Hyperspectral Remote Sensing
of
Vegetation Species Distribution
in a Saltmarsh

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Contents

Abstract

The availability of quality empirical data on vegetation species distribution is a major factor limiting the understanding, if not resolution, of many nature conservation issues. Accurate knowledge of the distribution of plant species can form a critical component for managing ecosystems and preserving biological diversity. Remote sensing is an important tool for mapping and monitoring vegetation. Advances in sensor technology continually improve the information content of imagery for airborne as well as space-borne systems.

The unifying hypothesis of this dissertation was that vegetation associations can be differentiated using their hyperspectral reflectance in the visible to shortwave infrared spectral range.

For this purpose the field reflectance spectra and airborne hyperspectral images of detailed saltmarsh vegetation types of the Dutch Waddenzee wetland were analysed. Prior to analysis the field spectra were smoothed with an innovative wavelet approach which, compared to other techniques, showed the best trade-off between noise reduction and the preservation of spectral features.

In the first stage of the analysis, the reflectance spectra of the vegetation types were tested for differences between type classes. It was found that, although vegetation spectra consist of similar detectable absorption features making them an important source of information about the biochemical constitution of vegetation, there are significant differences between vegetation types, both in absolute reflectance and in curvature.

Using the airborne hyperspectral imagery, an alternative method was demonstrated that uses an expert system to combine airborne hyperspectral imagery with terrain data derived from radar altimetry. The accuracy and efficiency of production of the detailed vegetation map increased when generated by the expert system compared to those of a vegetation map produced by conventional aerial photograph interpretation.

Lastly, the accuracy of classification for vegetation types was determined for the three data reduction techniques on both the field spectra and the imagery. Compared with the selection of individual bands, linear transformation of hyperspectral space into lower-dimensional spectral space (i.e canonical variate analysis as well as principal component analysis) improves the classification accuracy for vegetation classes, and therefore should be the preferred method.

Therefore, the results confirm the main hypothesis that it is possible to differentiate vegetation using hyperspectral remote sensing.

Deutsch

Die Verfügbarkeit guter empirischer Daten über die Verbreitung der Pflanzenarten ist ein bedeutender Faktor, der den Einblick, wenn nicht die Auflösung, der Fragen des Naturschutzes einschränkt. Genaue Fachkenntnis der Verbreitung der Pflanzenarten kann einen besonderen Bestandteil für die Verwaltung der Ökosysteme und die Erhaltung der biologischen Vielfalt ausmachen. Fernerkundung ist ein wichtiges Instrument für die Kartierung und Überwachung der Vegetation. Fortschritte der Sensorentechnik verbessern stetig den Informationsgehalt der Fernerkundungssysteme der Luft- sowie Raumfahrt.

Die vereinigende Hypothese dieser Dissertation war, dass Vegetationsassoziationen differenzierbar sind anhand ihrer hyperspektralen Reflektion im Bereich des visuellen bis zum kurzwelligen infrarotem Spektrum.

Zu diesem Zweck wurden die Bodenrefflektionsspektren und hyperspektrale Luftbildaufnahmen der detaillierten Salzwiesenvegetationsarten des Niederländischen Wattenmeeres analysiert. Vor der Analyse wurden die Bodenspektren mit einem innovativen Wavelet Verfahren geglättet, das—verglichen mit anderen Verfahren—die beste Abwägung zwischen der Reduzierung der Ungenauigkeiten und der Erhaltung der spektralen Merkmale zeigt.

In der ersten Phase der Analyse wurden die Reflektionsspektren der Vegetationsarten auf ihre Verschiedenheit zwischen den Kategorien geprüft. Es wurde festgestellt, dass bedeutsame Unterschiede zwischen Vegetationsarten in sowohl der absoluten Reflektion als auch der Rundung der Spektren bestehen, obwohl Vegetationsspektren aus ähnlichen wahrnehmbaren Absorptionsmerkmalen bestehen, die sie zu wichtigen Informationsquellen über die biochemische Zusammensetzung der Vegetation machen.

Mithilfe der hyperspektralen Luftbilder wurde eine alternative Methode demonstriert. Diese Methode gebraucht ein Sachverständigensystem (Entscheidungsmodell), um hyperspektrale Aufnahmen mit Geländeeigenschaften, die von Laserhöhenmessungen abgeleitet wurden, zu verknüpfen. Die Treffsicherheit und Effizienz der Produktion der detaillierten Vegetationskarte wurde mit dem Sachverständigensystem erhöht, verglichen mit der Vegetationskarte die mit konventioneller Luftbildausdeutung erschaffen wurde.

Schliesslich wurde die Treffsicherheit der Klassifikation der Vegetationsarten bestimmt, nachdem drei Datenreduktionsmethoden auf sowohl die Bodenspektren als auch die Luftbilder angewandt wurden. Verglichen mit der Selektion einzelner Kanäle, verbessert lineare Transformation des hyperspektralen Raumes in niedrigere Dimensionen (d.h. 'Canonical Variate' Analyse sowohl als auch Prinzipale Komponenten Analyse) die Klassifizierungstreffsicherheit der Vegetationsarten und sollte daher die bevorzugte Methode sein.

Daher bejahen die Ergebnisse die Haupthypothese, die besagt, dass es möglich ist Vegetation mithilfe hyperspektraler Fernerkundung zu differenzieren.

Nederlands

De beschikbaarheid van goede empirische gegevens over de verspreiding van plantensoorten is een belangrijke factor die in de weg staan van het begrip, zo niet de oplossing, van veel natuurbeschermingskwesties. Nauwkeurige kennis van de verspreiding van plantensoorten kan een kritiek onderdeel vormen van het beheer van ecosystemen en het behoud van de biologische diversiteit. Aardobservatie vormt een belangrijk gereedschap voor het in kaart brengen en het in de gaten houden van vegetatie. De voortschrijdende technologie van sensoren verbetert gestaag het informatiegehalte van beelden van zowel systemen in de lucht als in de ruimte.

De verbindende hypothese van dit proefschrift was, dat plantengemeenschappen (associaties) kunnen worden onderscheiden met behulp van hun hyperspectrale reflectie in het zichtbare licht tot in het kortegolf-infrarood spectrale gebied.

Hiertoe werden de spectrale reflecties uit het veld en de hyperspectrale luchtopnames van nauwkeurig omschreven plantentypen, die op de kwelders van het Nederlandse Waddenzeegebied voorkomen, geanalyseerd. Voorafgaand aan de analyse werden de veldspectra vereffend met een innovatieve benadering die gebruik maakt van wavelets, en die vergeleken met andere technieken, de beste middenweg liet zien tussen de onderdrukking van verstoringen (ruis) en het behoud van spectrale kenmerken.

In het eerste stadium van de analyse werden de reflectiespectra van de plantentypen getest op verschillen tussen klassen van typen. Vastgesteld werd dat, hoewel plantenspectra bestaan uit gelijksoortige absorptiekenmerken die ze tot een belangrijke bron van informatie maakt van de biochemische samenstelling van planten, er belangrijke verschillen bestaan tussen de plantentypen, zowel in absolute reflectie als in de vorm van de kromme zelf.

Met behulp van hyperspectrale opnamen kon de werkzaamheid van een andere methode worden aangetoond, die gebruik maakt van een expertsysteem dat een hyperspectrale luchtopname verenigt met een hoogtemodel afgeleid van radarhoogtemetingen. De nauwkeurigheid en doeltreffendheid van het maken van een gedetailleerde vegetatiekaart verbeterden wanneer deze werd voortgebracht door het expertsysteem, vergeleken met die van een vegetatiekaart geproduceerd met behulp van conventionele interpretatie van luchtfoto's.

Tenslotte werd de nauwkeurigheid van de classificatie van plantentypen bepaald van drie technieken voor reductie van gegevens op zowel de veldspectra als de opnamen. Vergeleken met de selectie van individuele banden verbetert een eerstegraads transformatie van de hyperspectrale ruimte naar een spectrale ruimte met minder dimensies (d.w.z. canonieke variatie analyse alsook principale component analyse) de nauwkeurigheid van de classificatie van vegetatieklassen, en zou daarom de te verkiezen methode zijn.

Derhalve bevestigen de resultaten de belangrijkste hypothese dat het mogelijk is vegetatie te onderscheiden met behulp van aardobservatie.

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Thanks to everyone who gave their valuable time, skills and enthusiasm to make this PhD dissertation...

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With gratitude I remember my family and friends who contributed to my overall well-being.

Chapter 1

General introduction

The availability of quality empirical data is a major factor limiting the understanding, if not resolution, of many nature conservation issues (Norton and Williams, 1992). Accurate knowledge of the distribution of plant species can form a critical component for managing ecosystems and preserving biological diversity. However, the spatial dimension is still largely ignored in ecology, although some population models defined in space do exist (Tilman and Kareiva, 1998). Consequently, for landscape ecology and monitoring habitat, vegetation remote sensing is of great importance, because remote sensing can extrapolate to synoptic scales and time sequences can be acquired (Roughgarden et al., 1991; Skidmore et al., 1998).

Traditional methods for mapping floristics involve intensive and time-consuming fieldwork (Kent and Coker, 1992). Species are identified by their distinctive phenology and their percentage cover is estimated. Remotely sensed imagery, often in the form of aerial photographs, is then used to aid extrapolation of these point observations (Zonneveld, 1974). The question is: Can the increased spectral and spatial resolution of hyperspectral sensors improve the mapping of floristics?

Since hyperspectral remote sensing has gained scientific and commercial importance in the field of exploration geology (e.g. Kruse (1988)), and the application of this technique to terrestrial ecology and land cover mapping is still rudimentary, it was proposed to develop methods to map floristics from hyperspectral images.

1.1 The ecology of Schiermonnikoog

The application of hyperspectral remote sensing was tested in the coastal wetlands of the Netherlands—specifically, the saltmarsh of Schiermonnikoog. Coastal wetlands are important as natural ecosystem remnants offering wildlife habitat and tourist destinations. They are also said to have important nutrient cycling capacity

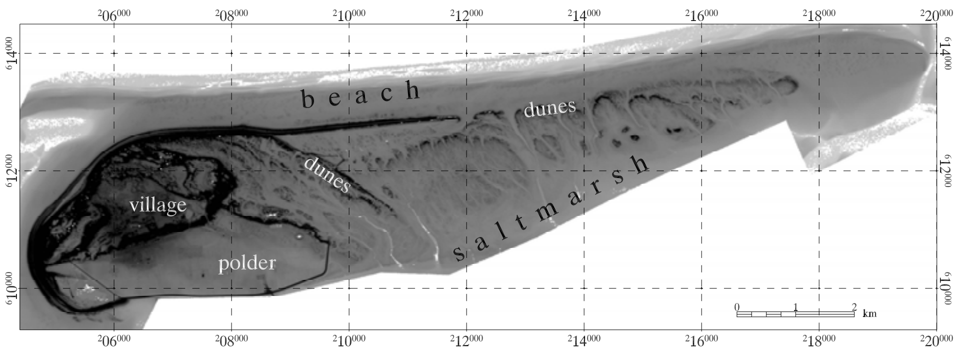

Figure 1.1: Schiermonnikoog (the grey levels indicate the elevation).

for maintaining water quality (Adam, 1990). Moreover, the wetlands have intrinsic value due to their naturalness. The management of these environments—especially in response to human activities such as livestock grazing and tourism—require information on the quality and quantity of vegetation (Adam, 2002). Longer-term threats to the wetlands include pollution, sea-level rise, climatic change and ground subsidence from gas extraction.

The island of Schiermonnikoog is one of the Dutch barrier islands, formed by the deposition of sediments eroded from the European continent by the river Rhine. The island is extending towards the east due to the prevailing eastward direction of the sea current, while the west and northwest are artificially fortified against erosion by the sea. The northern shore of the island consists of dunes, artificially created and maintained on the western half of the island. From the dunes the island gently slopes down in altitude towards the southeast (figure 1.1).

The vegetation on the south-southeastern shore of the island is adapted to regular inundation by seawater, forming a well-studied saltmarsh. Inundation by saltwater of the Wadden Sea is controlled by the tide. During the winter season the prevailing west winds cause higher sea levels than in summer. There is a gradient of succession from the west to the east of the elongated island, the pioneer vegetation establishing itself on the younger part of the island as it grows towards the east.

Factors determining the distribution of saltmarsh vegetation communities are (sources: Bakker (1989); Adam (1990); Bakker et al. (1993); Janssen (2001)):

- Climate
    - On a local scale, temperature and rainfall play a minor role in the distribution of vegetation types, but mainly determine the variation within vegetation types, such as the occurrence of annual species and variation in biomass.

  - Light shortage is caused by inundation by murky water (low saltmarsh) or vegetation structure (higher saltmarsh).
  - Wind causes erosion and sedimentation.

- Tidal regime

  - At the Dutch coast periodicity of the tide is more important than the episodic regime.
  - The vertical range determines duration and depth of inundation, which determine the oxidation and reduction status of the soil.
  - The distance to intertidal plain and creeks is also important because it is closely related to the duration and frequency of inundation by seawater.
  - The tidal disturbance controls the occurrence of the pioneer species *Salicornia spp* and *Spartina spp*.

- Geomorphology and sedimentation

  - The eastern part of the island is the geomorphologically youngest part, which originated as a sandy beach plain with a discontinuous system of dunes, and on the lower parts of the beach plain clay sedimentation takes place.
  - The highest sedimentation rates occur between mean high tide (MHT[1]) level and 20 cm above MHT level in *Puccinellia maritima* vegetation. Above that, sedimentation rates generally decrease as elevation and distance from intertidal flat, creeks and minor creeks increase, due to less frequent tidal flooding.
  - Stormy tides can break through the dunes, resulting in a wash-over with a combination of dune species along the higher edges and saltmarsh species in the depressions.

- Soil

  - Sandier, more aerated and well drained soil occurs on the higher saltmarsh, resulting in more vegetation.
  - In high clay content soils of enclosed clay depressions water logging takes place, causing anoxic conditions, and *Juncus gerrardi* or *Juncus maritimus* is dominant.

[1](MHT = NAP + 1.25m, NAP: Nieuw Amsterdams Peil, Amsterdam ordnance datum)

- Nitrogen is the limiting nutrient in salt marshes. Grazing and haymaking extract nitrogen from the soil, whereas blue-green algae in the lower saltmarsh fixate nitrogen from the air. Organic matter decomposes at a higher rate in older parts of the saltmarsh. Large amounts of organic matter accumulate on drift lines. At places where there is higher nutrient content, one or more species become dominant. On sandy saltmarshes of the barrier type *Elymus athericus* becomes dominant at high elevation and at low elevation *Atriplex portulacoides* becomes dominant. *Suaeda maritima* dominates on areas with much algae deposition.

- Water composition
  - Salinity is lower where fresh water seeps from dunes; *Phragmites australis* and *Juncus maritimus* can become dominant.
  - Higher nitrogen availability favours fast-growing species, such as *Elymus athericus*. Generally there is a negative relationship between the above-ground production of saltmarsh plant communities and their frequency of inundation. However, a high spatial and temporal variation of this relationship within plant communities is found. Severe nutrient loading has occurred in saltmarshes during recent decades, originating from anthropogenic activities. The water of the western Wadden Sea contains much more nitrogen and phosphorus than in 1950.

- Biotic factors
  - There is competition for light in high saltmarsh (phytogenic factor).
  - Parasitism, herbivory, droppings and trampling influence vegetation structure and floristics (zoogenic factors). Natural herbivory (hares, rabbits, geese) slows down the rate of succession by keeping the nitrogen level lower and increasing the availability of light, thus causing a shift from *Atriplex portulacoides, Artimisia maritima* and *Festuca rubra* to the dominance of *Puccinellia maritima* and *Spergularia media*. Geese prefer *Plantago maritima* to *Puccinelia maritima*. Saltmarsh species and vegetation types occur at a lower elevation on cattle-grazed saltmarshes than they would on the ungrazed saltmarsh. In general grazing favours the development of short-time strategy types, e.g. *Festuca rubra* is replaced by *Juncus gerrardi* on the middle high saltmarsh when grazed. Grazing reduces sedimentation rates in middle high saltmarsh and reduces nitrogen mineralisation.
  - When management (anthropogenic influence) is stopped the succession leads to:

  * *Salicornia* vegetation on high mudflats,
  * *Atriplex portulacoides* vegetation on low saltmarsh,
  * *Elymus athericus* vegetation on the middle and high saltmarsh, and
  * *Phragmites australis* vegetation on places with fresh water seepage.

- Anthropogenic influences

  - Humans impact the slatmarshes through management, seal level change through oil extraction, pollution and many more activities.

Many of these factors are directly (tidal regime) or indirectly (climate, geomorphology and sedimentation, soil, water composition, biotic factors) related to the elevation above mean sea level. Therefore, one can assume that the vegetation location is strongly related to position with respect to MHT, which cannot be directly mapped using passive remote sensing, but can accurately be mapped using laser altimetry.

1.2 The outline of this thesis

In order to fulfil the main aim of mapping floristics, alternative methods for analysing hyperspectral field spectra and hyperspectral imagery were developed. They are presented in the individual chapters as detailed below.

Chapter 2 is a review of literature on the use of hyperspectral remote sensing for vegetation science.

The first objective was to remove noise from the hyperspectral spectra, while meeting several requirements (chapter 3).

Then the detectable absorption features common to the reflectance spectra of the saltmarsh vegetation types were described, and brought into perspective with biochemical features cited in literature (chapter 4).

In order to identify saltmarsh vegetation associations and map them, the variance of the reflectance must be greater between types than within types. This was tested in chapter 5.

Consecutively, the use of hyperspectral imagery in combination with expert knowledge for vegetation mapping was demonstrated (chapter 6).

Then three dimension reduction techniques (CVA, PCA, and selected bands) were compared based on the resulting accuracy when using two statistical classifiers. First the field spectra were used (chapter 7) and then the image spectra were used (chapter 8).

Finally, the synthesis (chapter 9) brings all findings into perspective.

Chapter 2

Review of Hyperspectral Remote Sensing and Vegetation Science

Published as: Kumar, L., Schmidt, K. S., Dury, S. and Skidmore, A. K., 2001. Review of Hyperspectral Remote Sensing and Vegetation Science. IN: Van der Meer, F. D. and De Jong, S. M. (Eds.), Imaging spectrometry: basic principles and prospective applications, Kluwer Academic Press: Dordrecht, The Netherlands.

Abstract

A significant step forward in the world of earth observation was made with the development of imaging spectrometry. Imaging spectrometers measure reflected solar radiance from the earth in many narrow spectral bands. Such a spectroscopical imaging system is capable of detecting subtle absorption bands in the reflectance spectra and measure the reflectance spectra of various objects with a very high accuracy. As a result, imaging spectrometry enables a better identification of objects at the earth surface and a better quantification of the object properties than can be achieved by traditional earth observation sensors such as Landsat TM and SPOT. The various chapters in the book present the concepts of imaging spectrometry by discussing the underlying physics and the analytical image processing techniques. The second part of the book presents in detail a wide variety of applications of these new techniques ranging from mineral identification, mapping of expansive soils, land degradation, agricultural crops, natural vegetation and surface water quality.

Chapter 3

Smoothing vegetation spectra with wavelets

In press: Schmidt, K. S. and Skidmore, A. K., 2002. Smoothing vegetation spectra with wavelets. International Journal of Remote Sensing.

Abstract

In hyperspectral remote sensing, spectra are increasingly analysed using methods developed for laboratory studies, such as derivative analysis. These techniques require smooth reflectance spectra. Therefore, there is a need for smoothing algorithms that fulfill the requirement of preserving local spectral features while simultaneously removing noise. Noise occurs in variable intensity and over different band widths.

Several methods for smoothing a signal exist, including the widely used median and mean filters; the Savitzky-Golay filter generally applied to laboratory spectra; the cubic spline; and the recently developed transform-based thresholding using the wavelet transform. We compare all these methods using reflectance spectra of the canopy of salt marsh vegetation.

The best trade-off between noise reduction and the preservation of spectral features was found to be the wavelet transform, specifically using a translation invariant de-noising based on the non-decimated or stationary wavelet transform.

Chapter 4

Derivative analysis of saltmarsh vegetation reflectance spectra

Schmidt, K. S. and Skidmore, A. K., 2002. Derivative analysis of saltmarsh vegetation reflectance spectra. In prep.: International Journal of Remote Sensing.

Abstract

Scientists strive to explain vegetation spectral characteristics as a result of biochemical constituents. All vegetation contains similar biochemical constituents, but these vary in their proportions. In the laboratory spectroscopy is successfully used to determine biochemical constituents contributing to forage quality. The question remains whether these laboratory methods can be applied to hyperspectral remote sensing methods in order to be able to determine the biochemical constituents in landscapes.

This study looks at field spectra at the canopy level of saltmarsh vegetation and finds characteristic absorption features in the reflectance spectrum of 400–2500 nm, using a hand-held field spectrometer. Using derivative analysis, the detectable absorption features, i.e. dips in reflectance relative to the surrounding wavebands, are recorded.

Many features measurable at canopy level have previously been correlated with biochemicals in vegetation. Therefore, with the help of a hand-held field spectrometer, it is possible to distinguish many absorption features at canopy level, even though they are greatly masked by the strong absorption of the water constituting the main part of plants. The results of this paper might respond to the need for consistency with the spectroscopic approach in hyperspectral remote sensing. We pro-

pose that the absorption features we found serve as a guide for devising new indices using narrow spectral bands or for choosing endpoints to be used for continuum removal.

Chapter 5

Spectral discrimination of vegetation types in a coastal wetland

In Press: Schmidt, K. S. and Skidmore, A. K., 2002. Spectral discrimination of vegetation types in a coastal wetland. Remote Sensing of Environment.

Abstract

Remote sensing is an important tool for mapping and monitoring vegetation. Advances in sensor technology continually improve the information content of imagery for airborne, as well as space-borne, systems. This paper investigates whether vegetation associations can be differentiated using hyperspectral reflectance in the visible to shortwave infrared spectral range, and how well species can be separated based on their spectra. For this purpose, the field reflectance spectra of 27 saltmarsh vegetation types of the Dutch Waddenzee wetland were analysed in three steps. Prior to analysis, the spectra were smoothed with an innovative wavelet approach.

In the first stage of the analysis, the reflectance spectra of the vegetation types were tested for differences between type classes. It was found that the reflectance spectra of saltmarsh vegetation types are statistically significantly different for various spectral regions.

Secondly, it was tested whether this statistical difference can be enhanced by using continuum removal as a normalisation technique. For vegetation spectra, continuum removal improves the statistical difference between vegetation types in the visible spectrum, but weakens the

statistical difference of the spectra in the near infrared and shortwave infrared part of the spectrum.

Thirdly, after statistical differences were found, it was determined how distant in spectral space the vegetation type classes were from each other, using the Bhattacharyya- and the Jeffries-Matusita-distance measures. Six wavelengths we selected for this, based on the statistical analysis of the first step. The potential of correct classification of the saltmarsh vegetation types using hyperspectral remote sensing is predicted by these distance measures.

It is concluded that the reflectance of vegetation types are statistically different. With high quality radiometric calibration of hyperspectral imagery it is anticipated that vegetation species may be identified from imagery using spectral libraries that were measured in the field during the time of image acquisition.

Chapter 6

Mapping coastal vegetation using an expert system and hyperspectral imagery

K. S. Schmidt, A. K. Skidmore, E. H. Kloosterman, H. van Oosten, L. Kumar, J. Janssen, 2002. Using an expert system to map coastal vegetation. In prep.: Photogrammetric Engineering and Remote Sensing.

Abstract

Mapping and monitoring saltmarshes in the Netherlands are important activities of the Ministry of Public Works (Rijkswaterstaat). The Survey Department (Meetkundige Dienst) is producing vegetation maps using aerial photographs. However, it is a time-consuming and expensive activity. The accuracy of the conventional vegetation map derived using aerial photograph interpretation (API) is estimated to be around 43%. In this study, an alternative method is demonstrated that uses an expert system to combine airborne hyperspectral imagery with terrain data derived from radar altimetry. The accuracy of the vegetation map generated by the expert system increased to 66%. When hyperspectral imagery alone was used to classify coastal wetlands, an accuracy of 40% was achieved—comparable to the accuracy of the API-derived vegetation map. An analysis of the efficiency of the proposed expert system showed that the speed of map production is increased by using the new method. This means digital image classification using the expert system is an objective and repeatable method superior to the conventional API method.

Chapter 7

Canonical variate analysis increases vegetation classification accuracy with hyperspectral field data

Schmidt, K. S. and Skidmore, A. K., 2002. Canonical variate analysis increases vegetation classification accuracy with hyperspectral field data. In prep.: ISPRS Journal of Photogrammetry and Remote Sensing

Abstract

Hyperspectral remote sensing data requires data reduction before applying standard statistical classification techniques such as Mahalanobis distance, nearest mean, and others that have been developed for imagery of lower dimension. This paper investigates three methods of data reduction for both field and HyMap spectra. The methods include (a) canonical variate analysis, (b) principal component analysis and (c) selecting individual bands based on their ability to statistically discriminate between vegetation class pairs. The accuracy of classification for vegetation types is determined for the three data reduction techniques.

Tests using data collected with a field spectrometer show that the canonical variate analysis data reduction technique significantly increases classification accuracy (up to a kappa coefficient of 0.90). Classification accuracy of kappa equal to 0.72 is reached with the principal component analysis, which is significantly more accurate than when six selected untransformed reflectance bands are used (kappa = 0.46).

No significant decrease in accuracy was recorded with the reduced spectral resolution of simulated HyMap imagery spectra. In conclusion; canonical variate analysis significantly increases classification accuracies when applied to hyperspectral spectra and—given sufficient training samples—should be considered as the preferred data reduction technique during the analysis of hyperspectral spectra.

Chapter 8

Mapping saltmarsh vegetation using principal component and canonical analysis on HyMap imagery

Schmidt, K. S. and Skidmore, A. K., 2002. Mapping saltmarsh vegetation using principal component and canonical analysis on HyMap imagery. In Prep.: ISPRS Journal of Photogrammetry and Remote Sensing

Abstract

This paper describes how saltmarsh vegetation map accuracy is significantly improved by applying principal component (PCA) and canonical variate analysis (CVA) techniques to the spectra of HyMap airborne imagery. The map accuracies obtained using the untransformed reflectance spectra are compared with the accuracies of the classification applied to the PCA and CVA transformed data.

The overall percentage accuracies were 76% (PCA) and 75% (CVA) for six vegetation classes. However, when the classes were subdivided into 19 vegetation types the overall accuracies were 53% (PCA) and 52% (CVA). The low accuracies as compared with those achieved in an accompanying paper (Schmidt and Skidmore, 2002) were attributed to the small number of training samples in combination with spectral variance at maximum due to the large pixel size of the imagery. The field plots described in the centre of vegetation types were more likely to be classified correctly.

Chapter 9

Digital remote sensing with hyperspectral imagery

9.1 Introduction

From afar vegetation looks homogeneous, only closer inspection reveals differences in species composition to such an extent that one can define vegetation types by specifying their approximate species composition measured in percentage cover. Mapping thus-defined vegetation types is relevant for ecology as a science and consequently the sustainable management of ecosystems.

To date, most successful remote sensing applications have been undertaken at EUNIS[1] level I or II—in other words at broad vegetation community level such as coniferous versus deciduous forest (Skidmore et al., 1998). Equivalent to the Anderson system (Anderson, 1976), the EUNIS is a hierarchical habitat classification system that has been developed to facilitate the harmonised description and collection of ecological data across Europe. Mapping and monitoring vegetation up to the EUNIS habitat classification levels V and VI across a number of landscapes and ecosystems within the Netherlands is an important activity of the Ministry of Public Works (Rijkswaterstaat). The Survey Department has produced vegetation maps on an operational basis since the early 1970s. The maps are based on visual stereoscopic interpretation of (mainly) false-colour aerial photographs (API), using the landscape-guided approach (Zonneveld, 1979). However, mapping vegetation in this way is a time-consuming and expensive activity based on the manual interpretation of aerial photographs. Due to the manual nature of API the main disadvantage is a lack of objectivity, and therefore of repeatability (Janssen, 2001).

[1]European Nature Information System,
URL: http://mrw.wallonie.be/dgrne/sibw/EUNIS/home.html

Moreover, accuracy assessment is complicated by mapping units that contain a mosaic of vegetation types, and therefore the spatial allocation of a specific type within the mapping unit is not certain.

On the other hand digital remote sensing based on the spectral signature of vegetation cover increases objectivity. An understanding of the interaction of solar radiation with the vegetation leaf and canopy is a prerequisite of correctly applying remote sensing to map vegetation characteristics.

9.1.1 What is hyperspectral?

In this thesis spectra are said to be 'hyperspectral' when they consist of a large number of narrow and congruous spectral bands, which makes spectral information beyond normal limits available. The prefix hyper-, meaning above or in excess, comes from the Greek *huper*; meaning over (Collins Concise Dictionary). The topic of this thesis is whether the information contained in hyperspectra is enough to describe the measured object such as vegetation species associations.

In the field of remote sensing, *Spectroscopy*—the branch of physics concerned with the production, transmission, measurement and interpretation of electromagnetic spectra (Swain and Davis, 1978)—has found its way via spectrometry. *Spectrometry* is the measurement of photons as a function of wavelength. In remote sensing applications the actual mathematical analysis of waveforms is rarely performed by numerical calculations from spectral components. Instead, direct measurements are made with spectrographic devices such as airborne scanner or laboratory spectrometers (Suits, 1983).

Reflectance spectra of natural surfaces are sensitive to specific chemical bonds in materials, whether solid, liquid or gas. Variation in the composition and structure of materials causes shifts in the position and shape of absorption bands in the spectrum. Consequently, the large variety of materials typically encountered in the real world can result in complex spectral signatures. Spectrometers are used in laboratories, in the field, in aircraft and on satellites (looking both down at the earth and up into space). Similarly, an image can be constructed using an imaging spectrometer that records the spectra for contiguous image pixels.

Imaging spectrometry is a new technique for obtaining a spectrum in each position of a large array of spatial positions so that any one spectral wavelength can be used to make a recognisable image. Every pixel in the image has a spectrum, so we are able to spatially map the presence and abundance of materials. Imaging spectrometry has many names in the remote sensing community, including imaging spectroscopy, and hyperspectral and ultraspectral imaging.

It should be noted that operational satellite systems have been, and are planned to be, launched (e.g. ENVISAT by ESA). The hyperspectral scanners are passive; in other words they receive radiation reflected from the earth's surface. At an altitude of 500 km, a spaceborne sensor receives approximately 10 000 times less radiation than an aircraft at 5 km. Therefore, much less signal (information) is received by the satellite compared with the aircraft, with a lower signal-to-noise ratio. With aircraft sensors, it is possible to have small pixels (say 1–5 m) as well as narrow wavelength bands (usually around 10 nm). The advantage of aircraft scanners over satellite systems is that spatial and spectral resolution is high, and these sensors are therefore ideally suited for detailed local surveys.

9.1.2 The increasing theoretical base

Most of the initial research in the field of hyperspectral remote sensing was done in the laboratory in relation to plant biochemicals (chapter 2). This is not only because there is a greater potential for commercial exploitation, but also because the experimental setup in the laboratory is better defined, since only one variable is changed (i.e. studied chemical) while the plant species is kept constant. Detailed biochemistry is not accessible in a robust and accurate way from fresh leaf reflectance when observing within a large range of species (Fourty and Baret, 1998). Radiative transfer models were developed to understand and predict the reflectance from vegetation canopy in order to map foliar biochemicals (Chapter 2). On the one hand, there is progress in mapping biophysical variables (Chapter 2). On the other hand, few articles have been published on using hyperspectral imagery to map vegetation species diversity (Nagendra, 2001), although the trend is changing.

Researchers have been able to classify species based on their fresh leaf reflectance (Gausman and Allen, 1973; Gausman et al., 1973; Vanderbilt and Grant, 1986; Goward et al., 1994; Gong et al., 1997; Asner et al., 1998; Daughtry and Walthall, 1998; Knapp and Carter, 1998; Kumar and Skidmore, 1998; Schmidt, 1998; Cochrane, 2000; Schmidt and Skidmore, 2001), field reflectance at canopy (Satterwhite and Ponder Henley, 1987; Petzold and Goward, 1988; Peñuelas et al., 1993; Taylor, 1993; Dietz and Steinlein, 1996; Zhang et al., 1996; Thomson et al., 1998; Spanglet et al., 1998; Feyaerts and Van Gool, 2001), or remotely sensed multispectral (Skidmore et al., 1987; Lewis, 1994; Franklin, 1994; Trenholm et al., 2000; Salajanu and Olson Jr., 2001) and hyperspectral imagery (Clark et al., 1995; Zhang et al., 1996; Dibley et al., 1997; Martin et al., 1998). More references can be found in Treitz and Howarth (1999) and Nagendra (2001), who wrote important reviews on vegetation species mapping using remote sensing. Therefore, hyperspectral remote sensing potentially allows mapping at the level of species (Dibley et al., 1997; Schmidt, 1998; Skidmore et al., 1998).

9.2 Hyperspectral vegetation remote sensing

If one assumes that genetic differences among plant species result from differences in those environmental and competitive factors which influence photosynthetic efficiency, and that this will be expressed in differences in the concentration of plant pigments and biochemicals as well as difference in leaf and canopy structure, it is reasonable to expect that different plant species will exhibit different characteristic reflectance spectra.

This thesis aims to demonstrate the improved ability to map detailed vegetation species distribution with hyperspectral remote sensing. One of the most important habitats of Europe, the coastal saltmarsh, has been selected for study. The coastal wetlands of the Netherlands are important as natural ecosystem remnants offering wildlife habitat and tourist destinations, as well as functioning as important nutrient cycling capacity for maintaining water quality. Saltmarshes are often regarded as sinks for organic material, nutrients and heavy metals. The management of these environments, especially in response to human activities such as tourism and livestock grazing, requires information on the quality and quantity of vegetation, which provides a food source and habitat for wildlife. Long-term threats to these wetlands include pollution, sea-level rise, climatic change and ground subsidence from gas extraction.

The aim of this thesis was pursued in the following sequence:

1. The first objective was to remove noise from hyperspectral spectra. Several requirements have to be met by a smoothing algorithm. The absorption features should be preserved, while the wavelength position of the local minima or maxima as well as the inflection points should not move. Furthermore, the algorithm should be computationally straightforward (requiring little 'fine-tuning'). In other words, the trade-off between noise removal and the ability to resolve fine spectral detail should be optimised towards preserving the spectral detail. This is a problem with vegetation spectra, where absorption features are generally smooth (because of internal scattering in the leaves), do not have the same width or intensity, and tend to overlap.

2. Then the detectable absorption features common to the reflectance spectra of the saltmarsh vegetation types were described, and brought into perspective with biochemical features cited in literature. The research question was whether we can identify subtle spectral features in the reflectance spectra of vegetation canopies, using a standard field spectrometer.

3. In order to identify saltmarsh vegetation associations and map them, a basic underlying premise is that the vegetation types are indeed spectrally separable. In other words, the variance of the reflectance must be greater between types than within types. This was tested on 27 different saltmarsh vegetation associations. This would determine the probability of successfully classifying vegetation types by using hyperspectral imagery.

4. Then we demonstrated that the use of hyperspectral imagery in combination with laser altimetry and ecological expert knowledge of vegetation distribution relative to topographic characteristics of the landscape increases the

productivity of operational vegetation mapping of coastal ecosystems. The specific objectives were:

- to evaluate the ability to detect detailed vegetation types with hyperspectral imagery using the spectral angle mapper, an established classifier;
- devise expert rules from the cause-effect relationship of environmental variables on the distribution of vegetation types;
- assess the improvement when incorporating expert knowledge in the mapping process;
- compare the results with a conventional API map in order to evaluate whether the objectivity in mapping and monitoring vegetation can be increased; and finally
- to evaluate whether there is potential to automate vegetation mapping by introducing cost-saving technologies.

5. Even though the spectral angle mapper is a novel method for hyperspectral imagery, in it part of the spectral information (the albedo) is not used for discriminating between classes. Therefore, conventional statistical classifiers (based on strong statistical theory) might improve classification accuracy. However, they need input of lower dimensions. The aim of this study was to compare the three dimension reduction techniques (CVA, PCA, and selected bands), based on the resulting accuracy when using two statistical classifiers (Mahalanobis and nearest mean classifier). This test was conducted with both the:

   - field spectra and
   - the hyperspectral images.

The revelations from the analysis of the hyperspectral data of the saltmarsh vegetation are discussed in the following sections.

9.2.1 Dealing with the problem of noise

The signal-to-noise ratio is of prime importance in hyperspectral remote sensing, since it is closely related to unwanted noise in the spectra. Noise bound to be in any spectral measurement depletes the ability to detect subtle absorption features. Spectral noise can be dealt with by methods arising from the novel mathematical theory of wavelet analysis (Ogden, 1997). The study of wavelets as a distinct discipline started in the late 1980s and is only in its infancy.

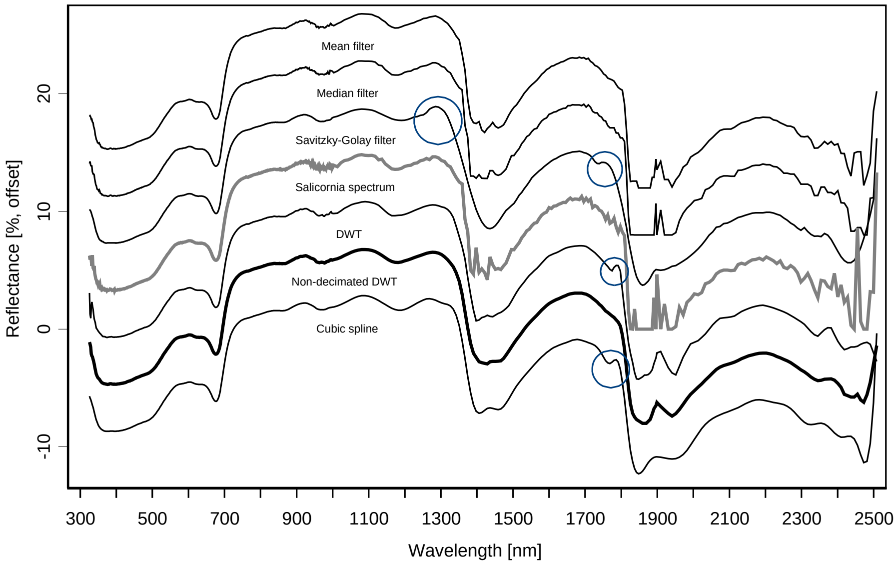

Figure 9.1: Comparison of the smoothing methods across the whole spectrum; the un-smoothed spectrum of *Salicornia europea* vegetation is in the centre (grey) and the various smoothed spectra are offset by 4%. Artifacts (circles) are created by the Savitsky-Golay filter, the decimated wavelet transform (DWT) and the cubic spline. The best smoother is the non-decimated DWT.

In this thesis the non-decimated wavelet transform has been shown to successfully remove noise from reflectance spectra (chapter 3). Compared with other smoothing algorithms such as the Savitsky-Golay filter or the cubic spline that produce unwanted artifacts, the non-decimated wavelet transform adjusts to local changes in noise level without adversely affecting other regions of the spectrum (see figure 9.1). With the non-decimated wavelet transform it is possible to preserve subtle but informative absorption features while removing strong noise near the atmospheric water absorption peaks (chapter 3).

9.2.2 What field spectra at canopy level reveal

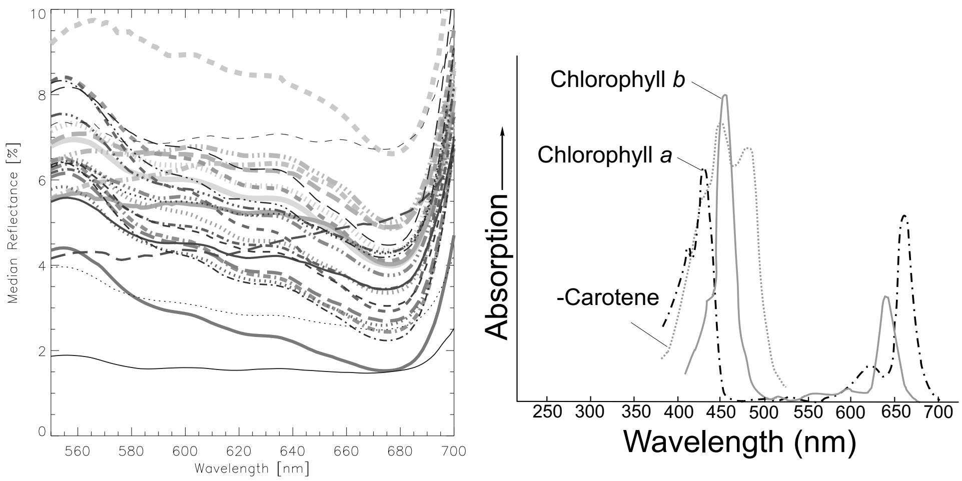

Figure 9.2: Median reflectance curves of 27 slatmarsh vegetation types in the visible part of the spectrum from 550 nm to 700 nm (a), and the absorption curves of plant pigments (b) (source: Purves et al. (1998)).

The reflectance spectra of the saltmarsh vegetation canopy are similar for all vegetation types. Spectral features (or curvatures) are caused by the biochemical content of the vegetation. For example the wavy appearance of the yellow part of the spectrum between 550 nm and 685 nm (figure 9.2(a)) is caused by the different absorption strengths of chlorophyll a and b and other pigments of the vegetation (see figure 9.2(b)). Taking into account that a field spectrometer has coarser spectral resolution and a lower signal-to-noise ratio relative to a high-precision laboratory spectrometer, it is important to know whether these weak absorption features can still be dissolved in the field and at canopy level.

In this thesis a summary of published literature and features that could be identified in the field by doing a derivative analysis on the more than 2000 field spectra

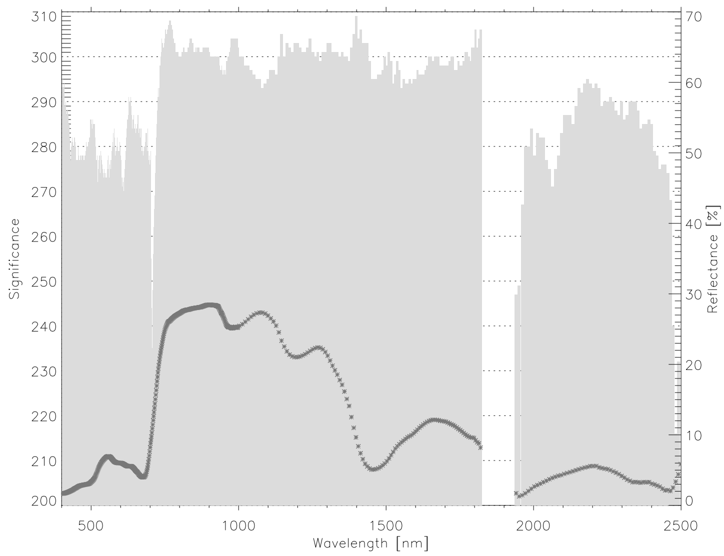

Figure 9.3: Frequency plot of statistically significant differences, using the U-test with significance level of $\alpha'' = 0.01$, between the field reflectance medians of 27 vegetation types at every channel. The median reflectance curve of '1.1*Spartina*' is displayed to indicate typical vegetation reflectance features.

brought their importance into perspective. It was shown that it is possible to identify where weak absorption features start and end (chapter 4). In order to avoid confusion, it was proposed to use inflection points as start and end points to define absorption features before analysis such as continuum removal, because these inflection points seem to be more stable in terms of wavelength position than maxima or minima.

9.2.3 The statistical difference between vegetation type reflectance

In the previous section it was shown that most absorption features detectable with the field spectrometer are present in all vegetation types. However, to what extent is this fact obstructing the possibility of differentiating vegetation types based on their reflectance spectra?

In this thesis it was shown through statistical analysis that the majority of the 27 studied saltmarsh vegetation types have a characteristic signature (chapter 5). In addition, a better understanding has been gained about those parts of the electromagnetic spectrum which offer the greatest information content for discriminating between and identifying saltmarsh vegetation types. A method was developed to extract important wavebands for classification using histograms of the frequency of statistically significant difference between the medians of the spectral classes (figure 9.3). Furthermore, it was shown that continuum removal (which is widely applied in geological hyperspectral applications) has mixed results when applied to vegetation spectra. It improves separability in the chlorophyll absorption pits, while reducing separability in the near-infrared and shortwave infrared, were canopy structure and moisture content influence the spectrum.

In this thesis it was concluded that there are certain saltmarsh vegetation types that have greater potential than others for being classified based on their reflectance spectra. Consequently those types that are spectrally too similar should be separated with information about the landscape derived from other sources. Potential candidates are GIS layers that contain the factors mostly determining the spatial distribution of these saltmarsh vegetation types.

9.2.4 Ecological knowledge as part of the image classification process

The periodic inundation by seawater is characteristic of a saltmarsh. Therefore, factors determining the distribution of saltmarsh vegetation communities are directly (tidal regime) or indirectly (climate, geomorphology and sedimentation, soil, water composition, biotic factors) related to the elevation above mean sea level (Adam, 1990; Bakker, 1989; Adam, 1990; Bakker et al., 1993; Janssen, 2001).

Remote sensing is the main source of information used in a GIS (Skidmore et al., 1998). In addition to information derived from the spectra of passive remote sensing images, active remote sensing can produce information for the GIS. For example elevation can be mapped accurately using laser altimetry, an established method that has rapidly developed and become a sprawling commercial enterprise (Baltsavias, 1999). Available GIS tools can be used to calculate additional information from the digital elevation model, such as the slope, aspect and terrain position (Skidmore, 1990).

In this thesis (chapter 6) the dependence of the spatial arrangement of saltmarsh vegetation types on the landscape characteristics related to the elevation was shown by the analysis of the field plots (figure 9.4). The expert knowledge gained from this analysis was converted to expert rules that, based on the ancillary GIS layers, can be used in an expert system (Forsyth, 1984) to aid in distinguishing between hard-to-separate spectral vegetation classes and thereby improve overall map accuracy.

In this thesis, when hyperspectral imagery alone was used to classify coastal wetlands for 19 detailed vegetation types, an accuracy of 40% was achieved—comparable to the accuracy of the API-derived vegetation map (43%). However, ecological knowledge can be captured in a set of expert rules much like those used

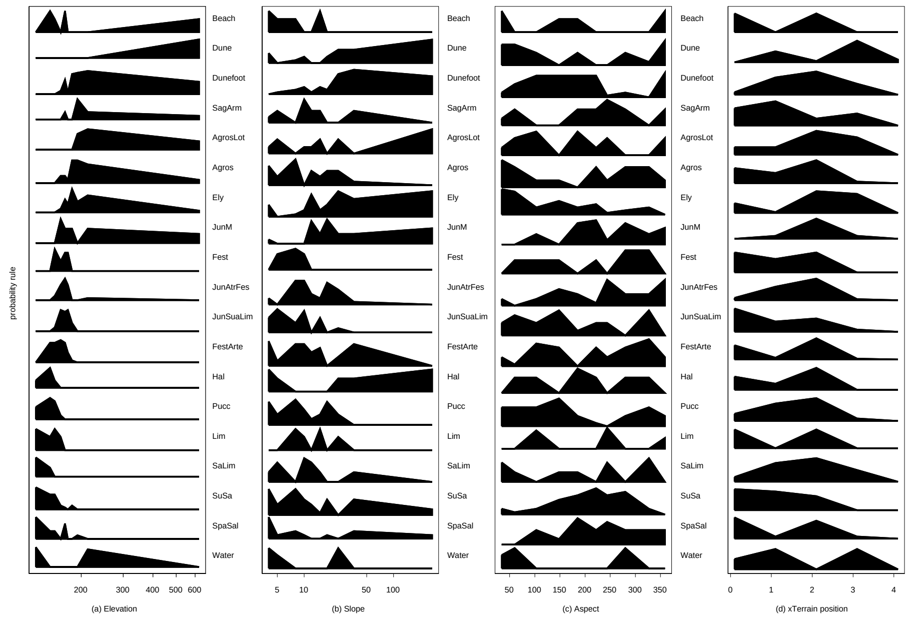

Figure 9.4: The expert rule weights for (a) elevation above NAP (Nieuw Amsterdams Peil, Amsterdam ordnance datum) in cm; (b) slope, increase in elevation per 10 000 cm; (c) aspect, where 0 degrees is north; and (d) terrain position, where: 0 = almost flat, 1 = gully, 2 = midslope, 3 = ridge, and 4 = more than 5 m above NAP. Each interval on the y-axis represents an interval of weights between 0 and 1 for each vegetation type as indicated.

in API to draw lines that denote boundaries of vegetation units.

In this thesis it was shown that the addition of expert knowledge to a classification of hyperspectral imagery increased the accuracy of the vegetation map to 66%. Moreover, the map with 19 vegetation types produced by the expert system was more accurate (66%) than a conventional API vegetation map (43%).

The proposed mapping method offered other important benefits. These are mainly in the form of objectivity, and therefore repeatability of the new system. There is also a marked reduction in time and therefore cost.

9.2.5 The 'curse' or 'blessing' of dimensionality

The spectral angle mapper is a useful classifier with which the 'curse of dimensionality' (Bellman, 1961) is uniquely averted. However, in chapter 5, by comparing the statistical differences of untransformed reflectance spectra with those of the continuum-removed reflectance spectra, it was found that absolute reflectance (or albedo) of vegetation types contributes largely to the difference between vegetation types. Therefore, a measure such as the spectral angle mapper, which is insensitive to albedo differences and only sensitive to differences in spectral shape, would not exploit a large part of the spectral information inherent in the reflectance curve. Consequently, other supervised classifiers were tested on the same mapping problem.

In solving the problems posed by the hyperspectrality of modern remote sensors, if we do not want to totally abandon the ideas pursued in statistical pattern recognition and completely switch to distribution-free methods (for instance neural networks), we have to apply data reduction techniques. These data reduction techniques should exploit the information contained in the smooth curvilinear shape of hyperspectral vegetation spectra, which may be lost by simply selecting 'most informative bands' based on search algorithms and criterion functions.

In this thesis it was found that the two methods of linearly transforming reflectance spectra into lower-dimensional spectral space by using either the canonical variate analysis (CVA) or the principal component analysis (PCA) greatly improved the classification accuracy of 29 vegetation classes, compared with classifying the reflectance of 'most informative' selected bands ($\hat{K} = 0.46$) when using conventional classifiers (chapter 7). The kappa statistic reached a high value ($\hat{K} = 0.90$) for 29 vegetation classes.

In a well defined classification of vegetation spectra, i.e. the number of training spectra is much greater than the number of spectral bands and the number of classes, the canonical transform performs better than the principal component transform in the first dimensions, because reflectance class clusters are distributed in the direction of maximum variation in more or less distinct elongated clusters that make a fan-shape (figure 9.5). However, as more principal components are included in the classifier the kappa accuracy almost reaches the magnitude ($\hat{K} = 0.88$) of that of the canonical variate analysis.

Furthermore, it was shown that in combination with principal components it is essential to use the Mahalanobis distance and never the nearest mean classifier. Also, the Mahalanobis classifier will be more accurate than the nearest mean classifier on untransformed vegetation spectra, because the fan-shaped distribution of classes in some waveband pairs suggests strong covariance between bands and including this information should improve the classification accuracy.

Considering this potential for extremely high classification accuracies of vegetation types in great detail, the linear transforms were also applied to the image

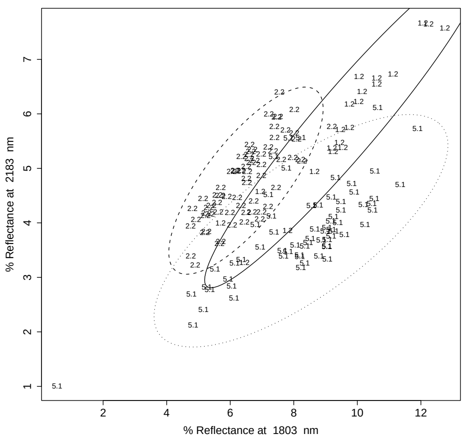

Figure 9.5: The scatterplots of two bands (1803 nm and 2183 nm) of three vegetation types with their 95% confidence ellipses make a fan-shape.

spectra in order to map the saltmarsh vegetation types in as much detail as possible (chapter 8). In the case of the field spectra the class statistics were well defined, due to the large number of replicate measurements. However, this was not the case in the image classification, where the number of training spectra per class was found to be insufficient to estimate the class probabilities accurately.

In this thesis it was found that, even though the linear transforms did not produce accuracies of the magnitude that were obtained in chapter 7 using spectrometer data from field measurements, they did improve on the accuracy obtained using the straight image reflectance spectra with the same statistical classifier.

The sensitivity analysis showed that the accuracy behaved just as predicted by Hughes (1968): when using fewer training samples optimal accuracy is achieved at the lower spectral dimensions; increasing dimension reduces classification accuracy as an increasing number of 'bins' needed to define the class distribution function remain empty. Moreover, this optimal accuracy is lower than when the number of training samples approaches infinity.

When the vegetation classes were aggregated to EUNIS level III, the overall accuracy for six vegetation strata was significantly higher (76% for PCA; 75% for CVA). The overall accuracy is comparable to other remote sensing studies where a similar number of classes were classified from images with similar spectral resolution (e.g. Marcus (2002); Martin et al. (1998)).

9.2.6 The eternal quest for accuracy

The supervised image classification assumes that the field classes are homogeneous and accurate, meaning they are very similar to one another in terms of species composition and no misclassification has been made. This assumption is not completely true, since a vegetation type is an abstraction of a number of concrete stands of vegetation with a similar floristic composition that cover part of the transition to other classes.

In this thesis it was found that field plots described at the edge of vegetation patches and therefore in the transition to another vegetation type have a greater probability of being misclassified—usually assigned to the type they are in transition to (chapter 8).

9.3 Conclusion

The main question of this dissertation was whether it is possible to differentiate vegetation using hyperspectral remote sensing, given that from afar vegetation looks homogeneous and only closer inspection reveals differences in species composition to such an extent that one can define ecologically meaningful vegetation types.

The answer is: yes! This answer can be drawn from the most important conclusions of this dissertation:

- It was found that, although vegetation spectra consist of similar detectable absorption features making them an important source of information about the biochemical constitution of vegetation, there are significant differences between vegetation types, both in absolute reflectance and in curvature.
- Consequently hyperspectral remote sensing of vegetated surfaces can be used to map species composition in considerable detail, with accuracies greater than those of conventional aerial photograph interpretation.
- Moreover, vegetation mapping up to a detailed level can be improved when adding expert knowledge about the ecology of the saltmarsh to the classification of the hyperspectral imagery.
- Compared with the selection of individual bands, linear transformation of hyperspectral space into lower-dimensional spectral space improves the classification accuracy for classifying vegetation classes, and therefore should be the preferred method.

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