United States Department of the Interior

GEOLOGICAL SURVEY
RESTON, VA. 22092

In Reply Refer To:
WGS–Mail Stop 520

December 12, 1985

Memorandum for the Record (EC–88–Landsat)

By: Research Cartographer (EROS Cartography)

Subject: New Papers Related to Space Image Mapping

Attached are three papers on above subject. Although they have been or may be published elsewhere their distribution to the concerned mapping community is considered worthwhile. The three papers and their possible significance are as follows:

1. The Status and Future of Satellite Image Mapping (A.P. Colvocoresses). This paper evaluates the status of satellite image mapping as practiced by the U.S. Geological Survey and forecasts the possible role of such products for the future. The paper points out that current U.S. Geological Survey practice calls for 3.3 of the original pixels per mm at publication scale. This is far fewer than had been proposed by others.

2. The Art and Science of Image Maps. (R.D. Kidwell and J.A. McSweeney). This paper describes the technical steps involved in converting digital data sets into published image maps. One point of significance lies in that enlargement through digital manipulation is far superior to the photographic enlargement of an image. Another point lies in that image processing in preparation for the lithographic process is considerably different from processing for photographic end products.

3. Image Mapping with the Thematic Mapper (A.P. Colvocoresses). This paper describes the three image maps published to date from Thematic Mapper data by the U.S. Geological Survey. It indicates that spatial resolution, geometric fidelity, and radiometric response are the three basic parameters involved in image mapping. It is noted that whereas two of the three image maps met U.S. National Map Standards for positional accuracy, the third (Great Salt Lake and Vicinity) failed to do so. This deficiency is due to processing rather than the original data and it is believed that steps now being taken will correct this matter. However, in areas of high relief, meeting the Standards will require the use of considerable control and, in some cases, digital elevation models. The U.S. Geological Survey has scheduled five Thematic Mapper image maps for production during the current fiscal year (October '85 to October '86).

Alden P. Colvocoresses

Alden P. Colvocoresses

Attachments

THE STATUS AND FUTURE OF SATELLITE IMAGE MAPPING
Based on Experience of the U.S. Geological Survey*

Alden P. Colvocoresses
U.S. Geological Survey
National Center, Mail Stop 520
Reston, Virginia 22092
USA

ABSTRACT

Three fundamental forms of maps are recognized herein. They are the line, thematic, and image form. Line and thematic maps are well defined but the image map is in a state of flux. Space systems now provide data in basically orthographic form which greatly simplifies the production of the image map. Moreover, the multispectral capability of space systems facilitates the use of the color mode when compared to aerial photography. Digital graphical information systems are now being developed on a global basis and the response from space which represents the image in multispectral form will undoubtedly be incorporated into such information systems. Thus, the capability of printing out the image along with more conventional map data will be a viable option.

1. BACKGROUND

For purposes of this paper, three fundamental forms of maps are recognized as follows:

- Line maps, which consist of symbols derived principally from human interpretation of source data such as aerial photographs and which portray a wide variety of standardized Earth-surface features.
- Thematic maps, which consist of symbols that portray some particular aspect or aspects of the Earth's surface. Thematic maps may be derived by computer or human interpretation or a combination of both.
- Image maps, which utilize a photograph or electro-optical recording as the map base. Many line and thematic maps display an image-like form based on such concepts as shaded relief and discrete selection of colors. However, for purposes of this paper such maps are not considered as image maps.

Publication authorized by the Director, U.S. Geological Survey on June 14, 1984. Any use of trade names and trademarks in this publication is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

*Presented at the Eighteenth International Symposium on Remote Sensing of Environment, Paris, France, October 1-5, 1984.

These map forms are by no means exclusive and are found in a wide variety of combinations of the three forms presented. Line and thematic maps are well defined and in general use, whereas the status of the image map is not so well defined and has been selected for further analysis.

The use of the image as a map base is not new. Ever since aerial photographs first became available, their conversion into a map base has been vigorously pursued. Controlled mosaics, photo maps, and the orthophotoquads are examples of image-form products derived from aerial photographs. Such image products have been used extensively for a wide variety of both civil and military applications. However, they all have a common limitation resulting from the relatively wide-angle field-of-view which created the photographs.

Wide-angle photographs provide the parallax necessary to resolve the third dimension of height, but this same parallax creates off-axis horizontal unwanted displacements for two-dimensional image mapping. Removing these displacements through differential rectification with orthophotoscopes is costly and degrades image quality. Wide-angle photographs also tend to have large variations in illumination whereby two similar objects at different locations have different spectral responses based on the sun-to-object-to-camera relationships. These two limitations stem from the same geometric condition. The imager (aerial camera) is too close to the scene in order to record a sizable area orthographically.

A third limitation lies in that most aerial-based image maps are black and white rather than colored. This is because of the expense and complexity of obtaining and processing color or multispectral (separate band recorded) images from an aircraft. In any case the aerial-based image map has had great difficulty in reaching the status of acceptability where it could successfully compete with the line or thematic maps as a standard product.

The advent of space systems has provided a new dimension to mapping by providing imagery of the Earth taken from a great distance. The meteorological satellites first demonstrated this mode by recording the Earth's surface and its cloud cover in small-scale synoptic form. Higher resolution** satellites such as the Landsats have provided a data base from which image maps showing significant Earth-surface detail can be made.

Today most of the Earth's land and shallow sea areas are covered by Landsat multispectral scanner data of the 75- to 80-meter (m) picture element (pixel) dimension. Landsat return beam vidicon panchromatic data of 30-m pixel size also covers a sizable percentage of the land areas, and recently 30-m Thematic Mapper (TM) multispectral data of selected areas have been acquired by Landsats 4 and 5.

Landsat images, because of their narrow field-of-view, are nearly orthographic. The angle between the ray to the edge of the imaged area from the sensor and the vertical is the true measure of this orthogonality. With a typical Landsat (1, 2, or 3) image this angle is less than 6° (7.5° for Landsat 4 and 5), whereas with a standard aerial mapping camera, this angle

---

**Resolution throughout this paper is described in terms of the picture element (pixel) dimension on the ground. It is recognized that the resolution of film cameras is normally indicated by the ability to discriminate line pairs. Estimates on the relationship of the pixel to the line pair vary from 1.6 to 2.83 but the value of 2 is in common use and considered to be an acceptable relationship insofar as information content is concerned.

is about 37°. The smaller the angle, the closer the system approaches orthogonality. Film mapping cameras flown by the U.S., FRG, and USSR in space have also acquired considerable photography, but these cameras include angles off the vertical of up to 21°.

Space systems of the electro-optical mode such as Landsat (or the French SPOT), can thus provide near orthographic imagery of the Earth and overcome some of the limitations of film cameras as a data source for image maps. However, this does not mean that space-derived image maps will replace the line map in the foreseeable future, but it does provide the cartographer with capabilities which simply did not exist before the space age. These new capabilities may be summarized as follows:

- Acquisition of data covering large sections of the Earth in near-real time.
- Near orthographic coverage of sizable areas with very high geometric fidelity.
- Multispectral response in digital form with high dynamic range and sensitivity.
- Flexibility in acquisition and processing relative to resolution and spectral bands.

These capabilities transform into real advantages for image mapping when compared to systems based on film cameras.

2. PRESENT STATUS

Many countries, or sections thereof, have been image mapped at small scale with Landsat multispectral scanner (MSS) data. These maps are generally of 1:500,000 or smaller scales, of variable geometric fidelity, and may be either black and white or multicolored. The MSS data (75-m pixel) is capable of being reproduced in acceptable image form at scales as large as 1:250,000 and the Landsat Thematic Mapper 30-m pixel data at scales up to 1:100,000. The U.S. Geological Survey has produced several multicolored image maps based on these criteria, typical example being:

- Upper Chesapeake Bay (1977 edition). This image format map is based on MSS data and published at 1:250,000 scale.
- Las Vegas, Nevada (1983). This standard quadrangle (1° by 2°) map is a mosaic of four images published at 1:250,000 scale.
- Washington, D.C. and Vicinity (1984). This map was made from a single TM image in quadrangle form and published at 1:100,000 scale.

Today the U.S. Geological Survey distributes over 30 Landsat-based image maps of portions of the United States and 9 of foreign areas. These image maps meet or at least approach the U.S. standards for positional map accuracy except for those of foreign areas where little or no ground control was available.

During June 1984 the USGS also published Miscellaneous Investigations report I-1616 titled "Landsat Thematic Mapper (TM) Color Combinations of Washington, D.C. and Vicinity." This report illustrates the 20 possible color combinations from the 6 bands (thermal band excluded) of the TM and samples of the 120 possible permutations. The report also includes a discussion of the mapping potential of the TM and sets forth a criterion which relates the ground dimension of the original pixel to the scale of a published image map. This criterion calls for the the equivalent of 3.3 pixels per mm at published scales and results in the following tabulation:

Original Pixel Size	Image Map Scale
75 m	1:250,000
30 m	1:100,000
15 m	1:50,000
7.5 m	1:25,000

3. FUTURE

As long as Earth-sensing satellites are flown, it appears likely that image maps in some form will be produced. However, the satellite image maps produced so far are planimetric and lack the elevation data of the topographic map that are essential for many critical applications. Film cameras are demonstrating that suitable stereo imagery can be acquired from space and several stereo electro-optical systems have been defined. Such systems have the potential of resolving the vertical dimension with relative accuracy somewhat better than the pixel dimension. Thus image maps of the future may include the third dimension defined by contours which have been derived from the same data used to create the image.

At this time it is hard to conceive of mankind giving up the printed map as an instrument of our society. However, the methods by which cartographic information can be displayed are by no means limited to the printed product. Geographic information systems, which consist of digital spatial data, are being developed all over the world, and the various methods for displaying such data are also in a state of rapid development. It is up to the mapping community to see that such information systems are geometrically sound and contain the data that map users want and need. In addition to definitive data such as names and other symbols, the remotely sensed response itself, in multispectral digital form, will undoubtedly form an essential part of any comprehensive geographic information system. Thus, the capability for display and/or printing of the Earth scene in image form will be a viable option. Perhaps the printed map as we know it today will disappear, but the information that line, thematic, and image maps now display must be readily available in some usable form as long as civilization, as we know it, exists.

Reprinted from
Proceedings, ASP 51st Annual Meeting
Vol. 2, March 10-15, 1985, Washington, D.C.

ART AND SCIENCE OF IMAGE MAPS

Richard D. Kidwell and Joseph A. McSweeney
U. S. Geological Survey
Reston, Virginia

ABSTRACT

The visual image of reflected light is influenced by the complex interplay of human color discrimination, spatial relationships, surface texture, and the spectral purity of light, dyes, and pigments. Scientific theories of image processing may not always achieve acceptable results as the variety of factors, some psychological, are in part, unpredictable. Tonal relationships that affect digital image processing and the transfer functions used to transform from the continuous-tone source image to a lithographic image, may be interpreted for an insight of where art and science fuse in the production process. In practice, there is little substitute for the skill acquired from experience and critical visual observation in the actual production of image map products. The application of art and science in image map production at the U.S. Geological Survey is illustrated and discussed.

INTRODUCTION

Even before days of Newton, science has been considered a body of natural laws that logically link cause and effect. While remotely sensed digital image data can be processed by logical scientific processes to produce geometrically accurate and radiometrically corrected image maps, it appears that there may not be sufficient scientific theory for radiometric image enhancement. The user's visual perceptions are often the ultimate judge of the completed map. "Scientific cartography is concerned with the dissemination of spatial knowledge while the aim of visual art is to provide aesthetic pleasure through visual and intellectual stimuli for desired mental responses, I don't know what is good, but I know what I like" (Robinson, 1952). When Einstein said "beauty is the first test", he reiterated the artist's comment that "what looks right is right". Art and science are generally considered to be totally separate; however, scientific theory, critical observation, and subjective perception each play a major role in modern image mapping. Image maps are both science and art in one medium.

One type of map is a two-dimensional symbolized display of surface features with a means of determining geographic locations according to a specified scale and projection. An orthographic image map is a photographic-like view that

---

Publication authorized by the Director, U.S. Geological Survey, on December 5, 1984.

is geometrically corrected to meet this same map definition. Image maps made from satellite-borne imaging sensors are now produced from discrete spectral wavebands. These bands of spectral data must be digitally transformed to fit a map projection and adjusted radiometrically to produce an enhanced image on film, and the cartographer must be concerned with both the scientific and aesthetic quality.

The satellite color image maps published by U.S. Geological Survey (USGS) have been primarily prepared from two multispectral sensor systems. The first is the Landsat multispectral scanner (MSS) with imagery recorded in 64 6-bit gray levels and with a net pixel ground dimension of 56 by 79 meters. These data are resampled by the USGS EROS Data Center (EDC) to 50-meter-square pixels in three primary spectral bands -- band 4 (green), band 5 (red), and band 7 (near-infrared). The second sensor is the Landsat Thematic Mapper (TM) with imagery recorded in 256 8-bit gray levels and with 30-meter pixels in six primary spectral bands -- band 1 (blue/green), band 2 (green), band 3 (red), and bands 4, 5, and 7 in increasing wavelength segments of the near-infrared. Band 6 is a thermal band and is not suitable for image mapping applications. The maps are printed using inks of the subtractive primary colors of yellow, magenta, and cyan in respective order of the primary additive colors, blue, green, and red (figure 1).

Line map Landsat TM Band 5

Figure 1.--Line map and Landsat TM Band 5 (1.55 to 1.75 μm) image at 1:100,000 scale enlarged for printing in the proceedings from 175 l/in to 133 l/in.

VISUAL RESOLUTION

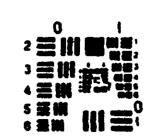
There are three essential factors in the determination of visual resolution for remote sensor imagery. These factors are (1) the pixel size, (2) the number of pixels accepted as representative of a line pair, and (3) the number of pixels required to properly define a map feature. The first two factors are relatively well defined and accepted. For example, at a map scale of 1:100,000, the original

30-m TM pixel size is 0.3 mm or 3.3 pixels per mm. If two pixels are accepted as equivalent to a line pair, the resolution is 0.6 mm (2 pixels x 0.3 mm) or 1.67 line pairs per millimeter (lp/mm). Similarly, MSS data at 1:250,000 scale has a resolution equivalent to 3.3 pixels per millimeter at a ground dimension of 79 meters square. Both MSS and TM data are frequently used at these map publication scales with acceptable results.

The third factor, number of pixels needed to represent a map feature, addresses the pixels judged necessary for minimum-size feature definition. Estimations range from 20 pixels per mm at publication scale to 3.3 pixels per mm (Colvocoresses, 1984). Some ground features can be represented by a number of small cell areas, each with different brightness values, while a complex feature will require a larger number of pixels per mm. At a reasonable viewing distance of 12 inches or more, the human eye cannot resolve a dot (pixel) smaller than 0.13 to 0.25 mm or 2 to 4 lp/mm (Herbert, 1982). A U.S. Air Force resolution target illustrates the dimensions discussed (figure 2).

		Pixel/dot width		USAF target
Image structure element	lp/mm	mm	inch	group/element
TM pixel at 1:100,000 scale	1.7	0.3	0.12	0/6
Smallest visible dot at normal viewing distance	2.0 to 4.0	0.25 to 0.13	0.010 to 0.005	1/6 to 2/6
Dot size 175 l/in screen	7.0	0.03 to 0.14	0.0013 to 0.0057	2/6 to 4/3

Figure 2.--The USAF high-contrast target illustrates visually the image dimensions discussed. Low contrast imagery, such as for Landsat, appears to have higher resolution as the pixels are difficult to visually distinguish at an 0.3 mm size.



USAF 1951 target

Halftone

Lithographic image maps are usually printed with dots called halftones (figure 3). Equally spaced halftone dots are either created by photographic exposure with a half-tone screen or are electronically generated to simulate the halftone screen. Screenless printing uses the press-plate random grain structure to form very fine random shaped and random spaced dots. Solid dots of increasing size form the tones of gray from the diffuse highlight to the midtone 50-percent dot. A diffuse highlight is the lightest neutral white area that contains detail. Open dots or holes form the tones of gray from the midtone 50-percent dot to the shadow endpoint that contains detail. At approximately the 50-percent dot area, the screen cell shifts from a solid to an open dot. The dots may be circular, square, elliptical, or irregular in shape. Image maps produced at the USGS have elliptical dot shapes to smooth out the transition in the 50-percent dot area. The 175-line screen has a maximum cell size of 0.0057 inch. The minimum size dot diameter that can be printed is located in the center of the 0.0057-inch cell and represents a 3-percent dot area with a diameter of 0.0013 inch.

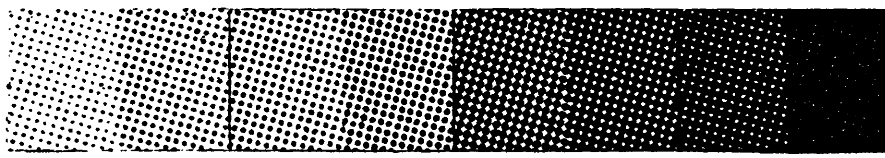


Figure 3.--Halftone 175-l/in screen enlarged to 24 l/in screen to show dot pattern from highlight to shadow endpoints.

Dots are not individually measured to determine dot area percentage values as no dot is perfect or repeated exactly due to chemical and physical actions that distort the original shapes. Electronically generated dots formed by rectangular or circular pixels have overlapping and stair-step perimeters that are further distorted by the requirement to create an angle rotation of 30 degrees between color separations to minimize moiré patterns as colors are overprinted. Therefore, halftone-screened film or prints are read on a densitometer using a 1- or 2-mm aperture to measure an integrated dot area. The densitometer is calibrated to zero in faint, broken-dot clear areas of the film or print. Integrated positive halftone dot densities (in logarithmic values) from 0.00 to 0.30 represent a 0- to 50-percent dot range. The integrated dot density interval between 1.00 and 2.00 density units represents a range from 90- to 99-percent dot area.

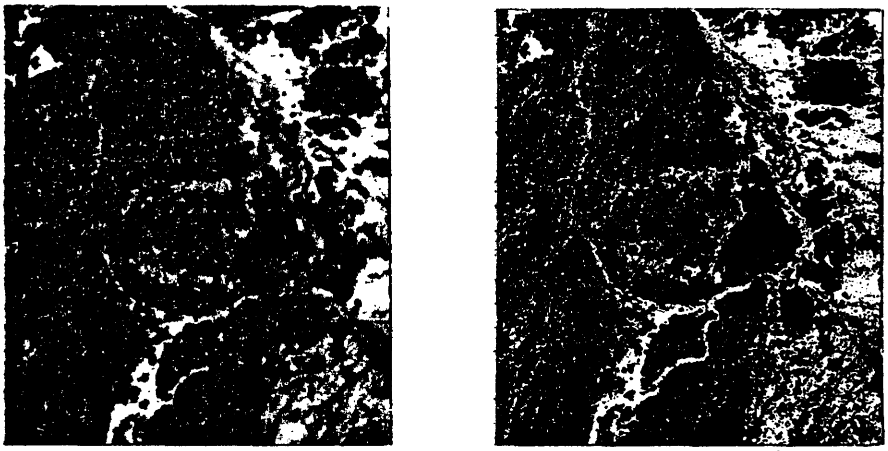
The screen does not improve resolution but acts as a mask or filter. The image is limited to the resolution dot spacing of the screen regardless of the original image resolution. Screen lp/mm ratings should preferably be twice the pixel lp/mm ratings to avoid loss in map feature definition. However, the use of very fine screens (more than 175 l/in) is primarily for reproduction of radiometric values by improving gradation of tones rather than for resolution.

Halftone dots produced by electronic methods and using a laser for exposure are far superior to photographic contact halftones. An appearance of improved definition and reproduction results from the clear crisp dot without the dot fringe typical with conventional contact screening.

Edge Enhancement and Enlargement

Image definition may be visually enhanced by a digital map processing technique called edge enhancement. The correct amount of enhancement will make map line features appear sharper by adding contrast between adjacent pixels with a noticeable differences in their brightness (gray) level. The process involves sampling the area surrounding a pixel and changing its brightness value higher or lower if the difference exceeds a specified value.

Enlargement by optical methods using a camera or enlarger generally results in significant loss in sharpness of pixels and map features. Enlargement by electronic methods using a graphic arts scanner/plotter retains resolution through the entire process of enlargement and no spherical distortions are apparent. The vertical and horizontal directions have independent distortion; however, these differences can be easily corrected by the scanner system software (Zhang, 1983). The highest resolution is obtained by electronic enlargement directly to film at publication scale using a laser output plotter that will accept direct digital data inputs (figure 4).



Camera | Electronic scanner/plotter

Figure 4.--Landsat MSS Band 7 (0.8 to 1.1μm) showing 8x enlargement comparison between camera and electronic equipment. Original halftoned at 175 l/in at 1.250,000 scale and enlarged for printing in proceedings to 150 l/in.

A blocky appearance will result if a Landsat image is enlarged past the limit supported by pixel resolution. Tests show that the problem can be partially solved by pixel duplication followed by spatial filtering to smooth the data and then edge enhancement, if necessary (Chavez and others, 1984). If only pixel duplication is used, the blocky appearance will be more obvious and this distracts from the aesthetic value of the map. The filter size must be adjusted to the size of the digital enlargement in order not to over or under smooth the data. Using the same procedure with TM data results in a defocused appearance; however, using an edge enhancement array twice the numerical value of the enlargement array results in an improvement. For example, use a 6 x 6 array for a 3x enlargement for TM data. Edge enhancement should not be added on a graphic arts scanner system if enhancement has already been performed on the digitally processed image. Too much edge enhancement will produce a blocky appearance and reduce detail definition.

Registration

The printing industry standard for register is that it must be within 0.006 inch, with the smallest dot size held within a range of 0.001 to 0.002 inch (Herbert, 1982). A misregister of 0.012 inch (0.3 mm or one pixel of TM data at 1:100,000 scale) is visible to the unaided eye. Misregister causes detail to appear blurred or fringed and the color balance begins to shift. Printing fine dots in register is necessary for the integrated eye/brain system to perceive tonal difference and fine detail.

TONE REPRODUCTION

Tone reproduction is the process of transferring and retaining image density values through all processing stages to final printing. Extending the tone gray scale so it properly reproduces the original is as critical in black-and-white reproduction as in color, except in color the problems are multiplied three times (Morgan, 1983). Tone reproduction requirements vary between original materials provided, so the reproduction system must have some flexibility for utilizing artistic license. The requirement for gray balance, however, is especially important in avoiding a significant magenta color cast which causes the overall image to appear reddish (Sunderland, 1982).

Much of the skill and expertise in the art of continuous-tone reproduction is in determining where to compress and where to spread the tones to emphasize detail. Photographic control is limited to the endpoints and the midpoint density. Between these multiple aimpoints on the linear density scale, the density is compressed or expanded. Only selected data or density levels can be shown on the map. The final aimpoints are determined by personal preference and/or requirements to match adjoining maps and/or the need to increase detail contrast in the highlight or shadow tone areas. The continuous-tone density range from highlight to shadow should not exceed 1.50 density units with a density minimum of 0.30 for contact-frame or camera-processed imagery. Electronically processed imagery can maintain a linear tone curve so the restriction on the minimum density can be reduced to 0.10. Tone transfer is uncontrolled beyond these density range limits and should be avoided in film processing and color print proofing.

Whenever two aimpoints such as a quarter-tone and midtone are brought closer together, the detail will increase; if separated, detail will be subdued. A midtone dot change of only 2 percent will make a noticeable change in the detail and image contrast on the printed map. Halftone aimpoints or density control aimpoints shape the tone reproduction curve. It is the precision of tone reproduction control in electronic image processing that permits excellence in reproduction that is very difficult to achieve using photomechanical methods.

<u>Density stretch</u>

A typical Landsat image uses only a few of the available brightness levels for each of the spectral bands. A contrast stretch over a longer range of density values is required to obtain an acceptable number of gray values for a visual representation of the natural features. The stretch is non-linear as the sensitivity of the eye is not based entirely upon contrast effects (figure 5).

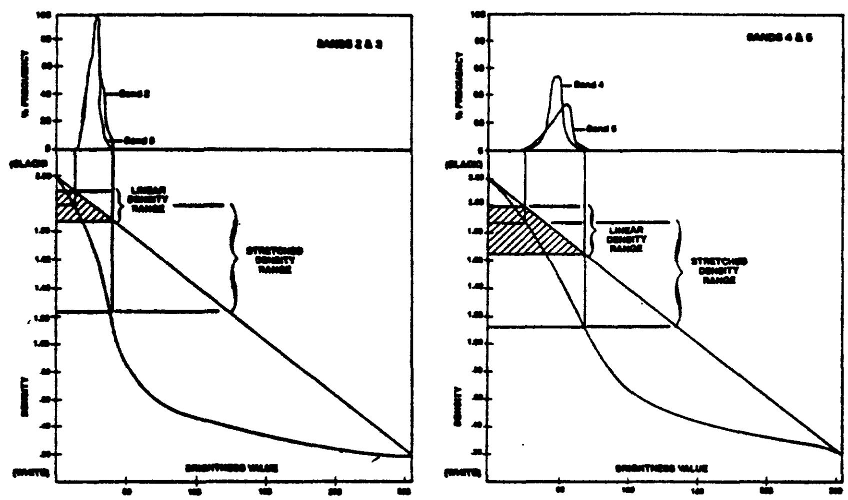


Figure 5.--Routine TM histograms and derived density transformation curves for Bands 2 to 5 (from NOAA, 1983).

The eye needs a greater difference in density value near the black and white for a change to be noted. A brightness value can be equated to lightness or darkness in a scale from black to white. A basic law of vision is the Fechner or Weber Law that states that the sensation produced by an increase in stimulation bears a constant ratio to the total preceding stimulation. A value visually perceived to be midway between black and white will not be composed of half white and half black, but much less black than white. Value appearance will be markedly different depending on environment and recognition of a midtone value between black and white. The selection of a middle value is difficult, if not impossible, in an environment of many contrasting features. The most striking difference in value is when an edge of light value next to a darker value makes the darker area appear lighter. One idea is to map to the median with 50 percent of the total pixels with values above the midpoint and 50 percent below. The median should be selected using only information of interest. Large amounts of water or cloud shadows, for example, should be omitted if water or cloud shadows are not of interest.

Halftone aimpoints

Typically, five aimpoints are selected in graphic arts for stretching the continuous-tone imagery to fit the halftone reproduction tone curve (figure 6). The cyan separation is evaluated first. One aimpoint is the highlight assignment of a 3-5-percent dot value in an area of interest. For Landsat imagery processed at EDC, this is step 2 or 3 (about 0.20 to 0.30 transmission density) on their 16-step linear control scale. The shadow aimpoint, step 14 (density about 1.35), is selected for a 95-97-percent dot and the midpoint aimpoint, step 8 (density about 0.80), is assigned a 60-percent dot.

Quarter-tones at 25 and 75 percent vary with the images, but in general they are assigned closer to endpoints than to the midpoint. The majority of data in the middle values should be stretched further than data near the extremes. The cyan separation carries the shape and contrast of the features in the imagery. If the cyan halftone black-and-white separation looks good as viewed on white paper (not backlighted), the final printed map is likely to look good. Image tonal match between scenes and maps is accomplished by maintaining midtone control in the cyan separation. Yellow and magenta separations generally follow the cyan tone curve with a 10-percent drop at the midtone and 5-percent drop in quarter tones. This reduction in the yellow/magenta tone curves is made to correct for lithographic ink deficiencies. If the ink pigments were pure, equal densities of ink in each of the separations would combine to make tints of gray.

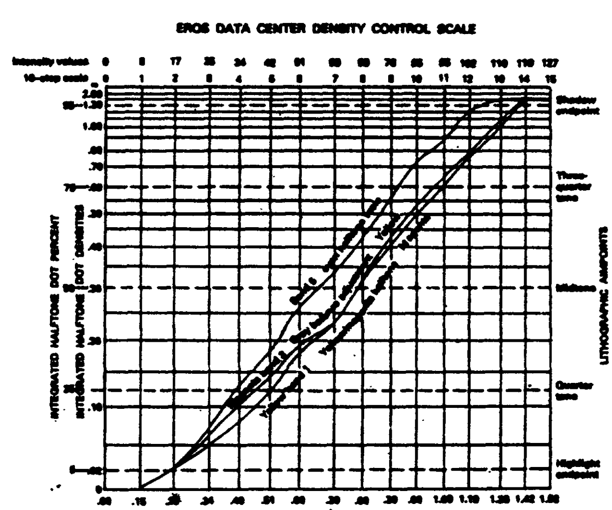


Figure 6.--Halftone reproduction curves of the Washington, D.C., and vicinity TM Landsat image map (USGS, 1984).

Color Interpretation

The combinations and permutations of assembling and processing TM imagery are practically unlimited for three-color lithographic printing. However, human perception, tradition, and physical limitations of the materials and equipment somewhat restrict the presentation possibilities.

The quality of light determines the appearance of color. Color exists only in the eyes of the observer, not with the physics of light, but on the sensations produced by the eye's reaction to different wavelengths of light. Hue is the color itself, for example, a red or green. Saturation is a range of hue from the saturated hue at one extreme to a neutral gray at the other and in no place would it vary in the third characteristic, brightness or value. The eye is less sensitive to saturation than to the other two primary sensations (hue and value). Color is complex because of the possibility of an infinite number of hue combinations and relationship between physical and psychological phenomena. Physical descriptions of hue are expressed as the dominant wavelength and its value and saturation (Rieser, 1972). A color can be physically determined by reference to spectrophotometry, but its visual character depends upon the environment. Each wavelength of light stimulates different visual cells in the eye, and the brain interprets the signals from the nerves as different colors. The details in the process of color vision are far from being completely understood (Williamson, 1983).

There is an after-image phenomenon which occurs when colors of different hues, values, or saturation lie adjacent to each other. Complementary colors in juxtaposition enhance the intensity of one another. Colors that are not particularly strong become unduly brilliant when placed side-by-side. Light areas usually appear larger than dark areas. Hue seems to have little effect on the relationship. If the printed surface is smooth, the color reflected will be bright. On the other hand, a matte or dull surface reflects diffused light. Diffused light is strongly influenced by selective absorption of certain hues. Thus, surface reflection/absorption significantly determines apparent color. In image map processing the phenomena of color sensations are natural occurrences and become a part of the image data.

The selection of color for an image map is very complex. The most useful guideline as a starting point is to look for good detail and tonal contrast in map features on the cyan separation. Then the yellow and magenta separations should be digitally mapped to the cyan to achieve clear, bright colors. The spectral highlights and white clouds should be free of any color. The darkest shadow should be black and not brown, or some other color. The midtones should have good contrast. There is no scientific method that can match a critical artistic eye for knowing when the color relationships are good. The problem with mathematical solutions is that the picture may show good tone separation over the entire scale from highlight through shadow and meet ideal conditions extremely well but not be acceptable because of personal choice and the nature of the original (Clapper, 1953). Electronic methods, following the visual evaluation, can then be used to replicate and match adjoining maps.

Electronic interactive color displays and color dyes in the blue, green, and red additive color gamut contain a wider range of colors than are possible using ink pigments of the subtractive colors of yellow, magenta, and cyan. The approximate differences are shown in the C.I.E. (Commission International d'Eclairage) diagram (figure 7), which is a universally recognized system for specifications and measurement of color (Williamson, 1983). The colors within the boundary of the C.I.E. diagram will produce a wider range of colors than are possible with any combination of three colors plus black. Color shifts and adjustments must be made to accommodate these physical differences which may require additional colors of inks to supplement standard three or four process colors.

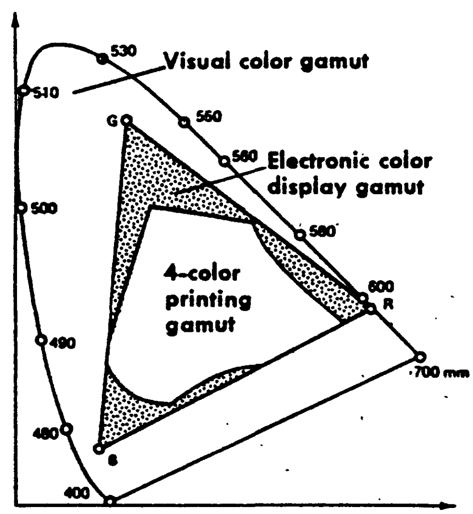


Figure 7.--C.I.E. diagram showing printing color gamut limitations compared to electronic color displays (adopted from Williamson, 1983).

In the selection of map separations, unusual visual combinations may be developed for improved map definition. An example is a TM map in preparation for Detroit, Michigan, where bands 3 and 4 were combined for the separation that will be printed in cyan. In the final printing of all three colors, the blue overcast, common on many image maps, is nearly eliminated; and the city road network is white rather than blue and shows improved contrast. The black and white reproduction of bands 3 and 4 are reproduced separately (figure 8) and combined to illustrate the results. This is an example of how endless variations are possible in processing image map products for publication.

Band 3 Band 4 Band 3 and 4

Figure 8.--Combination of TM bands 3 (0.63 to 0.69μm) and 4 (0.76 to 0.90μm) for printing in cyan with improved resolution. The 175 l/in screen original at 1:200,000 scale enlarged to 120 l/in for printing in the proceedings.

SUMMARY

Artistic skill and experience in the lithographic reproduction of multicolor art play a key role in the enhancement of digitally processed image maps. At the same time, a scientific approach must be developed to initiate as many photomechanical and electronic procedures as possible to improve productivity. Differences in color perception are perhaps the major problem to overcome in standardizing image map production, as the theory of color perception is not fully understood. In the final analysis, science must bend to the artistic expression, "I like this color," generated from visual perception. Lithographers must continue to call on scientific theory, but the successful production of color image maps remains with the good judgment of using both art and science to satisfy the user's needs.

REFERENCES

Chavez, Pat Jr., Guptill, S. C., Bowell, J. A., 1984, Image Processing Techniques for Thematic Mapper Data, Proceedings, American Society of Photogrammetry, Falls Church, VA, pp. 728-743.

Clapper, F.R., 1953, Factors Affecting Tone Reproduction with Contact Screens, Proceedings, Technical Association of Graphic Arts, Rochester, NY, pp. 28-40.

Colvocoresses, Alden P., 1984, Mapping of Washington, D.C., and Vicinity with the Landsat 4 Thematic Mapper, Proceedings, American Society of Photogrammetry, Falls Church, VA, pp. 757-764.

Herbert, Alan J., 1982, The Color Printing Process as a Well-Optimized System, Proceedings, Graphic Arts Technical Foundation, Rochester, NY, pp. 465-471.

Morgan, J. Tom Jr., 1983, Kiss Impressions -- My Love Affair with Lithography, Rochester Institute of Technology, Rochester, NY, p. 217.

NOAA Landsat Customer Service, 1983, Landsat Data Users Notes, Mundt Federal Building, Sioux Falls, SD, pp. 8-11.

Rieser, Dolf, 1972, Art and Science, Studio Vista, London, England, p. 95.

Robinson, Arthur H., 1952, The Look of Maps -- An Examination of Cartographic Design, The University of Wisconsin Press, Madison, WI, p. 97.

Sunderland, Bryan, 1982, Color Reproduction Specifications and Operations, Proceedings, Technical Association of Graphic Arts, Rochester, NY, pp. 455-464.

U.S. Geological Survey, 1984, Landsat TM Washington, D.C., and Vicinity Image Map, U.S. Geological Survey, 1:100,000 Scale.

Williamson, Samuel J., 1983, Light and Color in Nature and Art, John Wiley and Sons, New York, NY, pp. 488.

Zhang, Qingpu, 1983, Application of Color Scanners in the Reproduction of Remote Sensing Images, Proceedings, Technical Association of Graphic Arts, Rochester, NY, pp. 668-688.

United States Department of the Interior

GEOLOGICAL SURVEY
RESTON, VA. 22092

September 5, 1985

IMAGE MAPPING WITH THE THEMATIC MAPPER

Alden P. Colvocoresses
U.S. Geological Survey
National Center, Mail Stop 520
Reston, Virginia 22092
USA

ABSTRACT

This paper deals principally with Landsat Thematic Mapper (TM) image maps as published by the U.S. Geological Survey (USGS). While other agencies have produced similar products, technical data thereon are not generally available. Landsat data have certain characteristics that makes them suitable for conversion into image maps. These characteristics involve (1) spatial resolution; (2) geometric fidelity; and (3) radiometric response. By carefully controlled processing it is possible to publish TM multicolored image maps of 1:100,000 scale with suitable geometric fidelity and informational content. Moreover, such image maps can be produced within a fraction of the time and cost of a conventional line map once the satellite data is obtained. This paper analyzes the three mentioned characteristics and discusses the processes involved in producing TM image maps.

INTRODUCTION

Starting with Apollo photographs taken in 1969, the United States Geological Survey (USGS) has prepared and published a wide variety of satellite image maps of the Earth. Today 68 such products are sold by the USGS, the majority of which are based on Landsat Multispectral (MSS) data. In addition, the USGS has prepared a larger number of image maps for other U.S. agencies and foreign governments and is the key agency in the mapping of the moon and the planets (Batson, 1984).

Soon after Landsat 4 was launched in 1982 with the Thematic Mapper (TM), the USGS initiated the conversion of TM data into image maps. This program is experimental and, to date, has resulted in three published maps which are currently sold by the USGS. The preparation of these maps and the lessons learned therefrom are covered herein. Three factors or characteristics are recognized as fundamental to image mapping. These are (1) spatial resolution; (2) geometric fidelity; and (3) radiometric response. An analysis of TM data with respect to these three items provides the substance of this paper.

TM CHARACTERISTICS

Spatial Resolution. Since the TM produces 30–meter picture elements (pixels), the spatial resolution of any resultant product is limited by this factor. However, the digital, photographic, and lithographic processing involved also have a profound influence on the resolution of the final printed map product. These processing techniques are discussed separately. TM products are resampled* by NASA into 28.5 X 28.5 m pixels and others resample at a variety of pixel sizes. To keep from degrading resolution, such resampling should be done at a smaller pixel size (higher frequency) than the data being processed. Experience to date indicates that when processing is properly executed, the printed map should be of a scale which produces about 3.3 original pixels per mm. This criterion is based on the ability of the unaided human eye to properly distinguish all features of reasonable contrast that can be displayed in printed (image) form (Colvocoresses, 1984). For the TM this results in the scale of 1:100,000.

Geometric Fidelity. Digital TM data occur in a wide variety of geometric forms. A definitive analysis of NASA–produced data forms is covered by Irons (1983). However, four basic forms are described as follows:

Form 1. Raw data as received from the satellite. No known attempts have been made to analyze or utilize this type of data nor is it generally available to or usable by most agencies. However, NASA has performed a simple geometric correction to compensate for the TM's bi–directional scan mode and has introduced basic radiometric corrections. These data are available in so–called "A type" tape form but the data are difficult to work with and, in so far as is known, has never been utilized to produce a map.

Form 2. Data processed (resampled) by NASA without ground control. The geometry of such data depends on NASA's ability to reconstruct the geometry of the acquisition system, correct the data for geometric anomalies and resample data onto a defined map projection.** This is the standard Thematic Mapper Image Processing System (TIPS) product for areas where ground control is not available and is referred to as "P type" data. Prior to the introduction of TIPS the so–called "Scrounge" system was used which had geometric characteristics similar to that of TIPS.

Form 3. Data processed by NASA with ground control.** This is another standard TIPS product for areas such as the United States where control is available and is also known as "P type" data.

Form 4. Data processed by NASA with or without ground control and resampled a second (or third) time by other agencies.

Any analysis of geometric fidelity is dependent on the form of the data being analyzed.

---

* Resampled refers to the regeneration of a new digital data set which normally has different pixel size, geometry, and radiometric characteristics from the original data set.

** NASA normally casts TIPS data (Forms 2 and 3) on the Space Oblique Mercator (SOM) projection (Colvocoresses, 1974; Snyder, 1978). However, on request, data may be cast on the Universal Transverse Mercator (UTM) or Polar Stereographic (PS) projection depending on whether the area falls between or beyond the 65° parallels.

Raw Data (Form 1.). Insofar as is known no geometric analysis of this raw data has been made. However, it obviously has high internal geometric fidelity as all TM data sets are derived therefrom.

Data resampled by NASA but without ground control (Form 2). Such data exists in several tape formats and has been subjected to a wide variety of geometric analyses with widely divergent results. Canadians (Goodenough, and others, 1983) and EROS Data Center researchers (Thorsmodsgard and De Vries, 1983) report errors (root mean square, or rms) of 200 to 1000 m in positional accuracy whereas others (Welch and Usery, 1984; Batson and Borgeson, 1983) reported rms error in the order of 1 pixel (30 m) or less. Such variations are due to the difference in the form of the data and the various criteria used in the analysis. For example, if one takes the TM data and compares it directly to the computed latitude/longitude indicators, which were estimated without the benefit of ground control, very large errors (approaching 1 km) are bound to result. This accounts for the very large errors reported by Thorsmodsgard and De Vries (1983). The Canadians apparently made measurements on the hard copy image which means their results reflect errors in the digital to analog processor as well as those in the TM data itself. There is ample evidence that NASA's correction algorithms to TM data are excellent and that the original data itself has high internal geometric integrity. The most definitive analysis of this data available is that of General Electric personnel (Brooks, and others, 1984). This analysis indicates that once engineering tests were completed for Landsat 5 and TIPS fully implemented, geometric fidelity meets the design specifications for the system. This means that indicators of latitude/longitude should be within 20 pixels (600 m) and that internal accuracy will average about 0.5 pixel or 15 m. Recent analyses (Welch, and others, 1985) (Borgeson, and others, 1985) also indicates internal geometric accuracy of TM data as generated by the TIPS to be better than 15 m rms. This latter figure of internal accuracy is the key for the mapmakers since there are few areas of the world where some geodetic control is not available to permit elimination of the gross errors in the latitude/longitude indicators. However, displacement due to relief may preclude achieving such accuracies since such diplacement is up to 13% of elevation difference on TM data. Eliminating relief displacement is a slow and costly process and is not currently practiced with TM data. If possible, images should be selected in which areas of extreme relief fall close to the orbital track as this greatly reduces relief displacement.

There is no known published TM map with rms errors of less than 20 m. This is because the various processes required to convert digital data into a published map all introduce additional error. In theory, high quality maps could be made directly from processed (P) tapes data even though no ground control was introduced in producing the P tape. However, known TM image maps as published to date involve additional resampling of the data set (Form 4).

Data processed by NASA with Ground Control (Form 3). This third data form is now generally available for the U.S. as a standard TIPS product in P tape form. Such data eliminates the gross errors of the longitude/latitude indicators and, in theory, should provide better internal accuracy. However, the use of control will not necessarily improve internal geometric accuracy and there is no direct evidence to indicate that such data sets have any higher internal geometric accuracy than those produced without the benefit of ground control. Again there are no known cases where maps have been published from such data without additional resampling.

Data resampled a second (or third) time by a user agency (Form 4). As indicated above both Forms 2 and 3 (without and with ground control) have high internal geometric fidelity and can be directly utilized for producing image maps.*

However, an agency such as the USGS, as a matter of practice, now resamples all such data to be used for mapping. The principal reasons for doing so are three fold: (1) to orient the data according to cardinal directions which is in accordance with standard map quadrangles, (2) to reintroduce geodetic control and thus verify the geometric accuracy of the product, and (3) to cast the data on the specific map projection desired. NASA does offer TM data cast on the UTM projection which is standard for many USGS maps, but due to the data orientation problem, the NASA generated UTM data has not been utilized to date by the USGS to create an image map.

The present procedure used by the USGS also involves a third resampling. This is done because the current digital-to-analog printer used by the USGS (laser beam recorder) is limited to an approximate 9 inch (225 mm) format whereas the final map may be up to a meter in size. Photographic enlargements involve considerable degradation of the image quality. To avoid this degradation, the laser beam recorded data is again resampled and electronically enlarged and otherwise processed by a Hell** scanner/plotter. The Hell produces a hard copy screened transparency rendition of each band from which the press plate can be made. Ways of circumventing this third resampling are now under development (USGS, 1985).

Insofar as is known all published TM maps of reasonably high precision and scale have been made from Form 4 data. The USGS has published three such TM-image maps (USGS 1983, 1984a, b) titled: Dyersburg; Washington, D.C. and Vicinity; and Great Salt Lake and Vicinity. In the cases of Dyersburg and Washington, D.C. and Vicinity, the maps were compiled from single scenes, and since little relief and no mosaicking were involved the data processing was relatively simple. Great Salt Lake and Vicinity involved a 4-image mosaic and considerable relief displacement which degraded the map accuracy.

The geometric accuracy of a published image map depends on the cartographic preparation and lithographic printing as well as the source material. The accuracy of the final product is not specifically known until the map is printed and, even then, this accuracy may vary throughout the press run. The following table is based on measurements made on the published maps.

---

* USGS in the past has produced a sizable number of MSS maps without further resampling on the format of a complete single image. This is a relatively inexpensive and a rapid way to produce an image map. It can be readily applied to TM data and should be considered particularly for areas where standard quadrangle mapping is not well established.

** Any use of trade names and trademarks in this publication is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

ACCURACY OF USGS LANDSAT TM IMAGE MAPS

Map	Scale	Measured Map Error RMS	Measured Map Error 90%	Allowable Map Error 90% (NMAS)
Dyersburg	1:100,000	24 m	40 m	51 m
Wash., D.C. & Vic.	1:100,000	28 m	42 m	51 m
Great Salt Lake & Vic.*	1:125,000	128 m	154 m	64 m

*90% error with registration bias removed = 73 m

Although one of the three maps did not meet National Map Accuracy Standards (NMAS) it is believed that the Standards can be met by changes in procedure which are now being implemented. However, as previously discussed, relief displacement may preclude meeting NMAS in some areas unless complex algorithms, based on digital elevation data, are introduced.

Radiometric Response. The available literature on TM radiometry is voluminous (Barker, 1983) but here are certain facets thereof which are critical to the mapmaker as follows:

1. Band selection. For base image maps on which thematic data may be overlayed, it is customary to use a single waveband and print a monochromatic base map. The six TM bands (thermal excluded) all have certain attributes which might justify their selection as the band to be used. Although band 1 (0.45 – 0.52 µm) was expected to be of primary use for water penetration and water quality, it appears to be the most powerful single band, even over land areas where atmospheric scattering might be expected to degrade the response (Chavez, 1984; Sheffield, 1985). The other five bands have unique characteristics and their use, by themselves or in combination, will depend on the area and type of information to be highlighted on the map. Derivative data sets can also be made from two or more bands by such procedures as ratioing and principal component extraction. Such derivative data sets have not, as yet, proven to be of particular value for image mapping purposes. Band information has been seriously analysed by Chavez (1982) and Sheffield (1985) by computer to determine optimum band selection for a three-color display such as an image map. This type of analysis has also been graphically documented by the USGS (1984c). Although such analysis can be used for band selection, the mapmaker must also weigh other factors such as color conventions and specific user needs for which the computer may not be programmed. Although the USGS had the benefit of a computerized band selection, the final bands and colors selected for the three TM image maps so far produced were altered to accommodate what is perceived as convention and user acceptance.

Since six bands provide 20 combinations and 120 permutations, the selection of band and colors is no trivial task. An attempt is made to meet as wide a variety of user needs as possible, and it is interesting to note that there is considerable commonality in such user needs as expressed to the mapmaker. Two examples of the problems involved in waveband selection for image mapping relate to cultural features and water boundaries. Band 4 (0.76 – 0.90 µm) exhibits a very powerful response for growing vegetation and a somewhat lower response for cultural features such as roads and built-up areas. Thus, for a summer scene with heavy vegetation such as Dyersburg or Washington, D.C. band 4 was not utilized. Culture, which is considered essential in a general purpose image map, was simply overwhelmed by the vegetation response. Band 5 (1.55 – 1.75 µm), having a lower vegetation response, provided a more balanced presentation of culture and was utilized for both Dyersburg and Washington, D.C. Water boundaries are another essential element of any general purpose map and, in the case of Great Salt Lake it was noted that the boundary defined by band 4 was, in places, entirely different from that of bands 5 and 7. It was determined that the band 4 boundary was the more realistic. Moreover, bands 5 and 7 give a relatively low response for snow and the snow covered peaks in the area lost their classic portrayal with either band 5 or 7. Thus, band 4 was selected to present the infrared response for both the open water and land areas for the Great Salt Lake and Vicinity image map. Another factor is that the Great Salt Lake area does not present the dominance of growing vegetation found in the other two areas. An image map need not utilize the same band combination throughout and in the case of Great Salt Lake and Vicinity (USGS, 1984b) different bands were utilized for the open water than for the land. The two data sets were created by utilizing a threshold or radiance boundary in the near-infrared band (band 4) which clearly differentiates open water from land. The actual bands and color utilized on the three image maps published by the USGS are as follows:

BANDS AND COLOR SELECTION FOR USGS LANDSAT TM IMAGE MAPS

	TM Bands (Water)	TM Bands (Land)	Subtractive Color Applied
Dyersburg	#2 (0.52 – 0.60 µm)		yellow
	#3 (0.63 – 0.69 µm)		magenta
	#5 (1.55 – 1.75 µm)		cyan
Wash., D.C. & Vic.	#1 (0.45 – 0.52 µm)		yellow
	#3 (0.63 – 0.69 µm)		magenta
	#5 (1.55 – 1.75 µm)		cyan
Great Salt Lake & Vic.	#1 (0.45 – 0.52 µm)	#2 (0.52 – 0.60 µm)	yellow
	#2 (0.52 – 0.60 µm)	#3 (0.63 – 0.69 µm)	magenta
	#4 (0.76 – 0.90 µm)	#4 (0.76 – 0.90 µm)	cyan

2. Processing alternatives. Band selection is only one of the factors involved in radiometric response. The proper processing of the digital data is also essential to the image mapping process. Since the map itself is lithographed (printed on paper) such processing must be keyed to the printing process (USGS, 1985). The steps involved may include:

   - linear, nonlinear or multilinear stretches of data sets to accentuate desired features or areas.

   - edge enhancement to accentuate boundaries.

   - spatial filtering and feedback to hold each data set (band) to within prescribed radiometric limits and thus tend to equalize band response in local areas where one band would otherwise dominate.

   - thresholding of data sets which permits selective filtering or changes in bands as subscene characteristics undergo significant changes.

   Implementing such processing is quite complex and is still in the development stage. However, the USGS (1985) is publishing technical instructions for the "Preparation of Satellite Image Maps." There are also at least two technical papers (Kidwell and McSweeney, 1984; Chavez 1984) which describes various aspects of the digital and analog processing. The technical description of these processing alternatives is beyond the scope of this paper.

3. Area limitations. As the size of an area to be mapped increases and its characteristics change, the radiometric problems expand in complexity. The areas represented by the three USGS published image maps are quite limited and offer only moderate contrast in response. When one looks at a large state or a country with varied response a basic question arises. Should the several image map sheets involved retain the same response and thus form a continuous and uniform map series or should each sheet be optimized for its own response? This question has not been fully answered but the USGS mapmakers currently favor the view that processing algorithms should change as overall scene response changes. This is the basic principal on which spatial filtering and thresholding is based, but how far this concept can be carried remains to be seen. We do know that a processing algorithm which is optimum for a forested scene is not optimum for a desert scene.

SUMMARY

Thematic Mapper data is suited for image mapping at 1:100,000 and smaller scales and U.S. National Map Accuracy Standards for such scales may be met under most conditions. Informational content can be tailored according to the area involved and the intended use of the image map. The procedures involved in such image mapping are in a rapid state of development and it is expected that the current time and cost of producing such maps will drop in the near future. The USGS currently has programmed 25 space image maps for the coming fiscal year of which 5 are TM. Since TM data are being acquired on a global basis their expanded use in image map form may be expected. Perhaps the image map, based on the TM or other comparable data sources, will one day take its place beside the line map as an accepted tool of our society.

REFERENCES

Barker, J. L., and B. L. Markham, 1983, Introduction to Thematic Mapper Investigations. Proceedings of the Landsat-4 Scientific Characterization Early Results Symposium, NASA/Goddard Space Flight Center, Greenbelt, Maryland, February 22-24, 1983, v. II, p. 1-14.

Batson, R. M., and W. T. Borgeson, 1983, Tests of Low-Frequency Geometric distortions in Landsat 4 Images: Proceedings of the Landsat-4 Scientific Characterization Early Results Symposium, NASA/Goddard Space Flight Center, Greenbelt, Maryland, February 22-24, 1983, v. III, p. 565-570.

Batson, R. M., 1984, Status and Future of U.S. Extraterrestrial Mapping Programs. Proceedings of the International Archives of Photogrammetry and Remote Sensing, v. XXV, part A4, Commission IV, p. 39-47.

Beyer, E. P., J. Brooks, and V. V. Salomonson, 1984, Geometric Correction of Landsat 4 and 5 Thematic Mapper Data. Presented at the Eighteenth International Symposium on Remote Sensing of Environment, Paris, France, October 1-5, 1984, 11 p.

Bender, L. U., M. H. Podwysocki, L. C. Rowan, and J. W. Salisbury, 1983, An evaluation of Landsat-4 Thematic Mapper data for their geometric and radiometric accuracies and relevance to geologic mapping. Proceeding of the Landsat-4 Scientific Characterization Early Results Symposium, NASA/Goddard Space Flight Center, Greenbelt, Maryland, February 22-24, 1983, 5 p.

Borgeson, W. T., R. M. Batson, and H. H. Kieffer, 1985, Geometric Accuracy of Landsat-4 and -5 Thematic-Mapper Images. To be published in a future issue of Photogrammetric Engineering and Remote Sensing.

Brooks, J., E. Kimmer, and J. Su, 1984, Landsat-5 TIPS Geometric Correction Evaluation. Appeared in a Program Information Release (PIR U-1T81-LSD-GS-698) General Electric, Space Division, Philadelphia, PA.

Chavez, P. S., G. L. Berlin, and L. B. Sowers, 1982, Statistical Method for Selecting Landsat MSS Ratios. Journal of Applied Photographic Engineering v. 8, no. 1, February 1982, p. 23-30.

Chavez, P. S., S. C. Guptill, and J. A. Bowell, 1984, Image processing techniques for Thematic Mapper data. American Society of Photogrammetry annual meeting, 50th, Washington, D.C., March 11-16 1984, v. 2, p. 728-743.

Colvocoresses, A. P., 1974, Space Oblique Mercator. Photogrammetric Engineering and Remote Sensing, 1974, p. 921-926.

___________ 1984, The Status and Future of Satellite Image Mapping. Presented at the 18th International Symposium on Remote Sensing of Environment, Paris, France, October 1-5, 1984 4 p.

Goodenough, D. G., E. A. Fleming, and K. Dickinson, 1983, A Preliminary Assessment of Landsat-4 Thematic Mapper Data. Proceedings of the Landsat-4 Scientific Characterization Early Results Symposium, NASA/Goddard Space Flight Center, Greenbelt, Maryland, February 22-24, 1983, v. III, p. 257-272.

Irons, J. R., 1983, An Overview of Landsat–4 and The Thematic Mapper. Proceedings of the Landsat–4 Scientific Characterization Early Results Symposium, NASA/Goddard Space Flight Center, Greenbelt, Maryland, February 22–24, 1983, v. II, p. 15–46.

Kidwell, R. D., and J. A. McSweeney, 1984, Art and Science of Image Maps. Proceedings, ASP 51st Annual Meeting, v. 2, March 10–15, 1985, Washington, D.C., Technical Papers, Theodolite to Satellite, v. 2, p. 770–782.

Podwysocki, M. H., L. U. Bender, N. Falcone, and O. D. Jones, 1983, Evaluation of Landsat–4 Thematic Mapper Data for Their Geometric and Radiometric Accuracies. Proceedings of the Landsat–4 Scientific Characterization Early Results Symposium, NASA/Goddard Space Flight Center, Greenbelt, Maryland, February 22–24, 1983.

Sheffield, C., 1985, Selecting Band Combinations from Multispectral Data. Photogrammetric Engineering and Remote Sensing, v. 51, no. 6, June 1985 p. 681–687.

Thormodsgard, J. M., and D. J. DeVries, 1983, Geodetic Accuracy of Landsat 4 Multispectral Scanner and Thematic Mapper Data. Landsat–4 Scientific Characterization Early Results Symposium, NASA/Goddard Space Flight Center, Greenbelt, Maryland, February 22–24, 1983, v. III.

Snyder, J. P., 1978, The Space Oblique Mercator Projection. Published in Photogrammetric Engineering and Remote Sensing, v. 44, no. 5, May 1978, p. 585–596.

U.S. Geological Survey 1983, Dyersburg 1:100,000–Scale Satellite Image Map.

U.S. Geological Survey, U.S. Geological Survey, 1984a, Washington, D.C. and Vicinity 1:100,000–Scale.

U.S. Geological Survey, 1984b, Great Salt Lake and Vicinity, Utah, 1:125,000–Scale Satellite Image Map.

U S. Geological Survey, 1984c, USGS Landsat Thematic Mapper (TM) Color Combinations, Washington, D.C. and Vicinity: USGS Miscellaneous Investigation Report designated as I–1616.

U.S. Geological Survey, 1985, National Mapping Program, Technical Instructions, Printing of Satellite Image Maps Procedure Manual..

Welch, R., and L. E. Usery, 1984, Cartographic Accuracy of Landsat–4 MSS and TM Image Data: Published in the IEEE Transactions on Geoscience an Remote Sensing, v. GE–22, no. 3, May 1984.

Welch, R., T. R. Jordan, and M. Ehlers, 1985, Comparative Evaluations of the Geodetic Accuracy and Cartographic Potential of Landsat– and Landsat–5 Thematic Mapper Image Data: To be published in Photogrammetric Engineering and Remote Sensing, v. 51, no. 9, September 1985.