Multiresolution Fusion of Remote Sensing Images Based on Resolution Degradation Model

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ABSTRACT A new method based on resolution degradation model is proposed to improve both spatial and spectral quality of the synthetic images. Some ETM+ panchromatic and multispectral images are used to assess the new method. Its spatial and spectral effects are evaluated by qualitative and quantitative measures and the results are compared with those of IHS, PCA, Brovey, OWT (Orthogonal Wavelet Transform) and RWT (Redundant Wavelet Transform). The results show that the new method can keep almost the same spatial resolution as the panchromatic images, and the spectral effect of the new method is as good as those of wavelet-based methods.

KEYWORDS image fusion; resolution degradation model; spectral distortion; artificial visual effect; remote sensing

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Introduction

With the development of imaging sensor technology, remote sensing images have been improved greatly in spatial and spectral resolution. Most sensors of commercial earth resource satellites such as IRS, Landsat7, Spot5, IKONOS and QuickBird, provide high-resolution panchromatic (PAN) and low-resolution multispectral (MS) images simultaneously. The PAN bands are necessary for accurate description of image details such as shapes, features and structures, and the MS bands provide essential spectral information for object identification and interpretation. More and more applications in remote sensing require that both spatial and spectral resolution of images are high, but current imaging sensor systems can not offer both of these properties synchronously due to some technical limitations. A solution to obtain these high resolution multispectral images is image fusion.

Image fusion has been applied in many fields such as topographically mapping, map updating, land-use investigating and environment monitoring. Various fusion methods have been proposed for different applications. Some applications like object identification, require that the fused images have high spatial resolution while still preserving good spectral information, so that the targets which are spectrally separable in original MS are still separable in the fused images. But the commonly used methods, for example, IHS (intensity, hue, saturation) method, PCA (principal component analyses) method and Brovey transform method, can keep almost the same spatial resolution as PAN, but distort the spectral characteristics of the original MS images. And it is particularly crucial if the images to be fused were taken at different periods of time. The recently developing wavelet transform (WT) methods preserve good spectral information, but some spatial information of the PAN images is lost, and compared with those of the IHS method, the spatial visual effects are less satisfactory.
1 Current image fusion methods

A variety of different fusion methods to merge PAN and MS images have been proposed. In this section, the commonly used fusion methods, such as IHS, PCA, OWT and RWT methods, are briefly reviewed. For convenience, assuming that the images to be fused are radiometrically calibrated and geometrically registered. Moreover, the variable $X_{Si}$ denotes band $i$ of the MS image resampled to the same resolution as the panchromatic image, and the variable PAN denotes the panchromatic image.

1.1 IHS method

The IHS colour transform can effectively separate a standard RGB (red, green, blue) image into spatial ($I$) and spectral ($H$, $S$) information. Intensity refers to the total colour brightness, hue refers to the dominant or average wavelength contributing to a colour, and saturation refers to the purity of a colour relative to grey. The general IHS method uses three bands of MS and transforms them to IHS space. A contrast stretch is then applied to PAN so that the stretched image has approximately the same variance and average as $I$ component. Then replace the $I$ component by the stretched PAN image and perform the reverse transform to obtain the fused RGB image. The IHS method has become a standard procedure in image fusion.

1.2 PCA method

Principal component analysis is a statistical technique that transforms multivariate data sets with correlated variables into ones with uncorrelated variables. The principle of PCA fusion is similar to that of IHS method. The first principal component (PC1) of MS is replaced by PAN before the image is transformed back to the original image space. The main advantage of this method is that more than three bands can be used during the fusion process, which is especially useful for fusion of multispectral images.

1.3 OWT method

Multiresolution decomposition provides a simple hierarchical framework to fuse images with different spatial resolutions. The commonly used algorithm of OWT is Mallat algorithm. It can decompose an image into one approximation image (low-resolution content) and three detail images (horizontal, vertical and diagonal detail images) at each resolution level. In OWT fusion method, the high frequency coefficients of MS are replaced with those of PAN in wavelet domain, and the fused image is obtained by performing inverse wavelet transform. As the distribution of coefficients in detail parts have mean zero, the fusion result can minimize the spectral distortion. The well-known OWT fusion method is ARSIS.

1.4 RWT method

Because of an underlying down-sampling process in OWT, the multiresolution decomposition is shift variant, which is undesirable for image fusion, especially when the images to be fused are not perfectly registered. RWT avoids down-sampling by use of redundant wavelet decomposition known as "trous" algorithm. It decomposes the image into wavelet planes, and each wavelet plane has the same number of wavelet coefficients, so the redundant decomposition requires more calculations than usual OWT. In RWT image fusion, the detail wavelet planes of PAN substitute or add to those of MS, then combine them with approximation planes of MS to obtain the fused image. The particularity of the redundant wavelet decomposition lies in the pixel-by-pixel analysis of the image, which allows flexibility for defining the fusion rules, and this property ensures better detection of significant features.

2 Problems of current fusion methods

The problems and limitations of available fusion methods have been analysed by many stud-
ies 10][15]. TU T M (2001) indicates that spectral distortion problems of classic fusion methods arise from the change of the saturation during the fusion process 10]. A. Garzelli (2002) and ZHANG Y (2004) discussed the limitations of wavelet-based image fusion 15][16]. Of all these discussions, the most common problems are spectral distortion and spatial artificial effects.

2.1 Spectral distortion

The early fusion methods such as IHS, PCA and Brovey transform use all frequencies of PAN during the fusion process, so the fused images can keep almost the same resolution as PAN. But they suffer from obvious spectral distortion due to the low correlation between PAN and MS. High-resolution panchromatic images usually have spectral ranges different from the corresponding multispectral images, especially for NIR or SWIR channel, their correlation is usually low. When the intensity image I (or PCI) was replaced by PAN, the radiometry on the spectral band is modified during the fusing process. In order to reduce these differences, PAN is usually stretched to have similar grey distribution of I (or PCI) before replacement. But the spectral distortion is still obvious.

There are other reasons for spectral distortion. If the images to be fused were taken at different time, tones of PAN and MS images are usually different, which leads to low correlation between them. Moreover, some fusion transform models also affect the spectral quality. For example, the IHS model cannot transform all spectral information from RGB space to the H and S component due to the colour gamut being a finite triangle, and it changes the saturation of original MS 14]. The PCA model cannot separate the spectral and spatial information of MS, and the PC1 of MS also contains much spectral content. Therefore, when it is replaced by PAN, much spectral information will be lost.

2.2 Spatial artificial effects

Fusion methods such as high-pass filter (HPF), wavelet based methods, pyramid based methods etc., only use the high frequencies of PAN during the procedure. The detail image extracted from PAN has mean zero, so these methods do not or minimally distort the original spectral information of MS. But because the high frequencies of PAN can not be smoothly added to MS bands 15], which bring about "ringing effect" they tend to cause spatial artificial effect on the fused results. Compared with the IHS and PCA method, they usually can not have satisfactory visual effects. On the other hand, these methods are sensitive to the accuracy of registration errors of source images, and the added details of PAN can be blurred by slightly mismatched edges as a result of minor registration errors 14]. This case always happens when the images to be fused come from different sensors.

HPF and OWT based methods always cause visual artificial effects. In the HPF-based fusion, how to extract the high frequency part of PAN which exactly represents its high-resolution property is relatively difficult, much important textural information of PAN is lost during the filtering. Because of an underlying down-sampling process in OWT 13][14][15], its multi-resolution decompositions are shift variant and its fusion results are shift variant consequently, which can bring about "block effects".

2.3 Brief summary

Based on the above analyses, some conclusions are drawn as follows.

- Current methods either enhance the spatial resolution while altering the spectral information or preserve good spectral characteristics while bringing about spatial artificial effect.
- How to use PAN bands during the fusion procedure is important to the quality of the fused images.
- To some extent, it is difficult to get the same high spectral and high spatial resolution as the source images simultaneously. But we can take measures to control the trade-off between the spatial and spectral information.
Image fusion based on resolution degradation model

IHS method uses the PAN band to substitute I, but at the same time, causes significant spectral distortion due to the differences of their spectral range and spatial resolution. To avoid spectral changes of the fused results, we can adjust PAN in the following steps.

1. PAN firstly is separated into two parts: a detail part that represents high-resolution characteristic of PAN and the degraded part that has the similar spatial features with I;

2. Use the Local Correlation Modelling to match the degraded PAN with I, so that the degraded PAN and I have the same grey distribution;

3. Add the details to the adjusted degraded image and obtain the stretched PAN.

Replace I by this stretched PAN and perform the inverse transform to obtain the merged image. As the high-resolution information of PAN and the spectral information \((H, S)\) are not altered during the fusing process, the result image can better preserve the spatial and spectral information of the source images.

The general methods to separate PAN into the high-resolution part and the degraded part are spatial filtering and wavelet decomposition. But spatial filtering method has no specific criteria to differentiate low frequency part and high frequency part, and the type of filter and its size are hardly related to the resolution ratio of PAN and MS. Wavelet decomposition based on Mallat algorithm is shift variant, and only horizontal, vertical and diagonal high-frequency details are extracted, so the details cannot reflect high spatial information of PAN. Here a new method—resolution degradation model—is proposed.

3. Resolution degradation model

Resolution degradation is to decompose PAN into a low-resolution approximation part and a high-resolution detail part. The approximation part has similar spatial information with the corresponding MS image, and the detail part shows high spatial characteristics that MS has not. The difference between PAN and MS is on the high frequency details of PAN, so resolution degradation can be performed in frequency domain. And the formula is as follows.

\[
\text{PAN} = \text{PAN}_{\text{low}} + \text{PAN}_{\text{high}}
\]

where \(\text{PAN}_{\text{low}}\) is the degraded PAN image, and \(\text{PAN}_{\text{high}}\) is the details of the PAN image. The key point is to define which part of image is \(\text{PAN}_{\text{low}}\) and which part is \(\text{PAN}_{\text{high}}\).

A remote sensing image is one type of two-dimension digital signal. Its spatial resolution is dependent on the sampling interval. As known from the sampling theorem, the sampling interval is in inverse proportion to sampling frequency. Therefore, the maximal frequency of an image is in inverse proportion to its spatial resolution.

If the ratio of pixel resolution of PAN and MS is \(1 : m\), the maximal frequency of MS is \(1/m\) of that of the corresponding PAN. In the case of IKONOS PAN and MS images, PAN has higher spatial resolution than MS lies in that PAN has a broad frequency domain. Suppose PAN has the normalized frequency range \([-\pi, \pi)\), the corresponding MS may have the range \([-\pi/4, \pi/4)\). In order to get the degraded image of PAN, low-pass filtering in frequency domain is performed on PAN, and the cut-off frequency is \(\pi/4\) and \(\pi/4\), which is the maximal frequency of MS. In this way, the degraded PAN image has the same frequency domain as MS, so they have similar spatial information, and the high frequency details of PAN reflect the high spatial resolution that MS does not have. In order to avoid the ringing effects, Guass low-pass filter is used during the frequency filtering.

Fig. 1 shows the effect of resolution degradation of the ETM+ PAN image. The test data was ETM+ MS (30 m) and PAN (15 m) images, a small section was cut out from original images, as shown in Fig. 1(a) and Fig. 1(b), and the RGB MS image was combined by band 5, 4 and 3. Fig. 1(c) is the intensity of MS by IHS transform, which represents spatial infor-
mation of MS. And Fig. 1(d) is the degraded image of PAN. The degraded PAN image has more similar spatial effects as that of MS, and the correlation coefficient between Fig. 1(c) and Fig. 1(d) is 0.92. But before image degradation, their correlation coefficient is 0.83. Fig. 1(c) and Fig. 1(d) have the same resolution level and higher correlation, so their spectral difference is much easier to adjust.

Fig. 1 Performance of resolution degradation

3.2 IHS method based on resolution degradation

In order to reduce the spectral distortion of IHS fusion, a new IHS method based on Resolution Degradation (RDIHS) is proposed. The steps are as follows.

1. Transform the MS image (3 bands) from RGB space to IHS space.
2. Stretch the PAN band to have approximately the same variance and mean as I component.
3. Resolution degradation is performed on PAN to decompose it into degraded image $PAN_{low}$ and detail image $PAN_{high}$.
4. Use Local Correlation Modelling to adjust $PAN_{low}$, so that $PAN_{low}$ has high correlation with $I$, and $I'$ is produced.

$$I' = a \times PAN_{low} + b$$  \hspace{1cm} (2)

where $a$ and $b$ are coefficients from local regression analyses between $I$ and $PAN_{low}$. The equation is:

$$I = a \times PAN_{low} + b$$  \hspace{1cm} (3)

5. Add $PAN_{high}$ to the adjusted $PAN_{low}$ to combine a new component $I_{raw}$. As $PAN_{low}$ has been adjusted, $PAN_{high}$ needs to be adjusted to reduce spectral distortion.

$$I_{raw} = I' + PAN_{high} \times \frac{I'}{PAN_{low}}$$  \hspace{1cm} (4)

6. Replace $I$ by $I_{raw}$ and perform inverse transform to obtain the merged RGB image with high spatial information of PAN.

On one hand, as the degraded image $PAN_{low}$ is adjusted by $I$ component, it minimizes the spectral distortion. On the other hand, the detail part $PAN_{high}$ has mean zero, which causes little effect on spectral information. As a result, the fused result can not only improves the spatial resolution of MS, but also preserves its spectral characteristics.

4 Results and discussion

The experiment is based on ETM+ PAN (15 m) and MS (30 m) images in Fig. 1, and Fig. 2 shows the fusion results by IHS, PCA, Brovey, OWT, RWT and RDIHS.

Fig. 2 ETM+ PAN and MS fusion
During the fusion test, we found that the fused images have been improved greatly in spatial resolution compared with the original MS. The former three methods (IHS, PCA, Brovey) preserve the same spatial details as PAN, and the roads and house edges are clear and evident, but the spectral features have been changed in the area of the vegetation and bare lands. OWT, RWT and RDIHS have good spectral effects, and the colour of vegetation and residential areas in the fused images is almost identical with that of original MS. But RDIHS has better visual and spatial effects, its local contrast is better than that of OWT and RWT, and the high spatial details are naturally integrated into MS. Therefore, with a visual estimation, RDIHS get the best result among these methods.

To compare the spatial and spectral effects of RDIHS with those of the original MS and PAN, grey values of a profile line were measured in MS, PAN and the fusion results of RDIHS. Fig. 3 shows the spatial profiles of red, green and blue channels. The frequencies of RDIHS have much similar features as those of PAN, so the fused image has the same spatial information as PAN. The profile curves of RDIHS fluctuate slightly around those of MS. It shows that the RDIHS method not only improves spatial resolution, but also preserves most of the spectral information of MS.

Some quantitative measures are also applied to evaluate the performance of fusion methods. The spectral quality is evaluated by the correlation coefficients between the fused images and the original MS image, and the spatial quality is measured by the correlation coefficients between the panchromatic image and the intensity component of the merged image. The results are shown in Table 1.

It can be seen in Table 1 that the correlation coefficients of spectral quality can be divided into two parts; the fused images by IHS, PCA and Brovey have lower correlation with the original MS image, and their correlation coefficients are only around 0.9; The fused images by OWT, RWT and RDIHS have high correlations, whose correlation coefficients are around 0.95. So the methods; OWT, RWT and RDIHS have better spectral fidelity. The correlation between PAN and I component of fused images indicates the degree of preserving high-resolution spatial information. From the correlation coefficients of spatial quality, the first three methods preserve good spatial characteristic, yet the later three methods have relatively low correlation with PAN. But associated with spectral evaluations, RDIHS can better control the trade-off between the spatial and spectral information. It has almost the same spectral effects as RWT, and the spatial preservation is the best in later three methods.

Fig. 3    Spatial profiles of ETM MS, PAN and the fusion results of RDIHS
5 Conclusions

Qualitative and quantitative comparisons of merged ETM+ MS and PAN images have shown that the spectral effect of the RDIHS method is the best one of the methods studied, and the spectral information of fused images is almost the same as the original MS. The spatial resolution of the fused image has similar effects to that of IHS fused image, and the RDIHS recovers the spectral difference of PAN, so it has better spatial visual effects.

The use of RDIHS method is strongly recommended if the objective of image fusion is to preserve good spectral information and relative high spatial resolution. Other fusion tests show that the RDIHS method is independent of the spectral bands used, and this method is also effective in the fusion of IKONOS, SPOT, IRS multisensor images.

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