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Field measurements of spectral backscattering coefficient of the Baltic Sea and boreal lakes

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The spectral backscattering coefficient is a very important characteristic of waterbodies from the remote sensing point of view as the light backscattered from particles and water molecules makes it possible to get information about the properties of the water under investigation. Before this study very little was known about the backscattering coefficient in different parts of the Baltic Sea and in boreal lakes. We carried out backscattering coefficient measurements in the open parts of the Baltic Sea, in several relatively turbid estuaries, bays and in some lakes in southern Finland using HydroScat-6 backscattering sensor. The results show that spectral backscattering coefficient values vary by two orders of magnitude in the Baltic Sea and lakes under investigation. This has serious implications on interpretation of the remote sensing signal collected above these areas.

Introduction

Remote sensing is a successful tool to monitor water quality parameters (e.g. concentration of chlorophyll *a*) over extended water areas. Unfortunately, the standard products provided by space agencies fail in case of the Baltic and boreal lakes (Darecki and Stramski 2002, Reinart and Kutser 2006). There are several issues that may cause the failure of standard chlorophyll *a* retrieval algorithms. For example, atmospheric correction is a problem as assumptions made in atmospheric correction of oceanic images are not valid in case of turbid coastal and inland waters. Types of aerosol in the region may differ from those used in standard atmospheric corrections. Coloured dissolved organic matter (CDOM) is the dominating optically active substance in the Baltic Sea and many boreal lakes. Stronger than expected absorption of light by CDOM is the reason why band-ratio type algorithms using shorter (blue) wavelengths overestimate concentration of chlorophyll *a* in the Baltic Sea and many lakes. Knowledge about optical properties of waters under investigation and optical modelling studies are needed to determine what may be the main reasons causing the failure of the standard water quality parameters retrieval algorithms. Alternative methods to the band-ratio method have been proposed for interpreting remote sensing data. Reflectance spectra from spectral libraries of waters with known properties are compared with measured reflectance spectra to determine concentrations of optically active substances in the water under investigation. This method allows both determining concentrations of optically active substances (Kutser 2004) in the water column and/or estimating

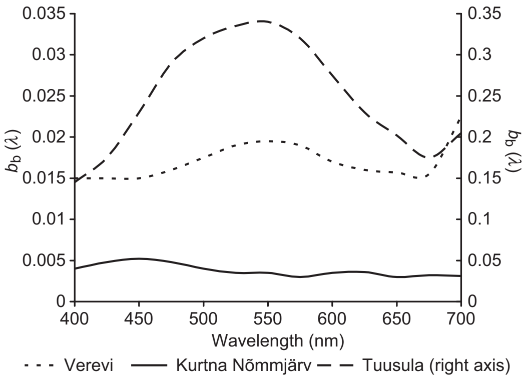

Fig. 1. Spectral backscattering coefficient of three lakes representing optically different types of lakes in Estonia and Finland. Reproduction from Kutser (1997).

water depth and bottom type in shallow water areas (Kutser *et al*. 2006). It is not possible to create spectral library for particular waterbodies or regions without knowing optical properties (including the backscattering coefficient) of the waters under investigation.

It has been shown (Gordon *et al*. 1975) that remote sensing reflectance of water is proportional to the ratio of backscattering and absorption coefficients:

$$R_{rs} \approx C \frac{b_b(\lambda)}{a(\lambda)+b_b(\lambda)}, \quad (1)$$

where C is a constant depending on solar zenith angle, $b_b(\lambda)$ is the total spectral backscattering coefficient, $a(\lambda)$ is the total spectral absorption coefficient and λ is wavelength. Equation 1 illustrates the important role of backscattering in formation of water reflectance spectra. This equation is also the basis of semi-analytical bio-optical models used to create the spectral libraries mentioned above. Absorption coefficients can be measured from water samples and the procedure is relatively straightforward. Instruments for *in situ* measurements of backscattering have been available for about a decade, but still relatively little is known about backscattering in the Baltic Sea and boreal lakes (Strömbeck 2001). Backscattering coefficients of pure phytoplankton cultures of several species present in the Baltic Sea and lakes have been studied in laboratory conditions by N. Strömbeck (Metsamaa *et al*. 2006), while backscattering coefficients of pure cultures of some oceanic species have been studied by Ahn *et al*. (1992). However, variability in the total spectral backscattering coefficient values is largely unknown for our study area. Nearest backscattering coefficient measurement results are available for Norwegian waters (Aas *et al*. 2005). Some backscattering coefficient spectra have also been published by Chami *et al*. (2006).

Kutser (1997) performed model simulation for Estonian and Finnish lakes when no *in situ* backscattering sensors were available. A semi-analytical model described in Kutser *et al*. (2001) was used together with measured irradiance reflectance, absorption and scattering coefficients as well as concentrations of chlorophyll *a*, suspended matter and CDOM measured from water samples (details of the measurements are given in Arst *et al*. 2008). The modelling results are shown in Fig. 1. Both shape and magnitude of the estimated b_b spectra varied dramatically. For example in the case of relatively clear lakes the backscattering coefficient values were around 0.005 m^{-1} and spectra were relatively flat with a slight decrease towards longer wavelengths. In the case of hypertrophic Tuusulanjärvi the modelled backscattering coefficient values reached 0.35 m^{-1} and the shape of the b_b spectra had arch shape in most of the visible part of spectrum.

The objective of the present study was to determine the extent of the variability in total backscattering coefficient in different parts of the Baltic Sea (open Baltic Sea waters, turbid estuaries, etc.) and some boreal lakes. Knowledge about the total backscattering coefficient will help to improve bio-optical and radiative transfer models of the Baltic Sea necessary for understanding of formation of underwater light climate and water leaving signal that can be detected by remote sensing sensors.

Methods

The instrument

Optical backscattering meter HydroScat-6 (HOBILabs) was used during *in situ* measurements in different regions of the Baltic Sea and some lakes. It has been shown (Maffione and

Fig. 2. Locations of the study sites in the Baltic Sea and Finnish lakes.

Dana 1997) that backscattering coefficient can be calculated from a single angle measurements instead of measuring volume scattering function over all angles and integrating it over backward directions. This result has been used in design of fixed angle backscattering sensors. HydroScat-6 is measuring scattering under the angle of 140° that has been theoretically shown to be the optimal angle. HydroScat-6, that we used measures backscattering at six wavelengths 442, 470, 510, 589, 620 and 671 nm. HydroScat is an active device i.e. it is emitting the light the instrument is measuring. Detailed description of the instrument and its operating principles are given in Maffione and Dana (1997).

The instrument was lowered from research vessels and boats by hand. The backscattering coefficient was usually measured from water surface to the bottom. Water depth in the studied lakes was usually less than 2–3 meters. In coastal waters under investigation water depths reached 17 m. The particular instrument we used does not have internal memory. Thus, the measurements were carried out using a laptop as commanding and logging device. This gave us immediate knowledge about the variation of backscattering in the water column, but limited the depth of measurements in the open parts of the Baltic Sea to the length of the underwater cable (20 m). This depth is adequate from the point of view of remote sensing and underwater light climate studies as the depth of penetration (the depth from where remote sensing signal is originated) is usually between centimetres (in dense cyanobacterial blooms) and about 10 m (in clear Baltic Sea waters) in waterbodies under investigation.

Study sites

Backscattering measurements were carried out in the Baltic Proper, the Gulf of Liivi, the western Estonian Archipelago and the Gulf of Finland (Fig. 2). In the Gulf of Finland the measurements were carried out both in the open parts of the Gulf and in several turbid estuaries and bays. Some of the measurements in the open parts of the Baltic Proper were carried out during cyanobacterial bloom. In addition to the natural conditions the backscattering measurements were also carried out near port dredging activities in Muuga port, south-eastern part of the Gulf of Finland. Lakes where the backscattering measurements were carried out are located in the southern Finland. Most of the lakes had CDOM-rich brown waters, but Tuusulanjärvi is a hypertrophic lake with relatively turbid water. We observed frequent cyanobacterial blooms in Tuusulanjärvi (Arst *et al*. 2008) and turbidity in the lake was usually

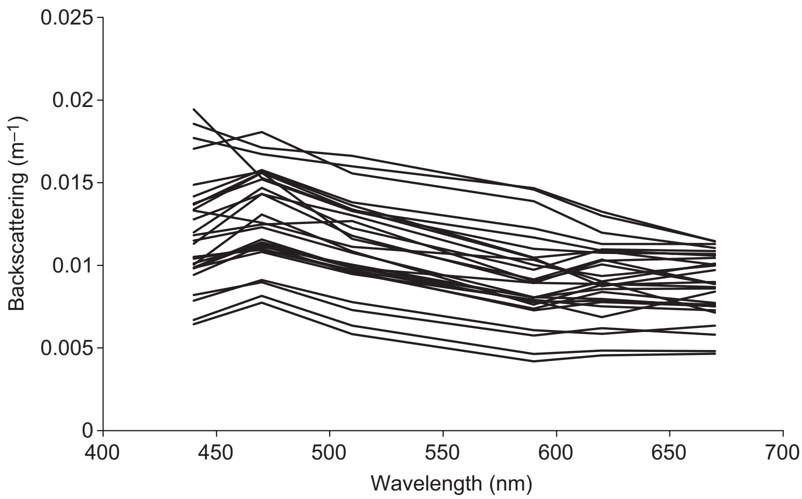

Fig. 3. Variability of spectral backscattering coefficient in the open parts of the Baltic Sea (Baltic Proper and Gulf of Finland).

associated with the high amount of phytoplankton rather than high concentration of inorganic particles.

The HydroScat measurements used in the present study were performed as a part of larger bio-optical experiments. Concentrations of chlorophyll *a*, CDOM and total suspended matter were measured by taking the water samples at each station where the HydroScat measurements were carried out. We measured also above-water reflectance with different spectrophotometers. Spectral absorption, attenuation and scattering coefficient measurements were carried out with AC-9 (WetLabs) in Finnish lakes and estuaries. Concentration of chlorophyll *a* varied between 0.5 and 58.9 mg m^{-3}; total suspended matter between 0.2 and 17.5 mg l^{-1} (52.1 mg l^{-1} in Pääjärvi during storm); and CDOM absorption coefficient at 420 nm varied between 0.59 and 11.33 m^{-1}.

Results and discussions

In the open parts of the Baltic Sea backscattering coefficient varied between 0.005 m^{-1} and 0.2 m^{-1} (Fig. 3). These backscattering coefficient values are similar to those obtained using model simulations for clear Estonian and Finnish lakes (*see* Fig. 1) or measured in oceanic waters (Stramska *et al*. 2000, Kutser *et al*. 2003). However, they are slightly less than those that had been measured in Norwegian coastal waters (Aas *et al*. 2005) The concentration of total suspended solids (TSS) in these areas was between 0.2 mg l^{-1} and 2 mg l^{-1} and concentration of chlorophyll *a* (Chl-*a*) was below 4 mg m^{-3}.

Moderately turbid waters include the Muuga, Tallinn and Matsalu Bays in Estonia, the Kymijoki estuary, Ormanjärvi as well as some measurements made in the northern part of the Baltic Proper during cyanobacterial bloom. Backscattering coefficient values (Fig. 4) in these waters were by order of magnitude higher than in the open Baltic Sea waters. TSS at these sites varied between 6 mg l^{-1} and 10 mg l^{-1} and Chl-*a* varied between 6 mg m^{-3} and 25 mg m^{-3}.

Backscattering values in the most turbid sites under investigation were almost by order of magnitude higher than in case of the moderately turbid sites (Fig. 5). The highest backscattering values were observed in Tuusulanjärvi in 2005 and 2006 (two highest spectra in Fig. 5). Both the arch shape and values of backscattering coefficient measured in the Tuusulanjärvi correspond to the model estimates (Kutser 1997) (Fig. 1) Almost as high backscattering was measured in the Porvoonjoki estuary near the river mouth. In the Porvoonjoki the high backscattering was caused by high load of suspended sediments (TSS = 18 mg l^{-1}) whereas phytoplankton (usually cyanobacteria) was the cause of high backscattering in Tuusulanjärvi ($17 < \text{Chl-}a < 59$ mg m^{-3}). Slightly lower (around 0.2 m^{-1}) backscattering values were measured in the Muuga Bay a few tens of meters from a working dredge

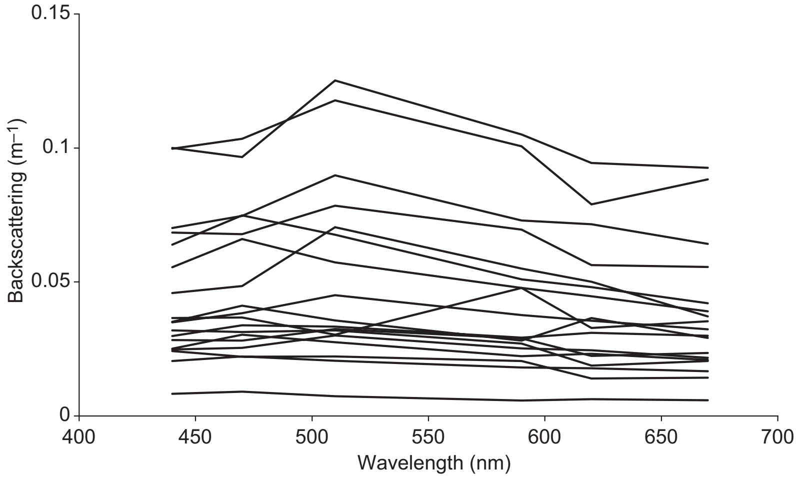

Fig. 4. Backscattering coefficients of moderately turbid coastal and inland waters.

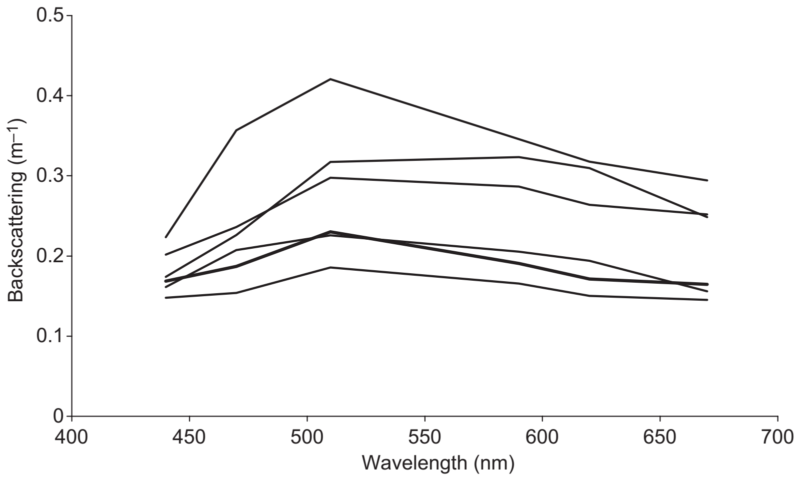

Fig. 5. Backscattering coefficients of turbid estuaries and lakes.

and in Porvoonjoki and Kymijoki estuaries where the TSS varied between 7 mg l^{-1} and 13 mg l^{-1}. It must be noted that the concentration of chlorophyll *a* was also quite high in the Porvoonjoki estuary (13 < Chl-*a* < 23 mg m^{-3}).

The most extreme backscattering was observed in Pääjärvi. Pääjärvi is a CDOM-rich lake where the concentration of suspended sediments is usually low (TSS below 2 mg l^{-1}). A very strong wind was blowing at the time when we tried to carry out our measurements. Therefore, we were not able to use a boat and carry out measurements in the open parts of the lake. Instead we made our measurements from a jetty. Water depth in this area is between 1–2 m and there was a very high resuspension of sand from the lake bottom due to strong wind. Total suspended matter concentration was 52.1 mg l^{-1}. The backscattering coefficient values (Fig. 6) are not very typical to most parts of Pääjärvi, but they illustrate an extreme case that can be observed in optically complex waters.

The volume, where HydroScat is measuring backscattering is small and the distance light has to travel from each light source to the corresponding receiver is short. Thus, in most cases the absorption coefficient of the water under investigation does not have significant effect on the measured signal. However, CDOM-rich waters absorb light significantly at shorter wavelengths. The backscattering coefficient spectra measured in so CDOM-rich lake like Pääjärvi ($a_{CDOM}(400)$ = 11.33 m^{-1}) are impacted by the absorption of CDOM. The HydroScat-6 processing software includes correction for the CDOM absorption (Maffione and Dana 1997), but it is

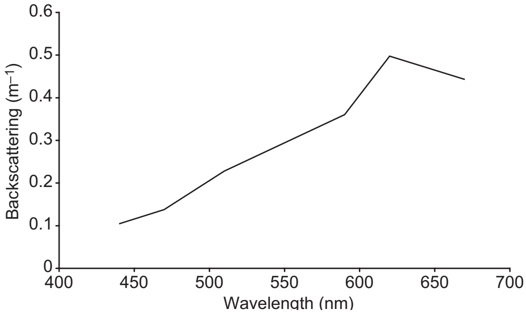

Fig. 6. Backscattering coefficient of a turbid shallow water area in a CDOM-rich Pääjärvi.

insufficient even in the open parts of the Baltic Sea (Fig. 3) as after the correction backscattering values at 440 nm should theoretically be higher than at 470 nm. Strömbeck (2001) proposed a method for correcting backscattering coefficient spectra that works in case of coastal and inland waters with higher CDOM concentration than assumed by the HydroScat's manufacturer and included in the processing software. However, suitability of the method for extremely CDOM-rich environments has not been tested.

Maffione and Dana (1997) showed with model simulations that the normalised volume scattering function have consistent shape and single angle scattering measurements can be used to measure backscattering coefficient in variety of conditions. However, normalised volume scattering function spectrum measured in turbid San Diego harbour by Petzold (1972) differs from those measured in other waters. Up to now this result has not been verified with the volume scattering function measurements by other authors. It is not known was the harbour data statistical outlier or are the normalised volume scattering functions really different in turbid waters. Therefore, the backscattering coefficient values obtained in turbid waters by single angle instruments may not be as accurate as for less turbid waters. However, our turbid water results fit well with model simulations (Kutser 1997). The model simulations were based on real bio-optical measurements data from the same or similar waterbodies where we performed *in situ* backscattering coefficient measurements. This allows us to assume that the HydroScat-6 performs acceptably also in turbid waters.

Results of the present study can be incorporated in the models used to create spectral libraries needed for the physics based approach in interpretation of remote sensing data (Kutser 2004, Kutser *et al*. 2006). Variation in the backscattering coefficient values should also affect significantly the reflectance values. However, if methods like the Spectral Angle Mapper (SAM) are used to compare reflectance spectra from image and spectral library then the effect of variability in backscattering values will be small as SAM normalises the spectra before comparing them. However, as we have shown, there is also variability in the shape of backscattering coefficient spectra. This has an impact on image classification results even if methods like SAM are used.

The HydroScat-6 is a profiling instrument which is providing data with frequency determined by the instrument operator. It means that the instrument is giving information not only about the value and spectral shape of the backscattering coefficient but also about vertical structure of particles (both organic and inorganic) in the water column.

In summer, a thermocline divides the Baltic Sea waters into two layers: a wind mixed surface layer down to a depth of 10–25 m, and a colder and denser water layer extending to the sea bed. This should make backscattering coefficient values constant in the upper mixed layer. However, we found interesting phenomena in the water column in some locations. For example measurements carried out a few miles away from a working dredge in the Muuga Bay (Fig. 7A) showed high backscattering at a depth of 7 meters. Most probable cause for this phenomenon was a layer of fine clay particles that settled out from the upper water column but were not capable of falling through thermocline due to the light weight of the particles. We were able to map the extent of dredging plume in the area and concentration of total suspended matter in surface layer with high accuracy using MODIS satellite 250 m resolution data (Kutser *et al*. 2007). However, the HydroScat measurements show that very fine sediments can travel further from their source than can be mapped by remote sensing or taking water samples from surface layer. The vertical profile of backscattering also showed higher values near the sea bottom (between 13 m and 15 m) which can probably be associated with bottom current causing resuspension or transporting sediments offshore from the port construction area.

Cyanobacteria, unlike most phytoplankton species, are capable of moving vertically in the water column. In bloom conditions and calm weather they tend to come close to the water surface and even form mats on the water surface. Some accumulation of cyanobacteria was observed in the northern part of the Baltic Proper where measurements were carried out (Fig. 7B). Unfortunately, it is practically impossible to measure surface accumulations with HydroScat (and other instruments) as the instruments disturb natural stratification of cyanobacteria. It must also be noted that the bloom was not very dense (Chl-*a* = 29.9 mg m^{-3}). However, most of the cyanobacteria were in the top 3–4 meters of the water column as seen from the HydroScat measurement. This confirms once again that the ferry-box systems on ships of opportunity are not good tools to map cyanobacterial blooms because they often collect water from the depth (usually about 5 m) below the layer where cyanobacteria are. The noisiness of the vertical profile is caused by aggregations of cyanobacteria which are too large (from millimetres to centimetres) for the optical instrument to measure. An aggregation in front of the instrument window gives high backscattering values and relatively clear (from unicellular cyanobacteria) water between the aggregations gives comparatively low backscattering values.

Very interesting stratification was observed in the Pakri Bay near the Port of Paldiski (Fig. 7C). The cyanobacterial bloom was visually noticeable in the water. However, the vertical distribution of cyanobacteria was bimodal with one maximum near water surface and second maximum near thermocline. Similar bimodal increase in backscattering occurred also below the thermocline, but this can probably be associated with mineral sediments originating from the adjacent port construction area or shallow water area with a river inlet nearby not from the cyanobacterial bloom in surface “mixed” layer. Unfortunately, we collected water sample only from the surface layer and cannot confirm what caused the increase in backscattering below the thermocline.

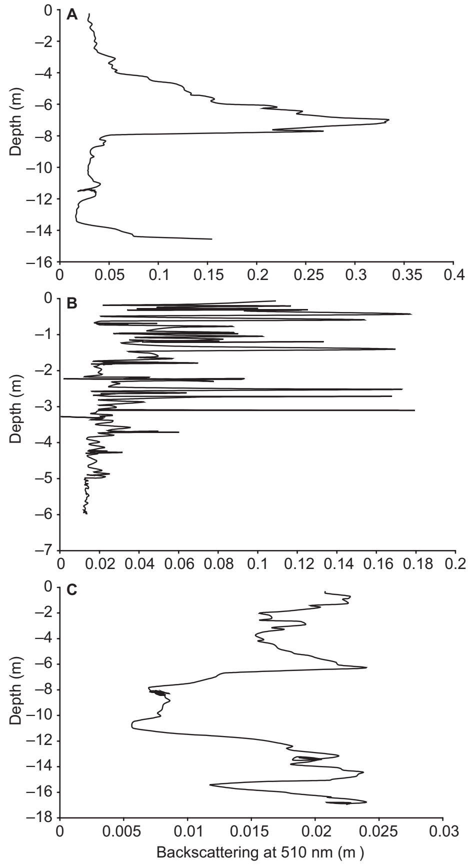

Fig. 7. Vertical profiles of backscattering coefficient at 510 nm in three situations: (**A**) Muuga Bay, a few miles from dredging activities; (**B**) cyanobacterial bloom in the Baltic Proper; and (**C**) cyanobacterial bloom and possible sediment resuspension in the Pakri Bay.

Conclusions

Our results show that the backscattering coefficient values in the Baltic Sea and boreal lakes are varying by two orders of magnitude. This has serious implications on interpretation of the remote sensing signal collected above these areas. Therefore, it is likely that different remote sensing algorithms may be needed for open parts of the Baltic Sea and turbid coastal regions if band-ratio type algorithms are used.

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References

Aas E., Hohedal J. & Sorensen K. 2005. Spectral backscattering coefficient in coastal waters. *Int. J. Remote Sensing*. 26: 331–343.

Ahn, Y.-H., Bricaud A. & Morel A. 1992. Light backscattering efficiency and related properties of some phytoplankters. *Deep-Sea Res*. 39: 1835–1855.

Arst H., Erm A., Herlevi A., Kutser T., Leppäranta M., Reinart A. & Virta J. 2008. Optical investigation of Finnish and Estonian lakes during the SUVI project (1994–2005). *Boreal Env. Res*. 13: 133–158.

Chami M., Shybanov E.B., Khomenko G.A., Lee M.E.-G., Martynov O.V. & Korotaev G.K. 2006. Spectral variation of the volume scattering function measured over the full range of scattering angles in a coastal environment. *Appl. Optics*. 45: 3605–3619.

Darecki M. & Stramski D. 2004. An evaluation of MODIS and SeaWiFS bio-optical algorithms in the Baltic Sea. *Remote Sensing Environ*. 89*:* 326–350.

Gordon H.R., Brown O.B. & Jacobs M.M. 1975. Computed relationships between the inherent and apparent optical properties of a flat, homogenous ocean. *Appl. Optics*. 14: 417–427.

Kutser T. 1997. *Estimation of water quality in turbid inland and coastal waters by passive optical remote sensing*. Diss. Geophys. Univ. Tartuensis 8, Tartu University Press.

Kutser T. 2004. Quantitative detection of chlorophyll in cyanobacterial blooms by satellite remote sensing. *Limnol. Oceanogr*. 49: 2179–2189.

Kutser T., Herlevi A., Kallio K. & Arst H. 2001. A hyperspectral model for interpretation of passive optical remote sensing data from turbid lakes. *Sci. Total Environ*. 268: 47–58.

Kutser T., Dekker A.G. & Skirving W. 2003. Modelling spectral discrimination of Great Barrier Reef benthic communities by remote sensing instruments. *Limnol. Oceanogr*. 48: 497–510.

Kutser T., Miller I. & Jupp D.L.B. 2006. Mapping coral reef benthic substrates using hyperspectral space-borne images and spectral libraries. *Estuarine, Coastal Shelf Sci*. 70: 449–460.

Kutser T., Metsamaa L., Vahtmäe E. & Aps R. 2007. Operative monitoring of the extent of dredging plumes in coastal ecosystems using MODIS Satellite Imagery. *J. Coastal Res*. SI50: 180–184.

Maffione R.A. & Dana D.R. 1997. Instruments and methods for measuring the backward-scattering coefficient of ocean waters. *Appl. Optics*. 36: 6057–6067.

Metsamaa L., Kutser T. & Strömbeck N. 2006. Recognising cyanobacterial blooms based on their optical signature: a modelling study. *Boreal Env. Res*. 11: 493–506.

Petzold T.J. 1972. *Volume scattering functions for selected ocean waters*. Scripps Institution of Oceanography Report No. 72–79.

Reinart A. & Kutser T. 2006. Comparison of different satellite sensors in detecting cyanobacterial bloom events in the Baltic Sea. *Remote Sensing Environ*. 102: 74–85.

Stramska M., Stramski D., Mitchell B.G. & Mobley C.D. 2000. Estimation of the absorption and backscattering coefficients from in-water radiometric measurements. *Limnol. Oceanogr*. 45: 628–641.

Strömbeck N. 2001. *Water quality and optical properties of Swedish lakes and coastal waters in relation to remote sensing*. Ph.D. thesis, Acta Universitatis Upsalaensis 633.