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Monitoring of coastal waters of the Baltic Sea by airborne imaging spectrometer AISA

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Abstract

Aim of the present work is to test what parameters of coastal waters could be quantitatively and operatively monitored with passive optical sensors from airborne and/or satellite measurements. Airborne imaging spectrometer AISA was used for remote measurements. Flight campaign was carried out in the Archipelago Sea, south-western coast of Finland. Simultaneous in situ measurements were carried out onboard research vessel Muikku and two outboard work boats. Suitability of more than seventy retrieval variables, proposed by different authors, was tested in estimation of concentrations of chlorophyll a, suspended matter and pheophytin, as well as water turbidity and Secchi disk depth.

1 Introduction

The Baltic Sea is a large semi-enclosed brackishwater basin surrounded by highly industrialized countries, inhabited by ca. 80 million people. The Baltic Sea (with Kattegat), has a surface area of 415,000 km^2, a

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volume of 21,600 km^3 and a mean depth of 54 m. The hydrography of the Baltic Sea is largely regulated high riverine inputs and sporadic inflows of saline North Sea water through the Danish Sound. The Baltic Sea has several sub-basins with typical stratification patterns (temperature and salinity). Besides the vertical salinity gradient, the Baltic has large horizontal salinity variation from almost marine 34 PSU in the Kattegat to limnic 2 PSU in the northern part of the Gulf of Bothnia.

The high riverine inflow is reflected in the high concentrations, compared to open ocean waters, of yellow substances (Gelbstoff) in the Baltic Sea water. The average recidence time of water in the Baltic Sea is about 25 years.The Baltic Sea was previously oligotrophic. Due to antropogenic influence over several decades, primarily high nutrient inputs, The Baltic Sea is now considered to be eutrophic in the coastal areas.

The eutrophication is reflected in the phytoplankton primary production. Extensive growth of phytoplankton, algae blooming increases in frequency and intensity.

Reliable monitoring of the pelagic ecosystem has proved to be problematic because of its high temporal and spatial heterogeneity. Consequently, it often remains unobserved using the traditional sampling methods based on temporally sparse sampling at a few fixed stations. Furthermore, the traditional programs are usually unable to report rapidly the observations in case of exceptional events. Monitoring of water state could be more effective if to use satellite and/or airborne remote sensing. Using of spectral ratios or the same kind of algorithms in interpretation of remote sensing data is widely used, but the algorithms seems to have local and seasonal variability and special algorithms are needed for coastal and inland waters. Therefore we tested suitability of more than seventy retrieval variables, proposed by different authors, in case of coastal waters of the Baltic Sea. Possibility of using hyperspectral modelling in interpretation of remote sensing data was also used to elaborate interpretation methods depending less on specific characteristics of water body under investigation.

2. Equipment and measurements

2.1 The study area and measurement campaign

The sudy area was at the Archipelago Sea. This sea is part of the Baltic Sea, located between the Southwest part of the Finnish coast and the island of Åland (Fig 1). The Archipelago Sea, surface area of about 8,300 km^2 is heavily eutrophicated, semi enclosed sea area with 22000 islands.

The largest loads of nutrients are discharged to Archipelago Sea by diffuse loading from agriculture and pointsource loading from fish-farming.

In this remote sensing measurement campaing August 1997 we had three different type of measurement lines. The first line “Paimio” (line 1) is located in a estuary of the River Paimionjoki. The Second measurement line “Airisto” (line 2) is situated close to City of Turku and near this line was dreding work going on. The last line “Houtskär” (line 3) goes through the Archipelago Sea and the water exchange in many parts of this measurement line is very poor.

On August 14th, three field measurement lines (Fig 1) were flown with the aircraft (Short SC7 Skyvan) owned by the Helsinki University of Technology, Laboratory of Space Technology.

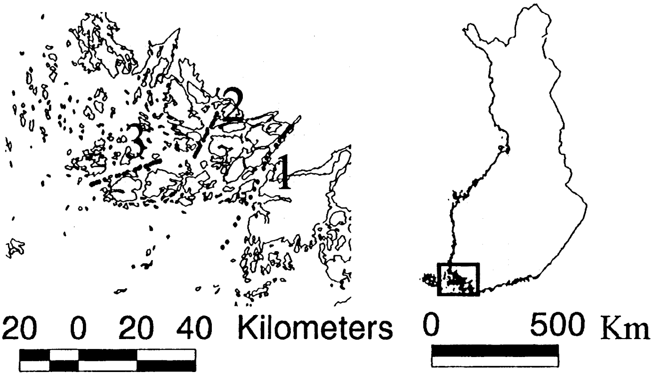

Fig. 1 Measurement lines in August 1997.

2.2 Water sampling and analysing methods

Water samples at each station were taken from the surface layer of the sea (0-0,5m) by using Ruttner-type water samplers. The Paimio measurement line (line 1, fig. 1) sampling was operated by the 28 metre research vessel Muikku with its two smaller motor boats. By using all three boats it was possible to take water samples from three different sampling stations of the Paimio at the same time as the aeroplane was flying over. The Airisto line (line 2, Fig.1) in situ measurements were done by a small outboard boat and the Houtskär line by R/V Aurelia.

The water quality variables measured and the standard methods were: water temperature, secchi disk transparency, chlorophyll a (ISO 10260 and pheophytins, suspended matter (filtered by Nuclepore polycarbonate 0,4 um), turbidity (FTU-units, EN 27027), water colour (comparison with standard platinium cobalt chloride disks, ISO 7887), total organic carbon (TOC, Carlo-Erba IR-analyzer), species of phytoplankton (preserved with Lugols solution and determined at the Finnish Environment Institute by the Zeiss inverted microscope using the Utermöhl [1] technique. All the other laboratory analyses were made at the Laboratory of Southwest Finland Regional Environment Centre. The chlorophyll-a and pheophytin samples taken at R/V Muikku (measurement line Paimio) were filtered immediately after sampling and then carried to a mainland laboratory for analysis. All samples from measurement lines Airisto and Houtskär were analysed in the mainland laboratory within 4-10 hours from sampling.

2.3 Water quality

The figures of the measured water quality date are shown in Figs. 2, 3 and 4. The phytoplankton species dominating at all three measurement lines were Cyanobacteria *Aphanizomenon spp*, and Cryptomonads *Teleaulax spp.*, and *Plagioselmis prolonga*.

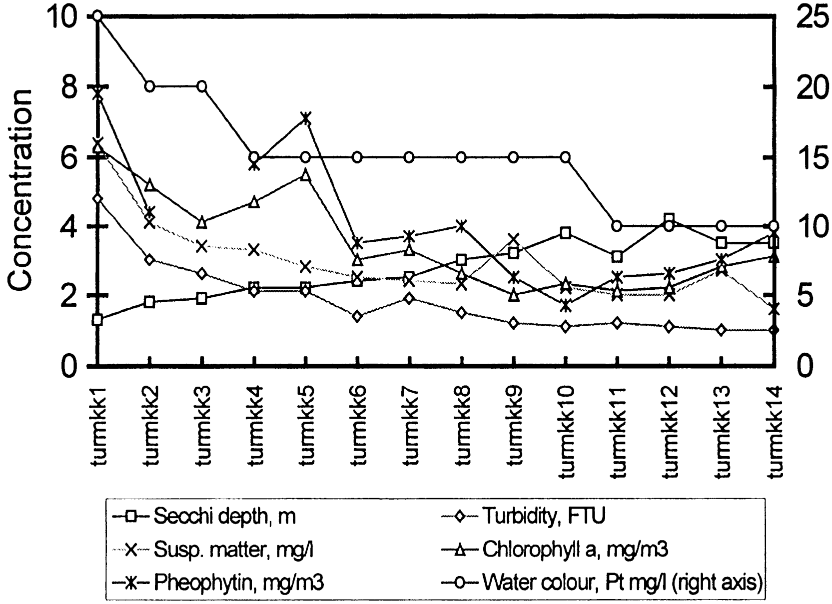

Fig. 2. Measured water quality parameters at Airisto 14.08.97.

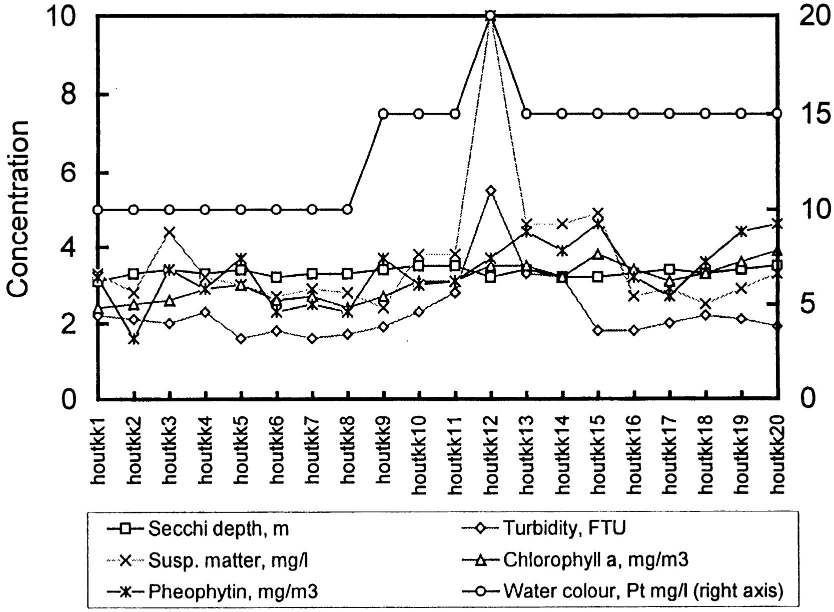

Fig. 3. Measured water quality parameters at Houtskär 14.08.97.

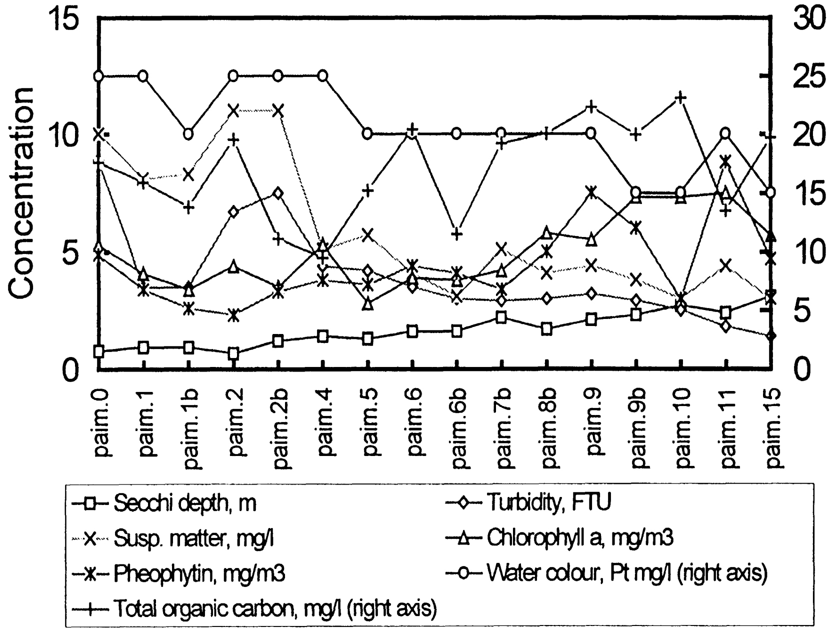

Fig. 4. Measured water quality parameters at Paimiolahti 14.08.97.

2.4 Imaging spectrometer AISA

Finnish imagine spectrometer AISA has been used during the measurement campaign in August 1997. AISA is a pushroom type instrument using a charge-coupled device (CCD) sensor matrix. AISA operates in the range of 450-900nm that is divided into 288 channels. The channel width is programmable from 1.6nm to 9.4nm. The number of spatial pixels is 384.

During the campaign the flight altitude has been 1000 meters. The instantaneous field of view of the CCD (AISA) is 1 milliradian and so the spatial resolution across the track has been 1 meter. The resolution along the track has been 4.5 meters using the integration time of 80 ms and the velocity of 110 knots.

The AISA can be used in one of four modes:

1. all of the information on the CCD is stored - a long integration time is needed (min. 350 ms),
2. all of the data is stored in the spatial direction, but only for a small number of selected wavelength bands (spectral channels),
3. all of the spectral information is stored at selected spatial locations,

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4. the user can select a set of wavelength bands where full spatial information is stored and a set of spatial location where full spectral information is stored (Mäkisara et al., [2]; Mäkisara, [3]).

During the campaign the second mode has been used on the coastal sites. Some flight lines have been also flown using the third mode for atmospheric correction development purposes. The used channels are shown in Fig. 5.

The geometric correction software makes a geocoded image using the raw AISA data, navigation data and information given by the operator (Mäkisara, [3]). Software for geometrical and radiometrical pre-processing is introduced in (Mäkisara et al., [4]) and (Mäkisara et al., [5]). The geocoded images of the campaign have been re-sampled to the resolution of 2m x 2m.

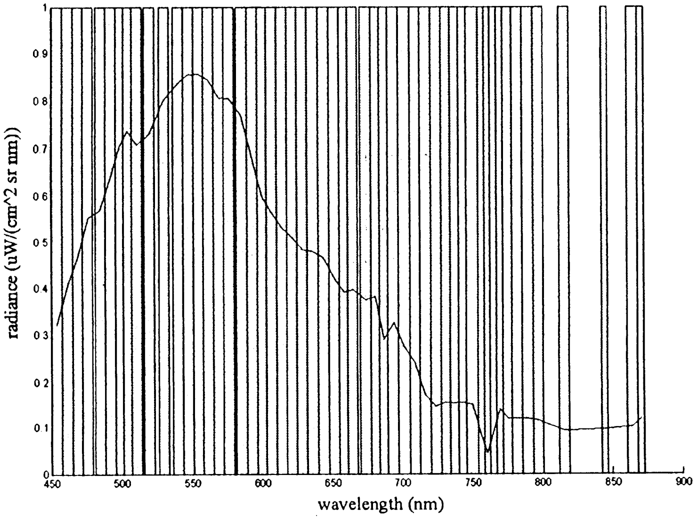

Fig. 5 Spectral channels used in August 1997 campaign.

2.5 Atmospheric correction

An atmospheric correction system was developed for the AISA airborne imaging spectrometer. The correction method is based on the method developed by de Haan and Kokke [6]. The method is based on fitting a single spectral in-situ measurement to a measured AISA spectrum. A number of sets of correction parameters are calculated with MODTRAN using different visibility and humidity values and the best fitting coefficients are searched in an automated iterative process. An averaged reference reflectance spectrum was measured from water at the exact time of aeroplane measurements.

In the correction method by de Haan and Kokke [6] the forementioned phenomena can be simplified to a following equation:

$$R_{APP} = \frac{c_1 + c_2 L_{rs,t} + c_3 L_{rs,b}}{c_4 + c_5 L_{rs,b}} .$$

The R_{APP} is the atmospherically corrected reflectance over the surface, $L_{RS,t}$ is the measured radiance from the targets direction and $L_{RS,b}$ is the mean radiation from the target's neighbourhood. c1 is atmospheric path radiance, c2 and c3 account for the adjacency effect. It should be noticed that if c2 = 1 (in which case c3 = 0) the reflectances are uniform in the neighbourhood of the target and the adjacency effect vanishes. c4 is proportional to the product of the transmittances from sun to target and from target to the sensor. c5 is the spherical albedo for illumination from below.

The coefficients are calculated by running the MODTRAN code three times in the considered situation: The albedo of the surface is set to 0.0, 0.5 and 1.0 respectively. In this way the equations for the software may be calculated as follows:

$$c_1 = -L_{path}\left(A_{app} = 0.0\right)$$

$$c_2 = 1 + \frac{L_{path}\left(A_{app} = 0.5\right) - L\left(A_{app} = 0.0\right)}{L(A_{app} = 0.5)}$$

$$c_3 = 1 - c_2$$

$$c_4 = \left(1 - c_5\right)\left\{L_{ground}\left(A_{app} = 1.0\right) + L_{path}\left(A_{app} = 1.0\right) - L_{path}\left(A_{app} = 0.0\right) - c_5 L_{path}\left(A_{app} = 0.0\right)\right\}$$

$$c_5 = \frac{2L_{ground}\left(A_{app} = 0.5\right) - L_{ground}\left(A_{app} = 1.0\right)}{L_{ground}\left(A_{app} = 0.5\right) - L_{ground}\left(A_{app} = 1.0\right)} .$$

In our automatic parameter estimation procedure the measured reference reflectance spectrum was compared to corrected AISA spectrum. In each iteration those atmospheric parameter values were selected which gave minimum sum of squared errors. System enables also a "recalibration" of AISA wavelenghts based on atmospheric absorption peaks.

3 Results and discussion

Spectral ratios, their combinations or similar kind of retrieval variables are widely used in interpretation of remote sensing data. We tested

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suitability of algorithms proposed by different authors ([7]-[15]) in the estimation of various water quality parameters.

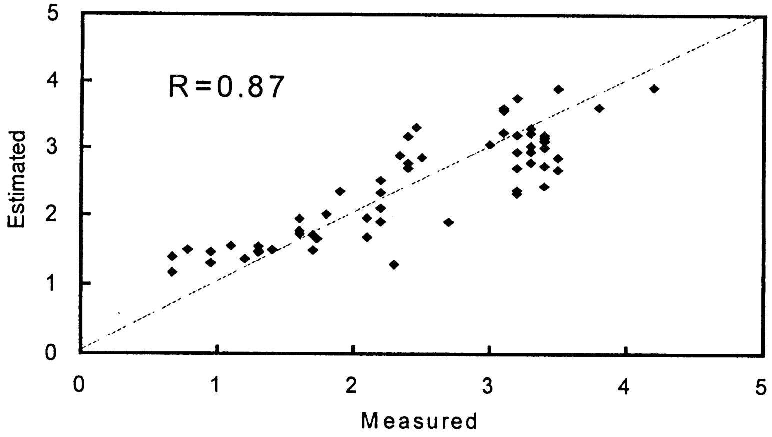

Fig. 6. Correlation between measured in situ and estimated from AISA data Secchi disk depths (in meter). Estimated Secchi depths are calculated by formula: $SD=-41.46F_2+45.96$, where $F_2=Lu(549)/Lu(527)$.

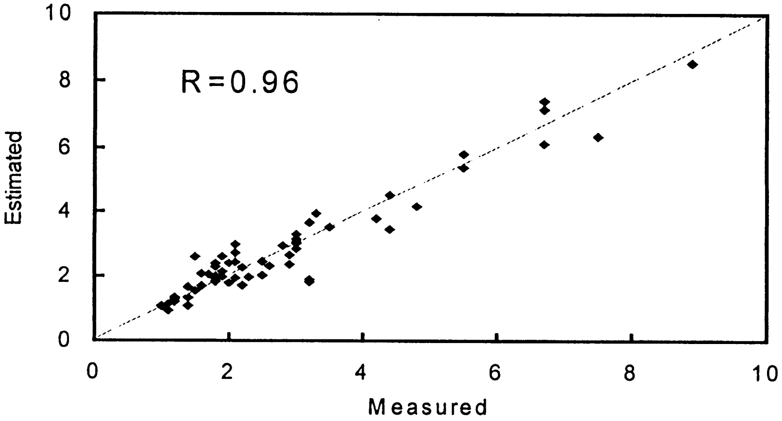

Fig. 7. Correlation between turbidity (in FTU) measured from water samples and estimated from remotely measured data. Estimated turbidity is calculated from AISA spectra using formula: $T_{FTU}=0.634De_4-4.70$, where $De_4=6.34+6.99[Lu(454)-Lu9753)]+4.23[Lu(556)-Lu(753)]+10.7[Lu(622)-Lu(753)]+10.9[Lu(673)-Lu(753)]$

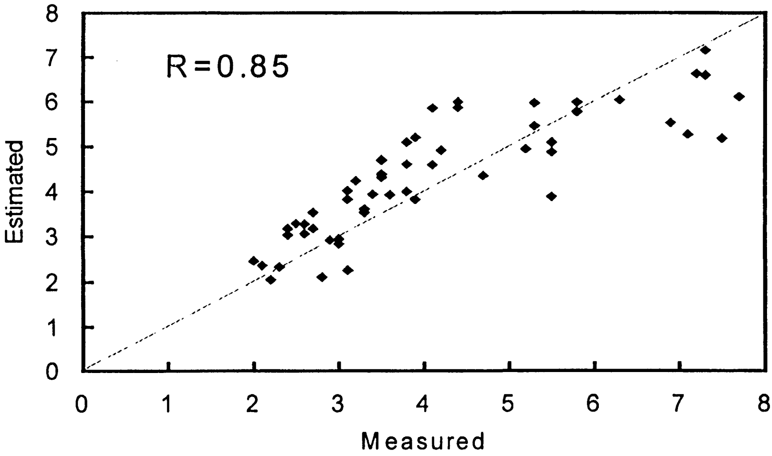

Fig. 8. Correlation between measured from water samples and estimated from AISA data concentrations of chlorophyll-a (in μg/l). Estimated chlorophyll concentrations are calculated using power function: $CHL=1.2De_{24}^{-7.78}$, where De_{24}=[Lu(520)-Lu(753)]/[Lu(629)-Lu(753)].

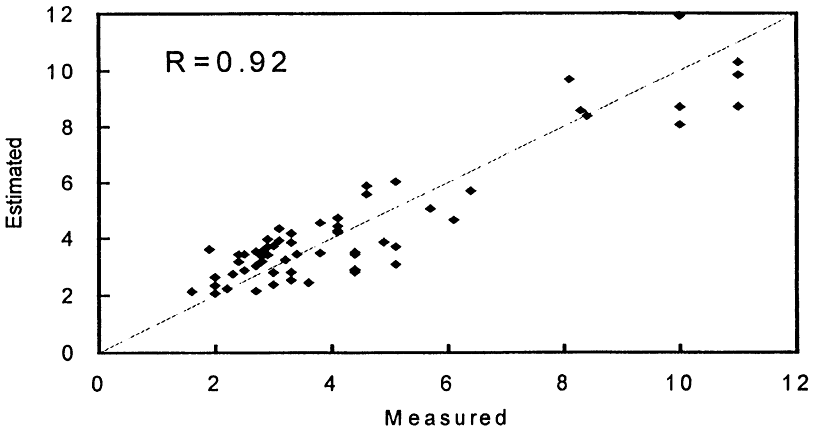

Fig. 9. Correlation between suspended matter concentrations measured from water samples and estimated from AISA data by algorithm: $SUS=2.72De_2-10.65$, where $De_2=-3.97-3.19$[Lu(563)-Lu(753)]+9.38[Lu(622)-Lu(753)].

Our results show that the chlorophyll a, and suspended matter concentrations as well as water turbidity and transparency can be estimated from airborne spectral data. Some algorithms elaborated for new satellite (SeaWiFS, MERIS) were also suitable for estimation of the same water characteristics. It suggest that these parameters can also be estimated from the satellite sensors.

Results obtained in interpretation of AISA data collected on Finnish lakes show that it is possible to estimate concentrations of dissolved and total organic carbon, pheophytin and total phosphorus from AISA data. We can assume that these parameters can be estimated also in case of coastal water whereas the difference between lake and coastal waters of the Gulf of Finland (differences in salinity, dominating algae species, bottom type) is small.

The Baltic Sea is 70% of the year totally or partly covered with clouds therefore the most effective way for monitoring of water state in the Baltic Sea could be organised by combining satellite images, airborne data and automatic in situ measurements from commercial ships and monitoring buoys.

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