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SURFACE ORIENTATION INVARIANT MATCHING OF SPECTRAL SIGNATURES

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ABSTRACT:

For monitoring purposes, change detection and segmentation of remotely sensed multispectral images it is necessary to normalize the images in order to yield spectral signatures independent of illumination, atmospheric conditions and surface orientations. For small scale artificial objects in high resolution images however, the surface orientation is not known, and hence comparison of spectral signatures is prone to error due to varying illumination. We assess the relative contribution of direct versus diffuse illumination, and present a spectral distance measure and a spectral transformation which provide color constancy and are independent of the degree of direct versus diffuse illumination and thus surface orientation.

KURZFASSUNG:

Für Monitoring, Änderungserkennung in und Segmentation von multispektralen Fernerkundungsbildern ist zunächst eine Normalisierung der spektralen Signaturen nötig, um diese invariant gegen Beleuchtung, atmosphärische Bedingungen und Oberflächenorientierung zu machen. Für kleine künstliche Objekte in hochaufgelösten Bildern ist die Oberflächenorientierung jedoch nicht bekannt, und somit der Vergleich der spektralen Signaturen aufgrund der wechselnden Beleuchtung fehleranfällig. Wir bestimmen den relativen Anteil der direkten gegenüber der diffusen Beleuchtung, und entwickeln ein spektrales Abstandsmaß und eine spektrale Transformation, die Farbkonstanz erzeugen, vom Grad der direkten gegenüber der diffusen Beleuchtung unabhängig und somit invariant gegen unbekannte Oberflächenorientierung sind.

INTRODUCTION

For monitoring purposes of multitemporal remotely sensed multispectral images as well as for segmentation and classification within a single multispectral image, it is necessary to normalize the images to each other, *i.e.*, to apply a radiometric correction in order to produce spectral signatures independent of illumination, atmospheric conditions and surface orientations.

Generally a Digital Elevation Model (DEM) of the image scene is required to compute surface orientation (e.g. slope and aspect) for each surface element. Then the actual illumination of the particular surface element can be calculated (a.o. Parlow & Scherer (1991), Richter et al. (1991)).

However, for airborne monitoring of small scale artificial objects, e.g. roof tops, buildings and streets, the surface orientation is usually unknown, due to practical reasons (limited resolution of DEM etc.). Therefore spectral signatures of those objects cannot be corrected for angular dependency and appear distorted in the image data. In the field of Computer Vision and Theoretical Biology this is known as the problem of lacking Color Constancy (Brill 1978), (Maloney & Wendell 1986). As a consequence, classification, segmentation and change detection will be prone to error.

The influence of the orientation of a surface element on its upwelling radiance is twofold:

i) The geometric configuration determines the direct and diffuse radiance downwelling to the surface element.

ii) The Bidirectional Reflectance Distribution Function (BRDF) determines the radiance being reflected in the direction of the observing sensor.

Since the knowledge of the BRDF of artificial surfaces is sparse, the actual state of our work is to approximate the BRDF by Lambert reflection. Then the observed spectral radiance reflected by a given surface element will simply be proportional to its global (= diffuse plus direct) irradiance, and the spectral signature can be expresed as the product of illumination spectrum and reflectance spectrum.

But as diffuse and direct irradiance (*i.e.*, skylight and sunlight) obey different angular dependencies, and the ratio of diffuse to direct irradiance at a given surface orientation decreases with increasing wavelength, the illumination spectrum can vary and thus the spectral signatures can appear non-linearly transformed. With only one light source present, the spectra can be made invariant by reducing them into spectral band ratios (Sabins 1978). However, if diffuse irradiance contributes significantly and the downwelling diffuse radiance distribution is not mainly centered around the sun, even spectral band ratios will not be invariant against surface orientation. In this context we consider the following aspects:

- In order to avoid misclassification and false change detection a criterion is developed to decide if two particular observed spectra can possibly have originated from equal surfaces of differing orientations, considering the respective ratios of diffuse to direct irradiance. The comparison of two such spectra yields a measure for their likelihood of equality which can be thresholded. The criterion can be used for segmentation by region growing in lieu of precise surface orientation knowledge as well as for temporal comparison of identical objects illuminated from differing sun angles.
- For two surface elements classified as equal, *i.e.*, consisting of the same material, constraints on their respective slope and aspect are investigated, in order to determine if inclinations of roof tops and other surfaces can be computed from two observed spectra of the object in question, as a multispectral extension of Shape From Shading theory, in complement to geometric displacement measurements.

Ho et al. (1990) have shown a solution for the case that all possible illumination and reflectance spectra can be described by a limited number of known basis spectra with orthogonal products. This is claimed true for the visible spectral range (400–700 nm). In contrast to that the spectral range considered here is significantly extended into the reflected infrared and no assumptions about the reflectance spectra are made by the following discussion.

SURFACE ORIENTATION AND SPECTRAL SIGNATURE

In this study we are concerned with multispectral image data recorded by an opto-electronic sensor. The calibration constants of the opto-electronic sensor allow to convert the raw Digital Counts [DC] into spectral band radiances L in units of [W m^{-3} sterad^{-1}]. For each image pixel we have N spectral bands i with radiances

$$L_i = \pi^{-1} \rho_i E_{\mathrm{glob},i} + L_{o,i} \quad ; i \in [1..N] \tag{1}$$

where $E_{\mathrm{glob},i}$ is the global irradiance welling down onto the reflecting surface element, ρ_i is the Lambert reflectance factor, and $L_{o,i}$ is the path radiance. The path radiance is computed using a Radiative Transfer Code (RTC) and subtracted. The global irradiance is computed as $E^{\perp}_{\mathrm{glob},i}$ for a horizontal surface element (zenith angle $\theta = 0$). Then, assuming a Lambertian reflectance model, a normalized reflectance signature $\vec{\rho}^* = (\rho^*_1, .., \rho^*_N)$ can be calculated:

$$\rho^*_i = \pi \frac{L_i - L_{o,i}}{E^{\perp}_{\mathrm{glob},i}} \tag{2}$$

However this is only a pseudo-reflectance (connoted by an asterisk), since a possible inclination $\theta \neq 0$ of the surface element is not considered.

The global irradiance onto the horizontal surface element consists of a direct and a diffuse part, from the sun and the dome of the sky respectively:

$$E^{\perp}_{\mathrm{glob},i} = E^{\perp}_{\mathrm{dir},i} + E^{\perp}_{\mathrm{diff},i} = E^{\perp}_{\mathrm{glob},i}(n_i + m_i) \tag{3}$$

where n_i and m_i are the relative spectral contributions of direct and diffuse irradiance, with $n_i + m_i = 1$.

When the surface element is tilted, the contributions of direct and diffuse irradiance vary with factors ν and μ respectively:

$$E_{\mathrm{glob},i} = E^{\perp}_{\mathrm{glob},i}(\nu n_i + \mu m_i) \tag{4}$$

Hence the true reflectance

$$\rho_i = \pi \frac{L_i - L_{o,i}}{E_{\mathrm{glob},i}} \tag{5}$$

is related to the pseudo-reflectance as

$$\rho^*_i = \rho_i(\nu n_i + \mu m_i) \quad . \tag{6}$$

The illumination factors ν and μ are functions of $(\theta, \phi, e_{\odot}, a_{\odot}, \Omega)$, *i.e.*, of the zenith or inclination angle θ and the azimuth angle ϕ of the surface element, the elevation $e_{\odot}$ and azimuth $a_{\odot}$ of the sun, and the directional downwelling radiance distribution of the sky Ω. The factors ν and μ describe the direct and diffuse contribution to the global irradiance downwelling onto the surface.

The possible feature vectors $\vec{\rho^*}$ of a certain surface with the true spectral signature $\vec{\rho}$ under different surface orientations are then restricted to

$$\vec{\rho^*} = \nu \begin{pmatrix} n_1\rho_1 \\ \vdots \\ n_N\rho_N \end{pmatrix} + \mu \begin{pmatrix} m_1\rho_1 \\ \vdots \\ m_N\rho_N \end{pmatrix} \quad (7)$$

$$= \nu\vec{a} + \mu\vec{b} \;\; ; \; \nu,\mu \in \mathbb{R}_0^+ \quad (8)$$

which is a two dimensional linear subspace of the feature space $\mathbb{R}^n$. The two degrees of freedom reflect the two light sources (diffuse and direct).

A deviation from this two dimensional plane can either indicate specular reflection with a different reflectance $\rho_{\mathrm{spec},i} \neq \rho_i$, or non-membership to the spectral class formed by the specific surface. Consequently surface specific spectral classes need to be represented not by single points in feature space (cluster centers) but by the proper two-plane. The measure of likelihood to belong to a certain class is then a function of the distance to the plane. Such planes can, but do not necessarily need to intersect in $\mathbb{R}^n$.
As the path radiance $L_{o,i}$ is already subtracted, the origin of the feature space will be a point of the plane (*i.e.*, $\nu = \mu = 0$), and thus in principle two further points are sufficient to constrain the plane. In case the path radiance is not yet known it can be estimated from the intersections of the plane with the axes of the feature space.

DISTANCE MEASURE FOR COMPARISON OF TWO SPECTRA

In order to avoid a distance measure which is dependent on the absolute magnitude of the reflectance, we consider the ratio of two spectral signatures $\vec{\rho^*}$ and $\vec{\rho^*}'$ (for instance from two parts of a roof top):

$$q_i^* = \frac{\rho_i^*}{\rho_i^{*\prime}} = \frac{\rho_i(\nu n_i + \mu m_i)}{\rho_i'(\nu' n_i' + \mu' m_i')} \quad (9)$$

$$= q_i \frac{\mu}{\mu'} \frac{(\eta n_i + m_i)}{(\eta' n_i' + m_i')} \quad (10)$$

$$= q_i \kappa \frac{\eta n_i + m_i}{\eta' n_i' + m_i'} \quad (11)$$

where $q_i = \frac{\rho_i}{\rho_i'}$, $\kappa = \frac{\mu}{\mu'}$, $\eta = \frac{\nu}{\mu}$, $\eta' = \frac{\nu'}{\mu'}$,
and $(\vec{m},\vec{n}),(\vec{m}',\vec{n}')$ are the respective diffuse and direct spectra in case the spectra $\vec{\rho}$ and $\vec{\rho^*}$ come from images of different illumination conditions.
Here, trivially, for equal spectra the ratio is $\vec{q} = \vec{1}$.
The distance d^2 between two unequal true spectral signatures can be then defined as the mean square deviation of the ratio vector $\vec{q}$ from unity:

$$d^2 = \frac{1}{N}\sum_{i=1}^{N}(q_i - 1)^2 \quad (12)$$

Substituting q_i from Eqn. 11 yields

$$d^{2^*} = \frac{1}{N}\sum_{i=1}^{N}\left[q_i^* \frac{1}{\kappa}\frac{(\eta' n_i' + m_i')}{(\eta n_i + m_i)} - 1\right]^2 \quad (13)$$

In order to get a distance measure independent of the unknown surface orientations, we evaluate the distance as the minimum of all possible values for (η, η', κ)

$$d^{2^*} = \min \left\{ d^2(\eta,\eta',\kappa) \; : \; (\eta,\eta',\kappa) \in \mathbb{R} \right\} \quad (14)$$

This definition ensures that

(a) spectral signatures which could possibly have originated from equal surface elements are assigned a distance $d^{2^*} = 0$, and

(b) spectral signatures from different surfaces are always assigned the same distance $d^{2^*} = \mathrm{const} \neq 0$ independently of both their actual orientations.

The (κ,η,η') tupel of minimal distance d^2 can be found by linearizing Eqn. 11 and demanding a least square deviation:

$$S = \sum_{i=1}^{N}\left[\eta' q_i^* n_i' + q_i^* m_i' - \eta\kappa n_i - \kappa m_i\right]^2 \stackrel{!}{=} \min \quad (15)$$

$$\Rightarrow \frac{\partial S}{\partial \kappa} = \frac{\partial S}{\partial \eta\kappa} = \frac{\partial S}{\partial \eta'} \stackrel{!}{=} 0 \quad (16)$$

which is solved by means of the pseudo-inverse:

$$\begin{pmatrix} \kappa \\ \eta\kappa \\ -\eta' \end{pmatrix} = \mathbf{P^{-1}} \begin{pmatrix} \sum_i q_i^* m_i m_i' \\ \sum_i q_i^* m_i' n_i \\ \sum_i q_i^* q_i^* m_i' n_i' \end{pmatrix} \quad (17)$$

where

$$\mathbf{P} = \begin{pmatrix} \sum_i m_i m_i & \sum_i m_i n_i & \sum_i q_i^* n_i' m_i \\ \sum_i m_i n_i & \sum_i n_i n_i & \sum_i q_i^* n_i n_i' \\ \sum_i q_i^* m_i n_i' & \sum_i q_i^* n_i n_i' & \sum_i q_i^* q_i^* n_i' n_i' \end{pmatrix} \quad (18)$$

The thus determined best fit (κ,η,η') tupel is then substituted into expression (13) for the surface orientation independent distance d^{2^*}.

The matrix $\mathbf{P}$ is singular and cannot be inverted if $q_i^* = \mathrm{const}\ \forall i$ and thus the third row is a multiple of the second. Then only a brightness ratio

$$\kappa = \frac{1}{N}\sum_i \rho_i^* \quad ; \quad \eta = \eta' \quad (19)$$

needs to be computed and the illumination ratios are equal.

TRANSFORMATION OF THE PSEUDO-REFLECTANCE IMAGE

The afore introduced measure of distance can among others be thresholded to compare individual objects, to search entire images for similiar signatures, or to grow regions from a given germ. Another option is to transform an entire spectral image into a surface orientation independent spectral space by comparing each pixel's spectral signature $\vec{\rho}^*$ to the true unity reflectance spectrum $\vec{\rho}' \equiv \vec{1}$. The aim is to reduce the N-dimensional color space by exactly those two dimensions which are induced by varying direct and diffuse illumination. In analogy to Eqn. 15 the best fit (κ, η) tupel is determined and then used to form the transformed spectral signature $\vec{Q}$:

$$Q_i = \rho_i^* \frac{1}{\kappa(\eta n_i + m_i)} \tag{20}$$

In the limit of only a single light source present, *i.e.*, $\lim \vec{m} \to \vec{0}$, this transformation corresponds to a simple normalization of each spectral signature by an average brightness κ and $\eta = 1$, which is equivalent to computing ratio channels:

$$Q_i = \frac{1}{\kappa}\rho_i^* \quad ; \quad \kappa = \frac{1}{N}\sum_i \rho_i^* \tag{21}$$

RECOVERING SURFACE ORIENTATION

Having different sources of illumination which can be distinguished by their color, the surface orientation and consequently shape of a such illuminated object can in principle be recovered, as demonstrated for laboratory conditions by Schlüns (1992). Can this be applied to remotely sensed spectral images?

By comparison of two spectral signatures the illumination ratios $\kappa = \frac{\mu}{\mu'}$, $\eta = \frac{\nu}{\mu}$, and $\eta' = \frac{\nu'}{\mu'}$ can be recovered as shown above, but not the illumination factors ν, μ, ν', μ', as an overall scaling factor remains always undetermined in separating the reflectance and illumination component. (Varying all four illumination factors would yield the trivial solution $\nu = \mu = \nu' = \mu' = 0$.)

Provided κ, η, η' are known as geometric functions of the surface element orientation (θ, ϕ) and the sun position $(e_\odot, a_\odot)$. Then the surface orientation of two surfaces with particular spectral signatures classified as equal can in principle be recovered.

However, evaluating experimental results of spectral image data and measurements of the sky dome's downwelling radiance distribution (Valko 1977), we cannot support the assumption of an isotropic diffuse sky illumination. As the proper intensity distribution varies significantly, recoverage of surface orientation is probably restricted to evaluating the spectral bands of longer wavelength only, where the diminishing diffuse illumination is negligible. This means that basically only one light source, the sun, is available for reliable geometric reasoning, and recovering surface orientation needs either additional symmetry assumptions (e.g. for roof tops) or more observed spectra.

NORMALIZATION OF THE EXPERIMENTAL IMAGE DATA

In cooperation with DLR (German Aerospace Research Establishment) and OSCAR (Open Skies for Conventional Arms Reduction, FB Informatik / KOGS, Universität Hamburg), multispectral aerial images were recorded with a DAEDALUS AADS 1268 Scanner in August 1991 and April 1992 at clear weather conditions over Nürnberg airport, industrial and residential areas. The DAEDALUS system records ten spectral bands in the visible and reflected infrared, and has an angular scan range of $-43°..+43°$ with a ground resolution of 0.7 m at a flight altitude of 300 m.

The images were converted into radiances and atmospherically corrected using the LOWTRAN-7 based SENSAT-4 package (Richter (1993), DLR), as described by Richter (1992). For horizontal surfaces the resulting reflectance images provide spectra independent of recording conditions (Hepp 1994).

ASSESSMENT OF DIFFUSE VERSUS GLOBAL ILLUMINATION

For the evaluation of spectral signatures from randomly oriented surface elements, it is therefore crucial to know the ratio of diffuse to direct irradiance for each spectral band. These ratios for a particular image can either be estimated from the respective solar and atmospheric conditions by means of a Radiative Transfer Code (as included in the package SENSAT), or extracted from the image data itself.

The downwelling diffuse radiance distribution can in general not be sufficiently modelled as isotropic. A sky of low aerosol content (rural areas) has a radiance distribution approximately concentric around the zenith with increasing radiance towards the horizon. In contrast to that, a high aerosol content (urban areas) causes dominating Mie-Scatter with a strong forward peak, and consequently a distribution concentric around the sun and decreasing with sun distance (Valko 1977). The stronger the diffuse radiation is concentrated around the sun, the less meaningful can it be distinguished from the direct sun radiation. Therefore the absolute diffuse contribution ratio is somewhat arbitrary and less significant than the exponential decrease with wavelength.

The ratios $\vec{m}$ of the diffuse to global irradiances for a horizontal surface computed by SENSAT simulation are plotted in Fig. 1. The diffuse spectrum $\vec{m}$ is well described by

$$m_\lambda \sim \lambda^{-1.41} \tag{22}$$

which indicates predominating Mie-Scatter on aerosols, and is in good accordance to Warnecke (1991) who gives -1.3 as a typical Mie-Scatter exponent.

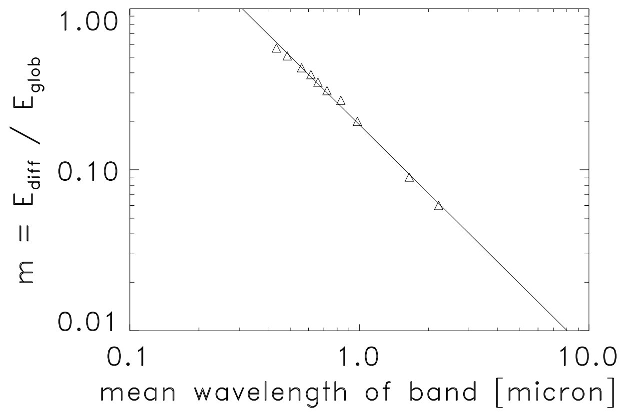


Figure 1: The ratios $\vec{m}$ of the diffuse to global irradiances for a horizontal surface computed by SENSAT simulation (triangles), with best fit exponential function (line).

Schott (1993) cites Piech & Walker (1974) to have pointed out that radiances from equal surfaces and equal orientation observed just beyond a shadow edge (global irradiance) versus just inside the shadow (diffuse irradiance only) are correlated in a linear relation:

$$\rho^*_{\mathrm{shad},i} = m^*_i \rho^*_{\mathrm{sun},i} \tag{23}$$

where the slope m^*_i is related to the diffuse to global irradiance ratio m_i by a factor F accounting for the fraction of sky eclipsed by the shadow casting building:

$$\left(m_i^{-1} - 1\right) = F\left(m_i^{*\,-1} - 1\right) \tag{24}$$

To avoid dependency on and selection bias of interactively measured individual sunlight/shadow borders, we developed a statistical approach to measure the diffuse to global irradiance ratios. At first all pixels are classified 'Shadow' or 'Sun' applying a threshold on the bands of longest wavelength where shadow areas have negligible irradiance. Then all 'Shadow'-pixels which have a 'Sun'-neighbor in opposite sun direction are processed to fill the bins of a two dimensional histogram regressing 'Sun' versus 'Shadow' for each spectral band respectively. To suppress spurious pixel pairs, only the first hundred highest bin peaks are used for a linear regression analysis. The thus determined slopes m_i are plotted in Fig. 2. We find a similiar Mie-Scatter dominated wavelength dependency:

$$m_\lambda \sim \lambda^{-1.7\pm0.3} \tag{25}$$

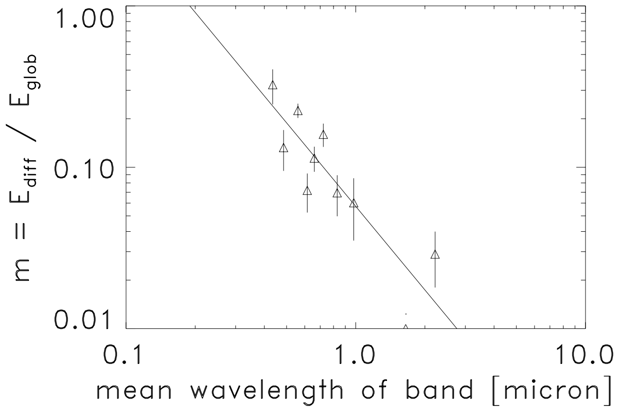
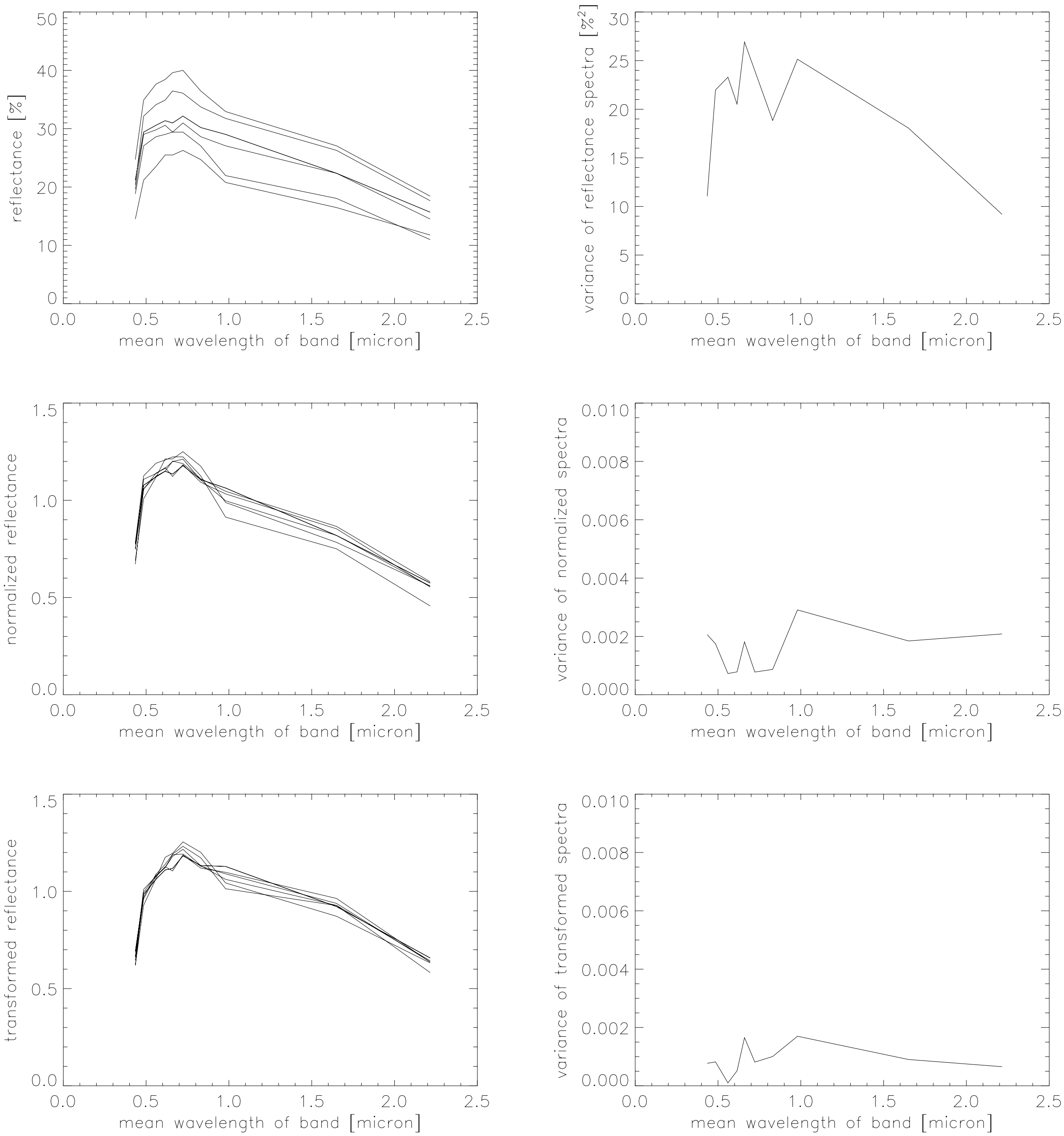


Figure 2: The measured ratios $\vec{m}$ of the diffuse to global irradiances (triangles), with best fit exponential function (line).

EXAMPLES FROM THE EXPERIMENTAL IMAGE DATA

As an example of the dependency of a specific spectral signature on the surface orientation, we chose roof tops consisting of uniform surface material but varying orientation. Fig. 3 shows selected spectra of a spherical gas container. These spectra can be well described by pure scaling of one principal spectrum. In contrast to that, Fig. 4 shows as another example spectra from a roof top. There the spectra cannot be brought into accordance by pure scaling, but the pseudo-reflectances in the infrared are increasing significantly faster than in the blue. The spectral signatures are plotted as original, normalized, and transformed (according to Eqn. 20), with the respective spectral variances σ_i^2. For the normalized and transformed spectra, the differences due to illumination are removed, and the spectra are now scaled to unity, since the overall brightness can in princple not be determined. For the first example the mean intrinsic variance $\frac{1}{N}\sum_{i=1}^{N}\sigma_i^2$ is reduced from $19.9\%^2$ (original) to 0.0016 (normalized) and finally 0.0009 (transformed). For the second example the mean intrinsic variance is reduced from $9.0\%^2$ (original) to 0.0126 (normalized) and finally 0.0019 (transformed), which corresponds to an intrinsic variance reduction of 85% between simple normalization and the transformation using knowledge about the illumination conditions (Fig. 1).



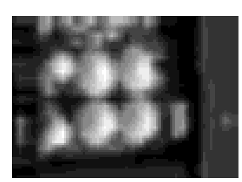


Figure 3: Spectral signatures of a spherical gas container (see picture on the right) originating from patches of varying surface orientation. The original, normalized and transformed spectra are shown on the left panel. The reduction of the intrinsic variance by the presented transformation is shown on the right panel.

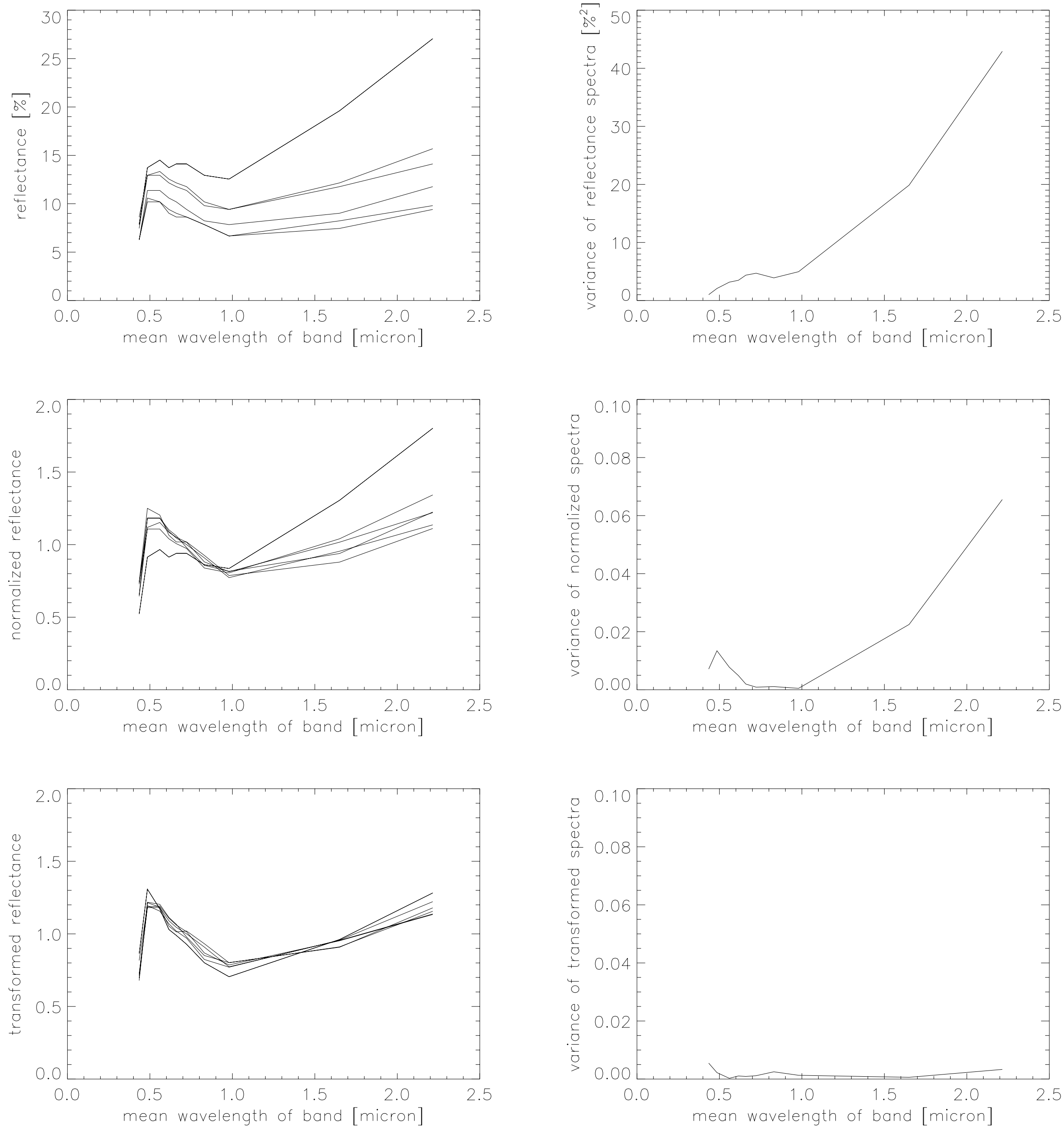
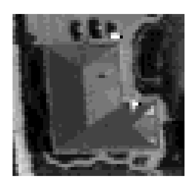


Figure 4: Spectral signatures of a roof top (see picture on the right) originating from patches of varying surface orientation. The original, normalized and transformed spectra are shown on the left panel. The reduction of the intrinsic variance by the presented transformation is shown on the right panel.



CONCLUSION

We have shown that in order to evaluate spectral signatures of artificial objects, it is essential to consider their intrinsic variability caused by varying surface orientation and illumination conditions. Therefore a representation of a specific surface in feature space by a cluster center and a full dimensional covariance ellipsoid is not appropriate, but rather a representation by a two dimensional plane. The SENSAT-4 package has proved useful for assessing the spectral dependency of the diffuse illumination. In case of strong atmospheric aerosol content the diffuse sky light is centered around the sun, and most spectra of uniform surfaces but varying surface orientation appear as simply scaled from a principle spectrum and can be normalized by their average reflectance or spectral ratio channels, while with distributed skylight even normalized spectra will not match. A recovery of surface orientation parameters without further geometric assumptions is only possible if the sky light radiance distribution is well known. An isotropic distribution is not a sufficient approximation. The presented spectral distance measure and spectral transformation, based on a physical model of illumination and Lambertian reflection, are independent of the sky light distribution and knowledge about surface orientation. By transforming the image spectra, illumination information is separated from reflectance information and discarded. Hereby the intrinsic variability of the spectral signature of a specific surface material is significantly reduced and performance of classification improved.

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