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A general variational framework considering cast shadows for the topographic correction of remote sensing imagery

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ABSTRACT

Topographic shadows are inevitable obstacles for the interpretation of remote sensing images covering rugged terrain. A general variational topographic correction (TC) framework is proposed in this paper by considering not only self shadows but also cast shadows. Cast shadows are first detected by integrating the radiometric and topographic features of the observed region. The cosine values of the incidence angles for the cast shadows are then corrected by the variational framework. The corrected incidence angles can be used in any traditional TC model to compensate for the shadows in mountainous regions. The proposed variational framework was utilized in eight different traditional TC models, and the results were compared with the traditional results. Images from two different regions were employed to test the framework. The results suggest that the proposed framework can raise the accuracy of shadow correction by both subjective and objective evaluations, owing to the correction of the cast shadows.

1. Introduction

Great parts of the earth's surface are covered by rugged terrain, in which mountains and valleys are widely spread. The variation of the elevation affects the distribution of the sun's radiation, causing sunlit and shaded areas, which correspond to the bright and dark pixels in remotely sensed imagery (Sandmeier and Itten, 1997). As a result of the lack of radiation in shaded areas, the information in shaded pixels is less than that in sunlit pixels. This is the reason why it is difficult to interpret remotely sensed data of mountainous areas. Topographic correction (TC) aims to compensate for the lost radiation for shaded pixels in remotely sensed imagery, which can help to raise the quality and applicability of images covering mountainous terrain (Smith et al., 1980). Thus, TC is usually considered as an important step before remote sensing imagery is used in many applications (Richter et al., 2009; Vanonckelen et al., 2013).

The current TC methods can be divided into two types: physical model based methods and data-based empirical methods. The former type depends on the radiative transfer model, considering both the atmospheric and topographic conditions (Balthazar et al., 2012; Dymond et al., 2001; Richter, 1996). The physical model based methods require in-situ atmospheric parameters, which are often unavailable (Ghasemi et al., 2013; Proy et al., 1989). These methods are physically accurate, but are complicated and not widely used. The latter type is based on the topographic features and statistical information of the observed images (Civco, 1989; Teillet et al., 1982). These data-based empirical methods are simple and general approaches that can be used with most remote sensing data (Ge et al., 2008; Minnaert, 1941). In this paper, we concentrate on the latter type of TC method, and we attempt to make some improvements by constructing a general variational framework.

According to the geometric relationship between the sun and the earth, shaded pixels locate in two different regions: the shady slopes of mountains and the shadows of mountains cast on adjacent regions, corresponding to self shadow and cast shadow (Funka-Lea and Bajcsy, 1995; Teillet et al., 1997; Li et al., 2014). This paper focuses on the cast shadow and the specific definitions of self and cast shadow are given in Section 2. The topographic features used in the current methods are extracted from the digital elevation model (DEM) data, which describe the elevation, slope, and the aspect of the land surface (Riaño et al., 2003). The

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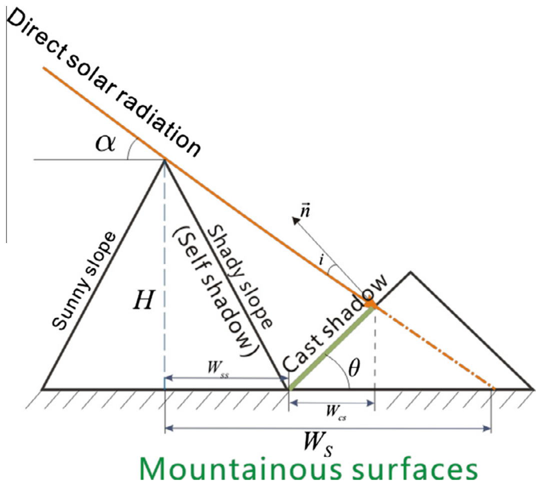

Fig. 1. The full shadow, including the self shadow and cast shadow, where the incident angle i is the angle between the solar radiation vector and the normal vector of the surface ($\vec{n}$).

correction is based on one important topographic feature: the cosine of the solar incidence angle ($\cos i$) of the land surface, as shown in Fig. 1, which is calculated by considering the solar position, the slope, and the aspect of the surface. The $\cos i$ is small for shaded slopes, and large for sunlit slopes. Thus, shaded slopes can be corrected by the current TC methods. However, the cast shadows actually locate on sunlit slopes. The current TC methods only consider the radiometric distortion caused by the self shadows, and overlook the adjacent cast shadows (Gao and Zhang, 2009; Kobayashi and Sanga Ngoie, 2008; Meyer et al., 1993). This is the reason why some dark regions often still exist in the correction results adjacent to self shadows (Kobayashi and Sanga Ngoie, 2009).

We attempt here to propose a TC method that can correct all the radiometric distortion caused by shadows, including both self shadows and cast shadows in remote sensing images with medium spatial resolutions. The cast shadow range and its influences are first discussed in detail. The topographic features and the radiometric information are then combined to distinguish between self shadows and cast shadows. Finally, a variational framework is constructed to optimize the topographic features by treating the self and cast shadows differently. This variational framework can be generally applied to all the current TC models, and is effective in correcting cast shadows.

The rest of the paper is organized as follows. The shadow components are analyzed in details and three traditional TC models are reviewed in Section 2. The proposed method is described in Section 3, including cast shadow detection, the variational framework, and its application. The experiments and results are described in Section 4. Finally, the paper is concluded in Section 5.

2. Problem analysis for topographic correction (TC)

Topographic correction has been studied by many researchers and some classical TC models have been proposed and improved. The shadow components and their effects on TC are analyzed in details, and meanwhile three traditional TC models are reviewed.

2.1. Shadow components: self shadows and cast shadows

Shadows refer to regions lacking direct solar illumination, which can be attributed to two reasons: opposing the sun and cast by obstructions. As shown in Fig. 1, the light source locates on the upper left of the 2D space. The shady slope opposes the sun, causing the self shadow, while the cast shadow is caused by the obstruction of the neighbor peak, even though it locates on a sunlit slope. An important criterion to distinguish self shadow and cast shadow is whether there is free space between where the shadow is and where the obstruction is (Funka-Lea and Bajcsy, 1995). If the free space exists, it is the cast shadow, otherwise it is the self shadow. It is noted that the mount is constituted by a lot of peaks, which are adjacent, convex and independent objects. They can cast shadows on the neighborhoods rather than themselves along the incident direction of the sun. We focus on processing the cast shadow in the topographic correction which is neglected in the traditional models.

How large are cast shadows, and can they be neglected in a remote sensing image? Assuming that the sun elevation is α and the height of the mountain is H, then the shadow width W_S can be calculated by the following equation:

$$W_S = H/\tan(\alpha) \tag{1}$$

The width of the self shadow W_{ss} is equal to the half width of the mountain, which is included in the total shadow W_S. The cast shadow width W_{cs} can then be calculated by the sine theorem, i.e.

$$W_{cs} = \cos\theta \sin\alpha(W_S - W_{ss})/\sin(\alpha+\theta) \tag{2}$$

where θ is the slope of the adjacent surface. W_{cs} is negatively related to the slope of the adjacent surface, which means that the smaller the value of θ, the larger the value of W_{cs}. Assuming $\alpha = 35°$, $H = 1000$ m, $W_{ss} = 500$ m, and $\theta = 40°$, the cast shadow width can be calculated as $W_{cs} = 422.2$ m. This cast shadow would cover more than 10 pixels in an image with a 30-m spatial resolution. If a TC method only treats self shadows, the correction will not be complete because the radiometric distortion caused by cast shadows will still exist in the image. Thus, cast shadows cannot be neglected in TC. The self shadow plus the cast shadow comprises the full shadow.

Pixels covered by shadows, either self shadows or cast shadows, are dark with a low radiance. The difference is that the incidence angles of self-shadow pixels are large, but they are small for the cast shadows. This means that the $\cos i$ of self shadows is small, and the $\cos i$ of cast shadows is large. For sunlit pixels, the $\cos i$ is large, as well as the radiance. Therefore, a positive linear relationship between $\cos i$ and the radiance holds for the sunlit and self shadow pixels, which can be expressed as:

$$L_T = a + b\cos i \tag{3}$$

where L_T is the observed radiation, $\cos i$ is the cosine of the incidence angle, b is the slope of the regression line, and a is the intercept. The same symbols represent the same variables in this paper. However, the cast shadows violate this relationship. Most of the traditional TC models are constructed based on this linear relationship. Thus they cannot be used to correct the radiometric distortion of cast shadows. That is the reason why we especially consider cast shadows in our work. Before illustrating the proposed framework, three traditional TC models are first reviewed in the following.

2.2. Traditional TC methods

A number of traditional empirical TC methods are currently used, among which three widely used methods are reviewed and compared in this paper: the C-correction model (Teillet et al., 1982; Hantson and Chuvieco, 2011), the sun–canopy–sensor (SCS) correction model (Gu and Gillespie, 1998; Soenen et al., 2005; Fan et al., 2014), and statistical empirical correction (SEC) (McDonald et al., 2002). These models aim to remove the effects of rough terrain on the radiation, and obtain the radiation L_H under the supposing condition that the terrain is horizontal.