appeared in: Proceedings of the 1995 International Geoscience and Remote Sensing Symposium IGARSS '95, IEEE 1995.

IMPROVED COLOR CONSTANT CLASSIFICATION OF REMOTELY SENSED MULTISPECTRAL IMAGERY*

RAFAEL WIEMKER

Universität Hamburg, II. Institut für Experimentalphysik
Mail: FB Informatik / KOGS, Vogt-Kölln-Str. 30, 22527 Hamburg, FRG
Phone: ++ 49 40 54715 601, Facs.: ++ 49 40 54715 572
E-mail: wiemker@informatik.uni-hamburg.de
http://kogs-www.informatik.uni-hamburg.de/~wiemker/raf

Abstract – For improved multispectral classification and retrieval of Lambertian reflectances from patches of arbitrary surface orientation, we investigate the consequences of a *dichromatic illumination model* accounting for direct sunlight and diffuse skylight. This illumination model leads to the concept of spectral classes as two dimensional planes in the feature space. This paper addresses three questions arising from this concept and applies them to experimental data:

- We presents the *projected spectral angle* as a novel spectral distance for the classification of multispectral images.
- We show how the normalized Lambertian reflectance of a surface can be retrieved from at least two observed spectra under arbitrary angles.

INTRODUCTION

Classification of multispectral images relies on the premise that different surface materials have significant spectral signatures. Assuming the Lambertian model, the spectral reflectances r_λ can be recovered from the observed reflected radiance spectra if the proper incident irradiance spectra are known. However, we prefer to call these magnitudes *pseudo-reflectances* x_λ, if they are computed with the simple assumption of the surface patch being horizontal and without accurate knowledge about the surface orientation. The uncertainty about the actual irradiance incident onto a specific surface element is twofold:

- In general the surface orientation for a specific surface element is not known, because Digital Elevation Models have coarse resolution and also do not comprehend artificial objects like houses etc.
- Moreover, the skylight cannot be sufficiently modeled as isotropic. Its directional distribution is strongly dependent on the sun position, atmospheric aerosol content, etc. [1]. So even if the surface orientation was known we could not reliably estimate the diffuse contribution of the illuminating sky.

But then if the actual irradiance is not sufficiently well known, only a pseudo-reflectance spectrum can be recovered and we face the *Color Constancy Problem* as known from Computer Vision.

*This work is supported by the Volkswagen Foundation

PLANAR SPECTRAL CLASSES

In this paper we want to discuss pixel-wise purely color based classification. A spectrum will commonly be described as the radiances x_i at N spectral wavelength bands i. In the representation of a spectrum as column vector $\mathbf{x}$ with N entries, the brightness is its magnitude $|\mathbf{x}|$, while the color is the direction of the vector $\mathbf{x}$. Multispectral classifications are based on the definition of a spectral distance of an observed spectrum $\mathbf{x}$ to a certain spectral class a. Then the spectrum $\mathbf{x}$ is assigned the spectral class a for which the spectral distance is minimal. So the definition of the spectral class and the spectral distance is crucial for the multispectral classification process.

Commonly used distances such as Euclidean or Mahalanobis are brightness dependent, i.e., the spectral distance is influenced by the magnitude $|\mathbf{x}|$. However, as pointed out in the introductory section, we face uncertainty about the brightness when the surface orientation is unknown. Purely color dependent is the spectral angle α [2], which describes the angular difference $\cos\alpha = \frac{\mathbf{a}^T\mathbf{x}}{|\mathbf{a}|\,|\mathbf{x}|}$ between the observed spectrum $\mathbf{x}$ and the class spectrum $\mathbf{a}$. However, α is only invariant against an illumination spectrum $\mathbf{e} = \nu\mathbf{n}$ which varies with ν in magnitude but not in its spectral distribution $\mathbf{n}$, i.e., color. This is true only if we model the sun as the only source of illumination with $\mathbf{n}$ the spectrum of the sunlight. The next order of approximation, so to say, is to add a diffuse illumination component, i.e., skylight, with a spectrum $\mathbf{m}$. Here we take the simplification that the color of the skylight is homogeneous over the sky hemisphere, whereas the brightness can vary arbitrarily. From Atmospheric Physics we know that the directional distribution of the skylight cannot in general be modeled as isotropic [1]. The enhanced dichromatic illumination model is:

$$\mathbf{e} = \nu\mathbf{n} + \mu\mathbf{m} \quad , \quad \text{or} \quad \mathbf{e} = \mathbf{E}\mathbf{c} \quad , \tag{1}$$

where the vectors $\mathbf{n}$ and $\mathbf{m}$ are stacked column-wise in the $N\times 2$ matrix $\mathbf{E}$, with the contributions $(c_1, c_2) = (\nu, \mu) \in \mathbb{R}^2$. Now we consider a Lambertian reflectance spectrum $\mathbf{r}$. As we concentrate on the spectral signature and neglect the brightness, only the normalized reflectance $\hat{\mathbf{r}} = \frac{1}{|\mathbf{r}|}\mathbf{r}$ is meaningful for our purpose. Then for this spectral class all possible spectra $\mathbf{a}$ are

$$a_i = \hat{r}_i e_i = \nu \hat{r}_i n_i + \mu \hat{r}_i m_i \quad , \quad \text{or} \quad \mathbf{a} = \mathbf{A}\mathbf{c} \quad , \tag{2}$$

where we have stacked the reflected direct and diffuse components $\hat{r}_i n_i$ and $\hat{r}_i m_i$ column-wise into the $N \times 2$ matrix $\mathbf{A}$. Then all spectra $\mathbf{a}$ belonging to class a with the reflectance spectrum $\hat{\mathbf{r}}$ can be represented as the linear combinations (2).

This is a two-plane, i.e., a two dimensional linear subspace of the feature space $\mathbb{R}^N$. The two degrees of freedom reflect the arbitrary contributions ν, μ of the two light sources (direct and diffuse). This concept has been investigated for the three dimensional case of RGB-colors [3, 4], and is in this paper extended to the higher dimensional multispectral space.

Consequently, for direct sunlight and diffuse skylight the spectral class must not be represented by cluster centers as single points or directions in feature space, but rather by the respective two-planes spanned by Lambertain reflection of the direct and diffuse spectra. Two such two-planes $\mathbf{A}$ and $\mathbf{A}'$ might but do not necessarily intersect in $\mathbb{R}^N$.

THE PROJECTED SPECTRAL ANGLE

The distance of an observed spectrum $\mathbf{x}$ to a spectral class a shall be its minimal angle with the class plane $\mathbf{A}$ (where $\mathbf{A}$ consists of two column vectors spanning the plane). Thus we consider the proximum $\mathbf{A}\mathbf{A}^{+}\mathbf{x}$ on the class plane closest to an observed spectrum $\mathbf{x}$, where $\mathbf{A}^{+}$ is the Moore-Penrose Generalized Inverse [5], and the $N \times N$ matrix $\mathbf{Q} = \mathbf{A}\mathbf{A}^{+}$ is an orthogonal projector. Then we take the angle between the spectrum $\mathbf{x}$ and its *orthogonal projection* $\mathbf{Q}\mathbf{x}$ onto the respective class plane:

$$\cos^2 \alpha = \frac{(\mathbf{x}^{\mathrm{T}}\,\mathbf{Q}\mathbf{x})^2}{|\mathbf{x}|^2\,|\mathbf{Q}\mathbf{x}|^2} = \frac{\left(\mathbf{x}^{\mathrm{T}}\mathbf{Q}\mathbf{x}\right)^2}{\mathbf{x}^{\mathrm{T}}\mathbf{x} \quad \mathbf{x}^{\mathrm{T}}\mathbf{Q}^{\mathrm{T}}\mathbf{Q}\mathbf{x}} = \frac{\mathbf{x}^{\mathrm{T}}\mathbf{Q}\mathbf{x}}{\mathbf{x}^{\mathrm{T}}\mathbf{x}} \tag{3}$$

because $\mathbf{Q}^{\mathrm{T}} = \mathbf{Q}$ and $\mathbf{Q}\mathbf{Q} = \mathbf{Q}$. The expansion of the squared cosine function to second order at $\alpha \approx 0$ is $\cos^2 \alpha \approx 1 - \alpha^2$, and substituting (3) we get

$$\alpha^2 \approx 1 - \frac{\mathbf{x}^{\mathrm{T}}\mathbf{Q}\mathbf{x}}{\mathbf{x}^{\mathrm{T}}\mathbf{x}} = 1 - \frac{\mathbf{x}^{\mathrm{T}}\mathbf{A}\mathbf{A}^{+}\mathbf{x}}{\mathbf{x}^{\mathrm{T}}\mathbf{x}} = d^2 \tag{4}$$

which is the approximation for small angles α avoiding the cosine computation, and the range of which is $d^2 \in [0, 1]$.

The projected spectral distance d^2 is color constant and illumination invariant for the underlying dichromatic illumination model, and accounts for the concept of spectral classes as planes spanned by the Lambert reflected direct and diffuse illumination spectra. The plane of illumination $\mathbf{E}$ for a white reflector $\mathbf{r} = \mathbf{1}$ can be established by eather a white reference surface, or by knowledge of the sunlight $\mathbf{n}$ and a mean skylight spectrum $\mathbf{m}$ (as estimated from Radiative Transfer Codes such as LOWTRAN / MODTRAN, or e.g. measured from light / shadow transitions in the image data [6]).

RETRIEVAL OF THE REFLECTANCE

The class plane is fixed by two observations $\mathbf{x}$ and $\mathbf{x}'$ together with the origin $\mathbf{0}$. Hence from at least two observations $\mathbf{x}$ *under arbitrary angles* we can retrieve the reflectance $\mathbf{r}$ up to a constant. If more than two observations are given, we will extract the two most significant principal components $\mathbf{g}^1$ and $\mathbf{g}^2$. Then we can recover the normalized reflectance $\hat{\mathbf{r}}$ in closed form by demanding

$$\hat{r}_i n_i m_i \approx c_1\, g_i^1 n_i + c_2\, g_i^2 n_i \stackrel{!}{=} c_3\, g_i^1 m_i + c_4\, g_i^2 m_i \tag{5}$$

These four vectors stacked column-wise into a $N \times 4$ matrix $\mathbf{B}$, we want the non trivial solutions of $\mathbf{B}\mathbf{c} \approx \mathbf{0}$ with $\mathbf{c}^{\mathrm{T}}\mathbf{c} = 1$, i.e., $\mathbf{c}^{\mathrm{T}}\mathbf{B}^{\mathrm{T}}\mathbf{B}\mathbf{c} + \lambda(1 - \mathbf{c}^{\mathrm{T}}\mathbf{c}) = \min$, where λ is a Lagrange multiplier. Now we demand a vanishing partial derivative w.r.t. $\mathbf{c}$: $\mathbf{B}^{\mathrm{T}}\mathbf{B}\mathbf{c} - \lambda\mathbf{c} \stackrel{!}{=} 0$, which is the eigenvalue equation for the 4×4 matrix $\mathbf{B}^{\mathrm{T}}\mathbf{B}$. So we substitute the least significant eigenvector $\mathbf{c}$ in (5) to get the reflectance $\hat{\mathbf{r}}$. Note that the system is overdetermined and thus the goodness of fit can be assessed.

APPLICATION TO EXPERIMENTAL DATA

We are currently applying the above considerations to experimental spectral data recorded with the 1000-band-spectrometer OVID (Meteor. Inst. Univ. Hamburg, described in [7]). As an example we choose two sets of spectra $\mathbf{a}$ and $\mathbf{a}'$ recorded under arbitrary observation angles from a diffuse reflecting white reference and a a diffuse reflecting cork tile (Fig. 1). The following steps are applied to the calibrated radiance data:

- Principal Component Analysis shows that the spectra can indeed be well described by two eigenvectors (the relative variance eigenvalues are 99.97% and 0.02%, and all others less than 10^{-3}% for both white reference and cork).
- The spectra are normalized to $\mathbf{x}^{\mathrm{T}}\mathbf{x} = 1$ and thus forced onto a hypersphere in the spectral space. A principal component projection of the normalized spectra shows that they lie on two distinct great circles (Fig. 4).
- The plane of illumination is represented by the two most significant relative eigenvectors of the spectra, Fig. 3).
- The Lambertian reflectance of the cork surface can be retrieved from from the plane of the cork spectra (observed under arbitrary angles) and the illumination plane, and is in good agreement with the reflectance as measured directly under horizontal orientation (Fig. 2).
- The observed spectra $\mathbf{a}$ and $\mathbf{a}'$ can be classified into the two classes a and a' by the projected angular distance to the two class planes $\mathbf{A}$ and $\mathbf{A}'$ (Table 1). A comparison to the simple angular distance (Table 2) shows that the ratio of off-diagonal to diagonal entries and thus the classification performance has improved.

SUMMARY

We have investigated an enhanced illumination model for remotely sensed spectra under natural illumination. This dichromatic illumination model accounts for Lambertian reflection of direct sunlight and diffuse skylight. The spectral classes then span two dimensional planes in the feature space.

- We have successfully tested the underlying assumptions on experimental examples.
- We have suggested the *projected spectral angle* as a spectral distance measure which accounts properly for the planar class concept.
- We have shown how to retrieve the normalized Lambertian reflectance from two or more spectra observed under arbitrary angles when the direct and diffuse illumination spectra are provided.

The model of dichromatic illumination and the consequent concept of spectral class planes promises better performance for classification and change detection based on remotely sensed spectral signatures, because it relies on a more accurate description of the spectrum formation.

ACKNOWLEDGEMENT

I very much enjoyed the permission and guidance of Barbara Bartsch and Margareta Betancor (Meteor. Inst. Univ. Hamburg) for usage of the piece of art OVID spectrometer. Moreover I would like to thank the coworkers of CENSIS (Johann Bienlein, Martin Kollewe, Thomas Kollewe, Gerhard Meister, Hartwig Spitzer) and OSCAR (Leonie Dreschler-Fischer, Christian Drewniok, Harald Lange, Carsten Schröder) for help and inspiring discussions.

REFERENCES

[1] P. Valko. Meteorologische Strahlungsmessungen mit fahrbarer Station, 1977. In H. Häckel, editor, *Meteorologie*. Ulmer Verlag, Stuttgart, 1985.

[2] R. O. Duda and P. E. Hart. *Pattern Classification and Scene Analysis*. Wiley, New York, 1973.

[3] S. A. Shafer. Using color to separate reflection components. *COLOR Research and Application*, 10(4):210–218, 1985.

[4] M. S. Drew and L. L. Kontsevich. Closed-Form Attitude Determination Under Spectrally Varying Illumination. In *Computer Vision and Pattern Recognition CVPR 1994*, volume IEEE, pages 985–990. IEEE, 1994.

[5] A. Albert. *Regression and the Moore-Penrose Pseudoinverse*. Academic Press, New York, 1972.

[6] R. Wiemker and T. Hepp. Surface Orientation Invariant Matching of Spectral Signatures. In *ISPRS Commission III Symposium on Spatial Information from Digital Photogrammetry and Computer Vision*, pages 916–923, SPIE vol. 2357, 1994.

[7] B. Bartsch, S. Bakan, and J. Fischer. Remote Sensing of Water Vapour within the Solar Spectrum. In *Atmospheric Sensing and Modelling*, pp. 197–206, SPIE vol. 2311, 1994.

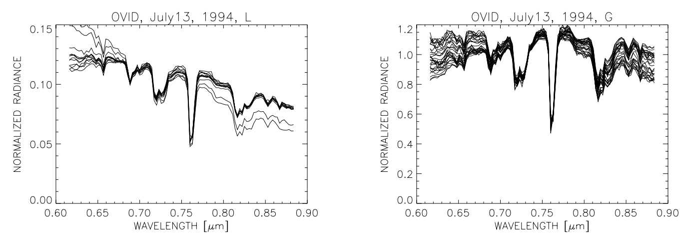

Fig. 1 The normalized spectra of the white reference (left) and of the cork surface (right), recorded under arbitrary angles.

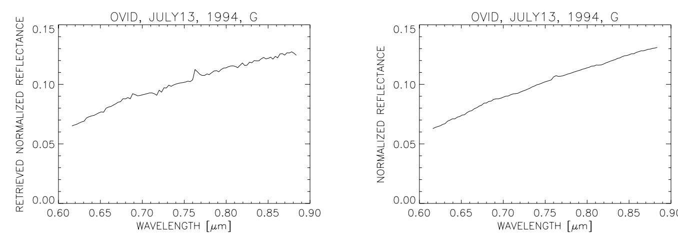

Fig. 2 The normalized reflectance of the cork surface, as retrieved from the observations under arbitrary angles (left), and as measured from horizontal orientation (right).

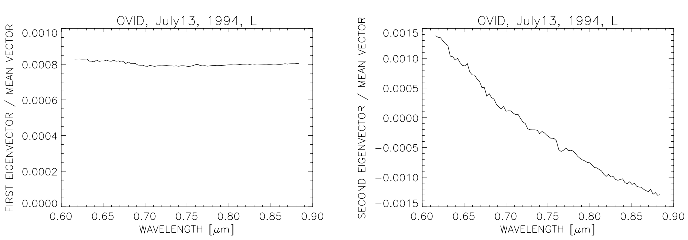

Fig. 3 The two most significant eigenvectors divided by the mean vector. The first eigenvector means a general increase in brightness (left), while the second shows the color shift caused by the color difference between sunlight and skylight (right).

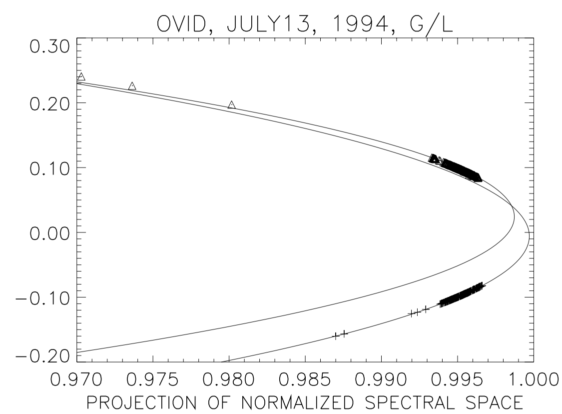

Fig. 4 The normalized recorded spectra ($+$, $\triangle$) lie on two distinct class circles (fit) centered at the origin of the spectral space (principal component projection).

TABLE 1
MN.SQ. PROJ. ANGLE

$\cdot 10^{-4}$	$\mathbf{A}$	$\mathbf{A}'$
$\mathbf{a}$	0.83	23.7
$\mathbf{a}'$	94.2	0.27

TABLE 2
MN.SQ. ANGLE

$\cdot 10^{-4}$	$\mathbf{A}$	$\mathbf{A}'$
$\mathbf{a}$	3.4	329
$\mathbf{a}'$	366	4.3