Closest Spectral Fit for Removing Clouds and Cloud Shadows

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Abstract
Completely cloud-free remotely sensed images are preferred, but they are not always available. Although the average cloud coverage for the entire planet is about 40 percent, the removal of clouds and cloud shadows is rarely studied. To address this problem, a closest spectral fit method is developed to replace cloud and cloud-shadow pixels with their most similar non-clouded pixel values. The objective of this paper is to illustrate the methodology of the closest spectral fit and test its performance for removing clouds and cloud shadows in images. The closest spectral fit procedures are summarized into six steps, in which two main conceptions, location-based one-to-one correspondence and spectral-based closest fit, are defined. The location-based one-to-one correspondence is applied to identify pixels with the same locations in both base image and auxiliary images. The spectral-based closest fit is applied to determine the most similar pixels in an image. Finally, this closest spectral fit approach is applied to remove cloud and cloud-shadow pixels and diagnostically checked using Landsat TM images. Additional examples using QuickBird and MODIS images also indicate the efficiency of the closest spectral fit for removing cloud pixels.

Introduction
A significant obstacle to extracting information from remotely sensed images is the presence of clouds and their shadows. The average cloud coverage for our entire planet is about 40 percent (Simonett, 1983). Sometimes cloudy images have to be used because they are all that are available. For example, satellite multispectral scanner images of the Earth's surface such as Landsat images are often corrupted by clouds because of nadir-only observing satellites having relatively infrequent revisiting periods (Song and Civco, 2002).

Mitchell *et al*. (1977) developed a cloud distortion model and filtering procedures to remove cloud cover in satellite images. Liu and Hunt (1984) and Chanda and Majumder (1991) further improved the distortion model and filtering procedures. However, their methods are used for removing thin clouds, and it is difficult to determine the range of cloud densities in which clouds and cloud shadows (CCS) are removed efficiently.

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Cihlar and Howarth (1994) and Simpson and Stitt (1998) developed special methods for detecting and removing cloud contamination from AVHRR images. These methods are not suitable for removing CCS in other satellite imagery. For example, one prerequisite of their methods is that there is at least one single maximum or a single minimum for the seasonal trajectory of a satellite-derived variable (Mitchell *et al*., 1977).

The multi-date effect brightness correction method (Caselles, 1989) is another approach to removing CCS. Song and Civco (2002) used this method to replace CCS with appropriate pixel values. In essence, this approach has an important assumption that the sample mean and standard deviation (SD) of band values in CCS imagery is as the same as the cloud-free imagery. It is apparent that the mean and SD can only be estimated as approximations for that image since CCS cover parts of the image; the bigger CCS areas in the imagery, the larger the difference between the estimated mean and SD and their real values.

This paper develops a closest spectral fit (CSF) technique for replacing CCS pixels with the most similar pixels at cloud-free areas in the same image. The CSF technique is applied to remove CCS pixels in Landsat-5 Thematic Mapper (Landsat TM) data, and then error diagnostics is conducted using the images of Landsat TM, QuickBird, and Moderate Resolution Imaging Spectroradiometer (MODIS) as examples.

Closest Spectral Fit Appr oach
Two satellite images covering the same area and acquired at different times are needed. The base image is the one with relatively less CCS, and should retain the information that is acquired. Also, the base image is the one to be used for further applications. The other image will be called the auxiliary image. As much as possible, cloudy areas in the base image should be cloud-free in the auxiliary image. There should be no overlap of cloud pixels or cloud-shadow pixels in the two images and both images are selected for this criteria based on a visual estimation. If there are overlaps of CCS pixels, we need select an additional auxiliary image, which can be used to remove the overlapped CCS pixels. Using only the base image, it is impossible to select the most similar pixels for the pixels whose signatures are distorted by cloud and cloud shadow, since CCS have corrupted the real energy received and recorded by the satellite sensor. The auxiliary image is used as a medium to determine the relationship in the base image of

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