The Development of a Land Use Change Detection Methodology for Mapping the Taita Hills, South-East Kenya: Radiometric Corrections

Barnaby J. F. Clark and Petri K. E. Pellikka

Department of Geography, University of Helsinki, P.O. Box 64, FIN-00014 Helsinki, Finland - barnaby.clark@helsinki.fi

Abstract –As a first stage in the development of a land use change detection methodology for the TAITA research project, an absolute atmospheric correction was applied to multi-temporal SPOT XS data using the proposed historical empirical line method (HELM). Based on a small verification sample, surface reflectance (P_s) was retrieved for all bands and all dates with an average RMSE better than 2%. Comparisons were made to simple DOS and COST atmospheric corrections, which derived accuracies of ~10%, but HELM was significantly better. The rugged terrain in the Taita Hills also required the SPOT imagery to be orthorectified and topographically normalized before it could be considered comparable.

Keywords: SPOT, atmospheric correction, empirical line method

1. INTRODUCTION

The Taita Hills study area in south-eastern Kenya (see Figure 1) forms a northern part of Africa's Eastern Arc Mountains, which have been identified by Conservation International as one of the top ten biodiversity hotspots in the world. In pressured environmentally sensitive and ecologically important regions, such as the Taita Hills, there is a continuing need for up-to-date and accurate land cover information that can be utilised in the production of sustainable land use policies. Whilst aerial photography or very high resolution satellite imagery is required for detailed *cartographic* mapping, the repeat coverage availability and low cost of multispectral optical satellite data make it more suited to the repetitive generation of *thematic* land use information for use in GIS based change detection and modelling tools. The accurate mapping of heterogeneous environments over time from multispectral optical satellite data does, however, present particular problems because of the requirement to spectrally calibrate multi-temporal imagery.

The TAITA[1] research project has available SPOT XS data for the years 1987, 1992, 1999, 2002 and 2003 (see Table 1 below). The first, and crucial, stage in the development of a practical land use change detection methodology is to make this imagery spatially and spectrally comparable. As can be seen from Table 1, the SPOT scenes are from various non-anniversary dates and have differing off-nadir sensor-view angles (θ_v), which adds further to the variance in measured at-sensor radiance up and above that attributable to changes in atmospheric conditions. Accurate change detection is dependent on the ability to successfully relate differences in corrected radiance or reflectance measurements to actual changes in vegetative state or land cover on the ground. As the TAITA project is multi-disciplinary, it was necessary to retrieve surface reflectance (P_s) from the imagery and therefore an absolute radiometric calibration, as opposed to a relative normalization, was required. A short field visit was made to the study area in January 2005 and measurements of P_s were made at a limited number of spectrally pseudo-invariant sites. In this study, comparisons of various simple atmospheric correction methodologies are made. The availability of ground data enabled an accuracy assessment of each of the utilized techniques.

Figure 1. The location of the Taita Hills in South-East Kenya

2. METHODS

2.1 Geometric Correction

The first step in processing the SPOT imagery was to make the various multi-temporal scenes spatially comparable. Because of the rugged terrain in the Taita Hills study area, it was necessary to orthorectify the imagery utilizing a 20-metre planimetric resolution DEM interpolated from 50-feet interval contours captured from 1:50,000 scale topographic maps. The 2003 image was orthorectified first using the scan-maps; all the other images were then orthorectified to this geometric master scene. A nearest-neighbour resampling technique was

[1] The TAITA project is supported by the Academy of Finland

Table 1. Details of the TAITA Project SPOT XS Imagery

Image Date	Path & Row	Sensor	θ_v	θ_z
1987-07-01	143-357	SPOT 1 HRV 1	R10.35°	36.35°
1992-03-25	*142-357* [a]	SPOT 2 HRV 1	R13.8°	26.5°
1992-03-25	*143-357* [a]	SPOT 2 HRV 2	R 9.3°	26.0°
1999-02-12	143-357	SPOT 4 HRVIR 2	L 4.2°	27.7°
2002-06-02	142-357	SPOT 4 HRVIR 1	L20.2°	32.4°
2003-10-15	143-357	SPOT 4 HRVIR 1	R10.4°	21.0°

[a] Adjacent scenes captured simultaneously.

employed to ensure that the original pixel values were preserved. As a consequence of utilizing 1:50,000 scale maps, the *absolute* planimetric accuracy of the geometrically corrected imagery is at worst ~ +/-75 metres, even though the multi-temporal inter-scene agreement is at a sub-pixel level (RMSE 0.45 pixels). The absolute accuracy is an important consideration when locating features measured in the field using GPS equipment, for example.

2.2 Atmospheric Correction

Although the geometric correction of multi-temporal satellite datasets is now a routine process, radiometric corrections continue to pose a challenge. The TAITA project SPOT images were all historical and no overpass-concurrent atmospheric data was available that could be used as inputs into radiative transfer models (RTM), such as 6S. Also, with only three broad spectral bands available in the VIS/NIR, the empirical estimation of the necessary atmospheric optical properties for an RTM correction was not possible. Ideally, for the operational use of historical optical satellite data, P_s could be accurately retrieved without the need for detailed atmospheric measurements or estimations. A limited amount of P_s measurements were made at a small number of spectrally pseudo-invariant sites in the Taita Hills. It was then possible to compare the Dark Object Subtraction (DOS) method (Chavez, 1988) and the Cosine of Solar Zenith Angle Correction (COST) method (Chavez, 1996) with a proposed correction based on P_s measurements. As a first step in radiometrically processing the SPOT imagery the raw DNs were divided, on a per-channel basis, by the gain values provided in the metadata files giving an at-sensor radiance (L_{SAT}) value in W m^{-2} sr^{-1} μm^{-1}. From there it was necessary to correct for variations in the solar zenith angle (θ_z), sensor view angle (θ_v), Earth-Sun distance, and atmospheric scattering and absorption between the image dates.

2.3 The Historical Empirical Line Method (HELM)

The empirical line method (ELM) corrects L_{SAT} data to P_s measurements, made at a number of spectrally stable calibration sites, utilizing a standard linear regression equation in the form $\boldsymbol{y = ax + b}$ (see Figure 2); where $\boldsymbol{a}$ is the slope of the regression line, representing the atmospheric attenuation, and $\boldsymbol{b}$ is the intercept with the x-axis, representing the atmospheric path radiance. A separate correction is derived for each spectral band in the data. The main assumptions are that the atmosphere is approximately homogenous throughout the image area and that there is a linear relationship between L_{SAT} and P_s. As Moran *et al*. (1990) note, although the relationship between L_{SAT} and P_s is quadratic for the full range of reflectance (0-100%), it is sufficiently linear over the range 0-70% to allow interpolation with negligible error. All P_s for the Taita Hills area are less than 70%.

Previous researchers have successfully retrieved P_s from remotely sensed data utilizing the ELM (e.g. Smith and Milton, 1999; Karpouzli & Malthus, 2003). The main problems with applying this method to SPOT data are to identify calibration targets that are large enough to counter the contaminating effects of the point spread function (PSF) on the instantaneous field of view (IFOV) of the sensor, and to account for the off-nadir θ_v of the imagery. As Karpouzli and Malthus (2003) note, the calibration and validation targets need to be at least three times the pixel size (60 x 60m for 20m resolution SPOT 1-4 XS data) to derive "correct" L_{SAT} pixel values. In outlining their Refined Empirical Line (REL) method for Landsat data, Moran *et al.* (2001) showed that, because of the near-linear relationship between L_{SAT} and P_s, an accurate estimation of the correction line can be obtained using detailed field measurements of only *one* appropriate within-scene bright calibration target, and a "reasonable" estimate of L_{SAT} for $P_s = 0$ derived using an RTM.

The proposed Historical Empirical Line Method (HELM) is based on the REL method, but derives the dark object radiance empirically directly from the imagery assuming a 1% reflectance (similar to the DOS method), rather than using an RTM to calculate L_{SAT} for $P_s = 0$. As Smith and Milton (1999) note, if the calibration targets are spectrally pseudo-invariant over time (which they should be if correctly chosen) then the measurement of P_s need not coincide with the image data acquisition. The objective of HELM is, therefore, to (re)construct the historical linear relationship between L_{SAT}, as recorded by the multi-temporal satellite imagery, and P_s for the Pseudo-invariant Pixels (PIPs) as measured in the field. Because of the extension of the assumptions across time, intelligent use of the technique is required. For example, the main bright target used in the TAITA project HELM was a road side quarry that migrated eastwards throughout the study period. Use of the same pixels in the 1987 image relating to ground measurements made in 2005 was clearly inappropriate as the land use has changed, and this area was not a quarry in 1987. Rather, as the planimetric difference was only in the order of ~100m, and having visited the site, it was evident that the surface material had not changed and the brightest central

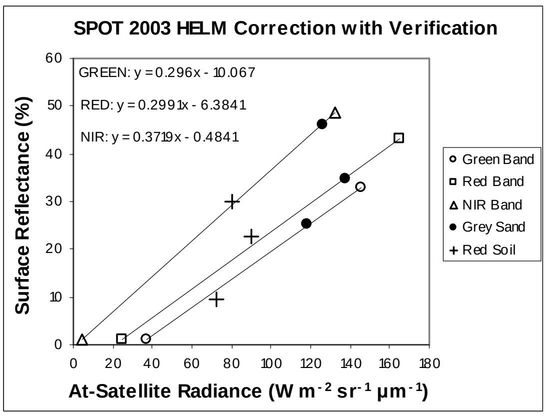

Figure 2. HELM correction to the 2003 SPOT-4 Image

pixel in the historical quarry location could be utilized as a PIP.

The bright calibration site should, then, be spectrally invariant, free of vegetation, as large as possible, and preferably a homogeneous flat area. Half-day long measurements were made at the roadside quarry in an attempt to measure changes in P_s with $\boldsymbol{\theta_z}$ and $\boldsymbol{\theta_v}$ (+/- 27° for SPOT), as suggested by Moran *et al.* (2001). The quarry area was flat, approximately 60m wide and 200m long, and formed mostly of light-grey calcareous fine sand, with some areas of angular pebbles of the same material. 15 sets of P_s measurements, each with a sample average of 15, were taken every 10 minutes using an ASD FieldSpec® Handheld VNIR (325 – 1075 nm, 3.5 nm spectral resolution) spectroradiometer calibrated to a Spectralon® $BaSO_4$ 99% reflectance panel before each measurement set. The device was handheld at ~1.2 m height, with a 25° bare-head optic giving an at-nadir ground view of 53cm in diameter.

In the event, it was found that the noise level of the handheld spectrometer measurements exceeded the signal of variation in P_s with $\boldsymbol{\theta_z}$ and $\boldsymbol{\theta_v}$, so it was not possible to quantify these relationships. However, it can be inferred from this that these variations must be relatively small and therefore that the calibration target exhibited near-Lambertian reflectance behaviour. It was thus considered that the average nadir reflectance characteristics of the target had been accurately captured and that the SPOT imagery with varying $\boldsymbol{\theta_v}$ could be normalized to this data with minimal error, given the measurement noise (coefficient of variation 12.69%). In order to increase the sample size to include some validation data, it was necessary to utilize sub-optimal locations because of the very limited number of vegetation free and spatially extensive sites in the Taita Hills area. Nadir P_s measurements were made of a sandy school playground, a compacted red soil road, and a tarmac road.

The spectrometer derived P_s data were processed to synthesis the SPOT response for the PIPs at each date based on the specific spectral sensitivities of each band (obtained from the SPOT website) for the SPOT sensor involved. The L_{SAT} values for the darkest in-scene object and the bright calibration site were determined for each spectral band from the SPOT images and regressed to the synthesized P_s to derive a correction equation which was then applied to the whole scene. In the case of the 1992 SPOT data, the two adjacent scenes were mosaiced together prior to a HELM correction by taking the mean average L_{SAT} value for each pixel in the overlap area.

2.4 Image Based Atmospheric Correction Methods

For a homogenous cloud free atmosphere and a uniform Lambertian ground surface, the relationship between L_{SAT} and P_s can be characterized as:

$$L_{SAT} = L_P + \frac{p_s \cdot (E_O \cdot \cos\theta_Z \cdot T_Z + E_{DOWN}) \cdot T_V}{\pi \cdot (1 - S \cdot P_s)} \quad (1)$$

Where L_P is the path radiance; S is the fraction of up-welling radiation back-scattered by the atmosphere to the surface and is small enough that it can be omitted (Song *et al.*, 2001); T_V is the atmospheric transmittance from ground target to sensor; T_Z is the atmospheric transmittance from sun to ground target; E_O is the exoatmospheric solar constant; and E_{DOWN} is the down-welling diffuse irradiance. To retrieve P_s Equation 1 can be rearranged as (Song *et al.*, 2001):

$$p_s = \frac{\pi \cdot (L_{SAT} - L_P)}{T_V \cdot (E_O \cdot \cos\theta_Z \cdot T_Z + E_{DOWN})} \quad (2)$$

$E_O = E \times d$; where E is the SPOT sensor and band specific equivalent solar irradiance in W m^{-2} μm^{-1} (obtained from the SPOT website), and d is the date corrected Earth-Sun distance in astronomical units (d = au^2). Due to the effects of atmospheric scattering the darkest object identified in a scene is not completely dark. Assuming a reflectance of 1% (Chavez, 1988), L_p can be calculated as:

$$L_p = L_{DOS} - 0.01 \cdot \left(\frac{E \cdot \cos\theta_Z}{\pi \cdot d} \right) \quad (3)$$

Where L_{DOS} is the radiance value of the identified darkest in-scene object. Chavez (1996) argued that T_Z can be approximated to a first order by $\cos(\boldsymbol{\theta_z})$: COST. Equations 2 and 3 were used as the basis for implementing a DOS correction and two COST corrections, utilizing varying parameters for T_V and T_Z, as outlined in Table 2 below. For the COST 2 correction, the optical thickness for Rayleigh scattering (τ_r) was estimated on a per-spectral band basis using Equation 4 (Song *et al.*, 2001), where λ is wavelength in μm, taking the median value of the spectral channel width in each SPOT band.

$$\tau_r = 0.008569 \cdot \lambda^{-4} \cdot (1 + 0.0113 \cdot \lambda^{-2} + 0.00013 \cdot \lambda^{-4}) \quad (4)$$

Table 2. Parameter Settings for use in Equation (2)

Method	T_V	T_Z	E_{DOWN}	Accuracy [a]
DOS	$cos(\theta_v)$	1.0	0.0	10.2%
COST 1	$cos(\theta_v)$	$cos(\theta_z)$	0.0	8.21%
COST 2	$e^{-\tau r/cos(\theta v)}$	$e^{-\tau r/cos(\theta z)}$	0.0	9.01%

[a] Average RMSE %P_s for all bands and all dates, based on two P_s measurement sites (quarry & tarmac road).

2.5 Topographic Normalization

The topographic correction of satellite imagery over rugged or mountainous terrain is at least as important as atmospheric correction, if comparable P_s are to be taken throughout the study area. For the TAITA project, a cosine correction method was applied to the HELM atmospherically corrected data based on empirically derived C-factors for slopes >5°.

3. RESULTS AND DISCUSSION

As Table 3 shows, HELM corrected the SPOT data with an average estimated RMSE better than 2% P_s for all bands and all dates. Figure 2 above details the HELM correction to the 2003 image. Note that the “grey sand” and “red soil” points were not used in the derivation of the regression line, but form verification data for the correction. It can be seen that, as expected, the intercept on the x-axis representing L_P is greatest for the green band and least for the NIR band. Also note the very similar slope of the correction line for the green and red bands but the slightly steeper slope for the NIR, representing lesser atmospheric attenuation. Table 4 shows that, even considering the variable paths of the SPOT imagery, the average difference in the mean P_s of all bands for all dates was reduced to 2.24%; compared to 3.39% for the uncorrected top-of-atmosphere (TOA) reflectance data. Note, however, that the mean variation for the NIR band actually increased slightly with the HELM correction from 1.46% to 2.57%. Table 2 shows that the image based corrections derived estimated RMSEs of ~10% P_s, although the standard COST 1 method was marginally better than either COST 2 or DOS. All three were, then, significantly less accurate than HELM. More importantly, however, as can be seen in Table 5, there was a bias in underestimating P_s for bright targets, which was present in all three image based correction methods. This is a known problem for DOS based correction techniques.

Table 3. HELM Accuracy* (all values % reflectance)

Image Date	Band 1	Band 2	Band-3	Average
1987-07-01	1.27	0.51	0.95	*0.91*
1992-03-25	2.60	1.81	1.75	*2.05*
1999-02-12	3.02	2.04	2.58	*2.55*
2002-06-02	1.97	2.49	3.23	*2.56*
2003-10-15	1.03	1.16	0.42	*0.87*
Average	*1.98*	*1.60*	*1.79*	**1.79**

* RMSE based on four P_s measurement sites for each date

Table 4. Mean Reflectance: Uncorrected & HELM Corrected

Uncorrected TOA *P* %	Band 1	Band 2	Band-3
1987-07-01 143-357	10.77	11.37	22.21
1992-03-25 142/3-357	12.46	13.56	20.94
1999-02-12 143-357	17.03	19.70	21.73
2002-06-02 142-357	9.50	11.38	19.64
2003-10-15 143-357	13.02	15.97	22.88
Mean Difference (*3.39*)	***3.90***	***4.85***	***1.46***
HELM Corrected P_s %	**Band 1**	**Band 2**	**Band-3**
1987-07-01 143-357	11.25	16.43	26.99
1992-03-25 142/3-357	11.90	18.26	26.41
1999-02-12 143-357	12.96	15.82	23.72
2002-06-02 142-357	9.50	19.23	22.53
2003-10-15 143-357	10.64	15.34	25.42
Mean Difference (*2.24*)	***1.77***	***2.31***	***2.57***

Overall, it is encouraging that HELM gives acceptable absolute atmospheric correction results using only one bright calibration target and an image derived P_s = 1% dark object. Although there is a requirement for a limited amount of field measurements to be made, most workers will visit their study area at least once during the lifetime of a research project, so this should not be an issue. One disadvantage of applying HELM to the TAITA SPOT data was that it was not possible to calibrate the SWIR Band 4 data (only available for 1999 and 2003), as the utilized spectrometer was limited to the 325 – 1075 nm range. Also, it was found that a handheld spectrometer is not suitable for deriving measurements of bidirectional reflectance factors, and the utilization of a goniometer (not available for the TAITA project) is recommended. Topographic or cloud shadows, or deep clear water for the NIR band, provide good P_s=1% dark objects. Band 1 and 2 estimations should utilize the same pixels.

Table 5. Bias in P_s Estimation for Image Based Corrections

Correction Method	"Dark" Target Bias[a]	"Bright" Target Bias[a]
DOS	0.08	-13.89
COST 1	0.99	-9.95
COST 2	0.67	-11.5

[a] Dark target is tarmac; bright target is quarry. Bias is average absolute difference in predicted & measured P_s for all three SPOT bands and dates combined.

4. CONCLUSIONS

Users of SPOT imagery should be aware that DOS or COST based atmospheric corrections may be expected to derive estimations of P_s with approximately 10% accuracy, but are likely to suffer from bias in underestimating P_s for bright surface features. Where there is a requirement for improved accuracy in retrieving P_s, a HELM correction based on field measurements at one calibration site and image derived dark objects or, if atmospheric measurements are available, an RTM correction should be implemented.

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