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Review Article

An effective thin cloud removal procedure for visible remote sensing images

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ABSTRACT

Clouds are obstructions for land-surface observation, which result in the regional information being blurred or even lost. Thin clouds are transparent, and images of regions covered by thin clouds contain information about both the atmosphere and the ground. Therefore, thin cloud removal is a challenging task as the ground information is easily affected when the thin cloud removal is performed. An efficient and effective thin cloud removal method is proposed for visible remote sensing images in this paper, with the aim being to remove the thin clouds and also restore the ground information. Since thin cloud is considered as low-frequency information, the proposed method is based on the classic homomorphic filter and is executed in the frequency domain. The optimal cut-off frequency for each channel is determined semi-automatically. In order to preserve the clear pixels and ensure the high fidelity of the result, cloudy pixels are detected and handled separately. As a particular kind of low-frequency information, cloud-free water surfaces are specially treated and corrected. Since only cloudy pixels are involved in the calculation, the method is highly efficient and is suited for large remote sensing scenes. Scenes including different land-cover types were selected to validate the proposed method, and a comparison analysis with other methods was also performed. The experimental results confirm that the proposed method is effective in correcting thin cloud contaminated images while preserving the true spectral information.

1. Introduction

With the rapid development of earth observation technology, remote sensing images with different spatial, temporal, and spectral resolutions are now available. Most of these remotely observed images are affected by atmospheric conditions and climatic factors, such as clouds (Richter, 1996a,b; Richter et al., 2011). The channels with short wavelengths, such as the visible channels, are more sensitive to the atmospheric conditions than those channels with long wavelengths, such as the infrared channels (Li et al., 2012). For the study of the land surface, clouds are considered as a kind of contamination, which result in the ground information being weakened or even lost (Richter et al., 2011; Li et al., 2012). Therefore, thin cloud removal is an important way to improve the quality of remote sensing images.

Thin cloud removal is a challenging task since images of regions covered by thin clouds not only contain the cloud information but also the ground features, including the radiation and textures (Du et al., 2002; Li et al., 2012). This results in the ground features being directly influenced when the thin clouds are removed. The model-based absolute atmospheric correction methods are capable of eliminating the atmospheric attenuation if the knowledge of the sensor profile and the atmospheric properties are available and accurate (Jensen, 1996). However, the atmospheric properties are difficult to acquire, even when planned (Jensen, 1996; Liang, 2001). Moreover, it has been found that the model-based methods cannot handle the locally concentrated thin clouds effectively. Thus, some image-based methods for thin cloud removal in remote sensing images have been explored which are independent of the model and correct the radiation of cloudy pixels. According to the data source, the image-based methods can be divided into two categories: multi-image based methods and single-image based methods.

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The multi-image based methods correct the brightness of the cloudy pixels by fusing complementary information from other temporal or other sensor images (Du et al., 2002; Poggio et al., 2012). Taking the cloud-free image as the reference data, a number of fusion strategies have been used to correct the cloudy pixels. A direct and simple fusion strategy is to replace the cloudy pixels with the referenced clear pixels. However, there are some limitations to the multi-image based methods. First, the cloudy image should be positively related to the reference cloud-free images; if not, the fusion will lead to breaks or errors in the results. Second, the clouds in the multiple images should not cover the same region; otherwise, no complementary information can be used to restore the ground information. Third, geometric and radiometric calibrations are necessary preprocessings, and the calibration accuracy is directly related to the final fusion result. Overall, the multi-image based thin cloud removal methods have strict requirements for data, which limits their application.

In contrast, the single-image based methods are independent of the referenced data, so their applications are broad. Several image enhancement methods have been used to restore the ground information under thin clouds, of which histogram matching has been the most widely used method (Stockham, 1972; Schreiber, 1978; Fries and Modestino, 1979). A typical image-based atmospheric correction method is the dark object subtraction (DOS) method, which treats all pixels equally (Chavez, 1988; Zhang et al., 2002). However, clouds are accumulations of liquid droplets or other particles suspended in the atmosphere, and are locally distributed rather than globally. Thus, DOS is capable of eliminating the influence of the global path radiation but fails to remove local thin clouds. Therefore, a level-based DOS method for thin cloud removal has also been developed, which segments the haze/cloud into several levels through haze optimized transformation (HOT) before the correction (Zhang et al., 2002). HOT is designed for the detection and characterization of haze/cloud distributions in Landsat scenes. It is a supervised procedure which requires cloudless samples to construct the clear-sky line. Thus, the results of HOT depend on the selection of cloudless samples from the cloudy scenes. Advanced HOT has also been developed to overcome land-cover confusion by introducing spatial constraints, but it still depends on the sample selection (He et al., 2010). Researchers have also tried to apply variational image processing methods to remote sensing images, but these methods are too complicated to handle the large scenes (Lan et al., 2013). All the above methods are operated in the spatial domain, but some methods that are operated in the frequency domain (with high computational efficiency) have also been developed. Thin clouds occupy the low-frequency parts of the image in the frequency domain, and can be extracted by a reasonable low-pass filter. Wavelet analysis (WA) (Du et al., 2002) and the homomorphic filter (HF) (Stockham, 1972; Schreiber, 1978; Fries and Modestino, 1979; Liu and Hunt, 1984) have both been utilized for thin cloud removal. WA involves the choice of wavelet basis, which is complicated, whereas the HF procedure is direct and clear. Moreover, the basic assumption of the HF can be used to model a cloudy image. However, the traditional HF is a global operation, which means that the brightness of both clear and cloudy pixels will be changed. This often leads to serious radiometric distortion in the results.

The existing methods are either complicated or not effective enough for the removal of locally aggregated thin clouds. In this paper, a simple but highly efficient and effective method that is based on the HF is proposed for the removal of thin clouds in visible remote sensing images. We intend to preserve the original radiometric DN values outside of haze areas in the multispectral image while removing the atmospheric scattering effects. This paper is organized as follows: Section 2 describes the HF and its use in thin cloud removal. The thin cloud removal method based on the HF is developed and the details are presented in Section 3. Several Landsat and high spatial resolution images are used in the experiments in Section 4. Section 5 concludes the paper.

2. Use of the homomorphic filter for thin cloud removal

Generally, the observed remotely sensed image $f(x, y)$ consists of two radiation components, namely the reflected component $R(x, y)$ and scattered component $S(x, y)$, in which the scattered component is also named as the path radiance (Vermote et al., 1997; Liang, 2001; Perkins et al., 2012). Thus, the observed image can be expressed as $f(x, y) = R(x, y) + S(x, y)$. It should be mentioned that the path radiance is neglected in the presented method and the effect of the thin cloud is attributed to the transmittance of the atmosphere. Therefore, the observing model can be written as follows, which is also the basic assumption of the HF.

$$f(x,y) = i(x,y) \cdot r(x,y) \quad (1)$$

where $i(x, y)$ represents the illumination component, which is distributed in the low frequency; and $r(x, y)$ represents the reflection component, which is distributed in the high frequency. Thus, the illumination and reflection components can be estimated by low-pass and high-pass filters in the frequency domain.

Thin clouds are mainly generated by the atmospheric scattering of large particles, including dust, smoke, and water droplets (Du et al., 2002). The spatial distributions of thin clouds are locally aggregated and continuous over the land surface. Therefore, thin clouds are usually assumed to locate in the low frequency of a cloudy image (Liu and Hunt, 1984; Du et al., 2002). It is possible to remove thin clouds by suppressing the low-frequency information while enhancing the high-frequency information. The universal procedure of the HF for thin cloud removal is described in Algorithm 1.

Algorithm 1. Thin cloud removal via the homomorphic filter

Input: observed image $f(x, y)$.
Logarithm: $z(x, y) = \ln f(x, y) = \ln i(x, y) + \ln r(x, y)$.
Fourier transformation:
$\mathscr{F}\{z(x,y)\} = \mathscr{F}\{\ln i(x,y)\} + \mathscr{F}\{\ln r(x,y)\}$, simplified as:
$Z(u, v) = F_i(u, v) + F_r(u, v)$,
where $F_i(u, v)$ and $F_r(u, v)$ represent the Fourier transformation of $\ln i(x, y)$ and $\ln r(x, y)$.
Filtering: use filter $H(u, v)$ to suppress the low-frequency information including the thin clouds, and meanwhile enhance the high-frequency information including the land cover:
$S(u, v) = H(u, v)Z(u, v) = H(u, v)F_i(u, v) + H(u, v)F_r(u, v)$.
Inverse Fourier transformation: $s(x,y) = \mathscr{F}^{-1}\{S(u, v)\}$.
Exponent: $g(x, y) = \exp[s(x, y)]$.
Alternative step: keep the dynamic range of the output consistent with that of the input by linear stretching:

$$g_L(x,y) = a_0 + \frac{b_0 - a_0}{b - a}(g(x,y) - a) \quad (2)$$

where $[a_0, b_0]$ is the dynamic range of the input, and $[a, b]$ is the dynamic range of $g(x, y)$.
Output: filtered image $g_L(x, y)$.

The HF is an unsupervised and efficient method for thin cloud removal. The cut-off frequency, which is used to separate the high and the low frequencies, is needed in the filter $H(u, v)$. Because the disturbance of clouds depends on the channel wavelength, the