A Tone reproduction study of a digital image processing system

Gerald Kashtan

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A TONE REPRODUCTION STUDY OF A DIGITAL IMAGE PROCESSING SYSTEM

by

Gerald L. Kashtan

A thesis submitted in partial fulfillment of the requirements for the degree of Bachelor of Science in the School of Photographic Arts and Sciences in the College of Graphic Arts and Photography of the Rochester Institute of Technology

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ABSTRACT

Photographic tone reproduction analysis was applied to a digital image processing system (DIPS). The problem was to calculate computer mapping functions for the DIPS that would cause input scenes to be reproduced having Clark's tone reproduction characteristics. Using the graphical method of a Jones Diagram, unique computer mapping functions were constructed for four images processed by the DIPS. After processing the imagery in the computer, the pixels were reconstructed into photographic transparencies for projection in a specially designed projection area. The results of this work concluded that tone reproduction analysis is useful in studying the macro effect of luminance transfer through a DIPS, and that tone reproduction characteristics may be modified digitally using pre-determined computer mapping functions.
ACKNOWLEDGMENTS

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INTRODUCTION

Two dimensional picture processing of photographic images using digital computers has been used successfully to correct degraded images\(^1\), perform pattern recognition and classification\(^2\), and subjectively enhance recorded scenes\(^3\). Early work in the applications of digital computers to picture processing gave emphasis to algorithm design to minimize computer time and resources, and to output images that resembled the input scene\(^4\). Current applications research is underway to study image quality of digitally processed images\(^5\). Much of this work takes the form of digital filtration functions in the spatial frequency domain to fit models of the human visual system. Investigation of spatial luminance transfer and image quality in an image processing system should also be considered. A type of spatial luminance analysis well developed and documented is known in the photographic community as tone reproduction.

A great deal of literature has been found dealing with tone reproduction and image quality of photographic processes\(^6\). Early work by Jones\(^7\), dealing with tone reproduction made it possible to determine graphically the relative relationships between input scene luminances and reproduced output luminances. Jones defined the objective of the photographic process as being the one to one reproduction of relative luminances\(^8\). Later work by Clark\(^9\), showed
that Jones's criterion was not an adequate method for reproducing scene luminances when visually evaluating a photographed scene. Clark found that optimum (preferred), image quality could be determined through subjective methods, and the results included into an objective tone reproduction system.

Clark's method to obtain data relating scene luminance reproduction to subjective visual requirements was by conducting psychological scaling experiments of photographic images on groups of observers. The results pointed out that there exists a preferred print or transparency (the prints were viewed in a bright surround, and the transparencies projected in a dark surround). Of both the prints and transparencies, it was found that the preferred tone reproduction curves were independent of scene type and lighting (night and very dark scenes were excluded from the imagery set Clark tested). A further examination of the transparencies viewed in a dark surround showed that the preferred mean density level of the image is dependent on screen luminance.\textsuperscript{11}

Work by Bartleson\textsuperscript{12} and Breneman\textsuperscript{13}, demonstrated the need to characterize and include the human visual and perception system as a part of a tone reproduction study. An important outcome of their work is that optimum tone reproduction will be obtained for any photographic reproduction process and any viewing condition when the reproduction of brightnesses proportional to white is made.\textsuperscript{14} When this work
was compared to Clark's research, where the relationships between stimulus characteristics and image quality were measured, the independent results agreed\textsuperscript{15}.

It is the aim of this experiment to apply tone reproduction analysis to a digital image processing system (DIPS), for black and white imagery. Clark's preferred tone reproduction curve for projected positive images in a dark surround (figure 1), will be used as the relationship between log scene luminances and projection density (log reproduced scene luminances).

\begin{center}
\begin{tikzpicture}
\begin{axis}[
    xlabel={LOG SCENE LUMINANCE},
    ylabel={PROJECTION DENSITY},
    xmin=0, xmax=4,
    ymin=0, ymax=4,
    xtick={0,1,2,3,4},
    ytick={0,1,2,3,4},
    grid=both,
    legend style={at={(0.5,-0.2)},anchor=north,legend columns=-1}
]

\addplot[domain=0:4, samples=100, smooth] {1/(x)^2};

\end{axis}
\end{tikzpicture}
\end{center}

Clark's Tone Reproduction Curve (figure 1)

This curve will be inserted into quadrant VIII of the Jones Diagram (figure 2). The computer mapping functions (quadrant IV), will be the variables left to be determined after the other quadrants are known. An overall pictorial description of the physical steps to this process are given in
KEY TO QUADRANTS:

Q I Flare Curve
Q II Panatomic-X film curve (D-log-H curve)
Q III Eikonix Image Digitizer Curve
Q IV Computer Mapping Function Curve
Q V Tektronix Video Monitor Curve
Q VI Contrast Process Ortho Film Curve
Q VII Viewing Conditions Curve
Q VIII Clark's Tone Reproduction Curve (figure 1)

Jones Diagram of the Digital Image Processing System (DIPS)

Figure 2
Quad II  Sensitometrically evaluate Panatomic-X film to find its D-log-H curve
Quad I  Determine the flare curve by photographing the Random Grey Test target on Panatomic-X
Quad III Determine the characteristic curve for the Eikonix Digitizer using the Random Grey Test target
Quad V  Determine the Tektronix monitor characteristic curve using a computer generated grey bar pattern displayed on the screen
Quad VI Sensitometrically evaluate Contrast Process Ortho film to find its D-log-H curve
Quad VII Set-up and measure the viewing conditions curve for the projection area

Photograph test imagery and determine the maximum log scene luminance of each scene

Insert Clark's tone reproduction curve into quadrant VIII that correspond to each maximum log scene luminance value

Digitize the test imagery on the Eikonix device

Cascade the known and measured quadrants to determine the computer mapping functions, and fit them to cubic equations

Map the input luminances to new luminances using the computer mapping functions in the computer, and send the digitally processed images to the monitor for display

Photograph and process the monitor images, and project them on a screen

* Data Acquisition Subsystem  ** Data Reconstruction Subsystem

Table 1 - Experimental Steps Used to Quantify the DIPS
Photograph a scene with a 35mm camera and panoramic film -> Digitize the negative image using an electronic digitizer and store on a computer -> Process the pixels in a PDP using a pre-determined computer mapping function -> Reconstruct the pixels into a negative image on a Tektronix video monitor.

Photograph the negative image of the monitor with contrast to make a positive transparency -> Mount and protect the processed imagery in a dark surround.

START

END
figure 3. The experimental steps used to quantify the DIPS is shown in table 1.

STATEMENT OF THE PROBLEM

The problem is to calculate computer mapping functions for the DIPS (figure 2), that will cause input scenes to be reproduced having Clark's tone reproduction characteristics16 (figure 1). The method of analysis will be to use the graphical approach of a Jones Diagram.

DISCUSSION

A part of Jones's theory of tone reproduction applies the principle of superposition to find a relationship between input and output log luminances. Superposition is a method applied to linear systems analysis that states the overall responses to linear combinations of stimuli is simply the same linear combinations of the individual responses17, i.e.,

$$0\left[ f(x) + g(x) \right] = 0\left[ f(x) \right] + 0\left[ g(x) \right]$$

(1)

The coefficients of equation (1) are taken as unity in this example. The photographic process is made up of stimuli-response components which are conventionally expressed as common logarithms (base 10). The result of log transforming each term of the right hand side of equation (1) is,
\[
\log \left[ \log(f(x)) \right] + \log \left[ \log(g(x)) \right] = \log \left[ \log(f(x) \cdot g(x)) \right] \tag{2}
\]

The right hand side of (2) says that in log space, the individual responses are multiplied (cascaded), onto each other. The justification for using superposition with tone reproduction is that the error involved in using a linear approximation to characterize the photographic system is small\(^{18}\). Additionally, the predicted values of a tone reproduction study correlate well with observed physical response. Superposition thus allows a photographic system to be constructed by identifying, quantifying, and cascading its system components together. The net result is a relationship between input signals and the system output responses.

In this experiment, key components of the DIPS (figure 2), are measured for their characteristic responses using "black box" analysis. This technique is useful in determining the input-output relationship of a system or subsystem without the need to know the internal details of the box (figure 4).

![Black Box Example](figure 4)

The DIPS (figure 2), is assembled into eight black boxes (each black box was determined by this experimenter
to be a key component of the DIPS). The analysis required the separation of figure 2 into three smaller four quadrant diagrams (figures 5, 6, and 7), in which five and six represent a component system (or subsystem), and seven is the simplified version of the DIPS. The three diagrams show the Data Acquisition Subsystem (figure 5), the Data Reconstruction Subsystem (figure 6), and the Jones Diagram (figure 7), of the DIPS. The subdivision of figure 2 was performed because major DIPS components were in themselves a system that could be characterized separately from figure 2. It must be pointed out that although figures 5 and 6 look and act similar to a Jones Diagram, they should not be called a Jones Diagram. This is because a Jones Diagram relates input to output log luminances of a photographic system.

The Data Acquisition Subsystem (figure 5), consists of the flare curve, the film characteristic curve, and the characteristic curve of the Eikonix Image Digitizer. The fourth quadrant of this figure contains the Data Acquisition curve found by cascading the other quadrants. Quadrant IV is descriptive of the events occurring when transforming log scene luminances into discrete picture elements (pixels), for computer processing.

The Data Reconstruction Subsystem (figure 6), consists of the Tektronix video monitor curve, the negative film characteristic curve used to make a positive transparency
QUADRANT III
Data reconstruction curve

QUADRANT IV
Clark's tone reproduction curve
A: max log = 3.85
B: = = 3.02
C: = = 2.63
D: = = 2.32

QUADRANT II
Computer mapping function curves

QUADRANT I
Data acquisition curve

JONES DIAGRAM
from the monitor image, and the curve of the viewing conditions when projecting these transparencies. The resultant of this diagram is the Data Reconstruction curve of quadrant IV. This curve graphically shows the relationship between log pixel code to projection density of the reproduced images.

The Jones Diagram of figure 7 is the tone reproduction diagram of the DIPS. This simplified version of figure 2 uses quadrant IV of figures 5 and 6 (quadrants I and III respectively), Clark's tone reproduction curve from figure 1 (quadrant VIII), and the computer mapping function in quadrant II (these are to be discussed later), to show the effects of tonal (luminance) transfer through the DIPS. The following sections will discuss in greater detail the two subsystems and the simplified DIPS Jones Diagram previously mentioned.

**Data Acquisition Subsystem**

Quadrant I of the Data Acquisition subsystem (figure 5), is the flare curve. This curve represents the mapping of scene luminances into illuminances incident on the negative film in the camera. These illuminances on the film over time become the exposures that correspond to the scene luminances. The measurement of flare was included in the DIPS because the author feels that it has a significant effect on the photographed imagery. The amount and effect is dependent on such factors as the
camera-lens-film combination, the directionality and position of scene illumination, and the intensities of the luminances in the scene\textsuperscript{19}.

Quadrant II is the characteristic curve (D-log-H curve) of Kodak Panatomic-X 35mm film. This curve describes the effects of log exposure (corresponding to log scene luminances), to the developed densities. A complete description of the sensitometry used to evaluate the film is located in Appendix 1.

Quadrant III is the characteristic curve for the Eikonix Linear Array Image Digitizer (figure 8). This instrument uses a linear array of 1,024 photodiode detectors to measure incident transmitted energy from an illuminated negative. Two dimensional digitization results from stepping the detector assembly 1,024 times across the imagery. The output of the digitizer is an array of pixels which are encoded into eight bits. The number of discrete codes representing grey levels range from $2^0$ to $2^8$, with the shadows of the scene taking on high pixel codes, and the scene highlights becoming low codes. The modulated energy transmitted from the negative to the detector generates a proportional analog voltage which is corrected for photodiode non-uniformities and artifacts. The analog signal is digitized into a numerical integer code by the analog to digital (A/D) converter, and stored on a computer compatible tape (CCT).

The Eikonix digitizer measures transmitted light
Eikonix Linear Array Digitizer Bench Layout

(figure 8)
Figure 9

Graphical description of the digitization procedure including quantization, used to numerically code photographic image and make it compatible for the DIPS.
modulated by the negative, and outputs quantized integer codes\textsuperscript{20}. The digitization operation is accomplished in linear space. To make the linear codes compatible to the DIPS, the pixels must be log transformed. Figure 9 shows the steps involved in digitizing, quantizing, and log transforming the negative image. The linear analog signal is quantized by truncating and rounding it to a discrete linear code (N), between 1 and 256. This is the pixel code that is stored on the CCT. To process the digitized information through the DIPS, the codes must be functionally evaluated by the computer (as real data types), to their log equivalent. The new log pixel codes are then stored in the computer or on CCT in floating point format.

Because of quantization and log transformation to the linear image signals, a modification of the negative image occurs. Quantization lumps a pre-determined range of continuous values into one integer code (i.e., all of the fractional signal about a certain value will become an integer number). If the quantization is made fine enough (as in the Eikonix device), no visual degredation is noticable to the image upon reconstruction. This assumes a one to one mapping of pixels in the computer, and that eight bit pixels were output to the reconstruction device. In the Results section, it will be pointed out how pixel mapping in the computer using the computer mapping functions can affect the visual appearance of the reconstructed image by aggrevating
the quantization effect.

After quantization, the log of the pixel values are computed. The operation produces 256 log codes that are unequally spaced on the log axis. Small numbers are spaced very far apart in log space relative to the fine separation of the larger numbers. A consequence of working in discrete log space is that little sensitivity to change occurs in the low code regions, and high sensitivity to change occurs in the high code area (this corresponds to the compression-expansion of equally spaced linear numbers in log space). When the log numbers are processed in the computer, and the values mapped to new log pixel codes, small changes in the low sensitivity area will have little or no effect on the image tone reproduction. On the other hand, small changes to the high end will produce the desired effects. The net effect of working in discrete log space is that the luminance resolution of the image in the low code region will decrease slightly, and that an equally subtle processing shift to the log pixels will produce an uneven log distribution to all of the discrete values.

The test target used to quantify quadrants I and III of this subsystem was a random grey test target (RGT target), shown in figure 10. This target was photographed on Panatomic-X film and developed as described in Appendix 1. The RGT target was chosen because it was thought to simulate a luminance distribution found in Clark's imagery set. Also, when
Random Grey Test (RGT) Target

Figure 10
the target was photographed full frame on the 35mm film, the individual grey patches could be measured on the processed film with a diffuse density densitometer. The RGT target consists of eleven grey patches ranging from black to white that are arbitrarily assigned a position within the target plane. Care was made in assuring uniform illumination and sufficient lighting to again comply with Clark's imagery set.

Data Reconstruction Subsystem

Quadrant I of the Data Reconstruction Subsystem (figure 6), is the Tektronix raster scanned video monitor characteristic curve. This precision monitor was designed for photographing images off its flat screen. At reconstruction time, the processed pixels were anti-logged, truncated, and rounded off to integer numbers between 1 and 256, and passed off to the monitor's circuitry. A negative image of the original scene appears on the screen as a distribution of grey tones, and is photographed with a 4x5 view camera. A bellows was placed between the camera lens and the monitor screen to eliminate most of the stray flare light. The size of the monitor's image was reduced on the film to conventional 35mm format, and mounted in a standard slide holder.

Quadrant II is the characteristic curve of Kodak Contrast Process Ortho 4x5 film. This film was chosen because it has an extremely low base plus fog level (approximately .05),
and the curve has a long straight line portion that begins after an abrupt and short toe (figure 12 in Appendix 1). A desirable attribute of the straight line section is that by changing development time, this section remains linear, while its slope changes. This property of the film allows it to be used as a gain control for increasing tonal separation, and can be used to increase the limited contrast range of the Tektronix monitor. The sensitometric evaluation of this film is reported in Appendix 1.

The Viewing Conditions curve in quadrant III measures the diffuse density of the slides to their projection density (which is indirectly measured from screen luminance). Special care was used in the design and construction of the projection area, and measurement of its characteristic curve. As described by Bartleson\(^2\), the viewing conditions have a significant effect on the level of information and image quality received by the human visual system. The projection area is a modification of a Bartleson design\(^2\), and is sketched below (figure 11).

Sketch of Slide Projection Area (figure 11)
The reason for the above layout is because of its simple design, economy of space, and measurable viewing conditions.

The level of veiling glare (flare), was minimized by blackening most of the reflective surfaces (walls, ceiling, floor), and baffling the sources of stray light. Flare which cannot be eliminated is present due to specularities in the optical system of the projector, and the luminance of the projection screen radiating out into the dark surround and partially back reflecting. The viewing area is designed for two persons. One person operates the projection equipment, and the other observes the screen. The observer is seated directly in front of the screen to view an image that subtends an angle of 17° x 22° degrees on a screen specially prepared by this author. The screen was made on a flat hard-board substrate to which many coats of flat white wall paint were applied (the dried screen became a diffuse reflector). The size of the screen was chosen to be only slightly larger than the projected image so that a minimum of unused reflecting surface would be present.

**Jones Diagram**

Quadrant I of the Jones Diagram (figure 7), is the resultant curve from the Data Acquisition Subsystem. This curve relates the effects of inputing luminance signals into the DIPS and transforming them into pixel codes. The output curve in quadrant III is the resultant from the Data Reconstruction Subsystem. This resultant graphically displays the
the effect of reconstructing pixels into a visual array of luminances.

In quadrant IV of the Jones Diagram is Clark's tone reproduction curve (figure 1). This curve along with the curves of quadrants I and III allow the determination of the curve shape of quadrant II. By cascading the experimentally determined quadrants, the computer mapping function results.

**EXPERIMENTAL**

The methodology for quantifying the quadrants of the Data Acquisition Subsystem (figure 5), the Data Reconstruction Subsystem (figure 6), and the Jones Diagram (figure 7), of the Digital Image Processing System, was to input a known set of luminance signals, and measure their output responses. The test signals used were the RGT target, computer generated grey bars, and sensi-strip densities. The following discussion will explain the methods of quantifying the quadrants of figures 5, 6, and 7.

**Data Acquisition Subsystem**

Quadrant I of the Data Acquisition Subsystem (figure 5), shows how the scene luminances map into log exposures on the film. This non-linear mapping is due to image forming and nearly uniform non-image forming (or stray), light. The method for obtaining data about this quadrant was to photograph the RGT target, measure the processed films densities,
and relate them through the films characteristic curve to find their corresponding log exposures (Appendix 1). The RGT targets luminances were determined before the grey patches were photographed by measuring them with a $1/4^\circ$ Spectra-Spot Meter (S/N RIT138772). The RGT target was evenly illuminated with diffuse light from two lamps positioned at $45^\circ$ angles relative to the center normal vector of the target. The spotmeter was placed in the same position as the camera, and the luminance of each grey patch measured (all of the luminance measurements in this work are reported in foot-Lambert).

Quadrant II was measured by sensitometric methods explained in Appendix 1. The RGT target was photographed on Panatomic-X film, processed, and measured on a McBeth TD-102 diffuse density transmission densitometer (S/N RIT58720).

The test image on Panatomic-X film was digitized on an Eikonix digitizer. The negative was set up on the digitizer bench (figure 8), and adjusted to give a maximum integer code ($N$), of 256 to the portions of the negative transmitting the most light (this corresponds to the shadows of the scene). The value of 1 was given to the highest density area (zero cannot be used because the log of zero is undefined). A further description of the digitizer calibration is given in Appendix 2.

Once the RGT target was digitized and entered into the computer, commands were given to the PDP 11/70 to display the digitized grey patches on a video monitor. The
digital code corresponding to each pixel was found by using an X-Y coordinate curser that was moved to desired positions on the display. The pixel value at the X-Y location was addressed in memory and given at the bottom of the screen. Knowing the densities of the digitized target and the corresponding log integer codes of each grey patch, the curve for quadrant III was drawn (fluctuations of N were averaged out by reading many pixels per patch).

The straight line of quadrant III indicates the expected linear mapping of density into log(N), but the slope of the line is greater than the predicted value. The predicted value is found by considering the effect of a straight line in linear space, and its transformation into log space. If the straight line relationship of the image digitizer (figure 15 in Appendix 2), in linear space is given by,

\[ y = mx + b \quad (b=0) \] (3)

(as seen in Appendix 2, figure 15, the y-intercept of the detector curve is (0,0). This is because the linear portion of the curve can be extrapolated to this point when considering an ideal detector)

In log space,

\[ \log(y) = \log(mx) \] (4)

\[ \log(y) = \log(m) + \log(x) \] (5)

Log(y) equals log(N) and log(x) equals density. The coefficient
of log(x) is unity, but the measured slope of the digitizer curve is 1.3. The fractional increase to the slope is probably due to the q factor\textsuperscript{23} of the digitizer system. If the slope of the curve in linear space was other than one, the curve in log space would not be linear. Rather, it would be a power curve dependent on the slope of the linear space curve.

Once quadrants I through III are known, the curves are cascaded upon each other to come up with quadrant IV. This quadrant is the resultant of transforming analog log scene luminance data into discrete log digital data for numerical processing. Quadrant IV of the Data Acquisition Subsystem becomes quadrant I of the Jones Diagram of figure 7.

Data Reconstruction Subsystem

The Data Reconstruction Subsystem (figure 6), begins in quadrant I with the transformation of pixel codes (log N), into log luminances on a Tektronix 634 video monitor. To quantify the monitor response, a computer generated grey bar pattern (eight grey bars whose luminance level ranged from 2\textsuperscript{1} to 2\textsuperscript{8} in succession), were displayed on the screen. The monitor was set to obtain the maximum luminance range between black and white by using a 1/4\textdegree Spectra-Pritchard Luminance Spotmeter to guide in the adjustment of the contrast and brightness controls. When the spotmeter indicated that the display was set to the maximum luminance range, the
monitors control panel was locked. The spotmeter was also used to measure all of the grey bars so that the curve for quadrant I could be drawn.

Once the monitor response was known, the computer was instructed to display the processed test and final imagery as negative images. The reason is that when the images are photographed and processed, positive reading transparencies are obtained.

The Tektronix monitor was chosen for the DIPS because the originally chosen device failed to provide acceptable imagery. The intended reconstruction device was an Eikonix Laser Beam Recorder (LBR), that writes images onto Polaroid P-N type 665 film. This device was rejected from the system because of the low contrast range of the imagery written out on P-N film, and the insufficient dynamic range of the laser to produce higher contrast imagery. The maximum obtainable density range was approximately 1.0, while a range of at least 2.0 was needed. By substituting the Tektronix monitor, the contrast range of the negative image was increased to about 100:1 \((\log(100)=2.00)\). An additional boost to the contrast range is available by increasing the slope of the Contrast Process Ortho film used to produce the positive transparencies from the monitor. The slope of the Contrast Process Ortho could be increased to make up for the loss of contrast when using the LBR, but would be unpractical because gamma's of two to five would be needed.
Quadrant II is the characteristic curve of the Kodak Contrast Process Ortho 4x5 film used to photograph images off of the monitor. This curve was obtained by the sensitometric methods described in Appendix 1. The choice of gamma for this process was made after all of the quadrants of the DIPS were known except for the computer mapping functions in the Jones Diagram (figure 7). Once the curve of quadrant II (figure 6), was chosen, the negative images on the screen were photographed using a 4x5 view camera, and processed.

Quadrant III is the viewing conditions curve, and is the relationship between input diffuse density and output projection density of the slide projector and screen. The shape of this curve was found by projecting homogeneous density patches onto the projection screen. These slides were made by exposing sheet of Contrast Process Ortho to uniform white light, and processing them exactly as the test imagery. The density range of the transparencies went from zero to 3.5. These slides were made on the same material as the reproductions to keep the Callier Q factor consistent from measurement of the quadrant to actual projection conditions. The projection density was indirectly obtained by measuring screen luminances with the 1/4° Spectra-Spotmeter. Maximum luminance is defined as open gate luminance. Open gate luminance is the luminance measured on the screen which occurs by inserting an empty 35mm slide mount into the slide gate of the projector. Since zero density corresponds to open gate
luminance, a scale was set up to relate relative increments between the two (i.e., half of the open gate luminance is equal to the addition of .30 projection density). The viewing conditions curve when plotted has a slope of 1.3 which explains any Callier Q factor influence in the projection system.

The resultant of cascading quadrants I through III is the Data Reconstruction Subsystem curve of quadrant IV. This curve relates projection density as a function of \( \log(N) \), and is placed into quadrant III of the Jones Diagram.

**Jones Diagram**

Quadrant I of the Jones Diagram (figure 7), is the resultant curve obtained from the Data Acquisition Subsystem of figure 5. This curvilinear function describes the effect of changing input log luminances to log pixel codes. The shape of the curve in quadrant I has three parts that are similar to a D-log-H curve (a photographic film curve usually has a toe, straight line, and shoulder). The toe of the Data Acquisition curve changes from threshold sensitivity of log luminances to a rapidly increasing function. The semi-straight line portion maps log luminances almost linearly. This is the region of the curve where most or all of the scene luminances should fall in order for the DIPS to detect and distinguish them. Additionally, this region coincides with the usable portions of the curves in the other quadrants. The third area
on the curve is the shoulder. This is where luminances map onto a saturated level and become merged into the same pixel code.

The Data Reconstruction curve in quadrant III shows the relationship between processed log pixel code and projection density of the reconstructed image. A high value of gamma is needed to separate the log pixel code range of zero to 2.41, to obtain a projection density range of zero to 3.85.

Quadrant IV of figure 7 is Clark's tone reproduction curve for projecting black and white transparencies in a dark surround. The four curves in this quadrant are identical in shape, but are shifted to a different point along the log scene luminance axis. This is because each curve represents a photographed scene that had to it a different maximum log scene luminance. Curve A of quadrant IV is a contrasty studio scene of a person holding a grey card and a step tablet. Curve B is the same as A, except the illumination on the person has been balanced to give a normal contrast ratio. Curve C is the RGT target, and curve D is a bright outdoor scene of a person holding the same grey card and step tablet. The maximum log scene luminances were measured by panning the scene until a maximum value of luminance was found.

Once quadrants I, III, and IV were quantified and plotted, the curves of quadrant II were found. The four
curves of this quadrant correspond respectively to the four curves in quadrant IV. The functional relationships mapping log pixel codes to a new set of log pixel codes, $\log(N)$ $\log(N)$, were established by cascading the responses of the other three known quadrants.

To input the curves of quadrant II into the computer, the X-Y coordinate pairs ($\log(N) = X$ and $\log(N) = Y$), were then fitted to cubic least squares equations. Cubics were used to fit quadrant II because the curves resemble third order equations. The cubics were then written into the computer software to make digital look-up tables for each image. The equation for the cubics and the coefficients for each computer mapping function are listed in the table below.

Cubic Least Squares Equation:

$$Y = b_0 + b_1X + b_2X^2 + b_3X^3$$  \hspace{1cm} (6)

Coefficients:

<table>
<thead>
<tr>
<th>Curve</th>
<th>$b_0$</th>
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</table>

Coefficients of the Cubic Equations of the Computer Mapping Functions

Table 2
RESULTS

After quantifying and assembling the quadrants of figures 5, 6, and 7, it was seen that the relative orientation of each curve with each other is of extreme importance. This is because the usable portions of each curve must be cascaded onto the usable portions of the other curves to maximize the DIPS effectiveness. The usable portions of the curves are defined as those parts of the curves where input signals are mapped into unique output signals between threshold and saturation levels. The following sections describe the effects of each subsystem curve on the others; the results of determining the computer mapping functions using the DIPS diagram of figure 7; and the visual results of the imagery processed by the DIPS to the computer mapping functions in the Jones Diagram.

Data Acquisition Subsystem

Quadrant IV of figure 5 shows the relationship between log scene luminances to log(N). The input of log scene luminances into the Data Acquisition Subsystem allows a luminance range of 1,000 levels between 10 and 10,000 ft-L to be digitized and coded into pixel values between log(1) and log(256). This input log scene luminance range permitted by the DIPS is sufficient for photographing general pictorial scenes and Clark's imagery set (since it falls into this luminance input range).
The effect of flare on the photographed scenes was insignificant (as long as the photographed scenes are described by the curve in quadrant I). This is because flare in quadrant I affects only the base plus fog (B+F) level of the negative film in quadrant II.

The dynamic range of the digitizer in quadrant III is able to utilize all of the curve in quadrant II. The range of log(N) obtained from digitizing the densities of quadrant II is 2.11 (.30 - 2.41). The B+F level of the negative film accounts for why the log(N) interval of 0.00 to .30 is not used (the antilog of 0.00 and .30 is 1 and 2 respectively). Only pixel code 1 is not assigned when digitizing. This code can be used if a negative with a B+F level approaching zero were substituted into quadrant II (which is not the case here). The effect of not using pixel code 1 is that specular highlights of a bright scene will not be uniquely coded (they will merge into the pixel codes assigned to the diffuse highlights and be lost).

Data Reconstruction Subsystem

Examination of the Data Reconstruction Subsystem curve enabled the experimenter to conclude that the scene luminance range and contrast processed through the DIPS is limited by the data reconstruction device. This is because a non-linear relationship exists when mapping log(N) into log reproduced scene luminances on the Tektronix monitor.
This relationship was fixed once the monitor had been adjusted to give its maximum log luminance range (approximately 2.00). The curve shape shows very little tonal separation occurring to low log(\(\hat{N}\)) codes, and increasing separation to the higher level pixels. The unwanted compression of low screen luminances from log(\(\hat{N}\)), is compounded when the screen image is photographed onto Contrast Process Ortho film. What happens is that the dark tones on the screen in quadrant I fall onto the toe region of the film in quadrant II.

The reduction of medium and high screen luminance contrast is compensated for when developing the photographed monitor image. This contrast boost is accomplished by using a development time that yields a high film curve gamma. When the processed transparencies are projected onto the projection screen, an overall linear amplification of the contrast range results from the characteristic curve of the viewing conditions (this curve has a slope of 1.3).

Jones Diagram

Clark's tone reproduction curve from figure 1 is inserted into quadrant IV (figure 7). The curve has a fixed shape and position relative to the projection density axis. This curve shape relative to the log scene luminance axis is determined by knowing the maximum log scene luminance value of the photographed scenes (by measuring the scene luminance prior to photographing them with the Spectra-Spotmeter).
In quadrant IV, the four identically shaped curves represent Clark's tone reproduction curve for the two studio scenes, the RGT target, and the outdoor scene (curves A, B, C, and D respectively). Once these curves were positioned in the Jones Diagram along with the Data Acquisition and Data Reconstruction Subsystem curves, the computer mapping functions corresponding to curves A, B, C, and D could be determined by cascading the known quadrants. Four computer mapping functions were needed for digital processing because each of the scenes had a different maximum log scene luminance.

An ideal scene for processing through the DIPS would have a maximum log scene luminance of 4.00 (this would be a very bright scene). If the maximum log scene luminance were less than 4.00, some of the shadow luminances would not be digitized to unique pixels in quadrant I. If the maximum log scene luminance were greater than 4.00, the digitized highlights would have no definition because they would fall on the threshold area of the Data Acquisition Subsystem curve.

If the maximum log scene luminance was less than 4.00, the reproduced shadow detail would be lost, and the reproduced scene would look dark and possibly dull in appearance. Even when the maximum log scene luminance value is 4.00, some of the highlights will be lost due to compression in quadrant III. Thus, is the maximum scene luminance value is other than 4.00, only a portion of Clark's tone reproduction curve in quadrant IV is used.
The effect of the computer mapping function on the quantization effect mentioned on page 17 had no bearing on scenes A, B, C, or D due to the computer mapping functions shapes. These unwanted modifications of the digitized scenes mentioned earlier, referred to increasing the quantization-log transformation error of the processed scenes by the computer mapping function in quadrant II. What happens is that the computer mapping function compresses small \( \log(N) \) codes into smaller \( \log(N) \) codes in quadrant II. Since the codes going to the Tektronix monitor must be integers, \( \log(N) \) values between 0.00 and .30, .30 and .48, .48 and .60, etc., are anti-logged, rounded, and truncated to an integer code and some of the log codes are lost. If the computer mapping function does shift high \( \log(N) \) codes into smaller \( \log(N) \) codes, the reconstructed image will show a loss of tonal resolution to the highlights of the scene.

The computer mapping functions for the four scenes in quadrant IV are shown in quadrant II respectively. The shapes of these curves in quadrant II are dependent upon the orientation of the photographed log scene luminance ranges relative to the usable portions of the Data Acquisition Subsystem curve, the Data Reconstruction Subsystem curve, and the tone reproduction curve shape in quadrant IV. In addition to digitally mapping \( \log(N) \) with the curves in quadrant II, the four images (curves A, B, C, and D of quadrant IV), were mapped in the computer with a linear one-to one computer
mapping function, and output through the Data Reconstruction Subsystem. This linear computer mapping function curve (not shown), transfers $\log(N)$ into $\log(N)$ without change to the pixel codes. This linear computer mapping function was substituted in quadrant II for the pre-determined computer mapping functions to study the effects of input and output in the DIPS. The following will explain the results of the processed and projected DIPS imagery using both the curves in quadrant II and the linear computer mapping function.

The processed and projected transparency of scene A visually appeared dull and dark because of low reproduced image quality. The reasons for this can be explained by studying curve A in quadrant II of figure 7. To begin the study, first note that when curve A in quadrant IV was cascaded onto the Data Acquisition Subsystem curve in quadrant I, the shadows and parts of the midtones of the log scene luminance scale were compressed into pixel code 256 (this code is the value assigned to all luminances that fall onto the saturation point of the curve in quadrant I). The scene highlight and the remainder of the midtone range fall on the shoulder of the Data Acquisition Subsystem curve. Quadrant I limits the amount of shadow and midtone detail in this scene that can be reconstructed after computer processing. Additionally, the average log scene luminance value for curve A is digitized to a high pixel code that should normally be reserved for the shadows of the scene. The scene highlights and
most of the midtones were mapped in quadrant II onto the insensitive lower toe region of the Data Reconstruction Subsystem curve in quadrant III. Because of this, highlights and midtones (detail and image tones), merged into a few projection densities on the transparency. The range of projection densities for scene A was less than .80.

Mapping Scene A in the computer with the linear computer mapping function produced a much better visually acceptable image. The reason for this is because the linear computer mapping function shifted log(N) of curve A onto the upper toe and straight line sections of the Data Reconstruction Subsystem curve in quadrant III. This stretched the contrast range for the processed and projected DIPS image.

Scenes B and C that were digitally mapped with curves B and C in quadrant II respectively, exhibited the same contrast and detail loss to the processed and projected imagery as did scene A (when scene A was mapped with curve A of quadrant II). The reasons for the similar degradation to the imagery is the same as explained for scene A. The severity of the image degradation was reduced for scene B, and reduced even further for scene C. The reasons why the DIPS image quality increased for scenes B and C can be explained by considering first the log scene luminance range originally input into the Data Acquisition Subsystem. This allows an experimenter to determine from the start of DIPS processing the working range of pixels available to the input images.
Curves B and C had more of their luminance range falling on the usable portions of the curve in quadrant I respectively. Since more log scene luminance values were digitized and coded into pixel other than the saturation code (256), more midtones and some shadow luminances were available for processing than those for scene A. Also, the average log scene luminance value was given a lower pixel value respectively from the curve in quadrant I. The highlights and some of the midtones of scenes B and C were mapped onto the lower portion of the toe and straight line section of the Data Reconstruction Subsystem curve. A very noticeable feature about the midtones as seen from the processed and projected imagery for curves A, B, C, and D is that the contrast of the midtones is extremely compressed. A possible explanation why the contrast of these scenes does not follow the predicted computer mapping function curves in the midtone region may be explained by the distribution of midtone grey levels in the photographed scenes. If the distribution of the scene grey levels for the midtones of scenes A, B, C, and D cluster about a few levels (which may be the case for the scenes tested in this experiment), they may be mapped onto the lower toe region of quadrant III, and be compressed onto less levels than they started out as.

The linear computer mapping function increased the reconstructed image quality of scenes B and C for the same reasons as curve A. This again is due to the linear computer
mapping function's ability to shift \( \log(N) \) onto the upper toe and straight line portion of the Data Reconstruction Sub-system curve in quadrant III.

Curve D in quadrant II produced a profound visual effect on the digitally processed and projected image of scene D. The entire log scene luminance range of scene D was digitized into the level between threshold and saturation for quadrant I. Because of this, the highlights, midtones, and shadows were given individual codes. The visual effect of the reconstructed image of scene D was caused by the compression of the midtones into a few grey levels, and the sharp contrast relationship of the muddy midtones with the compressed highlights. This contrast relationship of midtone and highlights tends to stress the boundaries of the reproduced scene luminances of some of the scene elements (this visual effect may be useful in feature enhancement and extraction for digital imagery).

When scene D was mapped with the linear computer mapping function, the natural contrast balance and scene detail of the originally photographed image was restored. The linear computer mapping function stretched the contrast of \( \log(N) \) over most of the upper toe and straight line portion of the curve in quadrant III. The linear one-to-one computer mapping function consistently gave better visual images than those mapped with the pre-determined functions in quadrant II. The experimenter feels that this is the case because the grey tone
distribution of scene midtones must be stretched out digitally to compensate for the Data Reconstruction Subsystem curve.

SUMMARY AND CONCLUSIONS

The application of tone reproduction analysis to the DIPS studied in this experiment proved successful in terms of understanding how input luminance signals are transferred and modified macroscopically by the system and its subsystems. This experiment also demonstrated the effect that digitization, quantization, computer processing, and reconstruction have on the processed and projected imagery. It should be pointed out that computer processing of scene luminances allows manipulation of these luminances in a way impossible for the photographic process alone (such as compressing midtones while extending the highlights). The following list of conclusions summerize the main points of this project.

1. The input log scene luminance range must match up with the Data Acquisition Subsystem input range so that as many luminances may be digitized without a loss to the scene luminance range.

2. The Data Reconstruction Subsystem is the limiting factor in producing acceptable reconstructed imagery from properly digitized input into the DIPS. This is because the image reconstruction device will severely compress the pixels in
3. The reason why the scenes processed and projected did not reproduce with Clark's tone reproduction characteristics was most likely due to the curve fitting of the hand drawn computer mapping functions (figure 7). The author used a straight-forward cubic curve fitting routine (equation 6), that was written into the software of a Hewlett-Packard desktop calculator. The cubic curve fitting routine took X-Y coordinates from the predicted curves in quadrant II of figure 7, and fit the best curve to them. Obviously, the "best fit" produced unacceptable results due to the massive compression seen in the midtone regions of the DIPS imagery. The recommendation is to use a different curve fitting routine to obtain a better "best fit".

4. The Data Reconstruction Subsystem should be redesigned to reduce the compression effects it has on highlight and midtone pixels being reconstructed.

5. The grey level histogram of photographed scenes should be examined before DIPS processing. This would allow an experimenter to know in advance of digital processing where the scene tones were distributed, and if a compression will occur as a result of a subsystem characteristic compression.
LIST OF REFERENCES


2. Ibid

3. Ibid

4. Ibid


8. L.D. Clark, "Picture Quality of Motion Pictures as a Function of Screen Luminance", J. SMPTE, 61, (August 1953): 241-47


11. Ibid

12. Ibid


15. Ibid


25. Ibid

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L.D. Clark, "Picture Quality of Motion Pictures as a Function of Screen Luminance", J. SMPTE, 61, (Aug 1953): 241-47


APPENDIX 1

The characteristic curves for Kodak Panatomic-X 35mm film and Kodak Contrast Process Ortho 4x5 film were obtained by sensitometric testing as outlined below. Additionally, sensitometric methods were used to monitor film processing of the two film materials. The same emulsion batch was used for Panatomic-X and Contrast Process Ortho respectively, to maintain consistency from negative to negative.

The first step for generating the characteristic curve for Panatomic-X film was by exposing strips (sensi-strips), of the material in a Kodak model 101 Process Sensitometer (S/N RIT58565), with a 1.4 neutral density filter (data for this sensitometer is at the end of this appendix). After exposure, the strips were tapped emulsion side up on the bottom of a 11x14 inch development tray. In complete darkness, Kodak D-76 film developer (1:1 dilution), at 70°F was poured in and agitated for seven minutes. The technique of agitation was to lift each corner of the tray one half of an inch above the processing bench with a cycle time of approximately six seconds. After seven minutes, the developer was poured out, stop bath poured in and agitated for one half a minute, and then fixer poured in and agitated for three minutes after disposing of the stop bath. After fixation, room lights were turned on, and the sensi-strips were washed and dried. Three sensi-strips were processed at a time,
and three runs were completed to quantify any variation in the process by averaging them into the densities of each strip.

The densities of every other patch (twenty one patches per strip), were measured with a McBeth TD-102 diffuse density transmission densitometer. All density measurements made in this experiment were done on this instrument. The densities of the measured patches were matched up with the corresponding sensitometer exposure, and the characteristic curve (D-log-H), drawn. This curve was inserted into quadrant II of the Data Acquisition Subsystem diagram (figure 5), and remained constant with subsequent processing of test and final imagery.

The consistancy of images being processed on Panatomic-X film was checked by tapping a sensi-strip along side the film to be developed. After development, the densities of the sensi-strips were measured against those of the film characteristic curve. If these densities were within the shape of the D-log-H curve, the processed imagery was accepted. Otherwise, the scene was re-shot and developed.

The characteristic curve of Kodak Contrast Process Ortho 4x5 film was generated in a similar manner to Panatomic-X. The film was exposed in the 101 Sensitometer with a 1.0 neutral density filter, and developed in Kodak D-72 film developer for 2.5 minutes at 70°F. A time-development series was run on the film so that a range of film gamma's
could be obtained. The purpose of this was to allow the experimenter to choose an appropriate gamma to compensate for tonal separation limitations of the video monitor. Four sheets of identically exposed film were tapped down to the development tray, and the developer poured in. A Kodak Wratten 1A safelight was used since the sensitivity of the film is orthochromatic. The agitation method was similar to that used on Panatomic-X film except that at one minute intervals, a sheet at a time was taken from the developer and placed into the stop and fix baths. After washing and drying, the characteristic curves for each time of development was plotted on the same set of axes. Because of the long straight line portion of the curves, it was easy to calculate the slopes. The gamma's were then plotted as gamma as a function of time-of-development. The working time-development D-log-H curve was later inserted into quadrant II of the Data Reconstruction Subsystem (figure 6). As with the imagery exposed on Panatomic-X, a sensi-strip was used to check the uniformity of processing Contrast Process Ortho images.
Sensitometer Data -

Kodak Model 101 Process Sensitometer
Serial Number RIT58734
Shutter Time .20 Seconds
Lamp Illumination at Film Plane 1700 lux
Calibration Current .790 amps
21 Step Kodak Silver Step Wedge (RIT101-897)

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Time-development curves for Kodak Contrast Process Ortho 4x5 film processed in D-72 at 70°F

![Graph showing log exposure (lux-sec) vs. diffuse density for different development times.](image1)

Time-gamma curve for the above time-development series

![Graph showing time vs. gamma for the development series.](image2)

Figure 12: Log exposure (lux-sec) vs. diffuse density

Figure 13: Time-Gamma Curve for Kodak Contrast Process Ortho 4x5 film
Appendix 2

The Eikonix Linear Array Image Digitizer is an apparatus designed to provide digital representations of photographed prints and transparencies24. The method of digitization is to step a linear array of photodiode detectors (Reticon 1024H Photodiode Array), across photographic imagery to produce a 1024 x 1024 pixel element array. The digitizer is shown in the block diagram of figure 14.

The photodiode array consists of 1024 individual detectors joined side by side in a line. The dimensions for each diode is 16 µm by 16 µm and they are spaced 16 µm apart (center to center), from each other. Before digitizing imagery, the photodiode array must be calibrated. This is done because diode-to-diode response must be made uniform for all of the detector elements (each diode in the array will vary slightly in response). The calibration procedure is to measure the response of each diode to a darkfield, and then to a brightfield. This is simply exposing the detector to no light, and then to white light at the detectors saturation point. A correction factor is computed for that diode's response data and stored. Upon digitization of the imagery, each diode response is corrected in real time with the correction factor.

The response of a typical photodiode25 in the array is shown in figure 15. The curve consists of a toe, straight line, and shoulder. The toe is the threshold level where the diode's response to exposure is indistinguishable from dark
Block Diagram of the Eikonix Digitizer Functions

figure 14
field noise. From .01 μJoules/cm² to 3 μJoules/cm² (in the straight line section), the curve maps exposures linearly into voltage. If this curve was extrapolated downwards, it would intersect the axes at the point (0,0). This would be the situation for an ideal diode exhibiting no dark current noise. Exposures greater than 6 μJoules/cm² saturate the diode to one voltage level (3 μJoules/cm²), as seen below in figure 15.

![Typical Response Curve for a Photodiode Detector in the Detector Array (figure 15)](image)

\[
V_{sat} = 3 \, \mu\text{Joules/cm}^2 = \text{Saturation Voltage}
\]

\[
V_{dark} = .01 \, \mu\text{Joules/cm}^2 = \text{Threshold Voltage}
\]
The typical dynamic range\(^2\) for the detectors is 160:1 \(\log(160) = 2.20\). Most outdoor scenes produce negative densities that range less than or equal to 2.20\(^2\). Because of the dynamic range of the digitizer, most general pictorial information can be handled. Additionally, the digitizer can handle the density ranges of Clark's imagery set.