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Flow Through System for Distinguishing Dynamic Features in the Baltic Sea

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Abstract

The freshwater input in to estuarine areas sets the scene for the stratification and the current field of the uppermost layer of the seas. Different dynamical features are relatively simple to distinguish from satellite images, but the comparison between remote sensing data and ground truth data is complicated due to the complex coastline and the length of time demanded by water sampling. A pilot study was made to study the use of a flow-through system with a fixed sampling depth, on a vessel moving at ~5 knots. It was carried out on 1st of October 1998 along a section between the central part of the Gulf of Finland and the end of Pohja Bay. The continuously measured parameters were salinity (conductivity), temperature and the inherent optical properties of the water. A clearly discernible frontal system is seen in the collected data. The salinity drops from 6 to 1.7, and temperature drops from 13°C to 10°C, in a distance less than 3km. Simultaneously measured attenuation, absorption and scattering of water in all nine wavelengths changed significantly. Attenuation values range from 1.8m^{-1} up to 9m^{-1} and scattering rises from 1.7m^{-1} to 8m^{-1}. Higher concentrations of particulate material, phytoplankton, and especially yellow substance in the freshwater are the most likely reasons for it to be optically more active than the sea water. The thickness of the productive layer changes from 8m in the open sea to 2.5m in the bay. By measuring the optical properties of water continuously together with conductivity and temperature a powerful tool is provided to us for water quality analysis.

Key words: Inherent optical properties, flow through system, frontal features, coastal oceanography, freshwater input

1. Introduction

Spreading of freshwater into the sea can be studied using remote sensing algorithms (*Cullen and Lewis*, 1995), but a fast way of making synoptic surface measurements is still necessary for validation. Even a small amount of freshwater added to saline coastal water causes a change in the surface current field, because the freshwater has a smaller density. Changes in freshwater density are the main driving force for the current fluctuations (*Apel*, 1987; *Fischer et al.*, 1979).

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The motive for this study comes from the need for a powerful tool to estimate water quality and freshwater spreading into sea areas. Different dynamic features are relatively simple to distinguish from satellite images, but the comparison between remote sensing data and ground truth data is complicated due to the complex coastline and the length of time demanded by water sampling. The use of a flow-through system with a fixed sampling depth is thus motivated firstly by the fact that satellites can see only a relatively thin layer of the studied water mass and secondly because a large area of water can be sampled in a short period of time.

Phytoplankton, yellow substance and inorganic suspended particulate material are the typical optically active substances in the coastal waters. The biggest differences between a freshwater and a brackish water ecosystems are in the variant phytoplankton species. These are adapted either to low salinity river water or higher salinity Baltic sea water (*Niemi*, 1973).

The study area, Pohja Bay, is located in southern Finland near Hanko peninsula. There is a freshwater source, river Mustiojoki, with a mean flow of 22.2m^3s^{-1} (in 1995) at the end of a narrow fjord-like bay (*Hyvärinen*, 1999). The starting point for measurements was in the open sea where the salinity is typically 6-7 (*Myrberg*, 1998). Frontal features at the surface were distinguished from the continuously recorded beam absorption and attenuation coefficients of water (which will be referred to in this paper as the optical properties), temperature and salinity.

2. *Material and methods*

Different phytoplankton species, yellow substance and particulate material all have different specific absorption and scattering spectra, which can be observed. Equation (1) shows the way in which the beam attenuation coefficient is the sum of the effects of the different optically active substances. Because of the additive way in which the optically active substances work together, the effects of a change in phytoplankton species, or a change in the concentration of an optically active substance can be seen in the attenuation spectrum (*Dekker*, 1993).

$$c(\lambda) = c_w(\lambda) + C_{ph}c^*_{ph}(\lambda) + C_{ys}c^*_{ys}(\lambda) + C_p c^*_p(\lambda) \quad (1)$$

In equation (1), c is the total beam attenuation coefficient, c_w is the beam attenuation of water, C_{ph}, C_{ys} and C_p are the concentrations of phytoplankton pigments, yellow substance and suspended particulate material, c^*_{ph}, c^*_{ys} and c^*_p are the specific attenuation coefficients of phytoplankton, yellow substance and suspended particulate material and λ denotes wavelength.

In order to characterise the optical properties of seawater, a dimensionless parameter, ω_0, which is called the scattering-attenuation ratio, is defined as:

$$\omega_0 = \frac{b}{c} = \frac{b}{b+a} \tag{2}$$

Here *b* is the beam scattering coefficient, *c* is the beam attenuation coefficient and *a* is the beam absorption coefficient. If the absorption is zero, the scattering-attenuation ratio is equal to 1, but in an environment in which the scattering is small, the ratio approaches zero (*Dera*, 1992). In surface waters the attenuation coefficient is dominated by the scattering coefficient making the attenuation coefficient less sensitive to the contribution of phytoplankton (*Roesler and Zaneveld*, 1994).

The optical properties of the water affect the biological production. It is also true that the production affects the optical properties. For example, the optical properties determine at which depths production is possible, but production causes an increase in cells and substances originating from cells, causes larger attenuation coefficients.

It is possible to give an estimate of the photic depth ($z_{0,01}$), which is the depth at which the light level has reduced to 1% of its value at the surface, from the beam attenuation and absorption coefficients. Kirk's formula (*Kirk*, 1994):

$$K_d = \frac{1}{\mu_0}\sqrt{a^2 + (0.425\mu_0 + 0.190)ab} \tag{3}$$

where μ_0 is the cosine of the angle of refracted photons just underneath the surface of the water and K_d is the diffuse attenuation coefficient, used together with Beer's law for the exponential decay of radiation (*Apel*, 1987; *Bukata et al.*, 1995):

$$E(z) = E_0 e^{-K_d z} \tag{4}$$

where *z* is depth, gives an estimate of the maximum of the photic depth when $\mu_0 = 1$ (cosine 0°):

$$\Rightarrow z_{0.01} = \frac{4.605}{\sqrt{a_{PAR}^2 + 0.235 a_{PAR} b_{PAR}}} \tag{5}$$

The values for *a*, *b* and K_d must be averaged for the whole of the PAR wavelength band. PAR (Photosynthetically Active Radiation) ranges from 400nm to 700nm.

A flow-through system, shown in Figure 1, was developed and set up for this study. Water was pumped in from a fixed depth of 1.5m. Measurements of temperature and conductivity were made using a conductivity cell and thermistor by Aanderaa Instruments installed in an air-removing chamber, and a parallel system, which was a Chelsea Instruments CTD placed in a small volume container. The use of the parallel system made the comparison between these two separate systems possible.

Optical properties were recorded with an AC-9 attenuation and absorption meter manufactured by WET Labs Inc which measures at nine wavelengths: 412, 440, 488, 510, 532, 555, 650, 676 and 715nm. For this reason, the integration over the PAR region was made from 412nm to 715nm. A bubble removing chamber was needed before the optical sensor because it is very susceptible to errors caused by air bubbles. Some buffering of the inflowing water always results from using a bubble removing chamber, but this has only a small effect on the results, because the volume of the chamber (~1l) compared to the capacity of the pump (~15lmin^{-1}) was relatively small.

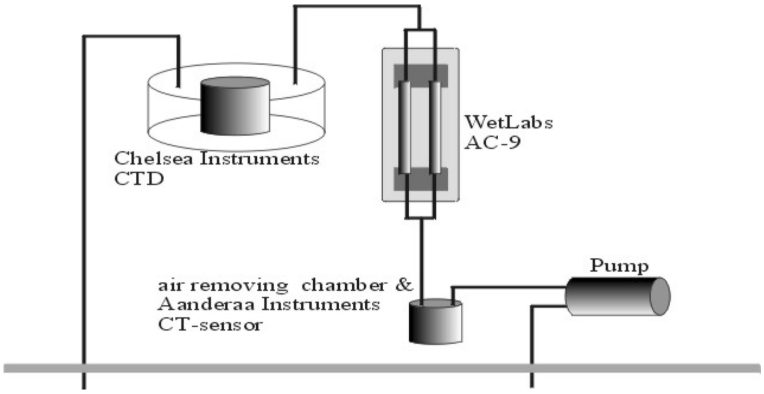


Fig. 1. Measurement setup in the r/v Saduria.

The biggest errors were caused by the research vessel, the propeller currents and the hull of the vessel which develops lots of small bubbles that easily penetrate the bubble removing chamber, and cause an increase in the observed absorption and scattering values. This demands that the velocity of the vessel be kept relatively low (~5knots), which in the estuary areas of small rivers does not have a strong influence (the area can be covered in a few hours), but in larger rivers it means that the measured values are not necessarily synoptic.

Position information was recorded with a NavalTracks DGPS (Differential Global Positioning System). The system collected a correction signal that gave an accuracy of 10m.

The CT-data was ASCII-modified and re-sampled, and then by using a Matlab-program the data was calibrated. In this process the test report from Chelsea Instruments was used (*Chelsea Instruments*, 1997). The optical data was corrected for temperature and scattering effects (*WET Labs Inc*., 1995), and the pure water values were subtracted. In the calculation of the photic depth the pure water values were included. Afterwards the CTD and optical data were re-sampled to match the time scale of the CT-data.

An enclosed bay was selected as the study area for this work so that the freshwater input into the sea would be relatively easy to handle. Also the location of the bay was suitable for finding a large salinity gradient, because the central parts of the Gulf of Finland are only 50km away from the river mouth. The track of the vessel is shown in Figure 2.

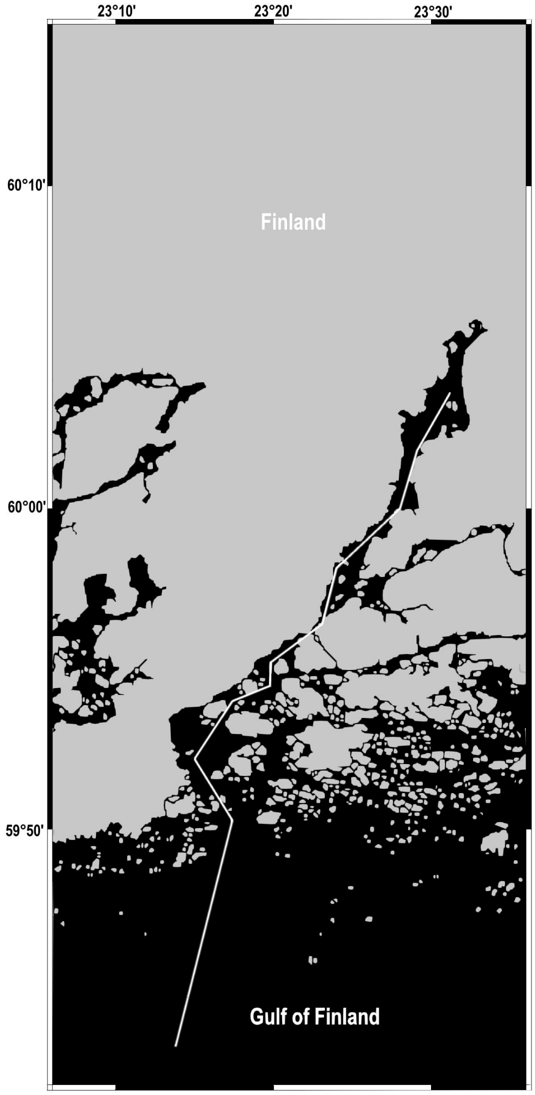


Fig. 2. Map of the study area.

3. Results

Temperature, salinity, and attenuation, absorption and scattering coefficients at nine wavelengths, are plotted as a function of distance in Figure 3, the photic depth is plotted in Figure 4 and additional spectra of attenuation, absorption and scattering coefficients are plotted from eight points in Figure 5. The spectra have been evenly selected along the section from open sea to the end of bay. Spectra of the scattering-attenuation ratio are plotted in Figure 6. Optical parameters are plotted without water absorption values.

Fig. 3. Attenuation-, absorption- and scattering-coefficients of nine wavelengths vs. temperature and salinity values. Values are plotted as a function of distance starting from the central part of the Gulf of Finland and ending close to the river mouth at the Pohja-bay.

Fig. 4. Photic depth variation along the track from the opean sea to the end of the bay.

The attenuation spectra show a clear increase going from the open sea to the end of the bay (see the map in Fig. 2). Values of the measured optical properties show a strong change at the zone where the values of salinity and temperature have the strongest change. The salinity drops from 6 to 1.7 and the temperature drops from 13°C to 10°C in a distance of less than 3km. The spectral shape changes and at the same time the attenuation coefficient rises from $2m^{-1}$ up to $11m^{-1}$. A similar effect can be seen in the scattering coefficient values. The scattering coefficient values rise from $1.7m^{-1}$ to $8m^{-1}$. Attenuation, absorption and scattering coefficients show an increase in shorter wavelengths. A second, but slightly smaller, front can be seen after a few kilometres.

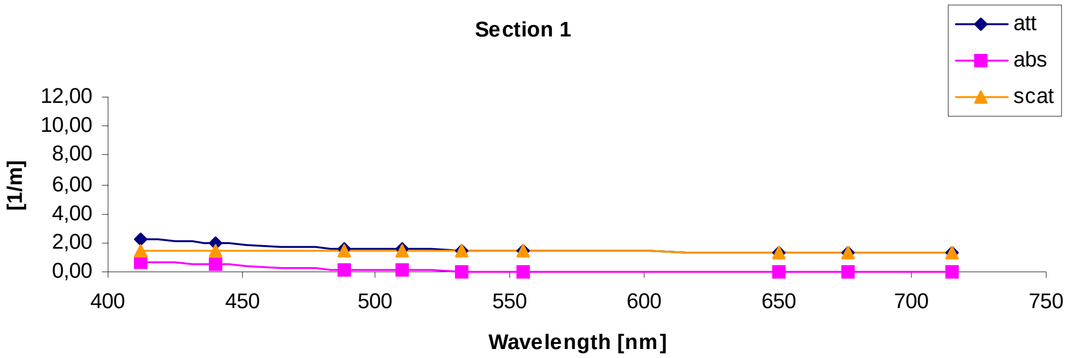
The photic depth, shown in Figure 4, diminishes from 8m close to 2.5m while going from the open sea to the end of the bay. In the shorter wavelengths the absorption is the dominant factor in the attenuation and it causes the largest differences to the shape of the scattering-attenuation spectra, but even then, scattering does exist.

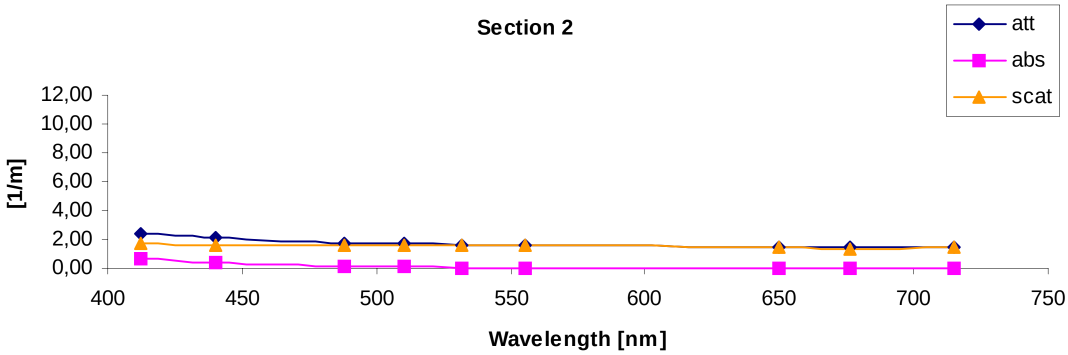
4. Discussion

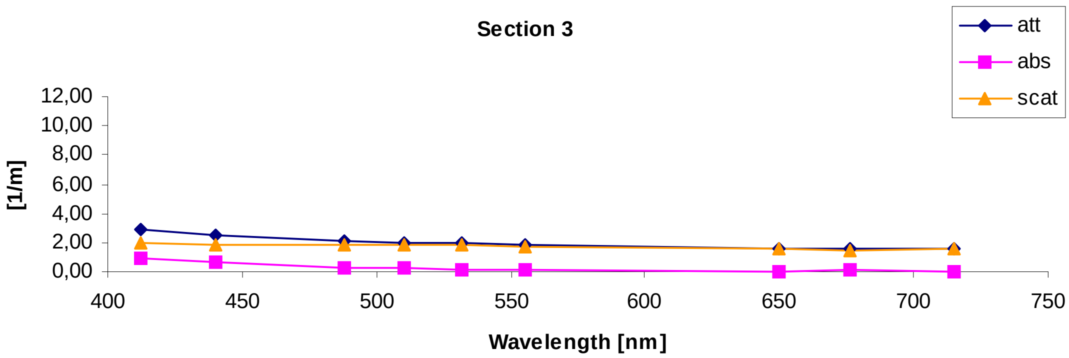
Freshwater is usually optically more active than coastal sea water. The main reason for this is the suspended and dissolved matter that river water carries into the sea. Ditches and underdrains increase the sediment and nutrient loading of the rivers from fields. This explains observations of increased absorption that has its source in this emergent nutrient content (*Spinrad et al.*, 1994). Increased nutrient content causes an increased growth of phytoplankton. Turbidity of water is partly related to the amount of phytoplankton in it.

Phytoplankton in the water causes attenuation because it absorbs strongly with absorption maxima at 440nm and 675nm and minimal absorption at 715nm (*Bukata et al.*, 1995). The absorption maximum at 675nm can be seen in the absorption coefficient spectra from sections six, seven and eight in Figure 5. The absorption maximum at 440nm has been masked by yellow substance absorption.

Besides phytoplankton, inorganic and organic particulate matter in suspension absorb weakly in the blue range, and scatter strongly at all visible wavelengths. This explains the increased values of scattering in sections six, seven and eight (Fig. 5).







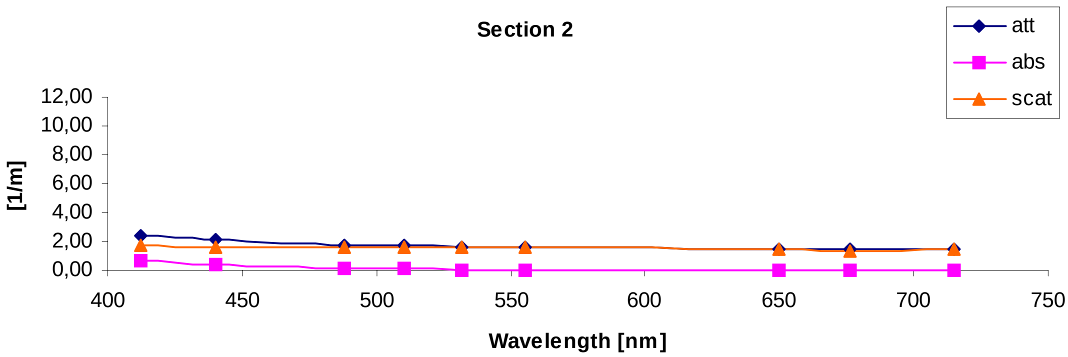
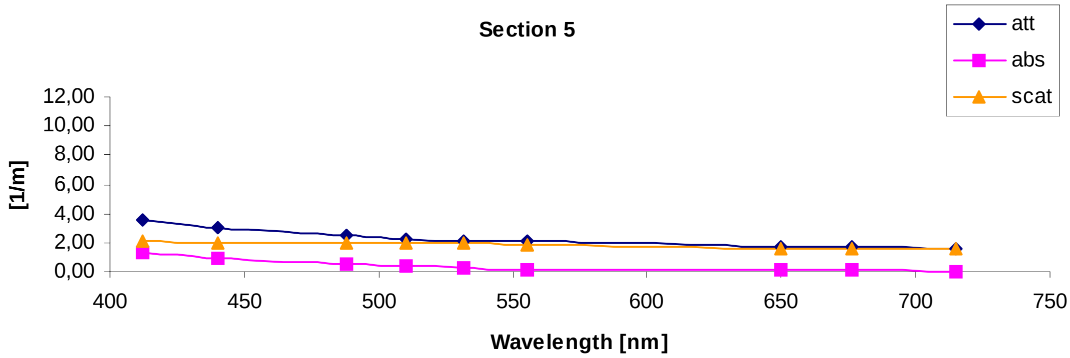
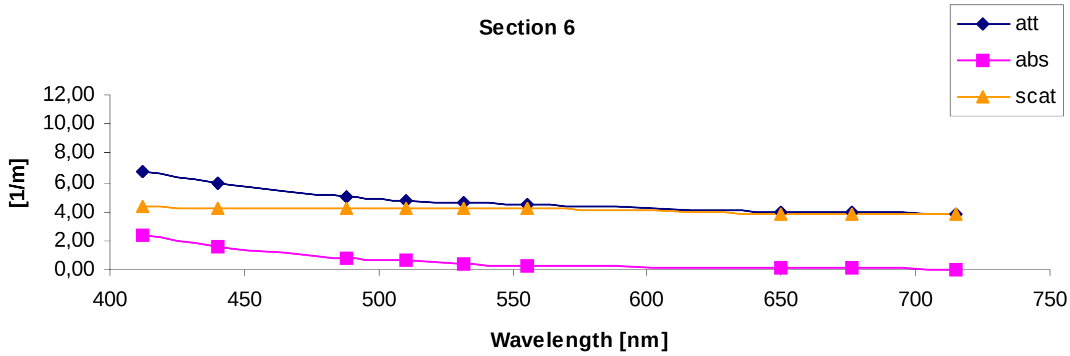
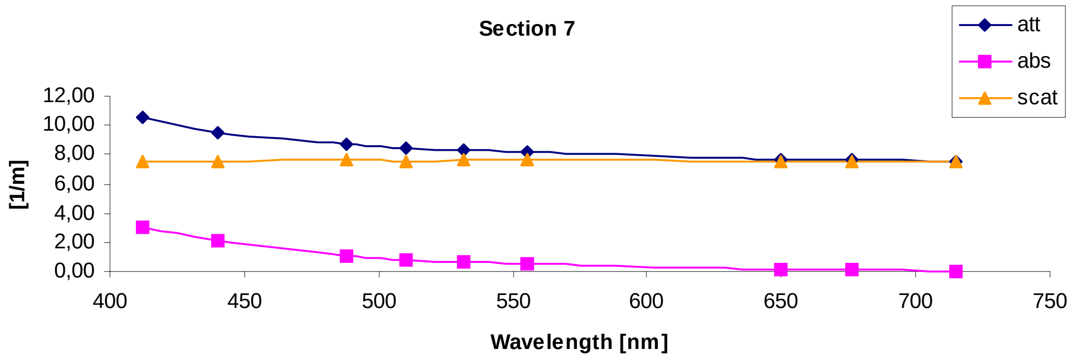


Fig. 5. Attenuation, absorption and scattering spectra in evenly selected points along the track. First point is located to the central part of the Gulf of Finland and point eight is in the end of the bay. (Continues on next page.)







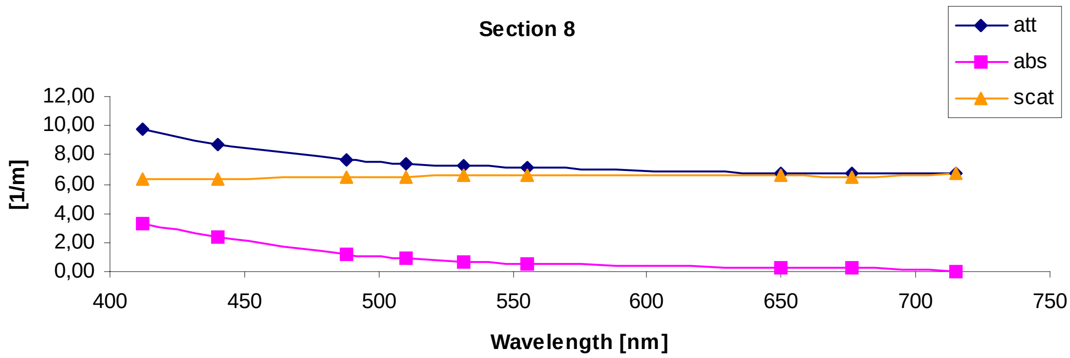


Fig. 5. (Continuation from previous page.)

Dissolved organic compounds or yellow substances, which originate in the decomposition of plant tissue when organic material is broken into carbon dioxide, inorganic compounds of nitrogen, sulphur and phosphorus, and complex humic substances. These metabolic products give some inland waters their distinctive yellow-brown colouration. Yellow substances absorbs strongly at the short wavelength (blue) end of the visible spectrum and scatters well in the yellow-red. This effect strengthens the attenuation of blue light and causes the typical bending of spectra at short wavelengths.

The measured values from the open sea to the river end of the bay show an increasing trend in the absorption at 440nm. This would seem to indicate that the yellow substance content is larger in the river water compared with sea water. Smaller absorption values in the open sea in the blue wavelengths can be partly explained by this. Another reason may be the mixing caused by waves and turbulence in the open sea. Freshwater input is small, so mixing occurs after only a few hundred metres. The velocity of coastal currents in the northen Gulf of Finland can be up to $0.5ms^{-1}$ (*Myrberg*, 1998), so the original smaller density water is blended into the very much larger volume of salty Baltic water effectively. Figure 5. and Figure 6. show much stronger wavelength dependence for absorption compared to scattering. One possible explanation for this is an increased yellow substance concentration.

Fig. 6. Spectra of the scattering-attenuation ratio in evenly selected points along the track. Point one represents open sea values and point eight values from the end of the bay.

It must be noted that the used flow through system provides information only from one fixed depth. The layer visible to satellite sensors may contain a nonuniform profile of optically active substances, which means that the remote sensing surface layer actually presents a weighted integral of the depth distribution (*Sathyendranath and Platt*, 1989).

The photic depth (Fig. 4) can only be interpreted as a theoretical quantity in this case, because no radiation measurements were made and the absorption and attenuation coefficients were measured only in the surface layer and assumed not to vary with depth. The photic depth decreases with increased absorption and scattering as expected. It is a maximum value for situations when the sun angle is zero (which never occur in Finland).

5. Conclusions

The flow through system seems to be an effective way of distinguishing frontal systems, if a change in the properties water occurs simultaneously. Temperature and salinity changes are easy to measure, but they can provide only a little information about the studied water masses. Optical parameters are a much more informative way. The spectral behaviour and the characteristic features tell us much about the origin of the water and its composition. Also, the optical parameters have a wider interface between remote sensing and *in situ* measurements, especially in biology.

The flow-through method does not make discrete measurements redundant, it makes them more important. Only using discrete measurements of vertical radiation profiles and water quality parameters, e.g. concentrations of optically active substances, can good interpretations of the flow-through data be made. It then becomes important to optimize the number of discrete stations and the amount of time spent on them, so as to keep the flow through measurements as synoptic as possible.

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