1976

Distinguishable Density Levels in Image Recording of Earth Resources Satellite Data

Steven Beiser

Follow this and additional works at: <http://scholarworks.rit.edu/theses>

Recommended Citation

Beiser, Steven, "Distinguishable Density Levels in Image Recording of Earth Resources Satellite Data" (1976). Thesis. Rochester Institute of Technology. Accessed from

This Senior Project is brought to you for free and open access by the Thesis/Dissertation Collections at RIT Scholar Works. It has been accepted for inclusion in Theses by an authorized administrator of RIT Scholar Works. For more information, please contact ritscholarworks@rit.edu.

Title: Distinguishable Density Levels in Image Recording
of Earth Resources Satellite Data

Author: Steven Scott Beiser

Thesis Advisor: Prof. M. Abouelata

To the
Rochester Institute of Technology
Department of Photographic Science
and Instrumentation
1976

6923915

Abstract; The Earth Resources Technology Satellite (ERTS) system produces a large volume of images of the Earth, with exposed film as the final output. These images are presented to the user in pictorial form for interpretation and analysis. Specifications for this output film include MTF requirements, development method requirements, geometric tolerance and the number of DDL's (distinguishable density levels). Given the specification of 64 levels of gray, with a minimum density range of 2.0, the following investigation is warranted.

Using theoretical calculations, granularity will be determined at different density levels. Assuming that Selwyn's Law is valid for the range of apertures and films in this specific investigation, granularity as a function of density will be calculated. Further, assuming these calculations are valid, a procedure will be established by which films can be selected for the ERTS project, solely on the basis of these calculations.

Several experiments were performed to evaluate the merit of the theoretical calculations. The results were similar, however inconclusive.

A series of experiments were performed in attempt to establish a new measure by which the films could be judged. The sum of the variations caused by granularity, area to area variation and pixel to pixel interaction were generated with this new technique.

ACKNOWLEDGEMENT

With my sincere appreciation, I wish to thank;

Mr. Abouelata, as my research advisor, aided substantially in the development of this project.

Mr. J. H. Altman, for sending some references as background material.

Mr. R. D. Anwyl, who very generously spent an afternoon helping me organize and understand the practical aspects of the project.

Mr. Lance Bassage, and Kodak, for supplying me with Kodak High Definition Aerial Film.

Mr. Leo Beiser, for introducing me to this project, and helping tremendously by defining appropriate goals and by helping straighten out inevitable snarls.

Mr. G. T. Keene, for spending an hour or two with Mr. Anwyl and myself, discussing technical aspects of the project.

Mr. Bernard Peavey, for sending a letter confirming the need for this investigation, and the desirability of a solution to this problem.

Dr. G. Schumann, for cognitating the "random squares" approach.

On July 23, 1972, the NASA ERTS (Earth Resources Technology Satellite) was launched. It now orbits the earth every 103 minutes, completing fourteen orbits each day and photographing every spot on the earth every eighteen days. These high quality photographs are used for environmental studies. The spacecraft is in a sun-synchronous orbit, which means that it can take photographs of a given area on earth at approximately the same local sun time, which is about 9:40 AM at the Equator.

The images taken by the spacecraft are sent electronically to receiving sites in the United States. Videotapes are made from these electronic signals, and the tapes are sent to the NASA Data Processing Facility at Goddard Space Flight Center, Greenbelt Maryland. Here, they are reconstructed into photographs using an EBR (Electron Beam Recorder), to be used as the archival first generation photographic product. This described information transfer sequence is shown in Figure 1.

Figure 1

BLOCK DIAGRAM OF INFORMATION TRANSFER SEQUENCE (ERTS)

The operational requirements on the present and future recording systems include specifications for film transport,¹ geometric tolerance of the output film and radiometric accuracy of the output film. This investigation will be limited to the practicability and satisfaction of the radiometric requirements of the output photographic film. Specifically, the output film must produce at least 64

levels of gray with a density range of about two. In terms conforming to information theory,, these 64 levels of gray are equal to six Bits since;

$$I = N \log_2 M$$

where, I represents information in terms of Bits

N represents the confidence in terms of σ

and M represents the number of messages, or in this case the number of levels of gray

$$\text{so, } I = 1 \log_2 (64)$$

and I = 6, with (1) σ confidence.

This investigation will be limited to considering the film as exposed by light. The present ERTS pictures are exposed by an EBR (Electron Beam Recorder), and by a laser. Given the problem of determining a method by which a film may be selected to meet these specifications, this investigation will then be a theoretical solution to this problem, involving the parameter of granularity.

There has been an outstanding response from "industry" regarding the merit of this investigation. The problem was first suggested to the author by his father, Leo Beiser of EPSCO (formerly CBS Laboratories, Stamford, Conn.). Peter Turrel of RCA in Camden, N.Y. telephoned to offer insight and help.

4

Robert Anwyl⁶, of Kodak arranged a lunch and conference with George Keene (also from Kodak), and the author, so that a discussion could be made insuring complete understanding of the aspects and the problems involved with this project. Much information and insight was gained during that afternoon at Kodak. Finally, Bernard Peavey of NASA, wrote a letter (Appendix I) confirming the need and desirability of an investigation such as this.

The statistical fluctuation in density of an evenly exposed and processed sheet of photographic film, is defined as the noise, or the granularity. Granularity is related to the mean density of the film, and may be calculated with the following assumptions and approximations:

1. The grain pattern arrangement is random.
2. All grains have the same projected area.
3. The grains are opaque.
4. The aperture area is much larger than the projected area of a grain.

By using the Nutting equation²,

$$D = 0.434 n a$$

an expression representing granularity, $\sigma(D)$, as a function of the number of grains, n , and the cross-sectional area of a grain, a , may be obtained. Since $0.434 a$ is a constant, taking the total derivative of both sides of the Nutting

equation yields:

$$\Delta D = 0.434 a \Delta n,$$

and by dividing both sides of the equation by Δn ,

$$\frac{\Delta D}{\Delta n} = 0.434 a$$

By employing the Poisson distribution, whereby the population mean, μ , is equal to the population variance, σ^2 , and by considering this $\frac{\Delta D}{\Delta n}$ as the mean density, we find,

$$\sigma_D^2 = 0.434 a$$

or the variance of density measurements. At a constant density we would have,

$$\sigma_D^2 = 0.434 a D,$$

giving a standard deviation in density measurements of

$$\sigma(D) = 0.66 (a)^{\frac{1}{2}} D^{\frac{1}{2}} \quad [2]$$

which is the relationship given by Eyer.³

This equation may then be used to predict $\sigma(D)$, the RMS (root mean square) fluctuation of a particular average density, D .

By using this equation with a given film, given cross-sectional area of a grain, given density and aperture area, A , the corresponding granularity may be calculated. Furthermore, it can be shown that this relationship is analogous to Selwyn's law,

$$S = \sigma(D) \sqrt{2A},$$

Equation [1]

Selwyn's law

$$\sigma(D) = 0.66 \sqrt{a/A} \sqrt{D}$$

$$S = \sigma(D) \sqrt{2A}$$

at a given density of one,

$$\sigma(D) = S / \sqrt{2A}$$

$$\sigma(D)_1 = 0.66 \sqrt{a/A}$$

$$\sigma(D) = 0.66 S / \sqrt{A}$$

and by letting Selwyn's constant, S , be equal to the square root of " a ", these equations are identical.

With this theoretical equation, Eyer developed a method for determining the number of DDL's (distinguishable density levels) of a photographic film. The number of DDL's may be found by the following method;

1) Let the first DDL (distinguishable density level) be defined as the range in density from

$$D_1 - \sigma(D)_1 \text{ to } D_1 + \sigma(D)_1,$$

where D_1 is the mean "base plus fog" density, and $\sigma(D)_1$ is its corresponding granularity.

2) Let the second DDL be determined so that there

is a density level D_2 such that

$$D_2 - \sigma(D)_2 = D_1 + \sigma(D)_1$$

3) Let the third DDL be determined so that there is a density level D_3 such that

$$D_3 - \sigma(D)_3 = D_2 + \sigma(D)_2$$

4) This dividing method is continued until the desired density range is exhausted.

These DDL, are then the adjacent discrete levels of density.

By using this method, the first theoretical computation was performed. A comparison was made between the number of DDL's attainable using Eyer's method, with Eyer's experimental relationship of density and granularity, as compared with the calculated relationship of density and granularity. The same film (Photoflure) and aperture area was used in this evaluation.

$$\text{Since} \quad \sigma(D) = 0.66 (a/A)^{\frac{1}{2}} D^{\frac{1}{2}} \quad [1]$$

$$a = \left[\frac{\sigma(D) \sqrt{A}}{0.66 \sqrt{D}} \right]^2 \quad [2]$$

Using the experimental granularity value of 0.06, which was determined using an aperture area of $256 \mu\text{m}^2$, and a density of 0.4, the cross-sectional area of a grain, a , was calculated by equation [2],

$$a = \left[\frac{0.06 \sqrt{256 \mu\text{m}^2}}{0.66 \sqrt{0.4}} \right]^2 = 5.3 \mu\text{m}^2$$

Using this value of a , an equation representing the relationship between granularity and density could be theoretically determined by equation [1];

$$\sigma(D) = 0.095 \sqrt{D}$$

This relationship was used as the basis for theoretically determining the number of DDL's within the given density range of 0.1 to 2.1. Granularity as a function of density is shown in the two curves of Figure 2.

Figure 2

The curve determined experimentally is labeled "Experimental", and the curve representing the equation;

$$\sigma(D) = 0.095 \sqrt{D},$$

representing the theoretical granularity function is labeled "Calculated". The numerical calculations for the theoretical determination are included in Appendix II.

The calculations of DDL using the theoretically determined granularity relationship yielded a maximum of twelve DDL's in a density range of two, while the calculations of DDL's using the experimentally determined granularity relationship yielded a maximum of ten DDL's within the same density range. This comparison shows that, in this case, there is little difference between the maximum number of DDL's attainable with either method. Since only one aperture was considered, the approximations inherent in the use of Selwyn's law were not tested. Therefore this comparison only shows that the granularity as a function of density relationship for Photoflure may be reasonably approximated by the given equation, for this DDL determination.

Since it has been shown that (with Photoflure) the number of DDL's can be calculated from a given granularity value, for a specific aperture with reasonable accuracy, it follows that the next test should involve the use of different aperture sizes.

The aperture sizes to be used in this analysis are circular apertures of diameters; $6\mu\text{m}$, $10\mu\text{m}$ and $14\mu\text{m}$. The explanation of the use of the $14\mu\text{m}$ aperture is discussed by Shaffer.⁴ The use of the $6\mu\text{m}$ and $10\mu\text{m}$ aperture is explained in terms of the ERTS project imaging system. Since NASA specifies that a 202.2 mm line must contain 20,000 pixels (picture elements), there are;

$$\begin{aligned}
 & \frac{202.2 \text{ mm.}}{20,000 \text{ pixels}} \\
 = & \frac{202.2 \text{ mm.} \times \frac{10^3 \mu\text{m.}}{\text{mm.}}}{20,000 \text{ pixels}} \\
 = & \frac{10.111 \mu\text{m.}}{\text{pixel}}
 \end{aligned}$$

or approximately $10\mu\text{m}$ per pixel. Hence a $10\mu\text{m}$ aperture was used in this analysis. Further, since these pixels will be produced by a laser recorder having a line spread function of (very) roughly;

useful and accurate radiometric measurement may only be performed in a smaller area to avoid information from adjacent pixels. Hence the $6\mu\text{m}$ aperture was used.

Since granularity values are not published for these aperture sizes, these granularity values will be determined using Selwyn's law. From the published⁵ granularity values at $48\mu\text{m}$, Selwyn's law was used to determine the corresponding granularity at $6\mu\text{m}$. These calculated $6\mu\text{m}$ granularity values may then be compared to published $6\mu\text{m}$ granularity values with the following table;

GRANULARITY*

<u>Film Type</u>	<u>$48\mu\text{m}$ data</u>	<u>$6\mu\text{m}$, calculated</u>	<u>$6\mu\text{m}$ data</u>
High Definition	9	72	33
Aerial Film, 3414			
.....			
Recordak Microfilm 9		72	43
5460/2460			
High Contrast Copy			
5096			
.....			
Photomicrographic 7		56	66
Monochrome Film			
S0-410			

* table entries are 1000 times RMS granularity

The last column was calculated from the Kodak data, using Selwyn's Law as follows;

$$S = \sigma(D) \sqrt{2A} \quad (\text{Selwyn's Law})$$

with change of aperture,

$$\frac{S_1}{S_2} = \frac{\sigma_1 \sqrt{2A_1}}{\sigma_2 \sqrt{2A_2}}$$

for the same film, "S" is constant, so

$$\sigma_2 = \sqrt{\frac{A_1}{A_2}} \sigma_1$$

and when using a circular aperture with a radius of r,

$$\sigma_2 = \sqrt{\frac{\pi r_1^2}{\pi r_2^2}} \sigma_1 = \frac{r_1}{r_2} \sigma_1$$

Using this calculation the entries in the last column were made. If Selwyn's Law were valid, the column of experimental $6\mu\text{m}$ values would match the calculated $6\mu\text{m}$ values. Large differences were found.

The second test of the validity of using Selwyn's Law was performed using Kodak film type High Definition Aerial number 3414, because this film is the most relevant among the available films with a published granularity value at an aperture of $6\mu\text{m}$. As shown previously, the

determination of "a", the cross-sectional area of a grain, is essential to determine the required granularity versus density relationship (equation [2]). This calculated "a" is then used in a comparison, since "a" must be constant for a given emulsion regardless of the aperture, density, or granularity combination in order to use this calculation.

By using equation number two and the Kodak data, the values of "a" were calculated;

DATA

Apertures	48 μ m	6 μ m
$\sigma(D)$	0.009	0.033

CALCULATIONS

for 6 μ m aperture

$$a = \left[\frac{(0.033)(5.32)}{0.66} \right]^2$$

$$\underline{a=0.071}$$

for 48 μ m aperture

$$a = \left[\frac{(0.009)(42.4)}{0.66} \right]^2$$

$$\underline{a=0.334}$$

If Selwyn's Law were approximately valid, these two values of "a" would be approximately equal.

For the theoretical evaluation, it is necessary that the granularity values of the film in question, be known

at the apertures of interest ($6\mu\text{m}$, $10\mu\text{m}$, $14\mu\text{m}$). Using Selwyn's Law these values were calculated. The following table shows the published granularity values at the apertures of $48\mu\text{m}$ and $6\mu\text{m}$. Following this, the table shows the calculated granularity values using each of the published granularity values to determine the corresponding granularity at the apertures of $6\mu\text{m}$, $10\mu\text{m}$, and $14\mu\text{m}$ diameter.

GRANULARITY VALUES*

<u>Film</u>	<u>Published**</u>		<u>Calculated From $48\mu\text{m}$ Data</u>			<u>From $6\mu\text{m}$ Data</u>		
	$48\mu\text{m}$	$6\mu\text{m}$	$14\mu\text{m}$	$10\mu\text{m}$	$6\mu\text{m}$	$14\mu\text{m}$	$10\mu\text{m}$	$6\mu\text{m}$
3414	9	33	31	43.3	72	14	20	33**
.....								
5460	9	43	31	43.3	72	18	26	43**
.....								
SO-410	7	66	24	33.6	56	28	40	66**
.....								
5468		17				7	10	17**
8468								
.....								

*all entries are 1000 times $\sigma(D)$

**Kodak data⁵

The following calculations were then performed to determine the relationship between density and granularity at an aperture of $14\mu\text{m}$ diameter. On the left is the calculation using the granularity value at an aperture of $14\mu\text{m}$, calculated from the $48\mu\text{m}$ data. On the right is the calculation using the granularity value at an aperture of $14\mu\text{m}$, calculated from $6\mu\text{m}$ data. First "a" was determined from the theoretical granularity verses density relationship for High Definition Aerial film 3414;

data; at a mean density of 1.0, and an aperture diameter of $48\mu\text{m}$, the granularity is 0.009

data; at a mean density of 1.0, and an aperture diameter of $6\mu\text{m}$, the granularity is 0.033

Calculation using Selwyn's Law, as shown previously, gave a granularity value of;

0.031 at an aperture of $14\mu\text{m}$

0.014 at an aperture of $14\mu\text{m}$

Calculation of "a"

$$a = \left[\frac{\sigma(D) \sqrt{A}}{0.66 \sqrt{D}} \right]^2$$

$$a = \left[\frac{(0.031)(12.4)}{0.66} \right]^2$$

$$\underline{a=0.339}$$

$$a = \left[\frac{(0.014)(12.4)}{0.66} \right]^2$$

$$\underline{a=0.0692}$$

$$\sigma(D) = 0.66 \left(\frac{a}{A} \right)^{\frac{1}{2}} D^{\frac{1}{2}}$$

$$\underline{\sigma(D) = 0.031 D^{\frac{1}{2}}}$$

$$\underline{\sigma(D) = 0.014 D^{\frac{1}{2}}}$$

The curves showing the calculated granularity as a function of density are shown in Figure 3.

Figure 3

Granularity as a Function of Density for High Definition Aerial Film 3414 Calculated for an Aperture of $14\mu\text{m}$

These curves should overlap, as they represent the same film and aperture. As the only variable designed in this comparison is the use of Selwyn's Law, the obvious discrepancy in the curves can only be attributed to the failure of this law, under these conditions.

Using these theoretical granularity relationships, Eyer's method was used to determine the number of DDL's of the film for the $14\mu\text{m}$ aperture with the density range of 0.1 to 2.1. Since each of the two granularity relationships were used, the number of DDL's were first determined for the film from $48\mu\text{m}$ aperture data by;

1) Selwyn's Law was used to determine the granularity (0.031) at an aperture of $14\mu\text{m}$, given that the granularity at an aperture of $48\mu\text{m}$ is 0.009.

2) With the granularity value of 0.009, equation two was used to calculate "a", the cross sectional area of a grain, for the aperture of $14\mu\text{m}$.

3) Using this calculated "a" value of 0.340 and equation one, the granularity relationship, $\sigma(D) = 0.031D^{\frac{1}{2}}$ was determined.

4) Using this granularity relationship and the method as described, the DDL's were determined.

5) The number of DDL's were then determined for

the same film, using Selwyn's Law to calculate the granularity of the film at an aperture of $14\mu\text{m}$, given granularity data for an aperture of $6\mu\text{m}$.

The results of this analysis are shown in Figure 4.

Figure 4

DDL Number (n) as a Function of DDL Density (D_n)

High Definition Aerial Film 3414 For $14\mu\text{m}$ Aperture

* n is the number of DDL's as calculated at $14\mu\text{m}$

Each calculated number (n) of the DDL is plotted against its corresponding density (D_n) so that the DDL's may be read directly from the curve for any density range. For example, from the curve calculated with 48 μ m data, it may directly be read that within a density range of 1.0, there are 24 DDL's, as shown by the dotted lines in Figure 4. Since this density range of 1.0 is equivalent to the range from the "base plus fog" density of 0.1 to 1.0, then $D_n=1.1$, and $n=24$. A sample calculation of this determination may be found in the appendix.

As previously discussed, the density range to be investigated in the ERTS system is 2.0. Therefore DDL comparisons are made within this density range. By examining Figure 4, the number of DDL's within this given density range of 2.0 can be observed. For the curve calculated from 48 μ m data adjusted to 14 μ m data using Selwyn's Law, the number is 36, as opposed to 85 for the curve calculated from 6 μ m data similarly adjusted to 14 μ m data using Selwyn's Law. This discrepancy of order of two is extremely important to this evaluation. These results are calculated for the same film (3414), and same aperture of interest (14 μ m), and using the same techniques. The only difference is the use of Selwyn's Law to adjust granularity values to correspond to the same aperture of interest, 14 μ m. If Selwyn's Law were even approximately valid, for these apertures and this

film, these DDL numbers would be approximately equal. Since they very certainly are not, in relation to this calculation, Selwyn's Law can not be used satisfactorily.

This may be considered in the practical and specific terms of the ERTS radiometric requirements. The output film in the ERTS system must produce at least 64 DDL within a density range of 2.0. If the 14mm DDL curve from 48mm data were being considered, the film would have to be rejected according to this determination, since only 36 DDL are found. However if the 14mm DDL curve from 6mm data were considered, the film would be accepted since 85 DDL are found. Since the film can be neither selected nor rejected on the basis of this calculation, in relation to this project, Selwyn's Law can not be used satisfactorily.

As a result of this analysis, it has been determined that a microdensitometer should be used, with a scanning aperture conforming to the aperture area of interest in ERTS. A film sample that has been uniformly exposed and processed should be scanned to determine granularity as a function of density. Using a density of 1.0, and the equations described, a reasonably accurate granularity verses density relationship may be determined. If this is not sufficiently accurate, this granularity verses density relationship will have to be generated experimentally. This may be done by scanning a film sample with different

density levels, determining the granularity at these density levels and performing regression analysis to determine the regression coefficients "a" and "b" , so that the equation

$$\sigma(D) = a D^b$$

expresses the desired granularity verses density relationship. Once this relationship is known, the number of DDL's the film can produce, may be determined using the described method.

In view of the ERTS project application, it would be desirable if there were an investigation of the standard deviation in density on a piece of the film used. This source of variation should be incorporated into the DDL calculation, since it is the total variation in density that determines the maximum number of DDL's a film can produce. This source of variation may be incorporated using the following equation;

$$S_D = \sqrt{S_g^2 + S_a^2}$$

where, S_D is the standard deviation in density resulting from all sources of variation.

S_g^2 is equal to $[\sigma(D)]^2$, when $\sigma(D)$ is granularity and S_a^2 is the variance of density caused by area to area variations.

Fortunately each ERTS picture is printed with a sensitometric step tablet, so that the variation in density between pictures, does not have to be considered in this investigation. Each picture may be analyzed separately, thus picture to picture variation may be ignored.

An effect inherent in the scanning system used by ERTS to produce prints, may require further investigation before these DDL calculations will accurately predict the performance of the film used in the ERTS system. Since these ERTS pictures are produced by scanning the film with a small aperture, the picture is produced over a period of time. Latent images are produced first for areas scanned first, so effects commonly termed "exposure effects" are likely, and such an effect is observed.⁶ One "tail" of the spread function (of the scanner) produces the result of a low level exposure, a short time before the imaging exposure, and conversly the trailing "tail" gives the result of a low level exposure a short time after the imaging exposure. This effect is considered to be responsible for the decrease in gamma (the slope of the straight line portion of the density verses log exposure curve) observed with samples produced by the scanning recorder as opposed to samples produced with a sensitometer. This loss in gamma can be decreased substantially by the use of a high solvent photographic developer, and therefore this effect is believed

to be caused by the formation of a significantly greater proportion of internal latent image sites to surface latent image sites.

As may be expected, the DDL curves are extremely similar to the granularity curves. If the graphs are held up to light, it may be observed that corresponding curves very nearly overlap. The graphical difference appears mainly to be a shifting of the axes. This may be very useful because it may yield a much simpler procedure for determining the DDL curves. As opposed to Eyer's method (as was used), if this similarity in curves could be directly used to generate the DDL curves, many hours of work could be saved.

To provide a firm foundation for decision making regarding the number of data points necessary in the granularity traces, a statistical method was employed. An α (alpha) risk of 0.05 will be used, corresponding to the risk of a Type I error, and a β (beta) risk of 0.05 corresponding to the risk of a Type II error, will be used. The Student's t distribution will be employed. An explanation of the α risk, Type I errors, the β risk, Type II errors, and the Student's t distribution is included in Appendix III. An estimate of $\sigma(D)$ is in the order of 0.03, and the necessary difference (d), the smallest difference wished to be measured, is 0.01.

Since,

$$n = \left[(t_{\alpha/2} + t_{\beta}) \frac{\sigma}{d} \right]^2$$

$$n = \left[(1.960 + 1.645) \frac{0.03}{0.01} \right]^2$$

$$n = 117$$

at least 118 data points should be measured.

As required, an experimental investigation was performed to determine the merit of the theoretical evaluation. Attempts were made to generate a more realistic measure of the noise that limits the number of DDL's than solely the granularity of the film.

The first investigation involved a series of uniform ("flushed") exposures on a piece of film to produce areas of different average densities. Once these areas were scanned on a microdensitometer, the granularity could be determined for each average density, and regression analysis could be used to generate the necessary relationship between granularity and density. This relationship could then be used to calculate the DDL's of the film, as was done with the relationship generated theoretically.

The film being investigated is Kodak film type High Definition Aerial number 3414. This film was developed in Kodak Developer D-19 (see Appendix IV for processing chemical formulas) at 20°C, for eight minutes using RIT Tray Rock Agitation (Appendix V). The subsequent processing entailed Kodak Stop Bath SB-1 for 15 seconds, and Kodak Fixer F-5 for four minutes. The samples were washed in water for twenty minutes and dried at room temperature. The exposures were made in room R-24, the Radiometry Laboratory at Rochester Institute of Technology.

A laser is used in the actual imaging of these ERTS pictures, so nearly monochromatic light was used in this investigation. A neon gas discharge lamp was used with a Kodak Wratten Gelatin Filter number 92 (red), to simulate the spectral composition of a helium-neon laser, which has a peak emittance at around 632.8 nanometers. Several gas discharge lamp and filter combinations were investigated, including an interference type filter designed to simulate the spectral composition of a helium-neon laser. These other methods were not used because insufficient light reached the film plane for practical exposure times. The optical equipment was arranged on a long optical bench that passed through a hole in the wall between the two rooms of the Radiometry Laboratory. The red filter was at a distance of 161 cm. from the neon lamp, and the film was at a distance of 375 cm. from the lamp. The lamp and filter were in a different room from the film to reduce stray light. Black canvas was put on the optical bench to eliminate the reflections from the bench that might produce ununiform illumination on the film plane. Several light stops (apertures) were placed along the light path to further decrease unwanted light.

Since the light energy decreased as the light source was being made more nearly monochromatic, a shorter distance from the lamp to the film was required to maintain reasonable exposure times. Thus this experimental setup was accepted as a compromise between as nearly as possible monochromatic light, as long as possible distance between the film and lamp for even

illumination, with reasonable exposure times. A sketch of this experimental setup is given in Figure 5.

Figure 5

*distances are measured from the lamp

To estimate the exposure times necessary to produce the desired densities, a sensitometric strip was produced by contact printing two superimposed Kodak number two Sensitometric Step Tablets on the High Definition Aerial Film 3414. The resulting densities were read using a Macbeth TD-504 densitometer with an aperture diameter of one millimeter, even though the samples would be scanned with a microdensitometer having an aperture diameter of $10\mu\text{m}$.

The relative log H values were calculated by assigning a relative log H of zero to a point with a "base plus fog" density of 0.06. This area on the sensitometric strip with a density of 0.06 was produced by the step tablet at the density of 3.77. The next lower density on the step tablet was 3.47, so a relative log H value of 0.30 was assigned to this point ($3.77 - 3.47 = 0.30$). The next lower density on the step tablet was 3.15, corresponding to a relative log H value of 0.62. This procedure was continued until all the relative log H values were assigned. Using these relative log H values, a sensitometric curve was made. This curve was then used to determine the expected exposure times required for producing the desired densities for the granularity analysis. This sensitometric curve for High Definition Aerial film 3414 is given in Figure 6.

Figure 6

Sensitometric Curve for High Definition Aerial Film 3414

Since exposure is equal to the product of illuminance and time,

$$H = E \cdot t$$

$$\log H = \log E + \log t$$

and $\text{Relative log } H = \log E + \log t + \text{constant.}$

The densities produced on the sensitometric strip were made by attenuating the light with the densities on the step tablet.

The exposure on each step was determined by subtracting the density of the step tablet from the relative log H value calcu-

lated in the last equation. This is shown by the following equation:

$$\text{Relative log H} = (\log E + \text{constant} - D) + \log t$$

$$\text{or } \text{Relative log H} - \log t + (\log E + \text{constant} - D)$$

Since the point with a relative log H of 3.68 was exposed for twenty minutes with the light attenuated by the step tablet where the density was 0.09, the equation may be expressed as follows:

$$\begin{aligned} \text{Relative log H} &= 3.68 = \log (20) + \log E + \text{constant} - 0.09 \\ 2.47 &= (\log E + \text{constant}) \end{aligned}$$

The predicted time of exposure, t , is then equal to the antilog of the relative log H value from the plot, minus 2.47.

Assuming the same characteristic curve would result if a constant illuminance was used and the time of exposure was varied, the exposure equation can be solved for $\log t$ to predict the necessary exposure time to make the desired density.

$$\text{Relative log H} = (\log E + \text{constant}) + \log t$$

$$\log t = \text{Relative log H} - (\log E + \text{constant})$$

$$\log t = \text{Relative log H} - 2.47.$$

Thus by subtracting 2.47 from the relative log H corresponding to a desired density, the log of the necessary time of exposure may be found.

Using an ILEX #3 Synchro Electronic shutter and an ILEX Speed Computer timer, with the shutter mounted on the optical

bench at a distance of about 25 cm. from the light source, repeatable times of exposure were attained. The exposure times ranged from $\frac{1}{8}$ second to 20 seconds. the exposures for $\frac{1}{4}$, 1, and 2 seconds were replicated. Film samples were secured in a standard 4X5" film holder. The major problems encountered with this setup was finding apparatus to hold all of the components on the optical bench and on the optical axis.

The film samples were exposed and processed as described, and then scanned on an Ansco Model 4 Automatic Recording Microdensitometer using an objective of twenty power with a numerical aperture of 0.4. An eyepiece of 12.5 times magnification was used with a circular aperture of 2.5 mm. to achieve the desired final $10\mu\text{m}$ diameter circular aperture. The calibration of the microdensitometer was undoubtedly unacceptable, so under the instruction of Mr. Abouelata, Bruce Radl and the author calibrated the machine. Fortunately, with only the first adjustment (shunt), the calibration was sufficiently accurate for this experiment. The accuracy of the microdensitometer was relatively good only for densities below 2.68, however no densities above 2.68 are needed for this analysis.

A Bauch and Lomb stage micrometer was inserted in the film sample holder of the microdensitometer and focused upon so that it could be clearly seen what size the $10\mu\text{m}$. circular aperture would appear on the viewing screen.

To reduce flare, extraneous illumination in the microdensitometer should be eliminated as much as possible. Generally this is achieved by adjusting an aperture in the illuminating microscope of the microdensitometer so that the size of the illuminated area on the film plane is about one and a half times the size of the scanning area. Unfortunately the aperture on the illuminating microscope of the microdensitometer used, was inadequate for this purpose, assumedly because of the small scanning aperture desired. There was no alternative to using the slit in the illuminating microscope to reduce flare. This slit was closed to the smallest width felt to be safe. Since the illuminating microscope (especially) was on a mount with considerable play, the slit could not be narrowed as much as desired. The stage micrometer was then used to find the slit size, as it was determined that for every six markings on the micrometer of the slit, the slit traveled an apparent $10\text{ }\mu\text{m}$. The slit was then found to be $30\text{ }\mu\text{m}$. wide. Professor Carson had already tightened the microscope mounts in the microdensitometer, and there was nothing more that could be done at that time. Because this slit was about $30\text{ }\mu\text{m}$. wide on the film, and the scanning aperture diameter was only $10\text{ }\mu\text{m}$., considerable flare was unavoidably introduced due to the limitations of the equipment. This should make granularity numbers tend to be lower than expected.

The processed film samples had ten density levels with

replicates at three of these levels. Data points were taken from the resulting microdensitometer traces by eye, at equal intervals of distance, greater than $10\text{ }\mu\text{m}$. At least two hundred data points were recorded for every density level and each replicate. It has already been shown that only 118 data points are necessary for an estimate of the granularity, with an α risk and a β risk of 0.05. The results from the analysis with two hundred data points, will be considerably better.

A Monroe calculator was used to determine the standard deviation in density of the data points (granularity) and the mean (density). The results of these calculations are given below:

<u>Density</u>	<u>Granularity</u>
0.0808	0.00555
0.187	0.00963
0.330	0.0100
0.640	0.0159
0.650	0.0169
0.932	0.0183
1.20	0.0204
1.48	0.0238
1.49	0.0256
1.70	0.0270
2.01	0.0269
2.02	0.0295
2.38	0.0324

As the replicates were exposed separately on different pieces of film, developed separately, and scanned on the microdensitometer and analyzed separately, it should be expected that exactly the same density levels will not be produced within replicates. This means that there are no replicates in a strictly statistical sense. For the sake of being able to perform a regression analysis, an approximation was required. It was therefore necessary to treat the data produced by replicate runs, as replicates. The approximation is then an averaging of the densities of each of the samples that were produced as replicates. For example, the actual data :

<u>Density</u>	<u>Granularity</u>
0.640	0.0159
0.650	0.0169

would be treated as follows,

<u>Density</u>	<u>Granularity</u>
0.645	0.0159
0.645	0.0169

as would the other two replicates.

The regression model,

$$Y = b_0 + b_1 X$$

was transformed by performing a change of variables of the form,

$$X = Z^{\frac{1}{2}}$$

so that a relatively simple linear regression could be used with the non-linear model of

$$Y = b_0 + b_1 Z^{\frac{1}{2}}.$$

In this case, Y is the granularity, and Z is the density, yielding the equation,

$$G(D) = b_0 + b_1 D^{\frac{1}{2}}$$

Since there can be no granularity at a density of zero, the b_0 term should be zero. As an approximation, the number b_0 generated by the regression, will be ignored, as it should be zero. The resulting regression equation representing the relationship between density and granularity is now,

$$G(D) = b_1 D^{\frac{1}{2}}.$$

The following table shows the calculations necessary for this "least squares" regression ⁷ analysis. The column sums are at the bottom of each column.

$D^{\frac{1}{2}}$	$\sigma(D)$	D	$\sigma(D)D^{\frac{1}{2}}$	$[\sigma(D)]^2$
0.28433	0.0055470	0.080841	0.0015772	0.000030769
0.43205	0.0096235	0.18667	0.0041618	0.000092785
0.57477	0.010043	0.33036	0.0057724	0.000100861
0.80313	0.015931	0.64502	0.012795	0.000253796
0.80313	0.016929	0.64502	0.013596	0.00028659
0.96520	0.018290	0.93162	0.017614	0.00033452
1.0970	0.020413	1.2043	0.022401	0.00041669
1.2180	0.023804	1.4836	0.028994	0.00056663
1.2180	0.025574	1.4836	0.031150	0.00065403
1.3034	0.026969	1.6988	0.035151	0.00072733
1.4201	0.026938	2.0168	0.038256	0.00072566
1.4201	0.029453	2.0168	0.041827	0.00086748
1.5428	0.032385	2.3803	0.049964	0.0010488
13.0825	0.2619085	15.1037	0.303299	0.00610593

It has been found that the resulting regression equation is:

$$\sigma(D) = b_0 + b_1 D^{\frac{1}{2}}$$

$$\sigma(D) = -0.00481 + 0.0204 D^{\frac{1}{2}}$$

and since b_0 must be equal to zero for the above equation to be satisfied for all values of density, the experimentally found relationship between density and granularity is:

$$\sigma(D) = 0.020 D^{\frac{1}{2}}.$$

An ANOVA (analysis of variance) was performed to determine whether the mathematical model used fits the data, and to determine whether there is a real relationship between the variables. The ANOVA table contains the source of variation (labeled "Source"), the sums of squares (SS), the degrees of freedom (df), the mean squares (MS), the critical value for the "F" test (F_{crit}), and the observed "F" value (F_o). When the observed "F" value is greater than the critical F value, the factor tested is said to be significant, and this is denoted on the table by an asterisk.

ANOVA Summary Table

<u>Source</u>	<u>SS</u>	<u>df</u>	<u>MS</u>	<u>F_o</u>	<u>$F_{crit.}$</u>
Crude	0.0061059	13			
Due To b_o	0.0052766	1	0.0052766	3888*	18.5
Total	0.00082928	12	0.000069107		
Due To b_1	0.000814353	1	0.00081435	600*	18.5
Residual	0.000014927	11	0.0000013570		
Error	0.0000052271	2	0.0000026136		
Lack of Fit	0.0000097000	9	0.0000010778	0.41	19

From this ANOVA, it has been found that there is insignificant lack of fit, and that both the b_o , and the b_1 terms are significant. This means that the model fits the data and that there is a real relationship between the variables. Even though the b_o term has been found statistically signifi-

cant, it will be egnored as the b_0 value is actually only -0.000482, and should, as explained, be zero. There is no statistical justification for egnoring this b_0 term, the justification is solely based on the physical situation and interpretation of results.

Another method of judging the regression equation is the calculation of r^2 , the fraction of total variation in the values of granularity that is accounted for by the regression equation. This value of r^2 is calculated as follows:

$$r^2 = \frac{\text{the sum of squares due to } b_1}{\text{the total sum of squares}}$$

$$= \frac{0.000814}{0.000830} = 98\%$$

Therefore, about 98% of the total variation in the values of granularity is attributed to the calculated regression relationship..

After having calculated the experimental relationship between density and granularity of High Definition Aerial film 3414 to be:

$$\sigma(D) = 0.020 D^{\frac{1}{2}}$$

the theoretical relationship was calculated.

The granularity of High Definition Aerial film 3414 was previously calculated to be 0.020 for an aperture of $10\mu\text{m}$. diameter, using the data generated from scanning with a $6\mu\text{m}$.

aperture. The granularity of this film was also previously calculated to be 0.043 for an aperture of $10 \mu\text{m}$. diameter, using the data generated from scanning with a $48 \mu\text{m}$. aperture. The discrepancy in these data, as explained previously is the failure in Selwyn's Law. A linear extrapolation was used to calculate the expected granularity (X) for an aperture of $10 \mu\text{m}$. diameter. To determine X, the following proportion was used:

$$\frac{42}{4} = \frac{0.023}{X - 0.020}$$

and X was found to be 0.0222. Therefore the theoretical granularity of High Definition Aerial film 3414, at a density of one, with an aperture of $10 \mu\text{m}$. diameter, is 0.0222. Equation [2] was then used to calculate a, the cross-sectional area of a grain:

$$a = \left[\frac{\sigma(D) A^{\frac{1}{2}}}{0.66 D^{\frac{1}{2}}} \right]^2 \quad [2]$$

$$= \left[\frac{(0.0222)(78.5)^{\frac{1}{2}}}{0.66} \right]^2 = 0.0888$$

Equation [1] was used to calculate the theoretical relationship of density and granularity:

$$\begin{aligned} \sigma(D) &= 0.66 (a/A)^{\frac{1}{2}} D^{\frac{1}{2}} \quad [1] \\ &= 0.66 (0.888/78.5)^{\frac{1}{2}} D^{\frac{1}{2}} \\ &= 0.0222 D^{\frac{1}{2}} \end{aligned}$$

The theoretical ($0.022 D^{\frac{1}{2}}$) and experimental ($0.020 D^{\frac{1}{2}}$) relationships between density and granularity are given in Figure 7.

Figure 7

Granularity as a Function of Density for High Definition Aerial Film

The theoretical relationship,

$$\sigma(D) = 0.022 D^{\frac{1}{2}}$$

as expected, shows higher granularity than the experimental relationship, $\sigma(D) = 0.020 D^{\frac{1}{2}}$. This is the probable result of the level of flare light in the microdensitometer, as previously discussed.

A statistical test is available for determining whether the apparent similarity between these two equations may be justified by stating that there is no real difference between the graphs of these equations. This test, the Kolmogorov Goodness of Fit Test,⁸ makes a comparison in terms of the maximum difference in granularity of the graphs of the two functions. This maximum difference occurs at the maximum density value of interest, which is 2.1. Each equation was then evaluated at 2.1, and the difference between these two equations found as follows:

$$\sigma(D) = 0.022 D^{\frac{1}{2}} = 0.022 (2.1)^{\frac{1}{2}} = 0.0319$$

$$\sigma(D) = 0.020 D^{\frac{1}{2}} = 0.020 (2.1)^{\frac{1}{2}} = \underline{0.0290}$$

$$0.00290$$

The maximum difference is then 0.00290. Using a "two-sided test," with an α risk of 0.05, the Kolmogorov Test Statistic⁸ was found to be 0.361. Since the maximum difference of 0.00290 is certainly less than the test statistic, no difference between these equations has been found. Because of this result, there is no reason to perform the DDL calculations for both the theo-

retically and the experimentally found granularity relationships. The DDL's were calculated for the experimentally found relationship, $\sigma(D) = 0.020 D^{\frac{1}{2}}$, and the results are shown in figure 8.

Figure 8

DDL Number (n) as a Function of DDL Density (D_n) For High Definition Aerial Film 3414, For $10 \mu m$. Aperture

* n is the number of DDL's determined at $10 \mu m$.

By examining Figure 8, the number of DDL's within the given density range of 2.0, may be observed to be 57. Since 64 DDL's are required, this film would be judged unsatisfactory.

In the previous analyses, the standard deviation in density being considered was simply the granularity. In view of the ERTS project application, more sources of density variation should be considered. As previously explained, these variations in density may be summed by taking the square root of the sum of the variances:

$$S_D = \sqrt{S_g^2 + S_a^2}$$

where, S_D is the standard deviation in density resulting from both sources of variation

S_g^2 is equal to $[\sigma(D)]^2$, when $\sigma(D)$ is granularity

S_a^2 is equal to the variance of density fluctuations caused by area to area variations.

To produce an answer that would be more satisfactory in view of the ERTS project application, yet another source of variation should be considered. As the information (density levels) in a pixel is expected to have an influence upon adjacent pixels, a source of variation is introduced whenever there are adjacent pixels of different densities. The method used previously is strictly valid only when there is no significant interaction between pixels, as might be the case when pixels are very large (100 μ m. on each side). When the pixel size approaches or is smaller than the spread function of the film, pixel to pixel interaction should be expected. This interaction should be expected to decrease the number of DDL's attainable

since another source of variation is introduced.

Attempts were made to generate the RMS deviation in density attributable to this effect. Dr. Schumann originated the approach used to evaluate this effect. This approach involves the calculation of the RMS deviation in density of the print of a target of many randomly black and white squares. The size of the squares in the target is arbitrary, however the image of this target must be reduced at or near the limit of resolution of the system so that each square in the image is size of a pixel. With the effect of interaction between pixels, it may be expected that there will be a higher density when there are many adjacent black squares. As these differences in density are caused primarily by the interaction effect, the RMS deviation in density of the print of this target, should give an applicable measure of this interaction effect. This new $\sigma(D)$ may then be used to calculate the DDL's of the film.

Basically, this method involves:

1. The production of a target (transparency) that would be composed of many squares, half of which are clear, and half of which are black. These black and clear squares must be arranged randomly.

2. An imaging system so that the target could be imaged on High Definition Aerial film with the squares at pixel size.

3. An exposure series so that prints could be made with several average densities.
 4. Film processing,
 - 5.. Scanning of processed film with a microdensitometer.
 6. Data collection from microdensitometer traces.
- Density values being visually taken from the microdensitometer traces at the peak densities recorded.
7. Calculation of $\sigma(D)$ for each of the prints.
 8. Generation of the $\sigma(D)$ as a function of density relationship, using regression.
 9. Calculation of DDL's using this new relationship.

Since the production of a good target composed of random squares would be so time consuming that there would probably be insufficient time left to use the target, outside help was requested. Mr. H. Brent Archer, a research associate of GARC (Graphic Arts Research Center) at R.I.T., volunteered to produce the target for the experiment.

While the random pattern was being prepared, several screen patterns were supplied so that an attempt could be made to use them, in case the random pattern could not be prepared in time. The screen patterns were marked with "a", the fractional dot area. Since,

$$a = \frac{\pi \left(\frac{d}{2}\right)^2}{\left(\frac{1}{65}\right)^2}$$

where d is the diameter of each dot (in inches), then,

$$d = \left[\frac{4a}{(65)^2} \right]^{\frac{1}{2}}$$

After the diameter of each dot, d , was calculated, these values were converted to metric units. The following table shows the fractional dot area, a , of the screen pattern, and each corresponding diameter of the dots (d) in micrometers.

<u>a</u>	<u>d</u>
11.3	148.233 μm .
20.5	199.642
31.5	249.642
71.6	373.106
82.2	399.771
91.7	422.241

These calculations of the values of d , were necessary for the calculation of suitable distances for placement of the film, lens and target. For convenience, the target with dots of 199.642 μm . diameter was used. Since dots of 10 μm . diameter are to be imaged on the High Definition Aerial film, the required magnification, M , may be calculated:

$$M = \frac{10 \mu\text{m}.}{199.642 \mu\text{m}.} = -0.05009.$$

Using this calculated magnification, the target to lens distance,

S, was calculated:

$$S = \left(1 + \frac{1}{M}\right) f = 1155\text{mm.}$$

where f is the focal length of the lens used, which is 55 mm.

As recommended, a cut piece of the film was put in the back of a Mamiya/Sekor 1000 DTL camera with a 55 mm., f/1.8 lens. The lens to film distance, S', was then calculated:

$$S' = (M+1) f = 57.75\text{mm.}$$

Using the calculated S and S' and assuming the nodal separation of the lens to be about two millimeters, the total distance, l, between the target and the film was calculated. This distance is equal to the sum of S, S', and the nodal separation, and was equal to 1215 mm. The film was then 1215 mm. from the target.

Illumination was provided by a neon gas discharge lamp and spectral distribution limited by the use of a Kodak number 92 (red) filter. An ILEX #3 Synchro Electronic shutter and an ILEX Speed Computer timer were used to control the times of exposure. A ground glass type light diffuser was used to provide uniform, diffuse illumination. The optical arrangement is diagramed (not to scale) in Figure 9, with distances from the lamp in centimeters.

Figure 9

Three exposures of $\frac{1}{4}$, $\frac{1}{2}$, and 2 seconds were made at an aperture of $f/3.5$. After film processing as described previously, the film samples were viewed in a microscope. It was observed that although the exposure times were good, no dots were resolved. It was suspected that the poor film support within the camera was to blame. This dot pattern experiment was aborted at this point since the random pattern had been completed.

The random pattern of squares, produced by Brent Archer, was generated using a Hewlett Packard random number generator. This generator uses a program that calculates random numbers (RN) in the range $0 \leq RN_i \leq 1$, using the formula:

$$RN_i = \left[\pi + RN_{(i-1)} \right]^8 - \text{Int} \left[\left[\pi + RN_{(i-1)} \right]^8 \right]$$

where RN_i is the current random number and $RN_{(i-1)}$ is the last

calculated random number. Random numbers between zero and one thousand were generated, and a decision statement used to determine when the plotter would print a line. If the random number was less than or equal to 499, the plotter would skip an equally sized space. This was continued 49 times. The plotter would then repeat this pattern nine times so that each original line segment would have eight more line segments under it. The length of each line segment was equal to the width of the nine line segments together, so the printout appeared to be composed of squares and rectangles, until there were fifty rows. The end result was a 25.4 by 25.0 cm. printout of randomly white and red ink squares, each of which was 5 mm. by 5 mm. Several attempts were made before an acceptable random pattern was produced. Early attempts showed definite repeating patterns of squares. The program was then modified to doubly randomize; both the squares and the rows were randomized. The resulting print surprisingly showed very definite patterns, repeating on the diagonal of the printout. Double randomization was not used again. The most satisfactory reason for these problems is the quality of the "random numbers". Apparently, the "random numbers" were not genuinely random, which is understandable as the numbers were actually the last few digits in an arithmetic computation.

Still another problem was encountered in the generation

of the pattern. The plotter pen would drop after it had drawn a line, and produce a dot in the squares that were to be white. This problem was corrected by adding a "think ahead" statement to the program, whereby the plotter was instructed not to drop the pen until it had "thought ahead" to the next square. If the next square was white, it was instructed to keep "thinking" (pen off paper) until there was a square to be drawn.

The final acceptable computer print of these random squares was by no means random. After concentrating on the print for a while, repeating groups of patterns could be observed, however in view of the simple requirements set by the experiment upon the target, this random pattern was used.

This computer generated random pattern was then photographed with lithographic film. Standard lithographic processing was used, except for the method of agitation in the developer solution. The developer tray was placed on a fulcrum so agitation would only occur from side to side. The film was placed in the tray with the image of the printer lines going from top to bottom. This enabled the utilization of infectious development, inherent in lithographic processing, to merge the adjacent rows of computer generated lines to make rectangles appear solid. Surprisingly enough, this worked well, as can be seen by Figure 10, produced by contact printing this lithographic random pattern onto Dupont Velour Black projection

printing paper.

Figure 10

The next step in this experiment was the production of a reduction of the target transparency on High Definition Aerial film 3414, with resolved $10\text{ }\mu\text{m}$. random squares. A Mamiya/Sekor model 1000 DTL camera with a 55 mm. lens was used in the first

attempt to produce a satisfactory reduction. Since the High Definition Aerial film is not made in standard camera formats, Kodak film type Fine Grain Positive number 5302-189-461, was used. A satisfactory image on this film of the random pattern would be used as a master target by which contact prints using High Definition Aerial film could be produced.

The magnification, M , necessary for this reduction was calculated to be 0.00392, so the total length, L , between the target and the film was:

$$L = f \left(M + \frac{1}{M} + 2 \right) = 14.14 \text{ m.}$$

The optical bench in the Radiometry Lab was not long enough for this reduction, so a corridor was used. The target was secured to the diffuser of an "illuminator", which is simply a box with a diffuser on one side, containing several fluorescent lamps. Since this illuminator was designed for viewing transparencies, it provided uniform illumination and was ideal for illuminating the target transparency. Both the camera and the illuminator were supported by sturdy tripods, at equal heights, and placed at a distance of 14.14 m. A cable type shutter release was used on the camera to reduce vibrations. Illuminated areas on the diffuser around the target were masked to help reduce lens flare. During the exposures, hall lights were turned off to further reduce lens flare.

Using the "through the lens" metering systems of the camera, estimated camera exposure settings were determined. This estimated setting of $f/3.5$ at $\frac{1}{8}$ second, was used in an exposure series. By this varying of aperture, the aperture producing the highest resolution could be determined, and by the varying of exposure time, the detrimental effect of vibrations could be investigated. Even though the distance was only 14.14 m., the image appeared in focus at the infinite distance setting of the lens, so the exposures were made at this distance setting.

The exposed film was processed as before, except that the D-19 developer was used for 8.5 minutes, so that high contrast images would be produced.

The processed samples were examined with a microscope. No difference in sharpness was observed between reductions made with equivalent exposures, but different exposure times. Thus it was concluded that the effect of vibrations during exposure was not significant. The images however, were not satisfactory as the squares were not resolved. Since the image of a pair of black and white squares was to be 20 μ m. long, the necessary resolution was:

$$\text{Resolution} = \frac{\text{line pair}}{20 \mu\text{m.}} \quad \text{or} \quad \frac{\text{line pair}}{0.02 \text{ mm.}}$$

or fifty line pairs per millimeter. Since a 35 mm. camera should be expected to be able to achieve this, another trial was made.

Images produced by the first trial, appeared out of focus, so a focus series was made. Even though the image through the camera appeared to be focused when the distance was set at infinity, it was suspected that the image on the film might be sharper if the lens was focused at a closer distance. Apparatus setup and processing were the same as the first trial. Since it was concluded that this camera is simply not good enough, a finer lens was needed to produce a satisfactory reduction of the random pattern target.

An unused Schneider-Kruznach, Retina-Curtagon 28 mm., f/4 lens was provided by Prof. Abouelata for use in the next trial. This lens was believed to be very fine. A Kodak Retina Reflex IV camera was used because this lens would mount, only on this type of camera. The total distance, L, between the target and the film was calculated using the equation:

$$L = f \left(M + \frac{1}{M} + 2 \right)$$

and was found to be 810.6 cm. A resolving power target was secured next to the random pattern target on the illuminator so that the actual resolution could be calculated if desired. After processing identically to the previous trials, it was

observed that these images were slightly better than previous images. It was suspected that with less graininess, the images might be satisfactory.

The next trial was identical to the previous trial except that development in D-19 at 20 °C was used for only 7.5 minutes, as opposed to the 8.5 minutes used before. Resolution was determined using a microscope equipt with a Bauch & Lomb, BYL Filar Eyepiece at 1000 times magnification. The vernier scale of the micrometer used to measure relative distances on the stage, was calibrated using a Bauch & Lomb stage micrometer. It was determined that a shift of 110 increments on the micrometer was equal to a distance on 10 μm . on the stage. Since the smallest resolvable line pair required 300 increments of shift on the micrometer, this distance was equal to 27 μm . The resolution was then 37 line pairs per millimeter. For the reduction of the random pattern to be acceptable, at least fifty lines per millimeter must be resolved, so more attempts were made.

Although it was not believed that the graininess seriously limited the resolution, because of a suggestion, a "finer grain" developer was used. Kodak D-76 developer was used for 9.5 minutes. The apparatus was again set up, however a focus series was made with six different focus positions besides the

focus at infinity. Again, the images focused for an infinite distance appeared sharpest, but none of these reductions were better than the reductions made with the previous trial.

A different tactic was employed with the next attempt. As opposed to making a single reduction to obtain the final image of the random pattern, two smaller reductions were made. The Mamiya/Sekor camera was used because the Kodak Retina camera would not focus at a close enough distance. The first reduction was designed to make the squares with sides of $150\text{ }\mu\text{m}$. The magnification was then calculated as the desired image size divided by the object size, as follows:

$$M = \frac{150\text{ }\mu\text{m.}}{0.002841\text{ }\mu\text{m.}} = 0.0528$$

The total length, L , was then calculated as before to be 0.9383 m . Therefore the film should be 0.9383 m . from the target to reduce the squares on the target to $150\text{ }\mu\text{m}$. The film was processed in D-19 developer for 8.5 minutes. These images were then used as a target for the final reduction. Since the $150\text{ }\mu\text{m}$. squares were to be reduced to $10\text{ }\mu\text{m}$., the magnification was simply $\frac{1}{15}$. The total length, L , was then calculated to be 0.9387 m . The apparatus was again set up, but this time the target was the previous reduction, and the target to film distance was 0.9387 m . Under a microscope, it was observed that these final reductions were poor, and a new tactic was used.

In Research Lab 27, on the second floor of the College of Graphic Arts and Photography of R.I.T., there is an old, well designed but poorly built resolving power camera. This camera consists of an illuminator with fluorescent lamps, a crude holder for transparencies, bellows, a shutter, a microscope mounted on a track with micrometer focus adjustment, and a vacuum type film sample holder, all supported by a steel rail. The target to lens distance, S , and the lens to film distance, S' , were insecurely fixed with strips of adhesive tape, the components were loosely mounted on the steel rail, the shutter would not function at the marked speed of $\frac{1}{400}$ second, and adhesive tape was used where brackets, nails and screws should have been used. The camera however, allegedly had a resolution of 2500 lines /mm. Minimal effort to repair the unit was made, as it needed a complete rebuilding.

The magnification of the resolving power camera was fixed at $\frac{1}{80}$. Since a final magnification of 0.003911 was desired, two reductions had to be made. The first reduction would decrease the size of the random target so that the second reduction (of 80 times, in the resolving power camera) would give an image of the proper size. Since the magnification of the first reduction, multiplied by the magnification of the second reduction must equal the desired final reduction:

$$M_1 \times M_2 = M_{\text{final}}$$

The first magnification, M_1 , was calculated by dividing the desired magnification by the magnification of the resolving power camera:

$$\frac{M_{\text{final}}}{M_2} = \frac{0.003911}{\frac{1}{80}} \quad 0.3128$$

Therefore a reduction of the original random pattern target of 3.196 (the reciprocal of the magnification) was used as a target in the resolving power camera to achieve the desired final reduction.

A view camera with an eight inch (203.2 mm.) lens was used to make this first reduction. The distance between the lens and the target, S , was calculated as follows:

$$S = f. (M + \frac{1}{M}) = 713.2 \text{ mm.}$$

The distance was measured from the aperture ring of the lens. Kodak Fine Grain Positive Film number 7302-161-16 was used. The film was processed in Kodak developer D-19 for six minutes. An exposure series was made in the first attempt at producing the desired reduction. A microscope was used as an aid in focusing the image on the ground glass focusing screen. The exposure settings found to produce the most satisfactory reductions were $\frac{1}{5}$ second at $f/11$. These reductions were not used because the images appeared slightly out of focus. Since the focus was checked before the exposures, between

exposures, and after the exposures with a microscope, it was suspected that a focused image of the ground glass focusing screen of the camera did not insure a focused image on the film. A focus series was made using the exposure settings of $\frac{1}{5}$ second at f/11. A satisfactory reduction was produced by this focus series. A contact print was made of this reduction and is given in Figure 11.

Figure 11

There was no literature or data for the resolving power camera pertaining to the illumination it provided, nor was there a practical way to calculate the exposure or use an exposure or light meter, therefore the accepted method of determining a proper exposure was an exposure series. Mr. Abouelata, having used this camera before, had a rough idea about what exposure conditions to use, so an exposure series

was made with varying exposure times using Fine Grain Positive Film. A high contrast resolving power target was placed in the camera. The aperture setting was left at the position marked by a triangular piece of tape that supposedly marked the aperture to be used for highest resolution, therefore the only controls of exposure were the shutter speed and the use of neutral density filters. A properly exposed reduction of the resolving power target was produced with a 1.1 neutral density filter and a shutter speed of $\frac{1}{100}$ second.

Since the distance from the back of the lens to the film was only several millimeters, and since the total image size in the resolving power camera was less than one millimeter, there was no focusing method more practical than a focus series. Three focus series were made. The first was for coarse adjustment of focus, the second and third for finer adjustment.

Having accurately focused the resolving power camera, the resolving power target was replaced with the random pattern target that had been reduced. Another focus series was made using High Definition Aerial film. This series was primarily intended to check the ability of the resolving power camera to remain in focus between trials. A shift in focus was found and when another focus series was made, another shift was found. This assumedly was a result of the lack of stability

in the taped together components of the resolving power camera. Using the best focus attainable, the random pattern was reduced using High Definition Aerial film, to the desired size. Several reductions with varying average densities were made so that the relationship between the RMS deviation in density, and density, could be determined. A photomicrograph of an actual reduced random pattern target with squares of $10\text{ }\mu\text{ m}$. sides, is given in Figure 12.

Figure 12

Using the same optical configuration as with the uniformly exposed samples, these reduced random pattern targets were scanned with the Ansco microdensitometer.

Unfortunately, the resulting microdensitometer traces

were of no value. There was no information that could be derived from these microdensitometer traces. It was expected that the microdensitometer traces would show the effect of adjacent pixels by exhibiting a higher density when there are adjacent black squares, and even higher densities when there are many black squares. The more the adjacent squares, the higher the density was expected. This would account for the variation due to the adjacency of pixels. It was expected that the resulting microdensitometer trace would look (roughly) like this:

The differences in the heights of the peaks of the resulting densities would represent the effect of different combinations of adjacent black pixels. The RMS deviation in density of these variations in density then would represent the varia-

tion in density due to the adjacency of pixels. This RMS variation would then have been calculated for various average densities, so that the relationship between this variation and density, could be established. Unfortunately, the microdensitometric traces did not look like this. An illustration of a resulting trace is given below:

With the resulting traces, it was clear that the peaks in density could not be isolated. It was not possible to separate the adjacent pixels from the noise. There were peaks in density over a greater range than would have been caused by the variation due to adjacent pixels. With peaks in density over the entire range in density of the microdensitometric trace, it was impossible to isolate the peaks in density caused by the random pattern. In short, it was not possible to separate the signal from the noise.

It has been suggested that data points of density be collected at equal intervals of distance. The RMS deviation in density of this data however would contain information that could not be handled. A mathematical model for the resulting RMS deviation in density from this suggested analysis is given:

$$\sigma_{\text{calc}} = \sqrt{\sigma_g^2 + \sigma_{\text{adj}}^2 + \sigma_{\text{area}}^2 + \sigma_{\text{signal}}^2}$$

where;

σ_{calc} represents the RMS deviation in density calculated from data collected in the described manor

σ_g^2 represents the variance due to granularity

σ_{adj}^2 represents the desired variance due to the effect of adjacent pixels

σ_{area}^2 represents the variance due to the area-to-area variations inherent in photographic films and development methods

and, σ_{signal}^2 represents the variance of the resulting density variations due to the degraded signal within the final image

Since it was not possible to determine which were the density peaks representing densities on the target, it was not possible to determine the density variations due to the degraded signal. Therefore, the σ_{signal}^2 component in the calculated RMS deviation in density could not be identified, and hence a component of unknown value in the calculated RMS deviation in density. If the amount of degradation of the signal introduced by the lenses and the film were known, and a variance of the degraded signal calculable, this value might be subtracted from the other variances (σ_g^2 , σ_{adj}^2 and σ_{area}^2) so that only variations due to noise resulted. The relationship between noise and density could then be determined, and hence the number of attainable DDL's calculable. This unfortunately was impossible as the signal could not be separated from the noise.

If the resulting microdensitometer traces showed discernable peaks in density, the analysis would have been similar to the previous granularity analysis. Several (at least ten) random pattern reductions on High Definition Aerial film were made with different average densities. About two hundred data points in density (peaks) would have been collected from each trace. The RMS fluctuation in density, $\sigma(D)$, and average density, D , would have been calculated for each density level. This value of $\sigma(D)$ would represent the uncertainty in the density level, D , that may be attributed to

the combined effects of area-to-area variation , granularity and the variation due to the interaction of pixels. These calculated RMS values and densities would then have been used to calculate the DDL's.

It seems that the method is sound, but that the problem impeding analysis was a result of the lack of sharpness in the reduced random pattern, caused by the lack of quality in available materials. Even though the reduced images of the random pattern appeared to be at the limit of resolution as desired, it seems these images must appear sharper in order to produce usable microdensitometric traces. As shown before, the slightly reduced random pattern used as a target in the resolving power camera, was very sharp. The image degradation exhibited by the reduced random pattern must have been caused by the resolving power camera and/or the film. Since Kodak reports⁹ an MTF (Modulation Transfer Function) of about 90% at 50 cycles per millimeter, for High Definition Aerial film developed in D-19, and a resolving power of 630 lines per millimeter for a high contrast target, the film certainly does not seem to be the limiting factor. Therefore the resolving power camera is suspected, not because of the quality of the lenses, but because of the shoddy construction and the inability of the camera to remain in focus once the focus is set.

In conclusion, it has been found that when granularity is solely considered in DDL analyses, High Definition Aerial film produced 57 DDL's. Since 64 DDL's are required, this film has not been found good enough for the ERTS project. The theoretically generated relationship between granularity and density was found to be the same (statistically) as the experimentally generated relationship. This might however be simply a coincidence. The theoretical relationship was generated by using linear interpolation with values of granularity calculated using Selwyn's Law. Since these values were previously shown to demonstrate a severe discrepancy, the value calculated by the interpolation was a product of information that was at least partially incorrect. Therefore it may simply be a coincidence that the linear interpolation of two contradictory values, resulted in a value that agreed with the experimental results.

It might be interesting and informative for some interested person to continue this work and attempt to solve the problems that were discovered. The main problems that might be investigated are:

1. An evaluation and experiment to determine whether the linear interpolation of granularity data may be relied upon to result in usable answers.

2. An evaluation to determine whether the relationship between granularity and density could be directly used to determine the number of DDL's, as previously suggested.

3. An experiment to produce a better reduction of the random pattern target to see if this type of investigation can indeed provide usable information.

REFERENCES

- 1) "Image Recording Requirements for Earth Observation Applications in the Next Decade". Bernard Peavey and John Sos, NASA Goddard Space Flight/Center, Proc. SPIE Seminar, Laser Recording and Information Handling (1974).
- 2) P.G. Nutting, Philos. Mag., Volume 26, series 6, (1913).
- 3) J. Eyer, Appl. Spectroscopy, 14:4 (1960), PSE., 6:2, (1962)
- 4) "Film/Chemistry Selection For The Earth Resources Technonogy Satellite (ERTS) Ground Data Handling System", R. M. Shaffer, Image Technology, (1973).
- 5) "Kodak Products for Holography and Laser Photography, R. Anwyl, (1-75)
- 6) Rogert Anwyl, Marketing Specialist, Scientific Photohraphy Markets, Kodak Office; personal communication
- 7) Albert Rickmers, Hollis Todd, "Statistics", McGraw-Hill Book Company, (1967)
- 8) Conover, "Pratical Nonparameteric Statistics" John Wiley& Sons Inc., (1971)
- 9) "Kodak Aerial Films and Photographic Plates", Eastman Kodak Company, (1972).

APPENDIX I

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND 20771

June 10, 1975

REPLY TO
ATTN OF:

563

Mr. Steven S. Beiser

Dear Steven:

I was pleased to hear from your father about your proposed research project at the Rochester Institute of Technology (RIT) concerning the problem of distinguishing a large number (up to 64) of density levels on photographic film. As I pointed out in my paper on "film recording requirements," the basic problem of being able to achieve a wide dynamic range over a very small (less than 10 microns) recording area is still with us. If film is to be used as a medium for storing pictorial information with the resolution and radiometric fidelity obtained from satellites such as ERTS (now called Landsat), this problem will have to be solved, or at least investigated as to the ultimate limitations to such an application.

The need for such stringent requirements arises from the fact that information about observed phenomena on earth is conveyed as a "change". Of course, changes occur in the observed radiometry (optical density) and geometry of features. Even minute changes relate important data about various species of interest. This is especially true in agricultural observations such as the state of crop growth. Thus, in order to assess the health of plants of one kind or another, it is necessary to detect small density changes over small areas. One could obtain such information by using large film areas, i.e., representing relatively small (100 x 100 meters) areas on earth by large (1 x 1 millimeter) areas on film. However, this would be very costly.

Your desire to investigate films and their characteristics which might be suitable for ERTS type applications is highly appropriate. Your approach of attempting to correlate basic film characteristics (granularity, emulsion, required processing or developing conditions, etc.) to the film's capability of responding to small density (transmissivity) variations for small apertures is sound, and desirable from the standpoint of developing a realistic measure for film selection. This is not an easy job to do. But then very few interesting and significant problems are easy to solve. You certainly have chosen a challenging project. In my view, it is also beneficial to the user or customer community to know what can be achieved with existing media, and what might be expected in the future.

I wish you success in your work, and will be pleased to receive the results.

Sincerely,

Bernard Peavey
Manager, Quality Control Operations
Image Processing Facility

APPENDIX II

Sample DDL determination of Eastman Kodak Photoflure.

Given; the experimental granularity value of 0.06 at a density of 0.4.

$$a = \left[\frac{\sigma(D) \sqrt{A}}{0.66 \sqrt{D}} \right]^2 \quad \text{Equation [2]}$$

$$a = \left[\frac{0.06 \sqrt{256 \mu\text{m}^2}}{0.66 \sqrt{4}} \right]^2 = 5.3 \mu\text{m}$$

$$\text{Since } \sigma(D) = 0.66 \left(\frac{a}{A} \right)^{\frac{1}{2}} D^{\frac{1}{2}} \quad \text{Equation [1]}$$

$$\sigma(D) = 0.095 D^{\frac{1}{2}}$$

Since the first DDL is defined as the range in density from

$$D_1 - \sigma(D)_1 \quad \text{to} \quad D_1 + \sigma(D)_1,$$

where D_1 is the base plus fog density,

$$D_1 - \sigma(D)_1 = 0.18 - 0.095 (0.18)^{\frac{1}{2}}$$

$$D_1 - \sigma(D)_1 = 0.166$$

$$D_1 + \sigma(D)_1 = 0.18 + 0.095 (0.18)^{\frac{1}{2}}$$

$$D_1 + \sigma(D)_1 = 0.218$$

So, the first DDL has been determined to be the range in

density from 0.166 to .218, with $D_1=0.18$.

The second DDL may now be determined since;

$$D_2 - \sigma(D)_2 = D_1 + \sigma(D)_1.$$

$D_1 + \sigma(D)_1$ has already been determined to be 0.218, so both D_2 and $\sigma(D)_2$ must be determined to fit the above equation. By iteration, D_2 was found to be 0.24.

Now $D_2 + \sigma(D)_2$ may be determined to be 0.286, and this value used to determine D_3 , then D_4 , then D_5 until the desired density range of the film is exhausted. The steps in this calculation are presented in the following table;

<u>n</u>	<u>D_n</u>	<u>$D_n - \sigma(D)_n$</u>	<u>$D_n + \sigma(D)_n$</u>
1	0.18	0.166	0.218
2	0.24	0.218	0.286
3	0.34	0.286	0.395
4	0.46	0.395	0.528
5	0.60	0.528	0.678
6	0.76	0.678	0.843
7	0.93	0.843	1.02
8	1.13	1.02	1.24
9	1.34	1.24	1.45
10	1.57	1.45	1.69
11	1.81	1.69	1.94
12	2.07	1.94	2.20
13	2.35	2.20	the density range is exhausted.

APPENDIX III

The following Passage is from; Rickmers & Todd, Statistics, McGraw-Hill, (1967), Pgs., 65.66

population differing from the assumed population. If an average falls in the critical regions, we reject the null hypothesis. Here we show the α risk divided into two equal parts, one for each tail of the curve; sometimes we put the entire α risk into one tail of the distribution. The distinction between two-tailed and one-tailed tests will be discussed later in this chapter.

The nature of type II error and the associated β risk is indicated in Fig. 3-2. Curve A represents the normal distribution of the hypothesized process;

Fig. 3-2 β risk represented by area common to two normal curves.

curve B represents a different population with mean k units more than the first. The overlapping area marked " β risk" represents data properly belonging to curve B which are indistinguishable from some of the data in curve A. Even though the process has truly changed from a mean of μ to a mean of $\mu + k$, some of the data from the changed process could have come from the original process. The probability of this situation's occurring represents the β risk.

3.3 RISKS OF ERROR AND THE NORMAL CURVE

To design a test of significance, we first decide on the risk of a type I error we are willing to take. The probability of making this type of error is called the *level of significance* of the test. We should specify the α risk before taking samples so that the data do not influence our judgment.

If we are dealing with a normal population we can represent the α risk as in Fig. 3-1. The curve represents the assumed normal distribution; the α risk is shown by the areas under the shaded parts of the curve. These areas are called the *critical regions*. Whenever we find the average from a sample to fall in these areas, we agree to act on the basis that the data come from a

Fig. 3-1 Critical regions for the normal curve, based on the α risk.

Explanation of the Student's t Distribution

The following passage is taken from; Rikmers & Todd,
Statistics, McGraw-Hill, (1967), pgs. 81,82

3-13 STUDENT'S t DISTRIBUTION

Let us suppose that we take at random a large number of samples of size n from a normal population. For each sample we find the statistic t_v :

$$t_v = \frac{\bar{X} - \mu}{s_{\bar{X}}} \quad (3.4)$$

If we now plot the resulting distribution of t_v values, we obtain curves (one for each value of v) which have these characteristics (see Fig. 3-6):

Fig. 3-6 Curves for Student's t distributions, for $v = \infty, 4, 3$.

- 1 The curves resemble in general shape the normal distribution in standard form.
- 2 The curves have greater standard deviations than the standard normal distribution (which has a standard deviation of 1).
- 3 The exact curve shape varies with v . The curve of the t distribution is considerably different from the normal distribution if v is small, and becomes closer to the normal distribution as v increases. In fact, the t values for the normal distribution can be considered to be the limiting case for the t_v distributions; that is, $t = t_{\infty}$ ($v = \infty$).

TESTS OF HYPOTHESIS OF THE MEAN 81

3-14 TEST OF SAMPLE AGAINST STANDARD, σ UNKNOWN

We use the Student's t distribution as the basis for tests of significance in a way similar to that in which we used the normal distribution, with these differences: We estimate the standard deviation from the sample (instead of using a known σ) and we necessarily use the particular t_v distribution appropriate to each different sample size.

APPENDIX IV

The following chemical formulas are from; "Processing Chemicals & Formulas For Black-And-White Photography", Eastman Kodak Company, (1973)

Kodak Developer D-19

Water, about 50°C	500	milliliters
Kodak Elon Developing Agent	2.0	grams
Kodak Sodium Sulfite (Anhydrous)	90.0	grams
Kodak Hydroquinone	8.0	grams
Kodak Sodium Carbonate (Monohydrated)	52.5	grams
Kodak Potassium Bromide (Anhydrous)	5.0	grams
Cold water to make	1.0	liter

Kodak Stop Bath SB-1

Water	1.0	liter
Kodak 28% Acetic Acid	48.0	milliliters

Kodak Fixing Bath F-5

Water, about 50 °C	600	milliliters
Kodak Sodium Thiosulfate (Pentahydrated)	240.0	grams
Kodak Sodium Sulfite (Anhydrous)	15.0	grams
Kodak 28% Acetic Acid	48.0	milliliters
Kodak Boric Acid, Crystals	7.5	grams
Kodak Potassium Alum, Fine Granular (Dodecahydrated)	15.0	grams
Cold water to make	1.0	liter

APPENDIX V

Rochester Institute of Technology Tray Rock Agitation

The film samples are taped to the bottom of a 5 X 7" tray. The tray is lifted a half inch on the left, front, and right side, in that order. This eight second cycle is repeated throughout development processing.