Remote Sensing of Environment 179 (2016) 183–195

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

An empirical and radiative transfer model based algorithm to remove thin clouds in visible bands

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ARTICLE INFO

Article history:
Received 18 December 2015
Received in revised form 2 March 2016
Accepted 24 March 2016
Available online xxxx

Keywords:
Empirical analysis
Landsat-8
Radiative transfer model
Thin cloud and its removal
Visible bands

ABSTRACT

An algorithm for cloud removal in visible bands was developed. Thin clouds inside visible Bands 1–4 of Landsat-8 data acquired on 8 January 2014 disappeared after the algorithm. Values of mean and one standard deviation decreased, band-by-band. The reduction was supported by the leftward shift of the histogram curve in each band. To validate the algorithm, we used the cloud-free image acquired on 23 December 2013 of Landsat-8 as the reference image. Among the January image before the algorithm, the January image after the algorithm, and the reference image, values of mean and one standard deviation of the January image after the algorithm were much closer to those of the reference image. Histogram curves of the January image after the algorithm and the reference image were almost overlapped entirely. Spatial correlation coefficients of the January image before the algorithm and reference were 0.496, 0.547, 0.656, and 0.730 for Bands 1–4, respectively. Coefficients of the January image after the algorithm and reference image became 0.782, 0.822, 0.840, and 0.885 for Bands 1–4. In cloud-free areas, the algorithm did not alter spectral characteristics of cloud-free pixels. Thus, the algorithm was not only able to remove thin clouds, but also to preserve spectral characteristics of cloud-free pixels. The algorithm was then applied to other land use and land cover (LULC) types, and images acquired in other locations and seasons by Landsat-8 and WorldView-2 sensors. Results in cloud removal were satisfactory. Finally, this algorithm outperformed three widely-used cloud removal algorithms in comparison.

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1. Introduction

Clouds consist of tiny water drops and ice crystals with variable sizes, and exist between an optical sensor in space and ground targets. As the solar radiation travels through the clouds, it is scattered and absorbed before reaching ground targets. Then, the upward surface reflectance coupled with cloud reflectance is attenuated by the clouds before recorded by the sensor. Thus, the collected data are the combination of the cloud-affected ground reflectance and cloud reflectance. Without the removal of the cloud effect, the acquired optical data cannot be directly used to study the climate change, land use change, ecosystem, energy and minerals, environmental health, and natural hazards (Ju & Roy, 2008). Therefore, clouds adversely influence not only the quality of remotely sensed optical data but also their application.

As the thickness of clouds increases, the scattering and absorption of the reflectance of ground features by the clouds increase. Once the clouds are thick enough, the ground reflectance is entirely obscured and not sensed by an optical sensor. The restoration of the blocked ground reference from the original image alone becomes impossible (Roy et al., 2008). Thus, under variable types and conditions of clouds, the methods to remove the clouds are divided into two groups, the removal of thick clouds using another image as the replacement, and the removal of thin clouds with a single image as well as with the image replacement approach. Of the replacement approach, the reflectance of the cloud-free pixel inside an image is used to restore the reflectance of another pixel underneath cloud. Numerous methods have been developed (Cheng, Shen, Zhang, Yuan, & Zeng, 2014; Li et al., 2014; Lin, Tsai, Lai, & Chen, 2013; Poggio, Gimona, & Brown, 2012). The replacement approaches are, however affected by at least three factors. First, clouds cannot exist over the same ground areas of the original image and the replacement image. Thus, the replacement using the image acquired on date two to restore the cloud-covered ground features of the image collected on date one is feasible. Second, the correlation of the multi-temporal images must be maximized. The maximization can be achieved when the acquisition interval of the multi-temporal images is the smallest or when the acquisition dates are near anniversary. For a solo satellite (e.g., Landsat-8), the revisit period of 16 days is the shortest time interval. Finally, the temporal variation of the ground targets always influences the results.

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http://dx.doi.org/10.1016/j.rse.2016.03.034
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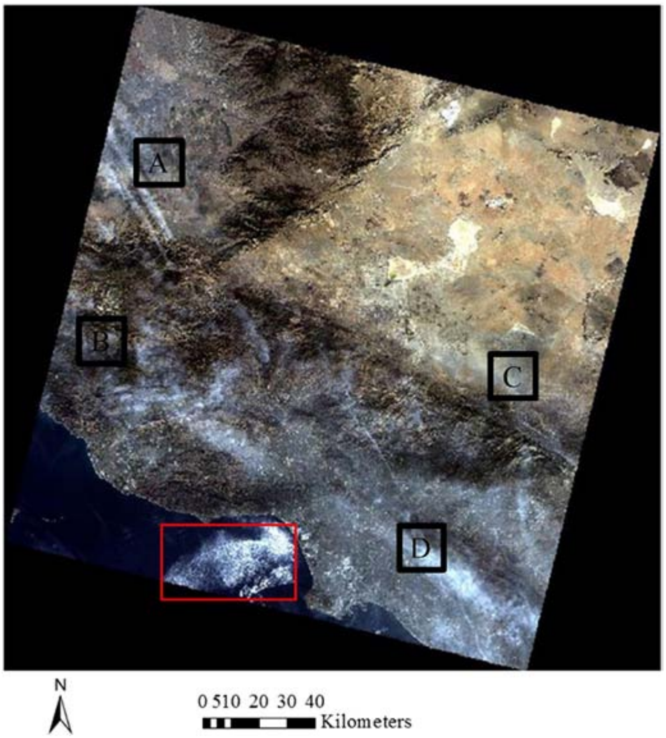

Fig. 1. A Landsat-8 image of 41/36 (path/row) acquired on 8 January 2014. The image is a color composite with Band 4 as red, Band 3 as green, and Band 2 as blue. Clouds exist. Los Angeles, CA is located near southeast. Mojave Desert is on the northeast. Areas A–D marked as black squares are four representative LULC types. The area outline by the red rectangle is predominately covered by thick clouds. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The (thin) cloud removal is done within one single image as long as the number of cloud-free pixels is sufficiently enough within an area of interest (Shen, Wang, & Lv, 2015). The removal is carried out in the image or frequency domain, through fusion, or with radiative transfer model (RTM). In the image domain, Zhang, Guindon, and Cihlar (2002) develop the haze optimized transformation (HOT) method. Using the intensity, hue, and saturation (IHS) transformation in the image domain, Souza, Pereira, Martins, Chagas, and Freitas (2003) create another cloud removal algorithm. The tasseled cap transformation (Crist & Cicone, 1984; Lavreau, 1991) is another example representing algorithms in the image domain since its fourth component is related to haziness/cloud. After the removal of the component and then an inverse transformation, the cloud effect on the data is minimized or removed. Although the method is efficient, a set of coefficients for the transformation has to be determined. Since the coefficients vary from one sensor to another, the determination is done on the sensor-by-senor basis and after the analyses of massive data statistically. The determination is not an easy task. For instance, coefficients of the fourth component of Landsat-8 have yet to be developed although coefficients of the first three components are published (Baig, Zhang, Shuai, & Tong, 2014; Liu, Liu, Huang, & Xie, 2015).

The representative methods in the frequency domain include the homomorphic filter (Shen, Li, Qian, Zhang, & Yuan, 2014) and wavelet analysis (Du, Guindon, & Cihlar, 2002; Maalouf, Carré, Augereau, & Fernandez-Maloigne, 2009) approaches. They are applied to the entire image that consists of cloud-free and cloud-covered pixels. Thus, the spectral characteristics of reflectance from the cloud-free pixels can be unnecessarily altered.

Fusion of shortwave infrared (IR) and visible band data is explored to remove thin-cloud in visible bands (Li, Zhang, Shen, & Li, 2012). However, a majority of current operational optical sensors in space consists only of multiple visible bands and one near infrared (NIR) band (https://directory.eoportal.org/web/eoportal/directory).

The RTM is widely-used in the cloud removal. The result is of high level in accuracy as long as the model is properly parameterized. Unfortunately, the parameterization is generally difficult (Liang, Fang, & Chen, 2001). A special spectral band designated for cloud detection is even needed (Gao, Kaufman, Han, & Wiscombe, 1998). Thus, if the parameters are not available, the existing RTM-based methods become inaccurate. Can one develop an empirical and RTM based thin-cloud removal algorithm in which the model can be well parameterized using optical data from multiple visible bands and one NIR band, and to remove thin clouds in the visible bands?

2. Methodology

2.1. A radiative transfer model

Gao et al. (1998) express the top of atmosphere (TOA) reflectance measured by a remote sensor, ρ_j^* as

$$\rho_j^* = \rho_{c_j} + T_j\rho_j \tag{1}$$

where subscript j stands for the j^{th} spectral band. ρ_{c_j} is the reflectance of clouds, T_j is the two-way transmission coefficient through the clouds. ρ_j is the reflectance of the surface underneath the clouds. ρ_j^* is the combination of cloud-affected surface reflectance and cloud reflectance. To remove the cloud effect or to get ρ_j, one needs to know T_j and ρ_{c_j} or

$$\rho_j = \frac{1}{T_j}\left(\rho_j^* - \rho_{c_j}\right). \tag{2}$$

T_j is derivable. ρ_{c_j} is calculated using data collected by designated cloud detection bands. Since a majority of existing and operational optical sensors onboard satellites does not have the bands, the applicability of Eqs. (1) or (2) is very limited. Alternative is sought.

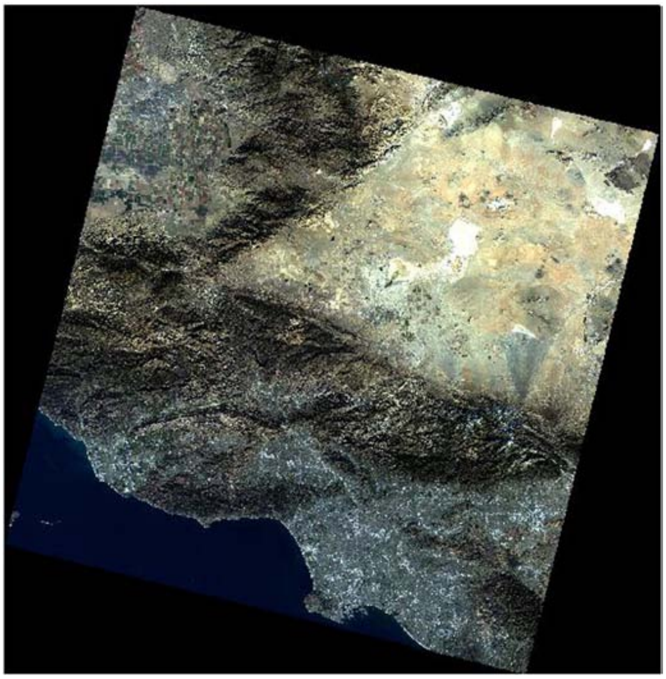

Fig. 2. A Landsat-8 image of 41/36 (path/row) acquired on 23 December 2013. The image is a color composite with Band 4 as red, Band 3 as green, and Band 2 as blue. There are no clouds. The image is used as a reference image. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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