Multispectral Imagery Band Sharpening Study

Jim Vrabel

Abstract

The fusion of multisensor and multiresolution satellite imagery is an effective means of exploiting the complimentary nature of various image types. With band sharpening (a type of imagery fusion), higher spatial resolution panchromatic data is fused with lower resolution multispectral imagery (MSI). This fusion creates a product with the spectral characteristics of the MSI and a spatial resolution approaching that of the panchromatic image (effective ground-sample distance, or GSD).

Others have fused 10-m SPOT panchromatic with 20-m SPOT MSI or 30-m Landsat TM (sharpening factors of 2:1 and 3:1). In this study, MSI of 10 m to 30 m was sharpened with 5- to 15-m imagery (sharpening factors of 2:1 to 6:1) using four algorithms.

The research goals were to (1) determine the validity of the concept of "effective GSD"; (2) determine the relative utility of band sharpening by different factors; and (3) compare the relative effectiveness of different band sharpening algorithms.

Introduction

This study evaluated fused imagery from different sensors at different spatial resolutions. The study evaluated a specific type of data fusion known as band sharpening. Band sharpening produces a higher spatial resolution multispectral image (ideally without the loss of spectral information) by merging a low-resolution multispectral image with a higher resolution panchromatic (pan) or multispectral band. Numerous band sharpening studies have been published (Ehlers, 1991; Shettigara, 1989; Conese *et al.*, 1992; Chavez *et al.*, 1991; Patterson *et al.*, 1992; Grasso, 1993; Carper *et al.*, 1990), but they have not typically looked at more than two algorithms and have generally only dealt with a single set of data and/or a single sharpening factor.

In addition, a literature search indicated that no studies have looked at the concept of effective GSD* (also called effective resolution). Effective GSD is defined as the apparent spatial resolution of an image that results from the fusion of a higher spatial resolution panchromatic image with a lower spatial resolution multispectral image. For example, if a 10-m panchromatic image is fused with a 20-m multispectral image, the theoretical spatial resolution of the resulting image is 10 m, but the effective GSD may be 12 m.

Band Sharpening Utility

The fusion of multisensor and multiresolution satellite data is an effective means of exploiting the complimentary nature of various imagery types. In band sharpening, the product has the spatial resolution of the panchromatic image and the spectral characteristics of the multispectral image. The spectral characteristics are useful for identifying features such as trees, water, soil, concrete, asphalt, etc. With increased spatial resolution, these features can be more accurately delineated, thus making a sharpened product more useful for various applications (the result is even more useful if there is no change in the spectral content of the sharpened product) (Patterson *et al*, 1992; Chavez *et al.*, 1991; Munechika *et al.*, 1993; Grasso, 1993).

Band sharpening with a single high-resolution panchromatic band allows the multispectral bands to be acquired at a lower spatial resolution. This permits systems to be designed that have lower bandwidth and storage requirements. Lower multispectral spatial resolution can also lead to the implementation of increased spectral resolution (i.e., more bands) on future sensors.

Common Sharpening Algorithms

The most commonly used algorithms have been Intensity-Hue-Saturation (IHS) (Chavez *et al.*, 1991; Patterson *et al.*, 1992; Ehlers, 1991; Shettigara, 1989; Grasso, 1993; Carper *et al.*, 1990; Pellemans *et al.*, 1993; Shettigara, 1992), Principal Components Analysis (PCA) (Chavez *et al.*, 1991; Conese *et al.*, 1992; Ehlers, 1991)), arithmetic techniques (addition and multiplication) (Ehlers, 1991; Munechika *et al.*, 1993), and band substitution. The IHS merge, which has been the most popular method, consists of the following three steps: (1) transform three MSI bands from Red-Green-Blue (RGB) color space into IHS color space; (2) replace the intensity component with the panchromatic image; and (3) perform an inverse IHS transform to put the data back into RGB color space. This process is fairly successful when applied to true color images using a conventional panchromatic sharpening band. It is much less successful when the color composite includes near- or mid-wave infrared bands, or when the MSI bands are not highly correlated with the sharpening band. Another shortfall of the IHS transform is its limitation to three multispectral bands.

Multispectral data can also be fused with panchromatic imagery using PCA. The PCA algorithm calculates the principal components of an image. The first principal component represents the largest variance, which typically resembles an intensity image; each of the remaining components represents successively smaller amounts of variances. The technique used is similar to the IHS merge. Three or more MSI bands are input to the PCA algorithm. Any of the resulting components can then be replaced by the panchromatic sharpening band. The final step is an inverse PCA.

*GSD, or ground sample distance, is the distance on the ground equivalent to the size of a pixel on the image. Effective GSD would be the GSD resulting from degradation due to the fusion process.

Booz·Allen & Hamilton Inc., Suite 500, 1953 Gallows Road, Vienna, VA 22182.

Photogrammetric Engineering & Remote Sensing,
Vol. 62, No. 9, September 1996, pp. 1075–1083.

0099-1112/96/6209-1075$3.00/0

TABLE 1. M-7 IMAGES, WITH SCENE CONTENTS

#	Site	Contents
1	Detroit	Industry, water treatment plant, storage tanks, water turbidity
2	Nevada Test Site (NTS)	Desert roads, weapons test area, buildings
3	Simmons Airfield	Runways, taxiways, parking aprons (helicopters)
4	San Diego	NOB, athletic field
5	East Detroit	Industrial, residential
6	Ft. Bragg Range 21	Forest, training range
7	Camp Ripley	Winter scene, snow, deciduous/coniferous trees, plowed roads
8	Hart Plaza, Detroit	Suspension bridge, barges/ferries/water
9	Detroit (park)	Water (wakes), industry, coal chute, rail, bridge
10	Fallon	Agriculture, storage tanks, rail, conveyor

The simplest mathematical technique for fusing imagery is through arithmetic operations such as addition and multiplication. These operations can be used to merge imagery to varying degrees. For example, in adding a Satellite Pour l' Observation de la Terre (SPOT) panchromatic image to a Thematic Mapper (TM) scene, we can specify weighting of 50 percent for each scene or weigh the SPOT scene more heavily by using a 70-30 percent split. The Color Normalized algorithm used in this study is one of the more sophisticated arithmetic techniques.

Perhaps the easiest and most straightforward method for fusing imagery is by direct band substitution. This involves replacing one of the three MSI bands by the high-resolution imagery. For example, instead of displaying TM bands 3, 2, and 1 in the red, green, and blue channels, TM bands 3 and 2 are displayed in the red and green channels, and the SPOT panchromatic imagery is displayed in the blue channel.

Previous Studies

Band sharpening has been used extensively with SPOT panchromatic imagery (SPOT was the first sensor to collect both high spatial resolution panchromatic and lower spatial resolution MSI), where it is fused with either SPOT MSI or Landsat TM imagery. When applied to SPOT imagery, the 20-m GSD of the spectral bands is sharpened with 10-m panchromatic, a 2:1 sharpening factor. When 30-m TM data is sharpened, the factor is 3:1. Experiments with even higher sharpening factors have been reported, but it is not clear whether the effectiveness of band sharpening is reduced as the sharpening factor increases (Grasso, 1993; Hallada and Cox, 1983). This study was undertaken in order to have more quantitative measures of the effectiveness of band sharpening as a function of the sharpening factor.

Most previous studies have been fairly limited in terms of the number of fusion factors that have been researched. A study was required that compared the utility of more than just two algorithms. A study was also necessary to look at what potential applications exist for imagery fused at various resolutions, various sharpening factors, and with different algorithms.

Objectives

The objectives of the study were to (1) determine the validity of the concept of "effective GSD," (2) determine the relative utility of MSI band sharpening by different factors, and (3) compare the relative effectiveness of different MSI band sharpening algorithms.

Methods

Ten scenes, collected by the M-7 airborne MSI sensor,* were selected for this study. MSI (10-, 15-, 20-, or 30-m) true color and MSI false color infrared (FCIR, used to represent both near- and mid-infrared in this study) images were sharpened with panchromatic imagery at 5 m or 15 m resolution. Imagery sharpening ratios evaluated include 2:1, 3:1, 4:1, and 6:1. True color and FCIR multispectral images were sharpened with panchromatic imagery using four different sharpening algorithms. Each sharpened image was compared to a "truth" image and rated. A total of 344 images were evaluated by each participant.

A total of 13 participants (image analysts and image scientists) from various Department of Defense and intelligence organizations took part in the evaluation. The participants had an average of seven years of MSI experience. All participants completed the evaluation within eight hours.

Evaluation Tasks

Imagery was shown to the participants in sets of three. The three images were the low-resolution multispectral image, the sharpened multispectral image (the product of fusing the low-resolution multispectral image with a high-resolution panchromatic image), and the truth image (a high-resolution multispectral image that is the theoretical best image achieved through fusion of the original low-resolution multispectral image and the high-resolution panchromatic image). For each set of three images the participants were asked to perform the following two tasks: (1) estimate the GSD of the sharpened image on a 0 to 100 scale using the original low-resolution (0 score) multispectral and high-resolution multispectral truth images (100 score) for comparison (this is a spatial comparison only), and (2) rate the overall utility of the sharpened image on a 0 to 100+ magnitude scale using the original low-resolution multispectral and high-resolution multispectral truth images for comparison.

On this 0 to 100+ magnitude scale, 0 means the sharpened image is only as useful as the original low-resolution multispectral image, 50 means the sharpened image is half as useful as the truth image, 100 means the sharpened image is equivalent to the truth image, 200 means the sharpened image is twice as useful as the truth image, etc.

Image Selection

In selecting images for the evaluation, an IAD (Imagery Analysis Division, National Exploitation Laboratory) image analyst reviewed the available M-7 testbed imagery. The primary goal was to select images that address as many of the following application areas as possible: (1) Naval Order-of-Battle (NOB); (2) Air Order-of-Battle (AOB); (3) Ground Order-of-Battle (GOB); (4) Missile Order-of-Battle (MOB); and (5) Winter, Industrial, Urban, and Desert features. Table 1 lists the scenes selected for use in this evaluation.

Image Processing

The 5-m M-7 images were used as "truth" images and were also degraded to 10-m, 15-m, 20-m, and 30-m resolution to

*This MSI sensor has 32 spectral bands, covering a spectral range of 0.4 to 12 μm; 16 of these bands can be selected for any given collection. The system is capable of collecting MSI data with spatial resolutions as fine as one metre.

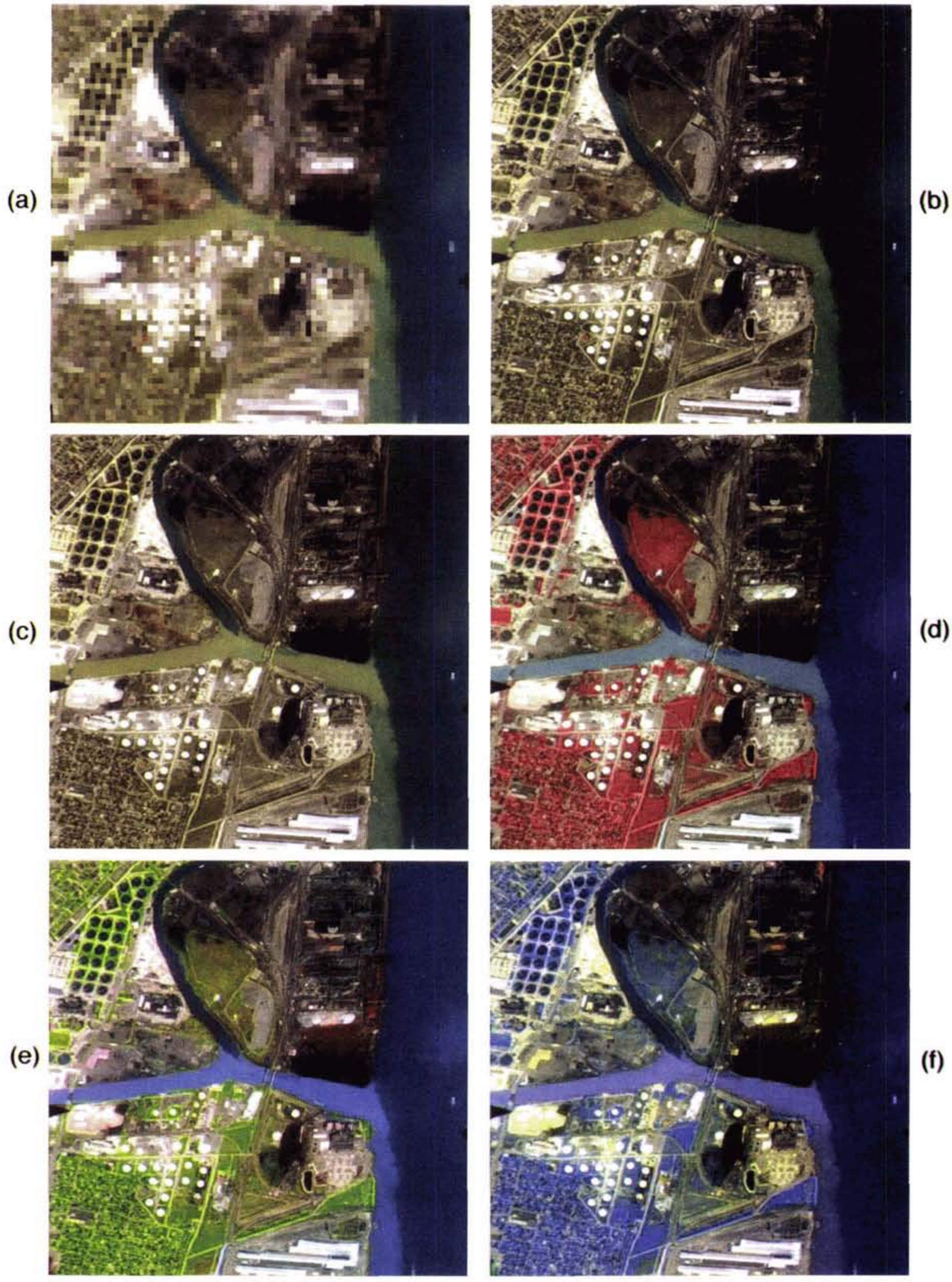

Plate 1. Color Normalized algorithm results for Detroit scene. (a) Original 30-m true color. (b) 5-m truth image. (c) True color sharpened product. (d) False color IR sharpened product. (e) SWIR1 sharpened product. (f) SWIR2 sharpened product.

simulate possible future multispectral imagery. The original 5-m imagery was cropped to 480 by 480 pixels and was not rectified. The 5-m and 15-m panchromatic bands were simulated from the 5-m imagery by averaging the data from sev-

TABLE 2. IMAGE SPATIAL RESOLUTIONS AND SHARPENING FACTORS

Resolution		Sharpening	Bands				Image(s)	
MSI	Pan	Factor	321	432	543	754	All	#1 (Detroit)
30	5	6:1			X	X	X	
30	5	6:1	X	X				X
20	5	4:1	X	X				X
15	5	3:1	X	X				X
10	5	2:1	X	X			X	
30	15	2:1	X	X	X	X	X	

eral of the original M-7 multispectral bands to simulate possible future panchromatic bandpasses. The bandpasses of the 5-m panchromatic band were 0.5 to 0.75 μm, while those of the 15-m panchromatic band were 0.5 to 0.9 μm.

MSI (10-, 15-, 20-, or 30-m) true color (TC) and MSI FCIR images were sharpened with panchromatic imagery at 5 m or 15 m resolution. The false color scenes were near-infrared (IR) and short-wave-infrared (SWIR) composites. Table 2 contains descriptions of the MSI bands and spatial resolutions that were sharpened. (Four band combinations were used in this study: true color (321), false color near-IR (432), SWIR1 (543), and SWIR2 (754). Use of these numbers (321, 432, 543, 754) in this paper is a reference to the band combination used.)

The MSI and panchromatic imagery were fused using four band sharpening algorithms. The four algorithms used were IHS (PCI, 1992), High-Pass filter (HP) (Chavez *et al.*, 1991), Color Normalized (CN) (Hallada and Cox, 1983), and Sparkle (P. J. Etzler and M. E. Stivers, personal communication). The IHS, HP, and CN algorithms were applied at the IAD. The Sparkle algorithm was applied to the imagery by the Sparkle developer. Technical details of these algorithms are contained in the Appendix.

All imagery (original, truth, and sharpened) was linearly stretched with 1 percent and 99 percent penetration points (except for the HP results which were acceptable only when using 2 percent and 98 percent penetration points). Any imagery smaller than 480 by 480 was pixel replicated to fill a 480 by 480 window.

Image Presentation

All participants evaluated Scene 1 (Table 1) before proceeding to the remaining scenes. Each participant evaluated the remaining nine scenes in a different order. Within each scene, the imagery was presented in the following order: first all 321, then all 432, then all 543, and finally all 754 images. The images were randomized within each of these combinations.

The evaluation was performed in soft copy on Silicon Graphics Onyx workstations. The screen presentation mode included three images: the original low-resolution MSI in the upper left, the truth image (MSI at the panchromatic GSD) in the upper right, and the sharpened image (product of the low-resolution MSI and high-resolution panchromatic) in the bottom center. In the lower left corner was an overview image along with roam and zoom controls. The lower right corner listed the band combination and image features; it also contained controls for collecting the participants' responses, including a slider bar and buttons.

Results

Data Analysis

Data analysis objectives included checking for anomalous responses, determining the effective GSD at the various sharpening factors, determining which algorithms perform the best for GSD and utility, and identifying the three-band combinations that are the best for GSD and utility. Data and analysis of the data used to derive these results are discussed in the following sections.

Data Screening

Responses were screened for apparent inconsistencies. Interrater correlation analysis determined whether any participants' results needed to be excluded from further analysis. After this initial data quality check, a variety of analyses were run on the data to provide the final answers to the study's objectives. Correlations between participants' responses were sufficiently high (0.3 to 0.7 rater-group correlation), permitting the use of all data for analysis (Allen and Yen, 1979).

Statistical Analysis

Mean participant response and standard deviation were computed for each rating. An analysis of variance was performed to identify statistically significant differences in mean participant responses. Results from this analysis were used to determine if each objective could be answered from data collected during the evaluation.

In the development of image interpretability scales for various types of imagery, it has become clear that perceived image quality is proportional to the logarithm of the GSD (National Exploitation Laboratory, 1994). Preliminary research results from the NEL/IAD MSI Imagery Interpretability Ratings Scale (MSIIRS) study indicate that it is also valid for multispectral imagery (Image Resolution Assessment and Reporting Standards Committee, 1995). The effective GSD ratings (in metres) used a logarithmic response which is based on the same assumption of a log relationship between GSD and interpretability.

Table 3 shows effective GSDs of the Detroit scene across all band combinations for the four sharpening factors evaluated. In Table 3, the GSDs were derived only from the two best performing algorithms, Sparkle and CN. As expected, the effective GSD continually improves as the sharpening factor is reduced from 6:1 to 2:1. The effective GSD in all cases is very close to the original GSD of the sharpening band. This can also be seen in Plate 1, which shows the results of sharpening the 30-m multispectral Detroit scene with a 5-m panchromatic image. Plate 1a shows the original 30-m image in true color (321). Plate 1b shows a 5-m truth image used for comparison. Plates 1c through 1f show the results of sharpening the 30-m MSI scene with a 5-m panchromatic image (not displayed in the plate) using the Color Normalized algorithm. Plates 1c through 1f show the sharpened products in true color (321), false color IR (432), SWIR1 (543), and SWIR2 (754), respectively. In particular, compare the sharpened product in Plate 1c to the truth image in Plate 1b.

Table 4 shows several effective GSDs for all scenes across all band combinations. Again, the effective GSD in all cases is very close to the original GSD of the sharpening band, even for the 30-m MSI sharpened with 15-m panchromatic imagery. Utility and GSD scores were, in general, very similar for all four algorithms. This is easily seen in Figure 1 where there is nearly a one-to-one correspondence in the scores. Figure 1 also shows how closely the Sparkle and CN algorithms performed, both in terms of utility and GSD (no signif-

TABLE 3. EFFECTIVE GSDS (DETROIT, ALL BANDS, SPARKLE AND CN ALGORITHMS)

MSI Resolution (m)	Pan Resolution (m)	Effective GSD (m)
30	5	6.3
20	5	5.8
15	5	5.4
10	5	5.3

Table 4. Effective GSDs (All Images, all Bands, Sparkle and CN Algorithms)

MSI Resolution (m)	Pan Resolution (m)	Effective GSD (m)
30	5	6.4
10	5	5.2
30	15	16.5

icant statistical difference), while the IHS and HP algorithms did not perform as well. The Appendix contains additional tables that break down the participants' utility and GSD responses (0 to 100 scores) by algorithm, image, band combination, and sharpening factor.

Figure 2 summarizes the algorithm effects on GSD. Sparkle performed best for the 432 and 543 band combinations (the significance bars at the top link values that are not significantly different). IHS was rated worst for all but the true color (321) composite.

Figure 3 summarizes the algorithm effects on utility. Sparkle and CN performed best for all four band combinations studied (there was no significant statistical difference between the two algorithms as indicated by the significance bars which link values that are not significantly different). Also note that HP and IHS have problems with the 543 and 754 SWIR composites.

Also apparent in several images was the effectiveness of the CN algorithm in enhancing certain features such as industrial facilities. This additional enhancement by the algorithm may have accounted for CN's high utility rating by the participants.

Figure 4 summarizes the band combination effects on GSD. It shows that Sparkle and HP performance were not very sensitive to band combination. In general, CN and IHS performed much better on the true color (321) band combination than on other band combinations.

Figure 5 summarizes the band combination effects on utility. The false color near-IR (432) band combination showed a low utility rating for all algorithms. A surprising result was the high utility scores for the SWIR2 (754). It is also apparent from the table that IHS shows the largest difference in utility between true color and other band combinations.

Some artifacts can be produced by the band sharpening process. This was observed in the San Diego image where the IHS and CN algorithms had problems (blockiness) with an athletic field that was visible in the upper left corner of the scenes. This problem was worst at the 6:1 (30:5) sharpening factor and is not as observable at lower sharpening factors. The worst anomalies occur in areas where Band 4 exhibits a contrast reversal with respect to the high-resolution band. These anomalies are more visible when Band 4 is displayed in the green or red channels, areas where the human visual system is more sensitive.

Discussion

The MSI Band Sharpening study led to a number of significant findings. Of the four algorithms investigated, two of

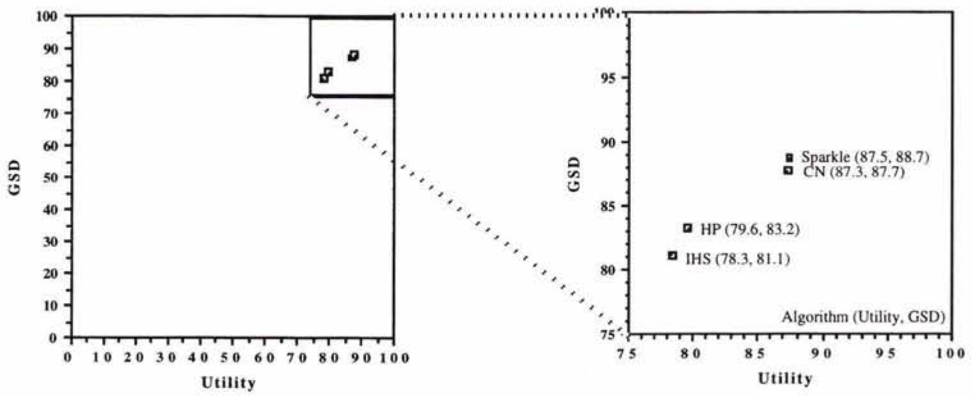

Figure 1. Algorithm response summary.

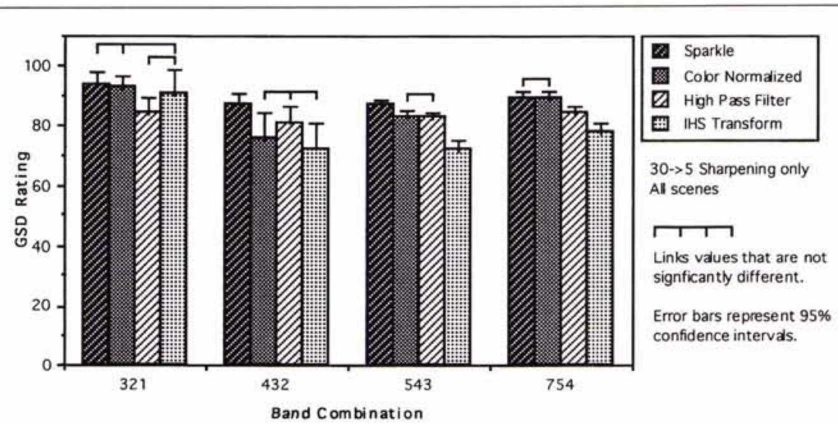

Figure 2. Algorithm effects on GSD.

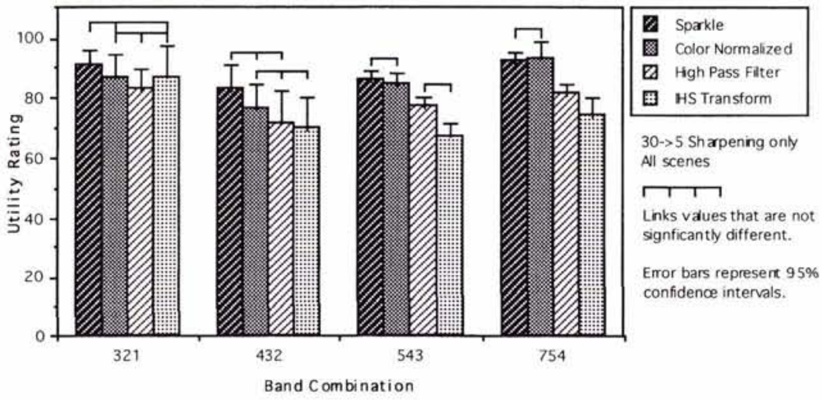

Figure 3. Algorithm effects on utility.

them, Sparkle and CN, performed significantly better than IHS or HP in terms of both GSD and utility. There was no significant statistical difference between the Sparkle and CN algorithms. It is also important to note that the algorithm difference was more significant for high bands (e.g., SWIR) than for low bands (e.g., visible).

Another finding is that the concept of effective GSD makes sense only if it is restricted to a specific band combination at a specific sharpening factor. This is seen by looking at the effective GSDs for the Detroit scenes sharpened at a 6:1 factor (30-m MSI and 5-m panchromatic-Sparkle and CN results only) where bands 321 resulted in a 5.7-m effective GSD, 432 a 7.1-m effective GSD, 543 a 7.6-m GSD, and 754 a 6.2-m GSD.

The study showed that there is a direct relationship between effective GSD and sharpening factor. This means that resolution improves when the sharpening factor is reduced. For example, 30-m MSI sharpened with 5-m panchromatic (6:1 sharpening factor) is not quite as good as 10-m MSI sharpened with 5-m panchromatic (2:1 sharpening factor). This dependence is not very strong over the range of sharpening factors used in this study.

As expected, an inverse relationship exists between the image utility and the sharpening factor. This means that image utility increases when the sharpening factor is reduced.

Certain sharpening results apply to both the effective GSD and overall image utility. First, sharpening achieved higher ratings for a higher resolution panchromatic image. For example, for the two 2:1 sharpening factors studied, scores were consistently higher for 10-m MSI sharpened to 5 m than for 30 m sharpened to 15 m. The scores were expected to be similar. The difference could be due to either the differing spectral content of the 5-m and 15-m pan bands or the differing magnification required to view all images at the same scale.

Second, sharpening generally works better for lower band images. This is due to the higher correlation that exists between the sharpening band and the visible bands than between the sharpening band and the IR bands. If a sharpening band is available that covers the IR portion of the spectrum, there would be better correlation with the MSI and therefore a better result. Band 4, the near-IR band, has very low correlation with the pan band, and any band combination that included Band 4 was down-rated. When Band 4 was shown in the green or red channels, giving it a larger influence, this negative effect was larger.

Conclusions

The main conclusions drawn from this study are

- The Sparkle and CN algorithms performed significantly better than IHS and HP for both GSD and utility;
- The effective GSD for 30-m MSI sharpened with 5-m panchromatic imagery is approximately 6 m (across all scenes and all band combinations studied);
- Algorithm difference is more significant for high (e.g., SWIR) bands than for low (i.e., visible) bands;

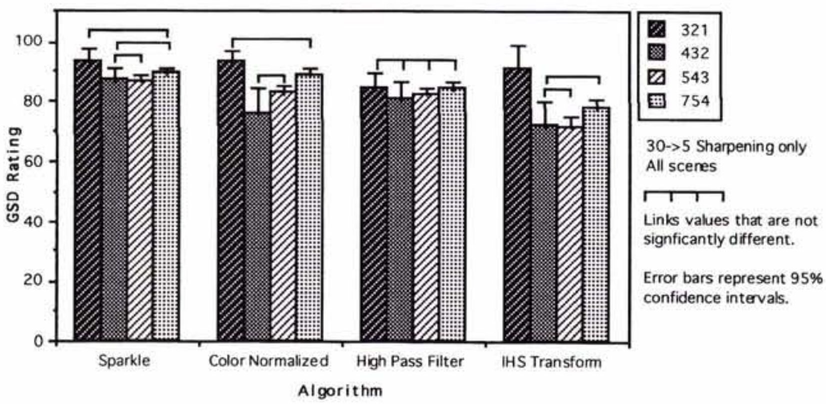

Figure 4. Band combination effects on GSD.

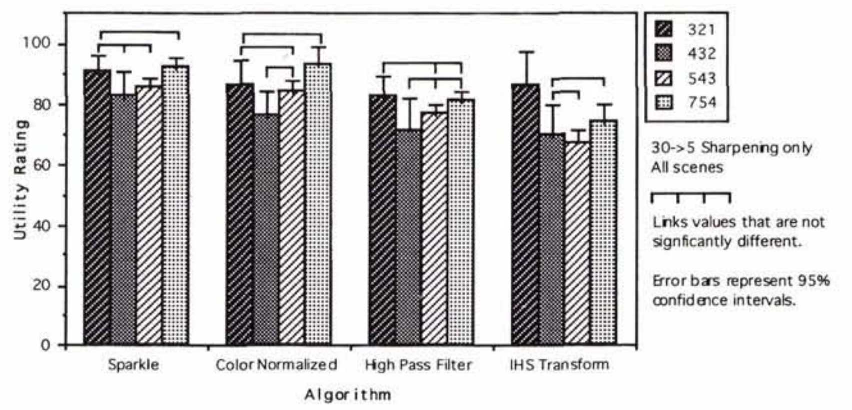

Figure 5. Band combination effects on utility.

- Band sharpening achieves higher ratings for higher resolution panchromatic images (for the two 2:1 sharpening factors studied [30-m MSI sharpened with 15-m panchromatic and 10-m MSI sharpened with 5-m panchromatic], scores [0 to 100 scale] were consistently higher for 10-m MSI sharpened to 5 m even when the scores for 30 m sharpened to 15 m were expected to be similar); and
- Band sharpening generally works better for lower band (i.e., visible) images.

Acknowledgments

This study was performed under contract to the National Exploitation Laboratory (NEL) Imagery Analysis Division (IAD) and sponsored by Lt. Col. Kevin Rose of the Defense Landsat Program Office (DLPO), which is now the Remote Earth Sensing Program Office (RESPO).

I am indebted to Gary Coleman for his expert technical advice in the design, execution, and data analysis of the evaluation and his advice and review of this paper. I am thankful to the following people for their assistance in evaluation design, data analysis, image processing, final report review, or any other way they may have provided assistance: Matt Heric, Mark Richardson, Ginny Garney, Kathy Mead, Rebekah Barrish, Becky Aiken, Tom Porter, George Doyle, Avrama Blackwell, Ellen Mohr, and Dave Miazza. I am also thankful to the 13 image analysts and image scientists who participated in the actual evaluation itself.

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(Received 3 March 1995; accepted 17 July 1995; revised 24 October 1995)

Appendix

Band Sharpening Algorithm Descriptions

IHS

The Intensity-Hue-Saturation (IHS) transform is a method for combining data such as SPOT panchromatic and Landsat Thematic Mapper (TM) MSI. The fusion of these two data sets produces an image with the distinct spectral features provided by the TM displayed in the image's various hues, while the SPOT imagery provides increased spatial resolution. The transform is defined by three separate, orthogonal attributes of intensity, hue, and saturation. The IHS coordinate system can be represented as a cylinder. The intensity, which is the brightness or total energy of the image, is defined by the vertical axis. The hue, which is the average wavelength of color, is defined by the circumferential angle of the cylinder and

TABLE A1. LOW- AND HIGH-PASS FILTER KERNELS

	1/49	1/49	1/49	1/49	1/49	1/49	1/49
	1/49	1/49	1/49	1/49	1/49	1/49	1/49
	1/49	1/49	1/49	1/49	1/49	1/49	1/49
low-pass kernel = 1/49	1/49	1/49	1/49	1/49	1/49	1/49	1/49
	1/49	1/49	1/49	1/49	1/49	1/49	
	1/49	1/49	1/49	1/49	1/49	1/49	1/49
	1/49	1/49	1/49	1/49	1/49	1/49	1/49
	−1/49	−1/49	−1/49	−1/49	−1/49	−1/49	−1/49
	−1/49	−1/49	−1/49	−1/49	−1/49	−1/49	−1/49
	−1/49	−1/49	−1/49	−1/49	−1/49	−1/49	−1/49
high-pass kernel = −1/49	−1/49	−1/49	−1/49	48/49	−1/49	−1/49	−1/49
	−1/49	−1/49	−1/49	−1/49	−1/49	−1/49	
	−1/49	−1/49	−1/49	−1/49	−1/49	−1/49	−1/49
	−1/49	−1/49	−1/49	−1/49	−1/49	−1/49	−1/49

(Note: Performance of the HP algorithm could conceivably be improved with tuned filter kernels.)

TABLE A2. RESPONSE SUMMARY (RESOLUTION COMBINATIONS)

MSI	Pan	GSD	Utility
30	15	83.0	79.6
30	5	82.7	81.4
20	5	86.4	85.0
15	5	89.1	89.1
10	5	91.9	91.4

TABLE A3. RESPONSE SUMMARY (ALL IMAGES)

Algorithm	10:5	30:15	30:5
CN - GSD	92.9	86.1	85.3
CN - utility	92.5	84.1	87.7
SP - GSD	94.2	86.1	87.8
SP - utility	95.0	83.3	88.1
IHS - GSD	89.9	80.1	74.7
IHS - utility	89.5	76.2	71.3
HP - GSD	90.6	89.9	82.8
HP - utility	88.9	89.5	78.5

TABLE A4. RESPONSE SUMMARY (DETROIT IMAGE - 30:5 RESPONSES ONLY)

Algorithm	321	432	543	754
CN - GSD	92.1	75.0	74.5	91.7
CN - utility	86.4	75.8	77.3	100.9
SP - GSD	93.0	86.6	78.9	84.7
SP - utility	90.2	82.3	73.5	84.4
IHS - GSD	90.2	71.9	61.7	78.2
IHS - utility	86.5	69.6	62.4	81.7
HP - GSD	83.7	80.2	74.7	82.3
HP - utility	82.4	70.9	71.0	79.3

TABLE A5. RESPONSE SUMMARY (DETROIT IMAGE)

Algorithm	10:5	15:5	20:5	30:5
CN - GSD	90.4	94.2	88.1	83.5
CN - utility	91.9	97.4	85.3	81.1
SP - GSD	93.5	91.8	91.2	89.8
SP - utility	93.5	89.3	89.4	86.3
IHS - GSD	89.3	83.8	81.7	81.1
IHS - utility	91.0	84.0	81.7	78.1
HP - GSD	87.8	86.5	84.5	81.9
HP - utility	84.8	85.7	83.4	76.7

has a range from blue (hue of 0) through green, yellow, red, and purple (hue of 360). The saturation, which is the percentage of white light in the image, is defined by the radius of the cylinder (PCI, 1992).

When performing an IHS transform, an analyst can use any three MSI bands, although the transform works best if the data are highly correlated. For example, TM Bands 3, 2, and 1 could be merged with SPOT panchromatic data.

The IHS merge processing steps for band sharpening are (1) transform three MSI bands into IHS color space, (2) replace the intensity component with the higher spatial resolution panchromatic image, and (3) perform an inverse IHS transform (back to Red-Green-Blue color space) on this modified IHS image.

Another step that may be required prior to fusion is enhancement of both images to be merged. Contrast enhancement of the images will generally produce results containing more useful information. Edge enhancement is also sometimes included as part of the procedure.

The IHS transform is common to most commercial of-the-shelf (COTS) imaging packages. The IHS transform routine from the PCI software package was used for this evaluation.

HP

The High-Pass filter (HP) transform used in this evaluation is a variation of previously researched techniques and consists of three basic steps: (1) perform a high-pass filter on the high-resolution panchromatic image to extract the spatial information from this image, (2) perform a low-pass filter on the multispectral image to extract the spectral information from this image, and (3) calculate the weighted sum of the high- and low-pass filtered results to create a band sharpened product (Chavez *et al.*, 1991). The HP transform is defined by the following equation:

$$HP_i = (W_a * MSI_{ilp}) + (W_b * PAN_{ihp})$$

where W_a and W_b are weights such that $W_a + W_b = 1.0$, MSI_{ilp} is a low-pass filtered MSI band *i*, PAN_{ihp} is a high-pass filtered PAN band, and HP_i is the output sharpened band.

The HP transform was implemented in the International Imaging Systems (I²S) Vista software. The 7 by 7 convolution kernels used were chosen after experimentation with various 3 by 3, 5 by 5, and 7 by 7 kernels. The values used for W_a and W_b are 0.5 and 0.5, respectively, while the low- and high-pass filter kernels are listed in Table A1.

CN

The Color Normalized (CN) transform (also referred to as an energy subdivision transform) is, like the IHS transform, a method for combining data such as SPOT panchromatic and Landsat TM imagery. The fusion of these two data sets produces an image with the distinct spectral features provided by the TM, while the SPOT imagery provides increased spatial resolution (Hallada and Cox, 1983).

The CN transform separates the spectral space into hue and brightness components. The transform multiplies each of the three MSI bands by the higher spatial resolution panchromatic imagery, and these resulting values are each normalized by dividing by the sum of the three MSI bands.

The CN transform is defined by the following equation:

$$\mathrm{CN}_i = \frac{(\mathrm{MSI}_i + 1.0)*(\mathrm{PAN} + 1.0)*3.0}{\sum_i \mathrm{MSI}_i + 3.0} - 1.0$$

where MSI_i is the MSI band and CN_i is the output color normalized band. The CN transform was implemented in the $\mathrm{I^2S}$ Vista software. (Note: The small additive constants in the equation are included to avoid division by zero.)

Sparkle

Sparkle is a proprietary algorithm developed by the Environmental Research Institute of Michigan (ERIM). The following description was provided by ERIM.

"The advantage of the Sparkle algorithm over others is that it preserves the ratios between the values of the multispectral overlays so color balance is unaffected. Another advantage of Sparkle is the sharpening and multispectral data sets do not have to be resampled to the same pixel size before the fusion procedure. Sparkle treats the digital value of a pixel as being the sum of a low-frequency component and a high-frequency component. It assumes that the low-frequency component is already contained within the multispectral data set. The Sparkle process then tackles two sub-tasks: (1) separate the sharpening image into its low- and high-frequency components, and (2) transfer of the high-frequency component to the multispectral image. The high-frequency component of an area is transferred by multiplying the multispectral values by the ratio of total sharpening value to its low-frequency component." (P. J. Etzler and M. E. Stivers, personal communication.)

Response Summaries

Included in this section are Tables A2 through A5 that break down the participants' utility and GSD responses by algorithm, image, band combination, and sharpening factor.