Comparision of Eight Topographic Correction Algorithms Applied to Landsat-8 OLI Imagery Based on the DEM

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Abstract. Topographic correction is one of the most important procedures for remote sensing image preprocessing, and it is also the premise for quantitative remote sensing. According to the latest calibration parameters provided by the USGS website, four Lambert body reflectance models and four Non-Lambert body reflectance models were used to carry out the topographic correction combining the DEM data in R platform. A total of three indicators were used to assess the effects including visual contrast, normalized evaluation of shady slopes and sunny slopes, and linear fitting. The results show that the corrected image of Cosine correction method based on the Lambertian reflectivity model is visually overexposed, and the DN value on the shady slope is over-corrected. The corrected images of Minnaert and Minaret-scs based on the Non-Lambertian reflectivity model visually reduce the amplitude of the terrain fluctuations, and the linear fitting has a small separation factor, which produces a better correction effect.

1. Introduction
Remote sensing technology is an effective means to quickly obtain large-scale vegetation distribution information. However, in mountainous and hilly areas, the accuracy and objectivity of remote sensing technology acquisition information are affected by many factors. Topographic fluctuation is an important factor that restricts the accuracy of surface information extraction. Affected by topographic relief, the same features exhibit different brightness values, which makes the spectral features of the same species on the shady and sunny slopes significantly different, and the phenomenon that "the same object has different spectra and different objects have the same spectrum" appears, this will not only challenge the accurate classification of remote sensing, but also affect the accuracy of surface reflectivity inversion. Some remote sensing works also mention that the influence of terrain slope and aspect on the recorded sensor signal response will adversely affect remote sensing image analysis [1,2,3].

Eliminating the effects of terrain relief can be achieved by topographic correction. Topographic correction refers to transforming the radiance of all pixels into a certain reference plane (usually taking a horizontal plane) through various transformations, thereby eliminating the variation of the image radiance value caused by the terrain fluctuations, make the image better reflect the spectral properties of the object. Jensen think topographic correction is an important part of remote sensing information extraction in complex terrain areas [4]. In quantitative remote sensing, the spectral information of objects on the surface of the Earth is an important basis for quantitative calculation. In the case that the mountainous area of China accounts for 70% of the total land area, accurate topographic correction is an indispensable prerequisite for any remote sensing application.

The Landsat-8 of Landsat series is currently the newest satellite for earth observation, and it is
necessary to preprocess the landsat8 image. The atmospheric correction algorithms for Landsat imagery have been already proposed and analyzed by dozens of authors [5,6,7]. Compared with the large amount of atmospheric and radiometric correction algorithms proposed and validated, there is relatively few studies on the topographic correction. This can be partially explained by the two reasons. One is that, high-resolution digital elevation models (DEM) have been made available only for less than one decade such as the SRTM and ASTER DEM [8], the other is that the degree of terrain fluctuations is different, the most appropriate correction method for a particular situation cannot be identified. The explanatory nature of the R language makes the modification and testing procedures very convenient and simple. The Landat-8 OLI multi-spectral image of in Huangshan City, Anhui Province, China, was selected as the test data, and two types of topographic correction methods based on Lambert and non-Lambert surfaces are implemented in R in combination with digital elevation model (DEM) data.

2. Materials and Methods

2.1. Study Area
Huangshan City is located in the northern subtropical zone. It has a humid monsoon climate with the mild and rainy weather and distinct four seasons. The annual average temperature is 6 °C-15 °C. In most areas, there is no severe cold in winter, and the frost-free period is 236 days. The average annual precipitation is 1670 mm, the highest is 2708 mm, and the precipitation is mostly concentrated in May to August. There are many types of topography and land-forms, mainly middle and low mountains and hills. The altitude of the mountain is generally 400-500 meters, and there are many peaks above the kilometer. The mountain area is 5,000 square kilometers, accounting for 51% of the total area; the hilly area is 3,540 square kilometers, accounting for 36.1% of the total area; the valley and basin area is 1,267 square kilometers, accounting for 22.9% of the total area. There are three types of terrain in the city: the northern part, the terrain is high in the south and the north is low; the southern Xin'an River valley is surrounded by mountains, the central terrain is low, it is a small basin; the western hilly area is high in the north and low in the south, and the hills are densely covered.
2.2. Data Acquisition and Image Preprocessing

Landsat-8 can collect a total of 725 scenes a day (Landsat-7 collects 438 scenes per day), which increases the probability of capturing cloudless images from the global continent. The Landsat-8 scene is 185 kilometers in length, spanning 180 kilometers along the track, and the height of the spacecraft is 705 kilometers [9]. The Landsat-8 remote sensing image data used here is from the USGS (https://earthexplorer.usgs.gov/). The imaging time of the selected image is October 9, 2018. The DEM image selects the 30-meter elevation data in the same area. After installing the sp, rgdal, and xlsx packages in R, a 600×600 pixel subset was selected and the readGDAL function was used to obtain the data in the SpatialGridDataFrame format. Radiation calibration was performed on the data before topographic correction, radiometric calibration is to convert the recorded original digital value (DN) into the surface reflectivity of the outer layer of the atmosphere, in order to eliminate the error generated by the sensor itself. There are various methods: laboratory calibration, on-board calibration, and Site calibration. According to the formulas and parameters provided by the Landsat-8 website, the DN value can be converted to the atmospheric top reflectance by the formula (1).

\[
\rho_{\lambda'} = M_{\rho} \rho_{\text{cal}} + A_{\rho}
\]  

(1)

Where \(\rho_{\lambda'}\) is the atmospheric top reflectance corrected without the solar angle, \(M_{\rho}\) is the reflectance adjustment factor of the band \(\lambda\), and \(A_{\rho}\) is the reflectance adjustment parameter of the band. \(\rho_{\lambda'}\) is the top reflectance through the correction of the solar elevation angle.

2.3. Experimental Methods

Since the 1980s, researchers at home and abroad have established a variety of topographic correction models to reduce or eliminate the influence of topographical factors in mountain remote sensing images. These models can be roughly divided into three types: band ratio based method, DEM based method and hypersphere based method. Among them, the DEM based method includes the Lambert body reflectance model and the Non-Lambert body reflectance model.

Here are three forms of reflection of electromagnetic waves on the surface of an object: Specular reflection (mirror), diffuse reflection (Lambertian surface), and directional reflection between the two (Non-Lambertian surface). Specular reflection means that the reflected energy is concentrated in one direction, and the reflection angle is equal to the incident angle; the uniform reflection of the entire surface to the incident light is called diffuse reflection; directional reflection is between specular and diffuse reflections, reflecting in all directions, and the intensity of the reflection is not uniform. When remote sensing applications enter the quantitative analysis phase, we must abandon the assumption that the goal is the Lambert. For Non-Lambert body, its ability to reflect and scatter short-wave radiation varies not only with wavelength but also with spatial direction. The so-called ground spectrum characteristic refers to the law that the reflection and scattering ability of the object on the ground changes with the wavelength. The spectral characteristics of the ground object are closely related to the composition of the ground object and the structure inside the object. The directional characteristic of the ground object is used to describe the spatial scatter ability of the ground object to the solar radiation. This spatial variation feature is primarily dependent on the surface roughness of the object.

Dr. Reeder from Dartmouth University in the United States performed the regression analysis of the brightness value of the Landsat TM 4 image in the broad-leaved deciduous forest area of Grand and the cosine, slope and elevation of the incident angle \(i\). It is found that the digital value is highly correlated with the \(\cos i\), and the correlation with the slope and elevation is relatively low [10]. Other researchers have also found a high correlation between the cosine of the incident angle of the sun and the brightness value of the image, and believe that once the angle of incidence of each pixel of the image is determined, the pixel brightness value can be corrected [11-12]. Therefore, establishing the correlation coefficient between the cosine of the incident angle of the sun and the wavelength response of the established band of the remote sensing image has become an effective means to evaluate the topographic effect of the remote sensing data of complex terrain satellites. The cosine of the incident angle \(i\) is also used to correct the terrain effect.
The angle of incidence is calculated according to formula 2, where $i$ is the incident angle, $\theta$ is the solar zenith angle, $\alpha$ is the slope angle, $\varphi$ is the solar azimuth, and $A$ is the slope direction.

\[
\cos i = \cos \theta \cos \alpha + \sin \theta \sin \alpha \cos (\varphi - A)
\]  

(2)

### 2.3.1. Lambert Body Reflectivity Model

1. **Cosine**

   The cosine correction model was proposed by Teillet [13]. The basic principle is that the corrected radiation received by the horizontal plane pixel and the radiation received by the corrected front slope pixel has a proportional relationship determined by the cosine of the solar incident angle. The cosine correction model is expressed as the following formula:

\[
L_{\text{H}} = \frac{L \cos \theta}{\cos i}
\]  

(3)

2. **Gamma**

   Based on cosine correction, Richter JR proposes to increase the sensor's viewing angle on both planar($\gamma$) and sloping terrain($\beta$), and to calculate horizontal reflectance based on sun and terrain angles [14]. This is another attempt to reduce overcorrection in areas with low illumination.

\[
L_{\text{H}} = \frac{L \cos \theta + \cos \gamma}{\cos i + \cos \beta}
\]  

(4)

3. **SCS**

   Gu considered that the correction algorithm based on the solar-surface-sensor geometry relationship is unreasonable [15]. They believe that regardless of the terrain, the trees grow vertically, and the canopy of the trees is not consistent with the direction of the terrain. Therefore, it is not appropriate to use the geometric relationship between the slope and the aspect of the terrain to correct the spectral reflectance characteristics of the vegetation canopy. Therefore, starting from the canopy of vegetation, the SCS (solar-canopy-sensor) correction algorithm is proposed.

\[
L_{\text{H}} = \frac{L \cos \theta \cos \alpha}{\cos i}
\]  

(5)

4. **SCS-c**

   Since the SCS model does not take into account the scattering properties, Soenen used the idea of C correction to introduce a semi-empirical parameter C for scattering radiation regulation [16]. Improve the SCS model to the SCS+ C model.

\[
L_{\text{H}} = \frac{L \cos \theta \cos \alpha + C}{\cos i + C}
\]  

(6)

### 2.3.2. Non-Lambert Body Reflectivity Model

1. **C**

   For the Cosine correction to ignore the scatter radiation defects, Teillet improved the Cosine correction and proposed a C correction. C correction is an empirical correction using the pixel luminance value and the cosine of the incident angle of the sun [13]. A new parameter (c) is generated by establishing a regression equation between the two and using the ratio of the intercept (b) to the slope (m) of the regression equation.

\[
L_{\text{H}} = \frac{L \cos \theta + C}{\cos i + C}
\]  

(7)

2. **Minnaert**
Based on the shortcomings of the Lambert's hypothesis, Smith introduced the empirical photometer function constant $k$ after considering the roughness of the ground in the topographic correction algorithm, and proposed a non-Lambertian reflectivity model, the Minnaert correction model [17]. The $k$ is the Minnaert constant, which was proposed by Minnaert in 1941. The $k$ value is between 0 and 1. When the local surface is Lambert, the $k$ value is 1, otherwise it is less than 1. It is mainly determined by regression method.

$$L_{\text{M}} = L \frac{\cos \alpha}{(\cos i \cos \alpha)^k}$$

(3) Ekstrand-e

In 1996, Ekstrand introduced the solar zenith angle $\theta$ and the reflection angle $e$ to develop the Minnaert correction to Ekstrand-e correction [18]. The cosine of the reflection angle $e$ represents the instantaneous field angle effect of the inclined surface, as the slope of the inclined surface increases, the surface area obtained by the sensor's instantaneous view will also increase.

$$L_{\text{E}} = L \cos e \left( \frac{\cos \theta}{\cos i \cos e} \right)^k$$

(4) Minaret-scs

Vincini found that there is a high correlation between the $c$ value in the C correction and the $k$ value in the Minnaert correction, and the correlation coefficient is as high as 0.99 [19]. In 2002, Reeder considered the correlation between the $c$-value and the $k$-value and the instantaneous field of view [10]. It is considered feasible to eliminate the reflection angle $e$ in the Ekstrand-e correction model. At the same time, considering the simplified Minnaert correction algorithm, the slope angle is introduced, and the Minnaert correction is developed into the Minnaert-SCS correction.

$$L_{\text{M}} = L \cos \alpha \left( \frac{\cos \theta}{\cos i} \right)^k$$

3. Results and Analysis

3.1. Visual Contrast

The implementation of several calibration methods is based on the slope and aspect of the DEM calculation. The slope is the degree to which the surface unit is steep. Usually, the ratio of the vertical height to the horizontal distance of the slope is called the slope. The slope calculation is generally based on the fitted surface method. The fitting surface generally uses a quadric surface, that is, a $3 \times 3$ window, and the center of each window is an elevation point. Aspect refers to the orientation of the terrain slope. The aspect is used to identify the downhill direction with the highest rate of change from the value of each cell to its neighboring cell. The aspect can be considered as the slope direction. The aspect is an angle that will be measured in a clockwise direction between 0 (positive east) and 360 (still east). The original DEM data derives the slope and aspect data of the DEM in R as shown in Figure 2.
Eight topographic correction methods are implemented based on slope and aspect data:

\[
\text{Band2Cosine} \leftarrow \text{Lambertian}(\text{Band2rad}, \text{DEMslope}, \text{DEMaspect}, \text{sunelev}=49.17, \text{sunazimuth}=150.55, \text{method}=\text{"Cosine"})
\]

\[
\text{Band2c} \leftarrow \text{NonLambertian}(\text{Band2rad}, \text{DEMslope}, \text{DEMaspect}, \text{sunelev}=49.17, \text{sunazimuth}=150.55, \text{method}=\text{"C correction"})
\]

Can be seen from the uncorrected image and the corrected image comparison chart: each correction method produces a correction effect, but different correction methods produce different effects. Cosine correction appears to be overexposed where the sun's angle of incidence is very low. The corrected images of SCS-c, C and Ekstrand-e still have strong stereoscopic three-dimensional effects, and the correction effect is not ideal. Correction by Minnaert and Minaret-scs reduces the extent of terrain fluctuations to a certain extent, making the corrected image look more like a "plane". This is the concept of topographic correction: the visual effect of transforming the radiance of all pixels onto a reference plane (usually taking a horizontal plane). It shows that these two methods better eliminate the change of digital value caused by terrain fluctuation.

3.2. Normalized Evaluation of Shady Slopes and Sunny Slopes
The undulations of the terrain cause same objects to exhibit different brightness values, especially in
mountainous areas, where the brightness values of the Shady and sunny faces of the mountain vary greatly. This is a major problem affecting the classification of remote sensing images, and topographic correction is to solve such problems. In order to test the effect of the correction, 10 points of shady slope and sunny slope were selected on the image, and the DN values of the images of the 5, 6 and 7 bands with obvious terrain fluctuations were selected and counted (Figure 4).

![Figure 4. Comparison for Normalization of Sunlit and Shadow](image)

Before the correction, there is a very large gap between the DN values of the shady slope and the sunny slope. After several correction methods, it can be seen that the DN value of the shady slope of the image after Cosine correction is greater than the sunny slope, indicating that there is excessive correction. The DN values of the images after SCS-c correction and C correction still have a very large gap, and the corrected images of Gamma correction and Ekstrand-e correction methods have not been significantly improved. SCS correction, Minnaert correction and Minnaet-scs correction significantly improved the difference in DN values between the shady and sunny slopes.

3.3. Quantitative Analysis of Linear Fitting

In order to further objectively evaluate the quality of image correction, this paper uses a linear fitting method to evaluate. According to the basic idea of C correction, if the DN value of the pixel is no longer affected by the change of the incident angle of the sun for the corrected image, then the linear regression fit, the slope of the equation should be small, and the smaller the slope value, the better the effect of the corrected image. McDonald E R proposed that a separation factor $r^2$ can be used to evaluate the correction effect [20]. The smaller the coefficient, the better the correction effect, and the evaluation formula is

$$r^2 = \left(\frac{b}{a}\right)^2$$  \(11\)

A total of 1200 pixels are randomly selected from different land cover types. The reflectance values of the original image and the corrected image are linearly fitted to the cosine of the solar incident angle (Figure. 5). Before the topographic correction, the DN value of the image of the sample area changes obviously with the change of the incident angle of the sun, and the DN value of the corrected image decreases significantly with the incident angle of the sun. Table 1 lists the slope value and
separation factor $r^2$ of the linear fitting line of the image DN value before correction and after correction by eight correction methods. It can be seen from Table 1 that the absolute value of the slope value of the straight line of the DN value of the image corrected by Gamma and Minaret-scs is small, and the separation coefficient of Minaret-scs is almost 0, indicating that the correction effect is better. This indicates that the DN value of the corrected image of this method is hardly affected by the terrain fluctuation, and the correction effect reaches the target. Among them, the Cosine correction appears to be overcorrected when the cosine of the incident angle of the sun is close to zero, and the DN value of the corrected image reaches 60 or more. However, the image DN value corrected by other correction methods remains uniform over the incident angle range, and this is not the case.

![Figure 5. Comparison for Fitting Results between DN and Incident Angle Cosine cos i](image)

**Table 1. Comparison of the Image Processing Results**

| Correction Methods   | Slope(b) | Separation Factor($r^2$) |
|----------------------|----------|--------------------------|
| Uncorrected          | -6.99    | 0.056                    |
| Cosine correction    | -5.05    | 0.016                    |
| Gamma correction     | -2.71    | 0.019                    |
| SCS correction       | -3.43    | 0.010                    |
| SCS-C correction     | -6.79    | 0.050                    |
| C correction         | -6.34    | 0.047                    |
| Minnaert correction  | -5.12    | 0.031                    |
| Ekstrand correction  | -4.86    | 0.028                    |
| Minaret-scs correction | -3.60 | 0.004                    |

**4. Conclusion**

The topographic correction results of eight algorithms are evaluated from three aspects: visual comparison, normalized evaluation of shady slope and sunny slope, and quantitative analysis of linear fitting. Among them, because the Cosine correction model is based on the surface reflection as the Lambert hypothesis, and ignores the effects of sky diffuse scattering and reflected radiation from surrounding terrain, therefore, the phenomenon of overexposure appears visually, and anomalies occur in the DN values of the shady slope and the sunny slope. Minnaert and Minaret-scs visually reduce the amplitude of the terrain, making the image look more flat, and the difference in DN between the shady
and sunny slopes is reduced, the linear fitting has a low separation factor and achieves a better correction. Existing topographic correction models have been over-corrected or undercorrected in ridges and valleys. Mainly due to the error in the calculated terrain factor of the DEM matching the remote sensing image, the application of high spatial resolution DEM data is expected to reduce this problem. Most models of topographic correction are based on the Lambert assumption of surface reflection, ignoring the effects of geometric relationships. However, the surface is usually a Non-Lambertian reflective surface. Although the Non-Lambertian reflection model introduces coefficients to describe the Non-Lambertian properties of the surface, these coefficients depend on factors such as the band, phase angle, and surface cover type, this affects the wide application of these models. In addition, you can consider eliminating the effects of the atmosphere before doing topographic correction, so the effect of topographic correction may be improved.

5. Acknowledgements
This work was supported by the Natural Science Research Project of Anhui Provincial Education Department (KJ2018A0009), Anhui Provincial Major Scientific and Technological Special Project (17030701062) and National Key Research and Development Program of China (2016YFD0800904).

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