Airborne Imaging Spectrometry for Mapping of the Chlorophyll A Distribution and Pollution in the Skagerrak Region

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Abstract

The increased frequency of toxic algae blooms that have occurred in the North and Adriatic Seas have caused severe problems to the industrial activities, ranging from aquaculture to tourism, taking place in these areas. On initiative from NRSC a multi-institutional cooperation between Norway and Canada was established to evaluate the potential of airborne imaging spectroscopy in Norwegian waters. The program Norwegian Remote Sensing Spectrometry for Mapping and Monitoring of Algal Blooms and Pollution - NORSMAP, was established. The Canadian Compact Airborne Spectrographic Imager (CASI) developed by Itres Research Ltd. was rented and installed in the surveillance aircraft of the Norwegian State Pollution Control (SFT) for a three week period in May 1989. The ESA and CEC initiative to the European Imaging Spectroscopy Airborne Campaign (EISAC'89) also selected the NORSMAP region as one of the test sites to be overflown by the Fluorescence Line Imager (FLI) and the 64 channel GER Imaging Spectrometer (GERIS). The IOS spectrometer from Institute of Ocean Science was installed on a variety of research vessels to provide near-surface waterleaving radiance spectra.

Water masses covering a wide range of optical properties have been analysed and chlorophyll *a* concentrations in the range from 0.8 ot 5 µg/l was observed. A good large scale match between the *in situ* and airborne data are found, although the point to point comparison are not convincing, due to large discrepancies in both time and space of the two types of observations.

1. INTRODUCTION

During the late spring of 1988 an extensive and unpredicted bloom of the toxic algae, *Chrysochromulina polylepis*, occurred in the Skagerrak region, where it outgrew all other species and influenced most marine life in the upper 30 meter of the ocean (Dundas *et al.*, 1989; Heimdal *et al.*, 1989; O.M. Johannessen *et al.*, 1989 and J.A. Johannessen *et al.*, 1989).

The lack of any remote sensing instrumentation capable of directly monitoring the surface layer distribution of the algae bloom was recognized as a significant deficiency by an ad-hoc established monitoring team in 1988 (O.M. Johannessen *et al.*, 1988). In particular this would have supplied information on the early stage extension of the bloom and on which area to focus the *in situ* observations as well as the day to day tracking of the algae front.

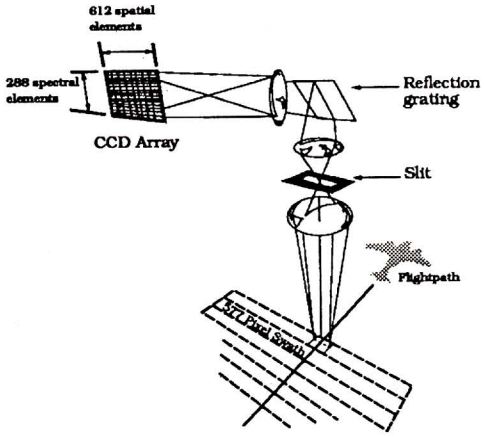

Fig. 1. The optical principles of the CASI.

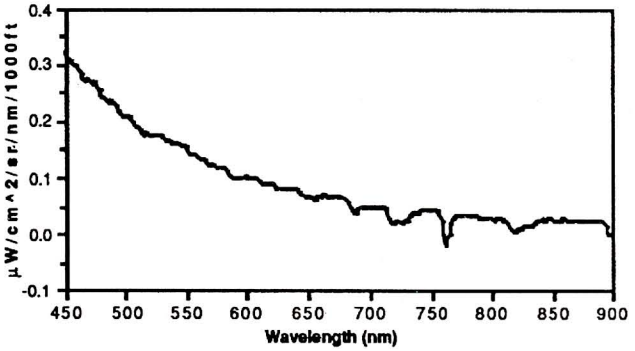

Fig. 2. The atmospheric contribution pr.1000 feet as obtained from measurements at three different heights over the same location.

Presently, there is no operational optical spaceborne satellite sensor system dedicated to monitoring of ocean color. While waiting for dedicated satellite ocean color sensors, scheduled to be launched from the mid part of this decade, preparatory studies and operational applications have to be perfomed with airborne sensor systems.

This fact was tne major argument for the initiative from Nansen Remote Sensing center to start the pilot study "Norwegian Remote Sensing Spectrometry for Mapping and Monitoring of Algal Blooms and Pollution - NORSMAP'89" (Petterson and Johannessen, 1988) as a joint project with Institute of Marine Research (IMR), Norwegian Institute for Water Research (NIVA), University of Bergen, Terra Orbit A/S, Akvaplan A/S, Borstad Assoc. Ltd., and Institute of Ocean Science (IOS), the two latter from Sidney, Canada.

A 3 weeks field experiment (Pettersson, 1989; Pettersson *et al.*, 1989; Pettersson *et al.*, 1990) was carried out in May 1989 with the Canadian Compact Airborne Spectrographic Imager (CASI) (Babey and Anger, 1989) installed in the Norwegian State Pollution Control Authority surveillance aircraft, and the IOS spectrometer installed in a series of three research vessels. The joint ESA and CEC - European Imaging Spectroscopy Airborne Campaign - EISAC'89 (Bodechtel *et al.*, 1989) contributed with overflights of the NORSMAP test region by the Canadian Fluorescence Line Imager (FLI) (Buxton, 1988) and the US 64 channel GER Imaging Spectrometer (GERIS) (Collins and Chang, 1988). The results from the NORSMAP'89 campaign will be discussed in the following, with particular emphasise on the results from the CASI data.

2. METHODOLOGY

The CASI airborne spectrometer is operational in two fundamentally different modes which either sample data with a high spectral or a high spatial resolution as illustrated in Fig. 1 (Borstad and Hill, 1989). The data presented below were generally obtained in spectral mode because of technical problems with the image mode during the campaign.

With the goal to map and monitor the distribution of the ocean chlorophyll *a* in the surface layer two methodologies have earlier proven their benefit applied on airborne spectral data in the visible spectral range. The Fluorescence Line Height (FLH) (Gower *et al.*, 1984; Borstad *et al.*, 1985) and the Blue Green Ratio (BGR) (Clarke *et al.*; 1970, Gordon *et al.*, 1983) methods have both been evaluated to give reasonable results in similar water masses as observed during the NORSMAP'89 investigations. Generally the BGR method is more dependent on the amount of suspended and dissolved organic constituents in the water masses, while the FLH method is more robust for use in turbid coastal waters and has therefore been selected for the major part of the NORSMAP'89 analysis.

An empirical approach for the correction of the atmospheric contribution to the spectra has been applied to the data. Collection of CASI data at three different altitudes over the same location, in near synoptic time, was obtained during two of the flights. These data have been used to calculate the average contribution from the atmosphere per height unit given by the correction spectra in Fig. 2. Due to the fact that the horizontal and time distribution of aerosol and the atmospheric scatter is significantly variable this correction approach must be used with care and evaluated against

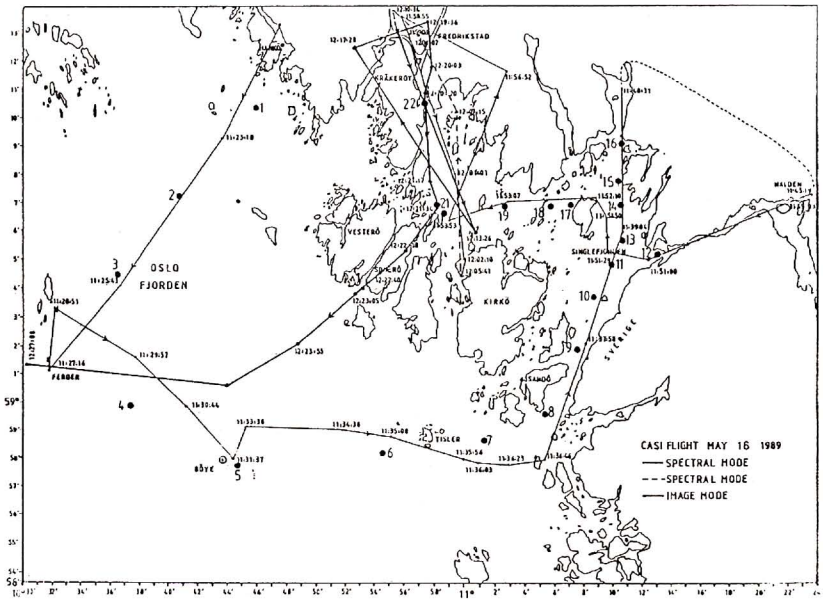

Fig. 3. The CASI flight lines and the in situ stations obtained in the Hvaler area on May 16.

atmospheric model corrections. A general altitude dependent correction technique, based on these measurements, turned out to overcorrect the spectra in the blue range for one of the flight dates. Therefore a technique, where a fraction of the correction spectra were subtracted from the measured spectra with a following test on the depth of the oxygen absorption line at 762 nm has been applied. This was repeated until the depth reached a preset threshold. This technique gives a better correction of the spectral region around 685 nm, which is used in the FLH calculation and where the oxygen absorption is one of the dominating error sources. However the blue range of the spectra, where oxygen concentration has little correlation with the amount of scattering, is not correctly compensated for the atmospheric scatter and therefore the application of this correction algorithm has been limited to the processing of FLH data.

3. RESULTS

During May 16 a combined airborne and field campaign of a total number of 22 *in situ* stations was carried out in the Hvaler archipelago in the outer Oslofjord, throughout the day (Fig. 3). The airborne data were collected under a low and variable cloud cover which forced the flight altitude as far down as to 1,000 ft.

The along track chlorophyll *a* concentration and the Fluorescence Line Height (FLH) calculated from the CASI data are shown in Fig. 4, as well as the *in situ* measured salinity (to differentiate the ocean and brackish water masses), and the light beam attenuation at 520 nm (c- 520).

The Chl-*a* concentration in the vicinity of the Glomma river outlet was about 3-4 µg/l (station 1-2), decreasing to 1-1,5 µg/l moving into the central part of the outer Oslofjord (station 3-5) and towards the outer part of the Hvaler archipelago (station 6). The FLH match the variation in the Chl-*a* concentration relatively well (Fig. 4.a), except at station 6 where a Chl-*a* minimum was reported. This discrepancy between the remotely sensed and *in situ* Chl-*a* resolving parameters appeared in the frontal zone between the more saline and nutrient poor water and the fresher water and hence might be caused by changes in the physiological state of the algae population. At station 7 and 8 at the eastern inlet of the archipelago the Chl-*a* concentration was approximately 3 µg/l and increased to a maximum of 5 µg/l at station 10 and 11. In this area, freshwater high in nutrients mixes with the more saline water, favouring increased growth of phytoplankton. Moving into the outlet of the Iddefjord (station 12), the Chl-*a* dropped to ca. 3 µg/l, but only a minor decrease in FLH was observed. From station 17 the influence of the fresh water increased and the salinity dropped to below 10 ‰ (Fig. 4.b) and the FLH and CHl-*a* values become very uncorrelated. The complexity of this area is partly caused by the mixing of saline water into an area with fresh water, where marine algae was exposed to fresh water with a resulting cell damage (Boney, 1975) and high variability in the chlorophyll fluorescence. Due to severe sun glints in the data, the CASI

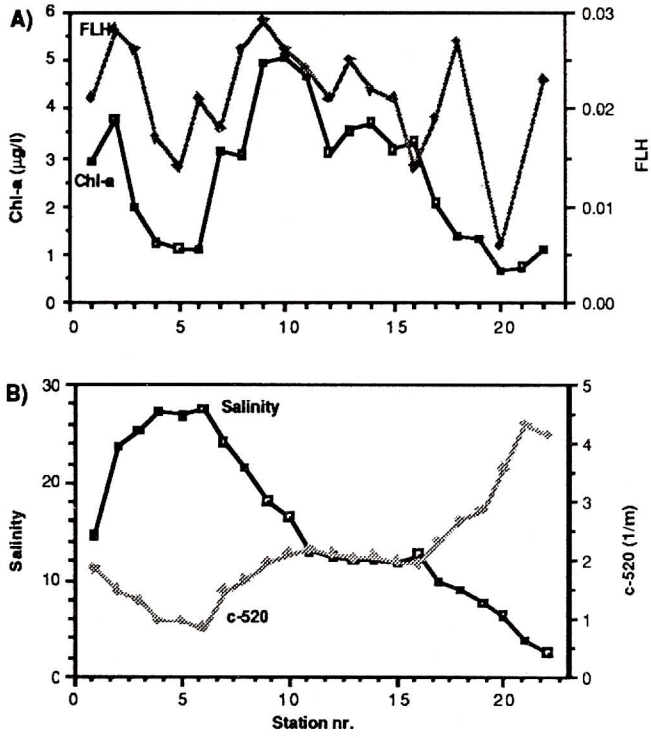

Fig. 4. The along flight line variation of (a) the Chl-*a* concentration and FLH as obtained on 16.May, (b) the variation of the *in situ* measured salinity and light beam attenuation at 520 nm (c-520).

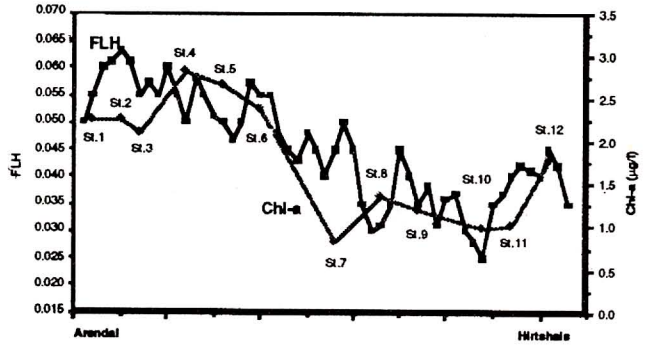

Fig.6. The variation of the Chl-*a* concentration and the FLH values as obtained along the open ocean transect between Arendal and Hirtshals on 18 May.

data from station 19 and 21 are omitted. The significant change in the FLH and Chl-*a* match in the main Glomma river (St.no. 22) might be explained by the effect of the increased sediment concentration on the CASI spectral signal. Due to problems with exact adjusting of the aircraft position to the location of the ship stations and large time dicrepancies (≈ 8 hr.) between the airborne and *in situ* observations, a statistical regression gives a relative low explained variance of only around 31%. However this does not give a fair picture of the capability of the airborne spectrometry data, since the along track values of Chl-*a* and FLH (Fig. 4a) clearly indicate a better match with respect to resolve the large scale variability, until the more

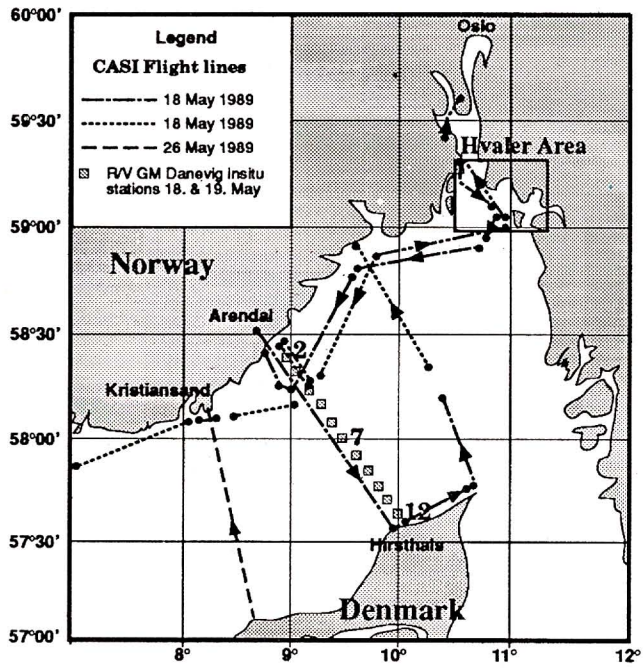

Fig. 5. The CASI flight lines and *in situ* stations obtained in the Skagerrak region under NORSMAP'89 on 18 May.

complex situation in the outlet of the Glomma river is reached.

An open ocean transect between Arendal and Hirtshals was flown on 18 May. The *in situ* observations was carried out by R/V Dannevig during the entire day, and stations no.10-12 were obtained on 19 May (Fig. 5). The CASI spectral data was obtained from a flight altitude of 9,000 feet under relatively good observational conditions, although with some haze close to the Arendal coast and some more patchy cloud structures in the central parts of Skagerrak. The data selection of the spectral data was done as close as possible to the ship stations, with additional measurements in between the ship stations. The profile along the section are shown in Fig. 6.

The along transect variation of the chlorophyll *a* concentrations, in the surface layer (0 meter), show generally higher concentrations on the Norwegian side of the basin than on the Danish coast (Fig. 6). A minimum Chl-*a* value is observed in the central Skagerrak (station no.7). There is a significant discrepancy between the *in situ* measurements and the FLH values observed at this station but the fact that the two observations are done 10 hours apart make a direct explanation difficult. A slight increase in the chlorophyll *a* value was observed in the high productivity part of the outer North Jutland Current (NJC) (st.no. 8) and a decrease (st.no. 10-11) thereafter in the chlorophyll concentrations. The

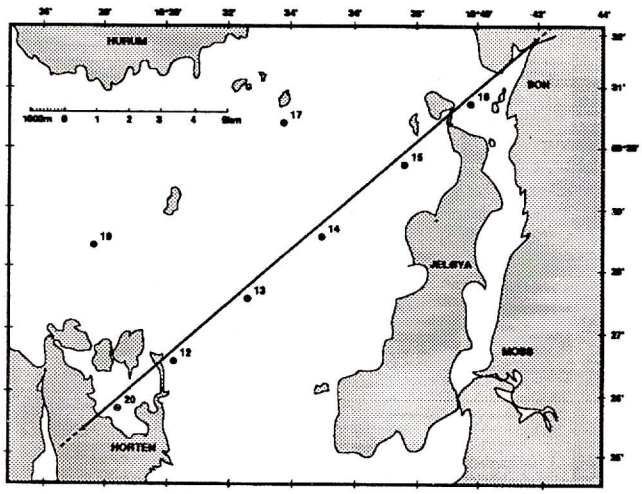

Fig. 7. The FLI flightline and in situ stations from Horten to Son as flown on May 23.

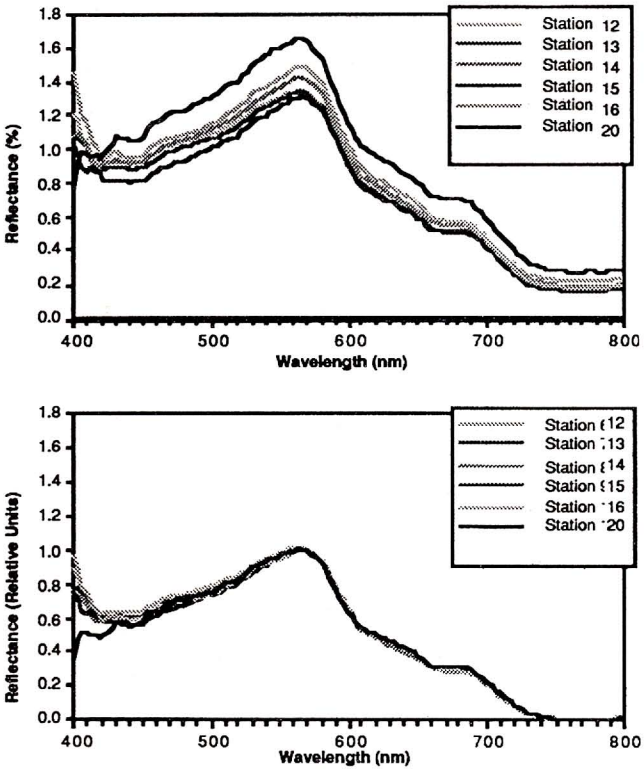

Fig. 8. The spectral intensities obtained by the ship-mounted IOS spectrometer from the Horten Son line flown by the FLI (a). (b) The same spectra as in (a) subtracted by the reflectance at 766 nm and normalized to unity at 568 nm to compensate for variable illumination and surface reflectance during the period of observations.

Chl-*a* concentrations increased in the shallow water region close to the Danish coast (st.no. 12). Although some station to station discrepancies are observed the overall correlated trend between the FLH and Chl-*a* data with respect to the large scale variability along the section are relatively good.

The EISAC'89 evaluation flights of the FLI and GER spectrometers were scheduled to be done during the open ocean investigations. Due to technical and weather problems this had to be altered at the last minute. An overflight of the GER was done on May 22 in the Hvaler area (a line from st. 5 to 9 in Fig. 3), while the FLI, due to technical problems was delayed until the day after, then flown in the inner Oslofjord area, where our research vessel was available (Fig. 7).

The surface measured spectra show some variation from station to station (Fig. 8a). However, as the stations were obtained between 13:00 and 17:40 local time and the major part of this variation appear due to changes in the sun illumination and surface reflection. Subtracting the reflectance at 766 nm and normalization to unity at 568 nm should compensate for these variations. The resulting spectra are shown in Fig. 8.b and indicate very little variation along the flightline.

The "forced" selection of the FLI flightline was therefore not optimal for demonstrating the capability of the FLI to resolve variable gradients of the Chl-*a* content. *In situ* measurements confirm that the along track variation was less than 1 µg/l in the absolute range around 4 µg/l. The turbidity has a slightly larger variation approximately 0.5 FTU in the range of around 1.2 FTU.

In general the signal to noise ratio and sensitivity of the GERIS (Bodechtel and Sommer, 1990) turned out to be too low for detection of the small contrasts observed in a low reflectance surface, such as the ocean. Unfortunately the data also suffers from severe sunlight. The effective bandwidth of the GERIS is also found to be much larger than the specified 12.3 nm in the visible and near infrared. Modelling of the 760 nm oxygen absorption band indicate an effective bandwidth of approximately 50 nm (Bodechtel and Sommer, 1990). Any further analysis of the GERIS data has therefore not been done for ocean applications of these data.

During the NORSMAP'89 campaign the CASI was also overflying oil spills during an oilspill monitoring and calibration experiment in the Netherlands off Rotterdam. 7 m^3 of Helm Helder crude oil were deployed and overflown by the CASI about 3.5 hours later. Evaluation of the image mode spectral bands show a clear discrimination between the core area, the outer part and the surrounding unpolluted water. A simple ratio of the spectral signatures from the

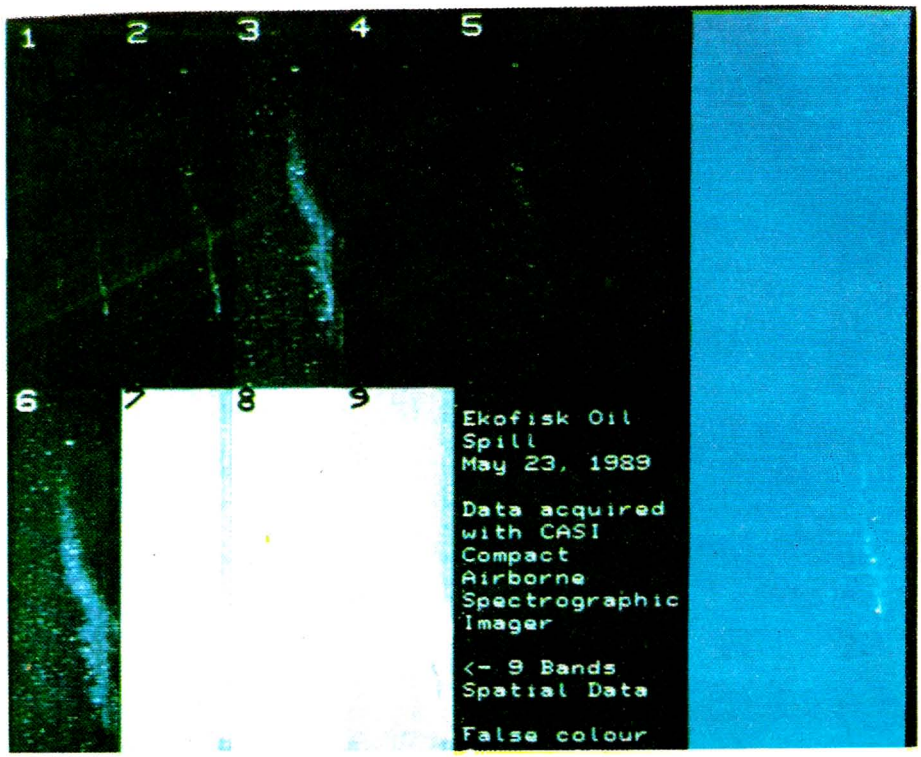

Fig. 9. The nine individual spectral images obtained when the CASI covered an oil spill during an oil spill calibration experiment in the Netherlands off Rotterdam on May 23. The data is presented with a cross track pixel size of 4 m and an along track pixel size of 4.3 m. A false color composite of three channels is included to right.

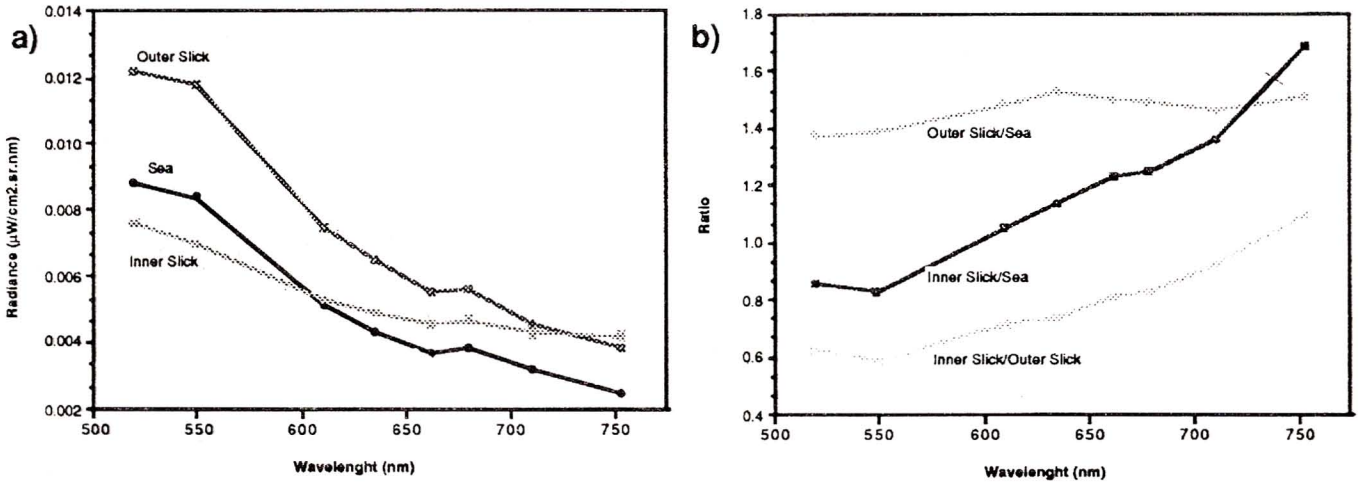

Fig. 10. (a): The spectral intensities obtained from the nine image mode channels shown in Fig. 9.
(b): The respectively ratio between the un- oiled sea, the edge and the core of the oilspill, and the edge and core of the oil spill (see legend on figure).

three regions of the spill area indicate an increased slope of the radiance ratio between lower and higher wavelengths for increased content of oil in water (Fig. 10). These preliminary results indicate a potential use of airborne spectrometry for estimation of oil spill concentrations or volume. Further investigations are foreseen on this topic within the continuation of this project.

4. CONCLUDING REMARKS

The impact of and need for monitoring and forecasting of algae blooms have been clearly emphasized during recent events in the Adriatic and Skagerrak Seas, which has caused severe effects on the activities in these regions.

The potential and efficiency of utilizing airborne remote sensing spectrometry to monitor the general chlorophyll *a* distribution, and hence the extreme situations, has been documented in the analysis of the NORSMAP'89 data set. A future operational use will require further development of operational tools for atmospheric corrections and further studies of the spectral band location and bandwidths used in chlorophyll resolving algorithms. However, at present it is still possible to utilize the airborne spectrometry technology in conjunction with *in situ* biological and physical oceanographic observations for monitoring of the surface layer extension of extreme algae blooms.

The marine chlorophyll and environmental monitoring capability and the potential use for land applications, demonstrated at other EISAC'89 test sites, make the airborne spectrometry technology an important multidisciplinary environmental monitoring tool with expanding future applications.

ACKNOWLEDGMENT

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