Merging Multispectral and Panchromatic SPOT Images with Respect to the Radiometric Properties of the Sensor

Abstract

A method for merging panchromatic SPOT images with multispectral SPOT images is described. This method is based on the radiometric properties of the sensors. After merging, the pixel values are strongly related to the original multispectral pixel values through which post-processing algorithms like the normalized vegetation index remain meaningful. The radiometric merging algorithm will be compared to other algorithms on statistical and visual properties. The radiometric method produces a sharpened multispectral image with respect to the pixel values compared to other available methods, but the method results in a less sharpened image. The presented method can easily be adapted to imagery from other sensors.

Introduction

SPOT, and in the future Landsat-6, will supply both multispectral (XS) and panchromatic (PAN) imagery. Each type of imagery has its specific advantages: a good spectral resolution and a good spatial resolution, respectively. A combination of the two would give the researcher and the user of remotely sensed imagery more adequate information.

A number of methods for merging panchromatic images with multispectral images are known from literature. The most common procedure is the Intensity-Hue-Saturation (IHS) method which is used, for example, by Carper *et al.* (1990), Chavez *et al.* (1991), and Ehlers (1991). Normally used standards for the success of the merged result are the improved correlation between the infrared and the panchromatic channel and the increased visual sharpening. However, the IHS method does not take into account the different spectral sensitivity curves of the channels and ignores correction for the different calibration factors of the channels. So the resulting image has lost its physical meaning. In addition to this, the IHS method can only handle three-band imagery.

For quantitative analysis of the merged image a method which preserves pixel values is necessary. In this paper a method is described which merges PAN and XS images with respect to their radiometric properties. The method uses the spectral sensitivity curves and the calibration factors of the different sensors to simulate the panchromatic channel using only the XS bands. This estimated value is radiometrically comparable with the panchromatic pixel value and may therefore be replaced by it.

General Procedure

The general procedure for merging panchromatic information into the multispectral bands is to transform the original xs image into a new coordinate system in which one of the axes represents the intensity. After replacing this intensity by the panchromatic channel and after the inverse transformation, the merging process is completed. If P_i (i=1,2,...,n) represents the pixel value of band *i*, I_i (i=1,2,...,n) the transformed pixel values, and *n* the number of bands, then the transformation from P_i to I_i can be written as

$$I_i = f_i(P_1, P_2, \dots, P_n)$$
 $(i = 1, 2, \dots, n).$ (1)

 I_i (i=1,2,...,n) can be defined as a vector in the intensity space in which I_1 is the intensity itself. The intensity determined by the panchromatic channel is written as I_P and here defined to be equal to the pixel value of the panchromatic channel (P_P); that is,

$$I_P = P_P. \tag{2}$$

If the two intensity estimators I_1 and I_P represent the same quantity, the two may be replaced by each other. The inverse transformation then looks like

$$P_i^N = f_i^{-1}(I_p, I_2, \dots, In) \ (i = 1, 2, \dots, n)$$
 (3)

where P_i^N stands for the pixelvalues of band *i* after merging with the panchromatic channel. The set of functions f^{-1} are the inverse of the set of functions of f_i . The following transformations are compared in this paper:

- Radiometric method
- Statistical method
- IHS method
- Spherical coordinate method

The index of the parameters will be extended with a description of the used method.

Radiometric Method

The radiances measured by each of the XS sensors represent a part of the radiance measured by the panchromatic channel. This is illustrated in Figure 1.

If the radiance reflected by a ground element as function of the wavelength λ , in the direction of the sensor, is given by $L(\lambda)$, then the total radiance measured by the sensor is

$$L_i = \int_0^* L(\lambda) H_i(\lambda) d\lambda \qquad (i = 1, 2, \dots, n)$$
(4)

$$L_{p} = \int_{0}^{*} L(\lambda) H_{p}(\lambda) d\lambda$$
(5)

in which $H_i(\lambda)$ and $H_P(\lambda)$ are the normalized spectral responses of band i (i=1,2,...,n) and of the panchromatic chan-

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nel, respectively, and L_i (i,1,2,...,n) and L_p are the radiance collected by each band. The panchromatic radiance can be simulated by a linear combination of the multispectral radiances, given by

$$L_P^s = \sum_{i=1}^n h_i \cdot L_i \tag{6}$$

where $L_{\tilde{P}}$ is the simulated radiance of the panchromatic band. The weighing coefficients h_i (i=1,2,...,n) depend only on the spectral sensitivity curves of the different sensors and can be calculated using:

$$h_{i} = \frac{\int_{0}^{x} H_{P}(\lambda) H_{i}(\lambda) d\lambda}{\sum_{j=1}^{n} \int_{0}^{x} H_{P}(\lambda) H_{j}(\lambda) d\lambda}$$
(7)

which models the overlap of the different XS bands with the PAN band, normalized with the total overlap. To determine the radiance from the pixel values of SPOT one has to consider three different modes of SPOT: low, standard, and high gain, in relation to the instrument, HRV-1 or HRV-2, and the platform, SPOT-1 and SPOT-2, and the gain number. See the SPOT User's Handbook (Spotimage, 1988) for more details. The relation between the radiance and the pixel value for standard gain is given in the SPOT User's Handbook as

$$L = \frac{P}{A} \tag{8}$$

where *P* is the pixel value, *L* is the radiance in $W.m^{-2}.sr^{-1}\mu m^{-1}$, and *A* is the absolute calibration gain. This implies that

$$L_P = \frac{P_P}{A_P} \tag{9a}$$

$$L_i = \frac{P_i}{A_i}$$
 (*i* = 1, 2, ...,*n*) (9b)

in which L_{ρ} and L_i are the radiances measured by the panchromatic sensor and band *i*, respectively.

Combining the Equations 6 and 9 and defining that



gives

$$I_{1(\text{RAD})} = \sum_{i=1}^{n} c_{i(\text{RAD})} P_i$$
 (11)

(10)

where

$$C_{i(\text{RAD})} = h_i \frac{A_P}{A_i}$$
 (*i* = 1, 2, ...,*n*) (12)

and $I_{1(RAD)}$ is the simulated intensity. This estimator of the intensity is defined as $I_{1(RAD)}$ because it is based on the radiometric properties of the sensors.

 $L_p = L_p^s$

The transformation of Equation 11 is to be completed with n-1 other linear equations, perpendicular to Equation 11 and to each other. The set of transformation equations can be written in a matrix:

where $c_i = a_{1i}$. Because SPOT has only three bands, an example of a complete transformation is given for n = 3.

$$\begin{pmatrix} C_1 & C_2 & C_3 \\ -C_2 & C_1 & 0 \\ \frac{-C_1^2 C_3}{C_1^2 + C_2^2} & \frac{-C_1 C_2 C_3}{C_1^2 + C_2^2} & C_1 \end{pmatrix}$$
(14)

The inverse transformation is found by inverting the matrix.

In order to distinguish between the coefficient c_i obtained with the different methods an index with the method will be added (i.e., $c_{i(RAD)}$).

This method will be evaluated for SPOT imagery. The values for A_i and A_p from Equation 9 are, for SPOT imagery, specified in header files which are supplied with each SPOT image. The number of bands is three (n = 3). Because the spectral responses of the different sensors are not numerically available, the spectral responses are idealized by assuming that the responses are uniform within the band and zero outside.

The coefficients h_i (i=1,2,3) from Equation 12 can be determined by evaluating Equation 7. Table 1 shows that channel 1 overlaps the PAN channel with 80 nm, channel 2 for 70 nm, and channel 3 does not overlap at all. The total overlap is 150 nm.

$$h_1 = \frac{80}{150} = 0.533 \tag{15a}$$

$$h_2 = \frac{70}{150} = 0.466 \tag{15b}$$

$$h_3 = 0$$
 (15c)

TABLE 1. SPOT BANDWIDTH.

band	lower bound [nm]	upper bound [nm]	
XS1	500	590	
XS2	610	680	
XS3	790	890	
PAN	510	730	

The two other transformation equations can be calculated using Equation 14.

$$I_{1(\text{RAD})} = c_1 P_1 + c_2 P_2 \tag{16a}$$

$$I_{2(\text{RAD})} = -c_2 P_1 + c_1 P_2 \tag{16b}$$

$$I_{3(RAD)} = c_1 P_3$$
 (16c)

Replacing $I_{1(RAD)}$ by P_P the inverse transformation becomes

$$P_1^N = \frac{C_1}{r^2} P_P - \frac{C_2}{r^2} I_{2(\text{RAD})}$$
(17a)

$$P_2^N = \frac{C_2}{r^2} P_P + \frac{C_1}{r^2} I_{2(\text{RAD})}$$
(17b)

$$P_3^N = \frac{1}{c_1} I_{3(\text{RAD})}$$
(17c)

with
$$r^2 = c_1^2 + c_2^2$$

Statistical Method

The intensity I_1 can also be defined as a linear combination of the XS bands with coefficients c_i (i=1,2,...,n) which can be calculated in such a way that i. the correlation $\rho(P_{p_i}I_{1(\text{STA})})$ between the simulated intensity and the panchromatic channel is maximal and ii. the energy balance.

$$I_{1(STA)} = \sum_{i=1}^{n} c_{i(STA)} P_i$$
 (18)

The correlation $\rho(P_P, I_{1(STA)})$ can be expressed in terms of the covariance between P_i (i=1,2,...,n) and P_P (Equation 7). Numerical methods (Press *et al.*, 1989) can be used to evaluate this formula in order to maximize $\rho(P_P, I_{1(STA)})$.

$$\rho(P_{P}, I_{1(\text{STA})}) = f(c_{1(\text{STA})}, c_{2(\text{STA})}, \dots, c_{n(\text{STA})})$$

$$= \frac{\sum_{i=1}^{n} c_{i(\text{STA})} cov(P_{*}P_{P})}{\sqrt{\sum_{i=1}^{n} \sum_{j=1}^{n} c_{i(\text{STA})} c_{j(\text{STA})} cov(P_{*}P_{P})}}$$
(19)

The second condition is the restriction of the energy balance. This implies that the average of the calculated intensity over the whole image is equal to the mean of the panchromatic pixel values.

$$\sum_{j=1}^{npix} P_P(j) = \sum_{j=1}^{npix} I_{1(STA)}(j)$$
(20)

The intensity is defined as a linear combination of the original XS bands; therefore, Equation 13 can be used to complete the transformation.

Notice that the coefficients $c_{i(STA)}$ (i = 1, 2, ..., n) are area

TABLE 2. SPOT	INSTRUMENT SI	ETTING FOR	SELECTED	MAGE.
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item	multispectral image	panchromatic image
satellite	SPOT1	SPOT1
mode	XS	PAN
instrument	HRV1	HRV2
date	1990/08/27	1990/08/27
time	11:23:24	11:23:19
gain factors	675	5
A ₁	1.00107	-
A_2	0.94591	_
A ₃	0.90668	-
A_p	-	0.91430

specific. Hence, they have to be calculated for each (sub-)image.

IHS Method

The IHS transformation is commonly used. This method requires three input bands. This is sufficient for SPOT imagery but not for sensors like the Landsat TM sensor which has six reflection bands. The intensity (I_1) is calculated as the average of three input bands which should be, by definition of the IHS color scheme, the bands RED, GREEN and BLUE which are for SPOT not available. Two other transformations, giving I_2 (=hue) and I_3 (=saturation), complete the transformation (Kay, 1990).

$$I_{1(lHS)} = \frac{P_1 + P_2 + P_3}{3}$$
(21a)

$$I_{2(lHS)} = \arctan\left(\frac{2P_1 - P_2 - P_3}{\sqrt{3}(P_2 - P_3)}\right) + C$$
where $\begin{cases} C = 0, \text{ if } P_2 \ge P_3 \\ C = \pi, \text{ if } P_2 < P_3 \end{cases}$ (21b)

$$I_{3(lHS)} = \frac{\sqrt{6}}{3} \sqrt{P_1^2 + P_2^2 + P_3^2 - P_4P_2 - P_4P_3 - P_4P_3}$$
(21c)

where P_i (*i* = 1, 2, 3) represent the pixel values of the XS bands and $I_{i(IHS)}$ is the intensity vector.

Spherical Coordinate Method

A three-band image sets up a color cube. The pixel values form a rectangular Cartesian coordinate system. A common mathematical representation is the spherical coordinate system where one of the coordinates is the radius r which represents the length of the vector. This length can be defined as the intensity (I_1) and may be replaced by the panchromatic pixel value. In this paper an important modification is



Fig. 2. Correlation between the panchromatic channel and the derived intensity for several methods for the agricultural site.

made : to conserve the energy, the radius vector r is not replaced by the PAN value, but the radius divided is by $\sqrt{3}$.

$$I_{1(SPH)} = \sqrt{\frac{P_1^2 + P_2^2 + P_3^2}{3}}$$
(22a)

$$I_{1(\text{SPH})} = \arctan\left(\frac{P_2}{P_1}\right) \tag{22b}$$

$$I_{3(\text{SPH})} = \arctan\left(\frac{\sqrt{P_1^2 + P_2^2}}{P_3}\right)$$
(22c)

Evaluation Criteria

To interpret the results of the different merging methods, three criteria are used:

- The correlation between the simulated intensity, based on the multispectral bands, and the intensity of the panchromatic channel must be highest;
- The mean of the simulated intensity and the panchromatic channel must be equal; and
- A visual inspection of the results done by professional photointerpreters.

The first two criteria are boundary conditions for the statistical method, so it is likely that this method gives the best results (see further).

Test Data

To test the transformation properties, a scene from a SPOT image was selected. The total frame covers the southwest of The Netherlands and was acquired on 27 August 1990. Both multispectral and panchromatic mode were available. More detailed information of the sensor during acquisition is given in Table 2.

The test site shows an agricultural site of 2 km by 2 km. The multispectral image is resampled to a pixel size of 10 by 10 m using nearest neighbor resampling. The original image is shown in Plate 1a (multispectral) and Plate 1b for the panchromatic band.

The calibration coefficients A_i and A_{PAN} of the sensor during acquisition were provided with the image. The coefficients c_i from the radiometric method can be calculated using Equations 12 and 15, giving

 $c_{1(\text{RAD})} = 0.4868$ (23a)

 $c_{2(\text{RAD})} = 0.4504$ (23b)

$$c_{3(\text{RAD})} = 0 \tag{23c}$$

The forward and inverse transformations can be combined into a single algorithm, which reduces computing time.

$$P_1^N = 1.105P_P + 0.461P_1 - 0.498P_2 \tag{24a}$$

$$P_2^N = 1.023P_P - 0.498P_1 + 0.538P_2$$
 (24b)

$$P_2^N = P_3 \tag{24c}$$

For the statistical method, the coefficients have to be determined using Equation 19. For the selected test site, this results in

$$C_{1(STA)} = 0.267$$
 (25a)

 $c_{2(\text{STA})} = 0.710$ (25b)

$$c_{3(STA)} = 0.036$$
 (25c)

The statistical results of the different intensity estimators are illustrated in Figure 2 and Table 3 which give the corre-

ABLE	3.	STATISTICS OF	THE	ORIGINAL	BANDS	AND	THE	DERIVED	INTENSITIES.
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method/band	correlation with PAN-channel	average	standard deviation
PAN	1	44.53	5.46
XS1	0.89	55.84	5.93
XS2	0.94	40.36	11.01
XS3	-0.23	49.02	5.46
II(RAD)	0.94	44.89	4.75
IIISTA)	0.95	44.49	5.15
I _{1(IHS)}	0.54	48.08	4.34
I _{1(SPH)}	0.45	48.72	4.59

lation of the intensity estimator with the original panchromatic image and the average of each band. The closer this correlation gets to unity, the better. It is clearly visible that the correlation of the $I_{1(RAD)}$ and $I_{1(STA)}$ with the original panchromatic band P_P is higher than that of $I_{1(IHS)}$ or $I_{1(SPH)}$. Hence, the latter two give a poorer intensity estimator. The second criteria, in which it was stated that the average of the intensities should equal the average of the panchromatic channel, gives some remarkable differences. In Table 3 the average and the standard deviation are listed for the different intensity estimators. It is obvious that the radiometric and the statistical method differ only slightly. This is due to the fact that these methods have boundary conditions that demand that the averages be equal to the panchromatic channel. Replacing these intensities with the panchromatic channel will cause no energy loss in the image. The other two methods, IHS and spherical, will give an energy difference of about 10 percent. However, these latter problems are easily solved by normalization.

Plate 2 shows the impact of the different methods on the image. It is clearly visible that some fields appear dark in the PAN-channel but bright in the $I_{1(IHS)}$ and $I_{1(SPH)}$ while they remain dark in $I_{1(RAD)}$ and $I_{1(STA)}$. This effect is visible for all areas with high infra-red reflection or with high vegetation coverage. The impact of this effect is that post-processing algorithms like the normalized difference vegetation index (NDVI) have lost their validity.

The results for the merged image using the radiometric method are given in Table 4. In this table the correlation between the original bands $(P_i \text{ and } P_p)$, and the new merged bands $(P_1^N \text{ and } P_2^N)$ is given. Because P_3 is not subject to the transformation $(P_3^N = P_3)$, the results of P_3^N are not listed explicitly.

It can clearly be seen that P_1 and P_2 correlate highly with each other and with the PAN channel. P_3 doesn't correlate at all. Obviously, P_3 contains no panchromatic information. This satisfies the assumption that P_3 should not be incorporated in the transformation. The new pixel values have a higher correlation with the panchromatic channel than the original channels. So information of the PAN channel is merged into the new channel P_1^N and P_2^N .

TABLE 4. CORRELATION BETWEEN THE ORIGINAL AND THE MERGED BANDS USING THE RADIOMETRIC METHOD.

	P_1	P_2	P_3	P_P	I _{1(RAD)}	P_1^N	P_2^N
P_1	1.00	0.89	-0.12	0.89	0.97	0.93	0.83
P_2	0.89	1.00	-0.33	0.94	0.98	0.88	0.96
Pa	-0.12	-0.33	1.00	-0.23	-0.24	-0.13	-0.31
P_{P}	0.89	0.94	-0.23	1.00	0.94	0.97	0.98
II(RAD)	0.97	0.98	-0.24	0.94	1.00	0.92	0.92
PN	0.93	0.88	-0.13	0.97	0.92	1.00	0.92
P_2^N	0.83	0.96	-0.31	0.98	0.92	0.92	1.00

Visual Interpretation

Ten professional photo-interpreters were provided with a hard copy print showing six prints of the agricultural site (see Plate 1) after merging with the different methods. They were asked to rate them on a scale from 0 and 10. (0= poor quality, 10= good quality). The results are given in Table 5 and Figure 3.

The professional photo-interpreters prefer the IHS method. The spherical method is second best. The radiometric method seems poor but is far better than the original multispectral image. Notice the great distribution of the scores. The observation of the photo-interpreters is subjective; they all have their own opinion of what is important in an image. This is caused by the fact that not all parts of the images are equally improved. The IHS methods tends to sharpen the image, though colors get a different meaning. The radiometric method will conserve the colors so that the sharpening will be less.

So the best merging method for visual interpretation is dependent on the phenomena that one is looking for. If one is looking for edges and topography, the IHS method will do fine. However, if one is more interested in vegetation, the IHS method should not be applied.

Conclusion

The newly developed radiometric transformation for merging panchromatic information with multispectral information is compared to other methods. The merging process with the radiometric method preserves the absolute pixel values. This implies that post-processing algorithms remain useful. The statistical method gives a comparable result. The two other methods (IHS and spherical-coordinates) do not take this into account. The pixel values of these merging methods are in no way comparable with the original image nor with other images. But the latter two methods give a better result if looking at the visual sharpening.

It is advised that one use the radiometric method if further numerical methods are to be used. Although the statistical method gives even better results, the computing time is such that operational use is difficult to achieve. Also, when the images are used for vegetation studies, the radiometric method should be used. Only if the topography is of interest is the IHS method adequate.

Another reason to use the radiometric method is the number of bands of the sensor. If the multispectral sensor has more than three bands, using the IHS method will make no sense because of bands having to be dropped. This causes a severe information loss at the beginning of the processing, which can not be neglected.

The effect of the different merging methods can be put in other words: the radiometric and statistical methods pro-

TABLE 5. SCORES FROM THE VISUAL INTERPRETATION CARRIED OUT BY THE PHOTO-INTERPRETERS.

PI	orig	RAD	STA	IHS	SPH	avg
1	1	5	9	8	3	5.2
2	4	6	8	7	4	5.8
3	1	4	7	8	10	6.0
4	1	4	6	9	10	6.0
5	4	5	6	8	8	6.2
6	2	7	5	8	7	5.8
7	4	10	8	6	6	6.8
8	0	4	6	10	8	5.6
9	4	6	6	8	7	6.2
10	3	6	4	8	7	5.6
avg	2.4	5.7	6.5	8.0	7.0	5.9



duce a sharpened multispectral image whereas the IHS and spherical methods give a colored panchromatic image.

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LIST OF SYMBOLS

Symbol	Units	Definition
A	DN.W ⁻¹ .m ² .sr.µm	absolute calibration factor
A_i	DN.W ⁻¹ .m ² .sr.µm	absolute calibration factor band <i>i</i>
A_P	DN.W ⁻¹ .m ² .sr.µm	absolute calibration factor panchromatic band
Ci	-	weighing coefficient
DN	DN	digital number (pixel value)
h,	-	weighing factor for spectral overlap between band <i>i</i> and the panchromatic band

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Plate 1. SPOT image test site. (a) original MS image, (b) original PAN image. Used method for merging: (c) radiometric, (d) statistical, (e) IHS, (f) spherical coordinates. (© SPOT image copyright 1990 CNES.)

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H_i	-	spectral response of band i	L_P	W.m ⁻² .sr ⁻¹	radiance of panchromatic
H_P	-	spectral response of			band
		panchromatic band	L_{P}^{s}	W.m ⁻² .sr ⁻¹	simulated radiance of
Ι	DN	intensity (in this report the intensity if defined as the pixel value in the pan-			panchromatic band by means of the multi- spectral bands
		chromatic channel)	n	-	number of bands
I.	DN	intensity calculated with	PAN	-	panchromatic band
-(.)		method (.)	P_i	DN	pixel value of multispectral
I_i	dependent	intensity of coordinate i			band i
	coordinate	in intensity space	P_{γ}^{N}	DN	pixel value after merging of
IP	DN	intensity of panchromatic			band i
		band	P_P	DN	pixel value of panchromatic
La	W.m ⁻² .sr ⁻¹ .µm ⁻¹	radiance as function of			band
(14)		wavelength	XS	-	multispectral band
L_i	W.m ⁻² .sr ⁻¹	radiance band <i>i</i>			

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