Robust Watermarking Scheme for Multispectral Images Using Discrete Wavelet Transform and Tucker Decomposition

Hai Fang
National Key Laboratory of Space Microwave Technology, China Academy of Space Technology, Xi'an, China
neatsea@126.com

Quan Zhou
National Key Laboratory of Space Microwave Technology, China Academy of Space Technology, Xi'an, China
qqxzz@yahoo.com

Kaijia Li
Kunming University, Kunming, China
Information Security Center, Beijing University of Posts and Telecommunication, Beijing, China

***Abstract*—Watermarking represents a potentially effective tool for the protection and verification of ownership rights in remote sensing images. Multispectral images (MSIs) are the main type of images acquired by remote sensing radiometers. In this paper, a robust multispectral image watermarking technique based on the discrete wavelet transform (DWT) and the tucker decomposition (TD) is proposed. The core idea behind our proposed technique is to apply TD on the DWT coefficients of spectral bands of multispectral images. We use DWT to effectively separate multispectral images into different sub-images and TD to efficiently compact the energy of sub-images. Then watermark is embedded in the elements of the last frontal slices of the core tensor with the smallest absolute value. The core tensor has a good stability and represents the multispectral image properties. The experimental results on LANDSAT images show the proposed approach is robust against various types of attacks such as lossy compression, cropping, addition of noise etc.**

***Index Terms*—multispectral images, watermarking, discrete wavelet transform, tucker decomposition**

I. Introduction

In the last decades, remotely sensed imagery has attracted a growing interest on the part of both public and private institutions because of the great potential it offers for monitoring natural and man-made resources at the global and local scales. Multispectral images obtained by satellites have gradually been the main data source of spatial geographic information. The positive trend of the remote sensing technology raises many problems, such as multispectral images are increasingly vulnerable to illegal possession, reproduction and dissemination. The digital watermarking technology is an effective way for solving these problems, it provides copyright protection and ownership assertion by embedding information into the host data [1-5].

There are different previous works dealing with satellite image watermarking. Wang et al. [6] presents a watermarking scheme to preserve a digital content, but only uses one band of the hyperspectral image. Tamhankar et al. [7] describes a method to embed one mark into the hyperspectral image using the whole signature, but it does not allow compression of the hyperspectral image. Serra and Megías [8] use the whole signature to embed a watermark, and they implement a Least Significant Bit (LSB) extraction in each pixel value, making the scheme robust against near-lossless compression. Farid and Redha [9] propose a spread spectrum watermarking method for multispectral images, the key idea consists of inserting the watermark in the middle-frequency range of the original image transformed in the Discrete Cosine Transform (DCT) domain. In [10], a multispectral image watermarking scheme based on Principal Component Analysis (PCA) and Singular Value Decomposition (SVD) is presented. The watermark is embedded into singular value vector of PCA-component and is robust to lossy compression. In [11] the watermark is embedded in the selected mid frequency sub band of the spectral images, this method is not good in imperceptibility.

Many modern applications generate large amounts of data with multiple aspects and high dimensionality for which tensors provide a natural representation. Multispectral images and hyperspectral images can be considered as third-order tensor: two spatial dimensions and one spectral dimension. For instance, in [12] hyperspectral images are considered as a 3-D tensor

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Corresponding author: Hai Fang.

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denoise the hyperspectral images in a higher dimensional feature space. In [13] tensor representation is used for hyperspectral images feature extraction. A method for hyperspectral image compression based on tensor decomposition is presented in [14]. Several tensor decompositions have been introduced in [15]. One of the most popular tensor decompositions is the Tucker decomposition (TD) [16]. TD is a higher order form of principal component analysis.

In this paper we propose a new multispectral images watermarking algorithm based on DWT and TD. DWT is applied to each spectral band by using the 'db1' wavelet. Next, TD is applied to the approximate wavelet sub-images of the multispectral images in order to achieve better Robustness.

The remainder of this paper is organized as follows. In Sec. II, a brief overview of the wavelet transform and TD is provided. Sec. III describes the proposed DWT-TD multispectral images watermarking method. Experimental results are provided in Section IV. Finally, Sec. V concludes this paper.

II. Discrete Wavelet Transform and Tucker Decomposition

Multispectral images are generated by the imaging spectrometer by collecting image data simultaneously in several of spectral bands or frequencies. Multispectral images can be represented as a third dimensional data by using DWT and TD.

A. Discrete Wavelet Transform (DWT)

DWT can be implemented as a filter bank composed of low-pass and high-pass filters. After applying the DWT to each band of multispectral images the filter bank decomposes the original image band into approximate (A), horizontal (H), vertical (V), and diagonal (D) sub-bands, each being one-fourth the size of the original multispectral image band [14]. DWT concentrates maximum signal power into the A sub-band images, so the watermark can be embedded in the A sub-band images to achieve better robustness.

B. Tucker Decomposition (TD)

The third-order TD tensor decomposes a given third order tensor $\mathcal{X} \in \mathbb{R}^{I\times J\times K}$ into a core tensor $\mathcal{G} \in \mathbb{R}^{P\times Q\times R}$ multiplied by a set of three factor matrices [12, 14, 15, 17], where, $\mathbf{A} \in \mathbb{R}^{I\times P}$, $\mathbf{B} \in \mathbb{R}^{J\times Q}$, and $\mathbf{C} \in \mathbb{R}^{K\times R}$.

$$\begin{aligned}\mathcal{X} &\approx [\![\mathcal{G};\mathbf{A},\mathbf{B},\mathbf{C}]\!] \\ &= \mathcal{G}\times_1 \mathbf{A}\times_2 \mathbf{B}\times_3 \mathbf{C} \\ &= \sum_{p=1}^{P}\sum_{q=1}^{Q}\sum_{r=1}^{R} g_{pqr}\mathbf{a}_p \circ \mathbf{b}_q \circ \mathbf{c}_r\end{aligned} \tag{1}$$

Here $\times_n$ is the n-mode product of a tensor with a matrix, i.e., multiplying a tensor by a matrix in mode n [15, 17]. P, Q, and R are the number of components (i.e., columns) in the factor matrices $\mathbf{A}$, $\mathbf{B}$, and $\mathbf{C}$ respectively. The core tensor dose not necessarily has the same dimension as $\mathcal{X}$. If P, Q, R are smaller than I, J, K, the core tensor $\mathcal{G}$ can be thought as a compressed version of $\mathcal{X}$.

A few facts regarding n-mode matrix products are in order. For distinct modes in a series of multiplications, the order of the multiplication is irrelevant [15].

$$\mathcal{X}\times_m \mathbf{U}\times_n \mathbf{V} = \mathcal{X}\times_n \mathbf{V}\times_m \mathbf{U} \quad (m \neq n) \tag{2}$$

If the modes are the same, then

$$\mathcal{X}\times_n \mathbf{U}\times_n \mathbf{V} = \mathcal{X}\times_n (\mathbf{VU}) \tag{3}$$

III. Proposed Method

Unlike natural images, multispectral images have two types of correlation simultaneously, which are the spatial correlation within images and spectral correlation between bands. Exploiting both of spectral and spatial correlations is the key for the success of a robust watermarking algorithm. In this paper, a hybrid scheme based on DWT and TD for multispectral images watermarking is introduced. The spectral-spatial information of the pixel is preserved by using TD. Tensor representation preserves as many as possible the original spatial constraints of a certain pixel and its neighbors, which helps to better represent the pixel's spectral-spatial feature. Compared to the vector-based feature representation, such structural information in the tensor feature is a reasonable constraint to achieve better image fidelity and robustness for multispectral images watermarking.

A. Basic Principles.

In general, we can have orthogonal columns of $\mathbf{A}$, $\mathbf{B}$ and $\mathbf{C}$ i.e. $\mathbf{A}^{\mathrm{T}}\mathbf{A} = \mathbf{I}_{P\times P}$, $\mathbf{B}^{\mathrm{T}}\mathbf{B} = \mathbf{I}_{Q\times Q}$, $\mathbf{C}^{\mathrm{T}}\mathbf{C} = \mathbf{I}_{R\times R}$.

Multiplying both sides of (1) by $\mathbf{C}^{\mathrm{T}}\times_2 \mathbf{B}^{\mathrm{T}}\times_1 \mathbf{A}^{\mathrm{T}}$ in mode 3 we have

$$\begin{aligned}&\mathcal{X}\times_3 \mathbf{C}^{\mathrm{T}}\times_2 \mathbf{B}^{\mathrm{T}}\times_1 \mathbf{A}^{\mathrm{T}} \\ &\approx \mathcal{G}\times_1 \mathbf{A}\times_2 \mathbf{B}\times_3 \mathbf{C}\times_3 \mathbf{C}^{\mathrm{T}}\times_2 \mathbf{B}^{\mathrm{T}}\times_1 \mathbf{A}^{\mathrm{T}}\end{aligned} \tag{4}$$

By applying (3) and the right side of (4) we obtain

$$\begin{aligned}&\mathcal{G}\times_1 \mathbf{A}\times_2 \mathbf{B}\times_3 \mathbf{C}\times_3 \mathbf{C}^{\mathrm{T}}\times_2 \mathbf{B}^{\mathrm{T}}\times_1 \mathbf{A}^{\mathrm{T}} \\ &= \mathcal{G}\times_1 \mathbf{A}\times_2 \mathbf{B}\times_3 (\mathbf{C}^{\mathrm{T}}\mathbf{C})\times_2 \mathbf{B}^{\mathrm{T}}\times_1 \mathbf{A}^{\mathrm{T}} \\ &= \mathcal{G}\times_1 \mathbf{A}\times_2 (\mathbf{B}^{\mathrm{T}}\mathbf{B})\times_1 (\mathbf{A}^{(1)})^{\mathrm{T}} \\ &= \mathcal{G}\times_1 (\mathbf{A}^{\mathrm{T}}\mathbf{A}) \\ &= \mathcal{G}\end{aligned} \tag{5}$$

By (4) and (5) we have

$$\mathcal{G} \approx \mathcal{X}\times_3 \mathbf{C}^{\mathrm{T}}\times_2 \mathbf{B}^{\mathrm{T}}\times_1 \mathbf{A}^{\mathrm{T}} \tag{6}$$

By applying (2) we obtain

$$\mathcal{X} \times_3 \mathbf{C}^{\mathrm{T}} \times_2 \mathbf{B}^{\mathrm{T}} \times_1 \mathbf{A}^{\mathrm{T}} = \mathcal{X} \times_1 \mathbf{A}^{\mathrm{T}} \times_2 \mathbf{B}^{\mathrm{T}} \times_3 \mathbf{C}^{\mathrm{T}} \quad (7)$$

Then the core tensor $\mathcal{G}$ is given by:

$$\mathcal{G} \approx \mathcal{X} \times_1 \mathbf{A}^{\mathrm{T}} \times_2 \mathbf{B}^{\mathrm{T}} \times_3 \mathbf{C}^{\mathrm{T}} \quad (8)$$

The watermark is embedded into the core tensor.

B. Watermark Embedding.

We assume a multispectral image $\mathbf{I}$ as the host image and binary image $\mathbf{W}$ as the watermark image. The watermark embedding process includes following steps:

Step 1: DWT is applied to each spectral band of the original multispectral images in order to obtain sub bands (approximate, diagonal, vertical and horizontal) for each spectral band. The approximate sub bands of each spectral band are used to construct a third order tensor $\mathcal{X}^{I_1 \times I_2 \times I_3}$.

Step 2: The TD algorithm is applied to the tensor $\mathcal{X}^{I_1 \times I_2 \times I_3}$. $\mathcal{X}^{I_1 \times I_2 \times I_3}$ is decomposed into three factor matrices { $\mathbf{A}$, $\mathbf{B}$, $\mathbf{C}$ }and a core tensor $\mathcal{G}^{I_1 \times I_2 \times I_3}$.

$$\mathcal{X} \approx \mathcal{G} \times_1 \mathbf{A} \times_2 \mathbf{B} \times_3 \mathbf{C} \quad (9)$$

Step 3: The *k*th frontal slice of the core tensor $\mathcal{G}$ is denoted by $\mathbf{G}_k, 1 \le k \le I_3$. The last *N* frontal slices are used to embed watermark information.

$$p = \arg\min_k \{abs(\mathbf{G}_k) \big| k = I_3 - N + 1, \cdots, I_3\} \quad (10)$$

$$\mathbf{G}_p'(i, j) = \mathbf{G}_p(i, j) + \alpha \times \mathbf{W}(i, j) \quad (11)$$

Where $1 \le i \le I_1$, $1 \le j \le I_2$ and α is a constant scaling factor referred to as the watermark strength.

Step 4: Produce the watermarked tensor by

$$\mathcal{X}' \approx \mathcal{G}' \times_1 \mathbf{A} \times_2 \mathbf{B} \times_3 \mathbf{C} \quad (12)$$

where $\mathcal{G}'$ is the modified 3D core tensor.

Step 5: Use $\mathcal{X}'$ as the approximate sub bands of multispectral. Inverse DWT is applied on the modified sub bands to obtain the watermarked image.

C.Watermark Extraction.

The watermark extraction process includes following steps:

Step 1: DWT is applied to each spectral band of the watermarked multispectral images in order to obtain sub bands (approximate, diagonal, vertical and horizontal) for each spectral band. The approximate sub bands of each watermarked spectral band are used to construct a third order tensor $\mathcal{X}_w^{I_1 \times I_2 \times I_3}$.

Step 2: Produce the watermarked core tensor $\mathcal{G}_w$ by

$$\mathcal{G}_w = \mathcal{X}_w^{I_1 \times I_2 \times I_3} \times_1 \mathbf{A}^{\mathrm{T}} \times_2 \mathbf{B}^{\mathrm{T}} \times_3 \mathbf{C}^{\mathrm{T}} \quad (13)$$

Step 3: Binary watermarks are reconstructed by

$$p = \arg\min_k \{abs(\mathbf{G}_k) \big| k = I_3 - N + 1, \cdots, I_3\} \quad (14)$$

$$\mathbf{W}'(i, j) = \begin{cases} 0 & \text{if } (\mathbf{G}_{wp}(i, j) - \mathbf{G}_p(i, j)) / \alpha < 0 \\ 1 & \text{if } (\mathbf{G}_{wp}(i, j) - \mathbf{G}_p(i, j)) / \alpha \ge 0 \end{cases} \quad (15)$$

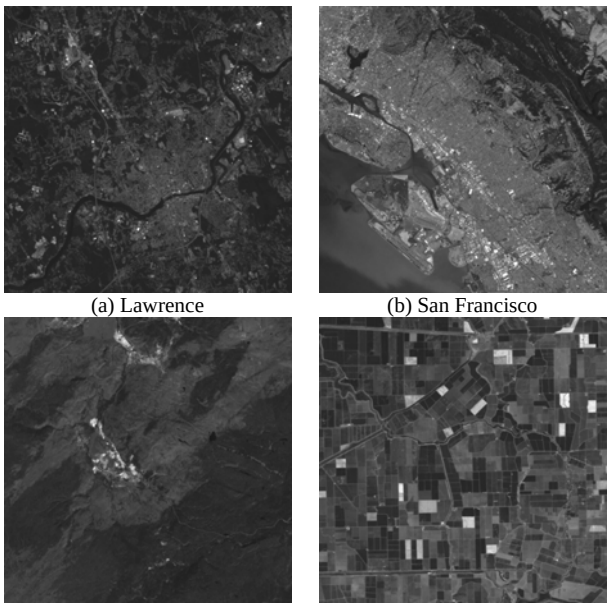
Where $1 \le i \le I_1$, $1 \le j \le I_2$ and α is a constant scaling factor referred to as the watermark strength, $\mathbf{G}_k, 1 \le k \le I_3$ is the *k*th frontal slice of the core tensor $\mathcal{G}$, and $\mathbf{G}_{wk}(i, j), 1 \le k \le I_3$ is the *k*th frontal slice of the watermarked core tensor $\mathcal{G}_w$.

Ⅳ. Experimental results and analysis

The watermark information shown in Fig. 1 is a binary image with size of 64×64.

Figure 1. Watermark information

Experiments are performed on Landsat multispectral images. The test images contain 6 bands, as shown in Fig.2, with a spatial resolution of 30 meters, each band consists of 512×512 pixels, and each spectral component is represented in 8-bit precision.

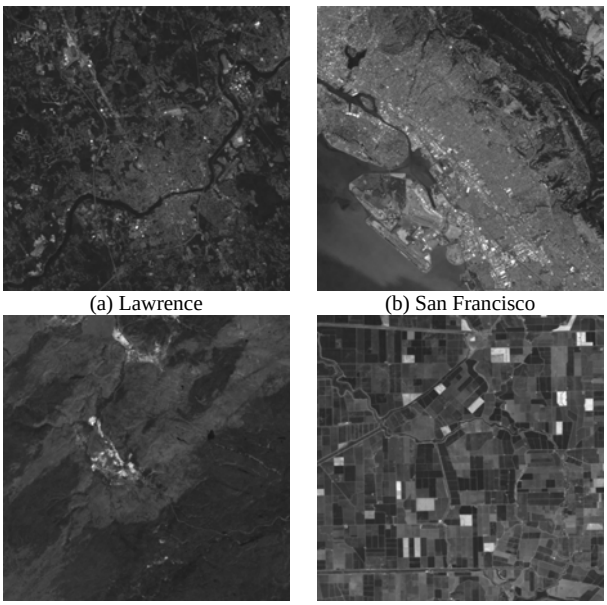


(a) Lawrence (b) San Francisco

(c) Yellowstone (d) Robinson Farm

Figure 2. Original images (band 3)

Fig.3 shows the results of watermarked images. They indicate that our suggested algorithm have a good visual quality.



(a) Lawrence (b) San Francisco

(c) Yellowstone (d) Robinson Farm

Figure 3. Watermarked image

A. Watermark Imperceptibility

To measure the perceptual quality, we calculate the peak to signal-to-noise ratio (PSNR) that is used to estimate the quality of the watermarked multispectral image in comparison with the original ones. The PSNR of the zth band is defined as follows:

$$PSNR_z = 10\log_{10}\left(\frac{255^2}{MSE_z}\right) \quad (16)$$

$$\mathrm{MSE}_z = \frac{1}{m\times n}\sum_{x=1}^{m}\sum_{y=1}^{n}\left(I(x,y,z)-I'(x,y,z)\right)^2 \quad (17)$$

Fig.4 shows the average PNSR of the test images by the proposed scheme with difference watermark strength. Fig.5 shows the PSNR results for each band of the test images when the watermark strength α is 25.

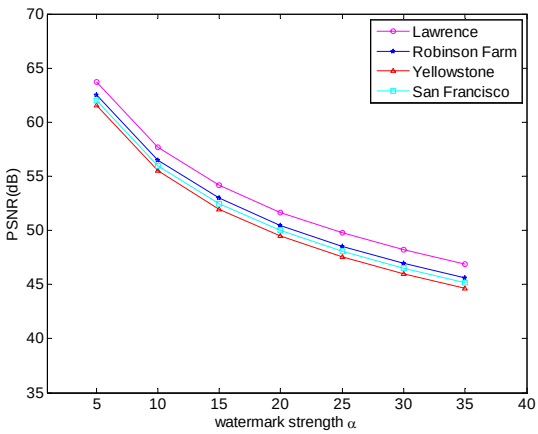


Figure 4. Average PSNR results for different images

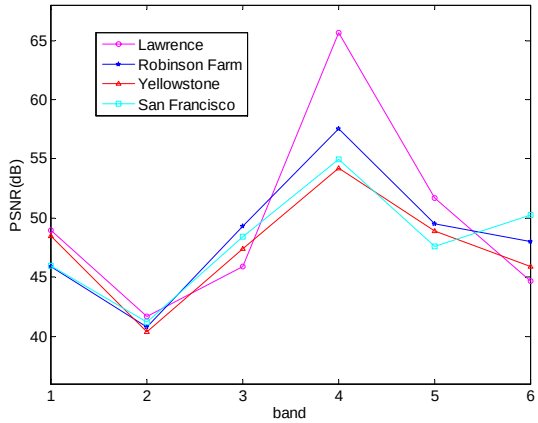


Figure 5. PSNR results for each band of different images ($\alpha = 25$)

Analogously to the radiometric distortion measurements, mean spectral angle (MSA) was defined for spectral distortion measurement. The spectral angle mapper (SAM) denotes the absolute value of the spectral angle between the couple of vectors [18]:

$$SAM(x,y) = \cos^{-1}\left(\frac{\sum_z I(x,y,z)\hat{I}(x,y,z)}{\sqrt{\sum_z I(x,y,z)^2 \sum_z \hat{I}(x,y,z)^2}}\right) \quad (18)$$

$$MSA = \max_{x,y}(SAM(x,y)) \quad (19)$$

Fig.6 shows the MSA results of the test images by the proposed scheme with difference watermark strength.

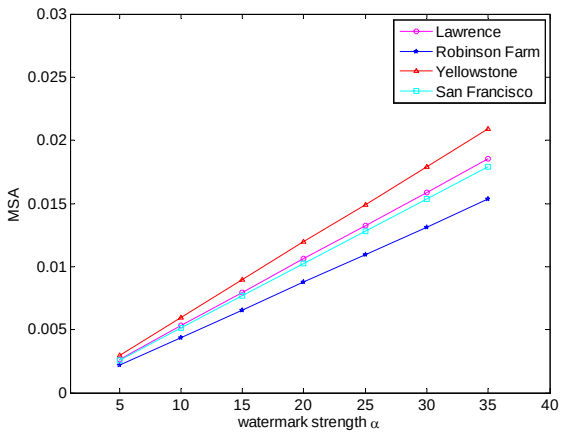


Figure 6. MSA results for different images

B. Watermark Robustness

Any watermarking system should be robust against various image processing attacks. To assess the robustness of our proposed method, we applied different attacks to the watermarked multispectral images. These attacks include Gaussian noise, filtering, compression, cropping etc. For all types of attacks we measured the similarity between the original and extracted watermarks

using the correlation coefficient, it may take values between 0 and 1. The correlation coefficient is computed by

$$r = \frac{\sum_m \sum_n \mathbf{W}_{mn} \mathbf{W}'_{mn}}{\sqrt{\sum_m \sum_n \mathbf{W}_{mn}^{\ 2} \sum_m \sum_n \mathbf{W}'^{\ 2}_{mn}}} \tag{20}$$

Storage and transmission of digital data are the most common operation and for this purpose a lossy coding operation is often performed on the data to reduce the memory and increase efficiency. JPEG2000 is usually used to compress multispectral images [19]. Hence, we have also tested our algorithm for JPEG2000 compression. Fig.7 shows the robustness of the proposed method against JPEG2000 compression attack.

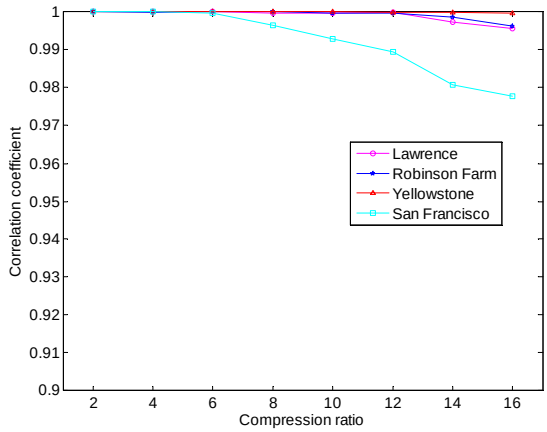


Figure 7. JPEG2000 lossy compression ($\alpha = 25$)

Another common manipulation in digital image is filtering. The extracted watermarks, after applying Wiener and median filtering, are shown in the Fig.8 and Fig.9. After applying these filters, images are degraded significantly and lot of data is lost but the correlation coefficient is still high and the extracted watermark is still recognizable.

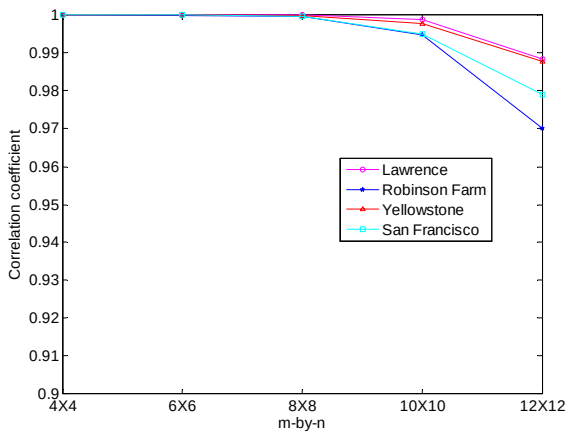


Figure 8. Wiener filtering attack

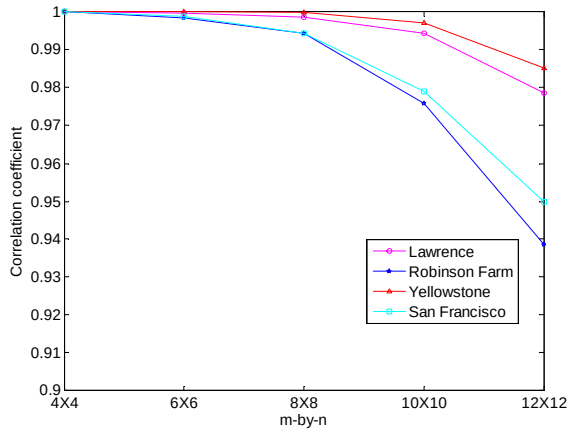


Figure 9. Median filtering attack

Image cropping is also a common attack in multispectral image watermarking. Cropping is a lossy operation and is very frequently used in multispectral images. Cropping an image is done by either hiding or deleting rows or columns. The results of cropping 10% to 50% from the top of watermarking multispectral images are shown in Fig.10.

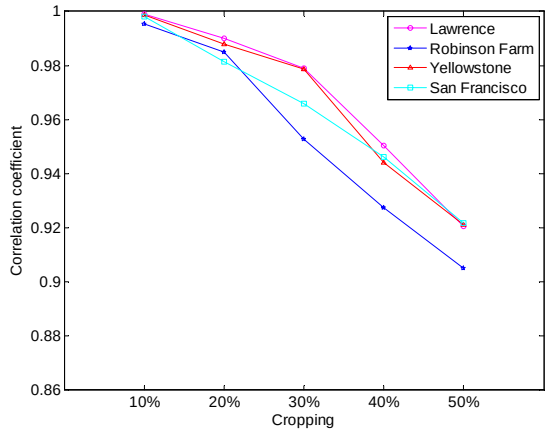
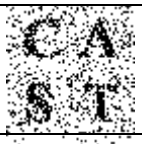


Figure 10. Cropping attack

Table I shows the extracted watermark and the correlation coefficient of recovered watermark from the Lawrence image under various kinds of attacks.

Addition of noise is another method to estimate the robustness of the watermark. Generally, addition of noise is responsible for the degradation and distortion of the image. Hence, the watermark information is also degraded by noise addition and that results difficulty in watermark extraction. Robustness against additive noise is estimated by degrading the watermark image by adding Gaussian and salt and pepper noise.

TABLE I.
EXTRACTED WATERMARKS AND CORRELATION COEFFICIENT UNDER VARIOUS ATTACKS ($\alpha = 25$)

Attacks	extracted watermark	correlation coefficient
no attack		1.0000
JPEG QF = 20		0.9892
JPEG QF = 70		1.0000
JPEG2000 (CR = 8)		0.9996
JPEG2000 (CR = 16)		0.9956
Gaussian noise addition (0.01)		0.8960
salt and pepper noise addition (0.01)		0.9749
Cropping (1/4)		0.9789
Cropping (1/2)		0.9207
Rescaling (100%–50%–100%)		1.0000
median filtering (8 × 8)		0.9986
Wiener filtering (8 × 8)		1.0000

C. Comparison with Existing Techniques

The watermarking scheme proposed in [10] is robust against attacks like lossy compression and mean filtering operations etc. But it is highly vulnerable to cropping operations which are widely used. The robustness of the proposed scheme against cropping attacks was evaluated. The proposed scheme is able to detect the watermark even when the watermarked image is cropped by cropping 25 or 50% of the whole image, as shown in Table I.

The proposed watermarking scheme is compared with existing recently published papers by S. Maheswari and K. Rameshwaran [11]. The test data based on AVIRIS multispectral images from Moffett field and Cuprites. The results are shown in Table II and Table III. In [11], the PSNR values are all smaller than 40 dB, which is unacceptable for multispectral images. The obtained results in terms of PSNR are shown in Table II. Table III presents a comparison between the proposed scheme and the method suggested in [11]. Comparison of the correlation coefficient of the watermark extracted from the attacked watermarked cover image is done for various attacks as shown in Table III. The results show that the proposed technique is better than the contemporary technique.

TABLE II.
COMPARISON OF PSNR VALUE IN PROPOSED METHOD AND EXISTING METHOD

image	PSNR(dB)	
	Maheswari's method	Proposed method
Moffett	38.57	52.37
Cuprites	36.46	53.16

TABLE III.
COMPARISON OF CORRELATION COEFFICIENT UNDER VARIOUS ATTACKS IN PROPOSED METHOD AND EXISTING METHOD

Attacks	correlation coefficient			
	Maheswari's method		Proposed method	
	Moffett	Cuprites	Moffett	Cuprites
JPEG QF=10	0.9903	0.9903	1.0000	1.0000
Salt & Pepper (0.001)	0.9903	0.9904	0.9986	1.0000
Median filtering (7×7)	0.9929	0.9921	0.9989	0.9965
Low pass filtering (7×7)	0.9905	0.9905	0.9997	0.9980

V. CONCLUSION

In this paper, a DWT-TD based algorithm for the watermarking of multispectral remotely sensed images is proposed. It is based on the insertion of the watermark in the last range of frontal slices of the TD core tensor. The approximate tensor has the lowest frequency components containing most of the wavelet coefficient energy, so the algorithm achieves its robustness against an ensemble of attacks. The experimental results carried out on LANDSAT multispectral remote sensing images show that the watermark insertion into the last frontal slices

range allows: 1) to achieve a significant image quality preservation capability demonstrated by the obtained important gains in terms of both PSNR and MSA; 2) to increase the robustness against a wide variety of attacks like compression, filtering etc; 3) to yield a sharp increase of robustness to the widely used cropping operation. The proposed algorithm can be applied to multispectral as well as hyperspectral data.

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REFERENCES

[1] Petitcolas, Fabien AP, Ross J. Anderson, and Markus G. Kuhn. "Information hiding-a survey." Proceedings of the IEEE 87.7 (1999): 1062-1078.

[2] Brannock Evelyn, Michael Weeks, and Robert Harrison. "The Effect of Wavelet Families on Watermarking." Journal of Computers 4.6 (2009): 554-566.

[3] Dutta Malay Kishore, Phalguni Gupta, and Vinay K. Pathak. "Audio Watermarking Using Pseudorandom Sequences Based on Biometric Templates." Journal of Computers 5.3 (2010): 372-379.

[4] Chien-Chang Chen, Zeng-Chuang Jiun, and Chien-Hsiang Hsu. "An Adaptive Reversible Image Watermarking Scheme Based on Integer Wavelet Coefficients." Journal of Computers 8.7 (2013): 1677-1682.

[5] Cai Yong-mei, Wen-qiang Guo, and Hai-yang Ding. "An Audio Blind Watermarking Scheme Based on DWT-SVD." Journal of Software 8.7 (2013): 1801-1808.

[6] Xianmin Wang, Zequn Guan, and Chenhan Wu. "A novel information hiding technique for remote sensing image." Advanced Data Mining and Applications. Springer Berlin Heidelberg, 2005. 423-430.

[7] Tamhankar, H., Bruce, L. M., & Younan, N. "Watermarking of hyperspectral data". In Geoscience and Remote Sensing Symposium, 2003. IGARSS'03. Proceedings. 2003 IEEE International. Vol.6, pp. 3574-3576

[8] Serra-Ruiz, Jordi, and David Megías. "A novel semi-fragile forensic watermarking scheme for remote sensing images." International Journal of Remote Sensing. 32(19) (2011): 5583-5606.

[9] Farid Melgani, Redha Benzid, and Francesco G.B. De Natale. "Near-lossless spread spectrum watermarking for multispectral remote sensing images". Journal of Applied Remote Sensing, 2007, 1(1):3501-3517.

[10] Long Ma, Changjun Li, Shun Song. "Digital watermarking of spectral images using PCA-SVD". Journal of Imaging Science and Technology, 2007, 51(1):80-86.

[11] S. Maheswari, K. Rameshwaran. "A novel blind 3-D CDHWT-SVD based watermarking algorithm for hyper spectral images". European Journal of Scientific Research, 2012, 71(2): 163-173.

[12] Karami, Azam, Mehran Yazdi, and Alireza Zolghadre Asli. "Noise reduction of hyperspectral images using kernel non-negative tucker decomposition." IEEE Journal of Selected Topics in Signal Processing. 5.3 (2011): 487-493.

[13] Liangpei Zhang; Lefei Zhang; Dacheng Tao; Xin Huang, "Tensor Discriminative Locality Alignment for Hyperspectral Image Spectral-Spatial Feature Extraction," IEEE Transactions on Geoscience and Remote Sensing, vol.51, no.1, pp.242-256. 2013

[14] Karami, Azam, Mehran Yazdi, and Grégoire Mercier. "Compression of hyperspectral images using discerete wavelet transform and tucker decomposition." Selected Topics in Applied Earth Observations and Remote Sensing, IEEE Journal of 5.2 (2012): 444-450.

[15] Kolda, Tamara G., and Brett W. Bader. "Tensor decompositions and applications." SIAM review 51.3 (2009): 455-500.

[16] L. R. Tucker, "Some mathematical notes on three-mode factor analysis", Psychometrika, 31 (1966), pp. 279–311.

[17] Bader B W, Kolda T G. "Matlab tensor classes for fast algorithm prototyping". ACM Transactions on Mathematical Software (TOMS), 2006, 32(4): 635-653

[18] Aiazzi B, Alparone L, Baronti S, et al. "Spectral distortion in lossy compression of hyperspectral data." Journal of Electrical and Computer Engineering. 2012

[19] Yu G, Vladimirova T, Sweeting M N. Image compression systems on board satellites. Acta Astronautica, 2009, 64(9): 988-1005.

Hai Fang was born in Xi'an, Shaanxi, China, in 1983. He received the BS. and MS. degrees in computer science and technology from Northwestern Polytechnical University, Xi'an, China, in 2006 and 2009, respectively.

He is currently pursuing the Ph.D. degree in signal and information processing at China Academy of Space Technology. His current research interests include data hiding and image compression.

Quan Zhou was born in Xi'an, Shaanxi, China, in 1965. He received his BS degree, MS degree and Ph .D. degree in communication and electronic system from Xidian University, Xi'an, Shaanxi, China, in 1986, 1989 and 1992 respectively. In 2009, he visited Illinois University at Urbana-Champaign (UIUC) as senior research fellow.

Since 1992, he has been with China Academy of Space Technology. He has been a professor since 1998 and has been the PhD supervisor since 2002. His research interests include image processing, data transmission, information hiding and satellite onboard switching.

Prof. Zhou has been the standing director of China society of image and graphics. He has been the vice chairman of image analysis committee of China society of stereology, information theory committee member of China Institute of Electronics Society, senior member of China Electronics Society, and senior member of China Communications Society.