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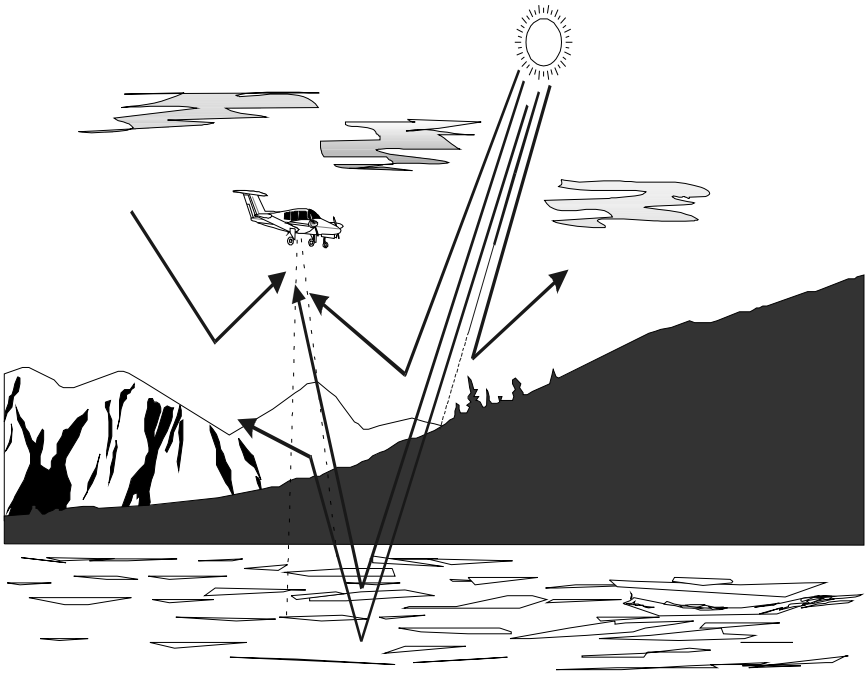
Utilisation of Airborne Imaging Spectrometers



for spectral Characterisation of Waste Water Plumes

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In situ measurements of chlorophyll *–a,* suspended matter and dissolved organic carbon are performed together with measurements of phosphorus, NOX and light absorption at 260 nm and 280 nm. Spectral profiles for sampling points and plume affected waters are extracted and analysed. Results from simple regression analysis show that best correlation are achieved for chlorophyll *–a* and suspended sediments, no significant correlation were found for dissolved organic carbon. It is shown that spectral difference between plume affected water and "clean" water reaches its maximum between 650 and 700 nm for this data set. Further more it is shown that spectral variations between different plumes is greatest between 400 and 550 nm. Correlation was confirmed for chlorophyll and suspended sediments but correlation coefficients were weaker than expected. High geometric resolution combined with a multitude of wavelength bands with narrow bandwidths is obviously not sufficient for high performance monitoring of the coastal zone. It is evident that image quality and thus information content, is in a high degree dependent on god weather conditions during registration. It is also important to gather information regarding optical properties of both the atmosphere and the water body for correction and calibration purposes. Nevertheless, in spite of poor quality in delivered data, the information content is higher than in data from now operating satellite systems, which should not be neglected.

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Abstract

This study report on an investigation of the performance of high resolution imaging sensors in the field of water quality monitoring in coastal waters affected by industrial wastewater plumes. The aim is to develop methods for detection and identification of different kinds of water discharges and to make these methods applicable to the next generation satellite systems. In this work data from two imaging spectrometers have been evaluated and compared. The study areas are located at the northern part of the Swedish East Coast. Heavy industries with large amounts of industrial waste water discharges, together with the outlets of several major Swedish rivers characterise this part of the Swedish coast.

In situ measurements of chlorophyll *–a,* suspended matter and dissolved organic carbon are performed together with measurements of phosphorus, NOX and light absorption at 260 nm and 280 nm. Spectral profiles for sampling points and plume affected waters are extracted and analysed. Results from simple regression analysis show that best correlation are achieved for chlorophyll *–a* and suspended sediments, no significant correlation were found for dissolved organic carbon. It is shown that spectral difference between plume affected water and "clean" water reaches its maximum between 650 and 700 nm for this data set. Further more it is shown that spectral variations between different plumes is greatest between 400 and 550 nm. Correlation was confirmed for chlorophyll and suspended sediments but correlation coefficients were weaker than expected. High geometric resolution combined with a multitude of wavelength bands with narrow bandwidths is obviously not sufficient for high performance monitoring of the coastal zone. It is evident that image quality and thus information content, is in a high degree dependent on god weather conditions during registration. It is also important to gather information regarding optical properties of both the atmosphere and the water body for correction and calibration purposes. Nevertheless, in spite of poor quality in delivered data, the information content is higher than in data from now operating satellite systems, which should not be neglected.

1 Introduction

1.1 Background

High pollution levels of coastal waters present a clear and present danger of a breakdown of the biological balance. The scale factor of the problem is ranging from eutrophication, which may result in unpleasant algae blooming to the development of toxic algae with severe consequences for both humans and animals. These kinds of environmental hazardous incidents have been reported several times during the last decades. An example the extreme algae blooming and the death of thousands of seals in the North Sea in the summer of 1988. Reports of complete extinction of benthic organisms in some areas in the Baltic Sea have also been discussed in the environmental research community. Monitoring systems detecting ocean and coastal pollutants and their spatial spreading is therefor urgently needed.

A crucial factor for the water quality of coastal regions is, especially in the Baltic Sea, the distribution and influence of industrial waste water plumes. Pulp and paper industries, chemical industries as well as other industrial plants occur frequently along the Swedish and Finnish coast. They affect the water quality of nearby recreational areas, sensitive nature protection areas, and the fish populations. There is a pronounced need for techniques capable to distinguish the types of plumes affecting specific areas of interest, whether it be areas where commercial activities utilise the water resource, recreational areas or nature conservation areas. Plumes originating from specific types of industrial processes are likely to have unique spectral fingerprints. However, the spectral characteristics of different types of plumes are not well known. This is the major topic for this study.

The treatment of industrial wastewater has been strongly improved in Sweden during the last decade. However, forest industry effluents still contain nitrogen and phosphorus. These compounds normally regulate the extent and intensity of algae blooms. They also contain metals and persistent organic compounds (POCs). POCs have been shown to be toxic to algae and may give an opposite, negative effect on the primary production. The resulting effect of this combination of nutrients, metals and POCs on phytoplankton blooms is still unknown for most types of effluents, although Ekstrand (1998) found no clear change in the top layer chlorophyll *a* concentrations in the Iggesund waste water plume compared to nearby bays with no industrial effluents. The water quality situation in the vicinity of forest industries has been improved, but the effluents still pose sub-lethal physiological effects in fish, apart from possible effects on the primary production. The plumes generally constitute no immediate threat to human health, but may strongly reduce the attractiveness of recreational areas. Long-term accumulation of e.g. metals in human populations consuming fish from waters affected by industrial waste waters, which includes a considerable part of the Swedish near-shore waters, is likely to occur, but is not well documented.

The large amount of water discharged from the pulp and paper industry is distributed in plumes that sometimes extend tenths of kilometres along the coast. Therefore, it is of significant interest to try to estimate the degree of dilution with sea water, as well as to determine the effect on phytoplankton production during algae blooms. Techniques that would give the opportunity to quantify these plumes at different times

and at different flow conditions would significantly improve the state of knowledge concerning the environmental effects of these effluents.

1.2 Objectives

The hypothesis on which this project is based is that the improved spectral resolution of future satellite sensors will give new possibilities to monitor and distinguish waste water plumes and thus the geographic extent of their influence on coastal waters. As a step towards satellite hyperspectral data we have analysed data from two airborne imaging spectrometers. Specific objectives were to:

- Validate the possibility to identify specific spectral changes caused by the industrial waste water studied.
- Evaluate the capability to distinguish chlorophyll *a* in plumes, and to verify possible improvements compared to existing satellite data.
- To compare the capacity of the two airborne imaging spectrometers CASI and GER for spectral characterisation of waste water plumes.

1.3 Fundamental remote sensing

When electromagnetic energy is incident on any given surface, three fundamental energy interactions are possible. Fractions of the incident energy on the element are reflected, absorbed and/or transmitted. Proportions of energy reflected, absorbed, and transmitted will vary for different features depending on their material type and condition. Further, these proportions will vary at different wavelengths. The interrelationship between these energy interactions can be expressed in an energy balance equation as:

$$E_I(\lambda) = E_R(\lambda) + E_A(\lambda) + E_T(\lambda)$$

Equation 1. Energy balance equation

Where $E_I(\lambda)$ denotes the incident energy, (the sun in most cases), $E_R(\lambda)$ denotes the reflected energy, $E_A(\lambda)$ denotes the absorbed energy and $E_T(\lambda)$ denotes the transmitted energy with all energy components being a function of wavelength λ.

The foundation of remote sensing of natural waters can be described like follows: When electromagnetic energy is incident on a water surface, physical reactions are started through reflection, absorption and transmittance. The irradiance reflectance spectrum or volume reflectance just beneath the water surface of a water mass is shaped by the absorption and scattering functions of the water itself and the optically active components that are present in that water mass. This subsurface irradiance spectrum is converted to an upwelling radiance spectrum through water-air interface and transferred through an atmospheric mass which, influences the signal. A downward-looking remote sensor measures the resulting signal.

1.4 Challenges in aquatic remote sensing

Monitoring of water quality in coastal water systems using remote sensing techniques presents both challenges and opportunities. In many cases remote sensing techniques is very well suited for to the task of assessing changes in the marine environment. Multi-temporal image acquisitions may be compared to assess the changes in the marine environment and thereby give an understanding of levels of variation naturally occurring , as well as acceptable levels of anthropogenic disturbance (Clark, 1993). One of the major advantages of using remote sensing systems in the field of environmental monitoring is the opportunity to gather measurements of large areas more or less simultaneously. This is an important aspect when the observed feature displays a high degree of temporal variability, which is often the case for coastal water systems. The challenge of utilising remote sensing techniques for water monitoring lies in interpretation of the achieved signal. Quantitative water applications are difficult to develop due to the high variability of the water body itself. The relatively high mutual correlation of water parameters, the influence of the water surface, the generally low spectral reflectance of water bodies, the low radiometric sensitivity of the sensors, and the relatively strong contribution of the atmosphere to the detector signal are examples of items which are difficult to cope with. In addition, spectral signatures of different water bodies, each containing a certain composition of constituents, are generally similar (Van Stokkom, *et al.*, 1993). This restrains the possibilities of distinguishing those constituents and estimating their concentrations, High resolution-imaging spectrometry, both in the sense of spectral and geometric resolution, could be valuable in assessing a number of these difficulties. In recent years there have been an increase in the use of hyperspectral imaging spectrometers for marine applications (Bagheri *et al.*, 1998 Gould and Arnone, 1998, George, 1997)

Ocean remote sensing refers generally to three different kind of remote sensing techniques,

1. Passive optical remote sensing
2. Passive thermal remote sensing
3. Active remote sensing

Passive remote sensing refers to passive sensor measurement of the reflected and/or emitted electro-magnetic radiation from the object or feature of investigation. Passive remote sensing is divided in two categorise depending on the wavelength of the measured signal, the optical region of the spectrum and the thermal region of the spectrum. In passive remote sensing it is possible to measure features that are either optically active or experience some kind of thermal variation.

Active remote sensing refers to the technique when the sensor itself are equipped with a transmitter and measure the backscattered signal originating from its own transmission. This technique is dependent on the ability of the object to alter the properties of the signal and are most frequently used for measurements of ocean wave height and speed and for the detection of oil slicks, and Sea ice, which are not in the scope of this investigation.

In passive optical remote sensing of surface waters the focus is on retrieval information of the optically active substances in the water body through measurement of the spectral radiance, i.e., the water colour. In natural open ocean waters, referred

to as case 1 waters, the optical properties is dominated by the water itself and the chlorophyll pigmentation of the phytoplankton population. Techniques to detect chlorophyll concentrations for case 1 waters have been described by Gordon *et al.*(1983) among others.

Optical modelling algorithms of the water body and its constituents can be divided in three methodologies, the empirical approach, the analytical approach and the semi-analytical approach. The empirical approach refers to methods where the spectral response is correlated to the *in situ* measured water parameters gathered in conjunction with spectrum/image registration. In the analytical approach the effort is focused on the solving of the radiative transfer function by understanding the mechanistics behind the relationship between water constituents concentrations, water volume reflectance and remote sensor-observed radiance. The semi-analytical approach is based on the combination of analytical models and empirically derived connections between spectral data and in field measurements. This study is conducted employing empirical modelling.

Coastal and inland waters are often referred to as non-case 1 waters, or more convenient case 2 waters, are not as easy to cope with. Three groups of substances are generally considered responsible for significant modifications of the absorbing properties of these waters: phytoplankton, suspended sediments and dissolved organic carbon, (Prieur and Sathyendranath, 1981). These waters present serious difficulties for successful application of remote sensing techniques because of their complex optical properties. A vast number of researches have conducted studies in this area, (Alföldi and Munday, 1978, Bukata *et al.,* 1983, Gould and Arnone, 1998, Gower *et al.*,1984, Novo *et. al.*, 1989, Kondratyev *et al*., 1998, Morel *et al.*, 1995, Lee et al., 1998, Sathyendranath *et al.*, 1989, Tassan, 1997).

The capability of the present satellite generation for monitoring of primary production and algae blooms is well-documented for ocean surface waters. For coastal and inland waters however, the presence of suspended sediment has obstructed reliable quantification of phytoplankton. The signal from chlorophyll *a*, which is commonly used as a measure of phytoplankton concentration, is masked by the signal from suspended sediments (e.g. Ekstrand 1992, Tassan 1987, Verdin 1985). However, Ekstrand (1998) indicate a possibility to distinguish chlorophyll a changes in the top layer of the water column using the near-infrared channel (Landsat TM 4), in one of the plumes studied here.

The use of TM band 4 for water quality applications have been limited, mainly due to the high water absorption of light at these wavelengths. However, light is actually reflected from particles in the top layer, and it is a well-known fact that near-infrared radiance is reflected to a much higher degree by chlorophyll, than by sediment.

Several researchers have evaluated the capacity of wavelengths close to and in the NIR region for chlorophyll estimation. These studies reveal a strong relationship between NIR reflectance and surface chlorophyll-a. Some of the authors found that single NIR bands, e.g. around 705 nm, were the most suitable for chlorophyll estimation (Gitelson 1992, Quibell 1992), others that a NIR/red ratio was more robust (Mittenzwey et al. 1992, Rundquist et al. 1996). Gitelson et al. (1993) showed that the visible spectral regions lost their correlation with chlorophyll when the concentration

of suspended matter was high, while wavelengths above 700 nm were still strongly correlated with chlorophyll. It should be noted that the above experiments were conducted either in water tanks or in extremely eutrophicated inland lakes. No references in literature have been found that apply these findings to satellite data, or to coastal waters where the chlorophyll concentration is considerably lower.

2 Materials and Methods

2.1 Study area

Two different study areas are investigated in this study, the coastal area of Iggesund (61°38'N, 17°05'E) and the coastal area of Sundsvall (62°25'N, 17°15' E). Both areas are situated at the Swedish East Coast, approximately 300 and 400 kilometres North of Stockholm. These areas are both characterised by their heavy industry and large amounts of industrial waste water discharge.

The industrial complex of Iggesund, a paper mill and pulp industry, has its processing water discharged via a sedimentation basin. From the basin the discharge water is transported through a submarine outfall pipe approximately 2 kilometres from the industrial complex. From the outfall area, in the strait of Iggesund, the plume emerges in to another bay "Gårdsfjarden" trough a narrow strait. Before it reaches open water the plume have to pass one additional strait "Dukarsundet". During Easterly wind conditions the plume may be forced back and severely increase the plume load of the

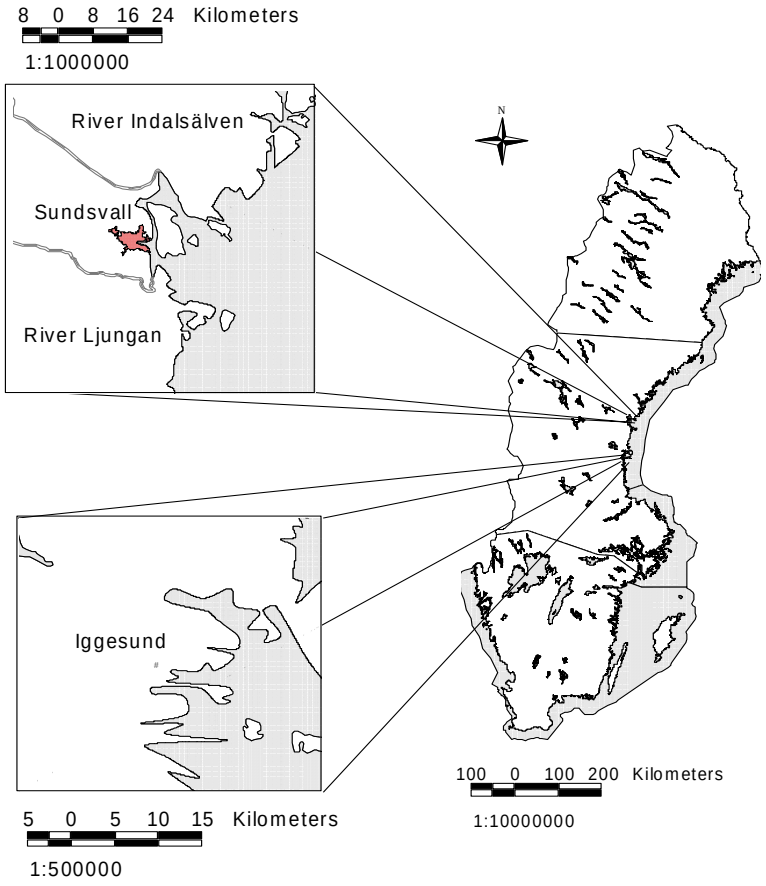

Fig. 1 Location of the study areas outside Sundsvall, and Iggesund respectively

inner bays. The industrial outlet is the only external waste water contributor, apart from the non point surface runoff after snowmelt or rainfall.

The Sundsvall test site covers three major industrial waste water discharges, all originating from paper mill or paper pulp industries. Together with the industrial discharge there are two riverine outlets, the river mouth of “Indalsälven” north of Sundsvall and the river mouth of “Ljungan” to the South. The archipelago is not so intricate as for the Iggesund site but the isle “Alnön” divides the general water flow in two separate branches “Alnösundet” and “Klingerfjärden”. In situations of Easterly winds the plume water from “Indalsälven” is forced to the eastern branch and will accumulate in the Bay of Sundsvall.

2.2 Acquisition of image data

Two different imaging spectrometers were used in this study. The 63 channel GER scanner, operated by the Geophysical & Environmental Research Corp., (GER) were used in the Iggesund area during the period July 10 and July 31, 1996. Between July 30 - August 8, 1997 flights with the improved CASI imaging spectrometer were carried out, now outside Sundsvall. The sensor characteristics during image registration are described in table 1.

Table 1. Sensor characteristics for the GER and CASI instruments

Band No.	**GER**		**CASI**	
	Centrum wavelength (nm)	**Band width (nm)**	**Centrum wavelength (nm)**	**Band width (nm)**
1	410.0	25	409.55	12.1
2	432.0	25	441.7	10.4
3	483.6	25	488.95	10.5
4	521.3	25	510.05	10.5
5	565.8	25	549.75	8.9
6	617.7	25	560.35	8.9
7	665.8	25	619.85	10.7
8	716.6	25	664.4	10.8
9	768.5	25	680.5	7.2
10	823.7	25	704.65	8.9
11	883.9	25	753	5.4
12	941.9	25	763.8	5.4
13	989.7	25	774.55	12.5
14			864.4	9
Swath angle	+/- 39 °		+/- 35 °	
Flight altitude	1500 m		2000 m	
Nominal pixel resolution	5 by 5 m		4 by 4 meter	

2.2.1 GER Image acquisition

During the GER campaign period low pressure events constantly passed over Sweden. The scenes are contaminated, by cloud, cloud shadows and turbulent air masses that causes small-scale undulations in the registrations. Further, no information was given on in flight calibration nor gain and offset scaling for different wavelength regions which implies that no conversion from digital number DN to up-welling radiance was performed. Only one scene of a total of four is usable. The scene covers an area ranging from the inner bay of Iggesund and out towards open water in an east south east direction. The covered are is approximately 2.5 kilometres wide and 17.5 kilometres long. This scene was registered and resampled to a 5 by 5 metre pixel resolution by the data provider. At this geometric resolution the sensor was only

capable to utilise 31 bands which depends on the integration time for the sensor elements. The wavelength bands were divided in three spectral regions. Band 1 to band 14 ranging from 410 to 1048.3 nm with a bandwidth of 25 nm, band 15 to band 28 ranging from 2039.3 nm to 2446.9 nm with a bandwidth of 17.5 nm and finally, band 29 to 31 the thermal region, ranging from 9468.4 nm to 10983.1 nm. From 850 nm absorption by water is rapidly increasing (Dekker and Peters, 1993) therefore spectral bands behind this threshold are seldom used for water monitoring. The thermal region could be of interest for tracking plumes based on temperature differences. However, the thermal channels were of poor quality and could not be used. Employed bands are presented in table 1.

2.2.2 CASI Image acquisition

The flight conditions were better for the CASI registrations, but not optimal. Frequent air turbulence resulted in considerable movement of the plane and hence distortion of the registration in turbulent air. The meteorological situation during the CASI campaign was as for the GER campaign far from perfect. Two flight transects were planned. Due to bad weather conditions it was impossible to fly the lines as originally planned and because of the long transit distance it was not possible to tray again another day. As a result the mission manager made the decision to stay in the Sundsvall area all day and repeatedly try to acquire data between clouds. All in all 22 flight lines were flown in the Sundsvall area, but only two of these scenes were considered usable here after denoted *CASI 1 and CASI 2. CASI 1* is ranging from the mouth of river Ljungan and northward over the Alnö strait and *CASI 2* is ranging from the moth of over river Indalsälven and south-eastward over the “Klinger-fjärden”. These two scenes were registered on Aug 5th during mid day. The time lag between scenes was less than 45 minutes. The band configuration was set to operate in a MERIS mode, to mimic the forthcoming MERIS sensor onboard the Envisat satellite. Fourteen bands ranging from 409.55 nm to 864.4 nm were used.

2.3 Acquisition of water constituents

2.3.1 Water samples for the Iggesund area

In conjunction with the flights a ground team gathered sea truth water samples but there was no possibility to move the planned sampling stations with respect to the altered flight routs. Therefore some of the sampling points were located outside or in the margins of the flight scenes and could not be utilised. Samplings of Chlorophyll *a*, suspended sediment concentration (SSC) and dissolved organic carbon (DOC) were collected at fourteen sampling points in conjunction with GER airborne data collection for the Iggesund area. Due to circumstances discussed above, only eleven of these sampling points were located whit in the scene.

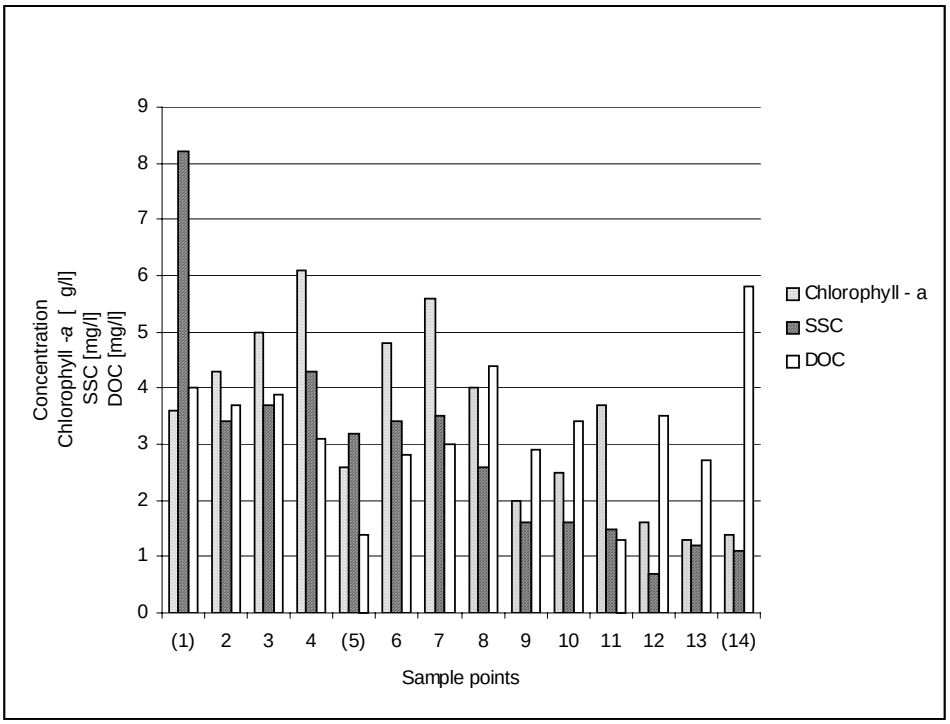

Fig. 2 Concentration of chlorophyll –*a*, suspended sediment and dissolved organic carbonoutside Iggesund. Sample points within parenthesis are located outside scene.

The two first sample points are located on the inside of the point of outlet. Points 3 and 4 are located close to the outlet source and 5 to 14 are successively located further away from the outlet source in a south-easterly direction. The high concentration of suspended sediments at point 1 is explained by a high degree of particle re-suspension in the shallow waters of the inner bay. The suspended sediment concentration is after this point decreasing with increased distance from the coastline except for points 2,3 and 4. These points are located close to the outlet point. Chlorophyll concentration co-varies with suspended sediment except for point 1and point 11. Highest concentrations of DOC are found far out in the Bay which suggest that DOC is not originating from the outlet water.

2.3.2 Water samples for the Sundsvall area

A total of 23 water samples were collected in the Sundsvall area simultaneously with the CASI data acquisition. Fifteen sample points were located within the two scenes, 9 in *CASI 1* and 6 in *CASI 2* respectively. All samples were analysed for chlorophyll *–a*, dissolved organic carbon, total phosphorus, NOX, and light absorbency at 260 nm and 280 nm, except for 4 sample points which were not analysed for chlorophyll. Measurements of light absorbency were conducted as an indirect measure of the lignine concentration, which presence was expected in the outlet water from the paper mill and paper pulp industry.

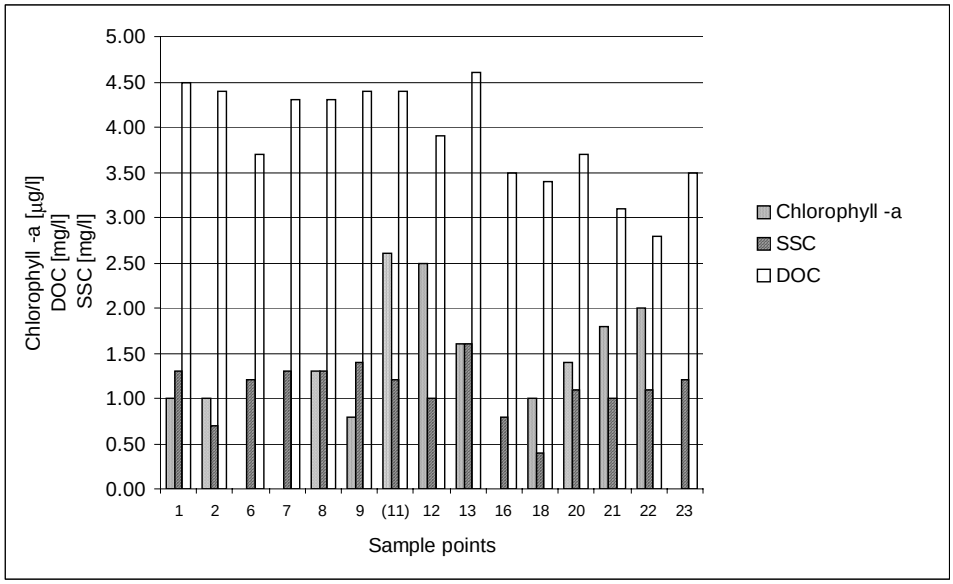

Fig. 3 Concentration of chlorophyll *–a*, suspended sediment and dissolved organic carbon outside Sundsvall. Note that only used sample points are presented. Chlorophyll concentrations are missing for points 6,7,16 and 23.

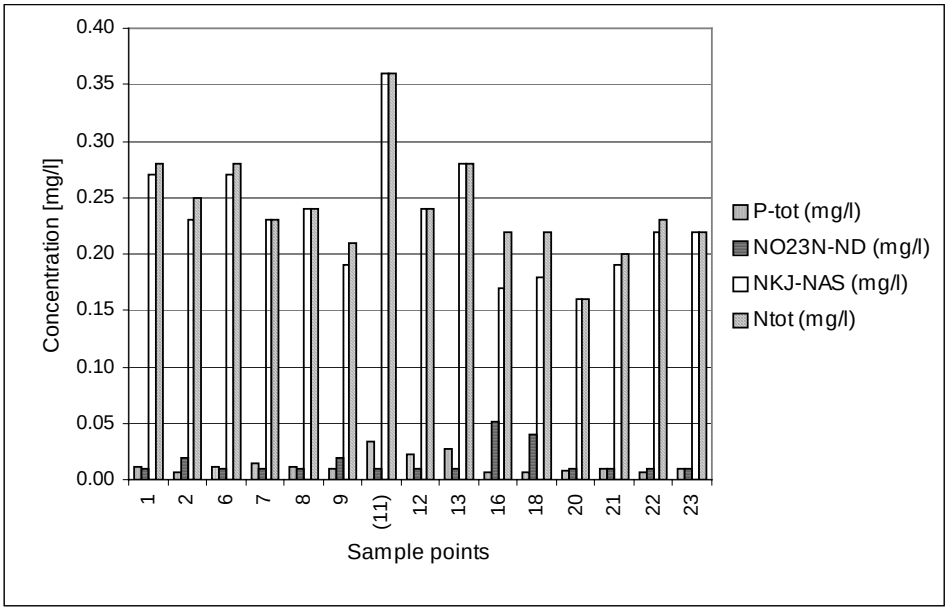

Fig. 4 Concentration of phosphorus and NOX outside Sundsvall.

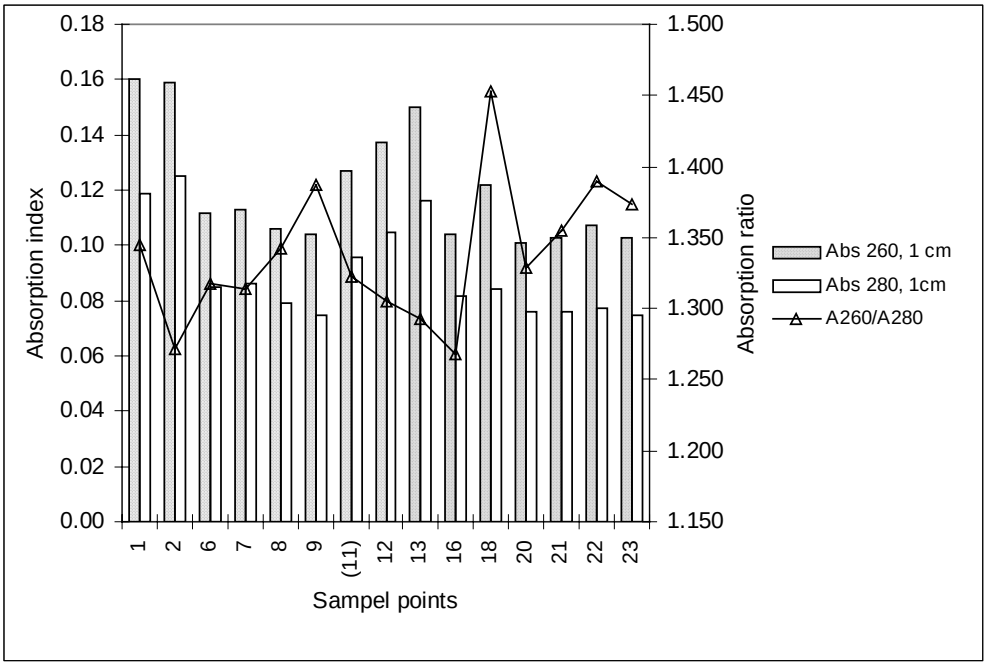

Fig. 5 Absorption coefficient at wavelength 260 and 280 nm outside Sundsvall.

The sampling points for the CASI data are collected at two transects on either side of the isle "Alnön" in the Sundsvall Bay area. The sampling points forms an angle surrounding three sides of the isle with point 1 to 16 on eastern side and 17 to 23 on the western side. The concentration of the measured constituents displays a fairly low degree of variation, which in turn implies a high degree of homogeneity regarding water quality of the water body.

2.4 Post processing

2.4.1 Atmospheric correction

The atmosphere influences the signal recorded by a remote sensing instrument in two almost contradictory ways. First, it attenuates the radiance in both directions, incoming radiance to the object and outgoing, reflected and /or emitted, radiance from the object. This is due to scattering by various components (areosols, water vapour, etc) in the atmosphere. Second, the atmosphere acts as a reflector itself, adding scattered light direct to the sensor, *path radiance*. The atmospheric effect is not linear trough out the spectrum. Due to particle size and composition, the scattering effect varies for different wavelengths. The blue region of the spectrum for example is subjected to selective scattering by the air molecules *Rayleigh Scattering* (Ahrens, 1991). Larger particles scatter all wavelengths of visible radiation more or less equally, *Mie scattering.* To be able to transform apparent spectral radiances measured by the sensor, into target reflectances it is crucial to derive a good approximation of the optical properties of the atmosphere coincidentally with image registration. Phillip *et al.*, (1998) have pointed out that a 5% sensor calibration error may result in an error

of as much as 50% in the calculated reflectance. In lack of necessary data on the optical properties of the atmosphere no advanced atmospheric correction was performed. It was seen as a better approach to analyse raw data then to risk the introduction of false radiance values.

The only atmospheric correction subjected to the *GER* data is the "dark object subtraction technique" (Chavez, 1988). Water absorbs virtually all radiation in the infrared part of the spectrum (> 900 nm). Water pixel values extracted from these wavelength bands should therefor not exceed zero. Levels above the zero threshold are considered to be caused by *Mie scattering*. To compensate for the additive radiance contribution from this effect, this value is subtracted from all wavelength bands. This method results in a DN subtraction constant of 3000 in the GER data. No atmospheric correction was performed on the *CASI* data. In consequence, the atmosphere is treated as homogenous over scenes, a reasonable assumption considering the small area of investigation. To compensate for vignette effects in data, which is caused by additional path radiance in the scene margins, sample points in the scene margin are excluded.

2.4.2 Geometric correction

All scenes were corrected for motion of the aeroplane and registered to the UTM system by the data provider. The scenes were transformed to the Swedish National geo reference system, RT90, trough a 2:nd order polynomial transformation with a resulting RMS error less the 3 pixels in both directions. If not else mentioned, DN values from of a 5- by 5-pixel window were derived for every wavelength band at each field sampling site to insure encompassing the sampling site within the 25-pixel group. The geometrical re-sampling performed by the data provider is questionable. Linear displacements are frequently occurring in both GER and CASI data, together with other re-sampling artifacts such as waveforms. The data provider did not include raw data why recalculation has not been possible to perform. Synoptic inspection of linear features like roads and railways reveals that pixel displacement between rows exceeds 3 pixels in some areas. It is therefore almost impossible to estimate the actual geographical accuracy after geometric tie down to the RT90 reference system.

3 Results and discussion

3.1 GER Analysis

To demonstrate the spectral differences between plume water and clean water spectral data were extracted from the source of the plume and from the clearest water in the scene, an area located 20 kilometres from the plume outlet. A nine by nine pixel kernel (45 by 45 metres) was extracted from the two areas and averages and standard variations were computed for each wavelength band.

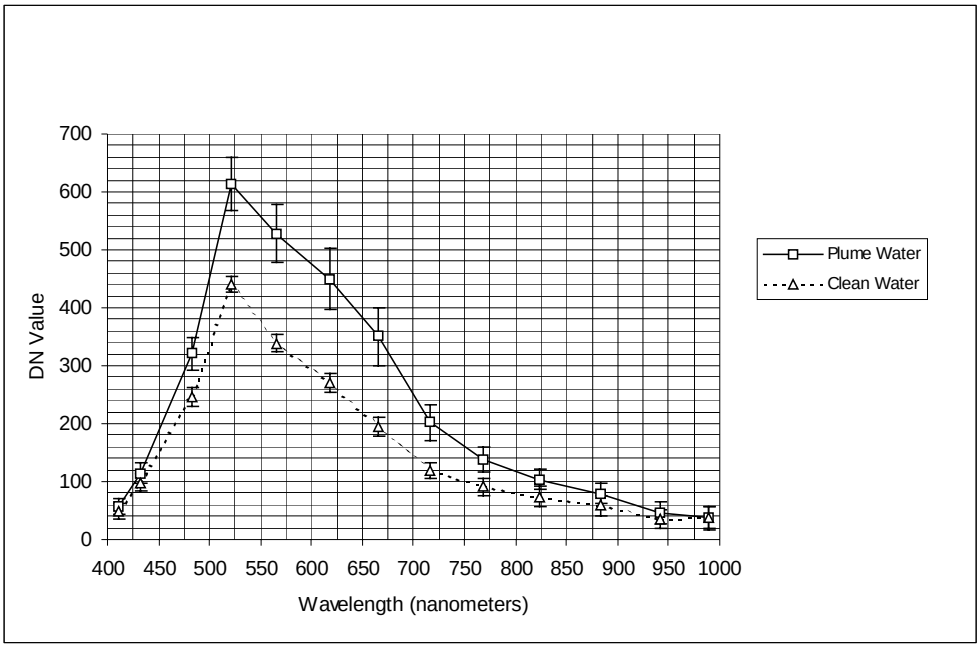

Fig. 6 Spectral profile extracted from paper industry outlet and spectral profile extracted from clean water, extracted from *GER* data.

It is evident that the constituents in the plume water give rise to an increase in spectral response for all wavelengths. Furthermore, the standard deviations are greater for the plume water, which means that the spectral variability, in spite of the rather small sample kernel, displays a higher degree of heterogeneity than clean water, even at this scale. The difference between plume and clean water expressed as both numeric values and as percentage and is given in figure 7.

As shown in figure 6. The intensities recorded by GER sensor in the blue spectral region are very low. The spectrum drops dramatically below 520 nm. This is very different from the spectra acquired with the CASI, and from our earlier experience of water in this region. The drop in the blue regions seems to be caused either by failing detectors or by mistakes in the system correction of the data. Since no information on calibration coefficients for transformation of intensities to radiance values have been provided by the data producer, in spite of persistent inquiries, no correction of the blue wavelength bands (or the other bands) have been possible. Consequently, the blue wavelength bands have not been used. Neither is it meaningful to conduct analyses such as mathematic functions based on the shape of the spectra, or on angle functions for specific parts of the spectra. Furtermore, the data cannot be directly compared with the CASI data.

What can be done with these data is to analyse spectral differences between 'clean' water and plume water within the data set. It is also possible to analyse the relationship between spectral bands and water constituents. Image algorithms such as ratios however, should be used with caution since it is very likely (from the look of the blue region) that the system correction (including post-flight stretch or additive intensity operations) has not been correctly applied and/or is not documented.

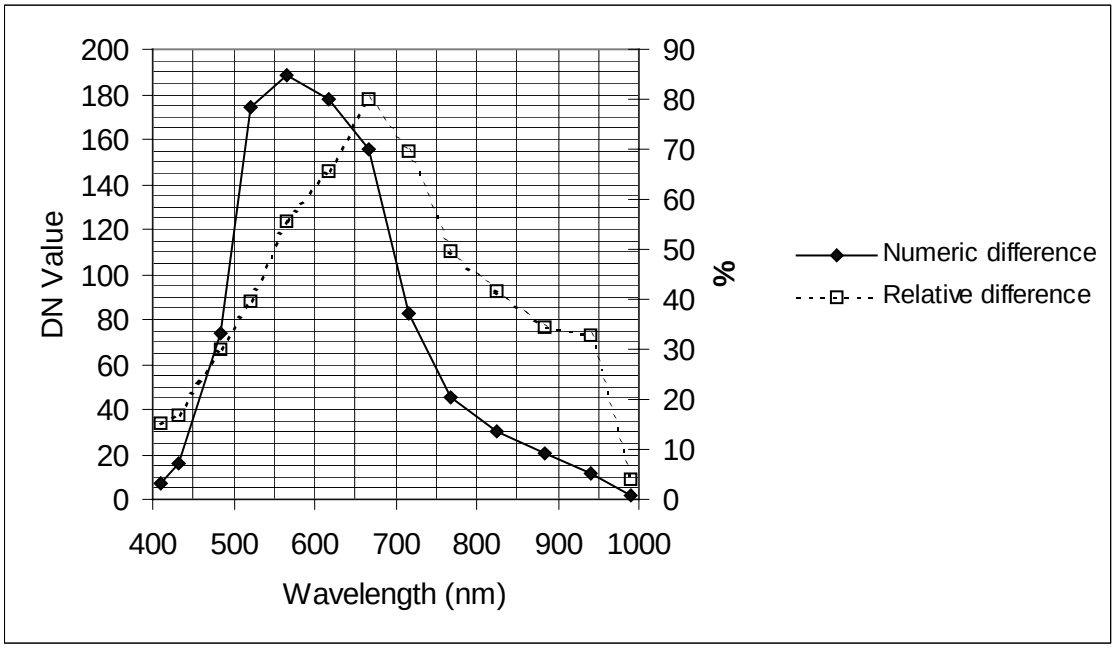

Fig. 7 Numeric and relative spectral difference between spectral profile extracted from paper industry outlet and spectral profile extracted from clean water, extracted from *GER* data.

The difference between 'clean' water and plume water reaches its maximum at 680 nm. The colour of plume to the human eye is brownish probably due to lignin and suspended matter such as gelbstoff. Thus a difference maximum in the red region seems logical. However the peak is at somewhat shorter wavelengths, and the difference is high also in the near-infrared regions. This could be attributed to the higher chlorophyll concentration in the plume, and would support the results of earlier studies mentioned in the introduction in that wavelengths around 700 nm are optimal for chlorophyll -*a* determination. However, the range of chlorophyll a concentrations is rather narrow, 1-6 mg/m^3 which makes it unlikely that chorophyll -*a* only explains the difference at these wavelengths. We assume that some other constituents in the plume water (perhaps lignin) cause this spectral effect in the near-infrared region. It should be noted that suspended sediments generally have a very low spectral effect in the NIR region, virtually no effect above 730 nm (Althuis and Shimwell 1995).
GER data were analysed according to simple regression analysis. Eleven samples, is a rather small amount for this kind of analysis but it is considered to be of interest to get a broad idea of the correlation between spectral data and measured water parameters.

Table 2. Correlation between GER spectral irradiance reflection and chlorophyll –a and suspended sedimentrespectively.

Wavelength (nm)		Chlor. -a	Susp.
Band 5	565.8	0.622	0.461
Band 6	617.7	0.726	0.598
Band 7	665.8	0.702	0.604
Band 8	716.6	0.712	0.589
B7/B3		0.620	0.614
B6/B3		0.821	0.852

The highest correlation between chlorophyll a and a single band is achieved in band 7 (665.8 nm) for suspended sediment and in band 6 (617.7 nm) when chlorophyll -a, is analysed. Band 8 at 716.6 is at approximately the same level as band 6 for chlorophyll a. One would expect a higher degree of correlation with the narrow bands provided by this imaging spectrometer, but it should again be noted that the range of chlorophyll -*a* concentrations at the sample points was rather narrow. Although only eleven sample points were located within the re-routed flightline the results constitute an indication of a discrimination capacity regarding chlorophyll that is somewhat better than for satellite data, e.g. Landsat TM in Ekstrand (1988), but not as good as was expected for airborne imaging spectrometer data. Correlation between chlorophyll and band ratio band6/band3 and correlation between suspended sediment concentration is shown in figure 8 and 9 respectively.

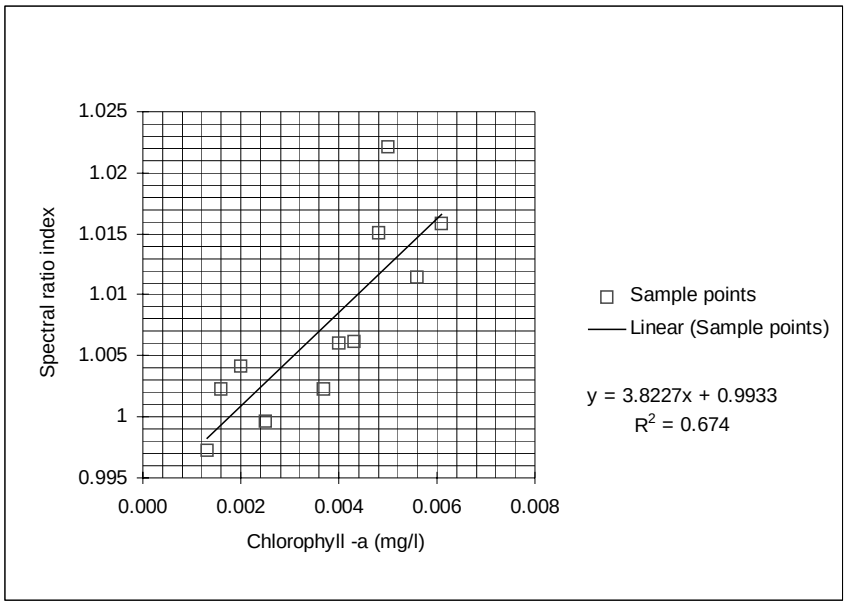

Fig. 8 Correlation between band ratio and chlorophyll concentration.

No correlation above 0.6 was found for dissolved organic carbon. One would expect some correlation in the lower region of the spectra due to DOC absorbtion. In the spectral region between 400 – 500 nm most of the irradiance penetrating the water is absorbed by DOC and chlorophyll *a*, (Dekker and Peters, 1993). Chlorophyll -*a* was very low outside the plume, and although no DOC data was available, it can be assumed that DOC was also low in the plume. Nevertheless the blue intensities were

low, both outside and within the plume, showing that DOC and chlorophyll –*a* was not the cause to the low intensities between 400 and 500 nm. The overall best correlation is achieved when the ratio of band 6 (617.7. nm) and band 3 (483.6 nm) and the ratio of band 7 (665.8 nm) and band 3 (483.6nm) are analysed. The ratio of band 7 and band 3 also significantly raise the correlation level for DOC, to 0.6.

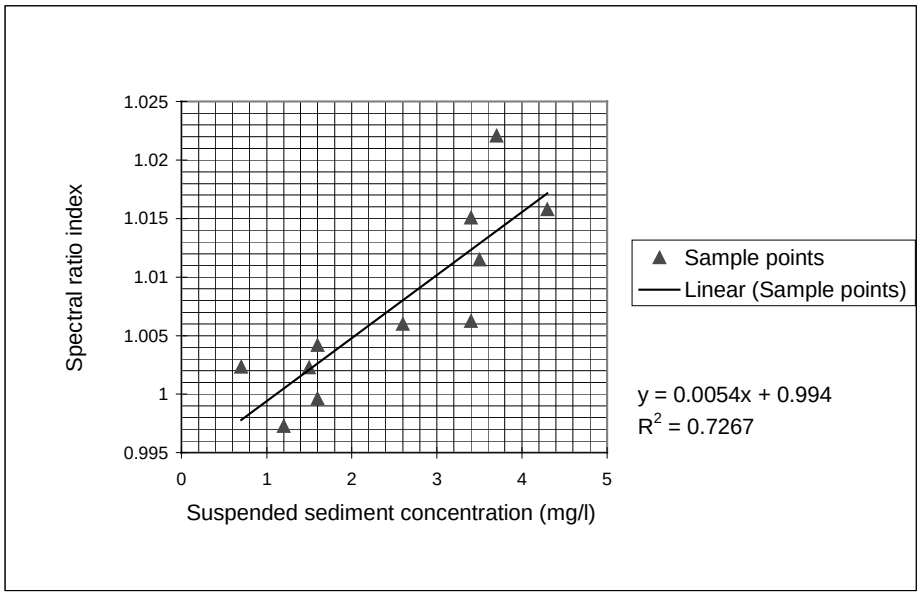

Fig. 9 Correlation between band ratio and suspended sediment concentration.

3.2 CASI Analysis

As shown in figure 10 the intensities recorded by the *CASI* sensor shows a different spectrum, compared to the *GER* instrument. The spectral curve is generally decreasing for all extracted spectrums. The highest intensities are recorded in the blue part of the spectrum and is from that point decreasing towards the infrared end of the spectrum. One feature that is present in nearly every extracted spectrum is the local minima at 763 nm. This dip is also present in spectrums extracted for land and clouds which, suggest that absorption in the atmosphere is a probable cause of this feature, rather than absorption by any constituent in the water. This effect is not present in the *GER* data.

To demonstrate the spectral variation between different waters, spectral data were extracted from the *CASI 1* scene. One point was selected from the moth of river Ljungan and one point from the location of the outlet pipe from Ortviken industrial complex, a paper mill industry. Inspection of image revealed no distinct plume, in spite of employment of different image enhancement techniques, contrast stretching and density slicing. Nevertheless, it was considered valuable to analyse the spectrum from this location since the waste water from Ortviken probably influences the water quality at this location. The third point was extracted from the Bay of Sundsvall and represents the clearest water in the area. Average and standard deviation for a 5 by 5 pixel window were extracted for all points.

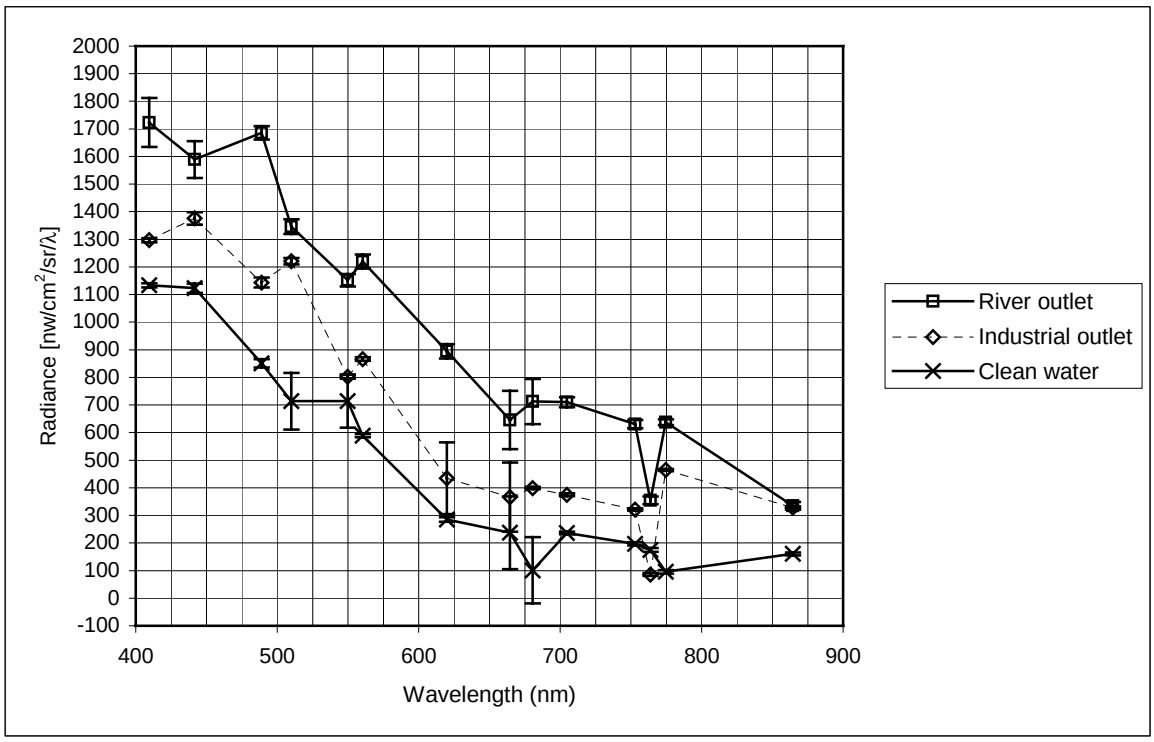

Fig. 10 Spectral signatures for river Ljungan and Ortviken industrial complex and spectra of clear water.

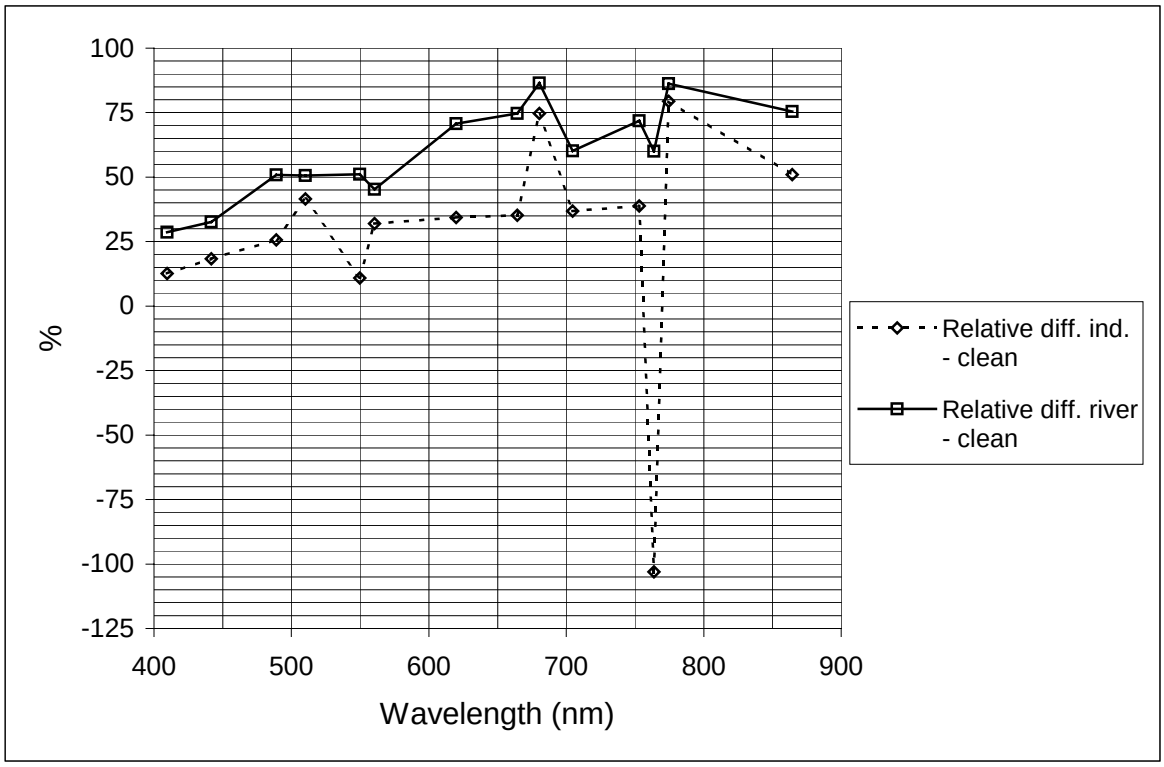

Fig. 11 Relative radiance difference between river Ljungan and Ortviken industrial complex against spectra of clearest water in the area.

As for the *GER* data there is a clear increase of reflected energy in the plume water. Maximum difference occurs at 680 nm. The river water shows the highest spectral intensity level and the sample from clean water shows the lowest. The sample from the outlet area display intermediate values.

The highest degree of variation occurs in the spectrum from the river outlet. The variation is not in the same magnitude all over the spectrum. Band 1 (409.55 nm), band 2 (441.7 nm), associated with chlorophyll – *a* and DOC absorption, band 8 (664.4 nm) and band 9 (680.5 nm) associated whit chlorophyll and suspended sediment backscattering, have significantly higher variation levels. The spectrum from the industrial outlet however exhibits low variation levels for all bands except for band 7 (619.85 nm) and 8. The spectral difference between river water and water from the industrial outlet point is probably due to higher concentrations of suspended sediments in the river water. Measurements of suspended sediment concentration reveals that both sampling points have the same concentration of 1.3 mg/l. Concentration levels varies between 0.7 and 1.6 mg/l for the investigated area and are considered to be low. These low levels of concentration in the river plume do not support the assumption that the difference in spectral intensity between plumes could be explained by suspended sediment concentration alone. More field measurements in and in the vicinity of the plume are needed to confirm the origin of the differences in intensity levels.

The spectral response pattern shows a clear difference between the river water and water from the industrial outlet point. The spectral response from river Ljungan decreases between 409.55 nm and 441.7nm and increases at 488.95 and decreases again at 510.05 nm whilst the intensity variation from the industrial outlet point displays a complete shift around for the same part of the spectrum. At band 6 (560.35 nm) and beyond the spectral patterns between the plumes only differ in magnitude. These differences are likely to be caused by different composition of constituents. The distance between these two sampling points is approximately 2 kilometres and it can therefor be assumed that the atmosphere is fairly homogenous over such a small area, minimising the atmospheric effect. The water depth in this region is above 20 metres, more than 2 times the secci disc depth which suggest that bottom reflectance have very little influence on the spectral profile. Nevertheless Bagheri *et. al.*, (1998) have shown that bottom reflectance can be traced in hyperspectral data for depths ranging to 30 meters in clear waters and thus shall not be neglected. The most plausible explanation for these measured differences in spectral response is subjected to the compositions of constituents in the water body.

In table 3 correlation between measured water parameters and spectral radiation extracted from the *CASI 1* scene are presented. It should be noted that only 8 points are included and for chlorophyll even less, 6 points. Point number 11 was cloud covered and could not be used. The correlation matrix shows dependencies quite different from expected. No significant correlation is found for chlorophyll –*a*. This could be due to the small variation in chlorophyll content among sample points. The chlorophyll concentration minimum is 2.8 mg/m^3 and the maximum reaches 4.6 mg/m^3.

The strong correlation between DOC and band 12 (763.8) is not easy to explain. With respect to the low correlation for DOC in bands directly above and below band 12, one can assume that this high value for band 12 is merely a random effect. Nevertheless, the DOC concentration is considerably higher than both chlorophyll and SSC. It is possible that DOC absorbs much of the radiation at this wavelength and thus masks the backscattering from chlorophyll and SSC. Low intensity levels and poor correlation with chlorophyll and SSC supports this conclusion.

Weak correlation coefficients were found for SSC in band 1 and band 13. Band 13 (774 nm) coincides whit local SSC reflectance minima, defined by Chen *et. al.,* (1992) in laboratory measurements. In water with low concentrations of chlorophyll, which is the case here, this correlation may be of interest. Again, it should be stated that the number of sample points is low and the correlation analysis performed here is not conclusive.

Table 3. Correlation matrix between CASI scene 1 and field samples. Note that all parameters are measured at 8 sampling points except for chlorophyll, which is measured at 6 sampling points.

	P-tot (mg/l)	NO23N-ND (mg/l)	NKJ-NAS (mg/l)	Ntot (mg/l)	DOC	SSC	Chl 6 samples	Abs 260, 1 cm	Abs 280, 1cm	A260/A280
Band 1	-0.49147	**0.651268**	-0.02387	0.228834	0.086779	**-0.62461**	-0.50618	0.486296	0.500459	-0.29473
Band 2	-0.37818	0.276834	0.348482	0.571665	0.188373	-0.42723	-0.4525	0.725413	0.700234	-0.23508
Band 3	-0.30665	0.299192	0.379977	0.612215	0.018879	-0.4618	-0.37031	0.664613	0.659524	-0.33449
Band 4	-0.02677	0.049136	0.642499	**0.827888**	0.241581	-0.02979	-0.32915	0.727803	**0.711343**	-0.32786
Band 5	-0.25314	0.219946	-0.00381	0.127062	0.130268	-0.25653	-0.23606	0.410429	0.33967	0.298086
Band 6	-0.25228	0.300531	0.419975	0.657303	0.177768	-0.2577	-0.45515	0.669425	0.66976	-0.38187
Band 7	-0.38435	0.178472	0.372771	0.571371	-0.0381	-0.53505	-0.28738	0.635817	0.619037	-0.26123
Band 8	-0.30565	0.282254	-0.05273	0.076592	0.38988	-0.3266	-0.34775	0.601357	0.533153	0.160617
Band 9	0.01501	-0.08421	0.455877	0.584571	0.033761	0.089725	-0.12654	0.450949	0.38135	0.216575
Band 10	-0.0475	0.386336	0.226354	0.445602	-0.05127	-0.42478	-0.06109	0.67792	0.683011	-0.40582
Band 11	0.115524	-0.19034	**0.701378**	0.796918	0.008455	-0.3691	0.163399	**0.88435**	0.887101	-0.6243
Band 12	0.246762	-0.2867	0.37125	0.341895	**0.735034**	0.549335	-0.23775	0.46326	0.387676	0.224515
Band 13	0.226915	0.07807	0.359422	0.455125	-0.32708	-0.60927	**0.531864**	0.669282	0.702432	**-0.64697**
Band 14	**0.599336**	-0.37873	0.33583	0.251227	0.431093	0.490407	0.339173	0.443586	0.373252	0.192207

Spectral data were also extracted from *CASI 2* scene. Sample points from this scene were located at the scene margin and were subject to strong vignette effects. Spectrums from river “Indalsälven” and “clean” water were taken at the same margin distance to circumvent this effect when comparing spectrums.

In figure 12 spectral profiles from clear and affected water are presented, now for river “Indalsälven” As for all extracted spectrums the affected water displays a higher intensity level than for clear water. No spectral features can be found in these profiles. One explanation could be the atmospheric effect which becomes more pronounced in the scene margin. The light have to travel a longer distance compared to at nadir. Presence of particles in the atmosphere contributes both by attenuation and addition to the signal measured by the sensor. This effect *Mie scattering* acts like a smoothing filter and attenuates small-scale variations in the upwelling signal through out the spectrum.

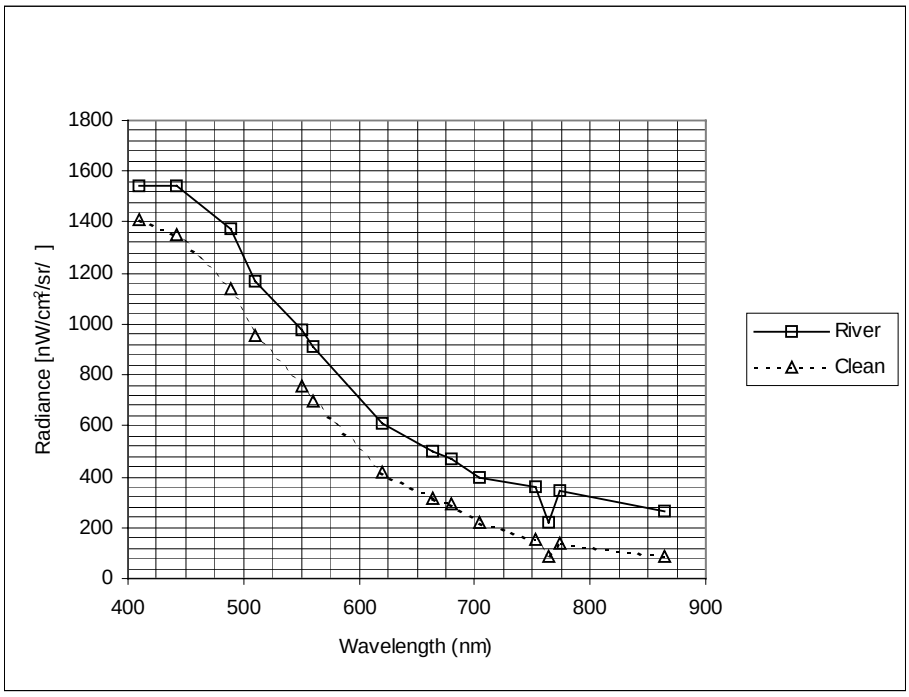

Fig. 12 Spectral signatures for river Indalsälven and spectral signature for clean water in CASI 2 data.

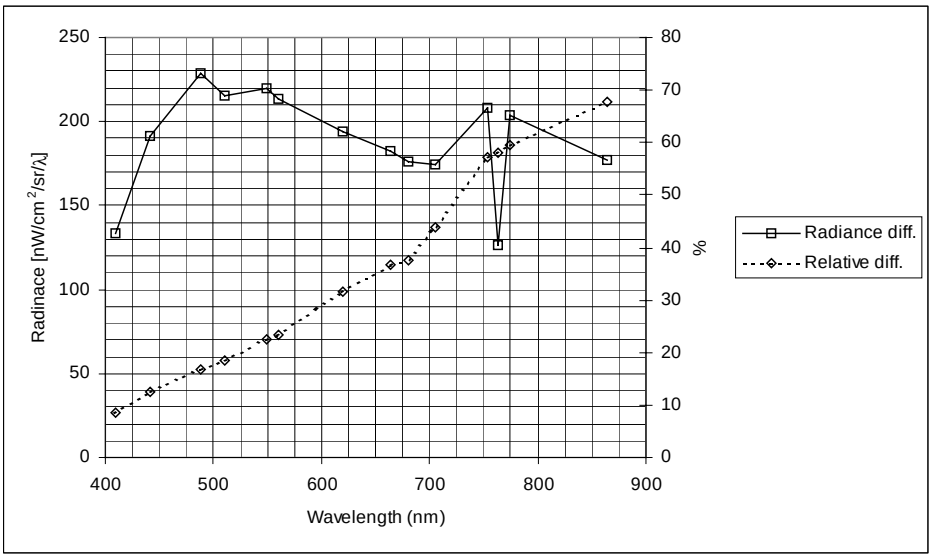

Fig. 13 Spectral signatures for river Indalsälven and spectral signature for clean water.

The only fact that can be confirmed from the spectral profiles presented in figure 13 and 15 is the increase of reflected energy for the river spectrum. The spectrums are shifted in magnitude but the general shape of the curve is preserved trough out the spectrum for both signatures . No spectral features can be identified and no significant correlation coefficients could be found. It is evident that influence of vignette effects is strong in the margins of the scenes and should be handled carefully when extracting signatures from airborne data.

4 Conclusions

The performance of multispectral airborne imagine spectrometers, *GER* and *CASI* have been investigated in teh field of water quality monitoring with emphasis on waste water discharges in the coastal zone.

Collected water samples are analysed for chlorophyll -*a*, suspended sediment concentration and dissolved organic matter known from the literature to be optically active. The water samples reveals that the concentrations as well as the degree of variation are low in the investigated areas. Measurements of NOX, phosphorus and absorbency at 260 and 280 nm were performed at some locations.

Image registration was performed during bad weather conditions and in the presence of both cumulous clouds and haze. Bad illumination and air turbulence introduced uncertainties regarding radiance levels and geometric accuracy. The data provider has not been able to fully compensate for these effects. Image artefacts like line displacement and waveforms are present in the data.

In spite of poor quality of the image data it is shown that spectrum extracted from outlet points exhibits a clear difference in terms of radiation compared to spectrums extracted at a large distance from the outlet point. It is evident that the constituents in the plume water give rise to an increase in spectral response for all wavelengths. Furthermore, the standard deviations are greater for the plume water, which means that the spectral variability displays a higher degree of heterogeneity than clean water. The maximum difference arises around 680 nm but is present trough out the measured spectrum.

Spectral features are present in profiles extracted from different outlet locations and from different origin. Intensity discrepancies is at maximum in the red part of the spectrum whilst spectral derivative differences occurs in the blue/green part of the spectrum between 400 to 550 nm. It is shown that spectral differences exist between outlet waters from different origin.

Correlation between spectral data and chlorophyll are confirmed but not in the degree expected. Although only eleven sample points were located within the re-routed flight line for the *GER* data and nine and six for the *CASI* data the results constitute an indication of a discrimination capacity regarding chlorophyll that is somewhat better than for satellite data. Correlation coefficients for suspended sediment concentration is also confirmed and are in the same magnitude as for chlorophyll. Strong correlation for some of the remaining constituents are present but not validated.

It is evident that image quality and thus information content, is in a high degree dependent on god weather conditions during registration.

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