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# MERIS Case II water processor comparison on coastal sites of the northern Baltic Sea

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ABSTRACT

Three MERIS Case II water processors included in the BEAM software package were studied for estimating the water quality in the coastal waters of the northern Baltic Sea. The processors, named Case II Regional (C2R), boreal (BOR), and eutrophic (EUT), for the associated lake types, have been developed for different types of coastal or inland (Case II) waters. Chlorophyll-a (chl-a), total suspended matter (TSM), absorption of colored dissolved organic matter ($a_{CDOM}$(443)), and signal depth ($Z_{90}$) products of the BEAM processors were compared with *in situ* data. In addition, total absorption ($a_{TOT}$) and scattering of TSM ($b_{TSM}$) from different BEAM processors were compared against the results of coastal field campaign measurements. The *in situ* water quality data consisted of monitoring station data gathered by the Finnish environmental administration during 2006–2009 and data from coastal field campaigns with a flow-through system. AERONET-OC (SeaPRISM) data from the Helsinki Lighthouse station were used to validate the BEAM reflectance products. The comparison with the BEAM processor results and *in situ* data showed that the bias of the original BEAM algorithms can be decreased through adjustment of the coefficients that relate IOPs such as the absorption of pigments and the scattering of TSM to water quality constituents such as chl-a and turbidity. The TSM products of the BEAM processors can be used to estimate the turbidity measured at monitoring stations with an $r^2$ of 0.76–0.84 and an RMSE of 0.7–0.85 FNUs (Formazin Nephelometric Units) on the coast of Finland. The best functionality for turbidity estimation was observed with the EUT processor, but the C2R processor also gave a sound performance. The BOR and C2R processors proved to be the best for deriving chl-a concentration. However, the accuracy of chl-a estimations was low with both processors ($r^2$ ranged from 0.45 to 0.47 and RMSE was between 44 and 45%). Chl-a products, particularly during the phytoplankton bloom seasons of spring and summer, require further development. The $Z_{90}$ product from the BOR processor was used to derive an algorithm for Secchi disk depth estimation with $r^2$ 0.48 and RMSE 0.97 m. The BOR processor was the most successful at CDOM estimation ($r^2$ 0.6 and RMSE 0.49 1/m), but a simple reflectance ratio was actually able to perform better ($r^2$ 0.75 and RMSE 0.39 1/m). In many cases, the differences between the outcomes of processors were small and related only to a part of the *in situ* dataset.



## 1. Introduction

In recent years, several studies have reported large error levels and differences in global remote-sensing based interpretations of chlorophyll *a* (chl-a) concentrations on various types of Case II waters. These studies have been dealing with the standard algorithms for SeaWiFS, MODIS, and MERIS instruments (Blondeau-Patissier et al., 2004; Darecki & Stramski, 2004; Gregg & Casey, 2004; Reinart & Kutser, 2006). The early works by Brown and Simpson (1990) and Bowers et al. (1996) addressed the problem of determining chl-a levels in the presence of inorganic particles. Our coastal study focuses on the northern parts of the Baltic Sea – i.e., the Gulf of Bothnia and the Gulf of Finland. These waters represent Case II waters with high amounts of CDOM (colored dissolved organic matter, known also as yellow substance). The concentration of chl-a in the Baltic Sea shows great seasonal variation, ranging from intensive phytoplankton spring blooms (10–120 μg/l) to a summer minimum (1–3 μg/l). In July–August, surface-floating cyanobacteria blooms occur regularly. During these bloom periods, chl-a concentrations have a typical range of 5–30 μg/l, according to conventional monitoring done at monitoring stations and data from ships of opportunity (Rantajärvi et al., 1998). Satellite instruments have been used to study the cyanobacterial bloom season in the work of Kutser (2004) and of Reinart and Kutser (2006). These two publications suggest that conventional monitoring of chl-a does not cover the

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small-scale heterogeneity of dense and surface-floating algal blooms in the Baltic Sea and suggest that during these bloom events, chl-a concentrations can easily rise to hundreds of micrograms per liter on the surface during calm weather. In addition to seasonal variations in chl-a concentrations, CDOM shows a large variation in the Baltic Sea, with an increasing gradient towards the northern parts. As explained by, for example, Kratzer et al. (2008) and Vepsäläinen et al. (2005), high absorption by CDOM hampers reliable estimation of chl-a concentrations at the short wavelengths (below 500 nm) that are used in the global chl-a algorithms. In our *in situ* dataset, the CDOM absorption coefficient at the wavelength 400 nm, $a_{CDOM}(400)$, varies from 0.8 1/m to 5.8 1/m. In the waters studied, especially near the coast, $a_{CDOM}(400)$ can have seasonally even higher variation, reaching up to 10 1/m. Another optically characteristic feature affecting the reflectance detected by earth observation (EO) data is the presence of suspended solids in the water. Turbidity of water (measured in FNU, Formazin Nephelometric Units) is caused by the presence of suspended particles. It is a parameter often used by the environmental administration when determining the state of a water body. Our dataset covers a turbidity range between 0.2 and 14 FNU that represents typical variation for the coast of Finland. Turbidity is approximately proportional to the concentration of total suspended matter. Finally, Secchi disk depth is commonly used to describe the transparency of the water in national monitoring programs. In our coastal dataset, the Secchi disk depth ranges from 0.5 m to 10 m. In addition to these critical water quality conditions, low sun elevation angle creates even more difficulties for the remote sensing of water quality in this northern region.

Because of the high spatial and seasonal variation of optical properties of water in the Baltic Sea (Darecki et al., 2003; Kowalczuk, 1999; Kowalczuk et al., 2005; Seppälä et al., 2005), the use of remote sensing has often been restricted to empirical or semi-empirical methods. These can provide high precision at a local scale but, unfortunately, often with limited spatiotemporal range on the algorithm performance (Attila et al., 2008; Darecki et al., 2005; Härmä et al., 2001; Koponen et al., 2007; Kratzer et al., 2008; Kutser, 2004; Kutser et al., 1998; Pulliainen et al., 2004; Vepsäläinen et al., 2005). The other alternative has been to study the usability of algorithms developed for global applications. Studies by e.g. Darecki and Stramski (2004), Kratzer et al. (2008), and Reinart and Kutser (2006) report rather large variations in the accuracy and performance of these methods.

The monitoring programs of environmental administrations in Europe are faced with the specific monitoring requirements of the EU Water Framework Directive (WFD) and the Marine Strategy Framework Directive (MSFD). There is a vast interest in developing cost-effective remote sensing monitoring methods for these areas. However, these methods must be accurate enough to qualify for the monitoring program. The evaluations by Blondeau-Patissier et al. (2004) and Darecki and Stramski (2004) demonstrate that the present standard MODIS and SeaWiFS algorithms from NASA do not offer a performance of adequate level for the Baltic Sea.

The MERIS-instrument on the ENVISAT-satellite with its enhanced spatial resolution in full-resolution (FR) mode can offer more than MODIS and SeaWiFS do for the meandering coastline in the northern parts of the Baltic Sea. Also the spectral band combination of MERIS is well suited to this type of water body, as demonstrated by Härmä et al. (2001). BEAM, a free software toolbox for satellite image processing by Brockmann Consulting, includes MERIS processors that provide estimates of water constituents for Case II regions (Doerffer & Schiller, 2008a).

The objective of this study is to determine under which conditions three of the BEAM Case II water processors for the MERIS instrument can be used for the coastal waters of the northern Baltic Sea. Results are presented for the processor known as Case II Regional, here C2R (Doerffer & Schiller, 2007), and for two processors based on C2R but modified for boreal (BOR) and eutrophic (EUT) lakes (Doerffer & Schiller, 2008a, 2008b; Koponen et al., 2008). Recent studies by Odermatt et al. (2010; 2012) and Binding et al. (2011) have validated the performance of these processors on Case II lake environments. Our validation data consist of an extensive four-year time series of coastal monitoring station data (2006–2009) and four coastal measurement campaigns. These coastal monitoring station data comprise laboratory analyzed measurements of chl-a, turbidity, $a_{CDOM}(400)$ and Secchi disk depth measurements from the Gulf of Bothnia and Gulf of Finland. Dedicated field campaigns include calibrated transect measurements of total absorption and scattering, chl-a, TSM (total suspended matter), turbidity, and $a_{CDOM}(400)$. Moreover, radiance reflectance products of the BEAM processors are compared here with radiance measurements made at the AERONET-OC station (Helsinki Lighthouse), in the Gulf of Finland.

## 2. *In situ* data

### 2.1. Monitoring station data

Routine monitoring station sampling data and dedicated field campaigns were used as *in situ* validation data for BEAM processor comparison. The Environmental Administration of Finland is responsible for collecting the coastal monitoring station data. The coastal waters are monitored in accordance with the program of the COMBINE Baltic Sea protection agreement, and the requirements of the Water Framework Directive (WFD) and national water protection programs. The monitoring includes 16 intensive monitoring stations and around 150 ordinary monitoring stations. The intensive monitoring stations are visited 20 times a year, while the other monitoring stations receive visits 2–4 times a year (Raateoja & Kauppila, 2009). The locations of the coastal monitoring stations are illustrated in Fig. 1.

Monitoring stations are used to collect measurements of chl-a, turbidity, $a_{CDOM}(400)$, and Secchi disk depth. The water samples collected from the monitoring stations were analyzed in laboratory using standardized methods. Chl-a (the sum of chlorophyll a and phaeophytin a) was determined by extraction with hot ethanol (ISO, 10260 Standard, 1992, GF/C filter). Turbidity was determined using the Nephelometric method (EN 27027, 1994), which is based on measurement of light at 860 nm scattered from a beam directed at the water sample (formazine used as a standard matching solution). Absorption coefficient of CDOM at 400 nm ($a_{CDOM}(400)$) and at 750 nm was measured with a spectrophotometer (cuvette length of 50 mm) from a sample filtered through a Nuclepore polycarbonate 0.4 μm filter. $a_{CDOM}(400)$ was corrected for residual scattering through subtraction of absorption coefficient at 750 nm from that of 400 nm according to Green and Blough (1994). In routine water quality monitoring in Finland, the concentration of humic substances is indirectly determined via the ‘water colour’ (mg Pt l-1) method, which is based on the comparison of water samples with standard cobalt chloride disks (ISO 7887, 1994). Pt water colour was here converted to $a_{CDOM}(400)$ with a relationship presented by Kallio (2006).

Many of these monitoring stations are close to shore; all stations that are closer than 900 m from any land, even a small island, have been removed from the dataset to minimize the adjacency effect. Table 1 shows the statistics of the monitoring station measurements that were made on the day of a MERIS non-cloudy fly-over or on the previous or following day during the years 2006–2009.

In Case II waters, it is often typical that the water constituents are cross-correlated. The monitoring station data were used to find the degree of cross-correlation in our dataset. The correlation between chl-a and $a_{CDOM}(400)$ was low: for the whole $a_{CDOM}(400)$ dataset ($N=60$), $r^2$ was 0.2. This poor correlation was related to five points with either a high chl-a concentration (>20 μg/l) or a large amount of CDOM ($a_{CDOM}(400)>3$ 1/m). Without these samples, the correlation between *in situ* chl-a and $a_{CDOM}(400)$ is clear, with $r^2=0.47$