	1120.00
1124.00	1104.00	1095.00	1092.00	1100.00
1099.00	1085.00	1098.00	1100.00	1088.00
1090.00	1082.00	1077.00	1078.00	1066.00
1072.00	1066.00	1058.00	1058.00	1060.00
1056.00	1039.00	1033.00	1027.00	997.00
1692.00	5354.00	6856.00	6886.00	6888.00
6882.00	6566.00	3370.00	1048.00	1086.00
1116.00	1134.00	1108.00	1110.00	1128.00
1138.00	1143.00	1133.00	1140.00	1141.00
1133.00	1142.00	1134.00	1140.00	1136.00
1140.00	1146.00	1150.00	1158.00	1140.00
1122.00	1108.00	1126.00	1138.00	1129.00
1125.00	1123.00	1138.00	1130.00	1125.00
1136.00	1124.00	1116.00	1126.00	1136.00
1120.00	1104.00	1111.00	1102.00	1100.00

Test Object Gradient Data

Row 50

6.00	4.00	6.00	2.00	0.00
3.00	7.00	3.00	−10.00	1.00
2.00	10.00	3.00	−7.00	−2.00
6.00	−6.00	18.00	2.00	7.00
−13.00	−6.00	8.00	−2.00	−4.00
0.00	6.00	−2.00	6.00	5.00
5.00	−6.00	2.00	13.00	−16.00
13.00	1.00	−7.00	−6.00	16.00
−1.00	6.00	−2.00	−3.00	0.00
1.00	−5.00	0.00	−2.00	−8.00
−7.00	14.00	−14.00	104.00	1949.00
3386.00	−914.00	−3288.00	−1249.00	33.00
2.00	−6.00	3.00	1.00	0.00
3.00	3.00	−2.00	3.00	−8.00
−6.00	9.00	−2.00	−2.00	2.00
0.00	12.00	−13.00	1.00	−1.00
3.00	2.00	−5.00	−1.00	2.00
6.00	−4.00	−3.00	11.00	7.00
−3.00	−3.00	9.00	−18.00	−4.00
10.00	12.00	5.00	−11.00	−12.00
1.00	5.00	−3.00	5.00	4.00
−8.00	4.00	−4.00	−10.00	8.00
−2.00	−4.00	−6.00	0.00	7.00
1.00	−7.00	−4.00	−5.00	0.00

Row 70

8.00	11.00	−1.00	4.00	−6.00
−4.00	−2.00	−6.00	9.00	11.00
−3.00	6.00	1.00	−9.00	−7.00
−2.00	4.00	3.00	12.00	5.00
0.00	−10.00	−8.00	10.00	2.00
11.00	−1.00	−4.00	−8.00	13.00
−5.00	−5.00	7.00	−8.00	−2.00
6.00	−10.00	12.00	2.00	5.00
−3.00	−3.00	3.00	−6.00	−3.00
5.00	−2.00	−8.00	−9.00	−7.00
1.00	−9.00	−21.00	12.00	1849.00
3538.00	466.00	44.00	16.00	24.00
−6.00	6.00	67.00	75.00	8.00
38.00	−32.00	5.00	47.00	156.00
−293.00	−2245.00	−2699.00	−999.00	−20.00
−6.00	−4.00	30.00	−3.00	−3.00
−6.00	13.00	2.00	−5.00	−12.00
−2.00	3.00	20.00	1.00	−10.00
−2.00	6.00	−2.00	−12.00	4.00
6.00	−5.00	−1.00	2.00	8.00
5.00	−17.00	6.00	5.00	−5.00
−2.00	6.00	−15.00	0.00	−17.00
6.00	−2.00	−5.00	4.00	16.00
−11.00	−9.00	−3.00	−2.00	0.00

Row 90

0.00	4.00	−3.00	5.00	−7.00
5.00	7.00	−13.00	8.00	2.00
−4.00	−1.00	−3.00	−2.00	−8.00
5.00	23.00	0.00	−12.00	−3.00
−2.00	−3.00	6.00	−9.00	9.00
8.00	−12.00	−11.00	0.00	11.00
8.00	8.00	−16.00	4.00	−10.00
−10.00	4.00	9.00	5.00	−8.00
−1.00	−1.00	−4.00	16.00	4.00
−20.00	−9.00	−3.00	8.00	−1.00
−14.00	13.00	2.00	−12.00	2.00
−8.00	−5.00	1.00	−12.00	6.00
−6.00	−8.00	0.00	2.00	−4.00
−17.00	−6.00	−6.00	−30.00	695.00
3662.00	1502.00	30.00	2.00	−6.00
−316.00	−3196.00	−2322.00	38.00	30.00
18.00	−26.00	2.00	18.00	10.00
5.00	−10.00	7.00	1.00	−8.00
9.00	−8.00	6.00	−4.00	4.00
6.00	4.00	8.00	−18.00	−18.00
−14.00	18.00	12.00	−9.00	−4.00
−2.00	15.00	−8.00	−5.00	11.00
−12.00	−8.00	10.00	10.00	−16.00
−16.00	7.00	−9.00	−2.00	0.00

Test Object Gradient-of-the-Gradient Data

Row 50

−2.00	2.00	−4.00	−2.00	3.00
4.00	−4.00	−13.00	11.00	1.00
8.00	−7.00	−10.00	5.00	8.00
−12.00	24.00	−16.00	5.00	−20.00
7.00	14.00	−10.00	−2.00	4.00
6.00	−8.00	8.00	−1.00	0.00
−11.00	8.00	11.00	−29.00	29.00
−12.00	−8.00	1.00	22.00	−17.00
7.00	−8.00	−1.00	3.00	1.00
−6.00	5.00	−2.00	−6.00	1.00
21.00	−28.00	118.00	1845.00	1437.00
−4300.00	−2374.00	2039.00	1282.00	−31.00
−8.00	9.00	−2.00	−1.00	3.00
0.00	−5.00	5.00	−11.00	2.00
15.00	−11.00	0.00	4.00	−2.00
12.00	−25.00	14.00	−2.00	4.00
−1.00	−7.00	4.00	3.00	4.00
−10.00	1.00	14.00	−4.00	−10.00
0.00	12.00	−27.00	14.00	14.00
2.00	−7.00	−16.00	−1.00	13.00
4.00	−8.00	8.00	−1.00	−12.00
12.00	−8.00	−6.00	18.00	−10.00
−2.00	−2.00	6.00	7.00	−6.00
−8.00	3.00	−1.00	0.00	0.00

Row 70

3.00	−12.00	5.00	−10.00	2.00
2.00	−4.00	15.00	2.00	−14.00
9.00	−5.00	−10.00	2.00	5.00
6.00	−1.00	9.00	−7.00	−5.00
−10.00	2.00	18.00	−8.00	9.00
−12.00	−3.00	−4.00	21.00	−18.00
0.00	12.00	−15.00	6.00	8.00
−16.00	22.00	−10.00	3.00	−8.00
0.00	6.00	−9.00	3.00	8.00
−7.00	−6.00	−1.00	2.00	8.00
−10.00	−12.00	33.00	1837.00	1689.00
−3072.00	−422.00	−28.00	8.00	−30.00
12.00	61.00	8.00	−67.00	30.00
−70.00	37.00	42.00	109.00	−449.00
−1952.00	−454.00	1700.00	979.00	14.00
2.00	34.00	−33.00	0.00	−3.00
19.00	−11.00	−7.00	−7.00	10.00
5.00	17.00	−19.00	−11.00	8.00
8.00	−8.00	−10.00	16.00	2.00
−11.00	4.00	3.00	6.00	−3.00
−22.00	23.00	−1.00	−10.00	3.00
8.00	−21.00	15.00	−17.00	23.00
−8.00	−3.00	9.00	12.00	−27.00
2.00	6.00	1.00	0.00	0.00

Row 90

4.00	−7.00	8.00	−12.00	12.00
2.00	−20.00	21.00	−6.00	−6.00
3.00	−2.00	1.00	−6.00	13.00
18.00	-23.00	−12.00	9.00	1.00
−1.00	9.00	−15.00	18.00	−1.00
−20.00	1.00	11.00	11.00	−3.00
0.00	−24.00	20.00	−14.00	0.00
14.00	5.00	−4.00	−13.00	7.00
0.00	−3.00	20.00	−12.00	−24.00
11.00	6.00	11.00	−9.00	−13.00
27.00	−11.00	−14.00	14.00	−10.00
3.00	6.00	−13.00	18.00	−12.00
−2.00	8.00	2.00	−6.00	−13.00
11.00	0.00	−24.00	725.00	2967.00
−2160.00	−1472.00	−28.00	−8.00	−310.00
−2880.00	874.00	2360.00	−8.00	−12.00
−44.00	28.00	16.00	−8.00	−5.00
−15.00	17.00	−6.00	−9.00	17.00
−17.00	14.00	−10.00	8.00	2.00
−2.00	4.00	−26.00	0.00	4.00
32.00	−6.00	−21.00	5.00	2.00
17.00	−23.00	3.00	16.00	−23.00
4.00	18.00	0.00	−26.00	0.00
23.00	−16.00	7.00	0.00	0.00

Real Object Intensity Data

Row 45

1598.00	2956.00	2388.00	2386.00	2212.00
2014.00	2186.00	1854.00	3200.00	2368.00
2395.00	1528.00	1556.00	1630.00	2110.00
3845.00	1398.00	2064.00	1951.00	1909.00
1896.00	2074.00	1823.00	2319.00	2370.00
2591.00	1943.00	1610.00	2054.00	1671.00
2180.00	2069.00	2634.00	1823.00	2327.00
1667.00	2156.00	2518.00	2450.00	1909.00
2379.00	2431.00	2014.00	1780.00	1630.00
2367.00	2845.00	1966.00	1679.00	2840.00
2293.00	2096.00	1580.00	1523.00	2579.00
1105.00	640.00	659.00	633.00	594.00
573.00	550.00	558.00	499.00	410.00
364.00	338.00	301.00	289.00	280.00
229.00	240.00	620.00	580.00	412.00
417.00	200.00	216.00	294.00	249.00
251.00	295.00	340.00	444.00	419.00
443.00	372.00	384.00	390.00	373.00
313.00	207.00	2344.00	2669.00	2366.00
3296.00	1685.00	2514.00	2579.00	2543.00
2100.00	1308.00	1571.00	1914.00	1783.00
2482.00	1460.00	2060.00	2191.00	2003.00
2432.00	1703.00	1550.00	1895.00	1904.00
2816.00	2332.00	1958.00	2170.00	1978.00

Row 101

1634.00	1286.00	2417.00	1829.00	2657.00
1880.00	2666.00	1544.00	2310.00	2589.00
2031.00	2106.00	2583.00	1470.00	2000.00
1508.00	1268.00	2378.00	1764.00	2062.00
1732.00	2976.00	2652.00	1590.00	2180.00
2444.00	2900.00	3440.00	4196.00	1320.00
2385.00	1976.00	1838.00	1995.00	1874.00
1779.00	1346.00	1420.00	1742.00	2217.00
1826.00	2106.00	2906.00	2593.00	2166.00
4858.00	2366.00	1586.00	1874.00	1690.00
1517.00	2391.00	1629.00	2806.00	1558.00
3086.00	2000.00	1578.00	3396.00	2605.00
1157.00	1489.00	1784.00	1417.00	2156.00
1582.00	1529.00	3040.00	2405.00	1638.00
1848.00	1813.00	1524.00	2392.00	3190.00
2828.00	2910.00	2841.00	1934.00	1576.00
2643.00	1783.00	1944.00	2403.00	1454.00
1426.00	1524.00	2344.00	1818.00	2402.00
1792.00	1939.00	2036.00	2216.00	3176.00
2419.00	1863.00	2926.00	1513.00	1862.00
1654.00	1798.00	1882.00	1856.00	1259.00
1843.00	2146.00	2459.00	2038.00	2960.00
1227.00	1335.00	1913.00	2876.00	1770.00
1896.00	978.00	1443.00	3254.00	2679.00

APPENDIX B

THE RETINAL COMPUTER PROGRAM

```
      PROGRAM ASLSOG(INPUT,OUTPUT,TAPE1)
      DIMENSION ARRAY(120,120),GRDRAY(120,120),GRDLIN(120)
C     PROCEDURE FOR SELECTING THE DESIRED PICTURE
      READ(1,8) K1,K2,K3,SAMPLE
      PRINT 9,K1,K2,K3,SAMPLE
      READ(1,10)((ARRAY(I,J),J=1,120),I=1,119)
      PRINT 6,ARRAY(1,1),ARRAY(2,1),ARRAY(3,1)
      DO 2000 IK=1,120
      DO 2000 JK=1,120
      ARRAY(IK,JK)=0.0
 2000 CONTINUE
      READ(1,8) K1,K2,K3,SAMPLE
      PRINT 9,K1,K2,K3,SAMPLE
      READ(1,8) K1,K2,K3,SAMPLE
      PRINT 9,K1,K2,K3,SAMPLE
      READ(1,10) ((ARRAY(I,J),J=1,120),I=1,120)
      PRINT 6,ARRAY(1,1),ARRAY(2,1),ARRAY(3,1)
C        WE NOW HAVE PICTURE B-2 IN THE MATRIX ARRAY
C     OUR PICTURE IS NOW IN THE MATRIX CALLED ARRAY
C     THE FOLLOWING PROCEDURE TESTS FOR ALIGNMENT OF OUR
C     PICTURE DATA AND PRINTS OUT THE DENSITY STEPS
      DO 18 IV=1,120
      DO 18 JV=1,120
      X=ARRAY(IV,JV)
      X=X/1000.0
      IF(X.LT.0.51) GO TO 1010
      IF(X.LT.1.50) GO TO 1015
      IF(X.LT.2.51) GO TO 1025
      IF(X.LT.3.50) GO TO 1035
      IF(X.LT.4.51) GO TO 1045
      IF (X.LT.5.50) GO TO 1055
      IF(X.LT.6.51) GO TO 1065
      IF(X.LT.7.50) GO TO 1075
      IF(X.LT.8.51) GO TO 1085
      GRDRAY(IV,JV)=1R9
      GO TO 18
 1010 GRDRAY(IV,JV)=1R0
      GO TO 18
```

```
 1015 GRDRAY(IV,JV)=1R1
      GO TO 18
 1025 GRDRAY(IV,JV)=1R2
      GO TO 18
 1035 GRDRAY(IV,JV)=1R3
      GO TO 18
 1045 GRDRAY(IV,JV)=1R4
      GO TO 18
 1055 GRDRAY(IV,JV)=1R5
      GO TO 18
 1065 GRDRAY(IV,JV)=1R6
      GO TO 18
 1075 GRDRAY(IV,JV)=1R7
      GO TO 18
 1085 GRDRAY(IV,JV)=1R8
   18 CONTINUE
      PRINT 1066
 1066 FORMAT(1H1,10X,*TEST TO CHECK FOR OBJECT ALIGNMENT*)
      PRINT 1067
      PRINT 1068
      PRINT 1069 ,((GRDRAY(I,J),J=1,60),I=1,120)
      PRINT 1070
      PRINT 1067
      PRINT 1068
      PRINT 1069,((GRDRAY(I,J),J=61,120),I=1,120)
C     END OF DENSITY STEP PROCEDURE
C     DENSITIES IN THE ROWS AND COLUMNS OF INTEREST ARE
C     NOW PRINTED OUT
      PRINT 3020
 3020 FORMAT(1H1,10X,*DENSITY VALUES IN ROW 50*)
      PRINT 21,(ARRAY(50,J),J=1,120)
      PRINT 3076
 3076 FORMAT(1H1,10X,*DENSITY VALUES IN ROW 70*)
      PRINT 21,(ARRAY(70,J),J=1,120)
      PRINT 3086
 3086 FORMAT(1H1,10X,*DENSITY VALUES IN ROW 90*)
      PRINT 21,(ARRAY(90,J),J=1,120)
C     NOW THE AVERAGE DENSITIES IN THE X DIRECTION AND THE
C     Y DIRECTION ARE CALCULATED AND PRINTED ALONG WITH AN
C     AVE DENSITY VALUE FOR THE ENTIRE PICTURE
      XAVE=0.0
      DO 12 J=1,120
      DO 11 K=1,120
      XAVE=XAVE+ARRAY(K,J)
   11 CONTINUE
      GRDLIN(J)=XAVE/120.0
      XAVE=0.0
   12 CONTINUE
      PRINT 20
      PRINT 21,GRDLIN
      AVE=0.0
      DO 30 JL=1,120
      AVE=AVE+GRDLIN(JL)
```

```
   30 CONTINUE
      AVE=AVE/120.0
      PRINT 51,AVE
      YAVE=0.0
      DO 22 JY=1,120
      DO 25 KY=1,120
      YAVE=YAVE+ARRAY(JY,KY)
   25 CONTINUE
      GRDLIN(JY)=YAVE/120.0
      YAVE=0.0
   22 CONTINUE
      PRINT 23
      PRINT 21,GRDLIN
      AVE=0.0
      DO 31 JK=1,120
      AVE=AVE+GRDLIN(JK)
   31 CONTINUE
      AVE=AVE/120.0
      PRINT 51,AVE
C     DO LOOP TO CALCULATE THE GRADIENT IN THE X DIRECTION
      DO 79 K=1,120
      DO 79 MN=1,119
      GRDRAY(K,MN)=ARRAY(K,MN+1)-ARRAY(K,MN)
   79 CONTINUE
C     GRADIENT VALUES IN THE ROWS OF INTEREST ARE NOW
C     PRINTED OUT
      PRINT 3120
      GRDRAY(50,120)=0.0
 3120 FORMAT(1H1,10X,*GRADIENT VALUES IN ROW 50*)
      PRINT 21,(GRDRAY(50,J),J=1,120)
      PRINT 3176
 3176 FORMAT(1H1,10X,*GRADIENT VALUES IN ROW 70*)
      GRDRAY(70,120)=0.0
      PRINT 21,(GRDRAY(70,J),J=1,120)
      PRINT 3186
 3186 FORMAT(1H1,10X,*GRADIENT VALUES IN ROW 90*)
      GRDRAY(90,120)=0.0
      PRINT 21,(GRDRAY(90,J),J=1,120)
C     AVE X DIRECT GRAD VAL FOR ENT PIX IS NOW CALCULATED
      XAVE=0.0
      DO 82 JK=1,119
      DO 81 KK=1,120
      XAVE=XAVE+GRDRAY(KK,JK)
   81 CONTINUE
      GRDLIN(JK)=XAVE/120.0
      XAVE=0.0
   82 CONTINUE
      TAVE=0.0
      DO 50 KK=1,119
      TAVE=TAVE+GRDLIN(KK)
   50 CONTINUE
      TAVE=TAVE/119.0
      GRDLIN(120)=0.0
      PRINT 80
```

```
      PRINT 21,GRDLIN
      PRINT 51,TAVE
   51 FORMAT(1H0,5X,*OVERALL AVERAGE VALUE IS*,F8.2)
C     NOW THE SDEV SORT FOR THE GRADIENT IN THE X DIRECT.
      DO 209 JK=1,120
      AVE=DEV=SDEV=DIF=0.0
      DO 229 IK=1,119
      X=GRDRAY(JK,IK)
      GRDRAY(JK,IK)=ABS(X)
      AVE=AVE+GRDRAY(JK,IK)
  229 CONTINUE
      AVE=AVE/119.0
      DO 239 MK=1,119
      X=AVE-GRDRAY(JK,MK)
      DEV=X*X+DEV
  239 CONTINUE
      DEV=DEV/119.0
      SDEV=SQRT(DEV)
C     SDEV IS THE BASIS FOR OUR DISCRIMINATOR
      GRDLIN(JK)=SDEV
      TDEV=SDEV
C     TDEV IS A MULTIPLE OF SDEV
C     HERE TDEV EQUALS ONE TIMES SDEV, I.E. TDEV=SDEV
C     NOW THE ACTUAL SORTING PROCESS
      DO 249 LK=1,119
      DIF=AVE-GRDRAY(JK,LK)
      DIF=ABS(DIF)
      IF(DIF-TDEV)250,250,252
  250 GRDRAY(JK,LK)=1R
      GO TO 249
  252 GRDRAY(JK,LK)=1R.
  249 CONTINUE
  209 CONTINUE
      DO 225 MK=1,120
      GRDRAY(MK,120)=1RN
  225 CONTINUE
C     NOW WE PRINT OUT THE COMPUTER OUTLINE
      PRINT 309
      PRINT 301,((GRDRAY(IK,JK),JK=1,60),IK=1,120)
      PRINT 310
      PRINT 301,((GRDRAY(IK,JK),JK=61,120),IK=1,120)
      PRINT 311
      PRINT 312,GRDLIN
C     NOW FOR THE GRADIENT VALUES IN THE Y DIRECTION
C     OUR PROCEDURE IS THE SAME AS THE THE PREVIOUS ONE
C     EXCEPT NOW WE ARE WORKING IN COLUMNS INSTEAD OF
C     IN ROWS
      DO 87 KL=1,120
      DO 87 ML=1,119
      GRDRAY(ML,KL)=ARRAY(ML+1,KL)-ARRAY(ML,KL)
   87 CONTINUE
      YAVE=0.0
      DO 90 KN=1,120
      DO 89 JN=1,119
```

```
      YAVE=YAVE+GRDRAY(JN,KN)
   89 CONTINUE
      GRDLIN(JK)=YAVE/119.0
      YAVE=0.0
   90 CONTINUE
      PRINT 91
      PRINT 21,GRDLIN
      TAVE=0.0
      DO 52 KN=1,119
      TAVE=TAVE+GRDLIN(KN)
   52 CONTINUE
      TAVE=TAVE/119.0
      PRINT 51,TAVE
      DO 709 JK=1,120
      AVE=DEV=SDEV=DIF=0.0
      DO 729 IK=1,119
      X=GRDRAY(IK,JK)
      GRDRAY(IK,JK)=ABS(X)
      AVE=AVE+GRDRAY(IK,JK)
  729 CONTINUE
      AVE=AVE/119.0
      DO 739 MK=1,119
      X=AVE-GRDRAY(MK,JK)
      DEV=X*X+DEV
  739 CONTINUE
      DEV=DEV/119.0
      SDEV=SQRT(DEV)
      GRDLIN(JK)=SDEV
      TDEV=SDEV
      DO 749 LK=1,119
      DIF=AVE-GRDRAY(LK,JK)
      DIF=ABS(DIF)
      IF(DIF-TDEV)750,750,752
  750 GRDRAY(LK,JK)=1R
      GO TO 749
  752 GRDRAY(JK,LK)=1R.
  749 CONTINUE
  709 CONTINUE
      DO 725 MK=1,120
      GRDRAY(120,MK)=1RN
  725 CONTINUE
      PRINT 379
      PRINT 301 ,((GRDRAY(IK,JK),JK=1,60),IK=1,120)
      PRINT 310
      PRINT 301,((GRDRAY(IK,JK),JK=61,120),IK=1,120)
      PRINT 381
      PRINT 312,GRDLIN
C     NOW WE CALCULATE THE GRADIENT OF THE GRADIENT IN THE
C     X DIRECTION
      DO 179 K=1,120
      DO 179 MN=1,119
      GRDRAY(K,MN)=ARRAY(K,MN+1)-ARRAY(K,MN)
  179 CONTINUE
```

```
      DO 189 L=1,120
      DO 189 N=1,118
      AX=GRDRAY(L,N+1)-GRDRAY(L,N)
      GRDRAY(L,N)=AX
  189 CONTINUE
C     GRDRAY NOW CONTAINS THE X DIRECT GRAD OF THE GRAD
      PRINT 3220
 3220 FORMAT(1H1,10X,*GRAD/GRAD VALUES IN ROW 50*)
      GRDRAY(50,119)=0.0
      GRDRAY(50,120)=0.0
      PRINT 21,(GRDRAY(50,J),J=1,120)
      PRINT 3276
 3276 FORMAT(1H1,10X,*GRAD/GRAD VALUES IN ROW 70*)
      GRDRAY(70,119)=0.0
      GRDRAY(70,120)=0.0
      PRINT 21,(GRDRAY(70,J),J=1,120)
      PRINT 3286
 3286 FORMAT(1H1,10X,*GRAD/GRAD VALUES IN ROW 90*)
      GRDRAY(90,119)=0.0
      GRDRAY(90,120)=0.0
      PRINT 21,(GRDRAY(90,J),J=1,120)
      AVE=DEV=SDEV=DIF=0.0
C     COLUMN AVERAGES ARE NOW CALCULATED AND PRINTED
      DO 199 LK=1,118
      DO 198 NK=1,120
      AVE=AVE+GRDRAY(NK,LK)
  198 CONTINUE
      AVE=AVE/120.0
      GRDLIN(LK)=AVE
      AVE=0.0
  199 CONTINUE
      PRINT 150
      PRINT 151, GRDLIN
C     AVE VALUE OF GRAD OF GRAD FOR THE ENTIRE PICTURE
      AVE=0.0
      DO 169 JK=1,120
      DO 169 IK=1,118
      X=GRDRAY(JK,IK)
      X=X/120.0
      AVE=AVE+X
  169 CONTINUE
      AVE =AVE/118.0
      PRINT 160,AVE
      AVE=DEV=SDEV=DIF=0.0
C     NOW WE ACCOMPLISH OUR LINE BY LINE  GRADIENT OF THE
C     GRADIENT SORT IN THE X DIRECTION
      DO 409 JK=1,120
      AVE=0.0
      DO 429 IK=1,118
      X=GRDRAY(JK,IK)
      GRDRAY(JK,IK)=ABS(X)
      AVE=AVE+GRDRAY(JK,IK)
  429 CONTINUE
```

```
      AVE=AVE/118.0
      DO 439 MK=1,118
      X=AVE-GRDRAY(JK,MK)
      DEV=X*X+DEV
  439 CONTINUE
      DEV=DEV/118.0
      SDEV=SQRT(DEV)
      TDEV=SDEV
C     WE WILL USE SDEV FOR THE VALUE OF THE TDEV DISCRI-
C     MINATOR
      GRDLIN(JK)=SDEV
      DO 449 LK=1,118
      DIF=AVE-GRDRAY(JK,LK)
      DIF=ABS(DIF)
      IF (DIF-TDEV)450,450,452
  450 GRDRAY(JK,LK)=1R
      GO TO 449
  452 GRDRAY(JK,LK)=1R.
  449 CONTINUE
  409 CONTINUE
      DO 425 MK=1,120
      DO 425 NK=119,120
      GRDRAY(MK,NK)=1RN
  425 CONTINUE
      PRINT 509
      PRINT 301,((GRDRAY(IK,JK),JK=1,60),IK=1,120)
      PRINT 310
      PRINT 301,((GRDRAY(IK,JK),JK=61,120),IK=1,120)
      GRDLIN(119)=0.0
      GRDLIN(120)=0.0
      PRINT 511
      PRINT 312,GRDLIN
C     NOW IN SIMILAR FASHION WE PERFORM OUR GRADIENT OF
C     THE GRADIENT SORT IN THE Y DIRECTION
      DO 279 KL=1,120
      DO 279 ML=1,119
      GRDRAY(ML,KL)=ARRAY(ML+1,KL)-ARRAY(ML,KL)
  279 CONTINUE
      DO 289 LK=1,120
      DO 289 NK=1,118
      AX=GRDRAY(NK+1,LK)-GRDRAY(NK,LK)
      GRDRAY(NK,LK)=AX
  289 CONTINUE
      AVE=DEV=SDEV=DIF=0.0
      DO 299 LM=1,118
      DO 298 NM=1,120
      AVE=AVE+GRDRAY(LM,NM)
  298 CONTINUE
      AVE=AVE/120.0
      GRDLIN(LM)=AVE
      AVE=0.0
  299 CONTINUE
      PRINT 350
```

```
      PRINT 151,GRDLIN
      AVE=0.0
      DO 269 JL=1,120
      DO 269 IL=1,118
      X=GRDRAY(IL,JK)
      X=X/120.0
      AVE=AVE+X
  269 CONTINUE
      AVE=AVE/118.0
      PRINT 160,AVE
      PRINT 4250
 4250 FORMAT(1H1,10X,*GRAD/GRAD VALUES IN COLUMN 50*)
      GRDRAY(119,50)=0.0
      GRDRAY(120,50)=0.0
      PRINT 21,(GRDRAY(J,50),J=1,120)
C        NOW FOR THE GRAD/GRAD SORT IN THE Y DIRECTION
      AVE=DEV=SDEV=DIF=0.0
      DO 809 JK=1,120
      AVE=0.0
      DO 829 IK=1,118
      X=GRDRAY(IK,JK)
      GRDRAY(IK,JK)=ABS(X)
      AVE=AVE+GRDRAY(IK,JK)
  829 CONTINUE
      AVE=AVE/118.0
      DO 839 MK=1,118
      X=AVE-GRDRAY(MK,JK)
      DEV=X*X+DEV
  839 CONTINUE
      DEV=DEV/118.0
      SDEV=SQRT(DEV)
      TDEV=SDEV
      GRDLIN(JK)=SDEV
      DO 849 LK=1,118
      DIF=AVE-GRDRAY(LK,JK)
      DIF=ABS(DIF)
      IF(DIF-TDEV)850,850,852
  850 GRDRAY(LK,JK)=1R
      GO TO 849
  852 GRDRAY(LK,JK)=1R.
  849 CONTINUE
  809 CONTINUE
      DO 825 MK=1,120
      DO 825 NK=119,120
      GRDRAY(NK,MK)=1RN
  825 CONTINUE
      PRINT 909
      PRINT 301,((GRDRAY(IK,JK),JK=1,60),IK=1,120)
      PRINT 310
      PRINT 301, ((GRDRAY(IK,JK),JK=61,120),IK=1,120)
      GRDLIN(119)=0.0
      GRDLIN(120)=0.0
      PRINT 911
```

```
      PRINT 312,GRDLIN
    6 FORMAT(10X,*ARRAY(1,1)=*,F8.2,*ARRAY(2,1)=*,F8.2,
     1*ARRAY(3,1)=*,F8.2)
    8 FORMAT(I4,I9,I17,A10)
    9 FORMAT(5X,*K1=*,I4,*K2=*,I9,*K3=*,I17,A10)
   10 FORMAT(12F5.0)
   20 FORMAT(1H1,10X,*AVE X-DIRECT DENSITY VALUES*)
   21 FORMAT(1H0,10X,5(2X,F8.2))
   23 FORMAT(1H1,10X,*AVE Y-DIRECT DENSITY VALUES*)
   80 FORMAT(1H1,10X,*AVE X-DIRECT GRADIENT VALUES*)
   91 FORMAT(1H1,10X,*AVE Y-DIRECT GRADIENT VALUES*)
  150 FORMAT(1H1,10X,*GRAD/GRAD AVE VAL IN THE X DIRECT.*)
  151 FORMAT(1H0,10X,5(2X,F8.2))
  160 FORMAT(10X,*AVE VAL OF GRAD/GRAD FOR ENT PIX*,F8.2)
  301 FORMAT(5X,*Y*,60(1X,R1))
  309 FORMAT(1H1,25X,*OUTLINE OF MANMADE OBJECTS*)
  310 FORMAT(1H1,25X,*PART TWO*)
  311 FORMAT(1H1,25X,*SDEV VALUES FOR EACH LINE*)
  312 FORMAT(1H0,10X,5(2X,F8.2))
  350 FORMAT(1H1,10X,*AVE GRAD/GRAD Y DIRECTION VALUES*)
  379 FORMAT(1H1,25X,*Y DIRECT OBJECT OUTLINES*)
  381 FORMAT(1H1,25X,*SDEV VALUES FOR EACH COLUMN*)
  509 FORMAT(1H1,25X,*MANMADE OBJECT OUTLINES*)
  511 FORMAT(1H1,25X,*SDEV FOR GRAD OF GRAD IN EACH LINE*)
  909 FORMAT(1H1,*Y DIRECT GRAD OF GRAD OBJECT OUTLINE*)
  911 FORMAT(1H1,*COL. SDEV OF Y DIRECT GRAD OF GRAD* )
 1067 FORMAT(25X,*PICTURE B-3*)
 1068 FORMAT(10X,*P*)
 1069 FORMAT(10X,60(1X,R1))
 1070 FORMAT(1H1,10X,*PART TWO*)
      STOP
      END
```

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In gathering data from the Optical Sciences Center's digital image analyzer, we found that the data were recorded in an awkward block size. This would have necessitated the author's having to write a program, in addition to the one contained in Appendix B, that would transform the data to a standard block size so that it could be used by the University of Arizona's CDC 6400 computer. However, Mrs. Barbara Fell graciously allowed the author to use her program ITAPE that performed the required transformation.

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