Image Mapping with the Thematic Mapper

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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 make them suitable for conversion into image maps. These characteristics involve (1) spatial resolution, (2) geometric fidelity, and (3) spectral response. By carefully controlled processing, it is possible to publish TM multicolored image maps of 1:100,000 scale with suitable geometric fidelity and information 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 are 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 U.S. 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 scanner (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 major factors or characteristics recognized as fundamental to image mapping are (1) spatial resolution, (2) geometric fidelity, and (3) spectral response. An analysis of TM data with respect to these three items provides the substance of this paper, and, in addition, the actual printing process is outlined. The TM records six wavebands of relatively high resolution and one (thermal) band of lower resolution. This paper does not cover mapping with the thermal band although it is recognized as having cartographic potential.

TM SPATIAL RESOLUTION

Because the TM records 30-metre 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 and are discussed separately. TM products are resampled* by NASA into 28.5- by 28.5-m pixels, and others may 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

TM GEOMETRIC FORMS AND FIDELITY

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

Form 1. Raw data, as received from the satellite, on which 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, insofar as is known, no geometric analysis of these raw data has been made. However, it obviously has high internal geometric consistency as all TM data sets are derived therefrom.

Form 2. Data processed (resampled) by NASA *without* ground control. The geometric integrity of such data depends on NASA's ability to reconstruct the

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

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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. Such data exist in several tape format and have been subjected to a wide variety of geometric analyses with widely divergent results. Canadians (Goodenough *et al.*, 1983) and EROS Data Center researchers (Thormodsgard and De Vries, 1983) reported 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 on the order of 1 pixel (30 m) or less. Another report (Bender *et al.*, 1983) indicated an rms error of about 70 m. 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 them 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. These are the absolute or translational errors and have nothing to do with the internal geometry of the data sets. However, this accounts for the large errors reported by Thormodsgard and De Vries (1983). The Canadians (and others) applied control but made measurements on hard copy images, which means their results reflect errors in the digital to analog processor as well as those in the original TM data. There is ample evidence that NASA's correction algorithms to TM data are excellent and that the original data have high internal geometric integrity. The most definitive analysis of this data available is that of General Electric personnel (Brooks *et al.*, 1984). This anlaysis indicates that, once engineering tests were completed for Landsat 5 and TIPS was 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 *et al.*, 1985) (Borgeson *et al.*, 1985) also indicate 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 mapmakers, because 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 in mountainous areas may preclude achieving such accuracies because such displacement is up to 13 percent of elevation differences on TM data. The worst case occurs when the image point is 92.5 km from the image nadir. The satellite altitude is 705 km and the relief displacement is defined (approximately) by the tangent of the viewing angle with the vertical or, in this case, 92.5 divided by 705 which is 0.13 (13 percent). Eliminating relief displacement is a slow and costly process and requires an extensive network of control or the use of a digital elevation model. Applying such a model to correct for relief displacement is well within the state-of-the-art, but, insofar as is known, Landsat data are not being so processed. If possible, images should be selected in which areas of extreme relief fall close to the orbital groundtrack as this greatly reduces relief displacement (Wong *et al.*, 1981). Even in an area such as Mount McKinley, which rises over 5000 meters from its base, the careful selection of portions of Landsat images lying relatively close to the orbital tracks are permitting the laying of a reasonably accurate 1:250,000-scale mosaic (MSS) of this area of extreme relief *without* the use of a digital elevation model.

In theory, high-quality maps could be made directly from processed P tape 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).

Form 3. Data processed by NASA *with* ground control.† The standard large-scale USGS maps provide such control for the United States. Its use by NASA, EROS Data Center, and others is a rather complex operation which is described by Eric Beyer (General Electric Co., Valley Forge Space Center, P.O. Box 8555, Philadelphia, PA 19101) in his draft paper, "An Overview of the Thematic Mapper Geometric Correction System (undated)." 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. This third data form is now generally available for the United States as a standard TIPS product in P tape form (Beyer *et al.*, 1984). Such data eliminate the gross errors of the latitude/longitude 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 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.

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

†NASA normally casts TIPS data (Forms 2 and 3) on the Space Oblique Mercator (SOM) projection (Colvocoresses, 1974; Synder, 1978); the SOM produces a near minimum of scale distortion for a single image. 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.

time by other agencies. Any analysis of geometric fidelity is dependent on the form of the data being analyzed. 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 a second time at their EROS Data Center. The principal reasons for doing so are threefold: (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 have not been utilized to date by the USGS to create a TM image map.

The present procedure used by the USGS also involves a third resampling. This is done because the current digital-to-analog printers used by the USGS are limited to an approximate 9-inch (225-mm) format, whereas the final map may be up to 1 meter in size. The USGS currently operates two digital-to-analog printers: (1) a Goodyear High Resolution Image Recorder† and (2) a MacDonald Dettwiler Color FIRE 240. The Goodyear utilizes a laser beam and records color separation in black and white on film. The MacDonald Dettwiler prints out a color image on multi-emulsion film. Both printers have high geometric fidelity. Photographic enlargements involve considerable degradation of the image quality. To avoid this degradation, the recorded data are again resampled, electronically enlarged, and otherwise processed by a Hell scanner/plotter which introduces no measurable distortion. The Hell instrument produces a screened transparency of each band from which pressplates can be made. Ways of circumventing this third resampling are now under development (USGS, 1985).

All known published TM maps of reasonably high precision and large scale have been made from Form 4 data. The USGS has published three such TM-image maps (USGS, 1983; USGS, 1984a; USGS, 1984b) 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, because little relief and no mosaicking were involved, the data processing was relatively simple. Great Salt Lake and Vicinity involved a four-image mosaic and considerable relief displacement, both of which degraded the map's accuracy. The geometric problems of digital mosaicking deserves additional comment. Normally each data set (image) is not cast on the same projection as the mosaic and thus must be resampled to the new projection. As the data sets are tied together, discontinuities invariably show up as a displacement or shear along the seam. These displacements can be minimized by selecting control near the seam and using it for both images involved. Even so, geometric image matching will involve some local adjustment along the seam, which can be considerable in areas of high relief. The Jet Propulsion Laboratory pioneered the development of digital mosaics (Zobrist *et al.*, 1983) which the U.S. Geological Survey has developed as their Large Area Mosaicking System (LAMS), now routinely used as their EROS Data Center for the laying of Landsat and other space imaging system mosaics.

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. Table 1 is based on measurements made on the published maps.

Although one of the three maps did not meet National Map Accuracy Standards (NMAS), it is believed that those standards can be met by changes in procedure that are now being implemented. Others (Welch *et al.*, 1985) have discussed TM accuracy as being commensurate with maps scales as large as 1:24,000 under ideal conditions. However, only a limited number of features, such as a straight or circular road, can be defined to the 7.5-m (rms) allowable error of 1:24,000 scale. Producing a general purpose TM image map that meets our accuracy standards at the 1:100,000 scale is considered to be a realistic goal. Even at this scale relief displacement

TABLE 1. ACCURACY OF USGS LANDSAT TM IMAGE MAPS BASED ON ROOT-MEAN-SQUARE (RMS) ERROR AND NATIONAL MAP ACCURACY STANDARDS (NMAS) WHICH REQUIRE 90% OF ERRORS TO BE LESS THAN 0.02 INCHES (0.5 MM) ON PUBLISHED MAP

		Measured Map Error		Allowable Map Error
Map	Scale	RMS	90%	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 = 79 m.

* USGS in the past has produced a sizable number of MSS maps without further resampling. These are based on the format of an image which is tilted with respect to cardinal directions. Using the image format is a relatively inexpensive and 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.

will preclude meeting NMAS in some areas unless complex procedures, which incorporate digital elevation data, are introduced.

TM SPECTRAL RESPONSE

The available literature on TM spectral response is voluminous (Barker and Markham, 1983), but here are certain facets that are critical to the mapmaker:

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 of choice. Although band 1 (0.45 to 0.52 μm) was expected to be of primary use for water penetration and water quality, it appears to be the most powerful of the three visible spectrum bands, 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. New 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 analyzed (Chavez *et al.*, 1982; 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 of color. Because 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 to 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 to 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, quite different from that of bands 5 and 7, which tend to display wet soil as water. It was determined that the band 4 boundary was the more realistic. Moreover, bands 5 and 7 gave a relatively low response for snow, and the snow-covered peaks in the area lost their classic portrayal with either band 5 or 7. Another factor is that the Great Salt Lake area does not present the dominance of growing vegetation found in the other two areas. 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.

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 shown in Table 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. Because the map itself is to be lithographed on paper, such processing must be keyed to the printing process (USGS, 1985). The steps involved may include:

- *Resampling of data* for geometric as well as radiometric reasons. The algorithm utilized will affect the quality of the final product. Nearest neighbor and cubic convolution are the two algorithms in most common use (Ragland and Chavez, 1976), and cubic convolution is considered to be the better for mapping purposes, as it smoothes the blocky pixel structure of original and nearest-neighbor data without appreciable loss of form or contrast.
- *Spectral enhancement* of data to accommodate the density range of the image medium, which is normally film (Ragland and Chavez, 1976). This includes mass adjustment of the digital data and linear, multilinear, and nonlinear stretches and compression of data sets (Schowengerdt, 1983). This procedure alters response in order to increase contrast between important features of similar response. For example, recorded data of an agricultural area may show very slight radiometric differences among various crop types. By stretching or expanding these differences in the digital domain, the analog (image) version will show better contrast between the crop types. On the other hand, some other data which do not involve crops will have to be compressed to hold the overall data set to within usable limits. In practice no more than ten gradations of gray can be recognized by the

TABLE 2. BANDS AND COLOR SELECTION FOR USGS LANDSAT TM IMAGE MAPS

Map	TM Bands (wavelength)		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.	1 (0.45 - 0.52 μm)		yellow
& Vic.	3 (0.63 - 0.69 μm)		magenta
	5 (1.55 - 1.75 μm)		cyan
	Water	Land	
Great Salt	1 (0.45 - 0.52 μm)	2 (0.52 - 0.60 μm)	yellow
Lake & Vic.	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

human eye (Robinson, 1952). Thus, the purpose of stretching/compressing is to assist in the visual detection of the important feature differences in the scene.

- *Edge enhancement algorithms* to accentuate boundaries or edges. These are a form of so-called high-pass filters which accentuate local feature differences. Such procedures must be carefully applied or else they create undesirable artifacts in the imagery. However, edge enhancement, when properly executed, increases the informational content and usability of the data in the image form (Ragland and Chavez, 1976). An example of the algorithm that may be used involves a 3 by 3 block of pixels. The new value for the center pixel is computed as nine times the center pixel value minus the sum of the eight surrounding pixel values. This simple algorithm is one of several which creates an artificial increase in the contrast as a boundary is crossed.
- *Spatial filtering and addback* 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. Again care and judgment must be used as filtering can reduce low frequency contrast to the point where important boundaries, such as an urban limit, may be lost. Filtering can be selectively applied to individual bands or to all bands when necessary. A look at an image or the histogram of occurrence versus response of an individual band will indicate whether filtering may be required (Chavez *et al*, 1984).
- *Thresholding of data sets* which permits selective filtering or changes in bands as scene characteristics undergo significant changes. This procedure is particularly important for scenes of very high contrast or where more than one major category must be displayed in detail. An example is an area that is part open water and part land, or part irrigated crop-land and part non-vegetated land. There is no reason to apply the same stretch, filter, or even bands to these unlike features, and thresholding provides an automated method for making the needed changes while still in the digital domain (Chavez *et al.*, 1982).

Area considerations. The areas represented by the three USGS published image maps are quite small and offer only moderate contrast in response. As the size of the area to be imaged mapped increases so do the complexities. Instead of a single image, one soon must go to a mosaic which involves data sets with different radiometric response. A system such as LAMS provides for the radiometric matching of the separate images. When one looks at a large State or a country with greatly varied spectral response, a basic question arises. Should the several image map sheets (or group of 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 principle on which spatial filtering and thresholding are based, but how far this concept can be carried remains to be seen. We do know that a processing algorithm that is optimum for a forested area is not optimum for a desert or shallow water area. We also suspect that, in addition to changing our algorithms as a function of scene response, we may deliberately create spectral discontinuities as we move across certain map sheet or other geographic boundaries.

Implementing the various processing alternatives is a complex procedure still in the development stage. However, the USGS is preparing technical instructions for the "Preparation of Satellite Image Maps." There are also at least two technical papers (Kidwell and McSweeney, 1984; Chavez *et al.*, 1984) that describe various aspects of the digital and analog processing.

PRINTING OF IMAGE MAPS

The lithographic printing of maps may appear to be a rather simple mechanical operation but, in fact, it is highly complex. Unless the printing process is carefully planned and precisely executed, it will seriously degrade the quality of the final product. A detailed description of the printing process is covered by Stoessel (1972) and USGS (1985), but some of the critical points that must be covered are listed as follows:

- Use of stable materials

- Geometric matching of various manuscripts
- Optimum screening of color separates*
- Proper distribution and range of dot patterns
- Proper selection of papers† and inks
- Continous monitoring and quality control of (1) press registration and (2) ink flow
- Proper curing, trimming, and shipping of printed maps
- Proper storage of reproducibles

SUMMARY

Thematic Mapper data are 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 to the area involved and the intended use of the image map. The procedures involved in such image mapping are in a state of rapid development, and the time and cost of producing such maps, once the satellite data are obtained, is far less than a corresponding line map. The USGS currently has programmed 25 space image maps for fiscal year '86 of which five are TM. Because 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 a widely accepted tool of our society.

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*Screenless printing has been successfully utilized by the USGS, but the use of conventional 175 line-per-inch screens is the currently preferred procedure for multicolored image maps.

† USGS has successfully experimented with image printing on plastic, but paper is still the standard medium used.

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This Conference on Education in Cartography, Geodesy, Geographic Information Systems, Photogrammetry, Remote Sensing, and Surveying — hosted by the University of Wisconsin in cooperation with the American Congress on Surveying and Mapping, the American Society for Photogrammetry and Remote Sensing, the Institute for Land Information, and the Wisconsin Society of Land Surveyors — will address the following suggested topic areas:

- Changing Educational Requirements
- Curriculum Development
- Emerging Technologies
- Computers in Education
- Accreditation
- Continuing Education
- Job Market/Job Placement
- Equipment
- Program Administration
- Research Needs
- Textbooks and other Resource Materials
- Programs for 2 Year/4 Year/Graduate Level
- History of Surveying Education
- Student Professional Organizations

Those wishing to present a paper should submit an abstract, not to exceed 200 words, by *15 November 1986* to

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