CAESAR: AN EXAMPLE OF A VERSATILE MULTISPECTRAL CCD PUSHBROOM SCANNER USING (NON) IMAGING SPECTROMETRY RESULTS

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Abstract

Within the framework of the National Remote Sensing Programme, an airborne pushbroom scanner was developed in the Netherlands by the National Aerospace Laboratory NLR and the Institute of Applied Physics TNO-TU. CAESAR was designed to make land and sea observations in up to the nine different spectral bands. CAESAR's major advantages are the capability of measuring directional reflectances, a spectroscopic potential, high spatial resolution, the ability of applying user- specified filter sets and the absolute and relative calibration of the data.

As an illustration of how to use high resolution spectrometric data for modelling and data reduction of future imaging spectrometry remote sensing missions (EOPP and EOS), an inland water mode of nine spectral bands was developed for the CAESAR scanner based on spectral signature analysis. Spectral band simulated values of upwelling (ir)radiance and water quality parameters were used as input data for statistical analysis. The selected spectral bands in the wavelength range of 500 to 800 nm were sufficient to obtain high correlations between spectral band (combination) values with water quality parameters.

In the summer of 1990 a remote sensing mission is foreseen to determine the scope of the CAESAR inland water mode for inland water quality detection.

1. INTRODUCTION

In 1981 a project was proposed by the National Aerospace Laboratory NLR and the TNO Institute of Applied Physics, with the aim of developing an airborne multispectral pushbroom scanner using linear Charge Coupled Device (CCD) detector arrays. The project was funded by the Ministry of Education and Sciences, the Netherlands Remote Sensing Board (BCRS) and the participating institutes, and was executed within the framework of the National Remote Sensing Programme (NRSP). The multispectral scanner, which was named CAESAR (CCD Airborne Experimental Scanner for Applications in Remote Sensing), and accompanying preprocessing algorithms were completed in 1988. From 1987 onward, as part of the NRSP, the Project Remote Sensing Loosdrecht Lakes was carried out at the Free University of Amsterdam. The aim of the project was to assess the potential applications of remote sensing for inland water quality detection. A water quality sampling programme coupled with *in situ* surface and subsurface spectroradiometric measurements and airborne spectrometric measurements was carried out. Based on this data a nine-channel multispectral bandset was developed for the CAESAR scanner for use in inland water quality detection. Results from an earlier study for a hypothetical "Loosdrecht Mode" were used (Dekker *et al.* 1990a).

2. THE CAESAR SYSTEM

The CAESAR scanner was configured both for land observation, in particular vegetation, and for observation of (sea) water colour. On the basis of the requirements for land and (sea) water observation four operation modes were identified:

- Land mode (land observation);
- Special land mode (high spatial resolution);

TABLE 1

CHARACTERISTIC CENTER WAVELENGTHS AND BANDWIDTHS FOR THE LAND MODE, SPECIAL LAND MODE AND FORWARD-LOOKING MODE.

The array code identifies the channel in the CAESAR coding system. In the first position, D stands for Down and F stands for Forward. The figures in the middle indicate the camera in the module and A/C/B stands for Ahead/Central/Backwards which indicate the arrays in the camera.

Array code	Wavelength	Bandwidth
D1C /F1B	550 nm	30 nm
D2C /F1A	670 nm	30 nm
D3C /F1C	870 nm	50 nm

CHARACTERISTIC CENTER WAVELENGTHS AND BANDWIDTHS FOR THE SEA MODE.

Array code	Wavelength	Bandwidth
D1B	410 nm	20 nm
D1A	445 nm	20 nm
D1C	520 nm	20 nm
D2B	565 nm	20 nm
D2A	630 nm	20 nm
D2C	685 nm	20 nm
D3C	785 nm	30 nm
D3A /D3B	1020 nm	60 nm

- Forward-looking mode (land observation);
- Sea mode (sea(water) observation).

A technical description and application possibilities of the CAESAR scanner are given in Donze *et al.* (1989).

Spectral response of the CCD arrays is governed by narrow bandpass filters constructed of interference filters in combination with absorption filters. Several filter sets are currently available and other filter sets can be defined (see Table 1).

Land modes: On the basis of the results of fundamental research it was determined that three spectral bands were required for land observation, positioned around center wavelength values of 550, 670 and 870 nm (special land mode and land mode). The channel orientation is the same in both the land mode and the special land mode. The three central arrays of the three cameras of the down-looking module are used. In the special land mode a shorter integration time is used, which results in an increased spatial resolution of 0.5*0.5 m at a flight altitude of 2000 meters.

Studies on the non-Lambertian properties of vegetation canopies (Bunnik et al. 1978) have shown that the discrimination between vegetation types can be increased by acquisition of multispectral data in different lookmodes (forward-looking mode). The three different channels forming the forward-looking module are pointing forward with angles of 45, 52 and 59 degrees, respectively. The focal length of the lens is adapted to the greater object distance.

With the implementation of the different lookmodes CAESAR obtained a stereoscopic potential (Looyen *et al.* 1990).

Sea mode: For measuring the spectral distribution of the radiance from (sea)water, nine spectral bands are required within the wavelength range from 400 to 1100 nm. It was decided to select the same set of bands within the available spectral region as were defined in 1982 for the Ocean Colour Monitor, which served as a basis for the development of MERIS. In this sea mode all nine arrays of the three cameras of the down-looking module are in use.

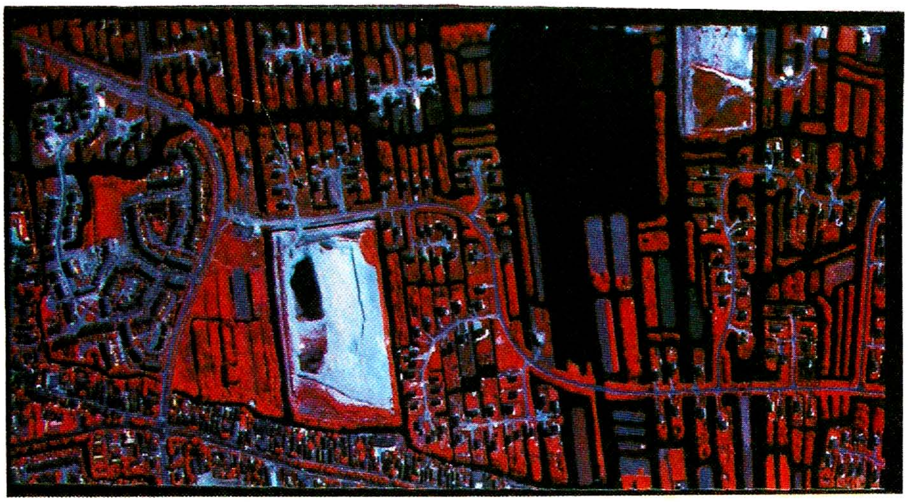

Fig. 1. CAESAR special land mode image of an polder area in the province of North Holland. The spatial resolution is 0.5 • 0.5 m.

Another feature of CAESAR is the possibility of tilting the down-looking module over an angle varying from 0 to 20, degrees in order to avoid sunlight. This feature is relevant for the sea mode operation of CAESAR.

3. DATA PREPROCESSING

For the preprocessing of CAESAR data, NLR developed a special software package (OPTIPARES) to compensate for aircraft motion and attitude as well as for specific sensor distortions. In the case of CAESAR, specific sensor corrections deal with the optical aspects of the scanner and the radiometric calibration, required for all individual elements for all CCD-arrays.

The radiometric correction is a two step activity. The first step is the application of a look-up Table containing the calibration points of the analogue to digital conversion. The second step is the application of the look-up tables containing the calibration data of the detector arrays. The actual radiance is calculated using the dark current and sensitivity value of each individual photosensitive element.

Since CAESAR is operated from an aircraft and mounted to that aircraft, aircraft motions influence the recorded images. Obtaining geometrically correct images requires compensation for errors introduced by these aircraft motions. During the flight aircraft motion parameters are measured by an Inertial Reference System (IRS).

OPTIPARES first considers the orientation of the four coordinate systems that are fixed to the CAESAR scanner, the IRS, the aircraft and the ground, respectively. These four coordinate systems are related to one system via translations and rotations. The next step is the calculation of the relationship between aircraft (with CAESAR) and the ground. Ground coordinates for each pixel are calculated. In a resampling routine the output pixel values are determined. The geometric correction makes no use of topographic maps or geodetic reference points.

Fig. 1 is an illustration of a preprocessed CAESAR-image recorded at an altitude of 2000 m over a polder area in the province of North Holland on 24 May 1989.

4. CAESAR PERFORMANCE

The CAESAR system has been calibrated relatively and absolutely. In order to fulfil the objective that the detector should be able to detect a ground reflectance variation Nedq 0.5% and Nedq 0.05% over land and sea respectively the performance of CAESAR in terms of radiometric resolution was investigated using multispectral images that were recorded by CAESAR using a similar method as used for detector normalization of the SPOT-1 satellite (Begni *et al.* 1986).

The radiometric resolution expressed by the Nedq, meets the requirement of 0.05% (sea mode) and 0.5 % (land modes) for all channels except for the 410 nm channel.

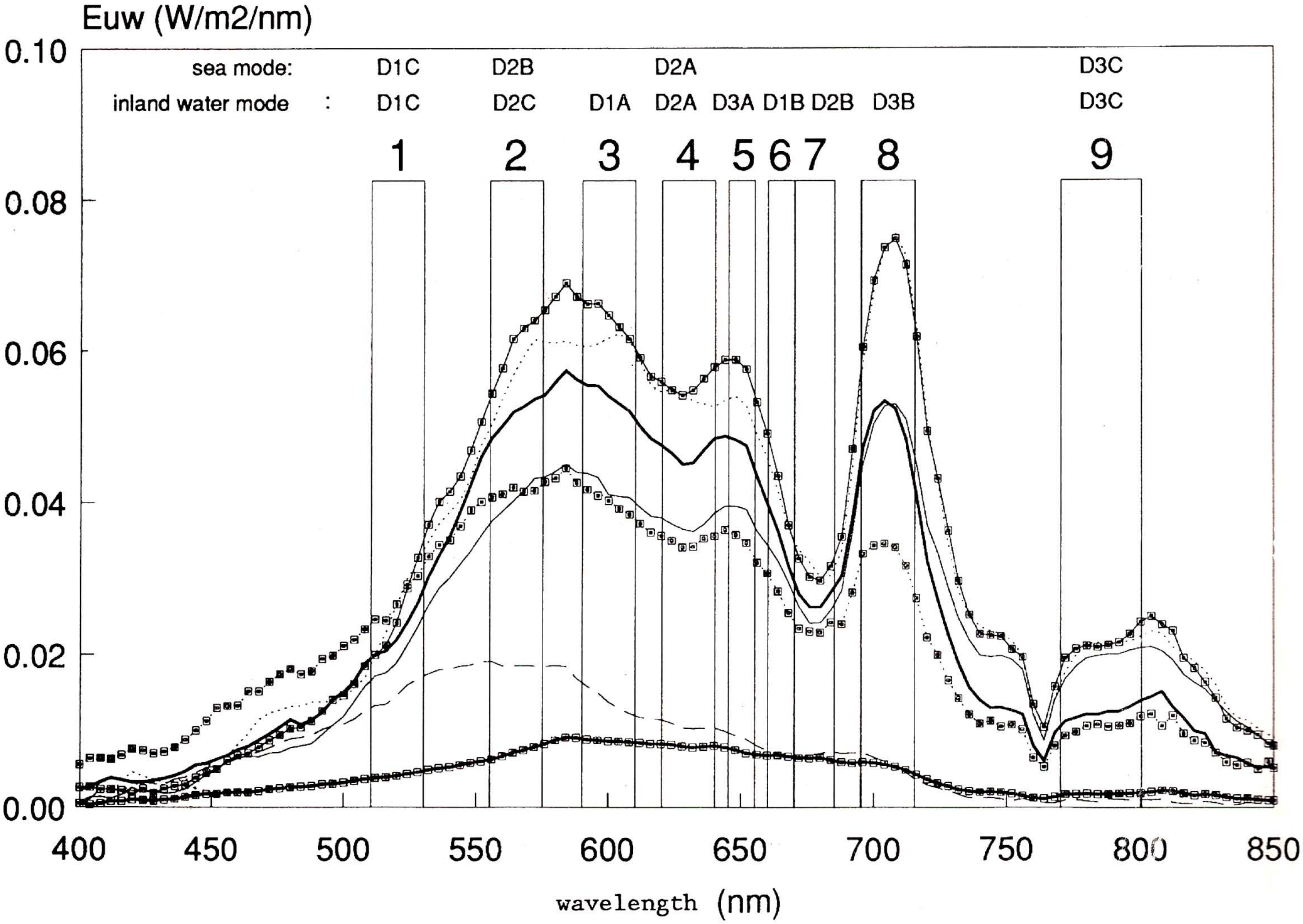

Fig. 2. CAESAR Inland Water Mode spectral bandset superposed on Eu_s spectra of 7 lakes in the Loosdrecht lakes system.

Calibration of this channel appeared to be very difficult because of the combined effect of low sensitivity of the CCD's in this wavelength band and a low input signal. Therefore, normalization constants for this channel could not be determined with sufficient accuracy.

5. AN INLAND WATER QUALITY BANDSET FOR THE CAESAR SYSTEM BASED ON SPECTRAL SIGNATURE ANALYSIS

In April 1988 a remote sensing mission using the Programmable Multispectral Imager PMI (Borstad *et al.* 1985) was carried out. Upwelling (ir)radiance spectra were measured both under water and at 1000 m altitude for the Loosdrecht Lakes in The Netherlands. The Loosdrecht Lakes form a system of 7 main lakes ranging in water quality from an oligotrophic water-storage basin to hypertrophic turbid lakes. This range of water qualities within one area of 10 x 15 km is well suited for developing models and algorithms for remote sensing applications. In this case water quality is focused on those aspects of inland water bodies which are directly related to the underwater light field. The related water quality parameters are: Secchi disk transparency; seston dry weight, sum of chlorophyll-*a* and phaepigments; vertical attenuation coefficient for downwelling irradiance; absorption coefficient; scattering coefficient and beam attenuation coefficient.

Subsurface hemispherical upwelling spectral irradiance, Eu_s ($W/m^{-2}.nm^{-1}$) was measured using an underwater spectroradiometer (LiCor LI-1800) fitted with a cosine correcting fibre optic sensor head (Fig. 2). A remote sensing mission was carried out using the PMI of Moniteq in both spatial and spectral modes (Borstad *et al.* 1985). Thus spectra, L_{air} ($W/m^{-2}.nm^{-1}.sr^{-1}$) from 1000 m above lake

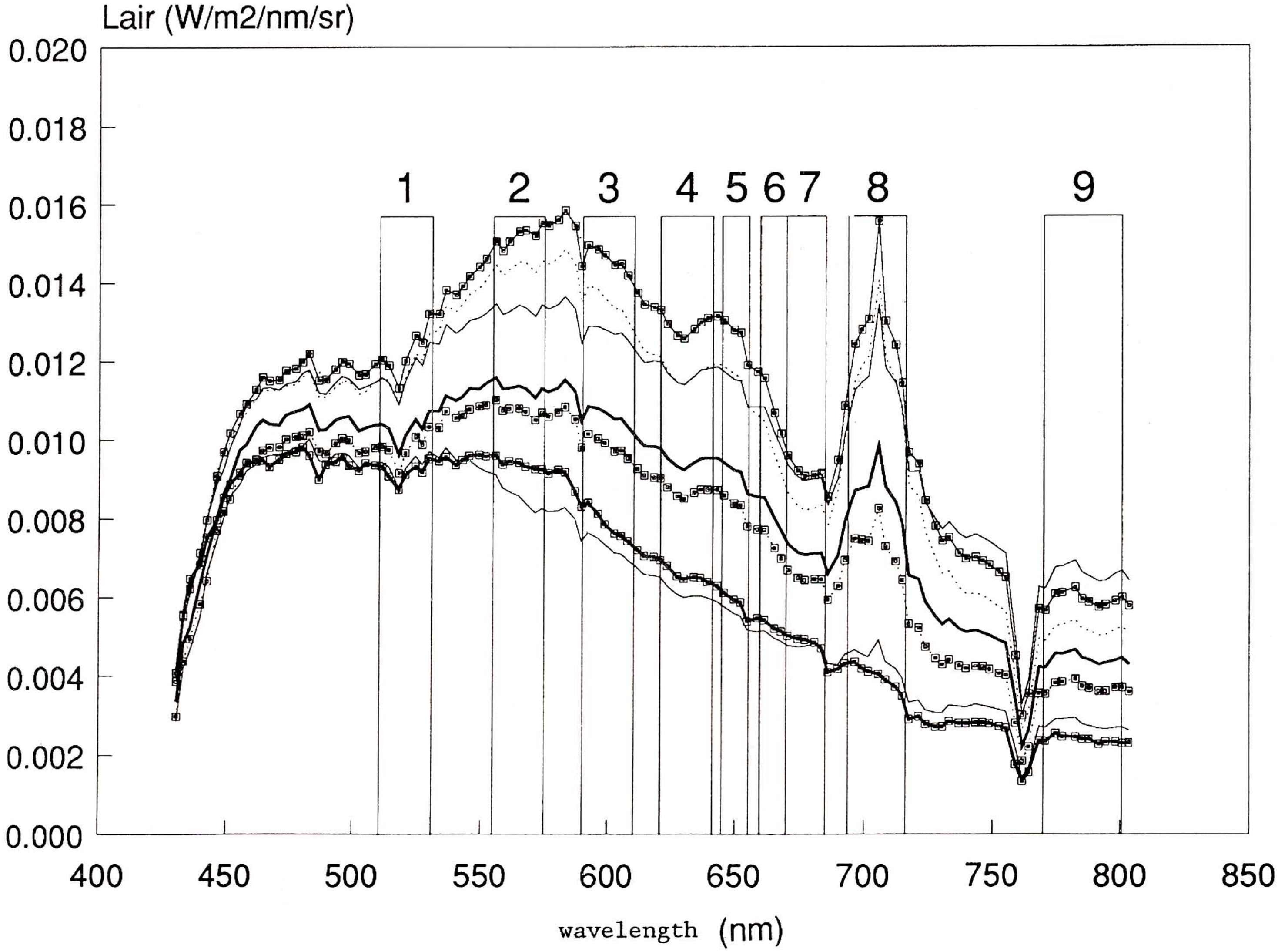

Fig. 3. CAESAR Inland Water Mode spectral bandset superposed on L_{air} spectra of 7 lakes in the Loosdrecht lakes system.

level were obtained (Fig. 3). The Eu_s measurements are point measurements. The L_{air} measurements are spectra from an area of 40 x 40 meters. An increasing similarity with increasing wavelength may be seen in the two types of spectra especially at wavelengths longer than 500 nm. Apart from differences in the instrumentation the essential difference between the spectra is surface reflection and atmospheric components in the airborne measured spectra. The sudden drop in the measured radiance values below 450 nm in the PMI spectra leads us to question the validity of the values of radiance measured in this region.

A pilot study for the development of an "Inland Water Mode" spectral bandset for the CAESAR scanner system was carried out in 1989 (Dekker *et al.* 1990a). This hypothetical "Loosdrecht mode" was specific to the Loosdrecht lakes system. For the development of an actual CAESAR "Inland Water Mode" several specifications and conditions, like versatility, costs, a minimum bandwidth of 10 nm were of influence in the final spectral band selection.

There were several reasons for incorporating a bandwidth of 10 nm:

- The EOPP/EOS missions will carry instruments having bandwidths of 10 to 20 nm (Goetz 1989; Rast 1989). - Manufacturing of filters with narrow wavebands is more expensive.
- Absolute radiance decreases possibly necessitating larger intergration times, specifically in low upwelling irradiance levels.

TABLE 2

CHARACTERISTIC CENTER WAVELENGTHS AND BANDWIDTHS FOR THE INLAND WATER MODE

Array code	Wavelength	Bandwidth
D1C	520 nm	20 nm
D2C	565 nm	20 nm
D1A	600 nm	20 nm
D2A	630 nm	20 nm
D3A	650 nm	10 nm
D1B	665 nm	10 nm
D2B	677 nm	15 nm
D3B	705 nm	20 nm
D3C	785 nm	30 nm

- Shifts in spectral features may occur within and between lake systems. Chlorophyll-*a* for instance has reported *in vivo* absorption peaks between 670 and 680 nm.
- At smaller bandwidths signal/noise ratios increase.

With the above criteria considered, the bandset presented in Table 2 and Figs. 1 and 2, was specified.

Spectral information from the water below 500 nm is virtually unmeasurable by remote sensing due to: low Eu_s caused by absorption by aquatic humus and by algal pigments (e.g. chlorophyll-*a*); high atmospheric influence at short wavelengths; decreasing sensitivity of electro-optical sensors with decreasing wavelengths, notably below 450 nm. Therefore the first band is situated beyond 500 nm. The rationale for the positioning of the spectral bands is given below:

<u>Band 1</u>: 510 - 530 nm (A CAESAR Sea Mode Band)

A measurement in this range is sufficient to model the spectral signature down to 400 m: a gradual decrease of Eu_s down to almost zero. In the spectral area of band 1 absorption by aquatic humus decreases from shorter wavelengths. There are no known absorption peaks of algal pigments and therefore reflectance increases to significantly measurable levels.

<u>Band 2</u>: 555 - 575 nm (A CAESAR Sea Mode Band) and <u>Band 3</u>: 590 - 610 nm

Measurement of irradiance at Band 1 is useful for determining the slope of the spectrum to bands 2 and 3, which are situated around the first peak in reflectance. This maximum is the result of low absorption by aquatic humus and algal pigments. Thus backscattering, which increases with increasing particulate concentrations becomes the dominant factor in this spectral area. Band 3 was considered important to detect a decrease in Eu_s from band 2, in less eutrophic waters, as may be seen in the spectral line of Lake Wijde Blik.

<u>Band 4</u>: 620 - 640 nm (A CAESAR Sea Mode Band)

This band is located around a region of lower reflectance at 625 - 635 nm evident in spectra from the eutrophic and hypertrophic lakes. Lower reflectance is considered to be due to absorption by cyanophycocyanine (Begni *et al.* 1986). This pigment occurs in cyanobacteria abundant in the more eutrophic lakes of this system. Algal counts showed 95 to 99 % of the algae in the eutrophic lakes to be dominated by cyanobacteria. If no CAESAR Sea Mode Band had existed preference would have been given to a narrower spectral band between 625 - 635 nm. A wider band has the advantage, however, of encompassing possible shifts in absorption wavelengths.

<u>Band 5</u>: 645 - 655 nm

This band serves two purposes. Firstly, it models the reflectance trough at 630 nm in combination with bands 2 and 3. If a line connecting bands 3 - 4 - 5 is straight with low Eu_s values it is certain that relatively clear water (e.g. Waterstorage Basin type water) is measured. If the line connecting bands 2 - 3 - 4 is concave with high Eu_s values it is caused by a relative peak in absorption of light at 630 nm perhaps indicative of a blue-green algal dominated system. Secondly it models the absorption peak resulting in a Eu_s low at 680 nm where the *in vivo* chlorophyll-*a* absorption band is evident.

<u>Band 6</u>: 660 - 670 nm and <u>Band 7</u>: 670 - 685 nm

These bands measure this *in vivo* chlorophyll-*a* absorption peak. Concentrations of chlorophyll-*a* may reach a level of 200 lg/l in the most eutrophic of these lakes.

Band 8 : 695 - 715 nm

A peak in Eu_s is visible at 705 nm in spectra measured over the more eutrophic Loosdrecht lakes. Vos *et al.* (1986), determined this peak to be caused by a minimum in the combined absorption curves of algae and water. Vertical attenuation in this spectral region is thus low compared to the surrounding wavelengths (Malthaus and Dekker 1988). This band is useful for modelling the absorption peak of chlorophyll-*a* and its byproducts at 680 nm.

Band 9 : 770 - 800 nm (A CAESAR Sea Mode Band)

Spectral band 9 is situated in the near- infrared. From 720 nm onwards absorption by water increases sharply and becomes the major absorbing component. Due to high (back)scattering levels there is still a substantial amount of Eu_s. Therefore, in the nearby infrared, water may not always be considered to have zero Eu_s. Atmospheric influences are lowest in this region. The marked trough in Eu_s at 760 nm is due to an oxygen/water absorption band in the atmosphere. This spectral bandset enables an accurate reconstruction of the spectral signature between 400 to 800 nm in these lakes.

The multivariate statistical analyses of detailed ground-based spectroradiometric and airborne spectroscopic measurements made it possible to assess the potential information contained in the selected spectral bands for the CAESAR Inland Water Mode. For this purpose CAESAR Inland Water Mode spectral bands were simulated by integrating the Eu_s spectra and the L_{air} spectra spread over 7 lakes.

Simulated spectral band values of subsurface and airborne upwelling (ir)radiance spectra were correlated with the water quality parameters. Both linear and log-transformed data were analysed. Only algorithms with one or two bands were considered, in order to minimise noise in the actual imagery once the inland water mode becomes operational. Highest results for the Eu_s derived data were obtained for the log-transformed data: correlation coefficients (R 0.95) for the single band values with all water quality parameters. For remote sensing purposes the L_{air} data are more relevant. Best results were obtained here using ratios of spectral band values. Highest correlation values (R 0.95) were found for band ratios with all water quality parameters. These results seem to validate the choice of spectral bands for the CAESAR "Inland Water Mode".

The results confirm earlier conclusions (Bunnik 1978; Dekker *et al.* 1990a) that in eutrophic systems such as the Loosdrecht lakes accurate estimation of within lake parameters can be achieved by using band ratios based on wavelengths from 500 to 800 nm, with particular emphasis on the area between 600 and 720 nm. An advantage of using longer wavelengths is that atmospheric distortion of the remotely sensed signal decreased with increasing wavelengths. The range and resolution in wavelengths on future instruments (MERIS, HIRIS) will make it possible to monitor water quality accurately from space in both a qualitative and quantitative manner. Nine spectral bands are sufficient to determine several water quality related optical parameters to a high degree of accuracy.

In the summer of 1990 a remote sensing mission is planned to investigate the use of the CAESAR inland water mode for inland water quality detection. The CAESAR-flight will be accompanied by an intensive high quality data collection campaign over 16 lakes in the central Netherlands. Chemical, physical and biological data will be gathered simultaneously with very high resolution *in situ* spectroradiometric measurements. Subsequent laboratory based spectrophoto- and spectrofluorometric measurements will complete the dataset.

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