The potential of Landsat images for studying sand dunes' topography

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ABSTRACT

We show that shading effects assessed by Landsat can be treated as a signal that stores important topographic information, especially when the spectral characteristics of a surface are homogenous. The coastal transverse dunes of the Ashdod area, and the desert linear dunes of Nizzana (both located in Israel), were selected to investigate the above-mentioned idea. An innovative method for extracting slope, aspect, and height data for sand dunes using Landsat TM and ETM+ images was developed, based on the regularity and periodicity of dunes' landscapes. Using two Landsat images representing different sun zenith and azimuth angles, reflectance values of each image were converted to cos(i) values (i = incident angle between the surface normal and the solar beam radiation) by applying histogram matching methods. The slope and aspect of each pixel were determined as those that give the best prediction of the observed value of cos(i). Height profiles were then extracted, using simple trigonometric relationships. The accuracies of heights and slopes along selected profile lines were to the order of 1 meter and 3º, respectively (at a spatial resolution of 15 meters). Best results were obtained when the images include one from the summer and the other from the winter, corresponding to maximum difference in solar zenith and azimuth angles. Errors in heights were attributed to surface heterogeneity (e.g., presence of biogenic soil crusts in the rainy season), geometric correction errors, cast shadows, and BRDF effects.

1. Introduction

Environmental phenomena measured by electromagnetic radiation can be treated either as noise or as a signal, depending on the theme under study. Topographic shading and cast shadows can introduce errors into accurate analysis of satellite images, since they mask significant spectral features and hamper signal based mapping. Consequently they are usually treated as noise that needs to be removed (Ekstrand, 1996). Nevertheless, shading also stores information about topographic characteristics (in our case, of sand dunes), and in this sense, the noise becomes an important signal that should be extracted and analyzed.

Digital Elevation Models (DEMs) are digital representations of topographic surfaces, containing only elevation data. The traditional methods to measure heights and create DEMs are (Toutin, 2001): (1) photo-clinometric methods (the use of information from either shadowing or shading; also termed photometric stereo or shape from shading); (2) photogrammetric methods (using stereo pairs of aerial photographs, or satellite images e.g., SPOT or ASTER); (3) radar (e.g., the shuttle radar topography mission- SRTM); (4) and laser altimeters. As aerial photogrammetry and laser altimeters are expensive and not applicable over wide range areas, remote sensing from satellite images may provide a favorable solution.

Planetary remote sensing used photoclinometry to determine the topography of the moon, Mars (mostly in the polar regions) and other planets since the 1960's (e.g. Bridges and Herkenhoff, 2002). The only attempt, however, to the best of our knowledge, to extract topo-graphic information of the Earth's surface from optical satellite images based on their shading effects, was that of Lodwik and Paine (1985), over the Barnes ice-cap on Baffin Island. A previous attempt to quantify dunes' topographic parameters was done by Qong (2000), that suggested a method for estimating Root Mean Square (RMS) of a dune's slope and height from Synthetic Aperture Radar (SAR) images. Zhang et al. (1999) have compared several algorithms that were developed for the extraction of shape-from-shading (SFS) and recommended the use of multiple images where the light source is moved – an approach that we will develop in the following sections.

Sand dunes are high albedo targets that may be considered homogeneous, where they are (1) bare of vegetation or biogenic soil crusts (Karnieli et al., 1999), and (2) homogenous in their mineralogy (White et al., 1997; Ben-Dor et al., 1999). The facts that (1) sand dunes are dynamic in nature, with the dunes changing their location, length, or height, depending on the dune type (Tsoar, 2001), (2) that they are generally poorly mapped around the world due to their dynamic nature and their remoteness, and (3) that their extent of area is usually known more accurately than their height (Cooke et al., 1993) make them an ideal target for the application of remote sensing photo-clinometric techniques.

The reflectance of sand is also dependent upon Bidirectional Reflectance Distribution Function (BRDF) effects. BRDF effects become important for sand and crust surfaces especially at solar zenith angles greater than 30º (Cierniewski and Karnieli, 2002). BRDF effects are stronger when the viewing angle of the sensor is wider, and their importance is of second order (in relation to shading effects) on nadir viewing sensors, such as Landsat, or when the area analyzed is relatively small (i.e., the azimuth angle between the sun and the sensor in the area is constant).

Based on the previous review that summarized the importance of dune morphology and shading effects, the objectives of this study were:

- Study the shading effects on transverse and linear dunes, as influenced by their orientation and the sun's zenith and azimuth angles;
- Develop and apply a method for extracting slope/aspect/height information of sand dunes from shading effects as seen on Landsat images;
- Determine the accuracy of the method, compared to height profiles extracted from photogrammetrically derived DEM's over sand dunes.

2. Materials and methods

Two research areas were selected at the center and the south of Israel, each representing a different kind of sand dune:(1) Coastal transverse sand dunes south of the city of Ashdod, Israel, and (2) Desert linear dunes of the Negev (near Nizzana), on both sides of the Israel-Egypt border. The mean and standard deviation of the heights of both dune areas is at the order of μ=10m and σ=4m. Five Landsat images (Table 1) were selected for this study in order to represent two generations of Landsat sensors, and to study the influence of the time of year on the shading effects.

Table 1: Time of year, and sun zenith and azimuth angles for the six Landsat images selected for the research

Sensor	TM	TM	ETM+	ETM+	ETM+
Date	August 1985	18-1-1987	7-8-1999	14-1-2000	21-5-2000
Solar zenith	34.2	62.4	28.6	58.6	24.6
Sun azimuth	108.6	142.6	116.6	151.6	112.5

All Landsat images were converted from DN to radiance values, and then corrected atmospherically using the MODTRAN 3 (Abreu and Anderson, 1996) radiative transfer model. The Ashdod dunes images were geo-rectified to Israel Transverse Mercator (ITM) coordinate system (Mugnier, 2000) using 10-20 ground control points (GCP's) located on an orthophoto, using the triangulation method available in ENVI 3.4 package (Research Systems, Inc., 2001). Satellite images over the Nizzana dunes were left in UTM coordinate system (as they were received), and the DEM was converted from ITM to UTM using standard projection tools.

For validation and calibration purposes we used detailed DEM's created in photogrammetric methods from aerial photographs. Shading can be modeled to a first degree as a function of how directly the sun's rays are incident upon the slope, that is, a function of cos(i) (Ekstrand, 1996, p. 152):

$$\cos(i) = \cos(e)\cos(z) + \sin(e)\sin(z)\cos(\phi_s - \phi_n) \quad \textbf{1.}$$

Wherei = incident angle between the surface normal and the solar beam,
e = surface normal zenith angle or terrain slope;
z = solar zenith angle;
ϕ_s = solar azimuth angle;
ϕ_n = surface aspect of the slope angle.

To determine whether a point is in shadow, the zenith angle to the horizon, should be calculated and compared with the solar zenith and azimuth angles. In sand dunes the maximum angle of slope (the angle of repose) is 33˚ (Bagnold, 1954). In three of the Landsat images used the solar zenith was less than 57˚ (i.e. sun elevation greater than 33º) and thus no shadowing was expected. In the other Landsat images that were used (Jan. 1987 and Jan. 2001) we estimated that there were only small shadowing effects, based on solar zenith angles between 58˚-62˚.

The magnitude of observed shading effects can be calculated from the variance of refletance values observed in an area. Expected shading effects for a given time of day and year can be calculated using a DEM, using equation 1, where the variance in cos(i) values stands for the amount of shading effects. In addition, calculated cos(i) values can be compared with the reflectance values observed in the Landsat images, for each of its spectral bands, in order to evaluate which bands are best for extracting topographic information. Correlation coefficient values between cos(i) and refletance values depend upon the homogeneity of the dunes' surface (therefore those parts of the dunes with no vegetation coverage were analyzed), accuracy of the geometric correction of the DEM, and the dynamic range of reflectance values and cos(i) values.

Equation 1 presents the shading effect as dependent on the sun's position (zenith and azimuth angles) with respect to the surface and the topography of the surface itself (slope and aspect). Given two images taken at different times (sun's position known), close enough in time so that no significant changes in the topography or the land cover emerge, they can be used as a database from which the slope and the aspect of the surface can be extracted using the reflectance values of the images. This is based on the idea that variation in the reflectance of the dunes' surface is only governed by the shading effects.

The problem presented here is actually solving for the values of two variables from two equations. As it is not possible to isolate either the slope or the aspect variables from equation 1, the following method is proposed:

- For each pixel a lookup table consisting of 192 possible combinations of slope and aspect were calculated (12 values of slope between 0˚ and 33˚ with intervals of 3˚, 16 values of aspect between 0˚ and 337.5˚ with intervals of 22.5˚). Cos(i) values were calculated for all these combinations.
- Cos(i) values were empirically calibrated from the reflectance values in the images using available DEM's (note that it suffices to have a DEM template

of the same dune type, rotated and stretched so it will have the same characteristics of the area under study, that is, dunes' orientation, height, spacing etc) using histogram matching techniques.

- For each of the 192 combinations, the difference between the actual value of cos(i) in the image, and the lookup table cos(i) was checked:

$$\textbf{Difference} = \textbf{abs} \left[\cos(i)_{j,\ date-a} - \cos(i)_{date-a} \right] + \textbf{abs} \left[\cos(i)_{j,\ date-b} - \cos(i)_{date-b} \right] \quad \textbf{2.}$$

Where j = 1-192 combinations;
date-a = image from time a;
date-b = image from time b;
abs = absolute difference

- Each pixel is assigned to those slope and aspect values that give the smallest difference between the calculated and actual cos(i) values.

The method proposed assumes lambertian reflectance, no cast shadows, and spectral homogeneity of the dunes' surface. As the calibration functions were found to be nonlinear, using linear correlation functions to calibrate from reflectance values to cos(i), as practiced by Lodwick and Paine (1985) is not appropriate.

The slope and aspect maps derived by the proposed method present the maximum slope (α) and its orientation relative to north. In order to calculate relative heights along a profile line from those values of slope and aspect, one needs to extract from the maximum slope α in a pixel, the slope β in the direction of the profile line. The following equations describe the relations between angles α, β and ϕ, mathematically.

$$\mathbf{l = h * \tan \alpha / \cos \phi} \quad \textbf{3.}$$

$$\mathbf{\tan \beta = \tan \alpha / \cos \phi} \quad \textbf{4.}$$

Where l = length of pixel along the profile line
h = height difference between adjacent pixels along the profile line
α = maximum slope angle;
β = slope in the direction of the profile line
ϕ = difference between the aspect angle of the maximum slope and the azimuth of the profile line.

3. Results

3.1 Simulating topographic effects on dunes in Landsat images

To investigate whether the relatively coarse spatial resolution of Landsat images (30 m) enables the characterization of desert and coastal dunes from shading effects on the images, we have simulated shading effects as seen by Landsat using detailed DEM's (controlling the time of the year and the dune's orientation).

The DEM's were resampled to a spatial resolution of 30m to match the TM spatial resolution, and rotated by 45º, so that eight DEM's were created representing transverse dunes (Ashdod) and linear dunes (Nizzana), with orientations of 0º, 45º, 90º, 135º, 180º, 225º, 270º, and 315º. Shading was simulated on these DEM's by calculating cos(i) values for the 22nd of each month (thus representing the winter and summer solstice, and the fall and spring equinox) at the time of day corresponding to the overpass of Landsat TM (10:00 am). All in all, 96 simulated cos(i) images (8 orientations * 12 months) were created for each of the dune fields. In addition we have examined the correlation between simulated cos(i) values and reflectance values over bare sand dune areas on the Landsat images.

Both the simulations and the correlation analysis led to the following conclusions: it was found that shading effects are greater in winter than in summer (as the sun's elevation angle is lower) and that the favorable orientation of the dune's crest line for achieving maximum shading effects is at angles orthogonal (90º and 270º) to the dune's crest line.The most recommended months to derive topography were thus expected be a combination of a wintertime image (highest correlation with cos(i) values) and a summer-time image (least correlated with the wintertime image).

Correlation coefficients between image reflectance values and cos(i) values were found to be higher when sparse vegetation and biogenic soil crust areas were excluded from the analysis. As for choosing the best bands for extracting topographic information, the following may be stated:

Among the optical spectral bands, correlation was higher in the NIR than in the VIS, as they are less effected by atmospheric scattering. The correlation of the thermal band of the ETM+ is usually higher than that of the optical bands, although its spatial resolution is coarser (60m vs. 30m), due to differential heating; And, the correlation of the panchromatic band was the highest, probably due to its finer spatial resolution (15m.).

3.2 Topographic information extracted from Landsat images

The method developed above was applied to band 4 of the Landsat TM images of August 1985 and January 1987, for the eastern part of the Ashdod sand dunes that are relatively bare of vegetation. Over the linear dunes of Nizzana, the panchromatic band of Landsat 7 ETM+ was used to derive the slope and aspect images, examining three temporal combinations (Aug99-Jan00, Aug99-May00, and Jan00-May00), to assess the stability of the method and the best temporal combination for the extraction of topographic information.

To examine the reliability of the slope and aspect maps extracted from the Landsat images, the slope, aspect and height values were measured along two profile lines from west to east along the Ashdod dunes, and from south to north along the Nizzana dunes. The profile lines were aligned normally to the orientation of the dunes' slip faces, in order to achieve the best estimates of the slopes, as was done in similar studies (e.g. Bridges and

Herkenhoff, 2002). Over each profile, the slope, aspect and height were measured from available detailed DEM information which was used as a reference. Slope and aspect were also extracted along the profile lines from the Landsat images, and relative elevations were calculated from these in the method described above (equations 3 and 4).

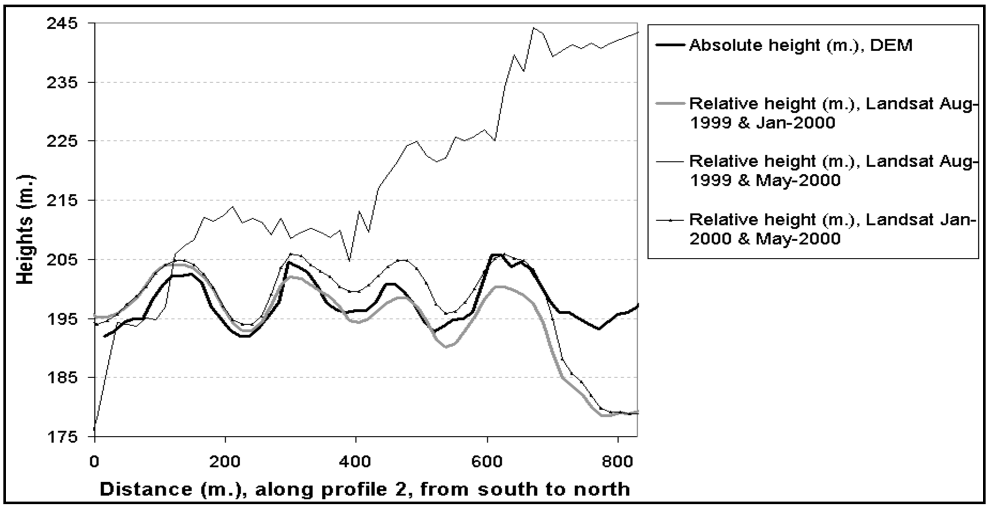

Figure 1: Heights calculated along profile line 2 along the Linear dunes of Nizzana.

Figure 1 presents the extracted heights along profile line no. 2 of Nizzana, calculated from three combinations of Landsat 7 ETM+ images: (1) August 1999 – January 2000, (2) August 1999 – May 2000, and (3) January 2000 – May 2000. A quantitative analysis (Table 2) reveals high correspondence between DEM elevations and those extracted from Landsat images over the Ashdod dunes: R = 0.63 for profile A, R = 0.88 for profile B, and that the average absolute differences between height changes along profile lines of both DEM's are only 0.9 meters.

From Table 2 and from a careful observation of Figure 1, it is clear that the worst results were obtained using the Aug1999-May2000 combination (lowest R values), and the best results using the Aug1999-Jan2000 combination (highest R values and lowest differences of elevation). Based on these results, our hypothesis that using a combination of a winter image with a summer image was confirmed. The average absolute errors of the slope (Table 2) were about 3º (for the combinations of winter and summer images), that is similar to the slope intervals defined in our lookup table for calculating slope values from reflectance. These errors can be reduced by applying smaller intervals than those used by us for identifying the slope and aspect. The difference in elevations between the photogrammetric DEM and those extracted from Landsat images, seen in the right hand side of Fig. 1, was found to be due to the presence of biogenic soil crusts there (therefore defying the assumption of the homogeneity of the surface in that stretch).

4. Discussion

The method proposed in this study demonstrated the potential of Landsat images for studying dunes' terrain, using two Landsat images taken at different times of the year. With a spatial resolution 10 times higher (15m in ETM+ band 8, and 30m in the other optic bands) than that of the dune's spacing (150-300m), subtle topographic features of sand dunes could be extracted, reaching an average accuracy of 3º in the estimation of slopes. Calculated relative elevations along selected profile lines, yielded highly accurate results, to the order of 1 meter (for pixels the size of 15 meters) that is 1/10

Table 2: Accuracy of elevations and slopes extracted from Landsat 7 ETM+ images over the dunes of Nizzana along profile lines 1 and 2, and from Landsat 5 TM images over the dunes of Ashdod along profile lines A and B, compared with the data extracted from detailed DEM

Study area		Nizzana						Ashdod	
Length of profile lines		1: 1,560 meters; 2: 830 meters						A: 720 m.; B: 460 m.	
Landsat images used		Aug 1999 & Jan 2000		Jan 2000 & May 2000		Aug 1999 & May 2000		August 1985 & January 1987	
Profile Line		1	2	1	2	1	2	A	B
Comparison with changes in DEM elevations along profile lines	R	0.67	0.76	0.63	0.75	0.00	0.00	0.44	0.74
	Average absolute difference	1.1	1.0	1.2	1.1	2.5	2.8	0.9	0.9
Comparison with DEM slopes (along profile line)	R	0.59	0.48	0.46	0.46	0.00	0.14	0.45	0.73
	Average absolute difference	2.9	3.3	3.6	1.3	5.9	7.6	3.6	3.4

of the average dune height. These accuracies were obtained in two areas of sand dunes, each having different characteristics: one of transverse coastal dunes, and the other of linear desert dunes. Best results were obtained for a combination of a winter and a summer image, offering maximum difference of sun position with respect to the surface. In addition, orientation of the dunes at an angle normal to the sun azimuth enhances shading effects, and is thus favorable for the success of shape from shading algorithms.

In spite of the good results that were obtained by the proposed method and its ease of use, we can identify several limitations, as follows:

a. The method can be applied only to homogenous surfaces (i.e., dunes, snow, glaciers), where differences in the reflectance are the result of shading effects (i.e., no vegetation, crust or rocks are present).
b. In order to calculate slope and aspect images from satellite images over large areas, BRDF effects should be dealt with prior to the processing of the images.
c. One of the major limitations of applying the proposed method is in the need to have some DEM information for the proper sand dune type in question, to calibrate reflectance into cos(i) values. Based on the findings of Breed and Grow (1979), we suggest creating a DEM library (lookup table) for varying dunes types worldwide. In this library there will be a collection of high-resolution DEMs for the different dune types — barchan, parabolic, transverse, linear, star, and so on. For each dune type several parameters will be recorded, such as the dune's mean length, width, spacing, orientation, and height. To apply these sample DEMs in order to predict the expected shading on a given sand dune's area, the DEM will be chosen according to the dune type and then rotated and stretched to fit the actual orientation and spacing (that can be visually estimated). These steps will enable the calibration of reflectance values to cos(i) and the calculation of sand dune characteristics for sand dunes all over the world with minor efforts, based on a few high-resolution measurements, using the proposed method.

Photometric stereo methods for the extraction of topographic information have several important advantages, for example: (1) DEM with a high spatial resolution (the spatial resolution of the sensor); (2) the extraction of topographic information from satellite images acquired by early Landsat MSS and TM missions. So far, optical satellite images were used to gain information regarding the spatial extent of sand dunes, their vegetation cover and mineralogical composition. The method developed here offers new opportunities for studies of aeolian geomorphology, adding the ability to analyze dynamic aspects of sand dunes topography in time and space.

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