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A physics-based atmospheric and BRDF correction for Landsat data over mountainous terrain

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ABSTRACT

Steep terrain affects optical satellite images through variations it creates in both irradiance and bidirectional reflectance distribution function (BRDF) effects. To obtain the corrected land surface reflectance and detect land surface change through time series analysis over rugged surfaces, it is necessary to remove or reduce the topographic effects. In this paper a physics-based BRDF and atmospheric correction model that handles both flat and inclined surfaces in conjunction with a 1-second SRTM (Shuttle Radar Topographic Mission) derived Digital Surface Model (DSM) product was applied to 8 Landsat scenes covering different seasons and terrain types in eastern Australia. Visual assessment showed that the algorithm removed much of the topographic effect and detected deep shadows in all 8 images. An indirect validation based on the change in correlation between the data and terrain slope showed that the correlation coefficient between the surface reflectance factor and the cosine of the incident (sun) angle reduced dramatically after the topographic correction algorithm was applied. The correlation coefficient typically reduced from 0.80–0.70 to 0.05 in areas of significant relief. It was also shown how the terrain corrected surface reflectance can provide suitable input data for multi-temporal land cover classification in areas of high relief based on spectral signatures and spectral albedo, while the products based only on BRDF and atmospheric correction cannot. To provide comparison with previous work and to validate the proposed algorithm, two empirical methods based on the C-correction were used as well as the established SCS-method to provide benchmarks. The proposed method was found to achieve the same measures of shade reduction without empirical regression.

1. Introduction

Topographic correction of satellite images over mountainous or hilly areas is very important (Liang, 2004), especially when the data are to be used for land cover mapping and monitoring over time. Steep terrain affects optical satellite images through both irradiance and Bi-directional Reflectance Distribution Function (BRDF) effects (Dymond et al., 2001; Gu & Gillespie, 1998). Slopes facing toward the sun receive more solar irradiance and appear brighter in satellite images than those facing away from the sun (Iqbal, 1983, Chapters 10, 11) where the darker pixels are often said to be "shaded". In addition, for anisotropic surfaces, the radiance received at the satellite from inclined surfaces is also affected by surface BRDF. That is, the signal results from the combined effects of surface land cover structure interacting with the sun and satellite geometry (sun and view and its relative azimuth angle) as well as topographic geometry (e.g. slope and aspect angles). Finally, all of these factors affect the inversion of land surface parameters and applications that aim to detect land surface conditions and changes through time series analysis.

Following some years of development and improvement, physics-based models for BRDF and atmospheric correction are relatively mature (Li & Strahler, 1985; Li et al., 1995; Li et al., 2010; Schaaf et al., 2002; Vermote et al., 1997). However, they have been applied mostly to surfaces that are essentially flat and seldom to significantly inclined surfaces. In the past, reported Digital Surface Model (DSM) or Digital Elevation Model (DEM) based topographic correction has mostly been undertaken separately from BRDF and atmospheric correction. Typical examples are terrain illumination correction for Lambertian surfaces (Dozier & Frew, 1981, 1990) and the "C-correction" (cosine) method which is based on an empirical relationship between observed radiance from inclined surfaces and the cosine of the incident angle (Richter, 1997; Teillet et al., 1982). Gu and Gillespie (1998) proposed the Sun-Canopy-Sensor (SCS) topographic correction which accounts for some of the BRDF effects over forested mountain areas and Shepherd

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and Dymond (2003) developed a semi-physics-based terrain and BRDF model which assumed an empirical relationship between diffuse reflectance and direct reflectance and other assumptions.

In this paper, a complete physics-based coupled BRDF and atmospheric model for both horizontal and inclined surfaces is introduced. The model unifies atmospheric, BRDF and topographic correction, extending work reported by Li et al. (2010) to include varying terrain within the same operational framework. It is important to specify that the work described is to be applied at the spatial resolution of Landsat, SPOT and similar resolution satellites. The correction assumes that the hill slopes are resolved by the sensor system. For satellites with large Instantaneous Field Of View (IFOV), such as MODIS 1 km data, the terrain effect is better treated as a modification to the BRDF, such as in the Hapke (1981) model. Two areas of Australia with significant terrain effects were selected to test the model and the model performance and make a comparison with other typical topographic correction methods.

The method, its relationship with other commonly used topographic correction methods and some implementation issues are described in Section 2 and Appendix A which provides greater detail for the mathematics. The information collected and materials used to validate the basic method are described in Section 3. Section 4 provides the results of three kinds of validation; visual, de-correlation with incident angle and land cover effects. Section 5 discusses some specific aspects arising from the results and the paper is concluded in Section 6.

2. Methods selected for the study

2.1. Basic approach

The base method introduced in this paper combines physical modelling with atmospheric, BRDF and terrain correction of the data. The approach seeks to avoid empirical or image dependent methods as much as possible and allow automation of products. The atmospheric and BRDF correction approaches have been described and validated in Li et al. (2010) and a number of issues relating specifically to the terrain information are discussed in Li et al. (2011). This paper extends the methods described by Li et al. (2010) to account for shading variations observed in areas with significant terrain complexity.

For flat terrain, as described in Hu et al. (1999), Vermote et al. (1997) and Li et al. (2010), radiance received by satellite sensors for non-uniform surfaces can be expressed as:

$$L_{TOA} = L_0 + \frac{1}{\pi} E'_0 \cos(\theta_S) \left(\begin{array}{l} t_V t_S \rho_S(\theta_S, \theta_V, \delta\varphi) + t_V t_d(\theta_S)\overline{\rho} + t_S t_d(\theta_V)\overline{\rho'} + \\ t_d(\theta_S) t_d(\theta_V)\overline{\overline{\rho}} + \dfrac{[t_V + t_d(\theta_V)][t_S + t_d(\theta_S)] S \left(\overline{\overline{\rho}}\right)^2}{1 - S\overline{\overline{\rho}}} \end{array} \right) \quad (1)$$

In this equation, δφ is the relative azimuth between the sun and view directions, $\overline{\rho}, \overline{\rho'}$ and $\overline{\overline{\rho}}$ are surface hemispherical–directional, directional–hemispherical and hemispherical–hemispherical reflectance (or bi-hemispherical) factors, respectively, other terms are defined in Table 1.

When the land surface is Lambertian (uniform bi-directional reflectance factor, or BRF, in all directions and denoted ρ_m) the model simplifies allowing a straightforward solution as:

$$\frac{\rho_m}{1 - S\rho_m} = \frac{\pi(L_{TOA} - L_0)}{E_h T_V} \quad (2)$$

Symbols are defined in Table 1. In the general case, the first four of five terms inside the brackets of Eq. (1) enable the atmospheric correction methodology to be extended to include non-Lambertian surfaces. The fifth term allows for the interaction between the surface and atmosphere. It is shown in Appendix A that a solution is possible if the "shape function" for the BRDF is known and Appendix A contains details of the solution as well as equations that extend it to include terrain shading effects.

When there is terrain variation in an area, the primary modification to the equation occurs because the diffuse and direct components of the total irradiance are modified. Assuming that the pixels are part of an inclined slope facet and that the modification to the diffuse and direct irradiance is as described by Iqbal (1983), the effects can then be incorporated into the four terms in Eq. (1) to take account of the modified irradiances. Appendix A also shows how BRDF is included by modifying the sun and view angles on the surface. The modified angles needed to describe solar radiation transfer for horizontal and inclined surfaces are illustrated in Fig. 1.

For both irradiance and BRDF modification, the sun and view angles are transformed into new angles relative to the slope normal rather than measured relative to the gravity normal. In particular, if the sun zenith and sun azimuth are denoted as (θ_S, φ_S), the view zenith and view azimuth as (θ_V, φ_V) and the slope facet zenith and slope azimuth as (θ_t, φ_t) then equivalent incident (i_t, φ_i) and exiting (e_t, φ_e) angles can be defined for the new coordinate system. For Lambertian surfaces, only the incident zenith angle is needed to define the configuration factor and it is:

$$\cos(i_t) = \cos(\theta_S)\cos(\theta_t) + \sin(\theta_S)\sin(\theta_t)\cos(\varphi_S - \varphi_t) \quad (3)$$

A mathematical description of the terrain is needed to implement the model, which is best provided by a DSM. The DSM allows the slope and aspect to be defined at any point and consequently the computation of the transformed angles and other information. The detailed expressions and solutions involving the interaction of BRDF terms and these components are given in Appendix A. The main assumption is

Table 1
Main symbols used in the paper.

θ_S	solar zenith angle
φ_S	solar azimuth angle
θ_V	sensor view zenith angle
φ_V	sensor view azimuth angle
θ_t	slope angle
φ_t	aspect angle of the slope
i_t	incident zenith angles between the sun and view directions and surface normal
φ_i	azimuth angle for incident direction in the slope geometry
e_t	exiting zenith angles between the sun and view directions and surface normal.
φ_e	azimuth angle for exiting direction in the slope geometry
t_S	direct transmittance in the solar direction
t_V	direct transmittance in the view direction
$t_d(\theta_S)$	diffuse transmittance in the solar direction
$t_d(\theta_V)$	diffuse transmittance in the view direction
S	the atmospheric albedo
T_S	total transmittance in the solar direction
T_V	total transmittance in the view direction
L_{TOA}	Sensor radiance at top of atmosphere
L_0	path radiance
E'_0	Solar exoatmospheric irradiance (earth-sun distance adjusted).
ρ_S	the surface reflectance (the BRF or bi-directional reflectance factor which is π times the BRDF)
ρ_{adj}	average reflectance of adjacent objects
ρ_m	the atmospherically corrected Lambertian reflectance
E_h	total irradiance on a horizontal surface
E_h^{dir}	the direct component of irradiance on a horizontal surface
E_h^{dif}	the diffuse component of irradiance on a horizontal surface
E	total irradiance on an inclined surface
E^{dir}	direct component of irradiance on an inclined surface
E^{dif}	diffuse component of irradiance on an inclined surface