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QUANTITATIVE MONITORING OF WATER PROPERTIES WITH THE AIRBORNE IMAGING SPECTROMETER AISA

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Abstract. Remote sensing measurements with an airborne imaging spectrometer (AISA) were carried out on Finnish lakes and the Archipelago Sea to test the suitability of passive optical remote sensing methods for quantitative monitoring of different water properties. Eight water characteristics were under investigation: concentrations of chlorophyll *a*, pheophytin, suspended matter (Nuclepore and Whatman GFC filters), total phosphorus, total and dissolved organic carbon; water turbidity; and the Secchi disk depth. Over 70 retrieval variables from simple spectral ratios and their combinations to more sophisticated functions were tested. The suitability of two different spatial resolutions (20×20 and 100×100 m) was tested. Algorithms were found for quantitative estimation of the above-mentioned water characteristics from spectral data measured with AISA.

Key words: airborne remote sensing, optical oceanography, limnology.

INTRODUCTION

Eutrophication processes are intensified in water bodies due to human influence. Reliable monitoring of the pelagic ecosystem has proved to be problematic because of its high temporal and spatial heterogeneity. Consequently, large areas of water bodies remain often unobserved if traditional monitoring methods, based on temporally sparse sampling at a few fixed stations, are used.

Furthermore, the traditional programs are usually unable to report rapidly the observations in case of exceptional events such as harmful algal blooms, pollution, etc. Remote sensing from board a research vessel, aircraft, or satellite could be a tool for solving the problem.

Spectral ratios or algorithms of the same kind are in wide use in the interpretation of remote sensing data; however, the algorithms seem to have local and seasonal variability and special algorithms are needed for coastal and inland waters. Therefore we tested the suitability of more than 70 retrieval variables, proposed by different authors (Afonin & Kravtsov, 1985; Gitelson et al., 1993; Arst et al., 1993, 1994; Arst & Kutser, 1994; Tassan, 1994; Kutser et al., 1995a, b, c, 1997, 1998; Althuis et al., 1996; Dekker & Hoogenboom, 1997; Kutser, 1997). Finnish lakes and coastal waters of the Baltic Sea served as the test area. The possibility of using hyperspectral modelling in the interpretation of remote sensing data was also used to elaborate interpretation methods that do not depend too much on specific characteristics of the water body under investigation.

IMAGING SPECTROMETER AISA

An Airborne Imaging Spectrometer for Applications (AISA), made by Specim (Finland), was used during the measurement campaigns in 1996–97. AISA is a pushbroom type instrument that uses a charge-coupled device (CCD) sensor matrix. AISA operates in the wavelength range of 450–900 nm that is divided into 288 channels. The channel width is programmable from 1.6 to 9.4 nm. The number of spatial pixels is 384.

During the campaigns the flight altitude was 1000 m. The instantaneous field of view of the CCD (AISA) is 1 mrad and so the spatial resolution across the track was 1 m. The resolution along the track was 4.5 m when integration time of 80 ms and the velocity of 110 knots were used.

AISA can be used in one of the following four modes:

1. All the information on the CCD is stored; in this case a long integration time is needed (min. 350 ms);

2. All the data are stored in the spatial direction, but only for a small number of selected wavelength bands (spectral channels);

3. All the spectral information is stored at selected spatial locations;

4. The user can select a set of wavelength bands where full spatial information is stored and a set of spatial locations where full spectral information is stored (Mäkisara et al., 1993; Mäkisara, 1998).

During the campaigns we used the second mode. Some flight lines were also flown using the third mode for atmospheric correction development purposes. The used channels are shown in Fig. 1.

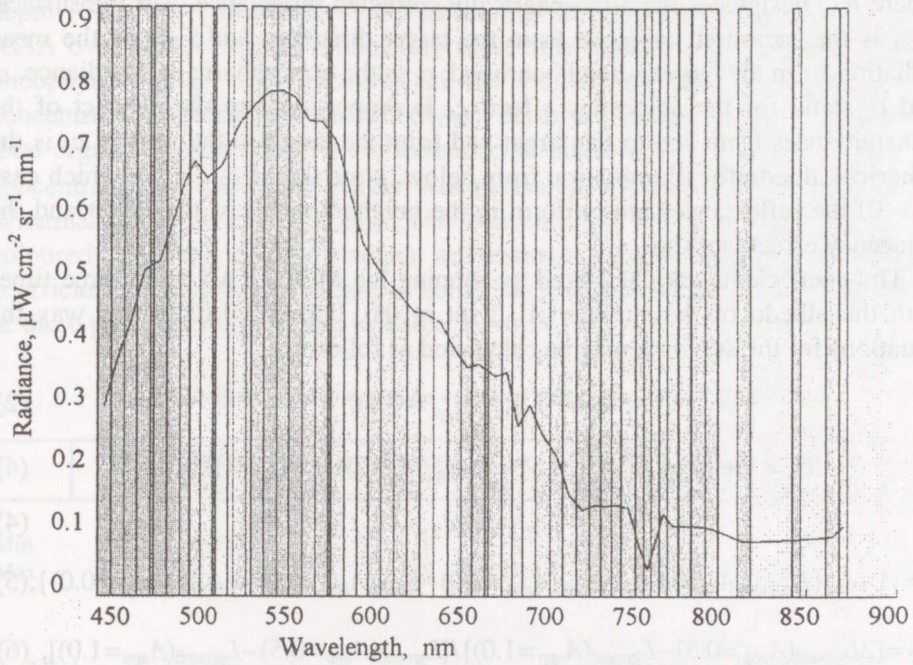

Fig. 1. Spectral channels of AISA used in the measurement campaigns of August 1997.

The geometric correction software makes a geocoded image using the raw AISA data, navigation data, and information given by the operator (Mäkisara, 1998). Software for geometrical and radiometrical pre-processing is introduced in papers by Mäkisara et al. (1994a, b). The geocoded images of the campaign were re-sampled to the resolution of 2×2 m.

ATMOSPHERIC CORRECTION

The correction method we used is based on the method developed by de Haan & Kokke (1996). 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.

The correction method can be described by a simplified equation:

$$R_{AC} = \frac{c_1 + c_2 L_{RS,t} + c_3 L_{RS,b}}{c_4 + c_5 L_{RS,b}}, \quad (1)$$

where R_{AC} designates the atmospherically corrected reflectance over the surface; $L_{RS,t}$ is the measured radiance from the target direction, and $L_{RS,b}$ is the mean radiation from the target's neighbourhood; c_1 is the atmospheric path radiance, c_2 and c_3 stand for the adjacency effect; c_4 is proportional to the product of the transmittances from sun to the target and from the target to the sensor; c_5 is the spherical albedo for illumination from below. Note that if $c_2 = 1$ (in which case $c_3 = 0$) the reflectances are uniform in the neighbourhood of the target and the adjacency effect vanishes.

The coefficients are calculated by running the MODTRAN code three times with the albedo of the surface (A_{app}) set at 0.0, 0.5, and 1.0. In this way the equations for the software may be calculated as follows:

$$c_1 = -L_{path}(A_{app} = 0.0), \tag{2}$$

$$c_2 = 1 + [L_{path}(A_{app} = 0.5) - L(A_{app} = 0.0)] / L(A_{app} = 0.5), \tag{4}$$

$$c_3 = 1 - c_2, \tag{4}$$

$$c_4 = (1 - c_5)\{L_{ground}(A_{app} = 1.0) + L_{path}(A_{app} = 1.0) - L_{path}(A_{app} = 0.0) - c_5 L_{path}(A_{app} = 0.0)\}, \tag{5}$$

$$c_5 = [2L_{ground}(A_{app} = 0.5) - L_{ground}(A_{app} = 1.0)] / [L_{ground}(A_{app} = 0.5) - L_{ground}(A_{app} = 1.0)], \tag{6}$$

where L_{ground} is the amount of radiation in the sensor that has been reflected from the ground and attenuated in the atmosphere; L_{path} is the remaining part of the total radiance in the sensor, which results from the scattering in between the surface and the sensor.

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

EQUIPMENT AND MEASUREMENTS

Field campaigns with the AISA spectrometer were carried out on lakes in August 1996 and May and August 1997. In August 1997 three measurement lines were studied in the Archipelago Sea, north-western part of the Gulf of Finland. The number of spectral channels used was 40 in August 1996 and May 1997, and 53 channels were used in August 1997 (see Fig. 1). The average channel width was 7 nm in both cases.

The number of measured water parameters varied from expedition to expedition. Chlorophyll *a* (C_{chl}) and suspended matter (Nuclepore 0.4 µm pore size filter) concentrations ($C_{SM,Nuc}$) as well as water turbidity (in FTU) and Secchi

depth (SD) were measured in all measuring stations simultaneously with an AISA overflight or within a relatively short time interval. The concentration of pheophytin (C_{Pheo}) was measured in the Baltic Sea and some lakes. The concentration of total phosphorus (C_{TOTP}), dissolved organic carbon (C_{DOC}), and total organic carbon (C_{TOC}) were measured in lakes in 1997. In some lakes the concentration of suspended matter was measured also with 0.45 μm pore size Whatman GFC filters ($C_{SM,GFC}$). The concentration of yellow substance (or coloured dissolved organic matter) was estimated from the beam attenuation coefficient measurements in case of some lakes. Minimum and maximum values of these parameters are shown in Table 1.

Table 1. Minimum and maximum values of measured water characteristics

	SD, m	Turbidity, FTU	$C_{SM,Nuc}$, mg L^{-1}	$C_{SM,GFC}$, mg L^{-1}	C_{TOC}, mg L^{-1}	C_{DOC}, mg L^{-1}	C_{chl}, μg L^{-1}	C_{Pheo}, mg L^{-1}	C_{TOTP}, mg L^{-1}
Min	0.4	0.39	0.1	1	4.4	4.3	1.3	1.6	5
Max	7	26	32	18	23.1	14.2	100	110	73

Underwater and low altitude spectral measurements were carried out on lakes. Vertical profiles of downwelling and upwelling spectral irradiance profiles were measured using an Li-1800 UW spectrophotometer (350–800 nm, with 2 nm interval). Downwelling spectral radiance and irradiance as well as upwelling irradiance were measured with an ST 1000 spectrometer (350–850 nm, with 0.5 nm interval). In a few marine stations a PSII portable spectrometer was used for remote measurements from board a research vessel.

RESULTS AND DISCUSSION

A number of remote sensing algorithms for quantitative monitoring of water environment have been elaborated and tested in the Estonian Marine Institute (and its predecessors) (Arst et al., 1993,1994; Arst & Kutser, 1994; Kutser et al., 1995a, b, c, 1997, 1998; Kutser, 1997; Miller et al., 1988) on the basis of data collected with a telespectrometer Pegasus. The most promising of these algorithms as well as algorithms found in literature were used for the interpretation of AISA data. Some of the algorithms used have been elaborated for the retrieval of chlorophyll, suspended matter, or yellow substance concentrations from new satellite sensors (SeaWiFS, MERIS). We tested the suitability of the algorithms not only for the estimation of the characteristics they were originally developed for, but for all measured water properties.

The AISA spectra used in the calculation of a retrieval variable are not from a single pixel, but are averaged values. Averaging was carried out for areas of

20×20 m and 100×100 m. Pixels showing effects of sun glint, cloud shadow, bottom, wind, or a research vessel were excluded before the averaging.

Comparison of the results obtained using 20×20 m and 100×100 m averaging shows no big difference between these two spatial resolutions. Correlation coefficients between retrieval variables and all measured water characteristics differ less than ± 0.1 for different spatial resolutions. The situation was similar in case of marine measurements. However, in case of lake measurements the variability in correlation coefficients is much higher. One may expect that it is better to use 20×20 m resolution in case of lakes where water is patchier; however, our results did not confirm it, even contrary results were obtained. For example, the correlation between water turbidity and a retrieval variable $R = 0.13$ if 20×20 m spatial resolution was used and $R = 0.76$ in case of 100×100 m resolution.

Correlations between the measured water characteristics and those estimated from AISA data are shown in Figs. 2–10.

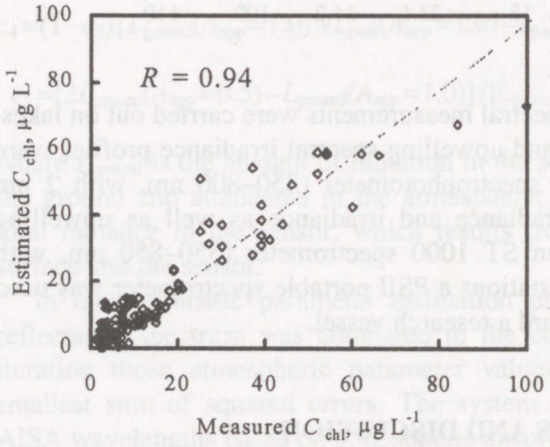

Fig. 2. Correlation between the concentration of chlorophyll *a* measured from water samples and estimated from AISA data by the formula: $C_{chl} = 89.8G_3 - 64.1$, where $G_3 = L_u(701)/L_u(673)$. Spatial resolution 20×20 m. Spectra from brown-water Keravanjärvi (1996 and 1997) and hypertrophic Tuusulanjärvi (1996) were excluded.

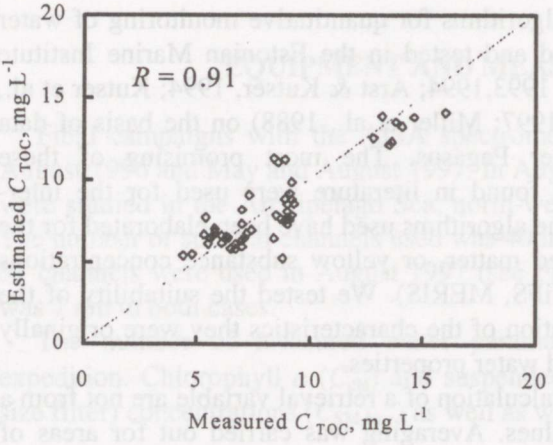

Fig. 3. Correlation between the concentration of total organic carbon measured from water samples and estimated from AISA spectra by the formula: $C_{TOC} = 0.24D_{13} + 5.3$, where $D_{13} = -22.155 - 0.8433L_u(815) + 365.89\{L_u(815)/[L_u(485) + L_u(560)]\}$. Spatial resolution 20×20 m.

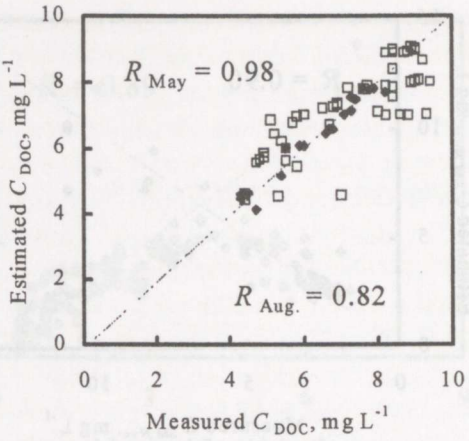

Fig. 4. Correlation between the concentration of dissolved organic carbon measured from water samples and calculated from AISA data using retrieval variable $D_{14} = [L_u(560) - L_u(754)]/[L_u(620) - L_u(754)]$. The algorithm for May 1997 measurements (♦) is $C_{DOC} = -5.77D_{14} + 13.14$ and the algorithm for August 1997 measurements (□) is $-3.65D_{14} + 13.08$. Spatial resolution 20 × 20 m.

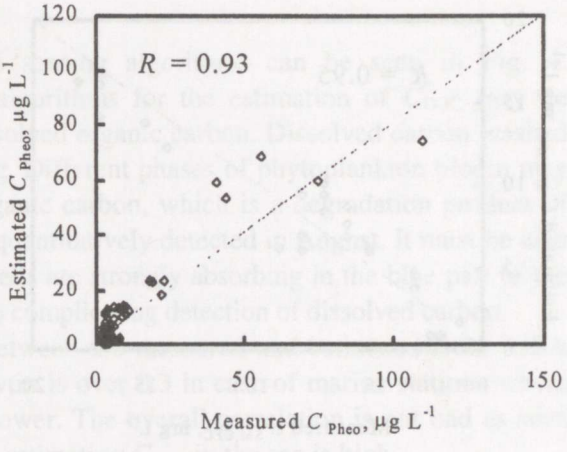

Fig. 5. Correlation between the concentration of pheophytin measured from water samples and estimated from AISA data using the algorithm: $C_{Pheo} = 92.98G_3 - 67.49$. Resolution 20 × 20 m.

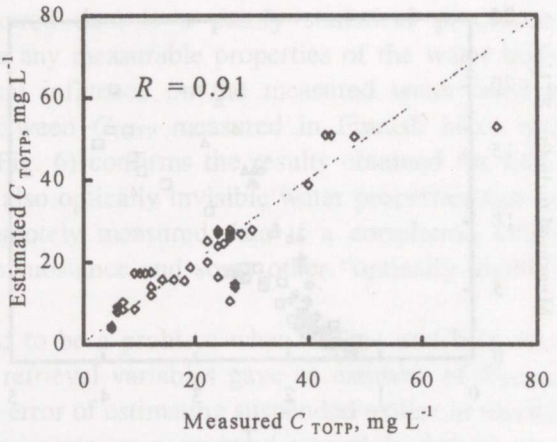

Fig. 6. Correlation between the concentrations of total phosphorus measured from water samples and estimated from AISA spectra. $C_{TOTP} = 2334G_5 - 24.6$, where $G_5 = L_u(700) \Big/ \int_{450}^{700} L_u(\lambda)d$. Resolution 20 × 20 m.

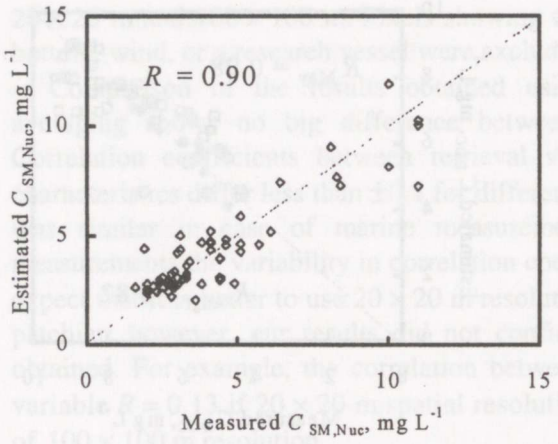

Fig. 7. Correlation between the concentration of suspended matter measured from water samples (using Nuclepore 0.4 μm pore size filters) and estimated from AISA data using the formula: $C_{SM.Nuc} = 154G_{15} + 0.68$, where $G_{15} = L_u(694) - \{L_u(674) - 20[(L_u(674) - L_u(731))/57]\}$. Resolution 20 × 20 m.

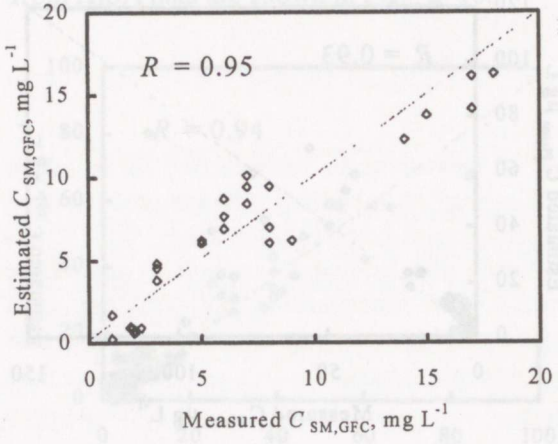

Fig. 8. Correlation between the concentration of suspended matter measured from water samples (Whatman GFC filter, 0.45 μm pore size) and calculated from AISA spectra by the formula: $C_{SM.GFC} = 6.20T_{12} - 8.59$, where $T_{12} = [L_u(\lambda)\max - L_u(750)]/[L_u(476) - L_u(750)]$. Resolution 20 × 20 m.

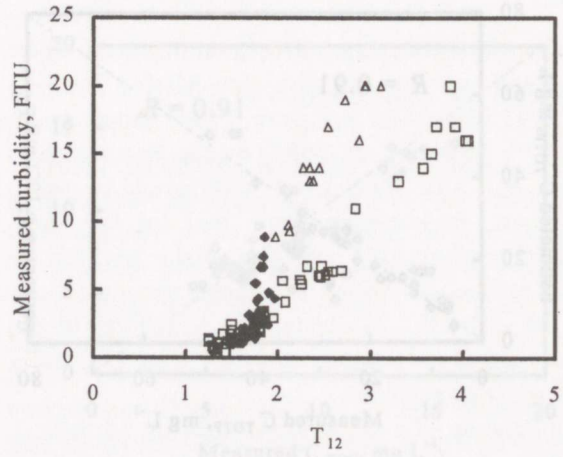

Fig. 9. Correlation between water turbidity measured from samples and retrieval variable T_{12}. The following linear correlations between T_{12} and turbidity were established: $R = 0.98$ (□ lakes August, linear regression); $R = 0.98$ (Δ lakes May, linear regression); and $R = 0.77$ (◆ the Baltic Sea measurements, exponential function). $R = 0.80$ for the whole data set. Spatial resolution 100 × 100 m.

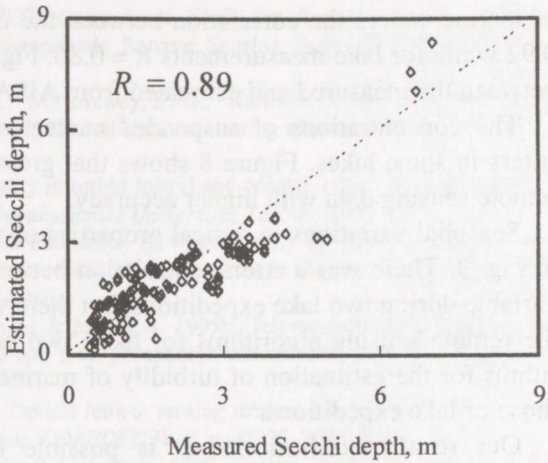

Fig. 10. Correlation between the measured and estimated from AISA data Secchi depths. The algorithm used was $SD = 1.52De_{26} - 0.71$, where $De_{26} = [L_u(665) - L_u(750)]/[L_u(702) - L_u(750)]$. Resolution 20×20 m.

Seasonal changes in remote sensing algorithms can be seen in Fig. 4. Differences in remote sensing algorithms for the estimation of C_{DOC} may be caused by different origin of dissolved organic carbon. Dissolved carbon washed out from soil dominates in spring. Different phases of phytoplankton bloom may be the reason why dissolved organic carbon, which is a degradation product of phytoplankton, cannot be easily quantitatively detected in August. It must be also noted that living phytoplankton cells are strongly absorbing in the blue part of the spectrum (like dissolved organics) complicating detection of dissolved carbon.

The correlation coefficient between the measured and estimated from AISA spectra concentration of pheophytin is over 0.3 in case of marine stations where the pigment concentrations are lower. The overall correlation is not bad as seen in Fig. 5, but the relative error in estimating C_{Pheo} in the sea is high.

Application of spectral ratios or the same kind of retrieval variables in the interpretation of remotely measured data is a purely statistical procedure. Therefore one can try to estimate any measurable properties of the water body even if there is no direct optical influence on the measured water leaving radiance. A good correlation between C_{TOTP} measured in Finnish lakes and estimated from AISA data (see Fig. 6) confirms the results obtained for Lake Peipsi (Kutser et al., 1995a) that also optically invisible water properties can be quantitatively estimated from remotely measured data if a correlation exists between the concentration of the substance and some other "optically visible" characteristic of the water.

Estimation of $C_{SM,Nuc}$ appeared to be a problem when marine and lake data were considered together. Some retrieval variables gave an estimate of $C_{SM,Nuc}$ with $R > 0.8$, but then the relative error of estimating suspended matter in marine waters is quite high. If two environments are considered separately then in case

of marine waters the correlation between the measured and estimated $C_{SM,Nuc}$ is 0.92 while for lake measurements $R = 0.86$. Figure 7 is an example of correlation between the measured and estimated from AISA spectra of $C_{SM,Nuc}$.

The concentrations of suspended matter were measured with two different filters in some lakes. Figure 8 shows that greater particles can be detected from remote sensing data with higher accuracy.

Seasonal variations in optical properties of water bodies are also clearly seen in Fig. 9. There was a strong correlation between water turbidity and a retrieval variable during two lake expeditions, but there was a seasonal difference between the remote sensing algorithms for these two expeditions. Remote sensing algorithms for the estimation of turbidity of marine waters are totally different from those of lake expeditions.

Our results confirm that it is possible to quantitatively estimate water properties from passive optical remote sensing data in case of turbid coastal and inland waters despite the absence of spectral regions where only one optically active substance is influencing the remotely measured spectrum.

The suitability of algorithms elaborated for the interpretation of satellite images suggests that quantitative monitoring of coastal and inland waters will be possible from future satellites with better spatial and spectral resolution and the number of detected parameters may be higher than expected. For example variable D_{14} was developed for the detection of suspended matter concentration from a future MERIS instrument, but the same algorithm appeared to be suitable for the estimation of the concentration of dissolved organic matter.

Cloud cover is often a problem in using passive optical satellite data in mid-latitudes. Therefore, a combination of airborne remote sensing with satellite and some *in situ* measurements could be the best solution for quantitative monitoring of turbid waters of the Baltic Sea and lakes around it.

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VEEKESKKONNA OMADUSTE HINDAMINE LENNUVAHENDILT SPEKTROMEETRI AISA ABIL

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Et klassikaliste, veeproovide analüüsil põhinevate meetoditega ei ole võimalik jälgida veekeskkonna seisundit suurtel aladel ega uurida protsesside dünaamikat, on vaja leida teisi monitooringus sobivaid meetodeid. Autorite eesmärk oli välja töötada meetodid järve- ja rannavete seisundi hindamiseks lennuvahendi pardalt kasutades spektromeetrit AISA. Parameetreid, mida püüti kaugseire abil kvantitatiivselt hinnata, oli kaheksa: klorofüll *a*, feofütiini, lahustunud orgaanilise aine

ja kogu orgaanilise aine, üldfosfori ja hõljumi kontsentratsioon ning vee läbipaistvus mõõdetuna FTU ühikutes ja Secchi ketta abil. Andmete interpreteerimisel lähtuti rohkem kui seitsmekümnest kaugseirekarakteristikust. Neid karakteristikuid on pakutud mitme autori poolt ja nad kujutavad endast vee heleduskoefitsiendi suhteid kahel või enamal lainepikkusel, selliste suhete kombinatsioone või ka keerulisemaid funktsioone vee kohal mõõdetud spektri suuruse ja kuju kirjeldamiseks. Regressioonarvutusega on leitud algoritmid, et hinnata AISA piltide abil veekeskkonna omadusi. Mitmete parameetrite (lahustunud orgaanika hulk, vee läbipaistvus) puhul on näha, et saadud kaugseire algoritmid on sesoonse iseloomuga. See tähendab, et kogu andmebaasi põhjal leitud kaugseire algoritm kirjeldab veekogu mõnda omadust halvemini (või puudub korrelatsioon hoopis) kui aastaaegade jaoks eraldi leitud algoritmid. Vahel ilmneb vajadus leida mere ja järvede kohal mõõdetud spektrite interpreteerimiseks omaette algoritmid. Arvestades AISA hinda ja produtseeritavat andmete hulka võiks monitooringuks soovitada lihtsamat aparatuuri, mille abil saadud andmed oleksid töödeldavad reaalajas. Mitmed kasutatud algoritmid on välja töötatud tulevaste satelliitide andmete tõlgendamiseks ja need sobisid järvede ning rannavete omaduste kvantitatiivseks hindamiseks. Võib oletada, et vastavad parameetrid on määratavad ka satelliidiinfo põhjal.