Bi-directional Reflectance Distribution Function Approaches to Radiometric Calibration of Landsat ETM+ Imagery

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Abstract - There are many remote sensing studies where it is desirable to have a radiometrically matched time series of images or image mosaics. This paper examines the use of bi-directional reflectance distribution function (BRDF) models for radiometric correction of Landsat 7 ETM+ imagery. It describes a simple radiometric correction method which combines a top-of-atmosphere reflectance adjustment with an empirical BRDF model. The model parameters were derived from an overlapping sequence of Landsat 7 images.

I. Introduction

Remotely sensed data is usually affected by the solar incidence angle, solar azimuth, earth-sun distance, viewing angle, atmospheric effects, the effect of bi-directional reflectance distribution function (BRDF) of the sensed surface, and sensor band spectral response functions. These combine to produce significant band-dependent radiometric differences, confounding the interpretation of both temporal and spatial data sets. When using Landsat satellite imagery to map vegetation cover or monitor vegetation cover changes, it is desirable to remove these effects by implementing a method which can produce a radiometrically consistent time series of images and mosaics covering large areas. This enables indices or classifications derived for individual satellite scenes to match other scenes both spatially and over time, and it enables better use of field measurement sites, as signatures derived for field sites can be used in the classification of multiple scenes.

Two main approaches for correction of radiometric variations in multi-date imagery emerge from the literature. The first approach aims to account for some or all radiometric effects on surface response by converting digital data to physical units of radiance, using sensor calibration coefficients; then calculating reflectance to correct for illumination variations; and then calculating ground reflectance, correcting for atmospheric effects using a radiative transfer model. The more complex of these models attempt to make allowances for non-Lambertian reflectance e.g. the 6S code developed by Vermote *et al.* [1]. The second approach aims to empirically correct for relative radiometric differences which exist between multiple data sets through radiometric registration i.e. registering one data set to another so it appears as if both were acquired under the same set of conditions.

This method has mostly been used for correction of time series of images, rather than spatial matching of images, although CSIRO [2] has used it to produce radiometrically matched mosaics.

The approach previously used by the Statewide Landcover and Trees Study (SLATS) was a combination of these approaches and included the conversion to top-of-atmosphere (TOA) reflectance, use of invariant targets and application of a simple BRDF correction [3]. The BRDF correction was a simple linear function of scan angle and was applied to each band.

While this correction generally improved the radiometric match of images, there was considerable scope for improvement and a new correction has been developed using Landsat 7 imagery.

II. Data for model development

In this study, the parameters for the models tested were calculated using the Landsat 7 imagery itself using image overlap areas. The Landsat 7 imagery over the state of Queensland (QLD) spanned the July to December period so there were sufficient differences in the solar angles in the overlap areas to enable models to be fitted. Landsat 7 imagery covering the state of Western Australia (WA) was also used for later development and checking. All imagery had previously been purchased from the Australian Centre for Remote Sensing as a level 5 product and had been georeferenced.

The imagery was pre-processed by converting the Landsat ETM+ digital numbers (DN) to reflectance units. This correction aims to minimise variation due to varying solar zenith angles and incident solar radiation but it assumes the surface is Lambertian. Firstly, DN values are converted to radiance values (L) using the calibration coefficients α_λ and β_λ supplied in the imagery report file and equation (1):

$$L_\lambda = \alpha_\lambda DN + \beta_\lambda \ \ \mathrm{W/(m^2\,sr\,\mu m)} \qquad (1)$$

Once radiance values are calculated, the reflectance (ρ) is then calculated for each band as in Vermote *et. al.* [1]. Reflectance is calculated on a pixel by pixel basis for each scene using the scene corner coordinates, overpass time and acquisition date contained in the image report file:

$$\rho_\lambda = \pi\, d^2 L_\lambda / E_{0\lambda} \cos\theta_s \qquad (2)$$

where d = earth sun distance correction
L_λ = radiance as a function of bandwidth
$E_{0\lambda}$ = exoatmospheric irradiance
θ_s = solar zenith angle

A total of 215 overlap images for Queensland were created using north-south and east-west scene overlaps. Where multiple date images were available for the same scene, the overlaps covered the entire scene area. Solar zenith, relative azimuth and scan angle were calculated for every pixel in each overlap image.

Solar zenith and azimuth angles were calculated for the scene corners and interpolated for each pixel in the image using bi-linear interpolation. The orientation of the Landsat 7 images were extracted from the image header files and used to calculate relative azimuths. The relative azimuth was calculated by subtracting the solar azimuth from the azimuth of the image scan lines. The scan line azimuth was defined as the easterly direction of the scan line e.g approximately 100^o. The scan angle was calculated for each pixel in the image using the distance from the pixel to the nadir point of the same scan line in the image and the height of the Landsat 7 satellite. Scan angle was defined as positive in the easterly direction and negative in the westerly direction.

In order to minimise the real change component in overlap areas, areas of cloud, smoke and recent fire scars were masked. Crop areas usually contain considerable seasonal change so they were also masked. Where visual inspection showed considerable seasonal differences, overlaps were rejected.

Masks of land cover type and tree cover were used to mask the overlap areas. Statistics were then produced for each cover type, combination of cover types or tree cover range. Land cover masks produced by the SLATS project [4] using Landsat TM imagery included water, crop, bare, woody and non-woody vegetation. The tree cover data consisted of an index of foliage cover ranging from 0-100 percent.

Overlap statistics were created by dividing each overlap image into one degree scan angle strips, applying the land cover or tree cover masks, and calculating mean values for each ETM+ band, solar zenith, relative azimuth and scan angle. There were 1602 overlap strips.

III. BRDF MODEL DEVELOPMENT

A Landsat 7 mosaic covering most of QLD (78 scenes) was first produced using imagery corrected to TOA reflectance only. There were two systematic trends evident in the land areas of this mosaic. Firstly, the scenes in this mosaic were darker on the east side and brighter on the west. The likely cause is an illumination effect where more shadow is seen looking towards the sun and more illuminated surface is seen when looking away from the sun. Secondly, there seemed to be a trend where the images with increased solar zenith angle were darker. This indicated that there were effects that the TOA reflectance adjustment was not correcting, perhaps a shadow component due to surface texture. These trends are also likely to include a systematic atmospheric component. Since most of the differences between the satellite scenes and paths seemed to be systematic, the use of BRDF models to correct these systematic differences was investigated.

Walthall's [5] model seemed to most closely match our experience. Three variations of that model were tested. In equation (3), the Walthall model was modified by dropping the θ_v^2 term, as we hoped that the scan angle variation would be linear for the narrow Landsat (14.5^o) field of view. Early testing of this model suggested that the relationship with solar zenith angle was non-linear, so another version of this model, equation (4) was examined. The modification by Liang and Strahler [6] as in equation (5) was also tested:

$$f = a + b\,\theta_s + c\,\theta_v \cos(\varphi) \qquad (3)$$

$$f = a + b\tan(\theta_s) + c\,\theta_v \cos(\varphi) \qquad (4)$$

$$f = a + b\,\theta_s\,\theta_v \cos(\varphi) + c\,\theta_s^2\,\theta_v^2 + d\,(\theta_s^2 + \theta_v^2) \qquad (5)$$

where f = BRDF factor
a,b,c,d are model parameters
θ_s = solar zenith angle
θ_v = scan angle
φ = relative azimuth

Two approaches to application of this correction were examined: the ratio approach, and the residual approach. The ratio correction is applied as in equation (6) and the residual approach is described by equation (7). In this study, the ratio approach was used as it can preserve the scaling of the data, which allows simple comparison of results from different models. Values for f_{std} were calculated using standard values of θ_v,φ, θ_s which were $\theta_v=0^o$, $\varphi=30^o$, $\theta_s=45^o$.

$$\frac{f(\theta_{v1},\varphi_1,\theta_{s1})}{f_{std}(\theta_v,\varphi,\theta_s)}\rho_{\lambda 1} - \frac{f(\theta_{v2},\varphi_2,\theta_{s2})}{f_{std}(\theta_v,\varphi,\theta_s)}\rho_{\lambda 2} = 0 \qquad (6)$$

$$(\rho_{\lambda 1} - f(\theta_{v1},\varphi_1,\theta_{s1})) - (\rho_{\lambda 2} - f(\theta_{v2},\varphi_2,\theta_{s2})) = 0 \qquad (7)$$

where $\rho_{\lambda 1}$ and $\rho_{\lambda 2}$ are TOA reflectance for overlap images.

The model parameters were calculated by minimising the difference between the BRDF-adjusted values in the overlap areas. Uniqueness of the intercept term was obtained by also minimising the separate terms in (7), but with very low weights.

The models were compared by fitting each model to the overlap statistics which included all masked land areas. The effects of using a common set of coefficients for all scenes, and of using varying coefficients for each scene were examined first. While using coefficients for each scene seemed to produce good scene-to-scene matches, it did not remove the east-to-west illumination effect and it also removed some real changes. It was decided that a common set of coefficients should be used.

The fitting of these models to the QLD overlaps are compared in Table 1. North-south overlaps of same-date imagery were excluded from the calculation of the residuals and r^2 values. The units are eight bit values, similar in scale to the original DN values. The best fitting model was that given by equation (1). This result was confirmed by visual comparison of image mosaics after applying the three models. The models were also tested with WA Landsat 7 overlaps and with 1991 Landsat 5 TM overlaps covering QLD. Equation (1) was again the best. While there is not much difference in the model fits, equation (1) is favoured because it is consistently better, and it is the simplest equation.

The fitted model has two linear components. For the scan angle component, the BRDF factor increases with increasing scan angle and decreasing relative azimuth. i.e. it is maximal when the sun azimuth is parallel to the scan line and the pixel is at the image edge. The scan angle component also has a wavelength dependence. The correction is greatest in band 1, less in bands 2 and 3 and the least in bands 4,5 and 7. The solar zenith angle component of the correction is an overall scene brightness change related to the solar zenith dependence; it again varies in magnitude by band.

TABLE 1

MEAN ABSOLUTE VALUE OF OVERLAP RESIDUALS AND CORRELATION OF FITTED MODELS

Band	Equation 1		Equation 2		Equation 3	
	Mean residual	r^2	Mean residual	r^2	Mean residual	r^2
1	2.71	0.904	2.83	0.900	3.08	0.900
2	1.05	0.976	1.14	0.974	1.23	0.975
3	1.87	0.974	1.92	0.974	2.07	0.974
4	1.90	0.938	2.07	0.929	2.32	0.929
5	3.53	0.962	3.62	0.962	3.94	0.962
7	2.04	0.988	2.05	0.970	2.34	0.970

IV. LAND COVER EFFECTS

The SLATS land cover data was used to mask the imagery and provide overlap statistics for individual land cover types and tree foliage cover ranges. Statistics were generated for five groups. They were; water, non-woody, woody, bare and the combined class of all land surfaces except water. Crop, cloud and fire areas were excluded from all overlaps. The model given in equation (1) was fitted to each of these data sets and a set of parameters for each land cover type were estimated. These parameters have been used to generate Figures 1 and 2 which show the effect of land cover type on the two main components of the BRDF model. The BRDF factor for the "all land surfaces" class has not been plotted in these figures, but if shown, it would fall between the lines for non-woody and woody land cover.

Figure 1 shows the scan angle component. The BRDF factor is slightly different in magnitude but similar for land, woody and non-woody surfaces. Bare areas show significantly less BRDF effect than for the vegetated surfaces. Water areas showed the opposite effect to all other cover classes tested. The eastern side of the imagery was brighter than the west side. This is most likely due to glint off the water surface. The water parameters were calculated using the combined QLD and WA overlaps so that data from both the eastern and western coastlines were included. This helped remove any potential correlation between scan angle and water depth which increases away from the coastline.

The solar zenith component shows some variation due to land cover type. Bare and non-woody surfaces show the least variation. For this component water behaves similar to the more textured woody vegetation land cover. However, the solar zenith parameter for water possibly contains errors due to the differences in water colour from north to south.

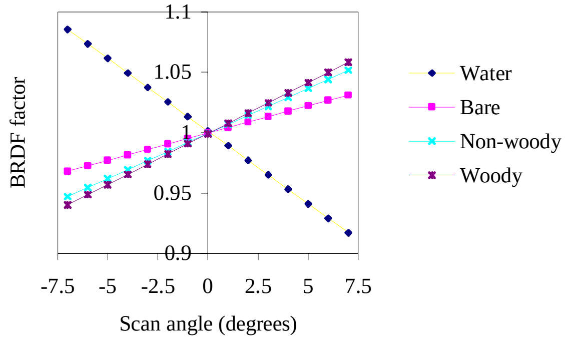

Fig. 1. BRDF factor for band 2 by land cover type at solar zenith 45° relative azimuth 30°

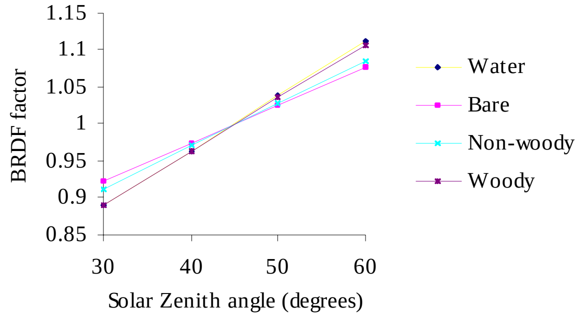

Fig. 2. BRDF factor for band 2 by land cover type at scan angle 0°

V. Comments on Application of the Model

The method developed has been applied to produce a continental Landsat ETM+ mosaic for Australia as described by Wu et. al. [7]. While it would be preferable to apply different parameters for each land cover type, this was not possible as a land cover mask, covering the continent at a suitable resolution was not available. A generalized correction based on all land surfaces was applied.

The resulting mosaic shows that the majority of differences between Landsat ETM+ imagery of different dates but with similar seasonal conditions are systematic and can be removed with the BRDF approach described here. A correction generalised for all land surfaces offers a considerable improvement in scene-to-scene radiometric match over a TOA reflectance adjustment.

Acknowledgment

The authors thank the Australian Greenhouse Office for provision of the WA imagery used in this study and its contribution towards the testing of methods.

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