Evaluation of different topographic correction methods for Landsat imagery

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ABSTRACT

The recent free availability of Landsat historical data provides new potentials for land-cover change studies. Multi-temporal studies require a previous radiometric and geometric homogenization of input images, to better identify true changes. Topographic normalization is one of the key steps to create consistent and radiometrically stable multi-temporal time series, since terrain shadows change throughout time. This paper aims to evaluate different methods for topographic correction of Landsat TM-ETM+ data. They were assessed for 15 ETM+ images taken under different illumination conditions, using two criteria: (a) reduction of the standard deviation (SD) for different land-covers and (b) increase in temporal stability of a time series for individual pixels. We observed that results improve when land-cover classes where processed independently when applying the more advanced correction algorithms such as the C-correction and the Minnaert correction. Best results were obtained for the C-correction and the empiric–statistic correction. Decreases of the SD for bare soil pixels were larger than 100% for the C-correction and the empiric–statistic correction method compared to the other correction methods in the visible spectrum and larger than 50% in the IR region. In almost all tests the empiric–statistic method provided better results than the C-correction. When analyzing the multi-temporal stability, pixels under bad illumination conditions (northern orientation) improved after correction, while a deterioration was observed for pixels under good illumination conditions (south orientation). Taken this observation into account, a simple but robust method for topographic correction of Landsat imagery is proposed.

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1. Introduction

Landsat imagery have been widely used for land-use/land-cover (LULC) studies (Huang et al., 2010; Kennedy et al., 2007; Lawrence and Ripple, 1999), since they currently offer the longest and more consistent historical archive of satellite data, at proper spatial and spectral resolution for regional studies. Any multi-temporal change detection study relies on comparing images acquired at different dates. That comparison assumes that images from those dates are geometrically matched (pixels to be compared are in the same area), and radiometrically consistent (the values of pixels refer to the same physical units). If those requirements are not met, the interpreter can detect as changes, what might be in fact different locations or calibration values (Zhan et al., 2002). Within the radiometric normalization of multi-temporal images, the correction of topographic shade is especially critical when the target area has rough terrain, since illumination conditions change along with seasonal sun zenith angle.

With the opening of the Landsat archive by the USGS in 2009, a huge amount of images have become available (Woodcock et al., 2008), causing an increasing need for automatic image preprocessing algorithms (Huang et al., 2009). The atmospheric correction algorithms for Landsat imagery already have been tested by various authors (Schroeder et al., 2006; Song et al., 2001; Vicente-Serrano et al., 2008). Compared with the large amount of atmospheric and radiometric correction algorithms proposed and validated, relatively little interest has been shown in the correction of the topographic illumination. This can be partially explained by two reasons; first because only for less than one decade, high-resolution digital elevation models (DEM) have been made available such as the SRTM and Aster DEM and second because the simple topographic correction algorithms do not give a satisfying result, while the more advanced algorithms are hard to generalize and not automatically applicable.

Many algorithms for topographic correction have been proposed, but most of them are not properly evaluated (Gao and Zhang, 2009a; McDonald et al., 2000; Riaho et al., 2003), since these studies only considered a limited set of illumination conditions (commonly one small study area and/or just one image taken under good illumination conditions is used). Furthermore, the impact of different land covers is not commonly assessed. The first study that is actually studying the performance of different topographic correction

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algorithms for images with very different land-cover was presented by Richter et al. (2009), but these images were still taken under favorable illumination conditions. In this paper, we have evaluated different topographic correction methods for a large number of images acquired at different periods of the year and under different terrain conditions, for the generation of radiometrically stable time series of Landsat imagery.

2. Material and methods

2.1. Algorithms for topographic correction

The first step in the correction of topographic shadows is the computation of the illumination angle, which is based on the following formula (Civco, 1989; Colby, 1991):

$$\cos \gamma_i = \cos \theta_i \cos \eta_i + \sin \theta_i \sin \eta_i \cos (\Phi_i - \Phi_e)$$

(1)

where $\gamma_i$ is the incidence angle, $\theta_i$ is the solar zenith angle; $\eta_i$ is the slope angle; $\Phi_i$ is the solar azimuth angle and $\Phi_e$ is the slope aspect. The Sun zenith and azimuth angles are computed for the specific conditions where the satellite image was acquired. For Landsat-TM/ETM+ data, we can assume a single set of angles since the scenes are relative small, while for larger areas (for instance MODIS or VEGETATION images), solar angles should be adapted to variations of latitude and longitude throughout the image.

To compute the slope gradient and aspect, a Digital Elevation Model (DEM) of similar resolution to the Landsat image is required. DEMs are increasingly available at medium resolution, based on topographic maps, photogrammetric methods or analysis of lidar data. World coverage of DEM was obtained from the Shuttle Radar Topography Mission (Rabus et al., 2003) acquiring interferometric data in 2000, and more recently from computation of ASTER stereoscopic images (ASTER GDEM Validation Team, 2009). Both SRTM and ASTER DEMs are suitable for topographic correction of Landsat imagery whenever higher resolution DEM are not available (Gao and Zhang, 2009b).

Once the illumination angle is known, the removal of topographic shadows may be based on different methods. They can be grouped in those that assume Lambertian conditions (reflectance is independent on observation angle) and those that consider directional reflectance. Within the former approach the most extended method is the cosine correction proposed by Teillet et al. (1982):

$$\rho_{\lambda,h,i} = \rho_{\lambda,i} \left( \frac{\cos \theta_i}{\cos \gamma_i} \right)$$

(2)

where $\rho_{\lambda,h,i}$ is the reflectance of a pixel $i$ in horizontal terrain; $\rho_{\lambda,i}$ is the reflectance of a pixel in rugged terrain.

This algorithm is easily applicable because it does not require external parameters. However, it has been shown that it overcorrects the areas under low illumination conditions (Meyer et al., 1993). An alternative algorithm was proposed by Civco (1989) taking into account the average illumination conditions:

$$\rho_{\lambda,h,i} = \rho_{\lambda,i} + \rho_{\lambda,i} \left( \frac{\cos \gamma - \cos \gamma_i}{\cos \gamma} \right)$$

(3)

where $\cos \gamma$ is the mean illumination angle.

Both of these methods are wavelength independent. To take into account the difference between bands in diffuse irradiation, different authors have proposed algorithms including band dependent parameters. One of the most extended was proposed by Teillet et al. (1982), and it was named the C-correction:

$$\rho_{\lambda,h,i} = \rho_{\lambda,i} \frac{\cos \theta_i + c_i}{\cos \gamma_i + c_i}$$

(4)

where $b_i$ and $m_i$ are the regression coefficients between the illumination and different band reflectances:

$$\rho_{\lambda,i} = b_i + m_i \cos \gamma_i$$

(5)

Therefore, $c_i$ is an empirical constant calculated for every band separately.

This method takes into account the diffuse irradiance by a semi-empirical estimation of the factor $C$. Both Civco and Teillet methods have a physical base, were only the extra correction parameters are estimated by empirical methods. However, Teillet et al. (1982) also proposed a method totally based on the empirical–statistical fit between the reflectance values and the cosine of the illumination angle:

$$\rho_{\lambda,h,i} = \rho_{\lambda,i} \cos \gamma_m - b_i + \tilde{\rho}_{\lambda,i}$$

(6)

where $\tilde{\rho}_{\lambda,i}$ is the mean reflectance of all $\rho_{\lambda,i}$.

One of the most cited non-lambertian methods is the Minnaert correction proposed by Minnaert (1941), which is defined as:

$$\rho_{\lambda,h,i} = \rho_{\lambda,i} \left( \frac{\cos \theta_i}{\cos \gamma_i} \right)^l$$

(7)

The factor $l$ is the Minnaert constant, modeling the non-lambertian behavior for every band and land-cover separately. The Minnaert constant has a value between 0 and 1. When the Minnaert constant $l=1$ than the surface is considered as a perfect lambertian reflector. In practice, this factor is estimated by linearizing equation (7).

A further improvement of the Minnaert method including the slope angle, further referred to as Minnaert method with slope, was proposed by Colby (1991):

$$\rho_{\lambda,h,i} = \rho_{\lambda,i} \cos \eta_i \left( \frac{\cos \theta_i}{\cos \gamma_i} \right)^l$$

(8)

One of the disadvantages is the fact that the Minnaert constant and the factor $c$ in the C-correction should be determined for every band and land-cover separately. In earlier studies it was observed that estimating these factors separately for different land-covers instead of using mean values improved the results considerably (Kobayashi and Sanga-Ngoie, 2009; McDonald et al., 2000). This makes it more difficult to apply these methods over entire Landsat scenes, since land-cover maps are often not available.

The first operational algorithm tackling this problem is the Modified Minnaert algorithm, proposed by Richter et al. (2009) where the model changes depending if the pixel is classified as vegetation or non-vegetation, and on the illumination conditions as well, following:

$$\rho_{\lambda,h,i} = \rho_{\lambda,h,i,\text{cosine}} \left( \frac{\cos \gamma_i}{\cos \beta_i} \right)^l$$

(9)

where $\rho_{\lambda,h,i,\text{cosine}}$ is the reflectance values resulting from (2), the variable $l$ is defined depending on the land-cover and wavelength, with a value of 0.5 for non-vegetation areas, 0.75 for vegetated areas but only for bands of the visible spectrum ($\lambda < 720$ nm) and 0.33 for vegetated areas with spectral bands ($\lambda \geq 720$ nm) and $\beta_i$ is an empirical variable depending on the solar zenith angle where:

$$\beta_i = \theta_i + t$$

(10)

The variable $t$ depend on the solar zenith angle, when $\theta_i < 45^\circ$, $t = 20^\circ$; $45^\circ \leq \theta_i \leq 55^\circ$, $t = 15^\circ$; $\theta_i > 55^\circ$, $t = 10^\circ$.

In recent years more advanced algorithms have been proposed (Kobayashi and Sanga-Ngoie, 2009; Lu et al., 2008). Although these algorithms provided good results in these studies, they need to
be further developed before they can be applied globally. Consequently, they were not included in our validation exercise. Furthermore an adaptation of the C-correction was proposed to optimize a specific spectral index (Veraverbeke et al., 2010), modifying the spectral characteristics of the imagery and thus should only be used for specific analysis.

Various authors have proposed methods to correct atmospheric and topographic illumination disturbances at the same time (Conese et al., 1993; Huang et al., 2008; Pons and Solé-Sugrañes, 1994; Richter, 1997; Shepherd and Dymond, 2003). However, in this study we first apply the atmospheric correction and later the topographic correction as proposed by Meyer et al. (1993). In this way we are able to analyze the effect of the topographic correction separately.

The algorithms tested in this study were the cosine method (2), the C-correction (4), the statistical–empirical method (7), the Minnaert method with slope (9) and the Modified Minnaert method (10). The original Minnaert correction (8) was not validated because the version with the slope introduced should give better results (Colby, 1991).

2.2. Land-cover separation

When applying advanced topographic correction methods over large areas some problems occur due to the fact that the different correction parameters such as the Minnaert constant and the factor c in the C-correction are land-cover depended. Various authors have indicated that it is necessary to estimate these parameters separately for the different land-covers present in the study area (Kobayashi and Sanga-Ngoie, 2009; McDonald et al., 2000). In this study we tested whether the separation between land-covers improved topographic correction results. However, land-covers can have an important seasonal and temporal variability, especially in Mediterranean areas. Therefore the use of land-cover maps is not adequate for an operative separation between land-cover classes. We used the proper image for land-cover separation, grouping the land-covers that have a similar spectral response. The separation between land-cover classes was based on an arbitrary threshold of 0.4 in the NDVI. Like this we separate areas with a high portion of bare soil form vegetated areas, while still keeping a high amount of pixels in both land-cover groups for a consistent estimation of the different parameters. Areas with a slope ≤2° are not included for parameter estimation. The different parameters necessary for the correction algorithms are estimated independently for every image.

2.3. Study area

The study area is located in the central part of the Iberian Peninsula (Fig. 1), consisting of Landsat scene 201/33 (path/row). It has an average altitude of 645 m, ranging from 175 to 1450 m. The eastern part of the scene presents parallel mountain ranges with flat valleys in between. Natural vegetation covers are mostly Mediterranean shrublands, evergreen deciduous woodlands and pine forests. However due to traditional land-use, the major part of the territory was converted to agricultural lands and pastures. Nowadays only remnants of the natural vegetation are present in the rougher areas. Gentle slopes are now covered by olive groves and vineyards while most flat terrains have cereals or pastures with scattered evergreen oaks (“dehesas”). In the eastern part of the study area vineyards also cover a significant part of these flat terrains. All these land-uses/land-covers are highly mixed.

2.4. Pre-processing of satellite data

A time series of 15 Landsat ETM+ images acquired over the study area with solar elevation angles ranging from 28° and 65° was selected. All images were obtained from the USGS image database (Woodcock et al., 2008). Images were georeferenced applying a new algorithm for multi-temporal matching (Pons et al., 2010). Sub-pixel accuracy was obtained for all images. The parameters for conversion of digital numbers (DN) to radiance as well as the solar and azimuth angles were obtained from the metadata, (Chander et al., 2009). All images had a low cloud cover (<25%). Clouds were masked by applying the cloud detection algorithm proposed by Irish (2001). Atmospheric correction was based on the dark object algorithm from Chavez (1996). In this case, the dark object was taken from the minimum digital value of the histogram with at least 200 pixels. The parameters determining the atmospheric transmittance for the first 4 bands were taken from the original publication of Chavez (1996) while the values for the SWIR region were taken from Gilabert et al. (1994). The upwelling atmospheric transmittance and the diffuse irradiance were ignored.

2.5. DEM processing

The DEM used for topographic correction is the standard DEM developed by the Spanish National Geographic Institute (IGN), extracted from topographic maps at 1:25,000 scale. It has a pixel size of 25 m × 25 m, being available for the complete Spanish territory.
### Table 1
Mean reduction (%) of the SD compared with the original image for bare soil pixels after topographic correction. _NDVI_ in the name of the methods indicated that separation between land-cover was applied. For each band, results of the best performing algorithm are presented in bold.

<table>
<thead>
<tr>
<th>% reduction in SD</th>
<th>Banda1</th>
<th>Banda2</th>
<th>Banda3</th>
<th>Banda4</th>
<th>Banda5</th>
<th>Banda7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cosine</td>
<td>–6.0</td>
<td>5.2</td>
<td>6.5</td>
<td>12.2</td>
<td>15.3</td>
<td>18.2</td>
</tr>
<tr>
<td>Empirc–statistic</td>
<td>14.9</td>
<td>17.7</td>
<td>18.2</td>
<td>28.3</td>
<td>36.0</td>
<td>33.7</td>
</tr>
<tr>
<td>Empirc–statistic <em>NDVI</em></td>
<td>13.2</td>
<td>16.5</td>
<td>18.5</td>
<td>27.2</td>
<td>38.0</td>
<td>34.4</td>
</tr>
<tr>
<td>C-correction</td>
<td>–6.7</td>
<td>–1.8</td>
<td>–8.9</td>
<td>21.5</td>
<td>9.8</td>
<td>–6.0</td>
</tr>
<tr>
<td>C-correction <em>NDVI</em></td>
<td>10.9</td>
<td>13.3</td>
<td>13.3</td>
<td>21.5</td>
<td>32.9</td>
<td>31.1</td>
</tr>
<tr>
<td>Minnaert with slope</td>
<td>–35.6</td>
<td>–38.9</td>
<td>–70.8</td>
<td>10.4</td>
<td>–9.0</td>
<td>–37.3</td>
</tr>
<tr>
<td>Minnaert with slope <em>NDVI</em></td>
<td>3.8</td>
<td>–1.1</td>
<td>–7.5</td>
<td>8.0</td>
<td>19.0</td>
<td>14.3</td>
</tr>
<tr>
<td>Modified Minnaert</td>
<td>10.0</td>
<td>14.8</td>
<td>14.7</td>
<td>20.5</td>
<td>25.6</td>
<td>28.0</td>
</tr>
</tbody>
</table>

### 2.6. Validation methods

The most widely used method for validating the performance of topographic shade removal is the decrease in the correlation coefficient between the incidence angle and the spectral bands (e.g. Gao and Zhang, 2009a; McDonald et al., 2000). Eventually, a perfect correction would imply that both sets would not correlate at all, implying that orientation and slope dependence on reflectance values would have been removed. This assumption is not valid were slope orientation determines the land-cover, as it is very common in the Mediterranean landscapes. Therefore, a residual correlation between reflectance and incidence angle is expected, even after successful topographic correction. For this reason, we did not use this method in our assessment.

Alternatively, we based our evaluation on the following methods:

- Changes in SD of pixel values within the same land-cover in different slopes and aspects (Kobayashi and Sanga-Ngoie, 2009; Riaño et al., 2003). The SD should decrease after a successful shade removal, meaning that impact of illumination is reduced. For this test, we selected 258 separate pixels of bare soil and 160 pixels over homogeneous pine forest in different areas covering different slopes and orientation.

- Increase in temporal stability of a time series for individual pixels. In this case, we do not analyze the topographic normalization of an individual image, but the robustness of the algorithms under different conditions over time. In this case, we computed the temporal SD of the above mentioned bare soil and pine forest pixels for the 15 Landsat images of our temporal series.

The tested land-covers have a different spatial distribution. While the bare soil areas are erosion patches mainly located on steep slopes, the pine forest are present in areas with smooth hills.

### 3. Results

The reduction in SD for bare soil pixels after correction is presented in Table 1. These are average values for the 15 images used for our assessment, taken under a wide range of solar elevation angles (from 25° to 65°).

First it can be observed that the simplest method tested, the cosine correction, reduces in general the SD but in a rather limited way, giving clearly higher SD than some of the other methods.

Secondly it can be observed that the separation between the two land-covers for the C- and Minnaert correction yields lower SD than when these advanced algorithms are applied over the complete image. This is not the case for the empiric statistic correction, where the separation between land covers gave similar results to the original methods. The Modified Minnaert method, being only different from the cosine correction in areas with low illumination angles improved its performance considerably compared to the cosine correction, solving part of the problem found with the cosine correction.

To explore why the advanced correction methods in general provided lower SD after separation between land-covers, we plotted the SD for every image over the solar elevation angles (Fig. 2). We can see that the results for the correction with and without land-cover separation are rather similar for images taken under unfavorable illumination conditions. However, when no separation between land-covers is performed, higher SD are obtained for images taken under good illumination conditions. For the cosine correction the opposite is true, with relative good results for images taken under good illumination conditions, but the algorithm is not able to correct images taken under bad illumination conditions.

When plotting the best performing algorithms in Fig. 3, we can see that all of them offered similar results, with similar SD for all images with a solar elevation angle >40°. When the image is taken at low sun elevation angles, none of the tested algorithms is able to correctly entirely the topographic illumination effect. The best results were obtained by the empiric–statistic algorithm, both with and without separation between land-cover classes. To a lesser extent, both the C-correction with NDVI separation and Modified Minnaert algorithm gave good results as well.

The same analysis was performed for the pine forest pixels and it is presented in Table 2. Similar results as for the bare soil analysis can be observed, with both the empiric–statistic correction and the C-correction giving the best results. Again, separation between
land-covers resulted in improved performance of the advanced correction algorithms for the majority of the bands. It is worth to emphasize the bad performance of the empiric–statistic correction without land-cover separation, in line with the other advanced correction methods, but contrary to the bare soil analysis.

It can be concluded that both the C-correction and the empiric–statistic correction are able to homogenize land-covers in rugged terrain by reducing the topographic effect. An example is given in Fig. 4, for a small area covering a hard to correct area. A large amount of small mountain ridges are present and the image was taken under bad illumination conditions. The original and the results after topographic correction for the two best performing methods, the empiric–statistic and the C-correction are presented. A clear reduction of the topographic effect can be seen for both of these methods.

Results for the temporal stability obtained from bare soil and pine forest pixels can be observed in Tables 3 and 4 respectively. For both the bare soil areas and the pine forest areas the
Fig. 3. SD of bare soil for the original image and 4 different topographic correction methods. NDVI indicates that at separation between land-cover was applied. The results obtained for 15 images taken under different illumination conditions are given for all bands.

Table 3
Results for the multi-temporal consistency test, as the mean SD of pixel reflectance over time for the bare soil areas. The results with the lowest SD are in bold. NDVI in the name of the methods indicated that separation between land-cover was applied.

<table>
<thead>
<tr>
<th>Band</th>
<th>Original</th>
<th>C-correction NDVI</th>
<th>Empiric–statistic NDVI</th>
<th>Empiric–statistic</th>
<th>Modified Minnaert</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>112.3</td>
<td>118.7</td>
<td>104.9</td>
<td>125.2</td>
<td>135.8</td>
</tr>
<tr>
<td>2</td>
<td>145.9</td>
<td>153.0</td>
<td>132.7</td>
<td>164.7</td>
<td>166.9</td>
</tr>
<tr>
<td>3</td>
<td>181.8</td>
<td>202.8</td>
<td>177.2</td>
<td>232.6</td>
<td>217.4</td>
</tr>
<tr>
<td>4</td>
<td>226.5</td>
<td>252.3</td>
<td>226.6</td>
<td>236.7</td>
<td>286.3</td>
</tr>
<tr>
<td>5</td>
<td>370.8</td>
<td>416.4</td>
<td>347.2</td>
<td>401.2</td>
<td>458.8</td>
</tr>
<tr>
<td>7</td>
<td>287.3</td>
<td>343.7</td>
<td>264.2</td>
<td>333.8</td>
<td>367.7</td>
</tr>
</tbody>
</table>
Fig. 4. Comparison between the original image (up) and after C-correction (centre) and empiric–statistic correction (bottom), both with separation between land-cover. The image was taken at 24/11/1999 with a solar elevation angle of 28°.

The empiric–statistic correction with separation between land-cover gave almost always the lowest SD compared to the other methods. However, a stronger reduction of the SD was expected for the temporal analysis.

To better understand the impacts of illumination conditions, the difference in SD from the temporal analysis after correction was plotted against the cosine of the orientation angle (Fig. 5). A clear trend can be observed, with an improvement of the temporal stability for pixels taken under bad illumination conditions (northern slopes), but status quo of the result for pixels taken under good illumination conditions. This same trend was observed when analyzing the temporal trend for the pine forest pixels.

During the visual validation of the results it was revealed that for one image, taken on 20/08/1999, there were artifacts visible in areas

<table>
<thead>
<tr>
<th>Band</th>
<th>Original</th>
<th>C-correction NDVI</th>
<th>Empiric–statistic NDVI</th>
<th>Empiric–statistic</th>
<th>Modified Minnaert</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>41.5</td>
<td>42.3</td>
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</tr>
<tr>
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<td>4</td>
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<td>7</td>
<td>87.5</td>
<td>87.7</td>
<td>81.6</td>
<td>88.0</td>
<td>88.6</td>
</tr>
</tbody>
</table>

Table 4

Results for the multi-temporal consistency test, as the mean SD of pixel reflectance over time for the pine forest areas. The results with the lowest SD are in bold. NDVI in the name of the methods indicated that separation between land-cover was applied.
under bad illumination conditions for the results obtained after empiric–statistic correction (Fig. 6). No artifacts could be observed in other image or for the results obtained after C-correction. When the threshold in the NDVI for the separation between land-cover classes was changed to 0.3, these artifacts disappeared.

4. Discussion

Some of the most common topographic correction methods were validated for a large number of Landsat ETM+ images taken under different illumination conditions. Our results are in line with results obtained by other authors, indicating the better performance of the C-correction and empiric–statistic correction (Riaño et al., 2003; McDonald et al., 2000; Gao and Zhang, 2009a). However, all earlier studies were assessed in small study areas and for one image taken under good illumination conditions, while here we have tested very different sun zenith angle conditions.

The main problems with the Cosine correction were found for images taken under poor illumination conditions, where other methods provided better results. The Minnaert method with the slope included did not give acceptable results, which was observed by Riaño et al. (2003) as well. The Modified Minnaert algorithm did improve the results obtained by the cosine algorithm in all tests, although not reaching to the level of the C-correction and empiric–statistic algorithm. We observed that both the C-correction and the empiric–statistic methods were able to correct the images for the topographic effect for solar elevation angles as low as 40° in our study area. For solar elevation angles of 30° and less, an increase in SD was observed where the correction methods could only partly correct the illumination effects.

As some other authors have already indicated, we observed a better performance of correction algorithms when they took into account land-cover, even when using a simple NDVI threshold. Therefore, the land cover dependency of the different correction
factors was evidenced. Furthermore, land-cover distribution is also dependent on aspect-slope factors, at least in Mediterranean environments, so problems arose in determining the $c$ and $l$ factors when the algorithms are applied to the image as a whole. Therefore it is not surprising that the three best performing algorithms in the various analyses all consider a separation between land-covers. When parameters for an entire image have to be estimated, the variation in reflectance values present over the whole image can make the regression analysis between incidence angle and reflectance values corrupt. This is especially true when the spectral variation cause by the topographic effect is rather small compared to the variation present in the image. When separating between different land-covers, this spectral variability is reduced, making it easier to obtain a consistent regression analysis and therefore a better estimation of the correction parameters. This also explains why the results presented in Fig. 2 provided worse results for images taken under better illumination conditions for the C-correction without separation between land-covers. Consequently, separation between land-covers is not necessary for rather spectral homogenous areas. This can be observed for band 4 in Tables 1 and 2. Band 4 is more homogenous than other bands, resulting in a better regression analysis between reflectance and incidence angle, and giving good results for the correction methods without separation between land-covers. Although in our study area it is necessary to divide the image in different land-cover classes, this does not imply that it is necessary in all areas, especially when they have a homogeneous land-cover.

A side effect of this separation between land-covers is the possible occurrence of artifacts, when for one of the land-covers the correction parameters are estimated erroneously due to a corrupt regression. This was the case for the image presented in Fig. 6. When the separation threshold in the NDVI was lowered to 0.3 instead of 0.4, the artifacts already disappeared due to a more similar estimation of the factor $c$ between the two land-covers.

Theoretically the result should improve even more if land-cover were to be further subdivided into more different classes, not solely based on the NDVI. However the first attempts to do this by unsupervised classifications introducing various normalized difference indexes did not result in an improved topographic correction (not presented). Further efforts should focus on the optimization of this division in land-cover classes.

The main purpose of this paper is to analyze the potential of different topographic correction methods to improve temporal radiometric stability for satellite time-series generation. When the multi-temporal stability of pixels present in sloped terrain was analyzed, we observed only a slight decrease in SD after applying the empiric–statistic correction and often not even an improvement after the C-correction (Table 3). A more thorough analysis revealed that, although the temporal stability for pixels under bad illumination conditions (northern orientation) improved strongly, this was undermine by the lower temporal stability for pixels under good illumination conditions (south orientated). This trend was also observed by Veraverbeke et al. (2010). Future tests should focus in improving the performance of correction algorithms for the pixels under good illumination conditions as well.

One of the main difficulties in topographic correction is to obtain a DEM of the adequate resolution and quality. Here we used a DEM with 25 m resolution. However this implies that the incidence angle is calculated not only for the pixel of the image to be corrected but for a $3 \times 3$ window surrounding this pixel. Therefore a DEM with a resolution of $1/3$ of the pixel size of image to be corrected is theoretically needed to precisely model the illumination conditions at the time of image taking. Furthermore, no DEM is perfect and all of them contain errors, introducing noise in the image during the topographic correction. Both the pixel size and the imperfections of the DEM explain the observations presented in Table 1, were the SD after correction was superior to the SD of the original image for an image taken under bad illumination conditions. The same factor explains why the temporal stability for pixels taken under good illumination conditions is lower after topographic correction. More detailed DEM could possibly improve future topographic correction, but few global DEM with an adequate resolution are currently available. Therefore it is interesting that Gao and Zhang (2009b) were able to reduce the topographic effect in Landsat imagery using the DEM obtained by the Shuttle Radar Topography Mission.
5. Conclusion

Different topographic correction methods were validated for a large set of images taken under different illumination conditions. From the assessed methods, the C-correction and the empiric–statistic method gave the best results when analyzing the homogeneity of different land covers after correction. However, good results for those algorithms were only obtained when the necessary parameters were estimated separately for different land-cover classes. As an operative way to obtain a separation between land-covers we divided our study area in two land-cover classes by a threshold in the NDVI. Although being a simplistic separation, an important improvement of the result was obtained. As a side effect the empiric–statistic method showed some, easy to solve, artifacts in the border area between land-cover classes for one image.

When focusing on the temporal stability of the algorithms the empiric–statistic algorithm gave clear superior results over all other tested methods.

We can conclude that the empiric–statistic topographic correction method we have presented here is able to correct for the topographic effects, giving satisfying results in the majority of the cases. These results were obtained from just one study area and should be verified over other areas with different spatial conditions and vegetation covers. Future improvements in topographic correction could be obtained by an improvement of the quality and resolution of the DEM, as well as by obtaining a better separation between land-cover classes, necessary for the estimation of the different correction parameters. Although the proposed correction method could still be improved, satisfactory results were obtained.

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References