Reflectance Enhancements for the Thematic Mapper: An Efficient Way to Produce Images of Consistently High Quality

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ABSTRACT: The reflectance enhancement algorithm, originally developed for the Landsat Multispectral Scanner, has been found to be a reliable method for producing consistantly high quality photographic images from satellite data. This paper describes the algorithm, and how it was adapted to Thematic Mapper Data. Four enhancements have been developed for forestry applications for a range of biophysical and phenological conditions. The principal characteristics of these enhancements are described.

INTRODUCTION

ONE OF THE MOST DIFFICULT PROBLEMS facing researchers has been to develop reliable methods for producing high quality hard copy imagery from digital satellite data. One problem which resisted solution for many years was the development of digital image recorders. These devices were plagued with problems of poor reliability and poor geometric and radiometric linearity and stability. Recorder generated artifacts such as image striping were another serious problem. Most of these problems have been solved now, but national and international organizations with a mandate to produce satellite image film products are still confronted with another difficult challenge: to find a way to ensure that digital satellite data from diverse geographic areas, with a wide range of solar illumination and ground reflectance conditions, can be well matched to the limit dynamic range of the photographic medium.

This problem is well illustrated in Figure 1, which shows the histograms of scene radiance for three different scenes of western Canada acquired during the summer of 1985. Within a given scene, the dynamic range occupied by the majority of the data is generally a small fraction of the dynamic range of the sensor in each band, particularly in bands 1, 2, 3, and 7. Note also that the histograms of the forested scenes have a long tail extending towards higher radiance values. This represents the relatively small number of pixels of unvegetated ground (recent clearcuts, mountain peaks, settlements, bare soil, and dry grass lands). The situation with global coverage is much more varied because of the wide variety of ground cover types, solar illumination angles, and atmospheric conditions encountered by Landsat in its daily travels. Yet the data from many Landsat scenes occupy only a small fraction of the wide dynamic range allocated to the Thematic Mapper to allow for global coverage.

To make photographic images from the digital data, film is exposed, one pixel at a time, by a light source whose intensity is modulated to be proportional to the radiance of each pixel. If a color image is being created, blue, green, and red light sources are modulated independently to expose the three dye layers sensitive to those three colors.

Researchers learned quickly that a unity transformation between the digital number (DN) representing radiance on an eight-bit (0 to 255) scale and photographic density (typically in a range from about 0.2 to 2.0) resulted in very unsatisfactory photographic products. The reason for this was the very narrow range of DN occupied by the data in most individual scenes, compared to the full dynamic range of the sensor, as we have been discussing. This problem is generally solved by "contrast stretching" the data, that is, by using a transformation between DN and photographic density which results in a portion of the digital dynamic range being stretched over a wider range of photographic density.

Researchers devising contrast stretching transformations have always been confronted with a serious conflict between the dual requirements of generality and scene-specificity.

Image interpreters always want the "best possible" rendition of their particular scene's information content. Many transformations have been defined which are based on the probability density functions of the particular scene being processed.

For example, a linear transformation which maps the data at the one-percentile level of the cumulative probability density function into the minimum photographic density (D_{min}) and the 95-percentile level into the maximum photographic density (D_{max}) often produces a photographic image which has suitable contrast. However, this approach is so scene specific that another scene recorded with the same technique may portray similar ground cover types quite differently in terms of color and brightness, if other objects in the scene alter its probability density function significantly. We have found this to be a serious problem for vegetated scenes in Canada where bright, ephemeral targets such as clouds, ice, and snow can drastically alter the scene statistics and, hence, the appearance of vegetation on the recorded image. It becomes difficult or impossible for an image interpreter to distinguish real differences between two images from differences which are artifacts of the enhancement process.

The alternative extreme, which is to record all data with the same transformation, has been equally unsatisfactory because of the variety of ground cover types, and user interests, as well as illumination and atmospheric conditions encountered over a country as large as Canada or a planet as diverse as the Earth.

One successful solution to this problem has been the development of reflectance enhancements which are tailored to particular information requirements for particular biophysical areas.

For Landsat Multispectral scanner (MSS) data we developed a rangeland enhancement for range managers (Brown *et al.*, 1981; Ahern *et al.*, 1982) and subsequently mixedwood and softwood enhancements for foresters (Ahern, 1984). During the development of these enhancements, we found that it was important to use a non-linear transformation for data distributions in which a large portion of the data of interest consisted of low

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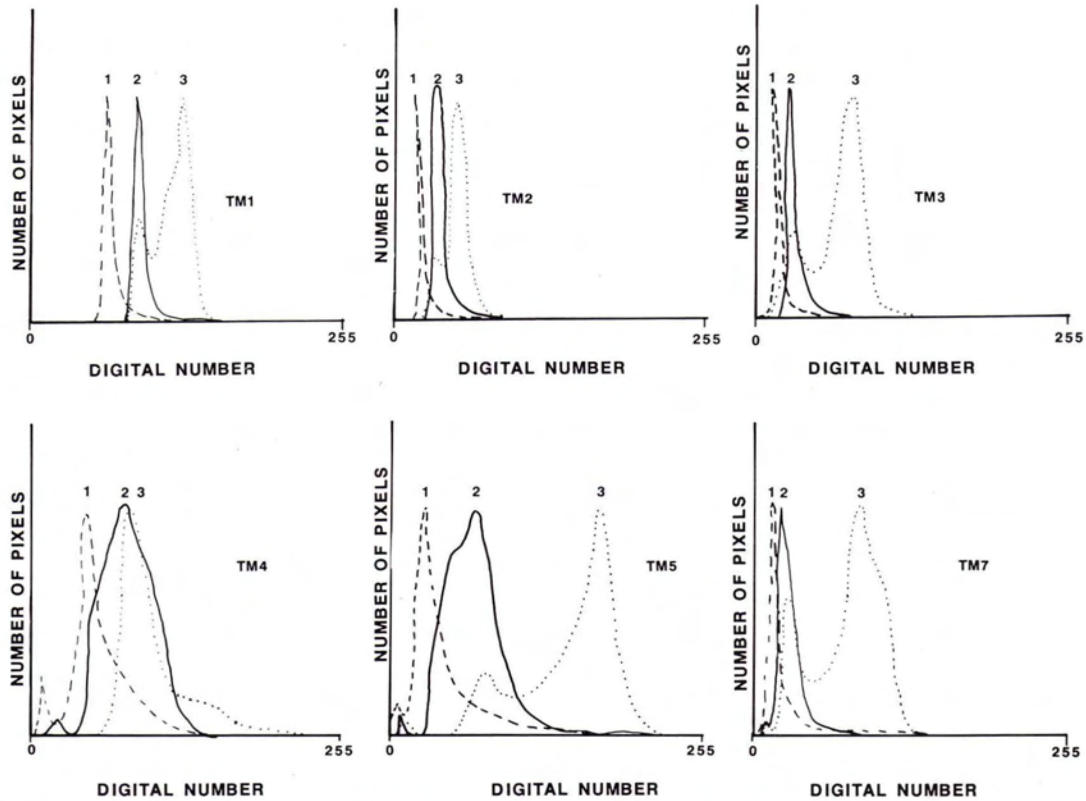


FIG. 1. Histograms of the scene radiance values measured by the Thematic Mapper in the six reflective bands for three different scenes. Scene 1, Path 52, Row 21, Quadrant 4: Acquired 17 August 1985. This is a predominantly conifer covered area of interior British Columbia. Scene 2, Path 43, Row 22, Quadrant 1: Acquired 30 July 1984. This is an area of mixedwood boreal forest. Scene 3, Path 40, Row 25: Acquired 12 July 1985. This is a prairie area in south central Alberta. The pronounced bimodal distribution is a consequence of two distinct ground-cover types: irrigated farmland with abundant green vegetation, and dry farmland and rangeland with abundant brown vegetation and bare soil.

radiance values, but which also contained a long tail extending to high radiance values. A square root function was chosen which increased the contrast of the low radiance data and which compressed, but did not truncate, the contrast of the high radiance data. This square-root function is shown in Figure 2.

The Canada Centre for Remote Sensing has been producing reflectance-enhanced Landsat MSS images for rangeland (Brown *et al.*, 1981) since 1982 and for forestry since 1984 (Ahern, 1984), using the automated technique described by Ahern *et al.* (1982) and reviewed in this section.

This paper describes the development of four reflectance enhancements for forestry for the Thematic Mapper (TM) where we were faced with the problems of learning to use new spectral bands and how to choose appropriate color combinations, as well as to modify our atmospheric and illumination corrections for the TM bands.

APPROACH

Conceptually, the reflectance enhancement process can be thought of as three sequential linear radiometric transformations which are applied to calibrated linear digital data:

(1) A transformation from digital numbers (DN) to radiance values (L) using published radiance calibration constants derived from Barker's (1983) calibration data

$$L = A_0 \, \mathrm{DN} + A_1. \tag{1}$$

(2) A transformation from radiance (L) to reflectance factor (R)

$$R = \frac{\pi (L - L_p)}{E\tau} \tag{2}$$

where L_p is the path radiance,

L is the total upwelling radiance (scene plus sky),

τ is the atmospheric transmission, and

E is the downwelling irradiance (direct sun plus sky) on the target.

(3) Transformation to an eight-bit (0 to 255) digital number (DN′) incorporating an appropriate contrast stretch (linear or square root) between predefined minimum and maximum reflectance limits, R_{min} and R_{max}

$$\mathrm{DN}' = 255 \frac{R - R_{min}}{R_{max} - R_{min}} \text{ (linear)} \tag{3}$$

or

$$\mathrm{DN}' = 255 \sqrt{\frac{R - R_{min}}{R_{max} - R_{min}}} \text{ (square-root)} \tag{4}$$

Negative values of DN′ are set equal to 0 and values greater than 255 are set equal to 255.

In practice, the three transformations can be combined into one linear equation:

$$\mathrm{DN}' = A \, \mathrm{DN} + B \tag{5}$$

where

$$A = \frac{255 \pi A_0}{E\tau (R_{max} - R_{min})} \tag{6}$$

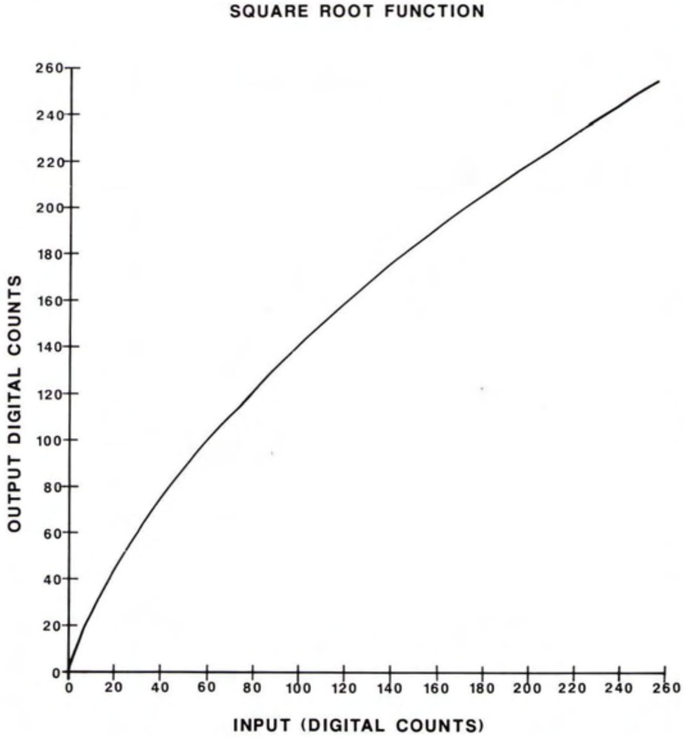


FIG. 2. Square-root transformation used for data distributions with many low-radiances pixels but with a long tail of data of interest extending to high radiance values. All bands of scene 1 (Figure 1) have such a distribution.

and

$$B = \frac{255}{R_{max} - R_{min}} \left[\frac{\pi (A_1 - L_p)}{E\tau} - R_{min} \right]. \quad (7)$$

Although this approach is quite straightforward in concept, two tasks which presented particular obstacles to operational application of the method were to find a reliable routine way to determine the atmospheric and illumination transformation variables E, τ, and L_p, and to define appropriate values for R_{max} and R_{min}.

Atmospheric and Illumination Corrections

The atmospheric and illumination corrections are derived from the scene content alone. The mean scene radiance provides an estimate of the average scene albedo, and the histogram lower bound gives an estimate of the path radiance. Together with geometrical factors derived from the latitude, longitude, date, and time, these estimates are used with a radiative transfer model (Turner and Spencer, 1972; O'Neill *et al.*, 1978; Ahern *et al.*, 1982) to provide estimates of the total downwelling irradiance and the atmospheric transmission.

Our success with a large volume of routine Landsat MSS image production since 1982 gave us confidence that this approach to deriving an atmospheric and illumination correction is sound and robust, so we adopted the same approach for the Thematic Mapper. Thirty-two TM scenes which contained clear water bodies were used to derive a relationship between path radiance and the histogram lower bound, using our technique to derive path radiance over clear water bodies described in 1977 (Ahern *et al.*, 1977), and regression analysis as used for the MSS (Ahern *et al.*, 1982). The relationship developed is presented in Table 1.

However, we found that the variability in path radiance and histogram lower bound in TM band 5 is comparable to ± 1 DN, which in turn is comparable to the noise-equivalent-radiance (Barker, 1983). This is shown in Table 2. The band 7 histogram consistently shows more cases of DN = 0 than one would expect by extrapolating from the number of values at DN = 3, DN = 2, and DN = 1. This indicates that the zero level is set too low to record the negative-going noise accurately. The actual standard deviation is therefore larger than indicated in Table 2. These conditions prevent us from making meaningful estimates of path radiance in bands 5 and 7. Because the path radiance and its variability are small in bands 5 and 7, we decided to incorporate a correction for a standard atmosphere for these bands, rather than trying to measure the actual atmosphere. This approach has not presented any problems in extensive testing.

The radiative transfer model currently used for the MSS was modified to operate for the TM bands. The radiative transfer model is an interpolation routine which uses results calculated by a discrete ordinate method program generated by O'Neill *et al.* (1978). As for the MSS, we use Deirmendjian's (1969) continental haze *L* aerosol phase function as tabulated by Valley (1965). Valley's tabulation covers the range 450 nm to 1190 nm. Because the phase function varies very slowly from with wavelength, we extrapolated the phase function to 1.65 micrometres for TM band 5 and to 2.2 micrometres for TM band 7. We feel that the choice of phase function is somewhat arbitrary and possibly unrealistic, so a re-examination of all aspects of our radiative transfer model is in progress.

Once we had derived the relationship between path radiance and histogram lower bound and developed a simple algorithm to detect the histogram lower bound automatically and reliably, the appropriate software to correct Thematic Mapper data was implemented on our Landsat image production system, MOSAICS (Friedel and Fisher, 1987).

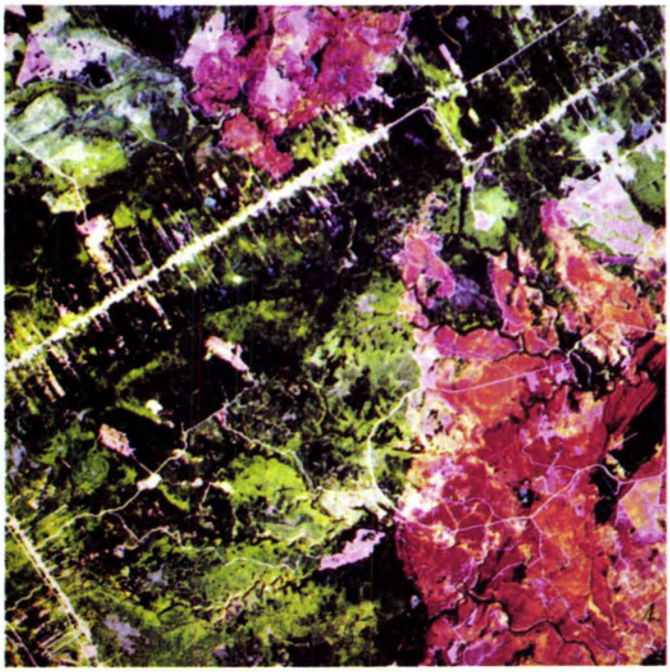
Reflectance Limits for Forestry

Forestry has become one of the most important applications of Landsat data in Canada (Ryerson, 1987), and foresters often use TM images to update their maps for logging, roads, and burned areas. The initial development of TM enhancements was for forestry, to satisfy both foresters and other users (such as those involved in wildlife habitat studies or biophysical inventories) who require consistent enhancements of forested areas.

The new blue and shortwave infrared bands on the Thematic Mapper presented an opportunity to provide additional information of value to foresters, but a challenge to determine exactly what new information is present and to determine how to record the data on film so that most, if not all, of the information is readily interpretable.

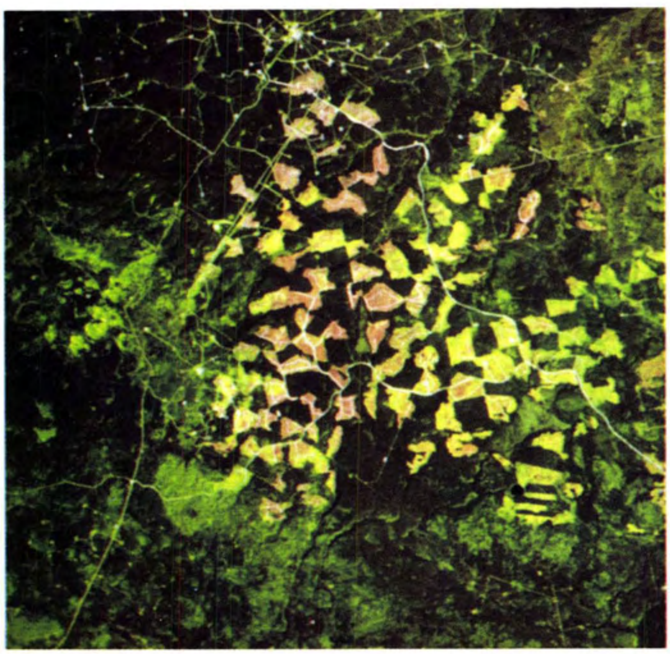
In order to learn about the new capabilities of Thematic Mapper images, we carried out joint studies of custom-enhanced Thematic Mapper images with forest inventory agencies in four provinces. The areas chosen include most of Rowe's (1972) forest regions of Canada: Montane, Sub-alpine, Columbia (British Columbia), Boreal (Alberta and Ontario), Great-Lakes, St. Lawrence (Ontario) and Acadian (New Brunswick). The TM scenes studied are listed in Table 3. These studies established which information was of greatest interest to the cooperating agencies, and how to enhance Thematic Mapper data to portray as much information as possible. Many of the results of these studies have been reported previously (Horler *et al.*, 1983; Horler and Ahern, 1986; Ahern and Archibald, 1986). Using the transformation to reflectance described earlier, we next determined the minimum and maximum reflectance limits corresponding to the digital number (DN) breakpoints which produced the enhancements used in our studies. As in the case of the MSS (Ahern, 1984), we also had to choose between a linear and a square-root transformation for the relationship between input digital number and output photographic density.

We found that the reflectance limits and transformation function (linear or square-root) which produced satisfactorily



(A)

(B)



(C)

(D)

PLATE 1. These examples show the four Thematic Mapper reflectance enhancements for forestry: mixedwood, softwood, boreal, and leaf-off. The mixedwood and softwood enhancements employ the color assignments TM3 = blue, TM4 = green, TM7 = red to emphasize the burned areas in each image. The boreal and leaf-off enhancements employ the color assignments TM3 = blue, TM4 = green, TM5 = red. In both cases a natural (green) appearing rendition of green vegetation results. In all cases conifers are dark green, deciduous trees are brighter green, recent cutovers are magenta, and revegetating cutovers are light green. Burned areas in the 3, 4, 7 band combination appear bright red. (a) Mixedwood enhancement, north-central New Brunswick, Path 10, Row 28, acquired 14 August 1986. (b) Softwood enhancement, southeast British Columbia, Path 42, Row 25, acquired 8 August 1984. (c) Boreal enhancement, central Alberta, Path 44, Row 22, acquired 28 August 1986. (d) Leaf-off enhancement, central Alberta, Path 44, Row 22, acquired 15 October 1986.

exposed black-and-white images of individual bands resulted in a good exposure whenever those bands were used in a three-color combination, independent of the colors to which they were assigned (blue, green, or red). This is an important finding because it allows us to specify the reflectance limits for particular enhancements without regard to the color assignments. The

TABLE 1. REGRESSION RELATIONSHIP BETWEEN HISTOGRAM LOWER BOUNDS AND PATH RADIANCE FOR BANDS 1-4

	$L_p = A * HLB + B$	
Band	A	B ($wm^{-2}sr^{-1}\mu m^{-1}$)
1	1.06 ± 0.06	−0.4 ± 1.2
2	1.15 ± 0.11	−1.0 ± 1.5
3	1.21 ± 0.12	−0.6 ± 1.2
4	1.18 ± 0.06	0.2 ± 0.3

TABLE 2. VARIABILITY IN TM BAND 5 AND 7 HISTOGRAM LOWER BOUNDS

	TM 5	TM 7
Mean value of histogram lower bound (DN)	1.56	0.03
standard deviation (DN)	1.50	0.18
standard deviation (% reflectance)	0.25	0.29

color assignment can be specified by the user to suit his or her particular preferences or requirements. In the course of developing the enhancements for forestry, we have determined the important characteristics of a number of particularly effective color assignments for forestry applications. These are listed in Table 4. Because the TM1, TM2, TM3 band combination is a natural color rendition, many foresters ask whether it is a good band combination for their purposes. We have found that it is sensitive to contrast between vegetation and bare soil, but has very little vegetation information (Table 4).

From our studies with trial enhancements, we determined that four different sets of reflectance limits and functional forms would be adequate to produce good enhancements of our test scenes.

The reflectance limits and functional forms for the forestry enhancements which we have chosen for operational production are presented in Table 5.

RESULTS

RADIOMETRIC CORRECTION AND ENHANCEMENT ALGORITHM

The radiometric correction and enhancement algorithm which is implemented on MOSAICS is indicated schematically in Table 6. It incorporates all of the incremental advances made at the Canada Centre for Remote Sensing since we began producing Landsat 1 data in 1972. These include the use of the scene mean and variance to derive detector equalization constants as developed by Strome *et al.* (1975), the histogram accumulation and faulty data rejection algorithm introduced by Ahern and Murphy (1978), saturated detector compensation introduced by Murphy (1981), and the zero-level drift correction for TM developed by Murphy *et al.* (1985), as well as the image enhancement techniques described in this paper.

FOREST ENHANCEMENTS

We have defined four forest enhancements (Table 4) which seem from our testing to result in high quality TM film products for all forested regions of Canada for three seasons–spring, summer, and fall. Examples of these four enhancements are shown in Plate 1. The main feature of these enhancements are described below.

Mixedwood. The mixedwood enhancement is very similar to the mixedwood enhancement defined for the Landsat Multispectral Scanner (Ahern, 1984). It uses a linear functional form and a high reflectance upper limit for band 4 to de-emphasize the high near-infrared reflectance of the dense areas of broadleaf trees commonly found in the Great Lakes-St. Lawrence and Acadian forest regions.

Softwood. Like the mixedwood enhancement, the softwood enhancement is very similar to that defined previously for the Multispectral Scanner. In the softwood enhancement, a lower reflectance upper limit and a square-root transformation serve to emphasize the TM4 reflectance, which is considerably lower for conifers than for deciduous trees.

Boreal. Our experience with the MSS indicated that the mixedwood enhancement did not provide enough emphasis for the deciduous trees commonly found in the boreal forest (Populus spp) and Birches (Betula spp), but the softwood enhancement could not be used because the infrared band often saturated for deciduous stands. The boreal enhancement was derived as an intermediate product to satisfy the requirement for an enhancement suited to the vast area of boreal forest in Canada.

Leaf-off. Difficulty in producing good Landsat MSS images during the snow-free leaf-off period (approximately April to mid-May, and late October to early December) indicated a need for a particular enhancement for that time of year. The leaf-off enhancement has produced good images of Alberta in April and October, but more experience will be needed nationwide before we can be sure it is optimally specified with the parameters in Table 4.

SUMMARY AND CONCLUSIONS

This paper describes the development of a reflectance enhancement technique for Thematic Mapper data which promises to allow reliable, automated production of high quality TM film products for forested regions of Canada. Extension of the technique to rangeland enhancement is under development, and development of enhancement for other biophysical regions should be straightforward following the approach used for forests. A number of advances made during this development are worthy of note:

TABLE 3. TM SCENES STUDIED TO DERIVE FOREST INFORMATION

LANDSAT	PATH	ROW	DATE	LOCATION	FOREST REGIONS
4	28	25	1982 Sept 26	Dryden, Ont.	Gt. Lakes-St. Lawrence, Boreal
5	11	27	1984 July 30	Edmundston, NB	Acadian
5	11	27	1985 July 1	Edmundston, NB	Acadian
5	42	25	1984 Aug 8	Cranbrook, BC	Montane, Columbia
5	43	25	1985 July 26	Canal Flats, BC	Montane, Columbia
5	44	22	1984 Oct 9	Whitecourt, Alberta	Boreal
5	44	22	1985 July 8	Whitecourt, Alberta	Boreal

TABLE 4. TM COLOR COMBINATIONS FOR FORESTRY

BLUE	GREEN	RED	GENERAL APPEARANCE	PARTICULAR CHARACTERISTICS
TM2	TM3	TM4	Color infrared photo	•good portrayal of roads, water bodies, deciduous/conifer differences
TM2	TM4	TM3	natural color	•good portrayal of roads •poorer deciduous/conifer contrast than 2, 3, 4
TM3	TM4	TM5	natural color	•good overall portrayal of vegetation type and condition •sensitive to vegetation damage •poorer road definition than 2, 3, 4
TM3	TM5	TM4	similar to color infrared photo, but more orange	•good portrayal of vegetation type and condition •roads more visible than with 3, 4, 5
TM3	TM4	TM7	natural color	•clearest definition of burned areas •revegetation of cutovers visible earlier than with 3, 4, 5 •very sensitive to vegetation damage
TM1	TM2	TM3	natural color	•very high contrast between vegetation and bare areas •very little vegetation information

TABLE 5. REFLECTANCE LIMITS (1.00 = 100% REFLECTANCE) AND FUNCTIONAL FORMS FOR FORESTRY ENHANCEMENTS

		THEMATIC MAPPER BAND					
NAME	VALUE	1	2	3	4	5	7
Mixedwood	R_{min}	−0.015	−0.020	−0.020	−0.020	−0.020	−0.020
	R_{max}	0.120	0.150	0.170	0.530	0.320	0.210
	Function	Lin	Lin	Lin	Lin	Lin	Lin
Softwood	R_{min}	0.000	0.000	0.000	−0.020	0.000	0.000
	R_{max}	0.140	0.250	0.230	0.530	0.350	0.260
	Function	Sqrt	Sqrt	Sqrt	Sqrt	Sqrt	Sqrt
Boreal	R_{min}	0.000	0.000	0.000	−0.020	0.000	0.000
	R_{max}	0.120	0.150	0.170	0.470	0.300	0.190
	Function	Sqrt	Sqrt	Sqrt	Sqrt	Sqrt	Sqrt
Leaf-off	R_{min}	0.000	0.000	0.000	−0.020	0.000	0.000
	R_{max}	0.150	0.190	0.210	0.430	0.300	0.260
	Function	Sqrt	Sqrt	Sqrt	Sqrt	Sqrt	Sqrt

Lin = linear Sqrt = square-root

- The atmospheric and illumination correction algorithm developed for the Landsat Multispectral Scanner has been modified and successfully used for the TM bands.
- The variability of atmospheric path radiance in TM bands 5 and 7 is comparable to the noise equivalent radiance, precluding reliable measurement and correction. This means, however, that the use of standard atmospheric conditions is satisfactory for the purposes of image enhancement.
- We have determined that a band which has been enhanced to produce a well-exposed black-and-white image can be combined with two other (similarly enhanced) bands in any color assignment and will reliably provide a well-exposed image.
- Four enhancements, which we have designated mixedwood, softwood, boreal, and leaf-off, appear to produce high quality TM film products for forested regions throughout Canada for the entire snow-free period.
- Based on our experience with many scenes, we have identified a number of effective band combinations and color assignments for TM data of forests. We have been able to determine which color combination are generally optimum for hardwood-softwood-mixedwood differentiation, for showing areas damaged by fire and insect attack, for showing minor roads in the forest, and for

TABLE 6. RADIOMETRIC CORRECTION AND ENHANCEMENT ALGORITHM

(1)	Obtain histogram of each band, rejecting data from dropout lines.
(2)	Acquire and process calibration lamp data for reference detector.
(3)	Correct histograms for saturated pixels.
(4)	Obtain mean and standard deviation for each detector.
(5)	Calculate transformations to match each detector response to that of reference detector.
(6)	Calculate absolute calibration transformation for reference detector.
(7)	Calculate absolute calibration transformation for all other detectors.
(8)	Transform histograms with absolute calibration transformation and combine all histograms for all detectors in a single band into one histogram.
(9)	Obtain enhancement type and bands from operator.
(10)	Calculate solar elevation, azimuth, and distance from scene center latitude, longitude, date, and time.
(11)	Calculate average scene reflectance factor from average scene radiance derived from histogram of full scene.
(12)	Detect histogram lower bound and calculate path radiance.
(13)	Determine downwelling irradiance and atmospheric transmission with radiative transfer model (use standard atmosphere for bands 5 and 7).
(14)	Calculate transformation constants (*A* and *B* in Equations 5 and 6).
(15)	Compute enhancement lookup table.
(16)	Transfer data from disk to film through lookup table.

showing the presence or absence of deciduous brush in regenerating areas.

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