A SPECTRAL-PRESERVING PANSHARPENING METHOD FOR MULTISENSOR SATELLITE IMAGERY

Xiaojing Huang, Soo Chin Liew, Leong Keong Kwoh

Centre for Remote Imaging, Sensing and Processing (CRISP), National University of Singapore,
Blk S17, Level2, Lower Kent Ridge Road, Singapore 119260
Email: crshxj@nus.edu.sg; scliew@nus,edu.sg; crsklk@nus.edu.sg

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ABSTRACT: Pan-sharpening is a data fusion process that combines lower resolution multispectral (MS) and high-resolution panchromatic (PAN) imageries to produce a high-resolution color image. For the commonly used pan-sharpening algorithms the intensity of MS, usually derived from combining digital numbers (DN) of each band, is replaced with the intensity of PAN. Thus, the spectral content of the pan-sharpened image is not the same as that of MS. In this paper, we implement a simple approach of pan-sharpening which produces pan-sharpened images with high spatial resolutions as in PAN while maintaining the spectral fidelity of the MS reflectance. The DN of MS is converted to the ground reflectance. The overlap of the spectral response function (SRF) of each MS band with the PAN SRF is used as the relative weight of the respective band to calculate the effective MS intensity. A look-up-table (LUT) of the effective MS intensity to PAN DN is derived. Finally, the resolution of the MS reflectance is enhanced by the ratio of PAN to the LUT value of the effective MS intensity. Since the DN of PAN and LUT value of the effective MS intensity have the same mean, the mean of the resolution-enhanced MS reflectance remains the same. The method has been applied successfully to sharpen the MS images of Sentinel-2 with PAN images of TeLEOS-1 satellites.

1. INTRODUCTION

Optical remote sensing satellite images are usually acquired in one of two modes: multispectral (MS) or panchromatic (PAN). A MS image contains several bands with narrow spectral bandwidths while a PAN image has only one broad spectral band but with a higher spatial resolution than a MS image. Pan-sharpening [Vivone et al., 2015] is a data fusion technique that combines a MS image and a PAN image of the same area to generate a product that has the spectral information of the MS image while retaining the high spatial resolution of the PAN. Common pan-sharpening algorithms include Hue-Intensity-Saturation (HIS) sharpening [Haydn, 1982]; the Brovey transformation; the ESRI pan sharpening transformation; the Gram-Schmidt [Aiazzi et al., 2007] spectral sharpening method; and principal component analysis (PCA) method [Shettigara, 1992]. In these methods, the intensity of MS derived from combining digital numbers (DN) of the MS bands is replaced with the intensity of PAN. Thus, the spectral content of the MS image is not preserved in the pan-sharpened image.

In remote sensing, the uncalibrated digital number (DN) or pixel values of satellite imagery have no direct physical meaning. They are related to the radiance detected at each band that may have different gains and offsets which may also be different for different scenes acquired at different time and location. Hence, it is difficult to compare the pixel values of satellite imagery acquired at different time period or by different sensors. For comparison or fusion of data acquired at different time or between different sensors, the DN are usually converted to radiance or reflectance. The spectral reflectance carries detailed quantitative information about the spectral characteristics of the surfaces or objects. It is widely used in classification, for example, to distinguish water, soil, vegetation, and plant types. The ideal pan-sharpened image should improve the spatial resolution while preserving the spectral fidelity of the MS image, i.e. the pan-sharpened pixels should have the same radiance or reflectance as that of MS.

In this paper, we implement a simple method of pan-sharpening which produces pan-sharpened images with high spatial resolutions as in PAN while maintaining the spectral fidelity of the MS reflectance. The algorithm is applied to pan-sharpen multispectral Sentinel-2 images using the panchromatic band of the TeLEOS-1 satellite. TeLEOS-1 is Singapore's first commercial satellite that was successfully launched on 16 December 2015 to a near-equatorial orbit at a nominal altitude of 550 km and an inclination of 15°. It carries a high resolution panchromatic camera with a 1-m ground resolution at nadir, and a swath width of about 12 km. The low inclination angle enables a revisit time of 12 to 16 hours [EO Portal, Teleos-1]. Sentinel-2 is a multispectral operational imaging mission within the GMES (Global Monitoring for Environment and Security) program, jointly implemented by the EC (European Commission) and ESA (European Space Agency) for global land observation. Its imaging instrument has 13 bands at various spatial resolution ranging from 10 m to 60 m [EO Portal, Sentinel-2]. Only the four VNIR bands at 10 m resolution are used in pan-sharpening.

2. METHDOLOGY

Detailed methodology covering the following major steps:

1) Conversion of MS DN to top-of-atmosphere (TOA) spectral radiance with the absolute radiometric calibration constants;
2) Conversion of radiance to TOA spectral reflectance accounting for the earth-sun distance and the solar zenith angle at the acquisition time;
3) Atmospheric correction to obtain the ground reflectance;
4) Computing the effective MS intensity using the relative weight of the respective MS bands;
5) Automatic georegistration of PAN and MS intensity bands by a correlation method;
6) Construction of a look-up-table (LUT) for substitution of MS intensity with PAN;
7) Enhancement of MS resolution using the LUT.

2.1 Reflectance Conversion

To derive reflectance, firstly the digital number of the imagery is converted to top-of-atmospheric spectral radiance (Todd et al., 2010) (eq. 1.),

$$L_i = K_i Q_i / \Delta\lambda_i \qquad (1)$$

where the subscript *i* denotes the band number, L_i is top-of-atmosphere band-average spectral radiance of each image pixel, K_i is the absolute radiometric calibration factor, Q_i is the pixel digital number, and $\Delta\lambda_i$ is the effective bandwidth of satellite image.

The radiance is then converted to top-of-atmospheric band-average spectral reflectance ρ_i by assuming a Lambertian reflecting target (eq. 2),

$$\rho_i = \frac{\pi L_i d^2}{E_i \cos\theta_s} \qquad (2)$$

where E_i is the band-averaged solar spectral irradiance for a given band, *d* is a correction factor for the different earth-sun distance at different day of the year and θ_s is the solar zenith angle during image acquisition. The spectral reflectance is then derived after atmospheric correction.

2.2 Computing the Effective MS Intensity

The MS image is first resampled to have the same pixel width as the PS image. The effective MS intensity for each resampled pixel is then calculated (eq. 3),

$$\overline{MS}_j = \sum_i w_i MS_{j,i} \qquad (3)$$

where $MS_{j,i}$ is the reflectance of MS band-*i* at pixel-*j*, $\overline{MS}_j$ is the effective intensity for each pixel-*j*. The spectral response function (SRF) is different for different spectral sensor. The weight w_i of each MS band is obtained by calculating the overlap of the spectral response function (SRF) of each MS band with that of the PAN band (eq. 4),

$$w_i = K \int_{\lambda_l}^{\lambda_u} R_i(\lambda) R_T(\lambda)\, d\lambda \qquad (4)$$

where $R_i(\lambda)$ is the SRF of MS band-*i*, $R_T(\lambda)$ is the SRF of the TeLEOS-1 PAN band, and *K* is a normalization constant such that the weights add up to one. Figure 1 shows the SRFs of TeLEOS-1 PAN and Sentinel-2 blue (B2), green (B3), red (B4) and near-infrared (B8) bands.

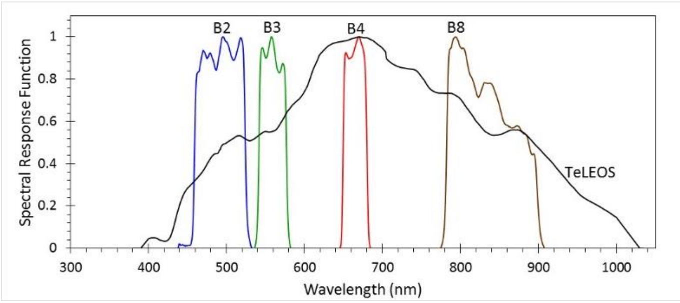

Figure 1. Spectral response functions of Sentinel-2 Bands 2, 3, 4, 8 and TeLEOS-1 PAN band.

2.3 Georegistration of MS and PAN Images

The effective MS intensity is georeferenced with the DN of PAN using a fully automated normalized cross correlation method. The candidate tie points are first detected using SIFT (Lowe 1999) or canny corner detection (Canny 1986) for the effective MS intensity imagery. The hieratical matching approach is used to increase processing speed, and the moving window is shifted one pixel at a time over the PAN image for high accuracy. The affine transformation between the two imagery is then derived. The accumulated histogram is calculated over the common area of PAN and MS to derive a look-up-table (LUT) that maps the effective MS intensity to PAN DN.

2.4 Derivation of Pansharpened MS Reflectance

Each MS band is pan-sharpened by the ratio of PAN to the LUT value of the effective MS intensity (eq. 5),

$$MS'_{j,i} = PAN_j / LUT(\,\overline{MS}_j)\cdot MS_{j,i} \qquad (5)$$

where $MS'_{j,i}$ is the pan-sharpened reflectance of each MS band-i at pixel-j, $LUT(\,\overline{MS}_j)$ is the PAN DN value in the LUT corresponding to $\overline{MS}_j$, the effective MS intensity of pixel-j. Since the DN of PAN and LUT value of MS intensity have the same mean, the mean of the resolution-enhanced MS reflectance remains the same. This method preserves both spectral fidelity of the multispectral bands and spatial resolution of the panchromatic band.

3. RESULTS

TeLEOS-1, Singapore's first commercial near equatorial orbit earth observation satellite, carries a high resolution camera that produces 1 metre resolution imagery. Since it does not have multispectral bands, colouring TeLEOS-1 imagery with multispectral images from another lower resolution satellite is meaningful. We randomly select some images from TeLEOS-1 catalogue and download the corresponding multispectral imagery of Sentinel-2 (10m resolution) from ESA (ESA web). For illustration, we show here the results of pan-sharpening using our simple algorithm described above. Figure 2 shows a subset (640 x 640 pixels) of the input TeLEOS-1 panchromatic image at 1-m resolution and the corresponding Sentinel-2 image at 10-m resolution. The low resolution Sentinel-2 image has been resampled to the same pixel width as the panchromatic image and displayed in true color and false color compositions. This sub-image shows a coastal built-up area with plantations (mostly oil palms) towards the inland region. Two highways, one running parallel to the coast and the other one perpendicular to it, intersects with a dome-like structure located at the intersection.

The results of pan-sharpening using our simple method are shown in Figure 3. The effective intensity of the pan-sharpened image is practically identical to the TeLEOS-1 panchromatic image. The pan-sharpened image also faithfully reproduces the spectral information of the Sentinel-2 multispectral image, by visual inspection, both in the true color and false color compositions. The following quantitative metrics are used to assess the performance of the pan-sharpening algorithm: Bias (B), Mean Absolute Error (MAE), Root-Mean-Squared Error (RMSE), Mean Spectral Angle (MSA), Mean Euclidean Distance (MED) and Mean Normalized Euclidean Distance (MNED). These performance metrics are defined by the following equations:

$$\text{Bias, } \mathrm{B}_i = \frac{1}{N}\sum_{j=1}^{N}(x_{ij} - y_{ij})$$

Mean absolute error, $\mathrm{MAE}_i = \frac{1}{N}\sum_{j=1}^{N}\left|x_{ij} - y_{ij}\right|$;

Root-mean-squared error, $\mathrm{RMSE}_i = \sqrt{\frac{1}{N}\sum_{j=1}^{N}(x_{ij} - y_{ij})^2}$

Mean spectral angle, $\mathrm{MSA} = \frac{1}{N}\sum_{j=1}^{N}\cos^{-1}\left(\frac{\sum_{i=1}^{4} x_{ij}y_{ij}}{\sqrt{I_{jx}I_{jy}}}\right)$

Mean Euclidean distance, $\mathrm{MED} = \frac{1}{N}\sum_{j=1}^{N}\sum_{i=1}^{4}\sqrt{(x_{ij} - y_{ij})^2}$

where x_{ij} and y_{ij} are the reflectance of band-*i* at pixel-*j*, I_{jx} and I_{jy} are the effective intensity at pixel-*j*, for the pan-sharpened image and low-resolution Sentinel image, respectively. These performance metrics are tabulated in Table 1. For comparison, the metrics for a pan-sharpened image produced using a PCA method are also shown in Table 1. In the PCA method, the resampled low-resolution Sentinel-2 multispectral (Blue, Green, Red, NIR) image were transformed into 4 PCA components. The first principal component (PC1) was replaced by the Teleos-1 panchromatic image after rescaling so that it has the same mean and standard deviation as PC1. The inverse PC Transform was performed to obtain the pan-sharpened image. In Table 1, our simple pan-sharpened image is denoted as S-PAN while the PCA pan-sharpened image is denoted as PCA-PAN.

Figure 2. TeLEOS-1 panchromatic image (left), Sentinel-2 true color image (middle) and Sentinel-2 false color (RGB=NIR,Red,Green) image (right). .

Figure 3. Results of pan-sharpening using our simple algorithm: Effective intensity (left), true color image (middle) and false color (RGB=NIR,Red,Green) image (right).

Table 1: Performance metrics of the pan-sharpening algorithms

	S-PAN				PCA-PAN			
	Blue Band	Green Band	Red Band	NIR Band	Blue Band	Green Band	Red Band	NIR Band
Bias	0.0025	0.0027	0.0039	0.0054	0.0000	0.0000	0.0000	0.0000
MAE	0.0085	0.0116	0.0130	0.0428	0.0182	0.0190	0.0228	0.0690
RMSE	0.0141	0.0176	0.0214	0.0564	0.0219	0.0229	0.0274	0.0831
MSA	0.0580				0.2278			
MED	0.0494				0.0773			

Note: Bias, MAE, RMSE, MED are in reflectance units, MSA is measured in radians.

The PCA-PAN has practically zero biases in all the four spectral bands as the replaced PC1 has been scaled to have the same mean as the original PC1, ensuring zero biases between the PAN and original multispectral images. Nevertheless, the biases of the 4 bands are considered small as they are in the third decimal place. The spectral fidelity is captured by the other metrics. The smaller the metrics, the better the pan-sharpened image retain the spectral information of the original multispectral image. It is noted that the MAE and RMSE values of S-PAN are significantly smaller than that of PCA-PAN for all 4 bands. These two metrics represent the deviation of the band reflectance values between the pan-sharpened and the original multispectral images. The overall deviation of the spectral reflectance is measured by MED, which is also lower in S-PAN. The spectral angle metric, MSA, measures the overall deviation of the spectral shape between the two images. It is noted that S-PAN has a much smaller MSA (0.058) than PCA-PAS (0.228). Thus, our simple pan-sharpening method is shown to have a much better spectral preserving property than the PCA based pan-sharpening implemented here.

4. CONCLUSIONS

We have successfully implemented a simple spectral-preserving pan-sharpening algorithm on 1-m resolution PAN images of TeLEOS-1 with 10-m resolution multispectral images of Sentinel-2. The method has also been applied to PAN and MS images captured simultaneously by sensors on a single satellite, such as Worldview-2 or GeoEye. This algorithm performs pan-sharpening using the ratio of the panchromatic DN to the equivalent DN value of the effective intensity of the multispectral pixels, determined by an LUT. The effective intensity of each pixel is calculated by a weighted sum of the reflectance of the multispectral bands. The weight of each band is determined by the overlap of its spectral response function with that of the panchromatic image. The performance metrics indicate that this simple pan-sharpening method preserves both the spectral shape and magnitude of the reflectance spectra. It is also superior in preserving spectral information than a PCA based pan-sharpening method.

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