SCIENCE CHINA
Information Sciences

• HIGHLIGHT •

January 2018, Vol. 61 018102:1–018102:3
doi: 10.1007/s11432-016-9085-y

Model-based variational fusion for reducing spectral distortion

Zeming ZHOU, Chaoqian CHEN*, Yong MENG & Biao HU

Institute of Meteorology and Oceanography, PLA University of Science and Technology, Nanjing 211101, *China*

Received 25 April 2016/Revised 20 November 2016/Accepted 16 March 2017/Published online 11 July 2017

Citation Zhou Z M, Chen C Q, Meng Y, et al. Model-based variational fusion for reducing spectral distortion. Sci China Inf Sci, 2018, 61(1): 018102, doi: 10.1007/s11432-016-9085-y

High-resolution remote sensing satellites such as IKONOS, QuickBird, and GeoEye-1 usually provide a panchromatic (PAN) band and four multispectral (MS) bands. Pan sharpening is the synthesis of MS images of high spatial and spectral resolution with the spatial detail extracted from PAN images. In this article, we present a model-based variational method for reducing the spectral distortion of an MS image pan-sharpened through the generalized intensity-hue-saturation (GIHS) fusion [1]. A modulation transfer function (MTF)-based low-pass filter was developed to retain the spectral fidelity of the MS image. Experiments using datasets of IKONOS, QuickBird, and GeoEye-1 validate the effectiveness of the proposed method.

Pan-sharpening model. The first observational model assumes that the pan-sharpened image is a combination of the PAN image and the up-sampled low-resolution MS images:

$$\begin{bmatrix} F(R) \\ F(G) \\ F(B) \\ F(\mathrm{NIR}) \end{bmatrix} = \begin{bmatrix} R+(P-I) \\ G+(P-I) \\ B+(P-I) \\ \mathrm{NIR}+(P-I) \end{bmatrix}, \tag{1}$$

where R, G, B and NIR denote red, green, blue, and near infrared bands; $F(\cdot)$ represents the fused image. The intensity component I is given by

$$I = \alpha_1 R + \alpha_2 G + \alpha_3 B + \alpha_4 \mathrm{NIR} = \sum_{j=1}^{4} \alpha_j M_j, \tag{2}$$

where M_j is the up-sampled image of the jth MS band; α_j is the weight coefficient. The weight coefficients were acquired from the satellite provider [2]. The PAN image was changed to match the histogram of intensity component I to produce P image in (1) for reducing spectral distortion. Spatial details extracted from the PAN band are given as

$$D = P - \sum_{j=1}^{4} \alpha_j M_j. \tag{3}$$

Motivated by the merit of the GIHS fusion model, the spatial details in (3) are injected into the MS bands with variational method, the first energy term is defined as

$$E_{\mathrm{spatial\_details}}(f_i) = \frac{1}{2}\int_{\Omega} (f_i - (M_i + D))^2 \mathrm{d}x, \tag{4}$$

where f_i is the pan-sharpened image of the ith MS band. Clearly, the optimal solution of (4) is

$$f_i = M_i + D. \tag{5}$$

However, a noticeable spectral distortion exists in the fused MS image. We assume that the cause

* Corresponding author (email: chenchaoqiannj@yahoo.com)
The authors declare that they have no conflict of interest.

© Science China Press and Springer-Verlag Berlin Heidelberg 2017

of the spectral distortion is the same amount of spatial details injected into each MS band. It is possible to reduce the spectral distortion of the fused images if the spatial details merged into each MS image are tuned adaptively depending on the spatial frequency response of sensors of different bands. The spatial frequency response can be measured with the MTF. As Wald's consistency property states, once the pan-sharpened MS image is degraded to the resolution of the MS image, it should be close to the original MS image. The filter applied for degrading the fused image can be validated to be MTF-shaped [3], and the shape of its frequency response can be approximated by a Gaussian function. For high-resolution imageries such as those from IKONOS, QuickBird, and GeoEye-1, the degrading operation can be implemented with à trous transform; the fused image is low-pass filtered with the MTF-shaped filter and the output is filtered again with the up-sampled version of the original filter by inserting zeros into the coefficients. Subsequently, the output is decimated by four. If we ignore the decimating operation, the low-pass filtered version of the fused MS image should resemble the original up-sampled MS image to a large extent. Inspired by the Wald's protocol and the idea of à trous transform, to reduce spectral distortion of the MS image by GIHS fusion, the second observational assumption in this article models the relationship between the pan-sharpened MS image and the corresponding up-sampled version of the original MS image, as

$$E_{\text{spectral\_preserving}}(f_i) = \frac{1}{2}\int_{\Omega}(L_i * f_i - M_i)^2 \mathrm{d}x, \quad (6)$$

where L_i is the low-pass filter of the ith band:

$$L_i = \widehat{L}_{\text{mtf-shape},i} * L_{\text{mtf-shape},i}, \quad (7)$$

in which, $L_{\text{mtf-shape},i}$ denotes the MTF-shaped low-pass filter of the ith band, $\widehat{L}_{\text{mtf-shape},i}$ is its up-sampled version by inserting zeros into the coefficients of $L_{\text{mtf-shape},i}$, and * denotes the convolution operation. The minimization of (6) indicates that the low-pass version of the pan-sharpened MS image filtered by (7) is exactly close to the original up-sampled MS image.

Combining the energy terms of (4) and (6) together, the proposed energy functional is defined as

$$E(f_i) = E_{\text{spatial\_detail}} + \lambda E_{\text{spectral\_preserving}}, \quad (8)$$

where λ is the weight coefficient to trade-off the spatial and spectral qualities of the fused image.

By minimizing the energy functional of (8), the spectral distortion originating from GIHS fusion was found to be alleviated remarkably. Each MS image was sharpened by restoring a suitable amount of spatial detail, which should have been presented in each MS image but was then restrained by its MTF.

Calculating the Gateaux derivative of the functional, we achieve

$$\frac{\partial E}{\partial f_i} = f_i - (M_i + D) + \lambda L_i^* * (L_i * f_i - M_i), \quad (9)$$

where L_i^* is the conjugate transpose of L_i. By introducing the time variable t, the minimization of the energy functional of (8) is obtained by finding the steady solution of the gradient flow equation:

$$\frac{\partial f_i}{\partial t} = -\frac{\partial E}{\partial f_i}. \quad (10)$$

Experiments. To validate and assess the proposed model, we conducted experiments using datasets of IKONOS, QuickBird, and GeoEye-1. The IKONOS imagery was acquired in Shanghai, China on March 29, 2007; the QuickBird imagery was accessed from the official website http://glcf.umiacs.umd.edu/data/quickbird/; and the GeoEye-1 imagery was acquired from the official website http://www.geoeye.com/CorpSite/resource/sample_imagery_response.aspx.

The optimal solution of the functional was acquired with the parameter configuration as: Δt=0.2, λ=5, $\varepsilon = 5 \times 10^{-3}$ and K=15. The MTF gains of IKONOS and QuickBird at Nyquist cutoff frequency were used for developing the MTF-shaped filter [3]. To evaluate the fusion performance quantitatively, we used sCC, ERGAS, SAM, and Q4 [4] as metrics. To calculate these indices of different methods, the fused image was degraded to its original resolution with the MTF-shaped filter, as recommended in [3] and the original MS image was taken as a reference. We also used D_s, D_λ, and QNR [5] for quality assessment without referring to the true high-spatial MS image. We compared the proposed method to five state-of-the-art fusion models including IHS-based GIHS [1] and GIHSA [6], MBO-based Adaptive IHS [7] and TV regularization (TVR) [8], and MTF-based MTF-CON [9]. The fusion results are presented in Table 1, in which the best index is labeled in bold.

The fused images of GIHS, GIHSA, Adaptive IHS and TVR seem slightly sharper than that confirmed by sCC; however, a higher spectral distortion occurred concurrently, as reflected in SAM and ERGAS in Table 1. Adaptive IHS offered

Table 1 Quality assessment of different fusion methods for each dataset

Dataset	Method	sCC	ERGAS	SAM	Q4	QNR	D_λ	D_s
IKONOS	GIHS	**0.994**	5.803	5.222	0.850	0.807	0.053	0.148
	GIHSA	0.989	4.145	4.441	0.858	0.764	0.105	0.146
	Adaptive IHS	0.987	4.834	4.586	0.852	0.864	0.042	0.098
	TVR	0.989	4.392	4.939	0.844	0.777	0.082	0.153
	MTF-CON	0.920	3.455	4.441	0.841	0.797	0.099	0.115
	Proposed	0.970	**3.451**	**3.574**	**0.899**	**0.890**	**0.028**	**0.085**
QuickBird	GIHS	0.969	2.357	2.008	0.916	0.776	0.088	0.149
	GIHSA	**0.975**	1.507	1.605	0.919	0.768	0.139	0.109
	Adaptive IHS	0.942	1.503	1.420	0.922	0.842	0.084	0.080
	TVR	0.937	1.457	1.545	0.918	0.871	0.054	0.079
	MTF-CON	0.908	1.101	1.331	0.918	0.796	0.129	0.087
	Proposed	0.912	**1.048**	**1.096**	**0.937**	**0.915**	**0.038**	**0.049**
GeoEye-1	GIHS	**0.991**	4.384	3.384	0.944	0.779	0.115	0.121
	GIHSA	0.991	2.713	2.529	0.948	0.806	0.102	0.103
	Adaptive IHS	0.968	3.049	2.597	0.948	0.879	0.050	0.074
	TVR	0.986	2.472	2.568	0.948	0.855	0.069	0.083
	MTF-CON	0.929	2.059	2.340	0.947	0.801	0.116	0.094
	Proposed	0.966	**1.960**	**1.800**	**0.968**	**0.898**	**0.045**	**0.060**

relatively lower values of D_λ, except for the proposed model, which means that the inter-band correlations are preserved better at different scales. MTF-CON and the proposed method offered lower values of SAM and ERGAS, except for the proposed model, which reveals that a higher spectral fidelity was preserved. The sharpened image of the proposed method had the highest spectral quality, as shown by indices of ERGAS, SAM and D_λ and provided the lowest values of D_s, indicating a relatively high spatial fidelity. The indices of the proposed method rank the first, except sCC in Table 1, which confirms that a suitable trade-off is obtained in sharpening the MS image while retaining its spectral content.

Conclusion. In this article, we present a fusion method with model-based optimization and the variational framework. The fusion performance of the proposed method is evaluated using IKONOS, QuickBird, and GeoEye-1 datasets. Visual inspection and quantitative indices testify that the proposed method can remarkably reduce the spectral distortion of MS images sharpened by GIHS fusion. Further research need to be conducted considering the improvement of the spatial detail extraction model to provide a sharper MS image while retaining a higher spectral signature.

Acknowledgements This work was supported in part by National Natural Science Foundation of China (Grant Nos. 61473310, 41174164, 41175025) and China Meteorological Administration (Grant No. GYHY201306068).

Supporting information The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

References

1 Tu T M, Huang P S, Hung C L, et al. A fast intensity-hue-saturation fusion technique with spectral adjustment for Ikonos imagery. IEEE Geosci Remote Sens Lett, 2004, 1: 309–312

2 Tu T M, Hsu C L, Tu P Y, et al. An adjustable pan-sharpening approach for IKONOS/QuickBird/GeoEye-1/WorldView-2 imagery. IEEE J Sel Topics Appl Earth Observ Remote Sens, 2012, 5: 125–134

3 Khan M, Alparone L, Chanussot J. Pansharpening quality assessment using the modulation transfer functions of instruments. IEEE Trans Geosci Remote Sens, 2009, 47: 3880–3891

4 Kallel A. MTF-adjusted pansharpening approach based on coupled multiresolution decompositions. IEEE Trans Geosci Remote Sens, 2015, 53: 3124–3145

5 Alparone L, Aiazzi B, Baronti S, et al. Multispectral and panchromatic data fusion assessment without reference. Photogramm Eng Remote Sens, 2008, 74: 193–200

6 Aiazzi B, Baronti S, Selva M. Improving component substitution pansharpening through multivariate regression of MS+Pan data. IEEE Trans Geosci Remote Sens, 2007, 45: 3230–3239

7 Rahmani S, Strait M, Merkurjev D, et al. An adaptive IHS pan-sharpening method. IEEE Geosci Remote Sens Lett, 2010, 7: 746–750

8 Palsson F, Sveinsson J, Ulfarsson M. A new pansharpening algorithm based on total variation. IEEE Geosci Remote Sens Lett, 2014, 11: 318–322

9 Vivone G, Restaino R, Mura M D, et al. Contrast and error-based fusion schemes for multispectral image pansharpening. IEEE Geosci Remote Sens Lett, 2014, 11: 930–934