Inherent Optical Properties of the NW Baltic Sea in Comparison to other Seas and Oceans

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SCOPE AND AIM OF STUDY

- Retrieval of geophysical products from remote sensing reflectance over coastal waters with high Coloured Dissolved Organic matter (CDOM) absorption remains a challenge
- Models and processors are generally parameterised with Specific Inherent Optical Properties (SIOPs), i.e. specific absorption and scattering properties that are different in the Baltic Sea compared to global parameterization
- The aim of this study is to improve sIOP characterization of the Baltic Sea for improved remote sensing inversion models for coastal waters with high CDOM.

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The remote sensing reflectance (R_{RS})

- The remote sensing reflectance (R_{RS}) can be defined as the ratio of upwelling radiance (L_u) and down-welling irradiance (E_d).

$$R_{RS} = L_u \bullet E_d^{-1}$$

- The irradiance reflectance is related to the ratio of backscattering to absorption coefficient in the following way:

$$R \sim f \bullet b_b \, (a + b_b)^{-1}$$

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Absorption and scattering

- The **Inherent Optical Properties (IOPs)** of natural waters are absorption, scattering and the volume scattering function
- The total absorption coefficient (a_{tot}) of light of wavelength λ in natural seawater is the sum of the absorption coefficient of water itself (a_w) and the absorption coefficients of all optical in-water constituents, i.e. that of coloured dissolved organic matter (*CDOM*), phytoplankton pigments (*ph*) and non-algal particles (*NAP*).

$$a_{tot}(\lambda) = a_{w}(\lambda) + a_{CDOM}(\lambda) + a_{ph}(\lambda) + a_{NAP}(\lambda)$$

- The total scattering coefficient (b_{tot}) of light of wavelength λ in natural seawater is the sum of the scattering coefficient of water itself (b_w) and the scattering coefficient of suspended organic and inorganic particles (b_p).

$$b_{tot}(\lambda) = b_{w}(\lambda) + b_{p}(\lambda)$$

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The volume scattering function

- Angular scattering is described by the volume scattering function [VSF = $\beta(\lambda, \theta, \varphi, \theta', \varphi')$], which is the ratio between the radiance (L) of wavelength λ scattered in the direction of the scattering angles (θ', φ') from radiation flux in the propagation direction (θ, φ) and the irradiance (E) of wavelength λ that illuminates a volume of water (dV).

$$\beta (\lambda, \theta, \varphi, \theta', \varphi') = dL (\lambda, \theta, \varphi, \theta', \varphi') \times (dE (\lambda) * dV)^{-1}$$

- The VSF is usually plotted as phase function. i.e. against the scattering angle from 0 to 180 °

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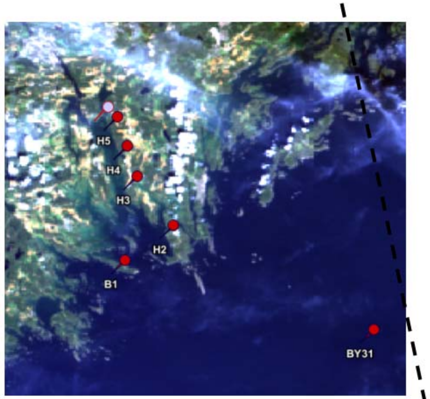
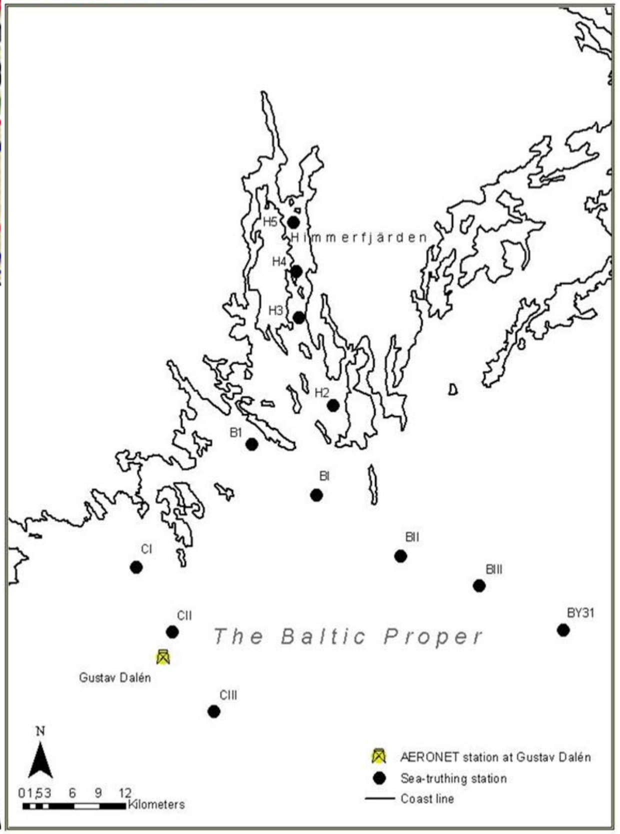


MERIS FR image (300 m)



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FACTS ABOUT THE BALTIC SEA

- Semi-enclosed sea with limited water exchange with the North Sea (turn-over time 30 - 50 years).
- High terrestrial freshwater input and intrusion of saline bottom waters from the North Sea leads to a strong halocline (at 40-80 m)
- Frequent coastal upwelling (10-20 km off coast) brings nutrient-rich bottom waters to the surface mixed layer, stimulating primary production
- Tidal action in the Baltic Sea is almost negligible, hence resuspension of sediments is mostly caused by wind
- The shores of the NW Baltic Sea are rocky, hence concentrations of Suspended Particulate Matter (SPM) are low
- Southern Baltic: sandy beaches lead to higher coastal SPM concentrations

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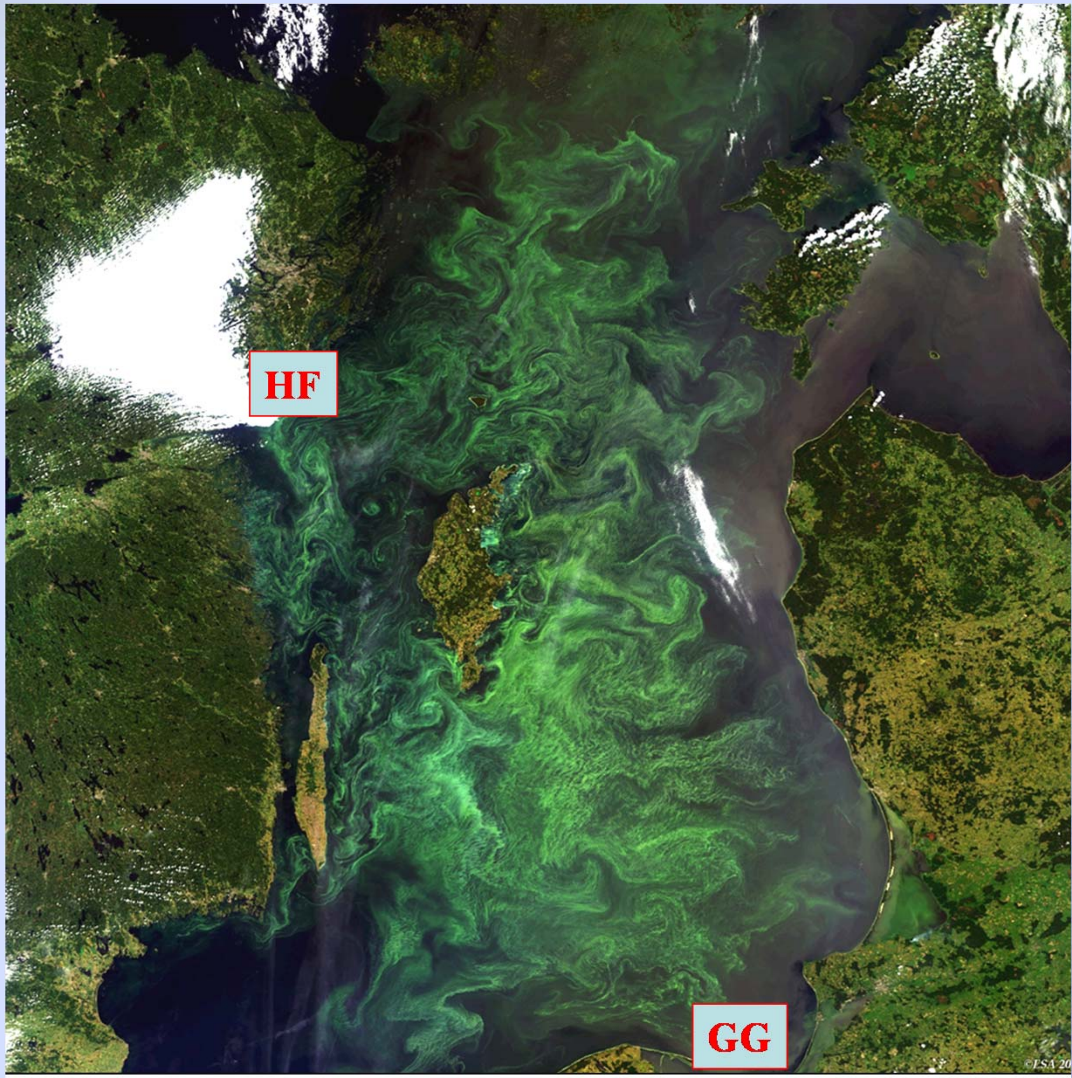

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Optical variables measured in summer	*Chlorophyll-a (Chl-a)*	*Suspended Particulate Matter (SPM)*	*Coloured Dissolved Organic Matter (CDOM)*	*Secchi Depth*
unit	***µg l^{-1}***	***g m^{-3}***	***m^{-1}***	***m***
Himmerfjärden (HF)	0.6-15	0.5-4.8	0.3-0.7	0.8-8.5
Gulf of Gdansk (GG)*	0.1-100	0.6-13	0.4-4	0.5-7.0

Range of optical variables in Himmerfjärden (HF) (NW Baltic Sea) compared to the Gulf of Gdansk (GG) (southern Baltic Sea)

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OPTICAL PROPERTIES

- Absorption by Coloured Dissolved Organic Matter (CDOM), i.e. yellow substances (YS), is optically dominant (Kowalczuk, 2006); optical classification of waters: case-2.Y
- In coastal areas: significant scatter by inorganic suspended particulate matter (Kratzer and Tett, 2009)
- Phytoplankton spring blooms dominated by diatoms and dinoflagellates
- In summer high standing stock of filamentous cyanobacteria in surface mixed layer; these cause high scatter because of gas vacuoles
- Seasonal stratification may develop due to low wind and high insolation; in stratified waters Chl-a concentrations can reach up to 100 µgl-1
- Large human impact – eutrophication is the main problem for Baltic Sea management

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APPROACH

- In this study the IOPs and sIOPs of the NW Baltic Sea were measured *in situ* (using a WetLabs AC9, a VSF3 meter and a spectrophotometer for CDOM and filter pad method).
- The data set (80 stations in total) was subsequently compared to the NASA NOMAD & European COLORS Reference Data Base (RDB) covering a wide range of optical provinces.
- The derived specific IOP relationships were also compared to those in MERIS reference model document (RMD).

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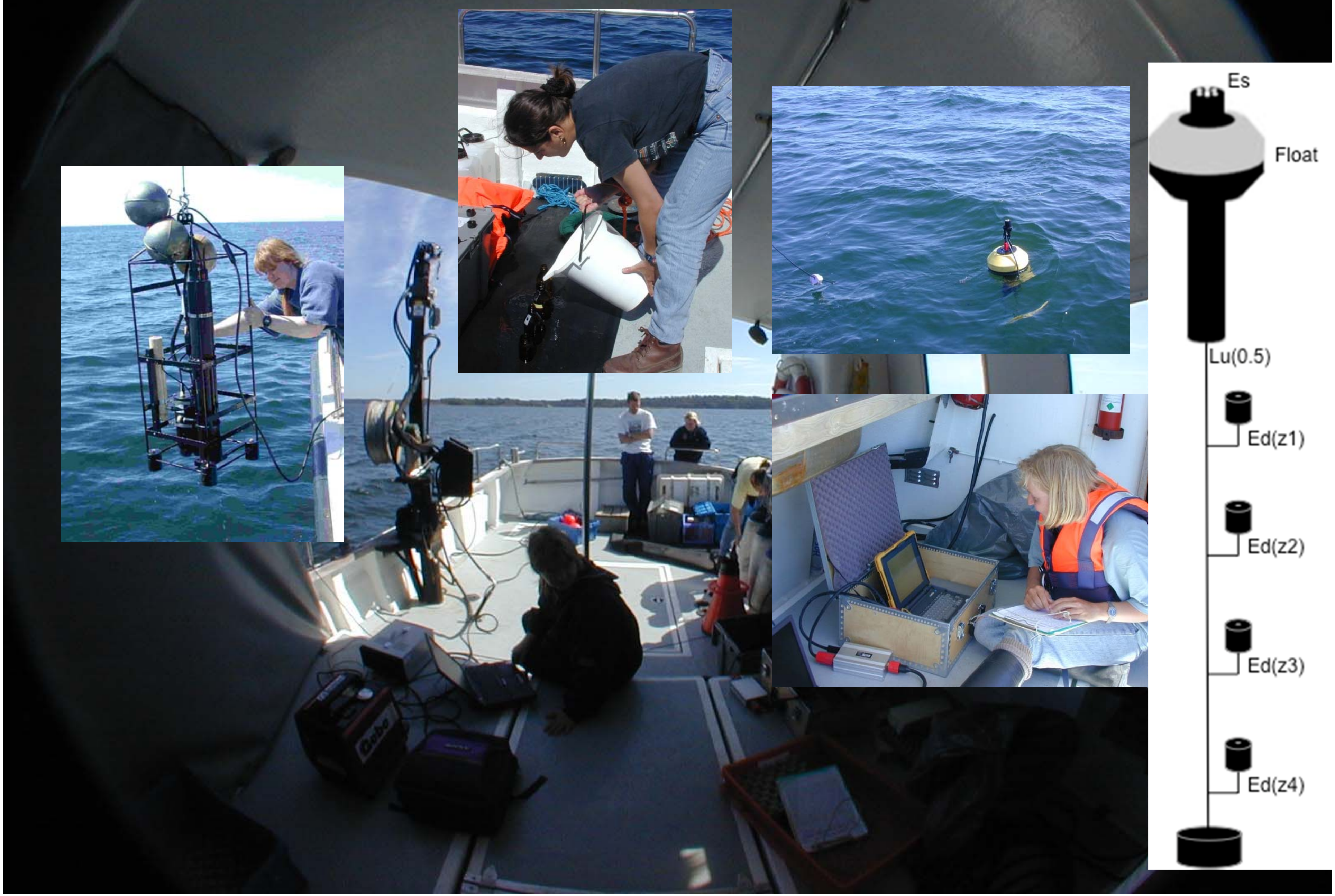
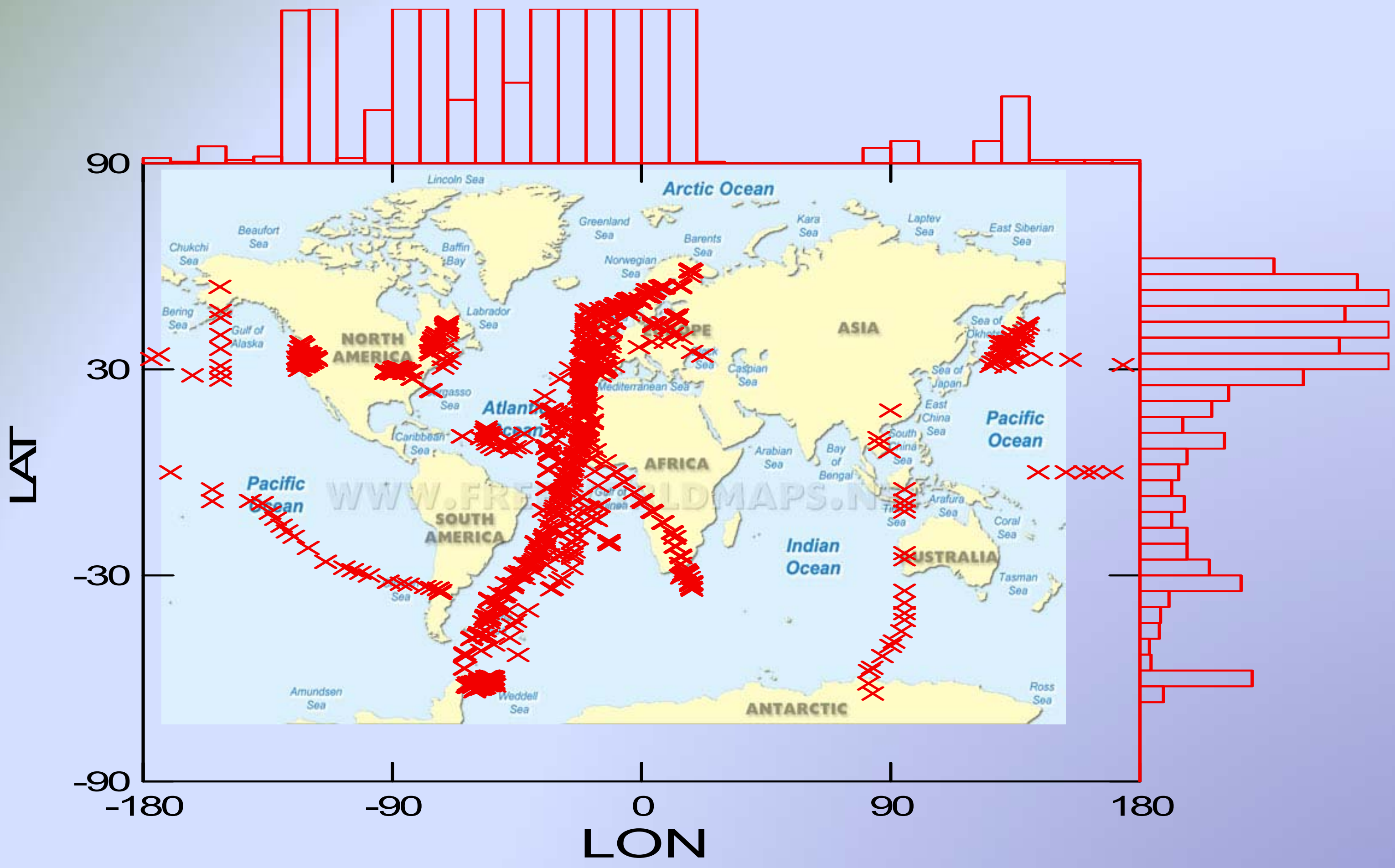
Optical measurements at sea

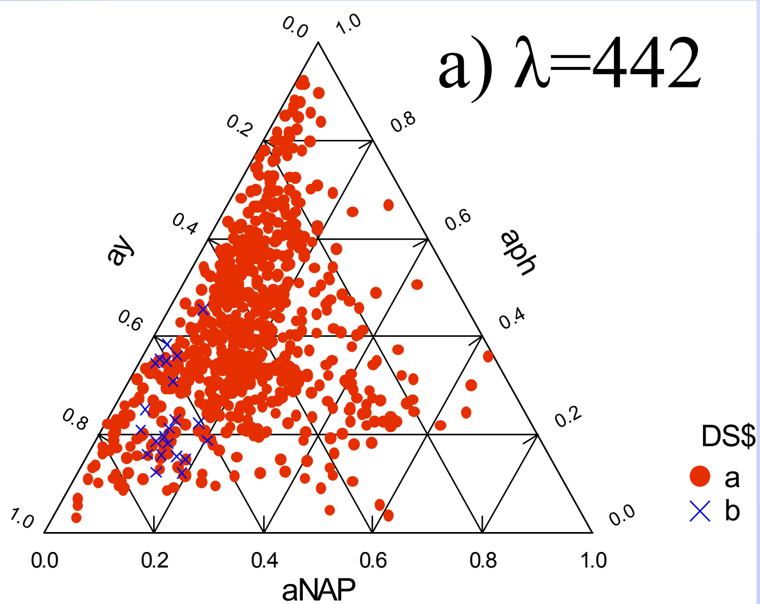


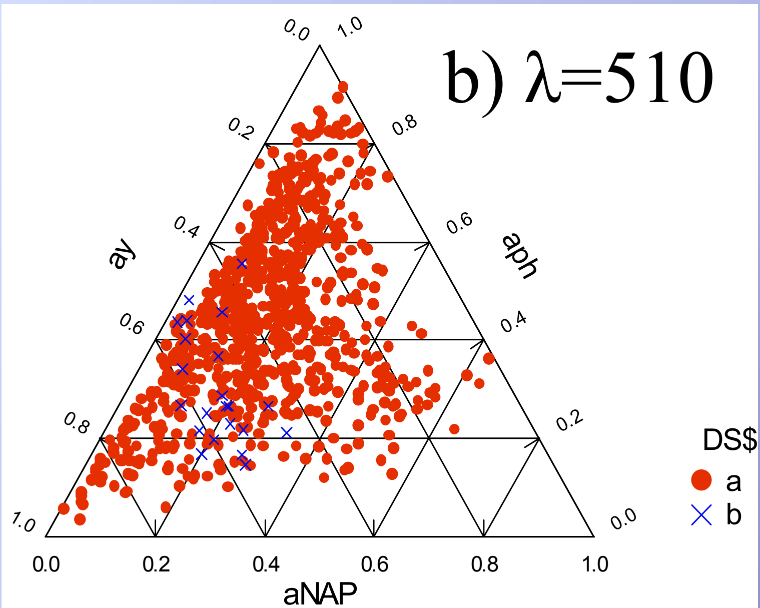


Geographic distribution of reference data base (RDB)

RESULTS: ternary plots (blue-green)

- Spectral ternary plots are presented for the NW Baltic Sea (blue crosses) in comparisons to the RDB (red dots)
- illustrating the relative dominance of CDOM absorption (a_y), compared to the absorption of phytoplankton (a_{ph}) and non-algal particles (a_{NAP}) in a) the blue (442 nm) and b) blue-green part of the spectrum.





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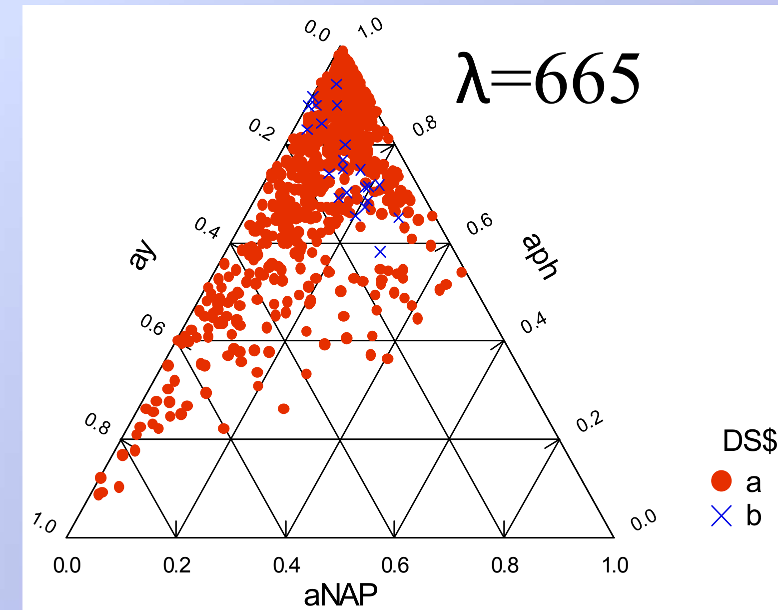
RESULTS: ternary plots (red)

- When the classification is instead applied in the red (665 nm) the distribution of Baltic Sea measurements coincided with those from optical case 1 waters.
- The ternary plots show that for Baltic waters the variations in $a_{ph}(442)$ are minor compared to those in $a_y(442)$, making it difficult to differentiate the chlorophyll-a absorption in the blue from CDOM absorption.



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RESULTS: *Chl-a*-specific absorption

- The chlorophyll-specific absorption, a_{ph}*(442) of samples dominated by filamentous cyanobacteria (filter-pad method) was compared to the RDB.
- The comparison showed that a_{ph}*(442) in the NW Baltic Sea does not differ significantly from the RDB (ANCOVA on log transformed data: p=0.114).

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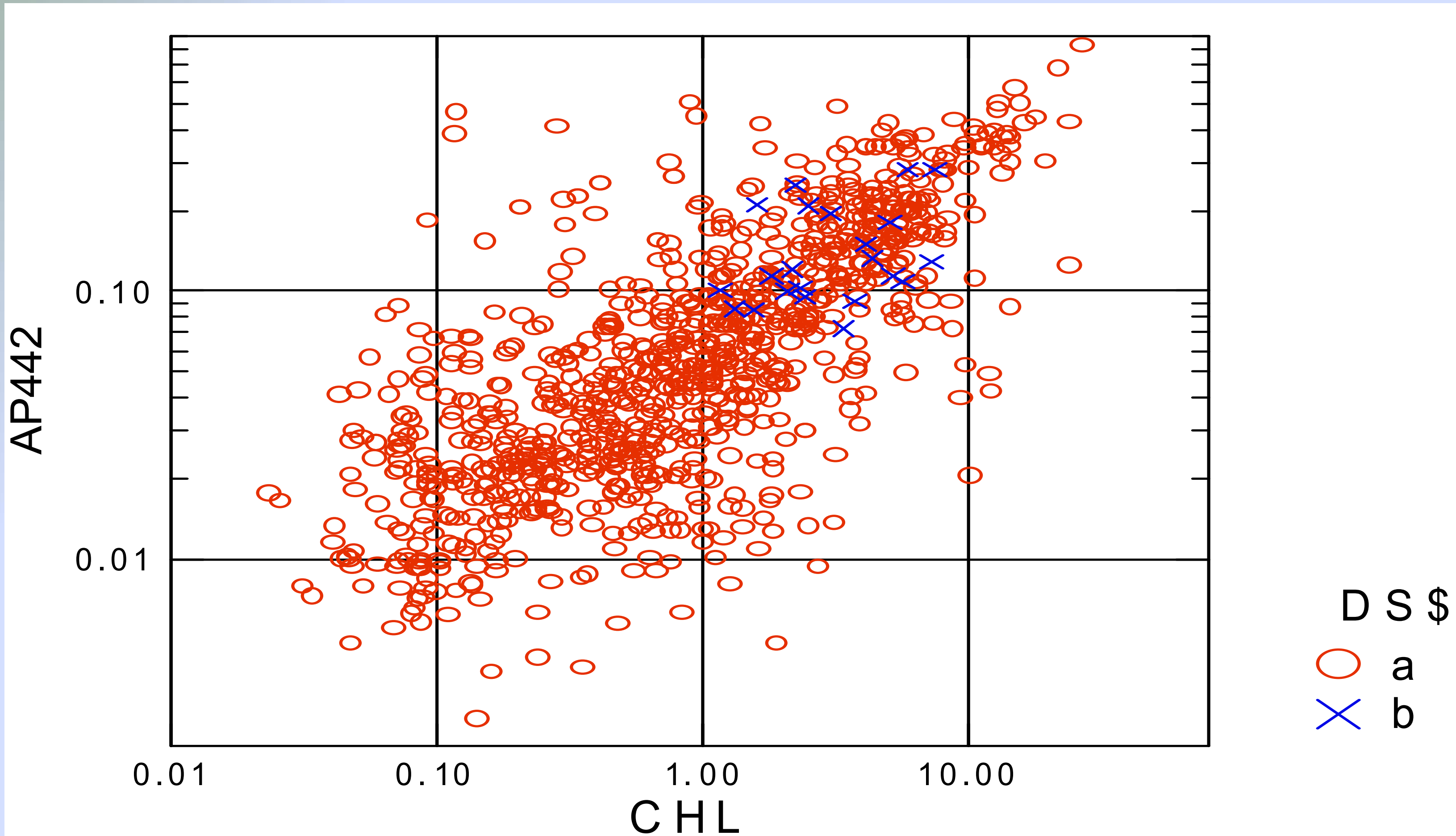

Chlorophyll-a specific absorption, a_{ph}*(442) for a: the RDB (red O) and b: Baltic Sea data set (blue x). The results of ANCOVA showed no significant difference between the two data sets.

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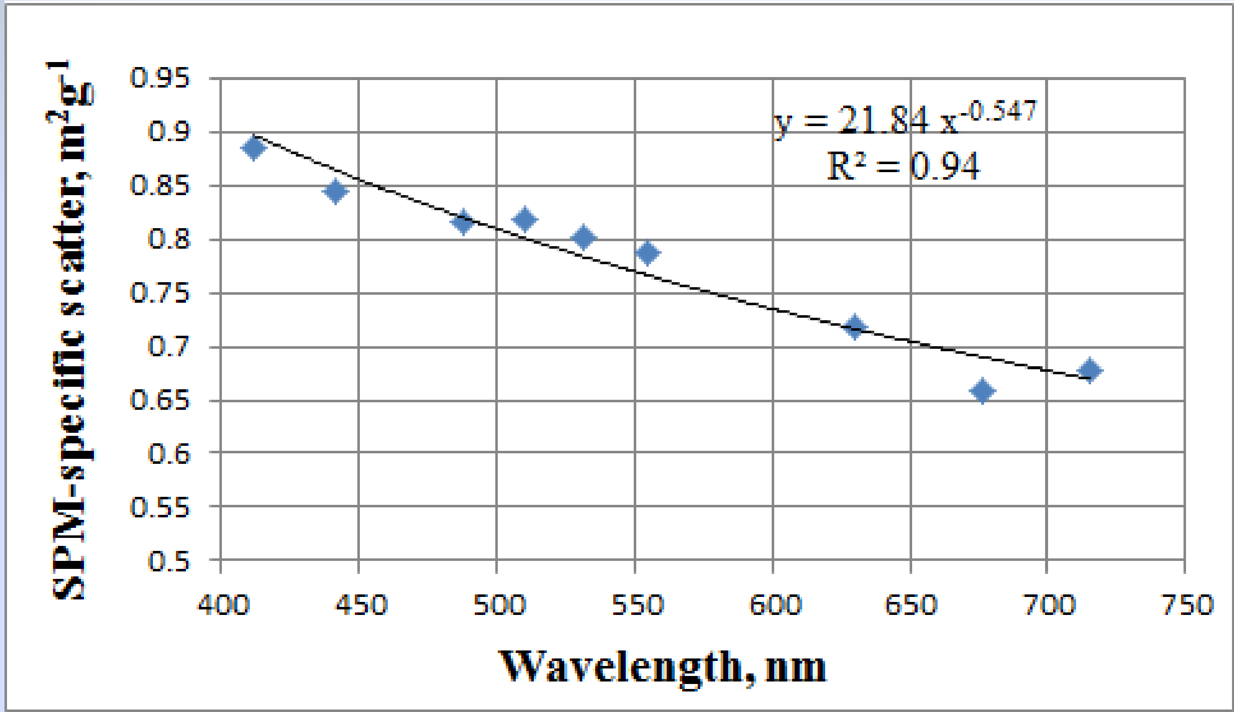
SPM-specific scatter, b_p*



The slope for particles for the Baltic Sea data set is higher (0.547± 0.188) than that assumed in the MERIS reference model (RM, which is 0.4).

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The Baltic Sea Phase Function

- The scattering was measured at angles (100°,125°,150°) by the Wetlabs VSF3 and normalised by b derived from the ac-9.
- These were fitted a Fournier-Forand marine phase function, with parameters: *n* –refractive index and μ – the derived Baltic Sea slope of the particle distribution.
- The backscatter ratio $\tilde{\boldsymbol{\beta}}$ (b_b/b) for the Baltic Sea was lower than Petzold phase function (0.0186) which is used in the MERIS RMD, but was similar for the Baltic Sea and the reference datasets, 0.0086 and 0.0094, respectively.

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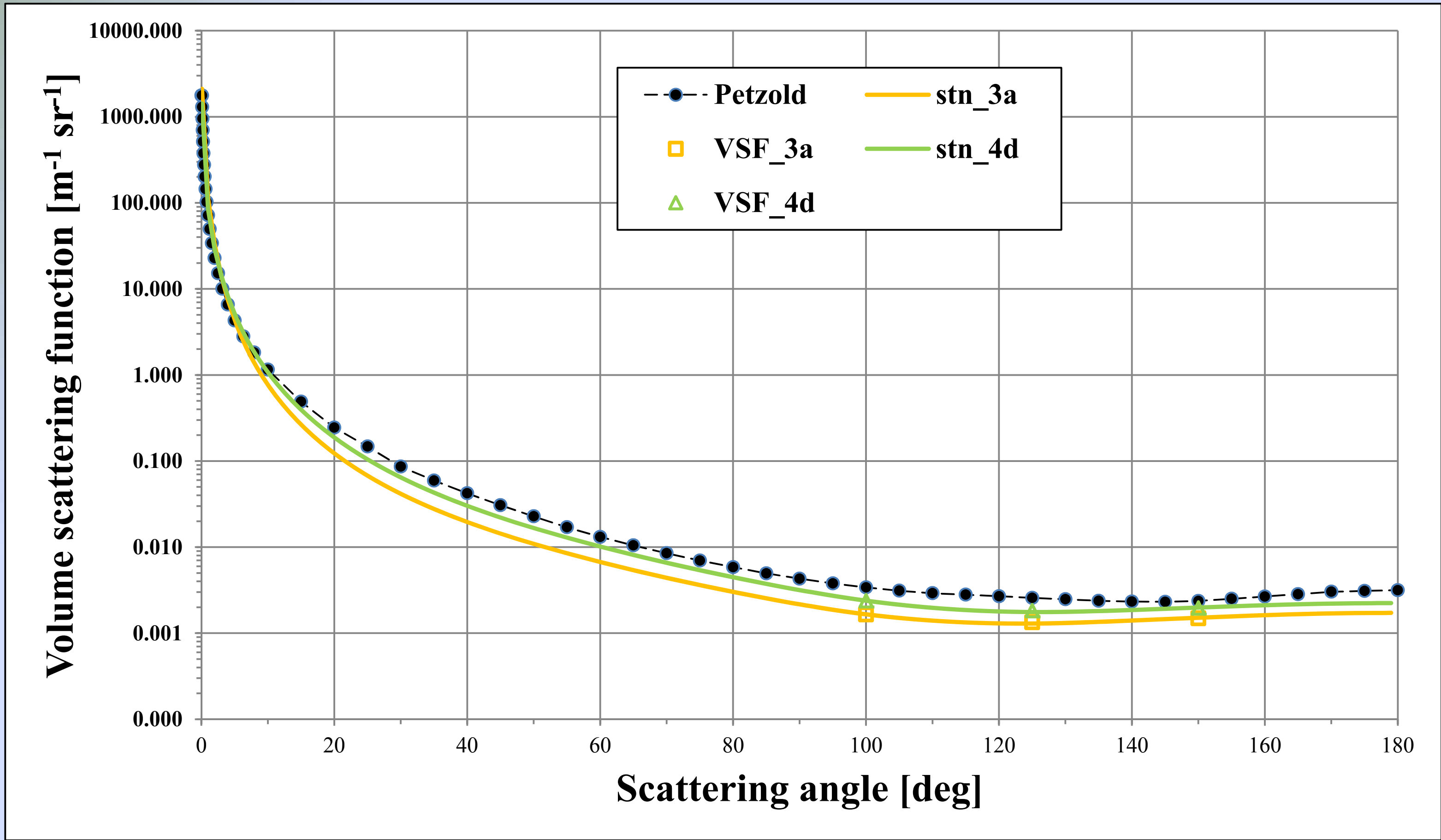

Phase functions from the Baltic Sea compared to the Petzold phase function; stations from Himmerfjärden (STN 3a) and the open Baltic Sea (STN 4d) solid markers are VSF3 measurements. Both examples differ from the Petzold phase function.

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RESULTS-SPM retrieval and CDOM slope

- The MERIS RMD derives TSM from the scatter at 442 nm. In the Baltic Sea the SPM specific scattering is higher: 1.016 ± 0.326 m^2g^{-1}) than the value assumed for the MERIS processor (0.578 m^2g^{-1}), i.e.*:[TSM]=b(442)/0.578.*
- The CDOM absorption slope for the Baltic Sea with a mean value of -0.018 (±0.002) was significantly higher than for other seas and oceans with -0.016 (±0.005), and the MERIS RMD with -0.0138 (±0.00284).

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CONCLUSIONS

- For the correct retrieval of CDOM absorption from MERIS data, the respective local processors should use a different CDOM slope for the Baltic Sea region, i.e. 0.018 (±0.002).
- We derived a new phase function for Baltic Sea waters from VSF3, and the backscatter ratio, $\tilde{\boldsymbol{\beta}}$ (b_b/b), is lower (0.0086+/-0.003) than in the MERIS RMD, which assumes the Petzold phase function (0.0186).
- a_{ph}*(442) in the NW Baltic Sea does not differ significantly from the reference database (ANCOVA on log transformed data). This implies that the retrieval of chlorophyll-a will not be improved by applying a local conversion factor.
- The ternary plots for a_{ph}*(665) compared to a_{ys}(670) and a_p*(670), however, indicate that the red/green ratio may be a viable alternative to improve the quantitative retrieval of chlorophyll-a from yellow substance dominated waters.

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