Basic Concepts of Computerized Digital Image Processing for Geologists

GEOLOGICAL SURVEY BULLETIN 1462

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By CHRISTOPHER D. CONDIT *and* PAT S. CHAVEZ, JR.

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Descriptive introduction to the terms and basic concepts of a computerized digital image processing system designed for geologic research

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[Plates are in pocket]

GLOSSARY OF TERMS

The terms in this glossary are defined specifically as they apply to digital image processing. The definitions are thus in many instances incomplete, in that other meanings for the terms are possible. Many terms are explained more completely in the text, within the context of their meaning. The Manual of Remote Sensing (Reeves, 1975, p. 2061–2110) and the Dictionary of Scientific and Technical Terms (Lapedes, 1974) provide more complete definitions.

albedo (Janza, 1975): The ratio of total radiant energy returned by a body to the total solar radiant energy incident on a body.

aspect ratio distortion: A difference in spatial scale that exists within an image (geometric distortion) such that within an uncorrected Landsat image, features are longer (because they are imaged at a higher resolution) in the horizontal direction than they are in the vertical direction.

assembler language: A machine-oriented language in which the user must take into account the characteristics of the machine to write a program. An efficient language for program execution.

atmospheric scattering (Lapedes, 1974): A change in the direction of propagation, frequency, or polarization of electromagnetic radiation caused by interaction with atoms of the atmosphere. Also called haze.

batch input callup procedure: A set of instructions given to the computer to follow a sequence of commands contained in a specific data set, for example, a deck of computer cards. Also referred to as batch mode or batch processing.

binary arithmetic shifts: An assembler language instruction that is used to multiply or divide by two and is implemented as a shift of the decimal point position in the computer registers.

bit: A single binary digit, which is either a one or zero. An analogy could be made to a switch which is either on (one) or off (zero). A collection of eight binary digits is termed a *byte;* the sequence of bit values allow the programmer to express a number. A byte is equal to eight bits, with possible values between 0 and 255.

central processing unit: Control, logic, and arithmetic unit of the computer. Controls the sequence of computer operations. Also referred to as C.P.U.

color composite: Image in which three black and white images, with reflectance values expressed in gray tones, are each assigned a color (blue, green or red) so that reflectance values are expressed in hue saturation. The three monochrome images are then combined or composited into a single polychrome image to produce either a false, artificial, simulated natural, ratio, or hybrid color product.

colorimetric variations: Changes in both the intensity and wavelengths of light.

computerized automated interpretation: Various methods used by a computer to recognize a specific spectral signature of a pixel and to assign it to one of several selected classes.

core: High-speed, random access memory of a computer.

digital image: A two-dimensional array of positive integers that correspond to discrete spectral reflectivity values arranged in a checkerboard pattern over a target area. See p. 3.

digital imaging system: A combination of instruments that measure radiation reflected from a target and translates its intensity into an electronic signal which is recorded as a digital value on a pre-selected scale.

digital number: An integer value related to the brightness (or intensity of radiation) for an area within an image. The value falls within a preselected range; for example, Landsat data is manipulated in eight-bit format, with values from 0 to 255 possible. Shortened to DN value.

disk storage device: A high-speed storage device that provides direct access to large numbers of data.

dropped line: A line or horizontal row of picture elements that is missing from an image.

filtering: A technique that allows the user to enhance either large patterns (low-pass filtering) or detail (high-pass filtering) within an image. A low-pass filter is the neighborhood average (defined by user as n × m pixels) of DN values around a particular pixel; a high-pass filter is the original DN value of the pixel minus the low-pass filter or neighborhood average DN value around the pixel. See p. 6.

frequency histogram: A tabulation that summarizes the number of picture elements occurring at each gray tone or digital number value within an image. See plate 3A-C.

geometric distortion: A misrepresentation of the spatial relationship of features within an image.

input/output device (Lapedes, 1974): A unit that accepts new data, sends them into the computer for processing, receives the results, and translates them into a usable medium.

list: Printed array of digital numbers. The position of the digital number in the array corresponds directly to the position of the pixel in the image. The number corresponds to the gray tone of the picture element. See figure 4.

look-up tables: Array of precalculated data arranged so that answers to multiplication, division, and other time-consuming computations can be obtained from the array by the use of indexing answers as a function of brightness values.

mosaicking: The process of fitting digital images together within a computer.

noise: Spurious spectral reflectance values that are not received from the target but rather introduced by the detector, by digital recording, and by data transmission, reception, and reduction instruments. Can be divided into two types: coherent noise, which has a systematic pattern, and random noise, which has no pattern.

photometry (Lapedes, 1974): The calculation and measurement of quantities describing light***such as luminous intensity, light distribution***.

pixel: Contraction of "picture element". A digital representation of the electromagnetic radiation from the smallest area measured by the detectors. In hard copy, the digital representation appears as a gray shaded square, with the gray tone corresponding to the amount of radiation received in that area.

ratioing: The process of dividing each picture element in one image (or band) by the corresponding picture element digital number of another band.

saturation: The condition in which a further increase or decrease in radiation produces no further increase or decrease in recorded radiation.

scanners: Instrument systems that measure and record the intensity of radiation reflected from a target. Also referred to as *detectors*. Scanners do not acquire the entire digital image simultaneously, as does a standard camera system, but instead record a scene by sequential scans over a period of n seconds.

single point perspective: The spatial relation that features within an image will appear to have if the entire target were photographed instantaneously, that is, from one point.

solar illumination angle: The altitude of the sun, measured in degrees of angular distance from the horizon as seen from the target (0° = horizon, 90° = solar zenith). Also referred to as sun elevation, sun angle, or illumination angle.

spectral bands: Preselected parts of the electromagnetic spectrum. Usually selected by eliminating all other parts of the spectrum by filtering or allowing only a given frequency or range of wavelengths to reach a scanner or recording system.

spectral reflectance (Janza, 1975): Ratio of reflected power to the total power incident or incoming to the surface per unit area of irradiated surface (at a specific wavelength).

stretching: A computer technique that allows the user to change the contrast by either increasing or decreasing the DN range of an image. Also referred to as contrast stretching. See p. 5.

ultraviolet spectrometer: Instrument designed to collect spectra in the wavelength range 0.11–0.34 μm.

BASIC CONCEPTS OF COMPUTERIZED DIGITAL IMAGE PROCESSING FOR GEOLOGISTS

By CHRISTOPHER D. CONDIT AND PAT S. CHAVEZ, JR.

ABSTRACT

Computerized processing of digital images, when used to maximize image content and quality for direct interpretation by the analyst, has proved a valuable tool for geologic research.

A digital image can be described as a two-dimensional array of integer values that correspond to discrete spectral reflectivity values arranged in a checkerboard pattern over a target area. Such an image, when recorded on magnetic tape, has a much greater dynamic range than its photographic equivalent and can be manipulated with a computer into a format usable without a machine.

Image processing tools used in this manipulation can be divided into four basic groups: (1) utility programs, which are used as diagnostic tools to derive numerical information from the image in magnetic tape form and to alter tape formats; (2) image correction techniques, which are designed to remove noise, replace lost lines of data, correct for variations in sun angle, remove the effects of atmospheric haze, correct geometry, and transform images into the desired cartographic formats; (3) enhancement techniques, which enable the user to change the contrast of an image and to emphasize either large or small-scale features within the image; and (4) multispectral techniques, which allow the user to display data collected in several spectral ranges as color digital images.

Devices and techniques exist to translate these magnetic tape data to both black and white and color hard-copy images. Five products commonly derived from multispectral data are: false color, artificial color, simulated natural color, color ratios, and hybrid color. The relative usefulness of each product depends upon the geologic problem.

INTRODUCTION

Systems that record images in digital format on magnetic tape, rather than on film, are becoming increasingly common. The geologic application of computerized processing of digital images, however, has been hampered because most computer systems are not designed for direct application to geologic research and because there is little communication between workers in geology and workers in image processing. This paper describes a computer system designed for geologic research by the U.S. Geological Survey in Flagstaff, Ariz. and provides the geologist with some insight into the application of image processing techniques as an aid to geologic research. Computerized digital image processing, like many other branches of science, has developed a peculiar terminology. In describing this subject the use of terminology in unavoidable; thus many terms are defined in a glossary and are italicized where first used.

Currently, two basic approaches prevail in the field of image processing. The first, commonly used in agriculture, forestry, land-use, and other environmental studies, stresses techniques involving *computerized automated interpretation* by the computer. The second approach, described in this paper, maximizes image content and quality for direct use by the analyst, with no computerized automated interpretation. This approach leaves photographic analysis, interpretation, and inductive reasoning to the geologist. The primary reasons for minimizing automated interpretation are that the images contain random, coherent, and natural (that is, vegetation and cultural effects) *noise* that are easily misinterpreted by automated interpretive techniques to be geologic features. In addition, geologic components are extremely complex in form and relation, and mixtures of materials are more common than pure components. With such complexity, the application of automated interpretation and classification to geologic research has been very difficult and often unsuccessful. The technique of maximizing image content and quality used by the U.S. Geological Survey in Flagstaff, Ariz., is similar to that used by the ILP (Image Processing Laboratory) of the JPL (Jet Propulsion Laboratory) in Pasadena, Calif. (Goetz and others, 1975).

Acknowledgments.—Three members of the U.S. Geological Survey warrant special acknowledgment: Alex V. Acosta, for his creation of quick, efficient assembler language software used in the filter, stretch, and input/output routines; Lynda Sowers, for her help in handling processing requests, from set-up to computer execution; and Eric Eliason, for his comments and programming help.

ORIGIN OF IMAGE PROCESSING

The basic techniques used to generate high-quality images from digital data were originally developed to process spacecraft images of Mars. These images represented one experiment that was included among others on the Mariners 4, 6, 7 and 9 missions. These *digital images* have a dynamic range (sensitivity) from 10 to 50 times that of the eye. Thus in raw format, only a small part of the data is available to the eye. In order to derive the maximum information available from the digital images, techniques were developed first at IPL/JPL and later at the U.S. Geological Survey to extract these data and put them into an optimally interpretable format for the human eye (Levinthal and others, 1973, Batson, 1973).

One of the basic problems that arose in processing the Mariner images was caused by coherent and random noise introduced by the detector, by digital recording, and by data transmission, reception, and reduction systems. Most of the processes used to enhance digital images will also enhance noise, thereby seriously degrading the quality of the final image. Therefore, major efforts were undertaken to develop image processing techniques to remove the noise (Rindfleisch and others, 1971; Chavez and Soderblom, 1975). After these clean-up procedures were applied to create noise-free data bases, other techniques were used to improve the images further, including techniques for removing effects of variation in *solar illumination angle* and for correcting geometry. The image was then processed to enhance fine detail (high-pass *filtering*) or *albedo* variations (low-pass filtering) and to enhance contrast (*stretching*).

Most of the image-processing techniques developed for Mariner 9 images were easily modified for application to Landsat (formerly ERTS, or Earth Resources Technology Satellite) data, although some alteration was necessary because of the much larger image data sets. Landsat data were acquired in four spectral bands (bands 4, 5, 6, and 7, respectively, 0.5 to 0.6, 0.6 to 0.7, 0.7 to 0.8, and 0.8 to 1.1μm). Each Landsat image contains roughly 60 times more data than a Mariner image. Although new problems were introduced because of this larger data set, the final product contains much more information than that available from Mariner 9 data.

BASIC CONCEPTS

THE DIGITAL IMAGE

A digital image, as it is handled in the computer, can be described as a two-dimensional array of integer values. Each value, referred to as a picture element or *pixel,* represents the average brightness in the image at one location. The horizontal rows of pixels are referred to as lines, and the vertical columns as samples. In standard notation the upper left element is line 1, sample 1. On black and white film, the digital image appears as a checkerboard pattern of rectangles of different shades of gray (fig. 1). Each shade corresponds to the numerical value of the pixel at the same location in the array of integer values.

Most digitized images are made up of several hundred to several thousand lines and samples. If an image is enlarged too much, the eye tends to dwell on individual pixels instead of integrating the pixels into a pattern. In a Landsat image to which no geometric cor-

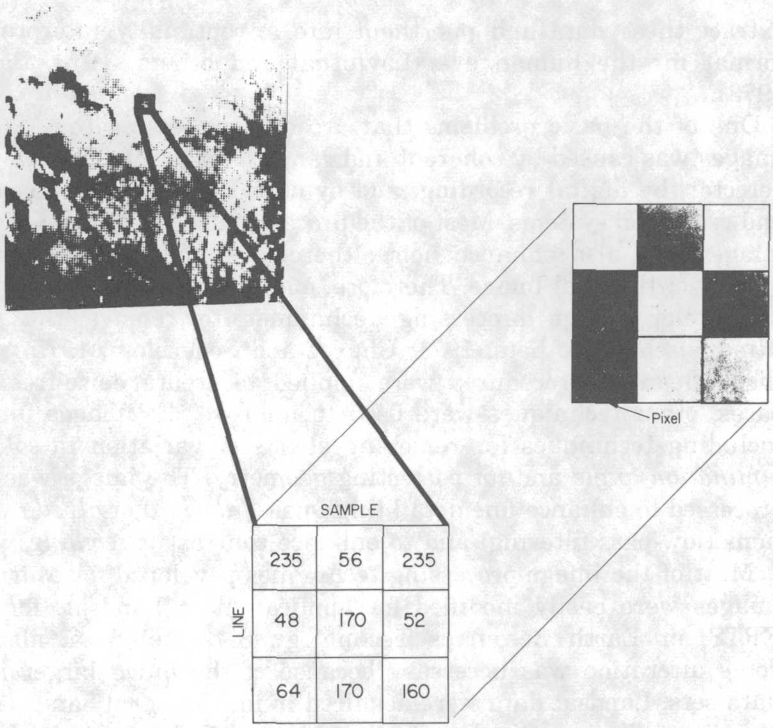

FIGURE 1. Relations between pixel brightness (gray levels) on hard copy print and values of DN (digital numbers) on magnetic tape for a digital image.

rections have been made, each pixel represents an area of the Earth's surface approximately 57 × 79 m; the total image is approximately 185 km on a side and is composed of about 2,340 lines and 3,240 samples, or 7.5 million pixels. The Landsat imaging system has six *scanners* (or detectors) for each spectral band; these scanners sweep an area of the target perpendicular to the spacecraft's path (cross track), collecting six lines of data per sweep. There are more samples than lines in the raw Landsat data because resolution is better in the cross-track direction (57 m) than the along-track direction (79 m), and this results in an *aspect ratio distortion* (rectangular pixels).

A digital imaging system measures the detected radiation within a specified spectral range (band) from each of many small areas collected in a predetermined pixel array format. Each pixel is assigned an integer value, termed a DN *(digital number)* that is related to the brightness of that area within the image. The integers fall within a discrete range. For instance, recorded in eight-*bit* format, the data range from 0 to 255, or 2^8 levels (0 = black or absence of radiation, 255 = white or *saturation* when dealing with black and white images).

For most images, the DN values can be recorded on magnetic tape, one line at a time. Each line within the image is called a record, and the lines are grouped together in a file. The number of files or images that can be recorded on one magnetic tape depends on the number of pixels in each image. An image that is to be enhanced is first transferred from tape to a *disk storage device*. After program execution, the image is transferred to another tape, and the original data are thus preserved.

BASIC ENHANCEMENT TECHNIQUES

Two basic techniques are used in image processing to enhance a digital image—stretching and filtering. The first changes the DN value of a pixel as a function of brightness independently of the nearby pixel values, thereby changing the contrast of an image. The second technique changes the value of a pixel as a function of the values of neighboring pixels; enhancement of detail relative to larger features is based on this technique.

Before an image is enhanced as a function of DN value, it is necessary to establish the numerical range and variation of its DN values. The primary tools used are numerical lists and *frequency histograms*. On a typical unenhanced image (pl. 1*A*), each of the pixels falls within one of seven gray levels within the upper 15 percent of the brightness range 0 to 255. When this image is enlarged (pl. 1*B*), the outlines of individual pixels become apparent. A *list* of part of this enlarged image is a printed array of DN values (pl. 2*A*). The position of the DN value in the list corresponds directly to the position of the pixel in the image. A frequency histogram (pl. 3*A*) of the entire image in plate 1*A* shows the relative percentage of pixels at each of seven gray levels (DN values). The largest percentage of pixels (51.08 percent at DN value 210) is shown as 100 percent, and the other percentages are normalized to this value.

The seven DN values presented in plate 3*A* are all very high (or bright); hence the contrast is low and little information is transmitted to the eye as can be seen on plate 1*A*. A simple technique (which operates on each pixel independently) to increase the image contrast is to reassign the brightness values by spreading them out over the entire available range. Plate 1*C* and 1*D* are products of a contrast stretch, obtained using the digital data that produced plate 1*A* and 1*B* as input to the stretch program. Reassignment of values is done by creating a conversion table. For example, an input value of DN 198 would be reassigned to an output of DN 32, DN 202 to DN 68, DN 210 (the midpoint in the input histogram) to DN 127 (the mid-range point of eight-bit data), and so on (pls. *2B* and *3B*). All other intermediate values are reassigned to proportionally spaced output DN values (pl. *3B*). More detail is visible in the stretched images even though there are still only seven gray levels.

The user must be careful because if the spread of the input DN values is very small, the image can be overstretched—that is, the contrast increased so much that it results in a blocky pattern (pl. *1C* and *1D*). The small range of input DN values (seven) when reassigned to output values has created large gaps in the output gray tones of the image (pls. *2B* and *3B*) because there are still the same number of gray levels.

A second technique called filtering, in which a pixel is changed as a function of a predetermined surrounding array of pixels, can be applied to the blocky data in plate *1C* and *1D* to smooth them into a more visually interpretable image. Filtering in this example is used to smooth (or defocus) the data (low-pass filtering). It can, however, be used to sharpen or amplify detail in the image (high-pass filtering). Detail is enhanced by first generating a smoothed image and subtracting it from the original image. The difference isolates the details (or high frequencies).

The size of the array of pixels examined in any filter has a profound effect on the final product. In a low-pass filter, features that are generally larger than the array examined will be enhanced, whereas in a high-pass filter features smaller than the array are enhanced. The size of the array of pixels is defined by the user in terms of a number of lines and samples. These numbers must be odd, but not necessarily equal so that the array in the line and sample direction is symmetrical around a central pixel.

After an image has been contrast stretched (pl. *1C* and *1D*) to better utilize the dynamic range of gray levels available, it can be smoothed (pl. *1E and 1F*) to increase the interpretability of the image. In this example of low-pass filtering (pl. *1E*), the neighborhood has been defined as three lines by three samples so that the total number of pixel values averaged around the central pixel is nine. Examination of the pixel at line 19, sample 663 in a list of the input data (pl. *2B*) reveals the average of its DN value and the DN values of its eight neighbors will be 169, as shown at the same line and sample location in the output data list (pl. *2C*). A new DN value is calculated for each pixel in the input data set, proceeding from left to right, top to bottom. This is a nonrecursive filter, which means that each time a new DN is calculated for a pixel, only the DN values of the original unchanged data set are considered. A comparison of a photographically enlarged part of the smoothed image (pl. *1F*) with a similarly enlarged part of the input image (pl. *1D*) will show that the boxlike or blocky pattern has been smoothed, resulting in the appearance of three small craters that were uninterpretable to the eye in the input image. This smoothing is the result of spreading the seven gray levels in the input data set (pls. 2*B* and 3*B*) over most of the dynamic range of gray levels (pls. 2*C* and 3*C*). The histogram for the filtered image (pl. 3*C*) displays a general bell-shaped curve, or Gaussian distribution of pixels over DN values with large fluctuations between adjacent DN values. This fluctuation in values is a result of incomplete filling of the large gaps between the stretched seven DN values. In order to smooth the image further, a second 3×3 pixel low-pass filter might be applied, which would result in a more continuous distribution of pixels over the gray level range.

OPTIMIZING PRINCIPLES FOR IMAGE PROCESSING OPERATIONS

The filtering routine shown in plate 2*C* demonstrates several principles and limitations of image processing. Because there are millions of repetitious operations, time-consuming mathematical operations within a computer such as division and multiplication are avoided by using *look-up tables* and *binary arithmetic shifts* in *assembler language*. Also, in an effort to minimize processing time and computer core usage, integer math is used on pixel DN values wherever possible. Thus, although the average DN value of the pixels surrounding pixel 19,663 (pl. 2*B*) is actually 169.66, the value is truncated to 169. If an image is to undergo many processing routines, errors introduced by integer truncation can be minimized if more bits per pixel are used. This increase in bits will make available a larger range of integer values for output assignments from a given operation. For example, in six-bit format (a range of 0–63), a computer value of 8.6 and 9.3 would be assigned to integer values of 8 and 9, respectively, whereas in eight-bit format (0–255), an equivalent six-bit value of 8.6 would be represented by 34 and 9.3 by 37.

PRODUCTION OF HARD COPY

Many devices are used in the production of hard copy digital images. Most transfer data from magnetic tape to black and white photographic film transparencies (for example, CRT (cathode ray tube), facsimile, and laser devices). The U.S. Geological Survey in Flagstaff uses an Optronics Photowrite P–1500 System[1] which is described here as an example of one of these devices. The P–1500 tape-to-film converter consists of three basic pieces of equipment: a tape drive and computer, a LED (light emitting diode), and rotating

[1]Use of trade names is for descriptive purposes only and does not constitute an endorsement of the products by the U.S. Geological Survey.

drum on which black and white photographic film is mounted. The LED is mounted on a rotating screw shaft and oriented so that it can expose the drum-mounted film. As the drum turns, the LED advances down the shaft to expose as much of the film as the computer has commanded. The computer reads the magnetic tape one line (that is, one record) at a time and commands the LED to transmit the correct amount of light corresponding to each pixel, one pixel at a time, thereby exposing the film. This film is then processed by standard darkroom photographic techniques to a finished negative. This procedure is the opposite of that for satellite data collection in that the DN values are translated from magnetic tape to voltage values and then to light intensities with which the LED exposes the film.

COLOR DIGITAL IMAGES

Multispectral digital images have a wide dynamic range because they are produced by simultaneously scanning many discrete parts of the spectrum; each scan very sensitively records radiation levels within these preselected bands. Because the eye is more sensitive to changes in color than to changes in gray level (brightness), much of the dynamic range of the data will be lost if they are displayed only in black and white. Therefore, techniques have been developed to combine black and white film output from three spectral bands into a single-color digital image (a *color composite).*

Using additive techniques, color can be constructed with three components, such as various proportions of blue, green, and red (for example, yellow is composed of roughly an equal amount of red and green with little or no blue; white is composed of equal amounts of all three). Proportions of these three components are mixed in two steps in image processing. First, the digital images are recorded on a black and white film positive (commonly termed internegatives), with one internegative for each of the three colors. Next, these internegatives are alined (registered) precisely upon one another, so that corresponding pixels are overlaid. The three internegatives are punch-registered together with a piece of unexposed color-transparent film. The internegatives are then contact printed, one at a time, onto the color film using blue, green, and red filtered light.

THE IMAGE PROCESSING COMPUTER

An image processing computer differs in design from the general-purpose scientific computer. Each image processing task involves relatively simple, highly repetitive operations on vast amounts of image data. This type of task can be performed efficiently using a relatively limited amount of core and a small *central processing unit.*

The use of such a core and processor combination keeps down the cost of computer time. The large amounts of data are dealt with most efficiently by combining several high-speed *input/output devices* with this small core and processor. Fast input/output is provided by disk storage devices, which are commonly used for sequential processing steps. The disk storage device eliminates the necessity of reading and writing more than once from the slower magnetic tape device. Programs are also stored on disk devices and are executed by a *batch input call-up procedure* using computer cards. Disk storage of programs gives quick accessibility to a range of programs and allows efficient access so that only the program in execution need be held in core.

DESCRIPTION OF IMAGE PROCESSING TOOLS

The most commonly used image processing programs available at the U.S. Geological Survey in Flagstaff are divided into four basic groups: utility, image correction, enhancement, and multispectral programs. Utility programs are used to collect data about an image and to alter magnetic tape format. Image correction programs are applied to an image to remove noise and to correct or transform its geometry. Enhancement techniques, such as the stretch and filter programs described in the preceding section, form the backbone of image processing. Multispectral processing is an extension of some of the enhancement techniques and is used to process multispectral data sets for output in color or in black and white. The proper sequence of program application to a data set is extremely important. A flow chart (pl. 4) demonstrates the proper sequence of program execution as applied to a Landsat data set. Some of the programs described in the following sections are applicable to Mariner 9 images only and are not shown in pl. 4. The same basic sequence of application, however, (for example, image correction followed by image enhancement) holds for all digital images.

UTILITY PROGRAMS

Utility programs are used to gather numerical information about an image in order to specify details of processing and to alter the image formats. Digital images have a large dynamic range of values in magnetic tape format; the diagnostic capabilities provided by utility programs enable a user to manipulate the data precisely into the most useful format. The two most commonly used programs (lists and histograms) have already been described. Other utility programs provide the capability to read identification labels at the beginning of image files, to change integer (bit) formats, to change tape formats (for example, to rearrange files), to count lines and samples present or the number of files (images) on a tape, and to transfer images between tapes and disks.

IMAGE CORRECTION TECHNIQUES

Image correction techniques form one of the most important stages in processing. These techniques are designed to remove noise which is inherent in digital images, replace *dropped lines* of data, correct for variations in solar illumination angle, remove the effects of *atmospheric scattering,* correct *geometric distortions,* and transform images to cartographic formats. Because enhancement techniques such as stretches and filters will emphasize image imperfections to the point at which they obscure useful data, it is imperative that imperfections be removed. Generally, the imperfections are dependent on the system used to generate the digital image. Hence, specific noise-removal programs are needed to clean up an image.

Bit errors.—Bit errors are "spikes" of high or low DN values (random noise) that are inconsistent with values of surrounding pixels. They are commonly found in Mariner spacecraft images. These errors are removed by replacing the aberrant pixel value with some average of the surrounding pixel values.

Ultraviolet spectrometer noise.—Ultraviolet spectrometer noise, a type of coherent noise, was introduced to Mariner 9 data when the ultraviolet spectrometer and television system were operating simultaneously. The electronic interference from the spectrometer introduced a systematic pattern in the images. A specific noise-removal routine is applied to recognize and adjust affected pixels (Chavez and Soderblom, 1975).

Six-line scanner noise.—Six-line scanner noise, a type of coherent noise, is a horizontal striping pattern found in Landsat images. The Landsat imaging system has 24 scanners or detectors used to collect data simultaneously in four bands. Thus within a single band, six independent scanners sweep cross track (horizontally if the image is viewed with north at the top) and acquire six lines of data before resetting to collect the next six lines. Because the scanners are independent, have a nonlinear response over the reflectance range collected, and are incompletely cross-calibrated, six-line scanner noise results. Two different types of noise removal routines can be used to correct this problem. A histogram noise removal routine compiles six histograms for lines collected by each detector and then generates conversion tables to adjust each histogram to an average histogram. Histogram noise removal should be run before dropped lines (see below) are replaced so the original detector responses are preserved. Although histogram noise removal does not completely remove scanner noise, it preserves the overall *photometry.* A filter noise removal routine uses an averaging technique to remove the six-line scanner noise. It is more complete in noise removal but may slightly change the overall photometry from area to area within an image.

Dropped lines.—Dropped lines of data, which occur in bands of some Landsat images, result from loss of data during acquisition, recording, transmission, or processing. Dropped lines can be recognized either as anomalous horizontal patterns in images, or as white noise (high or saturated DN values) on the tails of the histogram. Lost lines of data are normally replaced by the average value of the line above and line below.

Three additional modifications, which are not noise removal techniques, may be necessary to maximize the digital image input for the processing stage of image enhancement. These include correction for solar illumination angles, geometric distortions, and removal of the effects to atmospheric scattering.

Solar illumination angles.—The effects of varying solar illumination angle commonly cause images to range from total saturation to total darkness, especially affecting global images that contain large variations in solar elevation angle. In these images, the variation in brightness across the scene may be enormous compared to variation due to scene detail (for example, shadows due to local topography). In dealing with larger scale images, such as these from Landsat, a correction for illumination angle is less critical except in *mosaicking* different scenes, or in comparing data from different images of the same area. The illumination angle program corrects the image by dividing the DN value of each pixel in the image by the DN values of the corresponding pixel in a predicted image generated from a photometric model of a smooth sphere under the same lighting conditions as the original image. Variations due to topography and albedo are not removed because the program removes brightness variations for a smooth featureless surface.

Geometric distortions.—Geometric distortions, present in most digital images, are introduced by the imaging system (for example, rectangular pixels caused by the sequential scan of the Landsat system) and by the viewing conditions (for example, oblique pictures obtained by Mariner 9). A variety of geometric transformation programs is available to correct distortions in an image to *single point perspective* and then transform it into almost any cartographic projection including: Lambert conformal, Mercator, transverse Mercator, Albers conical equal-area, polar stereographic, orthographic, and simple cylindrical. The distortion corrections and transformations are mixed and applied smoothly in a single operation. The geometric transformation programs used by the U.S. Geological

Survey involve techniques commonly referred to as resampling and bilinear interpretation, which are discussed in detail in Bernstein (1974) and Taber (1974).

Atmospheric scattering.—If the effects of atmospheric scattering (haze) are not removed from Landsat data, contrast in the short-wavelength bands is substantially reduced. One technique for removing haze involves examining histograms of the DN values found in each band. If there is sufficient topographic relief in the image to produce shadows (which are black), the toe (lower values) of the histogram for band 7 will intercept zero DN because no radiation will be received by the imaging system in the shadowed areas for this 0.8–to 1.1-μm wavelength. The three shorter wavelength bands typically display progressively (from band 6 to band 4) higher value intercepts for the toe of each histogram. These higher intercepts are caused by atmospheric scattering. The intercept of the toe of the histogram in each band is assumed in this technique (if, in band 7, it equals zero DN) to be shadowed pixels that should have DN values of zero. The haze correction program then adjusts each band's histogram to zero DN, by truncating any lower values. Typical truncation values are 11, 7, 3 and 0 DN for bands 4, 5, 6, and 7, respectively (Chavez, 1975). A second technique is based on the premise that color ratios should not vary across topographic forms of uniform material. A value for the effects of haze is computed that will minimize variations in color ratios in the image (Chavez, 1975).

ENHANCEMENT TECHNIQUES

Enhancement techniques can next be applied to corrected images to emphasize different aspects within the image. The major enhancement programs are contrast stretching, spatial filtering, and *ratioing*. Ratioing is a technique of dividing individual pixel DN values from one band into another to emphasize *colorimetric variations* and is discussed in the following section. The variations possible in the application of each of these techniques can result in a variety of products.

Contrast stretching (see section entitled "Basic concepts") enables the user to assign new output brightness values to individual input values, thereby amplifying brightness variations in the image. Four types of stretches are commonly used: linear stretch, table stretch, auto-stretch, and histogram-equalization stretch. To apply linear or table stretches (see below), it is necessary first to obtain either a list or a frequency histogram, because the user must specify the input-output DN values for the stretch. The auto-stretch and histogram-equalization-stretch options generate histograms internally stored in the computer during execution and automatically select stretches based on percentage values of these histograms. The user may supply parameters for the program to process the histogram; if these are not supplied, standard default values are used. Stretch programs are commonly used to increase contrast so that the most interesting parts of an input brightness range are optimized, although, in rare instances, contrast suppression may be necessary. Four variations of the contrast stretch routine are described and compared below.

A linear stretch permits the user to choose minimum and maximum DN values of the input data set, which are reassigned to the lowest and highest values in the output (in eight-bit format the extreme values are 0 and 255 DN). All other intermediate values between the minimum and maximum are assigned to proportionally spaced DN values throughout the output range. For example, if there are eight DN values between and including the minimum and maximum values chosen (for example, in a 201 to 208 DN linear stretch), the input data set will be reassigned to the following eight output values: 0, 36, 73, 109, 146, 172, 219, and 255 DN.

The table stretch allows the user to execute several linear stretches on different segments of the input data set, by choosing input DN values to be reassigned to chosen output DN values. By using this stretch, a very complex nonlinear functional relation between input and output data can be applied.

Auto-stretch first generates a histogram of the input image that is internally stored in the computer. The user selects percentages of the histogram to be saturated on the high and low ends of the histogram. For example, suppose a 2–3 percent auto-stretch is specified. The computer might find that 2 percent of the data lie between 0 DN and 15 DN and 3 percent between 240 DN and 255 DN. The saturation points are then 15 and 240 DN, and DN values respectively lower and higher than those values are truncated. These two values are then used in a linear stretch as described above.

The histogram-equalization stretch also generates a histogram internally stored in the computer; the computer calculates the table stretch that will make the output histogram as flat as possible. This technique might be termed an auto-table-stretch. Although eliminating the necessity for generating and examining a histogram, both automatic techniques can generate peculiar results owing to unforeseen irregularities in the distribution of input DN values.

Spatial filtering, a frequently used enhancement technique, changes pixel values as a function of the values of neighboring pixels. The array of pixels considered in most digital filters (employed at IPL/JPL and the U.S. Geological Survey) is defined by the user as any odd number n × m lines and samples (odd numbered to be symmetric). "Frequency" refers to the spatial scale of the brightness variations within the image. High frequency means rapid changes over a few pixels. Low frequency means a gradual change over a large number of pixels. A high-pass filter amplifies high-frequency variations within the image; low frequencies are in effect subtracted from the image. A low-pass filter passes low frequencies by smoothing the image. Before spatial filtering, images can be contrast stretched to give the filter a useful range of input values on which to operate.

A high-pass filter emphasizes features generally smaller than the size of the averaging area by calculating the average DN values within the n × m neighborhood (array) of pixels and subtracting this average from the value of the pixel being operated upon. Because these differences fluctuate around zero, a constant (normally mid-range—that is, 127 in eight-bit format) is added to make the output values positive.

High-pass filter images may be confusing with only the high frequencies expressed and larger patterns removed. The program permits a percentage of the original image to be added back to aid in visual interpretation. For example, if 100 percent is added back, a version is produced in which the high frequencies are doubled and the low frequencies left the same.

A low-pass filter will enhance features that are generally larger than the averaging neighborhood. The enhancement is accomplished by a smoothing operation, which removes most of the high-frequency variations and thus emphasizes the low frequencies.

MULTISPECTRAL IMAGES

Color display of digital images has resulted in five products which, in most cases, significantly increases the interpretability of multispectral data. These products include false color, artificial color, simulated natural color, color ratios, and hybrids.

False color.—False color is generated from three *spectral bands* (usually two visible and one near infrared: bands 4, 5, and 7 or 4, 5, and 6 with Landsat data). These are contrast stretched to optimize the information available in each band and then composited in color. The name for this product was derived informally from the practice of shifting the yellow-green band 4 to blue (in compositing), the red band 5 to green, and one of the near-infrared bands (6 or 7) to red.

Artificial color.—"Artificial color" is used in this paper to delineate other false color products. Artificial color products are also expressed in the same three colors (blue, green, and red), but the source for internegatives used with these colors differs. For example, to aid in structural interpretation, linear features of various magnitudes can be enhanced by applying three high-pass filters of different sizes to a single band (or to any combination of bands), contrast stretching the result, and compositing.

Simulated natural color.—False color and artificial color products are commonly difficult to interpret because of their abnormal colors. Simulated natural color from Landsat data has been developed by the U.S. Geological Survey to help in this interpretation. Using Landsat data, the simulated natural color program synthesizes a blue band for use in color compositing by extrapolating to the blue part of the spectrum from the green and red bands ($5.5 \pm 0.5 \times 10^{-7}$m and $6.5 \pm 0.5 \times 10^{-7}$m). The method of extrapolating differs for soils and rocks or vegetation. Each pixel is first classified as soil or vegetation, and the appropriate algorithm (subprogram) applied. The extrapolated values are further modified as a function of the near-infrared to visible ratio. The green and red bands are then adjusted so that they more nearly match the spectral response of the human eye. Finally, the new blue, green, and red components are color composited to generate the simulated natural color image. The result can be further enhanced with filters to emphasize structural fabric and with contrast stretches to emphasize differences in materials. Because the Landsat multispectral scanner is far more sensitive to subtle colorimetric variations than are standard color photographic films or even the human eye, color differences not normally observable are emphasized (Eliason and others, 1974, 1975).

Color ratios.—Ratioing is the fourth major tool used to generate color products. It is normally used with multispectral images that have been collected simultaneously in several wavelengths, such as Landsat data. *Spectral reflectance* or color differences between rock units are commonly very subtle and difficult to detect visually even in contrast stretched color composites of single bands (false color); ratioing emphasizes color differences while suppressing topographic lighting effects and albedo variation. If a bright material and a dark material are of identical color, then their color ratios will be identical, independent of their albedo differences. The same is true of uniform materials that appear bright or dark because of topographically induced differences in brightness.

Ratioing is accomplished by dividing the DN value of each pixel in one band by the DN value of each corresponding pixel in another spectral band. The quotient is then scaled between 0 and 255. Care must be taken that data are neither compressed near 0 nor exceed 255. Contrast stretches are usually applied to ratio output in order to maximize the data available for visual interpretation.

Hybrids.—In some cases albedo differences, lost in ratios, are important in separating materials. A hybrid product, combining two ratios with a single band has been developed to enhance both albedo and color variations. Hybrids are valuable for separation of materials in areas such as volcanic flow units where even ratio products show only minor differences in color and where differences in albedo are the major means of distinguishing between materials.

REFERENCES CITED

Batson, R. M., 1973, Television cartography: U.S. Geol. Survey Interagency Rept., Astrogeology 58, 35 p.

Bernstein, Ralph, 1974, Scene correction (precision processing) of ERTS sensor data using digital image processing technique, *in* Third Earth Resources Technology Satellite-1 Symposium, v.1 (IBM Rept. FSC 73-0366): Natl. Aeronaut. and Space Admin. Spec. Paper 251, p. 1909–1928.

Chavez, P. S., 1975, Atmospheric, solar and MTF corrections for ERTS digital imagery: Am. Soc. Photogrammetry Proc., p. 69, 69a.

Chavez, P. S., and Soderblom, L. A., 1975, Simple high speed digital image processing to remote quasi-coherent noise patterns: Am. Soc. Photogrammetry, 41st Ann. Mtg., Washington, D.C. Proc. p. 595–600.

Eliason, E. M., Chavez, P. S., and Soderblom, L. A., 1974, Simulated "true color" images from ERTS data: Geology, v. 2, no. 5, p. 231–234.

Eliason, E. M., Soderblom, L. A., and Chavez, P. S., 1975, Simulating true color images of Earth from ERTS data: Am. Soc. Photogrammetry, 41st Ann. Mtg., Washington, D.C., Proc., p. 785–788.

Goetz, A. F. H., Billingsley, F. C., Gillespie, A. R., Abrams, M. J., Squires, R. L., Shoemaker, E. M., Lucchitta, Ivo., and Elston, D. P., 1975, Applications of ERTS images and image processing to regional problems and geologic mapping in northern Arizona: Jet Propulsion Laboratory Tech. Rept., 32–1597, p. 20–21.

Janza, F. J., 1975, Interaction mechanisms, *in* Reeves, R. G., ed., Manual of remote sensing, v. 1: Falls Church, Va., Am. Soc. Photogrammetry, p. 75–179.

Lapedes, D. N., ed., 1974, Dictionary of scientific and technical terms: New York, McGraw-Hill Book Co., 1660 p.

Levinthal, E. C., Green, W. B., Cutts, J. A., Jahelka, E. D., Johansen, R. A., Sander, M. J., Seidman, J. B., Young, A. T., and Soderblom, L. A., 1973, Mariner 9—Image processing and products: Icarus, v. 18, no. 1, p. 75–101.

Reeves, R. G., ed., 1975, Manual of remote sensing, v. 2: Falls Church, Va., Am. Soc. Photogrammetry, 2123 p.

Rindfleisch, T. C., Dunne, J. A., Grieden, H. J., Stromberg, W. V., and Ruiz, R. M., 1971, Image processing of the Mariner 6 and 7 pictures: Jour. Geophys. Research, v. 76, no. 2, p. 394–417.

Taber, J. E., 1974, Evaluation of digitally corrected ERTS images, *in* Third Earth Resources Technology Satellite-1 Symposium, v. 1: Natl. Aeronaut. and Space Admin. Spec. Paper 351, p. 1837–1844.

Condit and Chavez—BASIC CONCEPTS OF COMPUTERIZED DIGITAL IMAGE PROCESSING—Geological Survey Bulletin 1462