

AN INVESTIGATION OF
PHOTOGRAPHIC BAND-RATIOING

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A RESEARCH PAPER
submitted to
THE DEPARTMENT OF GEOGRAPHY
OREGON STATE UNIVERSITY

in partial fulfillment of the
requirements for the
degree of

MASTER OF SCIENCE

December 1987

Directed by
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ABSTRACT

A photographic band-ratioing technique was investigated. The data source consisted of 70 mm Landsat Multispectral Scanner (MSS) negatives. The process would require combining registered positive and negative transparencies to achieve a ratio modulation in the resulting print. This would also require compensation for atmospheric effects on the original negatives by special photographic processing. Results indicate an inability to easily correct for atmospheric effects photographically. This was due exclusively to low intensity reciprocity failure. Procedural revisions could include the use of a custom light source, the selection of a different emulsion, the hypersensitization of the emulsion, or some combination of these. Related work could include a less theoretically strenuous application of positive-negative masks for target enhancement.

INTRODUCTION

An implicit effect of the "multi" aspect of remote sensing (Colwell, 1975) is to inundate the image interpreter with more data than he or she is capable of effectively synthesizing. The net result may be a situation where pertinent information is present within the data, but is unrecognizable due to its dissociate nature. Fortunately, there exist both photographic and digital procedures which facilitate data compression and enhancement.

It has been customary in remote sensing to separate photographic and digital image data, a fact which is borne out by their separation in the imaging and image processing literature. This separation is also enhanced by the discussion of "conversion techniques" for obtaining digital output in photographic form or for digitizing photographic images. The validity of this imposed dichotomy is in part a function of context and scale.

Signal processing and the photographic-digital "dichotomy"

While each domain possesses unique characteristics, photographic and digital data should be regarded as different manifestations of the same signal. As an example, a photographic emulsion is composed of many very small grains of silver halide. Upon exposure, these grains are usually rendered either developable or not developable - i.e., a binary state. Similarly, many digital processes have directly equivalent photographic counterparts. Contrast manipulation is perhaps the most well

known example.

The "black box" model, consisting of an input signal, a system acting on that signal, and an output signal, is an excellent representation of this relationship. A diagram of this model by Ludeman (1986) shows two versions, one for analog data and one for digital. With the exception of "A to D" and "D to A" steps in the analog version, the diagrams are identical. As indicated previously, photographic data may not in fact be considered analog. Thus only data prior to capture can be considered "analog," and the photographic-digital "dichotomy" is perhaps not consistent with signal theory. Accordingly each domain should be evaluated in the context of its inherent strengths and weaknesses, and the specific interpretation task at hand.

Advantages and disadvantages of each domain

The quantitative nature of digital (discrete) image processing imparts flexibility and precision to the implementation of both point and local operations. Local operations are of particular importance, in that they represent a range of transformations which are difficult or impossible to implement in photographic image processing. Digital processing also allows the interactive analysis of statistics and images, thus permitting the interpreter to modify his or her strategy based on intermediate and timely results. In addition, the use of classification algorithms represents a powerful tool for the conversion of raw data to useful information.

Unfortunately, digital imaging and processing systems are usually more costly and complex than their photographic counterparts. While this may be a problem of limited scope in the United States and other technologically advanced nations, it is undoubtedly of greater relevance in nations with lesser capital and technological resources. These are frequently regions which could benefit greatly from applied remote sensing and image processing. Another restrictive aspect of digital image processing is the large volume of data which must be handled.

An increase in data volume is frequently related to an improvement in spectral, spatial, or radiometric resolution. While this may improve the information content of the data, depending upon the application, it also serves to increase digital processing costs. In addition, such improvements yield imagery that is more easily interpreted by direct visual analysis (Colwell and Poulton, 1984). Manual processing and interpretation thus provide a viable alternative to automated image interpretation for some applications (Roebig et al., 1984).

The quantity of data composing a single MSS scene is enough to prohibit full scene image processing without access to a minicomputer or mainframe. As calculated by Slater (1980), a MSS scene consisting of four bands with six bit quantization contains 1.68×10^8 bits of data. Similar calculations using Thematic Mapper (TM) parameters yields a total number of bits per scene equal to 1.78×10^9 . These figures equate to approximately 20 and 212 Mb, respectively. Though one may point out the

impressive improvements in the cost and capabilities of VLSI technology, sensor systems (e.g. the Airborne Imaging Spectrometer) have also tended to advance at a similar rate. The utility of parallel processing techniques is readily apparent.

Photographic (continuous) image processing allows the parallel processing of image data. This makes photographic processes independent of sensor characteristics such as spatial or radiometric resolution, and scene characteristics such as ground dimensions or scale. Parallel processing results in equal process time requirements regardless of scene data quantity.

Photo processing has the added advantages of requiring lower cost lab facilities and providing high resolution output in either paper or transparency form. As indicated previously, both the cost and complexity of a lab may be of considerable importance to individual researchers, or those in less affluent nations. Top quality output is of great utility to all researchers, requiring rather specialized and expensive equipment to acquire from digital systems.

Research description

The aim of this research was to develop a photographic band-ratioing technique, which would also necessitate the photographic compensation for atmospheric effects. Thus the first requirement was to develop a photographic technique which would adjust variations in film densities that are unrelated to scene reflectance values.

The second goal was to assess the ability of a positive and negative film mask to modulate a light source proportionally to the quotient of corresponding pixel values. This could most easily be achieved by obtaining both digital and photographic image data for the same scene. Since band-ratioing is easily accomplished digitally, a photographic product could be compared to its digital counterpart to determine the success of the procedure.

It was desired to keep the photographic processing as simple as possible, avoiding the need for any equipment beyond a color darkroom. While the technique was investigated using 70 mm MSS transparencies, it was intended to take advantage of the improved spectral and spatial characteristics of TM imagery.

Test image description

The test image selected was Landsat MSS image number 1243-13595, acquired March 23, 1973. The scene is of an area in southwest Bolivia, and includes surface mineralization of sufficient areal extent to compensate for the somewhat limited spatial resolution of the MSS system. Additionally, a digitally processed band-ratio color composite of this scene was available (Williams, 1983) which would allow the concentration of this work to be placed on photographic processing.

The scene is dominated by two large salt flats, the Salar de Uyuni, and the smaller Salar de Coipasa. These salt flats contain extensive areas of sodium chloride. Surrounding areas

include large amounts of gypsum and gypsiferous soils.

Black and white contact prints of the test image are presented in Figure 1. Exposure and processing for all four prints was held constant, with the Band 6 image being used to determine an appropriate exposure time. The exposure latitude of the paper used (Ilford Multigrade) tends to mask the considerable variation of negative densities in this scene.

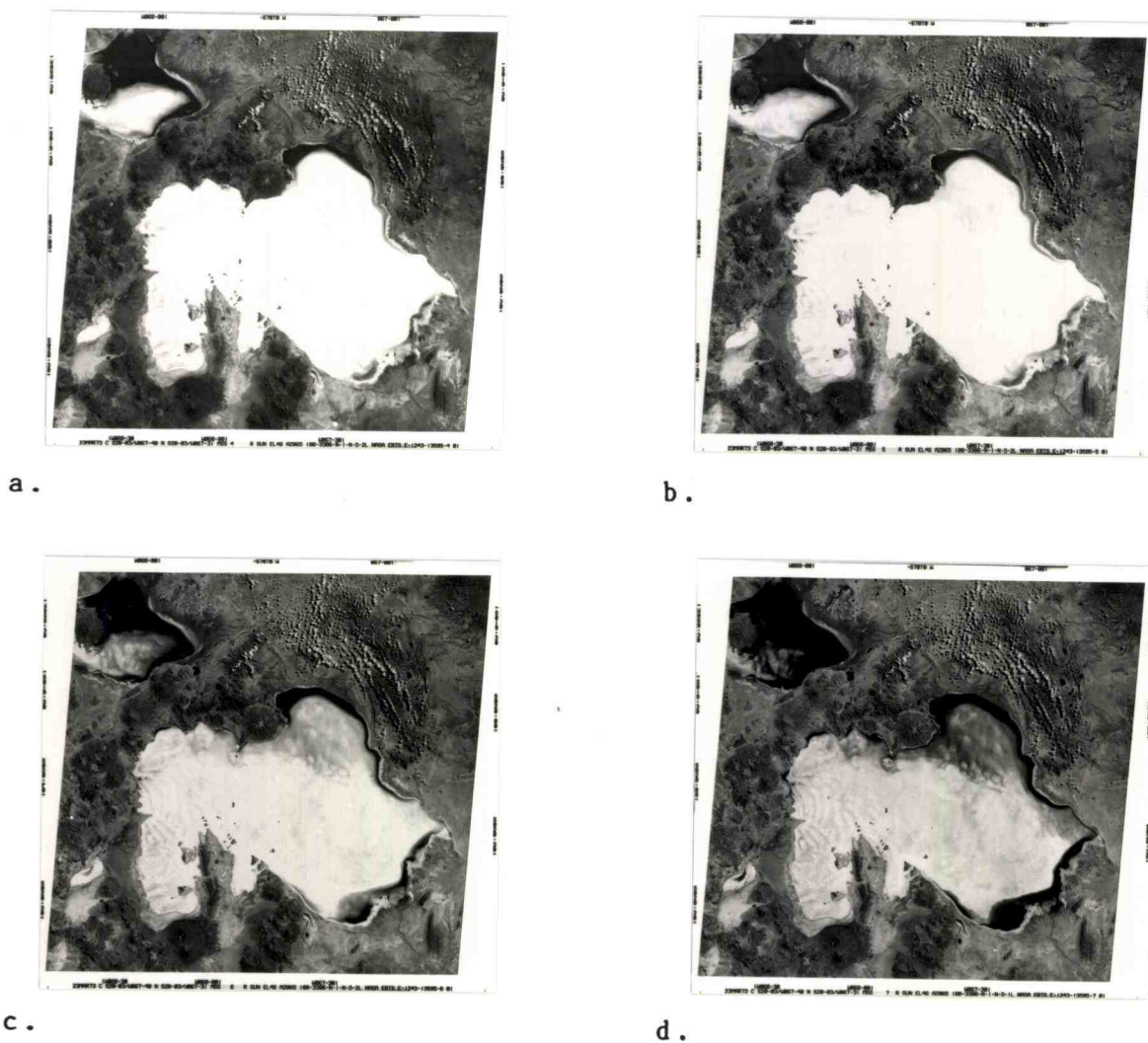


Figure 1. Black and white contact prints of the test image; a. Band 4; b. Band 5; c. Band 6; and d. Band 7.

RATIO THEORY AND COMPENSATION FOR ATMOSPHERIC EFFECTS

Digital band-ratioing has often been applied for the enhancement of digital image data (Avery and Berlin, 1986). Band-ratioing has been applied with particular success in the geologic sciences, being used to enhance subtle differences between surface materials (Rowan et al., 1974, Rowan and Lathram, 1980). Other uses include the removal of differential illumination and viewing angle effects, and a reduction in the number of input variables if classification is to be performed (Kriegler et al., 1969).

The digital ratio concept

The basic concept of the photographic technique is identical to that of digital band ratioing (Moik, 1980). A mathematical representation of the digital operation is:

$$DN_r = A * \frac{DN_{i,j}^a}{DN_{i,j}^b} + B$$

where $DN_{i,j}^a$ and $DN_{i,j}^b$ are the digital numbers at row i column j of bands a and b , and A and B are constants used to scale the resulting value DN_r to the desired output range (rewritten from Moik, 1980 and Gillespie, 1980). Since band ratioing increases interband noise and variation due to atmospheric effects, a

modified version of the equation:

$$DN_r = A * \frac{DN_{a,i,j} - S_a}{DN_{b,i,j} - S_b} + B$$

was derived (rewritten from Moik, 1980), where S_a and S_b represent a 'sky light' component which is subtracted to provide a first order compensation for atmospheric effects.

A photographic analogue

The photographic process substitutes the overlay of one positive transparency and one negative transparency for the digital arithmetic operation. "When a positive separation image of one color band is placed (in registration) over a negative separation image of another, the composite ratio mask displays densities proportional (logarithmically) to the ratio of the reflectances in the two spectral bands." (Lillesand and Kiefer, 1987) This process thus uses a positive-negative "sandwich" to produce a ratio modulation of light while exposing a photo-sensitive emulsion.

A mathematical representation of photographic band-ratioing was discussed by Malan (1976). By replacing the exposure component (the X axis) of a D-log E curve with reflectance, the density of a Landsat negative may be represented as:

$$D_a = A + \gamma * \log I_a$$

where A is a constant, γ is the slope of the film characteristic curve, and I_a equals the reflectance intensity in band a. A positive transparency may be represented in a similar form:

$$D_b = B - \gamma * \log I_b$$

where B is a constant and I_b equals the reflectance intensity in band b. From these equations and the fact that density is an additive quantity, a superimposed negative and positive may be represented as:

$$D_a + D_b = A + B + \gamma * (\log I_a - \log I_b)$$

$$\text{or: } D_a + D_b = C - \gamma * \log \frac{I_b}{I_a}$$

where D_a plus D_b equals a positive reproduction of the ratio of the intensities in band b to band a (Malan, 1976).

After several unsuccessful attempts, it was found that while the relationships described by Malan are correct, very strict process control is necessary for exact band-ratio reproduction. As indicated by Lockwood (1975), the process gamma of each separation must be exactly equal "to maintain the desired density-log exposure relationship when the separation is registered with the original transparency."

Photographic compensation for atmospheric effects

Photographic image data may be processed to compensate for atmospheric effects. Phillips (1974) discussed the correction of 70 mm MSS transparencies to equalize density and density ranges. It was indicated that atmospheric effects may have been the primary cause of intra-band density and density range variations. This technique, however, was rejected as being somewhat subjective, in that it relied on visual assessment of densities and density ranges. It was also considered to add too many process steps to the procedure under investigation.

The technique attempted for atmospheric correction is analogous to a digital method of atmospheric correction. The digital technique entails shifting the image histogram towards the y axis by subtracting the minimum reflectance value from each pixel (Chavez, 1975). The digital process is only one of subtraction, and does not alter the range of the distribution (analogous to the density range of a photographic image). The photographic process would thus necessarily rely on densitometry to in effect register the various bands at a common minimum density. Such processing requires precise control of photographic processing and thus an intimate familiarity with the mechanisms of latent image formation.

THEORY OF THE LATENT IMAGE

The theory of latent image formation is still in a state of evolution, which is not surprising, considering that photography itself is barely 150 years old. However, progress made in such closely related disciplines as physics and chemistry have helped contribute to a better understanding of photographic processes. One point which should be made, though, is that despite the sophisticated analytical techniques available in chemistry and physics, the latent or "developable" image still does not constitute a detectable alteration of a photographic emulsion. In this sense, even the most recent and detailed summaries of photographic theory acknowledge that there exist important gaps in current theory.

Despite the lack of a complete photographic theory, enough knowledge exists to provide a fairly detailed understanding of photographic image formation. Emulsion chemistry is of primary concern, in that it determines spectral sensitivity, radiometric sensitivity, and is the major influence on the final shape of the characteristic curve. Emulsion chemistry and the manufacture process also determines the basic physical state of the silver halide crystals. This, in combination with statistical probability, controls the sublatent and latent image formation of the emulsion. All these factors combine to determine the overall film system characteristics.

Emulsion Chemistry

Photographic emulsions usually consist of silver-bromide, -chloride, or -iodide, or more probably some combination of these three, suspended in a gelatin, modified gelatin, or synthetic polymer matrix. According to Mueller (1977), coprecipitates are usually preferred, as they "possess more lattice defects and imperfections which increase their photographic sensitivity." This accounts for the use of silver-iodide, which by itself is not very light sensitive, and silver-chloride, which is sensitive only to ultraviolet radiation. Their addition to silver-bromide (sensitivity to 400 to 500 nm) results in a mixture which is more spectrally and radiometrically sensitive than the sum of its components.

The sensitivity of these mixtures, as previously indicated, is still somewhat limited. This is remedied by the addition of chemical sensitizers. Sensitizers may be selected to extend the spectral sensitivity of the emulsion, and also to improve its speed and contrast characteristics. Such additives do not affect the graininess or resolving power of the film (Mueller, 1977). While chemical sensitizers are extensively used in emulsion production, the basics of photographic image formation are best explained in the context of silver halide chemistry and crystal lattice characteristics.

Consideration of the periodic table of elements indicates that the elements most frequently combined with silver - chlorine, bromine, and iodine, constitute part of group VIIA. That is, they occur in the same column and thus have similar

characteristics. Similarly, those elements sometimes used for emulsion sensitization - copper and (more commonly) gold, along with silver constitute part of group IB. The electron configurations of each of the group VIIA elements is such that five electrons exist in the outer subshell of each element where six would be preferred. Group IB elements possess one free electron in their outermost subshell. This relationship determines both the nature of the chemical bond and the preferred crystal structure.

Silver halides form an ionic bond which satisfies both the need of silver to lose one electron and the need of the halogen group to obtain one. This transfer of an electron results in a matrix of positive silver ions and negative halide ions, as depicted in an ideal state in Figure 2. Fortunately, other structures which deviate from this ideal are more common, for as previously indicated, the crystal imperfections are important to increased sensitivity of the emulsion.

Silver halide crystallite characteristics

Silver halides are commonly formed in cubic and less commonly in octahedral crystals. Figure 3 depicts the generalized

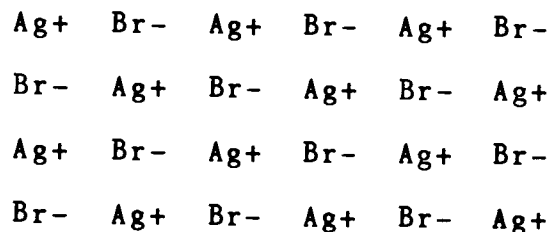


Figure 2. An ideal silver-bromine crystal lattice.

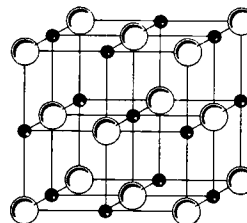


Figure 3. The cubic crystal structure of silver halide. (Hurlbut and Klein, 1977)

atomic arrangement of the cubic crystal structure. Such a structure surrounds each ion with six ions of opposite charge. This arrangement provides for an efficient transportation of charges

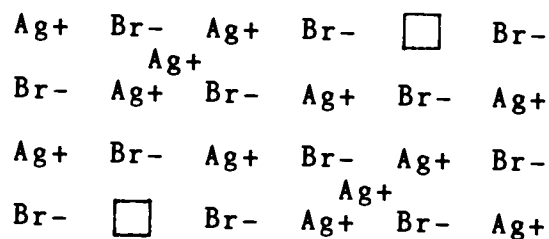


Figure 4. Point defects in a silver-bromine lattice.

through the crystal. The charges, in addition to those caused by photolysis, are the result of a variety of crystal imperfections, and the fact that surface ions cannot form complete bonds.

Common silver halide crystal imperfections include point defects, impurity defects, dislocations, and twinning (West, 1977). Point defects, depicted in Figure 4, occur when a silver ion is vacant from a point, or present at an interstitial point. Impurity defects result from materials present or introduced which substitute for an ion of silver or halide. Chemical sensitization in essence induces an impurity defect. Dislocations are structural defects in the crystal which result in an abrupt edge inconsistent with the surrounding ionic charges within the crystal. Twinning is the growth of a second crystal from a first along a line of inconsistent electron charges. All of these defects provide localized positive and negative charges which play an important role in sublatent image formation.

Sublatent image formation (nucleation)

The response of silver halide to exposure is determined by the laws of energy - matter interaction, silver halide chemistry,

silver halide crystal characteristics, and the distribution of the incident photons. When radiant energy strikes a silver halide crystal, photons are absorbed. On an individual level, an absorbed photon results in the excitation and liberation of an electron from the outer subshell of a bromine ion (Kowaliski, 1972). This liberation results in a negative charge (the free electron) and a positive charge (the "hole" left by the electron) which are both mobile within the crystal (Hamilton, 1977a). The two charges may recombine, but due to thermal energy are not able to remain together. The positive hole may combine with a silver ion vacancy, resulting in a free halide atom. Halogen production is a well documented aspect of silver halide exposure (Carroll, et al., 1980). The free electron provides the necessary charge for the reduction of ionic silver.

A free electron may combine with a silver ion in the crystal, or with an ion at the site of a crystal imperfection. The normal silver ion in the crystal is at a high energy level and thus will not preferentially bond with an individual electron. The ion at an imperfection site, though, is at a lower energy level due to its incomplete ionic bond, and the electron is therefore more stable at this site. This stability allows sufficient time for the attraction of a second interstitial silver ion. When a second free electron has been added, a sublatent image with a stability of several days has been formed. The sublatent image then acts as an integrator throughout the duration of the exposure.

Latent image formation (integration)

Latent image formation is simply a continuation of the process which occurred in nucleation. The sublatent image, which consists of at least two silver atoms, traps a third silver ion, and in turn a third free electron. When a fourth ion - electron pair have been trapped, a stable latent image is formed. This minimum accumulation (four Ag atoms) will continue to act as an integrator until the termination of the exposure, and will remain stable and developable for decades. Once this critical size has been attained, it will act as a center which may not only capture photoelectrons, but also electrons donated by the reducing agent in the developer.

Resulting system characteristics

The resulting system characteristics, as indicated by Slater (1980), are that of a gated multiquantum detector which behaves as a stable, high-gain integrating amplifier. The system is gated in that it responds to incident light above a certain threshold, and is not triggered by its own thermal noise. This results in a stable detector which acts as an integrator, i.e., it integrates the exposure given over a period of time. The high-gain aspect relates to that aspect of a latent image center which allows it to accept electrons from the developer. In this way, all the silver ions of a grain may be reduced, resulting in the commonly reported amplification factor of 10^9 .

MATERIALS AND METHODS

The photographic and methodological aspects of this work lend themselves to a division between black and white and color materials and methods. All initial preparation of transparencies from the original negatives was done using black and white materials. That is, the initial verification of the viability of this procedure (photographic band-ratioing) is in the black and white realm. The second step of testing various application techniques, should the black and white work prove viable, is more or less within the realm of color processing. This natural division thus provides the organization for the following section.

Materials for transparency production

The film used for transparency production was Kodak Aerographic Duplicating Film #4421 (7-mil Estar base). Chemicals used for processing included Kodak DK-50 developer, Kodak Indicator Stop, and Kodak Rapid Fix. The enlarger used as a point source was a Leitz Focomat model V35 with a Focotar f 2.8 40 mm enlarging lens, and a Beseler Audible/Repeating timer. The processor used was a Jobo model CPP 2 with lift. This processor provided digital temperature control, bidirectional rotation, and variable speed control. Density control was provided by Kodak T-14 density scales and a Photronix model 73 transmission densitometer.

Method of transparency production

The original images used for transparency production were 70 mm Landsat MSS negatives. From these negatives, two sets of contact prints were made on Ilford Multigrade black and white paper. One set was over exposed, and one set under exposed, to aid in the determination of maximum and minimum reflectance areas. Over exposed prints were used to determine negative D-max areas, and under exposed prints were used to determine negative D-min areas. From each of these prints the three highest and lowest density areas were selected for precise D-max and D-min determination.

Density readings were made directly from the original 70 mm negatives. Three readings were made in each high and low density area. Averages of these readings for each area determined the minimum and maximum negative density values. Table 1 lists the minimum, maximum, and density ranges for each band.

Darkroom work began with the plotting of characteristic

TABLE 1. MIN, MAX, AND DENSITY RANGE FOR ORIGINAL MSS NEGATIVES

| Band | D-Min | D-Max | D-Range |
|------|-------|-------|---------|
| 4 | 1.5 | 2.3 | .80 |
| 5 | 1.5 | 2.25 | .75 |
| 6 | 1.2 | 2.2 | 1.0 |
| 7 | .67 | 2.2 | 1.53 |

(all figures in density units)

curves for the Kodak 4421 film / DK-50 developer combination. Test strips were exposed through a T-14 scale and processed, then density readings made and input/output curves plotted according to the method discussed by Todd and Zakia (1974). Characteristic curves were determined for exposure times of 20 seconds @ f 2.8 with a 1/2 meter lens to copy distance and 6 seconds @ f 2.8 with a 1/4 meter lens to copy distance. The latter curve is displayed in Figure 5 (see also Appendix B). In this way process time and temperature could be manipulated to provide the desired gamma of 1 and maximum straight line portion of the curve. The length of this portion had to equal or exceed the greatest image density range. Had this not been the case, the image data would have been distorted by the nonlinearity of the characteristic curve.

Once the film characteristics had been determined, exposure of the images could begin. From the density readings listed in Table 1, approximate exposure times were estimated to produce a maximum density of 2.1 for each of the four bands. This density was selected so the maximum density range (Band 7, 1.53) would fit on the curve (in this case down to .57) without extending over the straight line portion and distorting the data. Band 7 was exposed first, the maximum density read, and the exposure adjusted to achieve a 2.1 maximum density. Both D-min and D-max

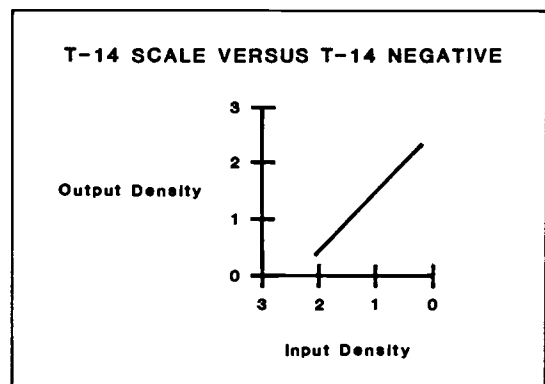


Figure 5. Characteristic curve for Kodak 4421, 3.25 minute development in DK-50.

values were monitored to ensure that the original density range was not being altered. Once an exact exposure was made for Band 7, the Band 6 estimate was revised, and the process continued.

At this point an uncontrollable variable was introduced in the procedure. The D-min value of the Band 6 negative was 1.2, almost double the D-min density of Band 7. This necessitated a large increase in exposure time, since the lens was at maximum aperture, and only 1/4 meter from the copy. When the Band 6 positives were processed, the original density range was found to have been altered. This seemed to indicate that photographic compensation for atmospheric effects on MSS images was either not possible, or that it would require an approach other than the one being attempted.

RESULTS AND DISCUSSION

The data listed in Table 2 indicates that the Band 6 density range was altered by the exposure increase required to provide the desired D-max value of 2.10. This conclusion may be drawn from the fact that other pertinent variables; emulsion type, developer type, developer concentration, development time, process temperature, and agitation rate were carefully held constant. Because of the high density of the original negative and the resulting long exposure time required for D-max registration, low intensity reciprocity failure was the probable cause.

Reciprocity is defined in photography as the relationship between exposure time and intensity which determines the total exposure. The reciprocal nature of this relationship is best exemplified by the f-stop shutter speed relationship. Thus an exposure of 1/125th second at f 5.6 is equal to an exposure of 1/250th second at f 4, or 1/60th of a second at f 8. In other words, to increase one parameter while decreasing the other, each by a factor of two, results in the same total exposure.

Reciprocity failure, as the name implies, is a condition

TABLE 2. MIN, MAX, DENSITY RANGE, AND
PROCESS TIMES FOR POSITIVE SEPARATIONS

| Band | E-Time | Dev-Time | D-Min | D-Max | D-Range |
|------|--------|----------|-------|-------|---------|
| 7 | 15 sec | 3.25 min | .53 | 2.10 | 1.57 |
| 6 | 46 sec | 3.25 min | .84 | 2.10 | 1.26 |

(all figures in density units unless labeled otherwise)

where the reciprocal relationship between exposure intensity and time break down. This results from the need of an emulsion to be exposed within a certain range of light intensity values (Davis, 1980). If the exposure intensity does not fall within the required range, high or low intensity reciprocity failure results.

Low intensity reciprocity failure

Returning to the photographic theory discussed earlier in this paper, some of the possible causes of low intensity reciprocity failure may be suggested. It has been found that during a low intensity exposure, a small number of relatively large latent image centers form (Hamilton, 1977b). This implies that low intensity exposures result in inefficient nucleation but efficient growth. West (1977) discussed two possible causes for this phenomenon. One is related to the influence of thermal energy in latent image formation. The other is related to halogen production induced by exposure.

The sublatent image center formed by the absorption of one photon will quickly dissociate due to thermal energy. As the exposure intensity is decreased, the likelihood of a second absorption occurring within the necessary time (prior to dissociation) also decreases. This results in the reported inefficiency of nucleation while growth remains efficient. Those image centers which do form encounter less "competition" for free electrons. This explanation of low intensity reciprocity failure

is very consistent with image formation theory.

A second potential source of low intensity reciprocity failure is the exposure induced production of halogen. Silver reduction during exposure results in free halogen which diffuses to surrounding silver atoms and latent image centers. These halogen atoms inhibit nucleation by combining with silver atoms. While halogen is produced during normal exposures, the increased number of photons (and thus free electrons) and decreased exposure time override the halogen induced suppressed nucleation.

Depending upon the application, low intensity reciprocity failure may be compensated for or even tolerated. In an application such as this, the alteration of film parameters is not tolerable. Compensation factors for reciprocity failure have been published by Eastman Kodak (see Table 3). These factors are very general, and would require a great deal of time to fine

TABLE 3. RECIPROCITY
CORRECTION FACTORS

| If Indicated Exposure Time Is (Seconds) | Use | | And in Either Case Use This Development Adjustment |
|---|--|---|---|
| | Either This Lens Aperture Adjustment | OR This Adjusted Exposure Time (Seconds) | |
| 1/100,000 | +1 stop | No Adjustment | +20% |
| 1/10,000 | +1/2 stop | No Adjustment | +15% |
| 1/1,000 | None | No Adjustment | +10% |
| 1/100 | None | No Adjustment | None |
| 1/10 | None | No Adjustment | None |
| 1 | +1 stop | 2 | -10% |
| 10 | +2 stops | 50 | -20% |
| 100 | +3 stops | 1200 | -30% |

(Eastman Kodak, 1980)

tune. Even this process would most likely be unacceptable.

Even finely tuned compensation of exposure and process times would probably result in undesired data alteration. According to Adams (1981):

The reciprocity effect is not identical throughout the scale of negative densities. For a long exposure, the low values tend to be affected (i.e., underexposed) more than the high values, causing a decrease in their density, and there is thus an increase in contrast in the negative. It is therefore necessary to decrease development as suggested in the chart to avoid excessive contrast.

This indicates that there are no processing corrections which could compensate precisely for reciprocity failure. Although process alternatives are not viable, other alternatives do exist.

CONCLUSION

In conclusion, an attempt was made to develop a photographic technique for the production of photographic band-ratios. The associated requirement of photographically compensating for atmospheric effects has proven difficult to achieve. While the desired results were not obtained, a variety of further work has become apparent. Future work could either be based on correcting this technique, or using a less theoretically strenuous version for image enhancement.

Recommendations for procedural revisions

A number of procedural revisions remain untried. The most direct way to avoid low intensity reciprocity failure is to increase the exposure intensity. A related possibility is to increase radiometric sensitivity by selecting a different emulsion. A third alternative would be to increase the radiometric sensitivity of the emulsion by chemical or photolytic means. Some combination of these could prove to be the only viable approach.

Increasing the exposure intensity in this case would perhaps be an easy and workable solution. Since the enlarger is used only as a point source, any custom light source could be used. A 500 watt photoflood could in itself be a solution. Even a bank of lights could easily be constructed and wired to a timer. This would allow the continued use of Kodak 4421 film, which proved to be very appropriate for this type of work.

The selection of a more sensitive film could also help avoid reciprocity failure. The trade off with greater sensitivity is of course an increase in emulsion grain size. Standard sheet films may simply have inadequate sensitivity for this type of application. In that case hypersensitization could be used.

The sensitivity of photographic emulsions can be increased by chemical treatment or preexposure. Chemical treatment requires the use of a special developer, special baths during development, or additives to the normal developer. Such fooling around could result in a variety of alterations to the film characteristic curve. Preexposure is a possible alternative. Preexposure helps to begin the nucleation process, which is inefficient in low intensity reciprocity failure. Determination of preexposure parameters as a function of negative density, though, would be a time consuming procedure.

Recommendations for related work

Work with fewer theoretical constraints would constitute a second group of alternatives. These have been investigated by Silvestro (1967) and Weller (1970). Silvestro used positive and negative film combinations to expose a high contrast black and white film. The black and white "bi-polar mask" was then used to generate enhanced print products. Weller used slightly offset positive and negative film combinations to produce black and white prints. Those prints were found to possess many of the

desirable characteristics of ratio images.

Unfortunately, the field of photographic image processing in the earth sciences has received little attention or financial support. The only attempt at summarization within this area is a text chapter by Skaley (1980). This leaves a great deal of work to be done in technique development, and in the review and synthesis of available techniques. As previously indicated, the practical advantages of photographic work are relevant in both technologically advanced nations and those with lesser capital and technological resources.

Only with the appreciation of signal processing and the close relationship of all image data can this situation be changed. The default abdication of image interpretation to computer algorithms may prove a form of intellectual myopia. An informed balance of options, based on a variety of techniques, can only enhance the probability of project success.

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APPENDIX A

GLOSSARY

Characteristic curve: Graph of input/output relationship for a photosensitive material between exposure and resulting density. Also known as D Log-E curve or H & D curve.

Density: The logarithm of opacity.

Density range: D-max minus D-min. Sometimes considered to be "useable" density range (i.e. not including pure white or pure black).

Developability: Condition of a silver halide grain having absorbed a sufficient number of photons to induce first nucleation and then integration of silver atoms. May be considered statistically as having a greater than .5 probability of development. See latent image.

D-max: Maximum density. Sometimes considered to be maximum "useable" density.

D-min: Minimum density. Sometimes considered to be minimum "useable" density.

Emulsion: Matrix of silver halide grains, usually a mixture of chloride, bromide, and iodide, suspended in gelatin.

Exposure: Product of light intensity and duration.

Gamma: Slope of the straight-line portion of the characteristic curve.

High intensity reciprocity failure: Reciprocity failure resulting from an exposure of short duration and high irradiance.

Integrator: The stable state of four or more silver atoms which then act as integrators during the remainder of the exposure. They also constitute the sites of initial development. See subimage center.

Irradiance: Intensity of light during exposure.

Latent image: The nondetectable, stable state of a silver halide grain provided sufficient exposure to alter the probability of development from less than .5 to greater than .5.

Latent image center: The initial site(s) of ionic silver reduction with electrons freed by photon absorption.

Low intensity reciprocity failure: Reciprocity failure resulting

from an exposure of long duration and low irradiance.

Nucleation: The formation of a stable silver atom pair, each formed from a silver ion and a free electron by the energy of an absorbed photon.

Opacity: The reciprocal of transmittance.

Photolysis: A chemical decomposition due to the action of incident radiation.

Photon: A quantum of radiant energy, emphasizes the particle like behavior of radiant energy.

Quantum: The basic unit of radiant energy of magnitude $h\nu$, where h is Planck's constant and ν is frequency.

Reciprocity failure: The breakdown of the reciprocal relationship between exposure intensity and duration. Results in decreased emulsion sensitivity and altered characteristic curve.

Subimage center: Site(s) of initial silver ion reduction with electrons facilitated by photon absorption. These sites act as integrators during the continued exposure.

Sublatent image: The first stage of latent image formation. Consists of two silver atoms, each formed by the combination of a silver ion and a free electron. Stable for a period of days, yet does not constitute a developable image.

Transmittance: The amount of light transmitted through a negative divided by the total amount of light.

APPENDIX B

T-14 SCALE VERSUS T-14 NEGATIVE

