

AN OPTIMUM THEOS PAN-SHARPENING METHOD EVALUATION USING MULTI-CRITERIA DECISION ANALYSIS

Suwit Ongsomwang* and Sawarin Lerk-u-suke

Received: March 10, 2015; Revised: May 27, 2015; Accepted: June 05, 2015

Abstract

In remote sensing applications, both high spatial and spectral resolutions are frequently required to achieve more spatial details and accurate thematic information extraction. Presently, there is little scientific research for selecting and applying an appropriate pan-sharpening method to THEOS imagery. The main objective of the study is, therefore, to evaluate the optimum pan-sharpening method for agriculture, forestry, and urban applications based on self-evaluation and the users' requirements on a multi-criteria decision analysis (MCDA) basis. Herein, 9 selected pan-sharpening methods including the Brovey transform (BT), multiplicative transform (MT), principle component analysis (PCA), intensity hue saturation transform (IHST), modified intensity hue saturation transform (MIHST), wavelet transform (WT), high pass filtering (HPF), Ehlers fusion (EF), and Gram-Schmidt pan-sharpening (GS) are firstly processed and examined by image quality criteria consisting of visual image analysis, edge detection analysis, image quality indices, and the effect on classification accuracy. Then, the optimum pan-sharpening method is evaluated based on self-evaluation and the users' requirements with the simple additive weighting (SAW) method of MCDA.

From the results, the most appropriate methods for THEOS pan-sharpening based on the single image quality criterion by visual image analysis, edge detection analysis, quality indices, and effect on classification accuracy are GS, HPF, MIHST, and EF, respectively. Meanwhile, the optimum THEOS pan-sharpening methods for the agriculture, forestry, and urban applications based on self-evaluation using the SAW method with equal weight are HPF, HPF or GS, and GS, respectively. At the same time, GS is the optimum THEOS pan-sharpening method in agriculture, forestry, and urban studies based on the users' requirements with specific weight from each in the experts' group. Consequently, the common optimum THEOS pan-sharpening method based on both approaches was GS, and HPF can be chosen as the optimum pan-sharpening method when software availability is considered. In addition, WT is the most inappropriate THEOS pan-sharpening method in 3 applications.

School of Remote Sensing, Institute of Science, Suranaree University of Technology, Nakhon Ratchasima 30000, Thailand. E-mail: suwit@sut.ac.th

** Corresponding author*

In conclusion, the integration of 4 image quality criteria using the SAW method of MCDA can be effectively used as a new tool to evaluate the optimum pan-sharpening method via self-evaluation or the users' requirements in remote sensing applications.

Keywords: Pan-sharpening methods, THEOS data, image quality criteria, multi-criteria decision analysis (MCDA)

Introduction

Pan-sharpening is a technique used to merge a geometric detail of a high-resolution panchromatic (PAN) image with the color information of a low-resolution multispectral (MS) image for generating a high-spatial resolution MS image (Zhang, 2004). This technique combines the higher spatial details of a PAN image with the high spectral resolution of the MS image for creating a high spatial and high spectral resolution image (Stathaki, 2008).

In remote sensing applications, both high spatial and high spectral resolutions are often required to achieve more spatial details and more accurate information acquisition. Effective fusion of PAN and MS images is required to improve the ability for information extraction (Zhang, 2008).

From literature reviews about the study of pan-sharpening, it was found that, during the last decade, most of the data used for the pan-sharpening processing were very high spatial resolutions from commercial satellites such as IKONOS and QuickBird with 1 case study of THEOS data. In the same period, most of the examined pan-sharpening methods relied on the availability of the existing function in the widely used digital image processing software such as ERDAS Imagine, ENVI, PCI Geomatica, and a few existing modified algorithms. Meanwhile, all of the case studies used image quality indices (QI) as the image quality criterion for image quality evaluation. Some researchers applied additional image quality criteria such as visual image analysis (VIA), edge detection analysis (EDA), and effect on classification accuracy (ECA) (Table 1). Unfortunately, none of the researchers combined all the image quality criteria for the pan-sharpening method of quality evaluation, especially the optimum

pan-sharpening method identification for a specific application.

Presently, there is little scientific research for selecting and applying an appropriate pan-sharpening method to THEOS imagery. Intajag *et al.* (2010) evaluated fusion methods (Choi, Tu, and Pradhan) for THEOS imagery with traditional image quality indices but their results did not address any specific application. To address the abovementioned issues, this research focuses on effective evaluation for the optimum THEOS pan-sharpening method by combining image quality criteria with MCDA for agriculture, forestry, and urban applications.

The main objective of the study is to evaluate the optimum pan-sharpening method for agriculture, forestry, and urban applications based on self-evaluation and the users' requirements under the basis of MCDA.

Materials and Methods

Study Areas

The study areas were selected from recent Land Development Department (LDD) land use data of 2011. Within the study areas, 6 test areas were identified: agriculture (A1 and A2) and forestry (F1 and F2) in Pak Chong district and urban (U1 and U2) in Mueang Nakhon Ratchasima district, Nakhon Ratchasima province, Thailand (Figure 1).

Data and Equipment

THEOS Data

MS and PAN data at level 1A acquired by THEOS on 19 February 2010 and 3 January 2010 were collected from the Geo-Informatics and Space Technology Development Agency

Table 1. Synthesis of literature reviews about image quality criteria

Title	Used Data	Pan-sharpening method	Image quality criteria				References
			VIA	EDA	QI	ECA	
Landsat TM and ERS data fusion: a statistical approach evaluation for four different methods.	Landsat TM and ERS-1	PCA, IHST, BT, MT	No	No	Yes	No	Parcharidis and Kazi-Tani (2000)
On the performance evaluation of pan-sharpening techniques	IKONOS, Quickbird	PCA, BT, MT, MT*, GS, Zhang	No	No	Yes	No	Du <i>et al.</i> (2007)
Multi-image fusion in remote sensing: spatial enhancement vs. spectral characteristics preservation	SPOT 2, 4, 5, and Formosat 2	MIHST, CN, GS, BT, PCA, MT, EF, WT	Yes	No	Yes	No	Ehlers (2008)
Evaluation of pan-sharpening methods	IKONOS	IHST, IKONOS IHST, Adaptive IHST, PCA, WT, P+XS, VWP	Yes	Yes	Yes	No	Strait <i>et al.</i> (2008)
Performance of evaluation methods in image fusion	Formosat, Spot 4, Spot 5, IKONOS, TerraSAR-X	WT, AWLP, MT, BT, CN, IHST, EF, PCA, GS, HPF, UNB	Yes	Yes	Yes	No	Klonus and Ehlers (2009)
Assessment and evaluation of different data fusion techniques	Quickbird	MIHST, BT, PCA, MT, WT, HPF, EF	No	No	Yes	No	Hely <i>et al.</i> (2010)
Evaluation of fusion techniques for pan-sharpened THEOS imagery	THEOS	IHST, Choi, Tu, Pradhan	No	Yes	Yes	No	Intajag <i>et al.</i> (2010)
Effect of image fusion algorithms on classification accuracy	Quickbird	BT, MIHST, PCA, HPF, SFIM, W+PCA, EF, Region	No	No	Yes	Yes	Li and Li (2010)
Analysis and evaluation on fusion methods of medium and high spatial resolution remote sensing image	SPOT 5, Quickbird	PCA, BT, IHST, MT	No	No	Yes	No	Ding and Wang (2011)

(GISTDA) along with the metadata, Metadata.dim, containing the ephemeris data. This information was used in the orthorectification process.

LDD Color Orthophoto and Digital Elevation Model (DEM)

Both LDD datasets produced in 2002 were used to identify and collect the well-defined ground control points for orthorectification.

LDD Land use Dataset

The land use dataset in 2011 of Nakhon Ratchasima province from the LDD was

collected for determining a number of classes for unsupervised land use classification and as reference data for an accuracy assessment.

Digital Image Processing Software

ERDAS Imagine was used to process 9 different pan-sharpening methods which include BT, MT, PCA, IHST, MIHST, WT, HPF, and EF. Meanwhile ENVI was used to process GS which is only available in this software.

MATLAB Software

MATLAB, which has a high-level language and high performance for numerical

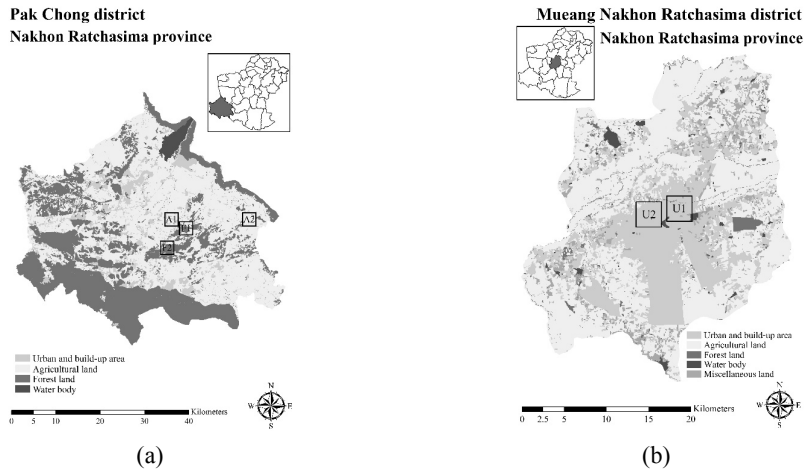


Figure 1. Location of study area and test areas for each application: (a) agriculture and forestry applications and (b) urban application

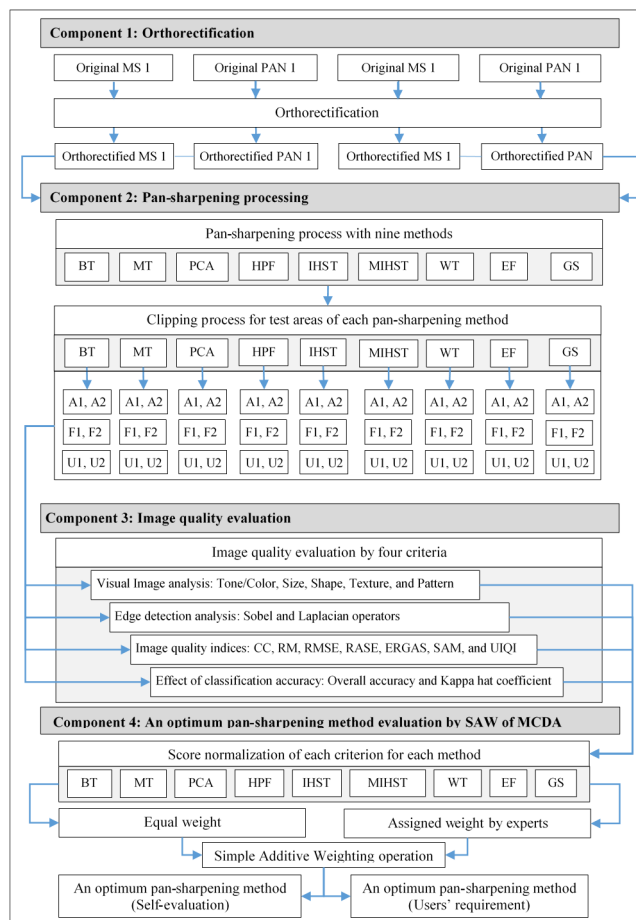


Figure 2. Work flow of research methodology

Table 2. General characteristic of pan-sharpening method

Method	Basic characteristics	Reference
BT	This method multiplies each MS band by the PAN band, and then normalizes each band by the sum of the MS bands	ERDAS (2003)
MT	This method applies a multiplication of each MS band by the PAN band for generating a pan-sharpened image.	ERDAS (2003)
PCA	The first principal component of the PCA transform of the MS image is usually replaced by the PAN image. Through a reverse PCA transformation, the PAN image combines with the low spatial resolution MS bands	Shettigara (1992)
IHST	This method is a process for converting a color MS image from the red, green, and blue color space into the IHS color space. An intensity (I) component is replaced by the PAN image in the combination process. A reverse IHS transform is then performed with the hue (H) and saturation (S) components to produce a pan-sharpened image	Zhang (2004)
MIHST	This method was firstly proposed by Siddiqui (2003). It allows combining a multispectral image with a panchromatic image more than 3 bands at a time. The method works best when there is a significant overlap of the wavelengths of the combining images (Nikolakopoulos, 2008).	Nikolakopoulos (2008) Siddiqui (2003)
WT	This method is a modification of the work of King and Wang (2001). The process involves separating the original image into different image components by wavelet decomposition and substituting their components between the MS and PAN image components to produce a pan-sharpened image.	Klonus and Ehlers (2009) King and Wang (2001)
HPF	This method involves a convolution using a high pass filter on the PAN image and merging the result with the MS image.	Gangkofner <i>et al.</i> (2008)
EF	This method is based on IHS transformation coupled with Fourier domain filtering.	Klonus and Ehlers (2009)
GS	This method firstly simulates a panchromatic band from lower spatial resolution spectral bands. Then the Gram-Schmidt transformation is performed on the simulated panchromatic band and the spectral bands and replaces the high spatial resolution panchromatic band with the first Gram-Schmidt band. Finally, an inverse Gram-Schmidt transformation is performed to generate a pan-sharpened image.	Laben and Brower (1998)

computation, was used to calculate image quality indices.

Questionnaire

A questionnaire was designed and used to survey the users' requirements from 3 expert groups (agriculture, forestry, and urban) on the importance (weight) of image quality criteria (VIA, EDA, QI, and ECA) for the optimum pan-sharpening method evaluation. Fifteen experts (5 from each group) with experience in THEOS pan-sharpening imaging and a good background in remote sensing were selected from government agencies and interviewed personally.

Research Methodology

The main research methodology comprised 4 components: (1) orthorectification, (2) pan-sharpening processing, (3) image quality

evaluation, and (4) the optimum pan-sharpening method evaluation by SAW of MCDA (Figure 2). The summary of each main component was separately described as follows:

Orthorectification

The orthorectification process eliminates scale, tilt, and relief distortions of images and the resulting image of orthorectification is called the orthorectified image (Wolf and Dewitt, 2000). In this study, THEOS data were orthorectified using the Leica Photogrammetry Suite module of ERDAS Imagine software. For this study 10 grid closest points (GCP) per image were selected which fulfill the minimum requirement of 7 GCP for orthorectification as suggested by Santitamnont and Lerk-u-suke (2009). Generally, a GCP is a point on the surface with the known location on a specific reference system. In this work, the horizontal coordinate of each GCP was measured from the LDD color orthophoto while the vertical

Table 3. Equations of image quality indices

QI	Equation	Symbol	Reference
CC	$CC = \frac{\sum (x_i - \bar{x}_i)(y_i - \bar{y}_i)}{\sqrt{(\sum (x_i - \bar{x}_i)^2)(\sum (y_i - \bar{y}_i)^2)}}$	x_i is original DN value of MS band i y_i is original DN value of PS band i $\bar{x}_i$ is mean DN value of MS band i $\bar{y}_i$ is mean DN value of PS band i	Meenakshisundaram (2005)
RM	$RM = \frac{\bar{y}_i - \bar{x}_i}{\bar{x}_i}$	m is number of pixels in column n is number of pixels in row N is number of bands	Parcharidis and Kazi-Tani (2000)
RMSE	$RMSE = \sqrt{\frac{\sum (x_i - y_i)^2}{mn}}$	h is spatial resolution of PS band l is spatial resolution of MS band	Ehlers (2008)
RASE	$RASE = \frac{100}{\bar{x}_i} \sqrt{\frac{1}{N} \sum_{i=1}^N RMSE^2(x_i - y_i)}$	α is spectral angle between MS and PS (in radian) σ_x is standard deviation of MS band σ_y is standard deviation of PS band σ_{xy} is covariance between MS and PS bands	Strait <i>et al.</i> (2008)
ERGAS	$ERGAS = 100 \frac{h}{l} \sqrt{\frac{1}{N} \sum_{i=1}^N \left[\frac{RMSE(x_i - y_i)}{\bar{mean}(x_i - y_i)} \right]^2}$	$\bar{x}$ is mean value of MS band $\bar{y}$ is mean value of PS band σ_x^2 is variance of MS band σ_y^2 is variance of PS band	Wald <i>et al.</i> (1997)
SAM	$Cos \alpha = \frac{\sum_{i=1}^N x_i y_i}{\sqrt{\sum_{i=1}^N x_i^2} \sqrt{\sum_{i=1}^N y_i^2}}$	Note: MS is Multispectral image and PS is Pan-sharpened image	Yuhua <i>et al.</i> (1992)
UIQI	$UIQI = \frac{\sigma_{xy}}{\sigma_x \sigma_y} * \frac{2\bar{x}\bar{y}}{(\bar{x})^2 + (\bar{y})^2} * \frac{2\sigma_x \sigma_y}{\sigma_x^2 + \sigma_y^2}$		Wang and Bovik (2002)

coordinate of each GCP was extracted from the DEM dataset. Practically, the selected GCP (horizontal and vertical coordinates) should be prominent and distinct features, e.g. a road junction on the THEOS image.

Pan-Sharpening Processing

The selected pan-sharpening methods including (1) BT, (2) MT, (3) PCA, (4) IHST, (5), MIHST (6) WT, (7) HPF, (8) EF, and (9) GS were applied to orthophotos derived from PAN and MS data with the nearest neighbor resampling technique (if it is required). The basic characteristics of pan-sharpening methods are summarized in Table 2.

Image Quality Evaluation

Four criteria for image quality assessment consisting of VIA, EDA, QI, and ECA were applied to quantify the pan-sharpened image quality for every pan-sharpening method stated earlier. Here, the elements of visual interpretation including tone, color, size, shape, texture, and pattern, as suggested by Jensen (2007) and Ongsomwang (2011), were used to measure the preservation of image properties for VIA. For EDA, Sobel (Sonka *et al.*, 2007) and Laplacian (Rosenfeld

and Kak, 1982) operators were applied to examine the preservation of the edge's structure. In the case of QI, the correlation coefficient (CC), relative shift of the mean (RM), root mean square error (RMSE), relative average spectral error (RASE), relative dimensionless global error in synthesis (ERGAS), spectral angle mapping (SAM), and universal image quality index (UIQI) were applied to measure the quantitative image distortion (Table 3). This criterion is most frequently used by researchers in the field of pan-sharpening method evaluation (Table 1).

Unlike other criteria, the ECA criterion examines the effect of classification accuracy using overall accuracy and the kappa hat coefficient. For this purpose, all the pan-sharpened images were firstly classified into specific land use type i.e., urban and built-up area, commercial land, field crop, perennial trees and orchard, horticulture, forest land, water bodies, and miscellaneous land using unsupervised classification with the ISODATA clustering algorithm under the ERDAS Imagine software. Then, the accuracy of all the classified land use data was accessed using the LDD land use data of 2011 and field verification in 2013.

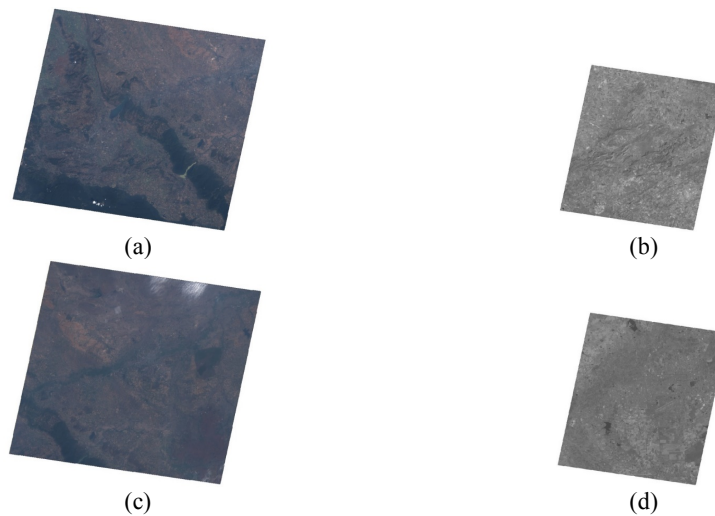


Figure 3. THEOS orthorectified images: (a) MS 1, (b) PAN 1, (c) MS 2, and (d) PAN 2

Optimum Pan-Sharpening Method evaluation by SAW of MCDA

The quantitative measurements of THEOS pan-sharpened image quality by 4 criteria (VIA, EDA, QI, and ECA) were combined with the SAW method assigning equal weight to justify the optimum pan-sharpening method for the agriculture, forestry, and urban applications based on self-evaluation. On the other hand, the SAW method with specific weight assigned by 15 experts from 3 groups (agriculture, forestry, and urban) to each criterion was then combined with the SAW method to identify the optimum pan-sharpening method based on the users' requirements.

Results and Discussion

THEOS Orthorectification

The orthorectified images of MS 1, PAN 1, MS 2, and PAN 2 with the total RMSE of 0.0294, 0.2327, 0.0408, and 0.2351 pixels, respectively, are displayed in Figure 3.

Pan-Sharpening Processing

Pan-sharpened images of 6 test areas for 3 applications are presented in Figure 4. From the results, it is revealed that IHST provided very high brightness and contrast for all the test areas. Meanwhile PCA, MIHST, HPF, EF, and

GS showed moderate brightness and contrast and BT, MT, and WT provided low brightness and contrast for all the test areas. Theoretically, differentiation of image quality by visual comparison is rather difficult because it is a subjective judgment and relies on the background, experience, and skills of the evaluator or interpreter. So, basic image statistics, including the mean and standard deviation of 3 visible bands (red, green, and blue) of all pan-sharpening methods, were here extracted to compare and quantify the characteristics of image quality, as shown in the stock charts in Figure 5.

From the results, all the charts can easily identify the image contrast classified into 3 levels: low, moderate, and high, based on the brightness value and its range in each band. Herein, IHST showed a very high brightness and contrast image with a brightness value higher than 100 and a wide range in all the test areas. Meanwhile, PCA, MIHST, HPF, EF, and GS provided a pan-sharpened image with moderate brightness and contrast with a brightness value between 50 and 100. In contrast, MT and WT in all test areas provided a low brightness and contrast image with a brightness value less than 50 and a narrow range. Similarly, BT also provided a low brightness and contrast image in the agriculture and forestry test areas.

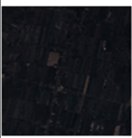
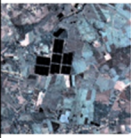
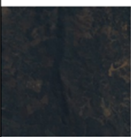
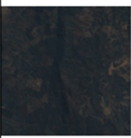
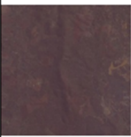
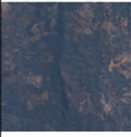
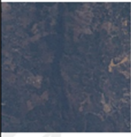
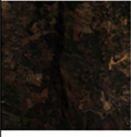
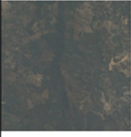
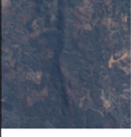
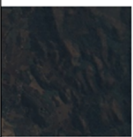
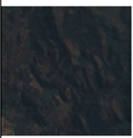
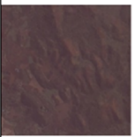
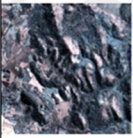
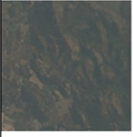
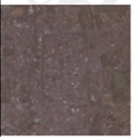
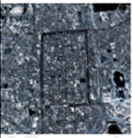
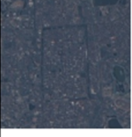
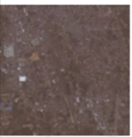
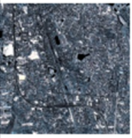
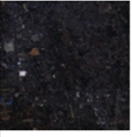
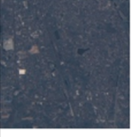
Test Area	Pan-sharpening method								
	BT	MT	PCA	IHST	MIHST	HPF	WT	EF	GS
A1									
A2									
F1									
F2									
U1									
U2									

Figure 4. THEOS pan-sharpened image in each test area from nine selected pan-sharpening methods

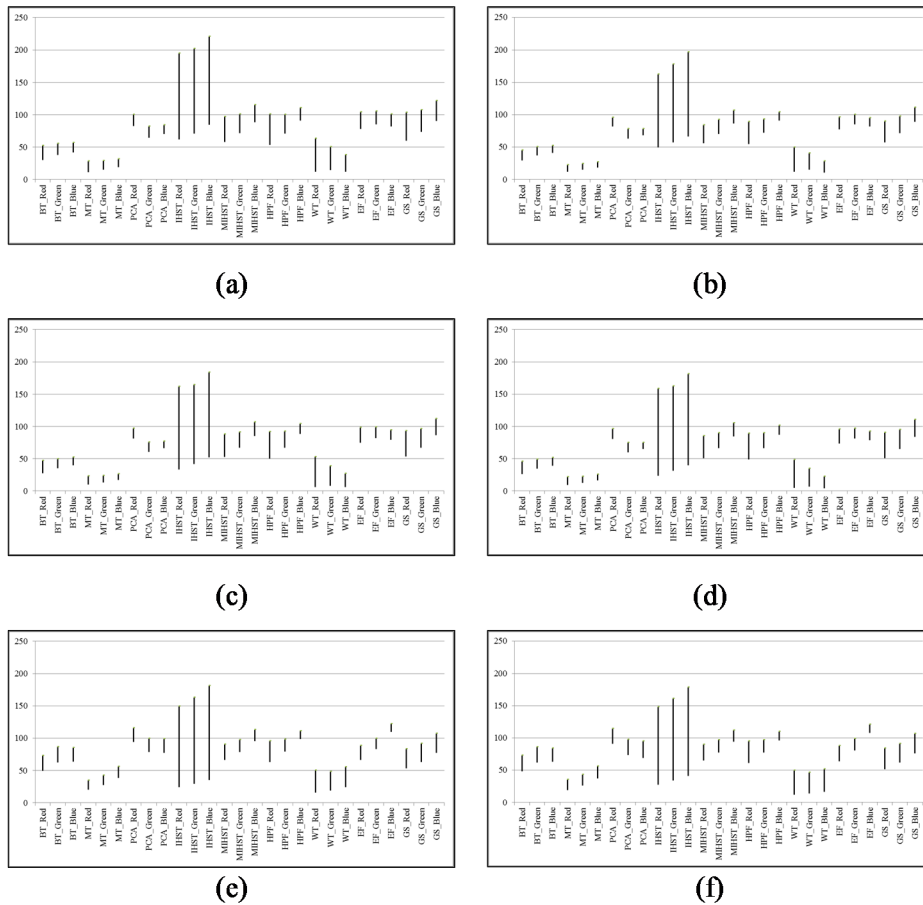


Figure 5. $\pm$ One standard deviation of the mean brightness value of each band of the pan-sharpened image from each method for 6 test areas: (a) A1, (b) A2, (c) F1, (d) F2, (e) U1, and (f) U2

Image Quality Evaluation Based on Single Criterion

The relevant results of image quality evaluation by a single criterion in each application (agriculture, forestry, and urban) can be summarized according to the derived total and normalized scores as follows:

Visual Image Analysis

The total and normalized scores of VIA and the level of visual interpretability (good, moderate, and poor) are presented in Table 4. It was found that most of the pan-sharpening methods including BT, PCA, IHST, MIHST, HPF, and GS provided visual interpretability at a high level for the agriculture application. The best and worst methods for VIA were GS and

MT, respectively. For the forestry application, BT, HPF, and GS provided a high-level capability for visual interpretability and the best and worst methods were GS and WT, respectively. In the case of the urban study, BT and GS could provide a high-level capability for visual interpretability and the best and worst methods were GS and WT, respectively.

Consequently, the most appropriate method in producing a THEOS pan-sharpened image based on VIA criteria for 3 applications was GS. This finding was similar to the previous work of Zhang and Mishra (2012) who applied VIA for image quality evaluation. They concluded that GS can produce a high quality pan-sharpened image from the very high spatial resolution images including

Table 4. Results of image quality evaluation using visual image analysis criterion for each test area with different pan-sharpening methods

Test Area	Method	Elements of visual interpretation						Total score	Normalized score (0-10)	Level of visual interpretability
		Tone	Color	Size	Shape	Texture	Pattern			
A1	BT	2	3	2	2	3	3	15	8	High
	MT	1	1	1	1	1	1	6	3	Low
	PCA	3	3	3	3	3	3	18	10	High
	IHST	3	1	3	3	2	3	15	8	High
	MIHS	3	3	3	3	2	3	17	9	High
	HPF	3	3	3	3	3	3	18	10	High
	WT	3	3	1	1	1	1	10	5	Low
	EF	3	2	2	3	1	2	13	7	Moderate
	GS	3	3	3	3	3	3	18	10	High
A2	BT	2	3	2	3	3	3	16	8	High
	MT	1	1	1	1	2	1	7	3	Low
	PCA	3	3	3	3	2	3	17	9	High
	IHST	3	1	3	3	3	3	16	8	High
	MIHS	3	3	3	3	2	3	17	9	High
	HPF	3	3	3	3	2	3	17	9	High
	WT	3	3	1	1	1	1	10	5	Low
	EF	3	3	3	3	1	2	15	8	High
	GS	3	3	3	3	3	3	18	10	High
F1	BT	2	3	3	3	3	3	17	9	High
	MT	1	1	3	3	1	3	12	6	Moderate
	PCA	2	3	2	2	2	2	13	7	Moderate
	IHST	1	1	3	3	1	2	11	6	Moderate
	MIHS	3	2	3	3	2	2	15	8	High
	HPF	3	2	3	3	3	3	17	9	High
	WT	2	1	1	1	1	1	7	3	Low
	EF	3	2	2	3	1	2	13	7	Moderate
	GS	3	3	3	3	3	3	18	10	High
F2	BT	2	3	3	3	3	3	17	9	High
	MT	1	1	2	2	2	1	9	5	Low
	PCA	3	3	2	2	2	2	14	7	Moderate
	IHST	1	1	1	1	2	2	8	4	Low
	MIHS	3	2	2	2	2	1	12	6	Moderate
	HPF	3	2	3	3	3	3	17	9	High
	WT	2	1	1	1	1	1	7	3	Low
	EF	3	2	2	2	1	2	12	6	Moderate
	GS	2	3	3	3	3	3	17	9	High
U1	BT	3	2	3	3	2	3	16	8	High
	MT	1	1	2	1	1	1	7	3	Low
	PCA	3	2	2	1	1	1	10	5	Low
	IHST	3	1	2	2	2	1	11	6	Moderate
	MIHS	3	1	2	2	2	2	12	6	Moderate
	HPF	2	2	2	3	2	3	14	7	Moderate
	WT	2	1	1	1	1	1	7	3	Low
	EF	1	1	2	3	1	2	10	5	Low
	GS	3	2	3	3	2	3	16	8	High
U2	BT	3	2	3	3	2	3	16	8	High
	MT	1	1	2	2	2	2	10	5	Low
	PCA	2	2	1	1	1	1	8	4	Low
	IHST	3	1	2	2	2	1	11	6	Moderate
	MIHS	3	2	3	3	2	3	16	8	High
	HPF	3	3	3	3	3	2	17	9	High
	WT	1	1	1	1	1	1	6	3	Low
	EF	2	3	2	2	1	2	12	6	Moderate
	GS	3	3	3	3	3	3	18	10	High

Table 5. CC values from Sobel and Laplacian operators of edge detection analysis criterion for each test area with different pan-sharpening methods

Test area	Method	Operator		Total score	Normalized score (0-10)
		Sobel	Laplacian		
A1	BT	0.7087	0.5503	1.2590	6
	MT	0.5331	0.4531	0.9862	5
	PCA	0.5731	0.4296	1.0027	5
	IHST	0.6076	0.7383	1.3459	7
	MIHST	0.7008	0.5324	1.2332	6
	HPF	0.8867	0.7531	1.6398	8
	WT	0.0238	0.0058	0.0296	0
	EF	0.7246	0.4976	1.2222	6
	GS	0.7872	0.5922	1.3794	7
A2	BT	0.7114	0.5076	1.2190	6
	MT	0.5664	0.4580	1.0244	5
	PCA	0.5831	0.3918	0.9749	5
	IHST	0.7633	0.7816	1.5449	8
	MIHST	0.6864	0.4775	1.1639	6
	HPF	0.8903	0.7248	1.6151	8
	WT	0.0216	0.0122	0.0338	0
	EF	0.7156	0.4585	1.1741	6
	GS	0.7813	0.5422	1.3235	7
F1	BT	0.6833	0.5676	1.2509	6
	MT	0.5534	0.4973	1.0507	5
	PCA	0.5676	0.4407	1.0083	5
	IHST	0.7008	0.7896	1.4904	7
	MIHST	0.6561	0.5249	1.1810	6
	HPF	0.8895	0.7758	1.6653	8
	WT	0.0199	0.0044	0.0243	0
	EF	0.6965	0.5073	1.2038	6
	GS	0.7611	0.6111	1.3722	7
F2	BT	0.6940	0.5673	1.2613	6
	MT	0.5398	0.4996	1.0394	5
	PCA	0.5879	0.4435	1.0314	5
	IHST	0.7028	0.7719	1.4747	7
	MIHST	0.6380	0.5212	1.1592	6
	HPF	0.8934	0.7738	1.6672	8
	WT	0.0063	0.0023	0.0086	0
	EF	0.6953	0.5056	1.2009	6
	GS	0.7934	0.6153	1.4087	7
U1	BT	0.8652	0.7369	1.6021	8
	MT	0.7777	0.6496	1.4273	7
	PCA	0.0288	0.0168	0.0456	0
	IHST	0.6291	0.8243	1.4534	7
	MIHST	0.7917	0.6739	1.4656	7
	HPF	0.9038	0.7607	1.6645	8
	WT	0.0124	0.0053	0.0177	0
	EF	0.7740	0.5622	1.3362	7
	GS	0.9197	0.7606	1.6803	8
U2	BT	0.8592	0.7257	1.5849	8
	MT	0.7622	0.6382	1.4004	7
	PCA	0.0330	0.0162	0.0492	0
	IHST	0.6297	0.8256	1.4553	7
	MIHST	0.7789	0.6483	1.4272	7
	HPF	0.9035	0.7621	1.6656	8
	WT	0.0082	0.0018	0.0100	0
	EF	0.7688	0.5547	1.3235	7
	GS	0.9131	0.7496	1.6627	8

Table 6. Normalized values of QI results as total score and normalized score for each test area with different pan-sharpening methods

Test area	Method	Quality indices							Total score
		CC	RM	RMSE	RASE	ERGAS	SAM	UIQI	
A1	BT	6.5200	3.8920	5.6716	5.5617	5.5608	9.1110	5.2473	41.5644
	MT	7.7420	0.0000	2.0728	1.8237	1.8544	8.1322	2.8323	24.4574
	PCA	1.9320	9.7860	8.9963	8.9498	8.9047	7.7290	5.6578	51.9556
	IHST	4.4380	2.4520	0.0000	0.0000	0.0000	3.2661	1.6340	11.7901
	MIHST	7.5270	10.0000	10.0000	10.0000	10.0000	10.0000	5.4927	63.0197
	HPF	6.9180	9.9330	9.7697	9.6237	9.4727	9.2361	5.7288	60.6820
	WT	2.9130	2.3170	3.8006	3.7567	3.6570	0.0000	4.3235	20.7678
	EF	6.8800	9.2170	9.8908	9.8118	9.7797	9.8709	7.6813	63.1315
	GS	7.3360	9.5610	9.6526	9.5648	9.5550	9.4911	6.2800	61.4405
A2	BT	6.8570	3.8650	4.7488	4.7074	5.5608	8.9613	4.2640	38.9643
	MT	7.6640	0.0000	0.5620	0.4174	1.8544	8.5848	2.1655	21.2481
	PCA	1.6950	9.9630	8.5155	8.4883	8.9047	7.2649	4.9488	49.7802
	IHST	3.3330	4.6830	0.0000	0.0000	0.0000	1.9919	1.0087	11.0166
	MIHST	7.7210	9.7740	10.0000	10.0000	10.0000	10.0000	4.5033	61.9983
	HPF	7.5340	10.0000	9.9066	9.8007	9.4727	9.6199	5.6315	61.9654
	WT	3.0810	2.0230	2.4737	2.5418	3.6570	0.0000	4.3748	18.1513
	EF	6.6830	8.9630	9.5330	9.4530	9.7797	9.4713	6.8375	60.7205
	GS	7.6880	9.8040	9.6362	9.5758	9.5550	9.4355	5.0525	60.7470
F1	BT	6.5220	3.9900	4.5965	4.6224	4.6133	9.1357	4.6360	38.1159
	MT	7.6620	0.0000	0.0329	0.0000	0.0000	8.5514	2.4258	18.6721
	PCA	0.0410	9.9870	8.3103	8.2859	8.1979	7.4722	5.2750	47.5693
	IHST	5.1520	6.1140	0.0000	0.2252	0.1899	2.8799	2.0390	16.6000
	MIHST	8.0070	10.0000	10.0000	10.0000	10.0000	10.0000	5.5470	63.5540
	HPF	6.9910	9.9940	9.6245	9.4780	9.2989	9.2765	5.1673	59.8302
	WT	2.2810	1.6700	1.5022	1.6885	1.5253	0.0000	3.6348	12.3018
	EF	6.1160	8.7270	9.3283	9.2240	9.1408	9.4029	6.5985	58.5375
	GS	7.8160	9.6160	9.6825	9.6206	9.6277	9.6713	5.7933	61.8274
F2	BT	7.3390	4.0800	4.9352	4.8584	4.8537	9.1197	5.4290	40.6150
	MT	8.2380	0.0000	0.6570	0.4479	0.4777	8.4286	2.7610	21.0102
	PCA	0.8660	9.8480	8.2456	8.1641	8.0064	7.3441	6.2880	48.7622
	IHST	5.3130	6.7440	0.0000	0.0000	0.0000	2.1815	2.0147	16.2532
	MIHST	8.5530	10.0000	10.0000	10.0000	10.0000	10.0000	6.1543	64.7073
	HPF	7.5490	9.9720	9.5883	9.4364	9.2616	9.2665	5.9495	61.0233
	WT	3.1310	1.3920	1.7985	1.8261	1.6747	0.0000	4.1935	14.0158
	EF	6.7210	8.6180	9.1371	8.9981	8.8804	9.2037	7.1923	58.7506
	GS	8.1420	9.6140	9.4917	9.4169	9.4062	9.4459	6.2443	61.7610
U1	BT	6.5540	5.9290	7.0302	6.9643	6.9183	8.5322	4.7038	46.6318
	MT	8.3850	0.0000	1.7909	1.4856	1.4783	7.8836	4.1665	25.1899
	PCA	1.0150	8.9177	8.3494	8.2322	7.9516	7.7664	6.6435	48.8758
	IHST	2.8560	9.2309	0.0000	0.0000	0.0000	0.0000	0.7513	12.8382
	MIHST	7.9930	9.6718	9.7721	9.7824	9.7796	9.7404	4.3490	61.0883
	HPF	6.9470	10.0000	9.3770	9.2418	9.0249	8.9638	4.6928	58.2473
	WT	4.3680	0.6515	1.9282	1.7462	1.7272	2.9674	3.4725	16.8610
	EF	9.0970	9.8748	10.0000	10.0000	10.0000	10.0000	6.8565	65.8283
	GS	7.0950	7.6266	8.0807	7.9907	7.9850	8.2044	4.1433	51.1257
U2	BT	6.4390	6.0613	7.0410	7.0450	6.9965	8.5792	5.4743	47.6363
	MT	8.3830	0.0000	1.3548	1.2186	1.2126	7.5193	4.6793	24.3676
	PCA	0.5840	9.1788	8.0583	7.9975	7.7329	7.2505	6.7638	47.5658
	IHST	3.3670	8.5482	0.0000	0.0000	0.0000	0.0000	1.0293	12.9445
	MIHST	8.2760	9.8109	9.9192	9.9011	9.9019	9.8666	5.5713	63.2470
	HPF	6.9080	10.0000	9.4149	9.3082	9.1088	8.9756	5.2955	59.0110
	WT	3.9540	0.3756	1.1832	1.1738	1.0950	1.1607	3.4273	12.3696
	EF	8.9270	9.8189	10.0000	10.0000	10.0000	10.0000	7.3098	66.0557
	GS	7.1540	7.8201	8.2173	8.1774	8.1847	8.2995	4.9555	52.8085

Table 7. Accuracy assessment and its normalized score in each test area with different pan-sharpening methods

Test Area	Method	Accuracy assessment		Total Score	Normalized Score (0-10)
		Overall accuracy	Kappa hat coefficient		
A1	BT	38.78	10.39	49.17	2
	MT	39.80	12.31	52.11	3
	PCA	39.80	11.66	51.46	3
	IHST	38.27	0.22	38.49	2
	MIHST	44.90	9.52	54.42	3
	HPF	39.80	5.16	44.96	2
	WT	44.90	8.99	53.89	3
	EF	43.88	8.61	52.49	3
A2	GS	39.80	7.15	46.95	2
	BT	69.90	38.96	108.86	5
	MT	67.86	32.15	100.01	5
	PCA	68.37	35.10	103.47	5
	IHST	66.84	27.88	94.72	5
	MIHST	65.31	35.18	100.49	5
	HPF	69.39	34.56	103.95	5
	WT	64.80	26.40	91.20	5
F1	EF	67.35	27.68	95.03	5
	GS	67.86	33.95	101.81	5
	BT	51.53	21.43	72.96	4
	MT	54.59	27.99	82.58	4
	PCA	47.45	14.48	61.93	3
	IHST	50.00	18.08	68.08	3
	MIHST	51.53	19.42	70.95	4
	HPF	53.06	21.29	74.35	4
F2	WT	54.59	23.98	78.57	4
	EF	51.53	20.40	71.93	4
	GS	51.02	19.48	70.50	4
	BT	72.96	31.08	104.04	5
	MT	65.31	17.30	82.61	4
	PCA	65.31	17.30	82.61	4
	IHST	68.37	27.23	95.60	5
	MIHST	67.35	22.55	89.90	4
U1	HPF	69.39	30.94	100.33	5
	WT	72.45	39.26	111.71	6
	EF	67.86	27.50	95.36	5
	GS	66.84	28.20	95.04	5
	BT	70.92	29.79	100.71	5
	MT	79.08	38.37	117.45	6
	PCA	56.12	19.82	75.94	4
	IHST	25.00	7.98	32.98	2
U2	MIHST	72.45	27.61	100.06	5
	HPF	61.73	26.71	88.44	4
	WT	64.29	23.35	87.64	4
	EF	85.20	42.98	128.18	6
	GS	63.27	26.91	90.18	5
	BT	69.39	0.23	91.97	5
	MT	70.41	0.28	98.53	5
	PCA	59.69	0.18	78.07	4
U2	IHST	67.35	0.21	88.14	4
	MIHST	40.31	0.10	50.37	3
	HPF	54.08	0.17	70.69	4
	WT	68.37	0.25	93.07	5
	EF	67.35	0.24	91.36	5
	GS	62.24	0.23	84.90	4

Table 8. Criterion score and total score by SAW with equal weight and its rank for each test area with different pan-sharpening methods

Test area	Methods	Image quality criteria				Total score	Ranking
		VIA	EDA	QI	ECA		
A1	BT	8	6	6	2	22	6
	MT	3	5	4	3	15	8
	PCA	10	5	8	3	26	4
	IHST	8	7	2	2	19	7
	MIHST	9	6	9	3	27	3
	HPF	10	8	9	2	29	1
	WT	5	0	3	3	11	9
	EF	7	6	9	3	25	5
	GS	10	7	9	2	28	2
A2	BT	8	6	6	5	25	6
	MT	3	5	3	5	16	8
	PCA	9	5	7	5	26	5
	IHST	8	8	2	5	23	7
	MIHST	9	6	9	5	29	3
	HPF	9	8	9	5	31	1
	WT	5	0	3	5	13	9
	EF	8	6	9	5	28	4
	GS	10	7	9	5	31	1
F1	BT	9	6	6	4	25	4
	MT	6	5	3	4	18	7
	PCA	7	5	7	3	22	6
	IHST	6	7	2	3	18	7
	MIHST	8	6	9	4	27	3
	HPF	9	8	8	4	29	2
	WT	3	0	2	4	9	9
	EF	7	6	8	4	25	4
	GS	10	7	9	4	30	1
F2	BT	9	6	6	5	26	3
	MT	5	5	3	4	17	8
	PCA	7	5	7	4	23	6
	IHST	4	7	2	5	18	7
	MIHST	6	6	9	4	25	4
	HPF	9	8	9	5	31	1
	WT	3	0	2	6	11	9
	EF	6	6	8	5	25	4
	GS	9	7	9	5	30	2
U1	BT	8	8	7	5	28	1
	MT	3	7	3	6	19	6
	PCA	5	0	7	4	16	8
	IHST	6	7	2	2	17	7
	MIHST	6	7	9	5	27	3
	HPF	7	8	8	4	27	3
	WT	3	0	2	4	9	9
	EF	5	7	9	6	27	3
	GS	8	8	7	5	28	1
U2	BT	8	8	7	5	28	3
	MT	5	7	3	5	20	6
	PCA	4	0	7	4	15	8
	IHST	6	7	2	4	19	7
	MIHST	8	7	9	3	27	4
	HPF	9	8	8	4	29	1
	WT	3	0	2	5	10	9
	EF	6	7	9	5	27	4
	GS	10	8	7	4	29	1

Table 9. Weight for each image quality criterion by three expert groups

Application	Expert	VIA	EDA	QI	ECA
Agriculture	1	80.00	10.00	0.00	10.00
	2	50.00	20.00	10.00	20.00
	3	40.00	10.00	40.00	10.00
	4	80.00	10.00	10.00	0.00
	5	50.00	20.00	20.00	10.00
	Average Weight	60.00	14.00	16.00	10.00
Forestry	1	37.50	12.50	12.50	37.50
	2	95.00	2.00	2.00	1.00
	3	90.00	3.00	5.00	2.00
	4	50.00	25.00	25.00	0.00
	5	60.00	10.00	10.00	20.00
	Average Weight	66.50	10.50	10.90	12.10
Urban	1	100.00	0.00	0.00	0.00
	2	100.00	0.00	0.00	0.00
	3	60.00	10.00	20.00	10.00
	4	30.00	10.00	60.00	0.00
	5	50.00	10.00	10.00	30.00
	Average Weight	68.00	6.00	18.00	8.00
		0.68	0.06	0.18	0.08

IKONOS, QuickBird, and GeoEye-1, but not from the WorldView-2 images.

a Formosat image with an average CC value of 94.98%.

Edge Detection Analysis

The total and normalized scores of EDA according to the CC value are reported in Table 5. It was found that the most appropriate pan-sharpening method for edge detection using Sobel and Laplacian operators in the agriculture application, based on the total score of the CC, was HPF while the worst was WT. In the case of the forestry application, the most appropriate and inappropriate pan-sharpening methods were also HPF and WT, respectively. For the urban study, the most appropriate pan-sharpening method was GS or HPF (when the availability of software is considered) and the least appropriate pan-sharpening method was also WT.

Thus, the most appropriate method in producing a THEOS pan-sharpened image for edge detection in 3 applications was HPF. This finding was similar to the previous work of Klonus and Ehlers (2009), who applied edge detection using the Sobel operator as 1 of the indicators for the pan-sharpening method evaluation. They concluded that HPF can detect the edge in the pan-sharpened data from

Quality Indices

The total and normalized scores of QI are presented in Table 6. From the results, it was found the most appropriate pan-sharpening method based on its frequency for the agriculture application, which provides a minimum spectral deviation, was MIHST. However, the total score showed that the possible appropriate methods for the agriculture application may include the HPF, EF, and GS methods. These possibilities are useful when software availability is considered. For the forestry application, the most appropriate pan-sharpening method was MIHST and the alternative methods included HPF and GS. In the case of the urban application, the most appropriate pan-sharpening method was EF or MIHST.

In summary, the most appropriate method for producing the THEOS pan-sharpened image, according to QI for 3 applications, was MIHST. This observation was similar to the previous work of Li and Li (2010), who applied 8 pan-sharpening methods (BT, MIHST, PCA, HPF, SFIM,

Table 10. Criterion score and total score by SAW with users' weights and its rank for each test area with different pan-sharpening methods

Test area	Methods	Image quality criteria				Total score	Ranking
		VIA	EDA	QI	ECA		
A1	BT	4.80	0.84	0.96	0.20	6.8	5
	MT	1.80	0.70	0.64	0.30	3.44	9
	PCA	6.00	0.70	1.28	0.30	8.28	3
	IHST	4.80	0.98	0.32	0.20	6.3	7
	MIHST	5.40	0.84	1.44	0.30	7.98	4
	HPF	6.00	1.12	1.44	0.20	8.76	1
	WT	3.00	0.00	0.48	0.30	3.78	8
	EF	4.20	0.84	1.44	0.30	6.78	6
	GS	6.00	0.98	1.44	0.20	8.62	2
A2	BT	4.80	0.84	0.96	0.50	7.1	6
	MT	1.80	0.70	0.48	0.50	3.48	9
	PCA	5.40	0.70	1.12	0.50	7.72	4
	IHST	4.80	1.12	0.32	0.50	6.74	7
	MIHST	5.40	0.84	1.44	0.50	8.18	3
	HPF	5.40	1.12	1.44	0.50	8.46	2
	WT	3.00	0.00	0.48	0.50	3.98	8
	EF	4.80	0.84	1.44	0.50	7.58	5
	GS	6.00	0.98	1.44	0.50	8.92	1
F1	BT	5.94	0.66	0.66	0.48	7.74	3
	MT	3.96	0.55	0.33	0.48	5.32	7
	PCA	4.62	0.55	0.77	0.36	6.3	6
	IHST	3.96	0.77	0.22	0.36	5.31	7
	MIHST	5.28	0.66	0.99	0.48	7.41	4
	HPF	5.94	0.88	0.88	0.48	8.18	2
	WT	1.98	0.00	0.22	0.48	2.68	9
	EF	4.62	0.66	0.88	0.48	6.64	5
	GS	6.60	0.77	0.99	0.48	8.84	1
F2	BT	5.94	0.66	0.66	0.60	7.86	3
	MT	3.30	0.55	0.33	0.48	4.66	7
	PCA	4.62	0.55	0.77	0.48	6.42	4
	IHST	2.64	0.77	0.22	0.60	4.23	8
	MIHST	3.96	0.66	0.99	0.48	6.09	5
	HPF	5.94	0.88	0.99	0.60	8.41	1
	WT	1.98	0.00	0.22	0.72	2.92	9
	EF	3.96	0.66	0.88	0.60	6.1	5
	GS	5.94	0.77	0.99	0.60	8.3	2
U1	BT	5.44	0.48	1.26	0.40	7.58	1
	MT	2.04	0.42	0.54	0.48	3.48	8
	PCA	3.40	0.00	1.26	0.32	4.98	7
	IHST	4.08	0.42	0.36	0.16	5.02	6
	MIHST	4.08	0.42	1.62	0.40	6.52	4
	HPF	4.76	0.48	1.44	0.32	7	3
	WT	2.04	0.00	0.36	0.32	2.72	9
	EF	3.40	0.42	1.62	0.48	5.92	5
	GS	5.44	0.48	1.26	0.40	7.58	1
U2	BT	5.44	0.48	1.26	0.40	7.58	4
	MT	3.40	0.42	0.54	0.40	4.76	7
	PCA	2.72	0.00	1.26	0.32	4.3	8
	IHST	4.08	0.42	0.36	0.32	5.18	6
	MIHST	5.44	0.42	1.62	0.24	7.72	3
	HPF	6.12	0.48	1.44	0.32	8.36	2
	WT	2.04	0.00	0.36	0.40	2.8	9
	EF	4.08	0.42	1.62	0.40	6.52	5
	GS	6.80	0.48	1.26	0.32	8.86	1

W+PCA, EF, and Region) with QuickBird data in the city of Wuhan, China. They concluded that the MIHST fused image had the lowest difference of information based on cross entropy (CE) and lower noise according to the weighted signal to noise ratio (WSNR). On the contrary, Intajag *et al.* (2010) applied 4 pan-sharpening methods (IHST, the Choi method, Tu method, and Pradhan algorithms) with THEOS data over Prince of Songkla University, Songkhla Province, Thailand. They stated that the Pradhan algorithm preserves the spectral characteristics and enhances the texture properties, although it had increasing noise based on the RMSE value.

Effect on Classification Accuracy

The accuracy assessment for land use classification from each image of the pan-sharpening methods for all the test areas are presented in Table 7. From the results, it was revealed that most of the pan-sharpening methods, including EF, MIHST, MT, PCA, and WT, were appropriate for land use extraction in the agriculture application. For the forestry application, most of the pan-sharpening methods were appropriate for land use extraction including BT, HPF, WT, EF, and GS. In the case of the urban study, the appropriate pan-sharpening methods were BT, EF, and MT. Therefore, the most appropriate method for producing the THEOS pan-sharpened image for land use extraction in the 3 applications was EF.

Optimum Pan-Sharpening Method by Self-Evaluation

The normalized and total scores for the optimum pan-sharpening method evaluation by self-evaluation are summarized in Table 8. From the results, the optimum pan-sharpening methods for the agriculture, forestry, and urban applications, according to ranking, can be summarized as follows:

Agriculture Application

The optimum pan-sharpening method for THEOS data was HPF. However, if ERDAS Imagine software is unavailable, GS, which is available in ENVI software, can be chosen as the optimum method. In addition, it was found

that WT was an inappropriate method for the THEOS pan-sharpening processing.

Forestry Application

The optimum pan-sharpening method for THEOS data can be HPF or GS. Furthermore, it can be observed that WT was an inappropriate method for THEOS data.

Urban Application

The optimum pan-sharpening method for THEOS data was GS. However, when software availability is considered, BT or HPF can be chosen as the optimum pan-sharpening method. Also, WT was an inappropriate method for THEOS pan-sharpening production.

All Three Applications

According to the summation of 6 total scores from the 6 test areas presented in Table 8 as overall scores, it was found that the optimum pan-sharpening method for THEOS data in the 3 applications was HPF or GS. This conclusion may be true for only 1 method, if availability of software is considered. In addition, WT was inappropriate for THEOS pan-sharpening creation in the 3 applications.

Optimum Pan-Sharpening Method Based on the Users' Requirements

According to the specific weight provided by 15 experts, as shown in Table 9, the most preferred image quality criterion for optimum pan-sharpening method identification among the 15 experts was VIA. This implies that the utilization of THEOS pan-sharpening data mostly relies on visual interpretation.

The optimum THEOS pan-sharpening method for the agriculture, forestry, and urban applications, according to the rankings as shown in Table 10, can be separately summarized in the following sections.

Agriculture Application

The optimum pan-sharpening method in the agriculture application, according to the users' requirements, was GS. However, HPF can be chosen as the optimum pan-sharpening method when ENVI software is unavailable.

Forestry Application

The optimum pan-sharpening method in the forestry application, according to the users' requirements, was GS; HPF can be chosen as the optimum pan-sharpening method when only ERDAS Imagine software is available.

Urban Application

The optimum pan-sharpening method in the urban application, according to the users' requirements, was GS. However, BT can be chosen as the optimum pan-sharpening method when ENVI software is unavailable.

All Three Applications

The optimum pan-sharpening method for THEOS data in all 3 applications, according to the users' requirements, which was justified based on the summation of the total score of each method in Table 10 from the 6 test areas as the overall score, was GS. However, if ENVI software is not available, HPF can be selected as the optimum pan-sharpening method. In addition, WT was the most inappropriate for THEOS pan-sharpening creation in the 3 applications.

Conclusions

Integration of image quality criteria, which includes (1) VIA, (2) EDA, (3) QI, and (4) ECA for the optimum THEOS pan-sharpening method evaluation using 2 approaches: self-evaluation and the users' requirements with the SAW method of MCDA, was successfully developed in the study.

From the results, it can be concluded that the optimum THEOS pan-sharpening method for the agriculture, forestry, and urban applications based on self-evaluation by the SAW method with equal weight is HPF, HPF or GS, and GS, respectively. Concurrently, GS is the optimum THEOS pan-sharpening method in the agriculture, forestry, and urban studies based on the users' requirements with specific weight from each in the experts' group. Consequently, the common optimum THEOS pan-sharpening method for the 3 applications from both approaches is GS. However, HPF can be chosen as the optimum pan-sharpening method when software

availability is considered. Furthermore, WT is inappropriate for the THEOS pan-sharpening process for the 3 applications based on both approaches.

In conclusion, the integration of image quality criteria (VIA, EDA, QI, and ECA) with the SAW method of MCDA can be effectively used as a new tool to evaluate the optimum pan-sharpening method based on self-evaluation or the users' requirements in remote sensing applications. Especially, the identified optimum pan-sharpening method for THEOS data by the 2 approaches can be directly applied to a specific application without trial and error.

References

- Ding, Y. and Wang, Y. (2011). Analysis and evaluation on fusion methods of medium and high spatial resolution remote sensing image. *Proceedings of the 19th International Conference on Geoinformatics*; June 24-26, 2011; Shanghai, China, p. 1-4.
- Du, Q., Younan, N.H., King, R., and Shah, V.P. (2007). On the performance evaluation of pan-sharpening techniques. *IEEE Geosci. Remote S.*, 4(4):518-522.
- Ehlers, M. (2008). Multi-image fusion in remote sensing: spatial enhancement vs. spectral characteristics preservation. In: *Advances in Visual Computing*. Bebis, G., Boyle, R., Parvin, B., Koracin, D., Remagnino, P., Porikli, F., Peters, J., Klosowski, J., Arns, L., Chun, Y., Rhyne, T-M., and Monroe, L., (eds). Springer-Verlag, Berlin, Germany, p. 75-84.
- ERDAS. (2003). *ERDAS Field Guide*. 7th ed. Leica Geosystems Geospatial Imaging, Atlanta, GA, USA, 673p.
- Gangkofner, U.G., Pradhan, P.S., and Holcomb, D.W. (2008). Optimizing the high-pass filter addition technique for image fusion. *Photogramm. Eng. Rem. S.*, 74(9):1,107-1,118.
- Hely, A.K., Nasr, A.H., and El-Taweel, G.S. (2010). Assessment and evaluation of different data fusion techniques. *Int. J. Comp.*, 4(4):107-115.
- Intajag, S., Wettayaprasit, W., and Kodchabudthada, W. (2010). Evaluation of fusion techniques for pan-sharpened THEOS imagery. *Proceedings of the International Conference on Control Automation and Systems*; October 27-30, 2010; Gyeonggi-do, Korea, p. 1010-1014.
- Jensen, J.R. (2007). *Remote Sensing of the Environment: An Earth Resource Perspective*. 2nd ed. Prentice Hall, Upper Saddle River, NJ, USA, 592p.
- King, R.L. and Wang, J. (2001). A wavelet based algorithm for pan sharpening Landsat 7 imagery. *Proceedings of the IEEE International Geoscience and Remote Sensing Symposium*; July 9-13, 2001; Sydney, NSW, Australia, p. 849-851.
- Klonus, S. and Ehlers, M. (2009). Performance of evaluation methods in image fusion. *Proceedings of*

- the 12th International Conference on Information Fusion; July 6-9, 2009; Seattle, WA, USA, p. 1409-1416.
- Laben, C.A. and Brower, B.V., inventors; Eastman Kodak Company, assignee. April 29, 1998. Process for Enhancing the Spatial Resolution of Multispectral Imagery Using Pan-sharpening. US patent no. 6011875 A.
- Li, S. and Li, Z. (2010). Effects of image fusion algorithms on classification accuracy. Proceedings of the 18th International Conference on Geoinformatics; June 18-20, 2010; Beijing, China, p. 1-6.
- Meenakshisundaram, V. (2005). Quality assessment of IKONOS and QuickBird fused images for urban mapping, [MSc. thesis]. Department of Geomatics Engineering, University of Calgary, Calgary, Alberta, Canada, 107p.
- Nikolakopoulos, K.G. (2008). Comparison of nine fusion techniques for very high resolution data. *Photogramm. Eng. Rem. S.*, 74(5):647-659.
- Ongsomwang, S. (2011). Principles of Remote Sensing and Digital Image Processing. School of Remote Sensing, Institute of Science, Suranaree University of Technology, Nakhon Ratchasima, Thailand, 466p.
- Parcharidis, I. and Kazi-Tani, L.M. (2000). Landsat TM and ERS data fusion: a statistical approach evaluation for four different methods. Proceedings of the IEEE 2000 International Geoscience and Remote Sensing Symposium; July 24-28, 2000; Honolulu, HI, USA, p. 2120-2122.
- Rosenfeld, A. and Kak, A. (1982). *Digital Picture Processing*. 2nd ed. Academic Press, NY, 349p.
- Santitamnont, P. and Lerk-u-suke, S. (2009). THEOS sensor modeling and its assessment [Slide]. In GEOINFOTECH2009 Conference. Thailand.
- Shettigara, V.K. (1992). A generalized component substitution technique for spatial enhancement of multispectral images using a higher resolution data set. *Photogramm. Eng. Rem. S.*, 58:561-567.
- Siddiqui, Y. (2003). The modified IHS method for fusing satellite imagery. Proceedings of the American Society of Photogrammetry and Remote Sensing Annual Conference; May 5-9, 2003; Anchorage, AK, USA, p. 1-10.
- Sonka, M., Hlavac, V., and Boyle, R. (2007). *Image Processing, Analysis, and Machine Vision*. 3rd ed. Cengage Learning, Independence, KY, USA, 829p.
- Stathaki, T. (2008). *Image Fusion: Algorithms and Applications*. Academic Press, Waltham, MA, USA, 500p.
- Strait, M., Rahmani, S., and Markurjev, D. (2008). Evaluation of pan-sharpening methods. Available from: http://www.math.ucla.edu/~wittman/reu2008/Reports/pan_report.pdf.
- Wald, L., Ranchin, T., and Mangolini, M. (1997) Fusion of satellite images of different spatial resolutions: assessing the quality of resulting images. *Photogramm. Eng. Rem. S.*, 63(6):691-699.
- Wang, Z. and Bovik, A.C. (2002). A universal image quality index. *IEEE Signal Proc. Let.*, 9 (3):81-84.
- Wolf, P.R. and Dewitt, B.A. (2000). *Elements of Photogrammetry with Applications in GIS*. McGraw-Hill Education, New York, NY, 608p.
- Yuhua, R.H., Goetz, A.F.H., and Boardman, J.W. (1992). Discrimination among semi-arid landscape endmembers using the spectral angle mapper (SAM) algorithm. Summaries of the Third Annual Jet Propulsion Laboratory Airborne Geoscience Workshop; June 1-5, 1992; Pasadena, CA, USA, Vol. 1, p. 147-149.
- Zhang, Y. (2004). Understanding image fusion. *Photogramm. Eng. Rem. S.*, 70:657-659.
- Zhang, Y. (2008). Pan-sharpening for improved information extraction. In: *Advances in Photogrammetry, Remote Sensing and Spatial Information Sciences*. Li, Z., Jun, C., and Baltsavias, E. (eds). CRC Press, Boca Raton, FL, USA, p. 185-204.
- Zhang, Y. and Mishra, R.K. (2012). A review and comparison of commercially available pan-sharpening techniques for high resolution satellite image fusion. Proceedings of the IEEE International Geoscience and Remote Sensing Symposium; July 22-27, 2012; Munich, Germany, p. 182-185.