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A GLOBAL TOPOGRAPHIC NORMALISATION ALGORITHM FOR SATELLITE IMAGES

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ABSTRACT:
Topographic normalisation, i.e. the elimination of shading due to sun illumination and terrain elevation is regarded as a useful pre-processing step to image analysis, in particular to multispectral classification. Though a strict solution has to concentrate on the individual object classes because of their class-related directional reflectances, we suggest to perform an improved global topographic correction of the whole image scene in order, for instance, to facilitate the pre-classification that may be input to a more refined class-specific normalisation process. The model presented here is based on Minnaert’s theory, as many others do, but extended by a simple skylight term. The algorithm has been developed for highly automatic determination of the model’s parameter by a least squares approach assuming a similar distribution of reflectance intensities within all categories of incident lighting angles. Though rather simple this augmentation is of particular importance for short wave channels where atmospheric scattering predominantly influences the image contrast and brightness and where models without skylight term fail. Examples applied to LANDSAT TM pictures of mountainous, heavily shaded areas of the Alps prove the suitability of the approach.

KURZFASSUNG:

1. INTRODUCTORY REMARKS

The interpretation of satellite imagery is quite often heavily influenced by shading effects caused by the terrain relief. In case of supervised classification, for instance, the image analysts are forced to select several training areas for the same object class in order to take into consideration the various spectral signatures caused by the different illumination. Theoretically one training sample per class for each slope category are to be found. Besides the possibility of choosing that many samples, the interpreter faces the problem of being unable to find the correct areas even visually. The ideal image for interpretation would be one of a surface diffusely and uniformly illuminated, without any atmospheric influence, observed perpendicularly to a horizontal reference plane and indenpent of the terrain slope. The aim of topographic normalisation is to create that sort of ideal image out of the actual given image.

This problem brought up the idea to develop a method for a radiometric correction as a function of the sun incidence angle to the terrain surface as well as of the observation angle. Many publications are the result of those investigations and research [e.g: Colby 1991, Meyer et al. 1993, Conese et al. 1993, Ekstrand 1996, Sandmeier 1997]. The predominant obstacle for an accurate solution lies in the undefined or at least not well defined reflection behaviour of the object classes. The theoretically ideal reflection property is described by the reflectance \( \rho \). The actual reflectance is dependent on the wavelength (i.e. \( \rho \) becomes \( \rho(\lambda) \)) and more severely, also on the lighting and observation direction. The reflectance properties are therefore best described by the so-called bidirectional reflectance distribution function (BRDF) \( \rho(\lambda, \theta_i, \phi_i, \theta_e, \phi_e) \), where the indeces \( i \) and \( e \) denote the Incident and exitant ray, respectively, and \( (\theta, \phi) \) the incidence angle and the incidence azimuth. As the BRDF is usually unknown or hardly determinable in practice the directional reflectance is more feasible \( \rho(\lambda, \theta_i, \phi_i) \) [Kraus et al., 1988]. In any case all reflectance functions are class dependent. That means, if applied for performing radiometric corrections, the object classes have to be known in advance as they are input to the correction algorithm. On the other hand the radiometric correction should help to facilitate the determination of the object classes. This basic contradiction demonstrates that the task of radiometric correction due to illumination effects is not trivial at all. Even the most sophisticated model will not be able to perform the procedure in one single step, it will always be an iterative approach.
2. THEORETICAL BACKGROUND

In practice a few assumption have to be made in order to be able to make a correction model feasible. The most important prerequisite is defining the object as an approximate Lambertian surface. This comes close to the actual reflection behaviour in many cases, in particular for imagery taken with sensors whose "poor" resolving power is not able to distinguish between small object details. Minnaert [1941] developed a simple BRDF (1) for correcting the shading and illumination effects of celestial bodies by slightly modifying the rules that would apply for ideal Lambertian surfaces.

\[
g_{\text{corr}} = \frac{g_{\text{org}} \cdot \cos^s(\theta) \cdot \cos^{s-1}(e)}{\cos^s(\theta) \cdot \cos^s(e)}
\]

where \( g \) are the greyvalues of the original image and the corrected image, respectively. \( k \) is the so-called Minnaert constant, the unknown that has to be determined. \( i \) is the incidence angle of the illuminating light beam and \( e \) is the exitance angle, which is approximately the terrain slope assuming a very narrow field of view, so that the observing direction is more or less constant over the entire sensed area and perpendicular to a horizontal plane. In the case of the common Earth observation satellites, such as Landsat TM, SPOT or IRS this assumption is justified. If the sun position is known for the given acquisition time and date, \( i \) as well as \( e \) can be calculated with the help of a terrain model. One can see that for \( k=1 \) Minnaert’s formula corresponds to the Lambertian reflection behaviour.

Though this simple approach cannot fulfil the reality, it is commonly used and/or slightly modified on the one hand, on the other hand it is rejected by those researchers who clearly see the limitations and who aim at a more universal and physically based solution. Our opinion is that a satisfying and thorough model is still far from realisation. Too many influences with hardly determinable parameters, such as mutual illumination of objects, atmospheric effects like skylight or airlight, deteriorate the radiance of the object surface leading to the impossibility of obtaining the characteristic spectral properties from the acquired grey-values with feasible effort.

3. THE EXTENDED MINNAERT MODEL

In order to find a rather primitive and generally applicable, though still approximate, algorithm we propose an extended Minnaert approach, whose parameters can be determined from the original greyvalues of the image, the digital terrain model, and a few assumptions that might look obscure at the first sight although, as the experience shows, are fulfilled in many cases.

Firstly, a few considerations should give some hints how the Minnaert model could be extended:

a. Satellite images show low contrast in the short wave channels due to skylight. Even not directly illuminated regions (i.e. areas with sun incidence angles greater than 90°) appear to be illuminated. This illumination is not that apparent in infrared, for instance.

b. The above Minnaert model applies a multiplication factor (in other words a contrast enhancement factor) to the original greyvalues that is inversely related to the cosine of the incidence angle. In any case this factor for incidence angles towards 90° becomes infinite very rapidly independent of the actual contrast between directly illuminated parts and unilluminated regions.

c. In (1) the correcting influence of the exitance or observation angle is strictly connected to the incidence angle and is solely driven by the magnitude of the Minnaert constant \( k \). Only in case \( k=1 \) an influence of the observation direction does not exist.

ad a: The skylight influence must not be neglected even by a simple model, otherwise the result will never be satisfactory in particular in the short wave ranges. (We shall see later that the entire visible spectrum is more or less heavily subjected to skylight). Therefore, the improved model must contain a parameter that is able to adjust to the actual influence of skylight or ambient light.

ad b: The \( k \)-parameter controls the steepness of the cosine function. The less \( k \) the wider the range of incidence angles with low contribution to the radiometric correction. In other words, for \( k \)-values near 0 there is a marginal contrast enhancement from \( i=0° \) up to rather great indicent angles. Then, close to \( i = 90° \) the steepness increases rapidly and the contrast enhancement during correction will be overrated significantly. For that reason many known approaches exclude areas with \( i \) near 90° from correction.

ad c: Although the observation angle of the object has certainly some influence to the detected radiance, we are convinced that the sole modelling by the parameter \( k \) is not - even not approximately - satisfactory for the great majority of object classes. (We should always bear in mind, that Minnaert developed his formula for a very different purpose). If taken into consideration, the effect of the observing direction must be modelled independently. Our suggestion is therefore to exclude \( e \) (or possibly another function of appropriate derivative) from the global correction we are aiming to, at least in the first step of our development.

The new augmented approach has still the same basic form of Minneart’s formula, ie:

\[
g_{\text{corr}} = g_{\text{org}} \cdot K(i,e,i,s)
\]

with:

\[
K = \frac{1}{f(\cos,i) \cdot f(\cos,e,s)}
\]

(2)

\[
f(\cos,i) = \tilde{i} - (1-\tilde{i}) \cdot \cos^s \tilde{\eta}
\]

(3)

\[
f(\cos,e,s) = -\tilde{\eta} - (1-\tilde{\eta}) \cdot \cos^s e - (1-\tilde{\eta}) \cdot s \cdot \cos^s e
\]

Let us call \( \tilde{i} \) skylight term and \( s \) slope term. Both are within the interval \([0,1] \). They describe the percentage of the influence of the respective error source for incidence angles around 90°. Figure 1 shows the graph of the above functions. The idea behind is, that the contribution of ambient light to directly lit areas remains negligibly small, while it increases with growing \( i \), but never so much that the function exceeds its maximum of 1. The constant extension to angles greater than 90° is justified because there is primarily the influence of the diffuse skylight illumination and therefore no deciding necessity to take into account any incidence angle.
As already mentioned above the correction due to the observation angle will not be pursued any longer in our current work. We recommend further investigations. The examples later show that the influence of the observation angle seems to be negligibly small.

Before we continue with the determination of the parameters of the normalisation function it is advisable to prove that in reality this function may serve as suitable model. For that reason we chose our test area in the Austrian Alps where high mountains and steep slopes guarantee all sorts of illumination effects, from brightly sun lit regions with incidence angles around 0°, to dark shadows where the (virtual) incidence angle is greater than 90°, all sorts of shades in between, and eventually even cast shadows. Figure 2 shows an overview of the some 35 km x 25 km large area in the so-called “Salzkammergut” with its lakes. We use in our investigation the six optical bands of a Landsat TM image (1 to 5 and 7).

The DTM provided by the Austrian Federal Office for Metrology and Surveying has a grid width of 25 m x 25 m. The geometrically rectified satellite image has the same resolution. We want to emphasize that the geometric rectification must be performed with the help of a parametric model, so that displacements due to terrain heights are also rectified. In our case we used the bundle block adjustment program ORIENT [Kager, 1989] in conjunction with the digital orthophoto modul of SCOP DOP [Molnar et al. 1998]. High geometric accuracy is a prerequisite for a good quality of topographic normalisation in particular along terrain discontinuities, such as steep ridges or narrow valleys.
First we generate an artificial illumination of the DTM by calculating the \( \cos \ i \). For that purpose the sun position can either be extracted from the image file header of the delivered TM scene or may easily be calculated for the known acquisition date through an astronomy program. The sun azimuth \( \alpha \) for the used image is 129°, the sun elevation (90 - 0) is 39.9° causing deep shadows on slopes of north western exposition steeper than 39.9°. Figure 3 shows a detail of the \( \cos \ i \) image. The black coded patches are areas with sun incidence angles greater equal 90°.

In order to visualize the functional dependence between the sun incidence angle and the actual image, we generate the two dimensional scattergram of image data (greyvalues along vertical axis) against the \( \cos \ i \) image ((1 - \( \cos \ i \)) along the horizontal axis). The “colour”−coded scattergram for band 4 can be seen in figure 4. A few conspicuous features in this scattergram need to be explained in advance: There is one quite obvious vertical linear feature in the centre of the diagram. This line is caused by the flat regions in the test area. The line appears at the position of \( i = 50.1° \) (= 0°). Below this line there is a short horizontal line of very dark grey. It is caused by the lakes. Though the lakes are ideally horizontal surfaces we realize from the scattergram that they stretch over a slope range of some 10°. By analysing the DTM we found that it is slightly erroneous in the lake area probably due to DTM interpolation problems. We should therefore exclude those problem areas later in order to avoid wrong modelling and/or misleading conclusions that have nothing to do with the problem of terrain normalisation.

The most interesting features in the scattergram are:

- Firstly the highly linear dependence of the arithmetic means of the greyvalues for each category of incidence angle on \( \cos \ i \) (see dashed line in figure 4). This suggests the existence of a Lambertian surface as an appropriate approximation to the actual reflectance behaviour and the usefulness of applying a kind of simple Minnaert correction model.

- Secondly, a sudden bend that interrupts the ideal linear dependence can be recognized near \( i = 90° \) (see circle in figure 4). For angles greater than 90° there is no significant greyvalue change any more. The brightness of the image becomes independent of the incidence angle. In other words, the areas in shadows are only influenced by skylight or possibly by passive illumination from neighbouring illuminated objects.

- Thirdly, we see that the greyvalues of the shadow areas are not the lowest in the image. The lakes for instance (see ellipse in figure 4) are darker. If we applied a sole \( \cos \ i \) correction we had to assume that shadowed areas are the darkest possible regions of an image. They may not be zero for the only reason of possible sensor or preprocessing offsets. Again we have the proof that there must exist at least a slight illumination by, for instance, skylight.

The conclusion of all these effects is that the Minnaert formula extended by the skylight term as presented above would probably fulfill all the requirements that are necessary to achieve a rather good topographic normalisation over the entire image at once.

(Remark: the dashed straight line in figure 4 is straight only in case of \( k = 1 \). The displayed scattergram suggests that for that example \( k \) should be very close to one. See actual values later)

4. THE DETERMINATION OF THE PARAMETER

The considerations of the previous section lead to the way how the parameters of the formula can be determined (Note: As already mentioned earlier we concentrate here on the determination of the Minnaert constant and the skylight term. We do not take into consideration the slope influence). The entire image is subdivided into portions of identical incidence angles (or intervals of incidence angles) for which the image statistics i.e. mean values and standard deviations are calculated. We obtain two lists of value pairs: incidence angles and mean values, and incidence angles and standard deviations. Later we shall see that the individual treatment of means and standard deviations can be advantageous for a further refinement.

Although it looks as the determination of a straight line in the 2D scattergram would be the way to proceed, for several reasons we modify our approach slightly and write the well-known formula as follows (equation 4):

\[
m_{\text{corr}} = \frac{m_i}{(1 - (1 - \cos i))} - \frac{m_i \cdot K}{(1 - \cos i)} \quad (a)
\]

\[
m_{\text{corr}} = \frac{m_i}{(1 - (1 - \cos i))} - \frac{m_i \cdot K}{(1 - \cos i)} \quad (b)
\]

\[
v_i = m_{\text{corr}} - \frac{m_i}{(1 - (1 - \cos i))} - m_i \quad (c)
\]

where \( m_i \) denotes the mean values as the representative values of the image portions classified by categories of the incidence angle \( i \). \( m_{\text{corr}} \) is the corrected mean value. It is the same for each incidence class and therefore the representative mean value for the whole normalised image. The term \( v_i \) denotes the difference between the observed mean value within the class \( i \) and the corrected value. The third equation (4c) is the observation equation for a least squares adjustment with the intermediate observations \( i \) and \( m_i \) and the unknowns \( m_{\text{corr}} \) and \( \cdot K \).

For the solution of the adjustment problem one needs to:

- Firstly, linearize equation (4c) by writing the observation equation as follows:
\[ V_i = \left( \frac{\partial f}{\partial m_{corr}} \right)_{0} dm_{corr} - \left( \frac{\partial f}{\partial k} \right)_{0} dk - \left( m_i - f(m_{corr}, k, \xi) \right) \]

where \( dm_{corr} \), \( dk \) and \( dV \) are the unknowns of the observation equation. (They are corrections to approximate values of \( m_{corr} \) and \( k \). The subscript \( 0 \) indicates that for function \( f \) the approximate values have to be applied.)

5. THE NORMALISATION PROCESS

For the topographic normalisation one just needs to apply the correction function (4a) to the original image:

\[ g_{corr} = g_i \left( 1 - \frac{1}{\cos \theta} \right) - g_i K \]

Each pixel of the image will be corrected according to the incidence angle on its location. The mean values within each incidence class of the corrected image will then be approximately the same. One should be aware that together with the correction of the mean values also the standard deviations are affected. We'll come back to this later.

In order to estimate the influence of the inaccuracy of the parameters, the correction term \( K \) (see equ. 4a) has to be partially derived with respect to its parameters \( \xi, k \) and \( i \) (equation 8):

\[ \frac{\partial K}{\partial \xi} = K^2 \cdot (\xi - 1) \cdot \cos^2 k \cdot \sin i \]

\[ \frac{\partial K}{\partial k} = K^2 \cdot (1 - k) \cdot \cos k \cdot \sin i \]

\[ \frac{\partial K}{\partial i} = K^2 \cdot (\xi - 1) \cdot \cos^2 k \cdot \sin i \]

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\[ \frac{\partial K}{\partial i} = K^2 (\xi - 1) \cdot \cos^2 k \cdot \sin i \]

From this derivatives one can easily obtain the root mean square error of the topographically corrected greyvalue by applying:

\[ \sigma_g = \sqrt{\frac{\left( \frac{\partial K}{\partial \xi} \sigma_\xi \right)^2 + \left( \frac{\partial K}{\partial k} \sigma_k \right)^2 + \left( \frac{\partial K}{\partial i} \sigma_i \right)^2}{\left( g_{corr} - g_i \right)^2}} \]

where \( \sigma_\xi, \sigma_k, \sigma_i \) can be obtained by the adjustment procedure and \( \sigma_g \) can be estimated from the DTM accuracy. By analysing the above formula it becomes obvious that the accuracy of normalisation deteriorates rapidly towards \( i=90^\circ \).

6. EXAMPLE

A practical example should prove the suitability of the presented correction model. The terrain heights of the “Salzkammergut” test area range from some 400 m to 1800 m a.s.l. The image is a Landsat TM scene from September 1991 (see Fig.2). The digital terrain model was available as 16bit integer intensity image with directly coded terrain heights. From the DTM image have been derived:

• a slope image (used for the calculation of \( i \) and for the exclusion of flat and very steep areas)

• and together with the given sun position - the cos-\( i \) image.

The image has been classified into seven incidence classes (0-15°, 15-30°, 30-45°, 45-60°, 60-75°, 75-90°, >90°), the mean values and standard deviations were calculated for each spectral band (except band 6), obtaining e.g. for band 1 and 4:
This leads to seven observation equations per spectral band (the absolute minimum would be three). The adjustment for the 6 spectral bands yielded the following values for the parameters (see also figure 5):

<table>
<thead>
<tr>
<th>(i^\circ)</th>
<th>(m_i)</th>
<th>(\sigma_i)</th>
<th>(m_i)</th>
<th>(\sigma_i)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.5</td>
<td>54.19</td>
<td>7.74</td>
<td>72.65</td>
<td>18.82</td>
</tr>
<tr>
<td>22.5</td>
<td>53.58</td>
<td>7.99</td>
<td>70.06</td>
<td>19.80</td>
</tr>
<tr>
<td>37.5</td>
<td>53.49</td>
<td>6.77</td>
<td>64.84</td>
<td>22.55</td>
</tr>
<tr>
<td>52.5</td>
<td>51.22</td>
<td>5.87</td>
<td>51.60</td>
<td>19.53</td>
</tr>
<tr>
<td>67.5</td>
<td>48.15</td>
<td>4.62</td>
<td>35.27</td>
<td>14.17</td>
</tr>
<tr>
<td>82.5</td>
<td>46.02</td>
<td>3.48</td>
<td>19.83</td>
<td>9.61</td>
</tr>
<tr>
<td>90.0</td>
<td>45.04</td>
<td>2.11</td>
<td>11.21</td>
<td>4.59</td>
</tr>
</tbody>
</table>

**Tab.1: Mean and standard deviation of incidence classes**

One can clearly see that the Minnaert constant \(k\) is always very close to 1 (= ideal cosine function!), while the skylight factor \(\iota\) is always greater than 0 and significantly greater than 0 for all bands in the visible spectrum, in particular in the blue band (82%). \(m_{corr}\), the adjusted mean for \(i=0\), is less important for the correction function. \(\sigma_i\) shows that the correction function fits the actual observations with an accuracy below one greyvalue interval (except band 4, where the mean error is still very good with \(\pm2.5\) greyvalues).

### 7. DISCUSSION AND CONCLUSION

Figures 8 and 9 show the original and topographically corrected band 4 image, respectively. This part of the whole image shows a few typical details that need further discussion:

1. Shadows in areas of incidence angles greater 90° (see black patches in Fig.3) can also be “corrected” by this approach. We must bear in mind that those areas are adjusted to the average mean. The correction is very unreliable and inaccurate. Not corrected, because not included in the illumination model used here, are the cast shadows as one can recognize along the mountain range in the right upper quarter of the image. The remainder of the shadow can be seen as dark stripe on flat terrain. As the algorithm cannot know the origin of that stripe it is treated like a dark object feature.

2. Dark linear elements along terrain discontinuities or mountain ridges or sudden changes from dark to bright resemble the effect of an high pass filter in some way. Many of these effects are caused by a slight misalignment between the image content and the terrain model. A closer check proved that the geometric rectification was not as accurate as necessary. A displacement of only one pixel leads to a visible wrong intensity correction. We conclude that the geometric accuracy is a crucial point for accurate topographic normalisation, in particular in mountainous regions.

3. The correction function not only moves the mean greyvalues within an incidence class, it, at the same time, also stretches the associated standard deviation (see Fig.6). The effect is that in shaded areas the contrast is severely enhanced thus causing bright features within darker surrounding areas. The following suggestion of a modified correction procedure helps to attenuate the unrealistic contrast enhancement.

The standard deviations of the incidence classes are now subjected to the same adjustment procedure as the mean values before. This notion is justified as we must expect and deduce from the scattergram (Fig.4), that the standard deviation also depends on the illumination properties. Therefore, we just apply the same basic rules as for the mean values. The adjustment is now performed with the \(i\) and \(\sigma\) listed in Table 1 (instead of \(i\) and \(m\)).

The result of this adjustment for our test example of all six spectral bands is listed in Table 3. The \(\sigma_0\) column shows that the functions fits very well the actual “measurements”. In the worst case (band 4 again) the \(\sigma_0\) is 2.27 that is about 10% of the actual standard deviations (see Table 1).
The idea is now to separate the correction of the mean from that of the standard deviation. Therefore equation (4b) cannot be applied directly. The modified steps are (see also equation 10):

1. Each greyvalue is reduced by its respective mean $m_i$ (according to equ. 4b) so that the new mean value becomes 0.
2. The shifted values are scaled by the correction function of the standard deviation.
3. Finally the greyvalues are shifted back by $m_{corr}$.

$$
K_m = \frac{1}{\xi_m - (1-\xi_m) \cdot \cos^k i}, \quad K_\sigma = \frac{1}{\xi_\sigma - (1-\xi_\sigma) \cdot \cos^k i}
$$

$$
g_{corr} = (g_i - \frac{m_{corr}}{K_m}) \cdot K_\sigma - m_{corr} \quad \text{or}
$$

$$
g_{corr} = g_i \cdot K_\sigma - m_{corr} \cdot (\frac{K_\sigma}{K_m} - 1) \quad (10)
$$

where the indices $m$ and $\sigma$ denote the parameters for the mean and sigma correction, respectively.

We notice immediately that in case of equal $K_m$ and $K_\sigma$ equations (10) and (7) are equivalent. The band 4 image corrected by this modified approach is shown in figure 10, its scattergram in figure 7. The high greyvalues for incidence angles >50.1° (flat terrain) could be reduced significantly, while the basic appearance remained the same.

**8. SUMMARISING REMARKS**

The intended goal of providing an algorithm for an approximate topographic normalisation
- that works mostly automatically,
- delivers accuracy measures,
- detects automatically how reliably the given model can be applied for a given image and finally
- yields satisfying results in order to facilitate an a-priori classification that can successfully be used for a subsequent class dependent normalisation could be reached by a simple extension of the primitive Minnaert BRDF model. We found out, that by introducing the skylight term $\xi$ the Minnaert constant $k$ is always close to 1 and therefore does not notably influence the correction function. The $\xi$ term is usually closer to 1 for the short wavelengths and closer to zero for infrareds. Following this knowledge one should be able to find appropriate $k$ and $\xi$ for a fairly good normalisation even manually just by trial and error. Eventually, we need to emphasize again, that a high quality rectification together with an accurate DTM are crucial preconditions for a successful topographic normalisation, independent of whether the normalisation just serves as a preprocessing step or it is the final correction based on a more sophisticated mathematical and/or physical model.
9. REFERENCES


