Monitoring of Plant Chlorophyll and Nitrogen Status Using the Airborne Imaging Spectrometer AVIS

Dissertation

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Vorgelegt von:

Natascha Oppelt

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1. Gutachter: Prof. Dr. W. Mauser

2. Gutachter: Prof. Dr. F. Wieneke

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„Don‘t panic"
(Douglas Adams)

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AIS	Airborne Imaging Spectrometer
asl	above sea level
AVIRIS	Airborne Visible/InfraRed Imaging Spectrometer
AVIS	Airborne Visible/near Infrared imaging Spectrometer
BAHC	Biological Aspects of the Hydrological Cycle
BITÖK	Bayreuther Institut für Terrestrische ÖKosystemforschung (Bayreuth's institute for terrestrial ecosystem research)
BRDF	Bidirectional Reflectance Distribution Function
C	Carbon
CAI	Chlorophyll Absorption Integral
CASI	Compact Airborne Spectrographic Imager
CCD	Charge-Coupled Device
CET	Central European Time
Chl	Chlorophyll
CHRIS	Compact High Resolution Imaging Spectrometer
DAIS	Digital Airborne Imaging Spectrometer
DAS	Days After Sowing
DC	Dark Current
DFD	Deutsches Fernerkundungs-Datenzentrum (Germany's remote sensing data centre)
DFG	Deutsche Forschungsgemeinschaft (German research community)
dGPS	differential Geographical Positioning System
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German aerospace centre)
DM	Dry Matter
DN	Digital Number
DOY	Day Of Year
DWD	Deutscher Wetter Dienst (German weather service)
EC	Eucarpia Code
EO-1	Earth Observation 1
FOV	Field of View
FWHM	Full Width Half Maximum
GIS	Geographical Information System
GPS	Geographical Positioning System

GSF	Forschungszentrum für Umwelt und Gesundheit (research centre for environment and health)
H	Hydrogen
hNDVI	hyperspectral NDVI
HYMAP	HYperspectral MAPping
IFOV	Instantaneous Field of View
IR	InfraRed
LAI	Leaf Area Index
Mg	Manganese
MIR	Mid InfraRed
MLA	Mean Leaf Angle
N	Nitrogen
NBoS	National Bureau of Standards
NASA	National Aeronautics and Space Administration, USA
NDVI	Normalised Difference Vegetation Index
NIR	Near InfraRed
nm	nanometer
NN	Normal Null
O	Oxygen
OSAVI	Optimised Soil Adjusted Vegetation Index
p	statistical significance level
Pixel	Picture element
Proba	Project for on-board autonomy
PULREF	Procedure to Use Lowtran for REFlectance calibration
rmse	root mean square error
ROSIS	Reflectance Optics System Imaging Spectrometer
SNR	Signal to Noise Ratio
SPECTRA	Surface Processes and Ecosystems Changes Through Response Analysis
SWIR	Short Wave InfraRed
TM	Thematic Mapper
VIS	VISible
µm	micrometer

Acknowledgements

Usually geographers are on the user's end of imaging spectrometers. Concerning oneself with the technical side of spectrometry, namely the construction and calibration of a new system, is not commonplace for a geographer and presented a particular challenge for me. Special thanks are therefore due to Professor Dr. Wolfram Mauser, who made it possible for me to become acquainted with the technology and as the sponsor of this thesis had a significant stake in its progress and success. In many mutual working hours and conversations, he gave me an insight into the fundamental aspects of not only the technical development and execution but also the practical application of AVIS. In the course of this doctoral thesis I constructed my first computer and "got my hands dirty" working on a sensor for the first time; things that I previously would not have considered possible. He also undertook the programming of the flight software as well as the software for the processing of the AVIS data. I would like to thank him cordially for the trust he placed in me, the favourable appraisement of my ideas and the freedom afforded to me in the implementation of the project.

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1 Introduction

Man has been monitoring plants for thousands of years, especially since he started to cultivate several species. Ever since these early beginnings, the aim has been to ensure and increase the yield to guarantee the basic food supply. The development of crop rotation in the 1st century A.D. and later on the application of organic fertilisers are examples for the progressive knowledge about plants and their dependence on environmental factors such as soil, temperature, water availability or nutrition. Nowadays, in many countries agriculture is a highly commercialised branch, which is characterised by the calculated use of fertiliser, herbicides, fungicides and machines for attaining the maximum yield.

Remote sensing is increasingly used for crop monitoring and the support of crop management. Satellite based sensors, especially the Landsat series, played and still play an important role in this task. In the last few decades, the impact of vegetation on the water budget or the carbon cycle on regional and global scales has been recognised. Remote sensing data is used to observe changes in vegetation cover and couple the results with models of the water budget and carbon cycle (ESA, 1999).

The development of spectrometers enables not only the investigation of the vegetation cover but also the derivation of individual constituents and furthermore the condition of plants. Ground-based spectrometers are used to derive plant parameters such as leaf area, water content, pigment content and biomass as well as the influence of stress or disease at leaf scale.

With the existence of airborne spectrometers, investigations and existing approaches at leaf scale were continued at canopy level. The first application of an Airborne Imaging Spectrometer (AIS) was described in 1983 (Vane & Goetz). AIS was a proof-of-concept instrument that led to the development of the AVIRIS (Airborne Visible/Infrared Imaging Spectrometer) – the first airborne spectrometer to contiguously cover the solar range from 400 to 2500nm with narrow bands which has been operational since 1989 (Vane & Goetz, 1993). Today, several airborne imaging spectrometers are available such as AVIRIS (Airborne Visible InfraRed Imaging Spectrometer, since 1987), CASI (Compact Airborne Spectrographic Imager, since 1989), ROSIS (Reflective Optics System Imaging Spectrometer, since 1990), DAIS (Digital Airborne Imaging Spectrometer, since 1991) or HYMAP (HYperspectral MAPping, since 1997).

Early research with hyperspectral data was difficult due to the lack of adequate calibration and knowledge of atmospheric effects in order to transform data to surface reflectances as well as the lack of tools to enable the scientists to analyse the data (Vane & Goetz, 1993). These issues have been overcome to a large extent, and several methods are now available for calibration, image processing and analysis of the hyperspectral data.

The first satellite-based imaging spectrometer was launched by NASA in December 2000: HYPERION, an imaging spectrometer with 220 bands in the wavelength region 400-2400nm, a geometric resolution of 30m and a spectral resolution of 5-6nm on board of EO-1 (Earth Observation 1). The first HYPERION data are now available. Examples for European sensors launched or planned are the CHRIS (Compact High Resolution Imaging Spectrometer) on board of Proba or SPECTRA (Surface Processes and Ecosystems Changes Through Response Analysis), both with similar specifications compared to HYPERION.

Airborne data acquisition benefits over satellite-based missions from being operational in the sense that the user can influence the mission in terms of flight line, position, calibration measurements, spectral resolution, ground resolution, acceptable weather conditions and time schedule (Wilson, 1994). Although airborne hyperspectral remote sensing becomes increasingly accessible due to the increasing number of commercial companies operating hyperspectral sensors, the data are often very expensive on account of the limited spatial coverage of an image scene and the fact that multitemporal approaches are often necessary. Furthermore, data processing and georeferencing is complex (Wilson, 1994). Thus the application of airborne imaging spectrometers nowadays is mainly restricted either to investigation on a local scale or to implication studies for forthcoming space-borne hyperspectral data.

At the Institute of Geography and Geographical Remote Sensing of the University of Munich, the above facts combined with the limited availability of airborne imaging spectrometers for multitemporal applications led to the development of an institute-owned system on a low-cost basis, especially for vegetation monitoring applications. The construction of the Airborne Visible / near Infrared imaging Spectrometer (AVIS) was carried out by Prof. W. Mauser with collaboration of Dr. I. Keding in 1998 and laid the foundations for this thesis (Mauser & Oppelt, 2000; Oppelt & Mauser, 2000; Mauser & Oppelt, 2001). The vegetation parameters to be investigated were determined within the scope of the project funded by the German Research Community (DFG) "Derivation of plant chlorophyll and nitrogen status with hyperspectral remote sensing techniques" (DFG MA 875-6). Therefore this thesis focuses on the following areas:

1. Calibration and validation of AVIS,
2. Multitemporal application in the years 1999 and 2000,
3. Processing of the remote sensing data,
4. Derivation of the chlorophyll and nitrogen content of vegetation applying a new approach with existing indices as references,
5. Investigation of the temporal coverage on the one side and the spectral coverage and resolution necessary for this task.

Three different land use types were investigated, namely wheat, maize and grassland, using an empirical approach. As part of this investigation, ground measurements (Ground Truth) were carried out regularly in different test sites in both 1999 and 2000, during which AVIS measurements were also conducted.

The investigation deals with several research questions:

1. Is hyperspectral remote sensing more accurate than multispectral sensors for the derivation of vegetation parameters?
2. What dependency exists between the chlorophyll and nitrogen content of plants using measurements conducted during the ground truth campaigns?
3. What measurements are necessary to derive vegetation parameters chlorophyll and nitrogen on a mean field basis?
4. Can the chlorophyll and nitrogen content of plants be derived applying species optimised as well as species independent vegetation indices?
5. Is it possible to derive the spatial distribution of chlorophyll and nitrogen content within a field?

This results in the following structure of the thesis, which is also presented in Figure 1-1.

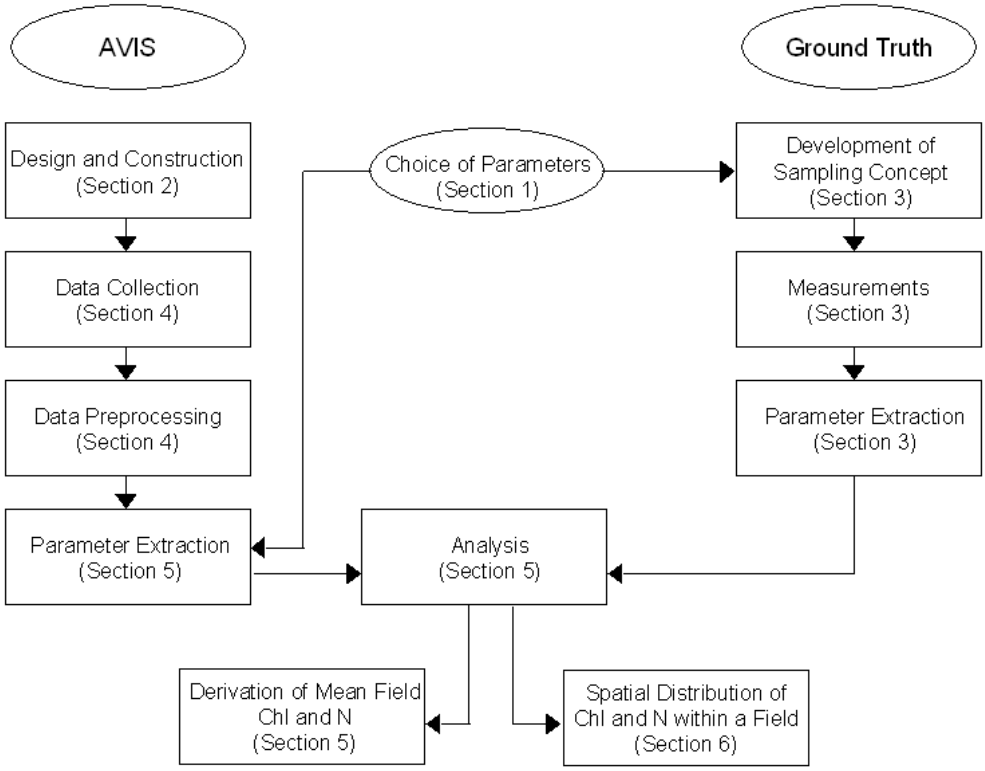

Figure 1-1: Structure of the thesis

An introduction to hyperspectral remote sensing and the importance of the vegetation parameters chosen, namely chlorophyll and nitrogen, follows in section 1. Section 2 describes the most important system parameters of AVIS and the system calibration. Sections 3 and 4 include the ground based and airborne measurements, which were conducted during the vegetation periods 1999 and 2000. In section 3 follows the analysis of the ground truth data, while in section 4 the processing steps for the remote sensing data are described. The measurements of section 3 and 4 form the basics for the analysis of the data regarding the derivation of the chlorophyll and nitrogen content for the investigated land use types, which is focused in section 5. This analysis is based on mean field values derived from either ground or airborne measurements. Finally, the application of the AVIS data for the derivation of the spatial distribution of chlorophyll and nitrogen within a field is described for a field, which is distinguished by an extensive data basis regarding ground based measurements as well as GPS-based yield measurements. This enables a detailed discussion of the derived parameter distribution. The last section includes a summary and an outlook on the further development of the system AVIS as well as the potentialities of the investigated approaches.

1.1 Hyperspectral Remote Sensing and Imaging Spectrometry

Remote sensing is practised by the examination of features as observed in several regions of the electromagnetic spectrum (Figure 1-2).

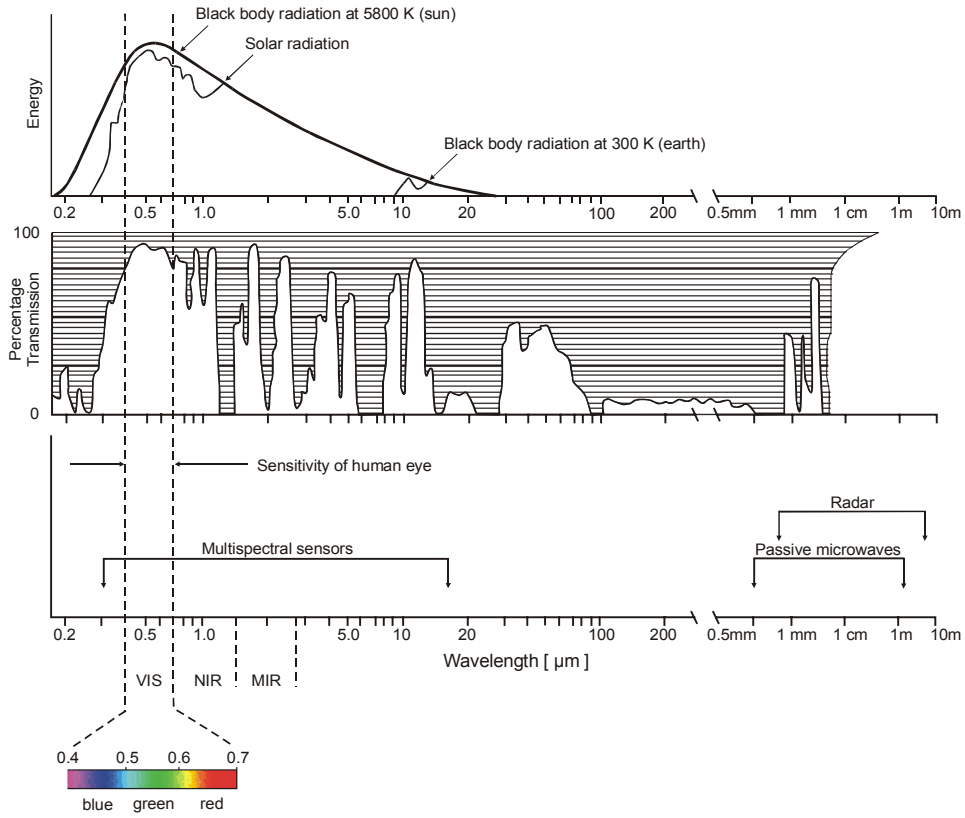

Figure 1-2: Electromagnetic spectrum (Kappas, 1994, modified; cartography: V. Falck)

Conventional remote sensing is based on the use of several rather broadly defined spectral bands, while hyperspectral remote sensing is based on the examination of many narrowly defined spectral bands over a broad range of the electromagnetic spectrum, which enables the recording of a continuous reflectance spectrum. Thus, hyperspectral data have detail and accuracy that permit investigation of phenomena and concepts that greatly extend the scope of traditional remote sensing. Such capabilities present opportunities for much more precise identification of features than is possible with broadband sensors, for use of spectral libraries, for detailed investigation of biologic and geologic phenomena. Due to the measurement that mainly includes the uppermost vegetation or soil layer the obtained spectra are top-of-canopy reflectance spectra (Campbell, 1996; Vane & Goetz, 1993).

Imaging spectrometry is the application of hyperspectral remote sensing for the recording of precise, accurate and detailed spectral measurements of the radiation, which is

reflected or emitted from the earth's surface. This part of the electromagnetic spectrum can be divided into several domains (Campbell, 1996; Wolfe, 1997):

- the visible spectrum (VIS) ranges from 400nm to 700nm and is limited by the sensitivity of the human eye. The visible light can be divided into three primary additives, defined approximately from 400-500nm (blue), 500-600nm (green) and 600-700nm (red), which is also illustrated in Figure 1-2.
- Wavelengths longer than the red portion of the visible spectrum are designated as the infrared region (IR). This segment of the spectrum is large relative to the visible region and extends from 700nm to 15µm. The reflected portion of the IR ranges from 700nm to 3µm and can be divided into the near infrared (NIR) ranging from 700nm to 1.3µm and the mid wave infrared (MIR, 1.3-3µm).

  Radiation in the NIR and MIR behaves, in respect to the optical systems, in a manner analogous to radiation in the visible spectrum. Whereas near and short wave infrared radiation is essentially solar radiation reflected from the earth's surface, the thermal infrared (TIR) beyond 3µm is emitted by the earth.

Hyperspectral sensors necessarily employ designs different from those of usual sensor systems. An objective lens collects radiation reflected or emitted from the earth's surface, a collimating lens projects the radiation as a beam of parallel rays through a diffraction grating or prism, whereby the radiation is dispersed into discrete spectral wavelengths (Figure 1-3). The energy in each spectral band is then detected by one ore several arrays as image line. The superimposition of the same surface, observed at different wavelengths lead to an image cube (Figure 1-4). The two dimensions formed by the x and y axes of the usual map or image display is formed by the movement of the sensor over the ground, while the third (z) is formed by the accumulation of spectral data as bands. The top of the cube is an image composed of data collected at the shortest wavelength, and the spectral band of the longest wavelength of the sensor forms the bottom. Intermediate wavelengths are found as slices through the cube at intermediate positions. Values for an individual pixel observed along the edge of the cube form a spectral trace describing the spectra of the surface presented by the pixel (Campbell, 1996; Wolfe, 1997).

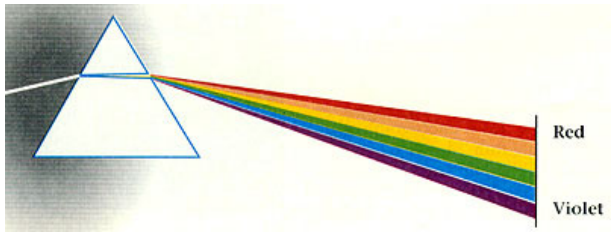

Figure 1-3: Dispersion of light by a prism

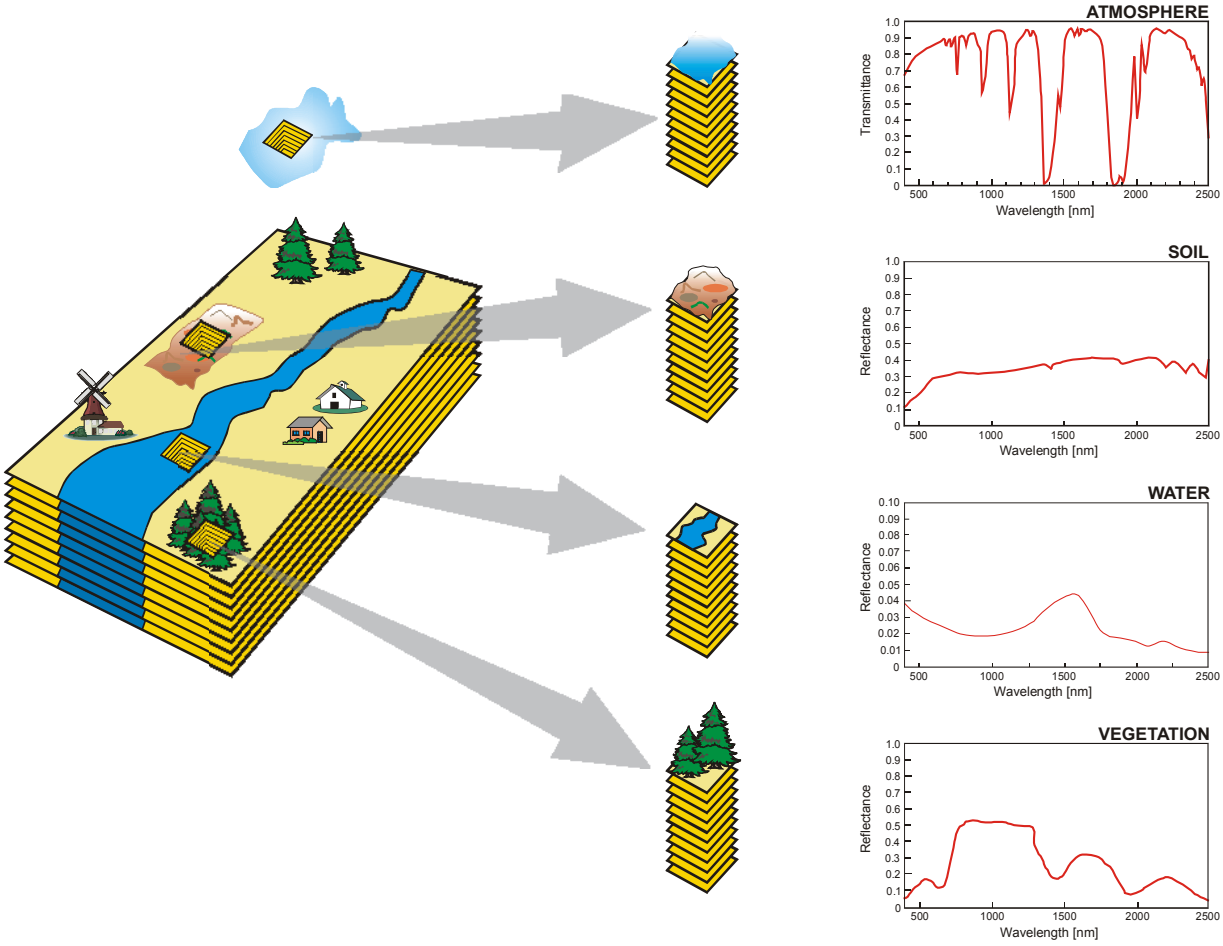

Figure 1-4: Hyperspectral image cube (based on NASA diagram; cartography: V.Falck)

1.2 Importance of Chlorophyll and Nitrogen

Chlorophyll is the pigment primarily responsible for harvesting light energy used in photosynthesis. Photosynthesis is unique in utilising light as a source of energy for the incorporation of carbon dioxide and water into an energy-rich product, sugar that can be metabolised by the plants (equation (1.1)) (Kaufman et al., 1989):

$$6\,CO_2 + 12\,H_2O \rightarrow C_6H_{12}O_6 + 6\,H_2O + 6\,O_2 \uparrow \qquad (1.1)$$

The common denominator in all photosynthetic plants is the occurrence of chlorophyll a. Special molecules of chlorophyll a are believed to accept light energy (electrons) from surrounding pigments and transfer it to an acceptor molecule, resulting in the conversion of light energy to a stable form of chemical energy, which is stored in the form of assimilated carbon. For this, chlorophyll a is viewed as playing the key role in the transfer of light energy. The other pigments are referred to as accessory pigments and include chlorophylls b, c and d, carotenoids, photocyanin and photocoerythrin (Kaufman et al., 1989). The specific structure as well as the absorption features of the chlorophylls are described in more detail in section 5.1.

The primary event in photosynthesis is the absorption of light by the photosynthetic pigments, i.e. the chlorophylls, which are located in the chloroplasts. Chlorophyll primarily is located in the leaves. Mainly this proportion is also viewed by a remote sensing system due to the more or less horizontal alignment of the leaves. The chlorophyll content is correlated with the depth and width of its absorption feature and can be measured by hyperspectral remote sensors.

As mentioned above, photosynthesis forms the basis of plant growth, development and primary productivity. A clear and detailed knowledge of bio-chemical processes as well as their change due to climatic and anthropogenic pressure is essential for the understanding of the environment. Therefore chlorophyll is an important parameter for an accurate characterisation of these processes as well as for their inclusion into hydrological or vegetation modelling.

There are four atoms of nitrogen in each molecule of chlorophyll. This close relation together with the fact that nitrogen itself does not absorb or reflect radiation leads to the derivation of nitrogen content via the chlorophyll content of the plant or leaf respectively.

Most plant tissues contain between 1 and 5% nitrogen on a dry weight basis, and its content tends to decline during the maturation. About 80% of the initial leaf nitrogen content is recycled before leaf abscission. The fraction in dead leaves presumably corresponds to structural leaf nitrogen, whereas the fraction remobilised corresponds to the metabolic pool. For the optimisation of canopy photosynthesis, the metabolic nitrogen pool can be remobilised to vivid parts of the plants (Lemaire, 1997).

Nitrogen is very important in plant nutrition. It is a component of all amino acids and proteins, including the enzymes vital to plant metabolism. It is a constituent of the building blocks of nucleic acids and is found in vitamins and many other plant constituents. Nitrogen is required in relatively large amounts for optimum growth and it is the availability of nitrogen that often causes the limitation to growth. To be available for the plants, it must be fixed, meaning that it must be combined with some other element to form a nitrogen compound. Examples for compounds are nitrate (NO_3^-) or ammonium (NH_4^+), which are available to plants (Kaufman et al., 1989) and are absorbed through the roots. In addition to that, plants can absorb some forms of nitrogen (particularly gaseous ammonia and nitrogen dioxide) through their leaves, but absorption through the leaves contributes only a small proportion (<5%) of the total uptake (Whitehead, 1995).

The knowledge of the impact of nitrogen to the plant as well as the low prices for nitrogen fertiliser led to increasing fertilisation with nitrogen during a period from about 1950 to the mid 1980s (Whitehead, 1995). Although other factors were involved, the increasing rate of nitrogen fertiliser was responsible for much of the amounts of nitrogen leached through the soil and lost in gaseous forms to the atmosphere. Nitrogen that is leached from soils into groundwater is almost entirely in the form of nitrate and, if the groundwater is used for domestic supplies, the nitrate may constitute a health risk to consumers. In 1980 the European Community adopted a directive, which includes a maximum concentration of nitrate in water intended for human use. This directive as well as the perception of the negative impact of overfertilisation to the yield led to a more sensitive handling of nitrogen fertilisation. Therefore the nitrogen content of plants is an important parameter for the nutrition management by farmers to optimise the plant development and thus yield.

In recent years, the spatial distribution of the nitrogen within the fields becomes increasingly important in the scope of optimising the field management. GPS-based yield measurements showed the heterogeneity of the yield within a field and therefore non-uniform plant nutrition status and enabled the spatially distributed employment of fertiliser. The advantage of hyperspectral remote sensors for this task is obvious as soon as they have shown their ability to derive plant constituents and the generation of two-dimensional data.

2 AVIS – the Airborne Visible/Near Infrared Imaging Spectrometer

The costs for the use of existing imaging spectrometers such as DAIS, AVIRIS or HYMAP are high. Also, it is difficult to obtain these sensors for multitemporal applications such as monitoring of vegetation. Therefore, there is a need for a cost effective as well as available tool in hyperspectral remote sensing.

To fill this gap, the imaging spectrometer AVIS (**A**irborne **V**isible / near **I**nfrared imaging **S**pectrometer) was built at the Chair of Geography and Geographical Remote Sensing of the Ludwig Maximilians University Munich, Germany.

The characteristics of AVIS, which include radiometric, spectral and spatial properties, depend strongly on the characteristics of its individual components. The quality of each property, which determines the performance of the AVIS system, is limited by the quality of the parameters of the individual components. Therefore, the most important characteristics of the AVIS components, related to the subject of this study, will be described as well as the resulting overall performance of the system. The calibration procedure as an important part for the assessment of the capabilities of the system will also be described.

2.1 System Description

The system was developed using commonly available components, leading to the Airborne Visible/near Infrared imaging Spectrometer AVIS (Figure 2-1 and Figure 2-2). AVIS is a line imaging spectrometer consisting of two main parts: the camera unit, which includes the camera, spectrometer, lens and filter, and the storage unit, which includes the PC, frame grabber and dGPS.

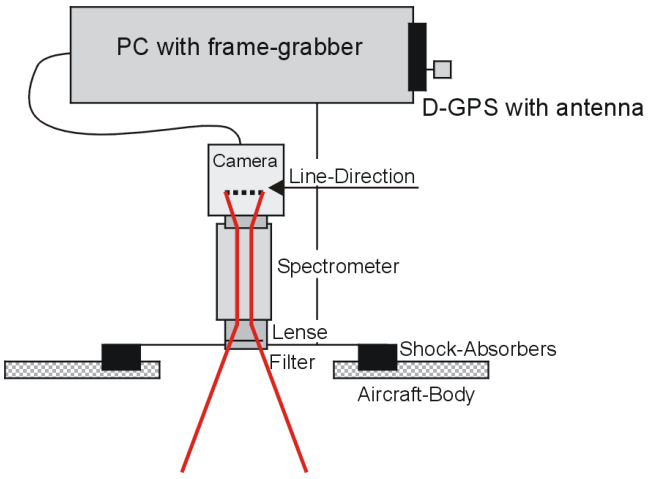

Figure 2-1: AVIS schematic (Oppelt & Mauser, 2000)

The power supply of AVIS is ensured by two 12V led batteries, which provide power for a runtime for at least three hours.

Figure 2-2: AVIS mounted into the aircraft

2.1.1 Camera Unit

The main part of the camera unit is the spectrograph, which is directly coupled to a standard B/W CCD camera via a C-mount. A lens is mounted in front of the spectrograph, and finally a filter is mounted in front of the lens (see also Figure 2-3).

The incoming light passes the filter and is focussed by the lens. Then it passes the spectrograph and is dispersed into the different wavelengths along its spectral axis. Finally, it is registered on the CCD element of the camera as an electrical charge, which is then read out and sent to the storage unit in form of a voltage signal.

Figure 2-3: AVIS camera unit with CCD camera, spectrograph, lens and filter (SPECTRAL IMAGING LTD., 1998a)