Physically Based Evaluation of Reflected Terrain Irradiance in Satellite Imagery for Illumination Correction

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Abstract: Radiation field reaching a slope surface was modeled with three additive terms: direct solar irradiance, diffuse sky irradiance $E_d$, and reflected irradiance from adjacent terrain $E_t$. Most methods of topographic effect correction of satellite imagery, however, did not treat $E_t$ properly partly because exact calculation would require huge computation power. In this paper, we use a fast algorithms for generating viewshed to evaluate $E_t$. The path radiance as well as the attenuation of reflected terrain radiance between two adjacent slopes are also considered. To demonstrate the difference between approximate methods and the exact method, we use an Landsat ETM+ image and evaluate $E_t$ as well as $E_d$ of every pixel in the image.

Key Words: radiative transfer code, 6S, surface radiance, rugged terrain, sky view factor, viewshed calculation

1 Introduction

For estimating surface reflectance of a target point from satellite imagery, we have to evaluate various possible radiation and irradiation sources [1]. The radiance ($L_s$) of the point detected at sensor on board consists of reflected target radiance, path radiance ($L_p$) and background radiance ($L_b$) as

$$L_s = T_s \cdot \rho \cdot I_o/\pi + L_p + L_b$$

where $\rho$ is the target surface reflectance, $s$ is a sensor scan angle, $T_s$ is the transmittance from target to satellite, and $I_o$ is the target surface irradiance. $I_o$ is also broken down into direct solar irradiance, diffuse sky irradiance $E_d$ and reflected irradiance $E_t$ from adjacent slope as

$$I_o = E_o T_\theta \cos \beta + E_d + E_t$$

where $E_o$ is the solar radiance at top atmosphere, $T_\theta$ is the transmittance from sun to target, $\theta$ is the solar zenith angle, and $\beta$ is the angle between surface normal and solar beam.

Over rugged terrain, in particular, the direct solar irradiance varies with the incident angle $\beta$. The path-radiance depends on the surface altitude and the atmospheric condition [2]. Although these two sources are dominant, following sources shown in Fig.1 should be considered for precise illumination correction of satellite imagery:

1. Diffuse sky light $E_d$ varies with the orientation of the surface and may be reduced by the surrounding terrain.

2. Some reflection from adjacent surface gives additional irradiation $E_t$, if it is visible from the target surface.

Proy et al. [1] noted that the sky light can never be neglected in comparison with the direct solar irradiation, while the reflected irradiation can be neglected for well illuminated pixels. For extracting information of shadowed pixels ($\cos \beta < 0.3$), however, the reflected radiation must be considered. He suggested to avoid the heavy computation by working on images only with high sun elevation greater than 45°.

The reflected irradiance can be calculated using an exact method [1], or approximate methods [3]. Without a fast algorithm for viewshed generation, it is not practicable to compute the reflected irradiance of every pixel, because it requires knowledge of its visible area (viewshed). Most papers on topographic correction have avoided this problem and used the approximate methods [4], though they put more emphasis on the reflection correction [5]. It should be noted that the attenuation of reflected radiance and path radiance between two adjacent slopes have been ignored even in the exact method [1].

Wang et al.[6] calculated the reflected irradiation using the exact method based on the distribution of viewshed. However, as they assumed homogeneous
surface, advantage of the exact method was not exploited sufficiently. By using the digital numbers of the satellite image instead of the averaged radiation, Iikura [7] calculated the index of reflected irradiation and found the correlation (0.4) between the index and the digital number of shadowed pixels for infra-red bands. Iikura [8] also proposed the digital number based illumination correction with two constant correction parameters based on the exact calculation of $E_d$ and $E_t$.

In this paper, we estimate surface reflectance of mountaneous area using a Landsat ETM+ image. First, atmospheric parameters for the satellite image are estimated using an atmospheric radiation code (6S [11]) assuming the homogeneous landcover (beech forest). Altitude dependence of these parameters is considered. The digital number is converted to at-satellite radiance $L_s$ and then to at-surface radiance $L_s'$. Second, topographic effects are considered. The diffuse sky irradiance $E_d$ is modified by using sky view factor and Hay’s anisotropy model. The detailed physical model is introduced to calculate the reflected irradiance $E_t$ from adjacent terrain, which is the sum of attenuated surface radiance and path radiance. The diffuse sky light and reflected irradiance are calculated using fast calculation algorithms [9], [10]. Finally, surface reflectance is derived as $\rho = \pi L_s'/I_o$.

2 Atmospheric Parameter

2.1 Study area and used data

The Shirakami mountaneous region of northern Japan was selected for this study, which was designated as World Natural Heritage for its well preserved beech forest. A digital elevation model (DEM) from Japan Geographical Survey Institute was used to calculate topographical parameters after it was resampled onto the UTM coordinate system with 30 m ground resolution covering an area of 36km x 36km.

A Landsat ETM+ scene of June 30, 2002 (path 108, row 32) was used. For this satellite image, direct solar irradiance was simulated using the digital elevation model (slope angle $S$ and slope azimuth $A$) as well as the solar zenith angle $\theta$ of 26.2° and azimuth angle $\phi$ of 123.6° given in the system information.

$$\cos \beta = \cos S \cos \theta + \sin S \sin \theta \cos(\phi - A)$$
The simulated image shown in Fig.2(a) was used as an reference for geo-coding the satellite image [12],[13] and is used for illumination correction as well. The true-color composite of the satellite image and vegetation map are shown in Fig.2(b) and Fig.2(c) respectively. Beech forest assigned light green is the major vegetation of this region.

2.2 Surface reflectance of beech forest

In order to make rough estimate of the reflectance, single and multiple regression analysis were applied to the satellite data. The data were carefully selected to include only beech forest and to avoid the clouds and their cast shadows.

\[ DN = a_0 + a_1 \cdot \cos \beta + (a_2 \cdot DEM) \]

The results of the linear regression are shown in Table 1. Comparing the correlation coefficients \( r_1 \) and \( r_2 \), we can find that the effects of \( DEM \) are very small except for Band 1.

Table 1: Single and multiple linear regression analysis

<table>
<thead>
<tr>
<th>Band</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a_0 )</td>
<td>59.61</td>
<td>39.33</td>
<td>26.01</td>
<td>55.58</td>
<td>37.62</td>
<td>20.61</td>
</tr>
<tr>
<td>( a_1 )</td>
<td>3.73</td>
<td>11.83</td>
<td>7.15</td>
<td>79.66</td>
<td>63.71</td>
<td>24.55</td>
</tr>
<tr>
<td>( r_1 )</td>
<td>0.317</td>
<td>0.621</td>
<td>0.560</td>
<td>0.815</td>
<td>0.811</td>
<td>0.765</td>
</tr>
<tr>
<td>( a_0 )</td>
<td>64.09</td>
<td>40.62</td>
<td>27.14</td>
<td>57.64</td>
<td>35.10</td>
<td>17.50</td>
</tr>
<tr>
<td>( a_1 )</td>
<td>4.16</td>
<td>11.96</td>
<td>7.26</td>
<td>79.86</td>
<td>63.47</td>
<td>24.25</td>
</tr>
<tr>
<td>( a_2 )</td>
<td>-7.10</td>
<td>-2.04</td>
<td>-1.78</td>
<td>-3.26</td>
<td>3.99</td>
<td>4.93</td>
</tr>
<tr>
<td>( r_2 )</td>
<td>-7.10</td>
<td>-2.04</td>
<td>-1.78</td>
<td>-3.26</td>
<td>3.99</td>
<td>4.93</td>
</tr>
</tbody>
</table>

By putting \( \cos \theta = 0.897 \) to \( \cos \beta \) and the averaged altitude \( 677[km] \) to \( DEM \) in the multiple linear regression model, we obtained the averaged DN of the beech forest for flat terrain. This process is demonstrated in Fig.3, where the DN is plotted against \( \cos \beta \) with the estimated single regression line. The estimated DN of band 5 is 94.78, almost same as the case of the multiple regression analysis shown in Table 2.

The DNs were converted to at-satellite radiance \( L_s[W/(m^2 \cdot sr \cdot \mu m)] \) using offset \( b_0 \) and gain \( b_1 \) attached to the satellite data.

\[ L_s = b_0 + b_1 \cdot DN \]

The 6S code was used to estimate the reflectance of beech forest corresponding to the at-satellite radiance. As this process was done through a trial and error, there was a little difference in \( L_s \) between Table 2 and Table 3. The conditions were set to mid latitude summer atmosphere with marine type aerosol of 15 km horizontal visibility which was observed at the nearest meteorological station Fukaura. The target altitude was set to 0.677[km]. Table 1 shows the main atmospheric parameters calculated by the 6S code, where \( E_s \) and \( T_0 \) are newly introduced while others were explained previously. \( E_s[W/(m^2 \cdot \mu m)] \) is the direct solar irradiance for flat terrain and given as \( E_o \cdot T_0 \cdot \cos \theta \), and \( T_0 \) is the transmittance caused by scattering and it does not include the effect of absorption.

We can see that the atmospheric effects are more significant in the visible bands than in the infra-red bands, even if we take the low reflectance of these bands into consideration. This is explained by the Rayleigh scattering theory of molecule: the shorter the wavelength is, the stronger the scattering becomes. The negative altitude dependence of visible bands in Table 1 could be interpreted as the increase in the path radiance, though the transmittance effects inversely. In infra-red bands, the effect seems small or almost all the increase in the path radiance is compensated by the decrease of transmittance. Anyway, we need quantitative and pixel-based analysis on this issue.

Table 2: Averaged DN and radiance of beech forest

<table>
<thead>
<tr>
<th>Band</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>( DN )</td>
<td>63.01</td>
<td>49.97</td>
<td>32.44</td>
<td>127.09</td>
<td>94.75</td>
<td>42.60</td>
</tr>
<tr>
<td>( b_0 )</td>
<td>-6.20</td>
<td>-6.40</td>
<td>-5.00</td>
<td>-5.10</td>
<td>-1.00</td>
<td>-0.35</td>
</tr>
<tr>
<td>( b_1 )</td>
<td>1.176</td>
<td>1.205</td>
<td>0.939</td>
<td>0.965</td>
<td>0.190</td>
<td>0.044</td>
</tr>
<tr>
<td>( L_s )</td>
<td>67.91</td>
<td>53.81</td>
<td>25.46</td>
<td>117.6</td>
<td>17.05</td>
<td>1.513</td>
</tr>
</tbody>
</table>

Figure 3: Regression analysis of Band 5 and \( \cos \beta \)
### Table 3: Result of 6S simulation for beech forest

<table>
<thead>
<tr>
<th>Band</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho )</td>
<td>0.050</td>
<td>0.066</td>
<td>0.028</td>
<td>0.418</td>
<td>0.282</td>
<td>0.075</td>
</tr>
<tr>
<td>( L_s )</td>
<td>67.82</td>
<td>53.70</td>
<td>25.79</td>
<td>117.4</td>
<td>17.00</td>
<td>1.52</td>
</tr>
<tr>
<td>( L_p )</td>
<td>46.65</td>
<td>26.70</td>
<td>15.61</td>
<td>7.45</td>
<td>0.77</td>
<td>0.14</td>
</tr>
<tr>
<td>( L_b )</td>
<td>6.72</td>
<td>7.55</td>
<td>2.60</td>
<td>25.64</td>
<td>3.13</td>
<td>0.23</td>
</tr>
<tr>
<td>( E^{\text{sh}}_s )</td>
<td>979.7</td>
<td>985.4</td>
<td>886.6</td>
<td>629.7</td>
<td>146.8</td>
<td>51.9</td>
</tr>
<tr>
<td>( E^{\text{hd}}_s )</td>
<td>516.1</td>
<td>430.8</td>
<td>341.3</td>
<td>214.4</td>
<td>39.2</td>
<td>11.3</td>
</tr>
</tbody>
</table>

### Table 4: Path radiance and optical depth per km

<table>
<thead>
<tr>
<th>Band</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>( dL_p )</td>
<td>8.92</td>
<td>6.40</td>
<td>4.46</td>
<td>2.48</td>
<td>0.33</td>
<td>0.08</td>
</tr>
<tr>
<td>( d\tau )</td>
<td>0.060</td>
<td>0.054</td>
<td>0.051</td>
<td>0.047</td>
<td>0.038</td>
<td>0.034</td>
</tr>
</tbody>
</table>

#### 2.3 Altitude dependence of optical depth and path radiance

The path radiance and the transmittance depend on the altitude of the target in the satellite observation. The reflected terrain radiance is also modified by transmittance and path radiance in proportion to the distance between the target point and adjacent slope. To simplified these calculation, we estimate the optical depth \( d\tau \) and path radiance \( dL_p \) per distance at the averaged elevation by setting the target point (600m) and observation point (700m) in 6S simulation as shown in Table 2.

By using these parameters and the elevation \( h \) of the target, the at-surface-radiance for each pixel is estimated as follows,

\[
L_s^* = \frac{L_s - L_p - L_b + (h - h_0) \cdot dL_p}{T_s \cdot e^{(h-h_0)/d\tau}}
\]

where \( L_b \) is the back ground radiance, which is set constant in this research, though it changes according to the radiance of neibohood. The difference between \( L_s \) and \( L_s^* \) was statistically anlyzed for beech forest. As shown in Table 5, the mean difference is positive and is larger in visible bands, but the deviation increase inversely. The surface radiance can be greater than at-satellite radiance in some pixels of infra-red bands.

Figure 4 shows the true color composite of the surface radiance images, which is less hazy than the original image in Fig.2(b). It should be noted that the color contrast of the image was determined automatically based on the histogram in order to make fair comparison.

### Table 5: Difference between \( L_s \) and \( L_s^* \)

<table>
<thead>
<tr>
<th>Band</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{mean} )</td>
<td>44.4</td>
<td>24.6</td>
<td>15.3</td>
<td>3.12</td>
<td>0.32</td>
<td>0.03</td>
</tr>
<tr>
<td>( \text{s.d.} )</td>
<td>1.9</td>
<td>2.5</td>
<td>1.3</td>
<td>6.69</td>
<td>0.81</td>
<td>0.08</td>
</tr>
</tbody>
</table>

### 3 Irradiance estimation

The target surface irradiance \( I_o \) over rugged terrain consists of the direct solar irradiance \( E_s \), the diffuse sky light \( E_d \) and the reflected irradiance from adjacent slope \( E_t \) as

\[
I_o = E_s + E_d + E_t
\]

The direct solar irradiance is the product of solar irradiance at top-atmosphere \( E_o \), the cosine of incident angle/\( \beta \), and the transmittance from the sun to the target \( T_p \), where \( \theta \) is the solar zenith angle. The direct solar irradiance \( E^{\text{sh}}_s \) of flat surface at the averaged elevation is given in Table 3. Using the \( dL_p \) and \( d\tau \) in Table 4, It can be modified to obtain the direct solar irradiance \( E_s \) for rugged surface as follows

\[
E_s = E^{\text{sh}}_s \cdot \frac{e^{(h-h_0)/d\tau}}{\cos \theta \cos \beta}
\]

As the 6S assumes flat ground surface, there is no direct estimation of \( E_t \) and \( E_d \) should be modified.

#### 3.1 Diffuse sky irradiation

The diffuse sky irradiance is separated into an isotropic and an anisotropic (circular) component. The anisotropic component can be modeled for topography in the same way as the direct irradiance, though
it is part of the diffuse irradiance. On the other hand, the amount of isotropic diffuse radiance is a function of a sky view factor \( V_d \) which is the proportion of sky hemisphere not obstructed by topography. The sky view factor is expressed by

\[
V_d = \int^{2\pi}_0 \left[ \cos S \sin^2 H_\phi + \sin S \cos (\phi - A) \cdot (H_\phi - \sin H_\phi \cos H_\phi) \right] d\phi
\]

where \( H_\phi \) is an angle from zenith to horizon in the azimuth direction \( \phi \), and \( S \) and \( A \) are slope angle and slope aspect of the target pixel.

The proportion of the isotropic and anisotropic components depend on the atmospheric transmittance \( T_\phi \) caused by scattering. The lower the atmospheric transmittance is, the stronger the isotropic components of the diffuse irradiance becomes: the optical depth caused by absorption has nothing to do with this process. The total diffuse irradiance can therefore be calculated for rugged terrain by

\[
E_d = E^M_d \{ (1 - T_\phi) V_d \}
\]

We calculated \( H_\phi \) from zenith to horizon for 64 azimuth directions \( \phi \), and summed up the values to obtain \( V_d \). As this operation is to be performed on every pixel in the image and time consuming, a fast algorithm developed by Dozier and Frew [3] for one dimensional data was applied with slight modification [10] for two dimensional data.

The result was compared to that by the conventional approximation \( V_d = (1 + \cos S) / 2 \) where \( S \) is the slope. The standard deviation of the difference is 0.05, and significant difference are seen at the valley and hollow. According to the approximation, the \( V_d \) becomes 1 at the bottom of valley though it should have smaller value. The difference can be identified visually in Fig. 5. Even in the images after adjusting the contrast, these characteristics are obvious. This approximation should not be used.

On the other hand, the number of direction can be reduced in the exact method. It was noted that 8 azimuth direction seemed sufficient. The algorithm was implemented using the IDL Ver.7.1 on Mac Pro (Quad-Core Intel Xeon 2.66 GHz). It took only 13 seconds for calculating \( V_d \) for one direction.

### 3.2 Reflected irradiation

Under the circumstance depicted in Fig.1, radiation from pixel \( P \) contributes to the irradiation at the target pixel \( M \) as [1]

\[
E_{PM} = (L_{PM} dS_M \cos T_M dS_P \cos T_P) / r^2
\]

where \( dS_M \) and \( dS_P \) denote the areas of pixel \( M \) and \( P \), \( T_M \) and \( T_P \) are angles between surface normal and line \( MP \), \( r \) is a distance between pixel \( M \) and pixel \( P \).

If we assume the Lambertian surface, the surface radiance \( L_s(P) \) at \( P \) can be used as the radiance directed to the target point \( M \). When the radiation reaches the target point, the radiance is attenuated but is added by the path radiance. Although the path radiance and optical depth per km in Table 2 are calculated for vertical distance, we apply them to calculate \( L_{PM} \) as follows

\[
L_{PM} = L_s(P) \cdot e^{-r\tau} + r \cdot dL
\]

where \( L_s(P) \) is the surface radiance at the point \( P \).

The reflected radiance at pixel \( M \) is the sum of \( L_{PM} \) for pixels which are visible from \( M \), that is, viewshed of \( M \).

\[
E_d = \sum_P L_{PM}
\]

Even using the fast algorithm [9] written in IDL, viewshed generation took more than 2 seconds for one target pixel. So we transplant the algorithm to Fourier code and compile it by gfortran with optimization option O2. To calculate the reflected radiance of the image, four process were generated in...
Mac Pro. It took 16 hours to finish the central part of the image of 1000 x 1000 pixels as shown in Fig. 6. Please note that the reliability of \( E_t \) is higher at the center than at the edge of the image.

The reflected irradiance is often approximated by using a terrain configuration factor \( V_t \) by

\[
\tilde{E}_t = \pi V_t \tilde{L}_s
\]

where \( \tilde{L}_s \) is the averaged radiance reflected from the surrounding terrain. The terrain configuration factor was calculated during the calculation of the \( E_t \) for six bands by setting \( L_{PM} = 1/\pi \), though it can be calculated as in the sky view factor calculation. It should be also noted that the distance from adjacent terrain to a target and its radiance are not considered in these approximation using \( V_t \). These characteristics are important in determining the radiation from adjacent terrain, since a nearby visible area gives more radiation compared with distant ones [6].

In Fig. 6, we compare the visual difference between (a) the approximate method and (b) the exact method. Though the difference is small as compared with Fig. 5, we can see that the surface radiation such as clouds is effecting the pattern of the reflected terrain irradiance. \( V_t \) is further approximated by \((1 - \cos S)/2\) as in the case of the sky view factor, which should not be used as well.

### 3.3 Validation of the calculation

We will check the validity of the calculation of sky view factor and terrain configuration factor as well as the 6S simulation. By definition, the sum of these two factors should be unity though the calculation method is different: \( V_d \) was based on the horizon in several directions, while \( V_t \) was based on the viewedshed calculation. Figure 7 is the histogram of these parameters for beech forest. The statistics of these values are shown in Table 6. We can see that there remains a little bias and deviation in the sum. The statistics of \( E_t \) by the exact calculation for every band are shown in Table 7.

Table 6: Statistics of \( V_d \) and \( V_t \)

<table>
<thead>
<tr>
<th></th>
<th>( V_d )</th>
<th>( C_1 )</th>
<th>( V_d + C_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean</td>
<td>0.8606</td>
<td>0.1305</td>
<td>0.9910</td>
</tr>
<tr>
<td>s.d.</td>
<td>0.0720</td>
<td>0.0782</td>
<td>0.0269</td>
</tr>
</tbody>
</table>

By using the calibration coefficients and the atmospheric parameters shown in Table 2 and Table 3, we can calculate the regression coefficients by

\[
a_0^* = [T_s \rho \{(E_s^0(1 - T_0^0) + E_t)/\pi + L_p + L_b - b_0\}]/b_1
\]

\[
a_1^* = [T_s \rho \{(E_s/\cos \theta + E_d^0 T_0^0)\}/\pi]/b_1
\]

where the anisotropy of the diffuse sky radiance is considered.

The results are shown in Table 8. The slopes \( a_1 \) are larger than those obtained by the actual regression analysis in Table 1, while the intercepts show the opposite trends. The difference is especially large in Band 1.

### 4 Illumination correction

Now we have obtained three components of surface irradiance \( I_o \): the direct solar irradiance \( E_s \), the diffuse sky irradiance \( E_d \), and the terrain reflected irradiance \( E_t \). By using the surface radiance \( L_s \), we can calculate the reflectance \( \rho = \pi L_s^0/I_o \) for every pixels at the surface.

In Fig. 9, we show the true color composite of

![Figure 6: Terrain configuration factor \( E_t \) for Band 3](image_url)
reflectance $\rho$ image. Though we can see that the shading of the image is much more mitigated in comparison with Fig. 4, blue color (Band 1) is enhanced in the shaded region in Fig. 4, which means over correction of the image. In this case, the correction seems excellent visually.

The statics of the estimated reflectance are summarized in Table 9. Compared to Table 1, the difference of the reflectance is large for Band 1 and Band 2. It should be also noted that the coefficients of variation (%) in the visible bands is greater than those in the infra-red bands.

For evaluating the contributions of the sky view factor $V_d$ and the reflected irradiance $E_t$ more quantitatively, it is convenient to normalize them to the value relating to the direct solar irradiance:

$$E_s^h \cos \theta + E_d^h T_\theta$$

By using normalized component $C_d$ and $C_t$, the total irradiance $I_o$ is expressed as

$$I_o = (E_s^h \cos \theta + E_d^h T_\theta)(\cos \beta + C_d + C_t)$$

The statistics of $C_d$ and $C_t$ are shown in Table 10. The contribution of $E_d$ decrease as the band number increases, while $E_t$ is small and depends mainly on the magnitude of reflectance.

## 5 Conclusion

In this paper, we proposed the estimation method for the reflected terrain irradiation, which was based on a strict physical model utilizing the fast viewshed calculation algorithm.

By integrating the method into other atmospheric and topographic parameter estimations, we have obtained the surface reflection images. Although there still remains some inconsistency between the actual data analysis and simulation data analysis, the reflection the images shows less shading than the original image except for Band 1. Although the contribution of the reflected irradiance $E_t$ is small, it is important...
Figure 9: Pseudo color composite of infra-red bands to improve the quality of the estimate and inevitable to analyze the shaded pixels.

The consideration of bidirectional effects and background radiance is beyond the scope of this study, but should be examined and treated appropriately.

References:


