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Education & Training

UNIVERSITY OF STIRLING

Hydrological optics and hyperspectral remote sensing of lakes

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ADDRESSS training course, 19-28 August 2010, Balaton Limnological Research Institute, Hungary

My research interests

Environmental remote sensing

- Bio-optical and hyperspectral imaging of inland waters
- Hyperspectral vegetation classification and biodiversity assessment in peatlands and wetlands
- Remote sensing of vegetation biophysical parameters; carbon cycling in terrestrial ecosystems
- Detection and mapping of plant stress; climate-induced drought stress
- LiDAR remote sensing in fluvial geomorphology

Other

- Phytoplankton ecology and toxicology
- Water resource socio-economics

see also: www.sbes.stir.ac.uk/people/hunter

Outline

- Why lakes and why remote sensing?

- Basic theory of underwater optics

- Measuring and modelling the underwater light environment

- Remote sensing of in-water constituents and water column processes

- NERC ARSF / EUFAR project in Lake Balaton

Why lakes?

Key component of global biosphere; ecosystem services (biodiversity, biogeochemical cycling, food)

Sinks for terrestrially-derived materials and pollutants (sediments, nutrients, pesticides, toxins)

Sensitive to meteorological forcing (e.g., Livingstone & Padisak, 2007); sentinels of climate change?

Statutory monitoring requirements under EU directives

- Habitats Directive (92/43/EEC)
- Water Framework Directive (2000/60/EC)

Why remote sensing?

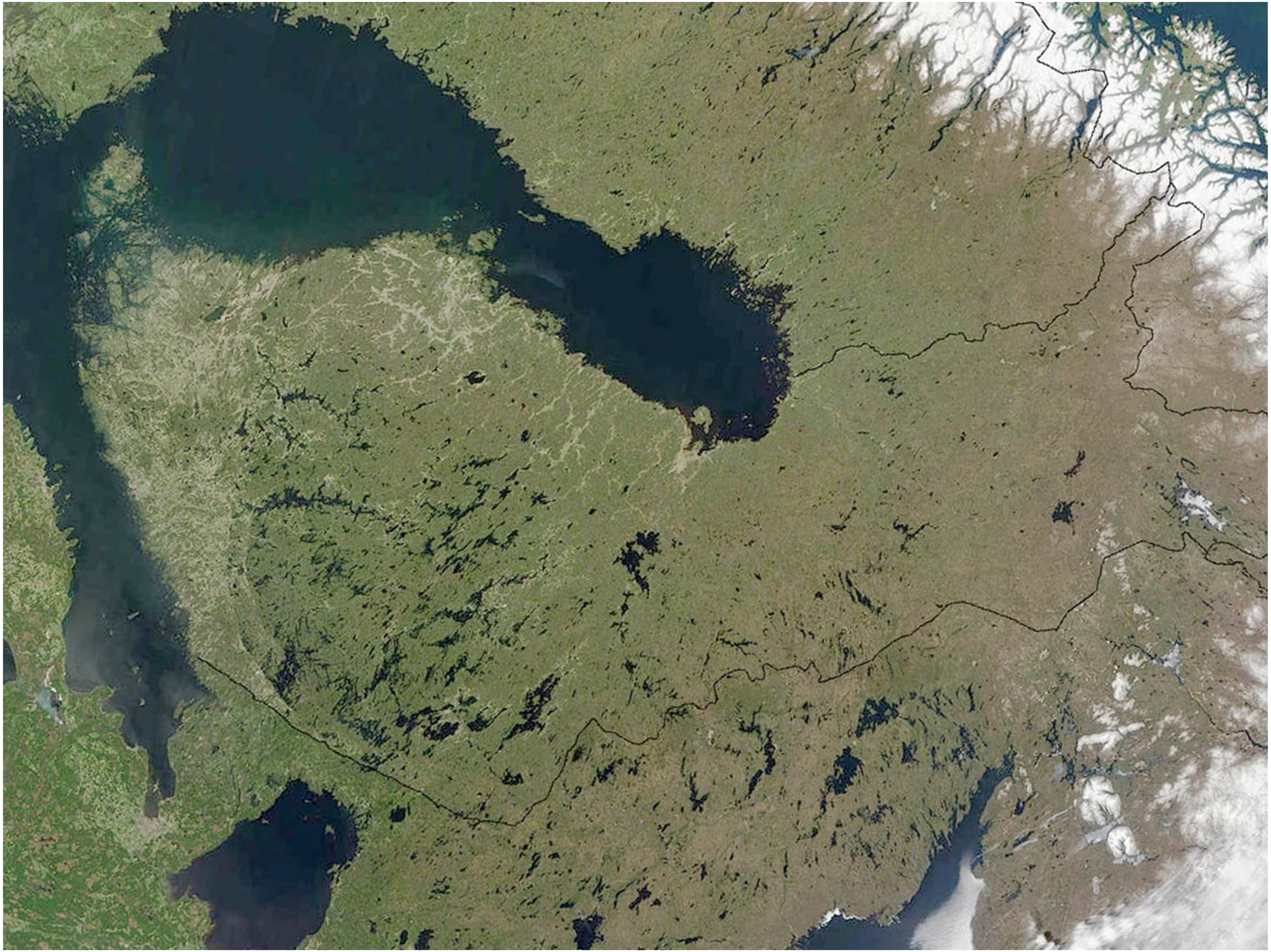
- numbers, densities and size distribution of lakes

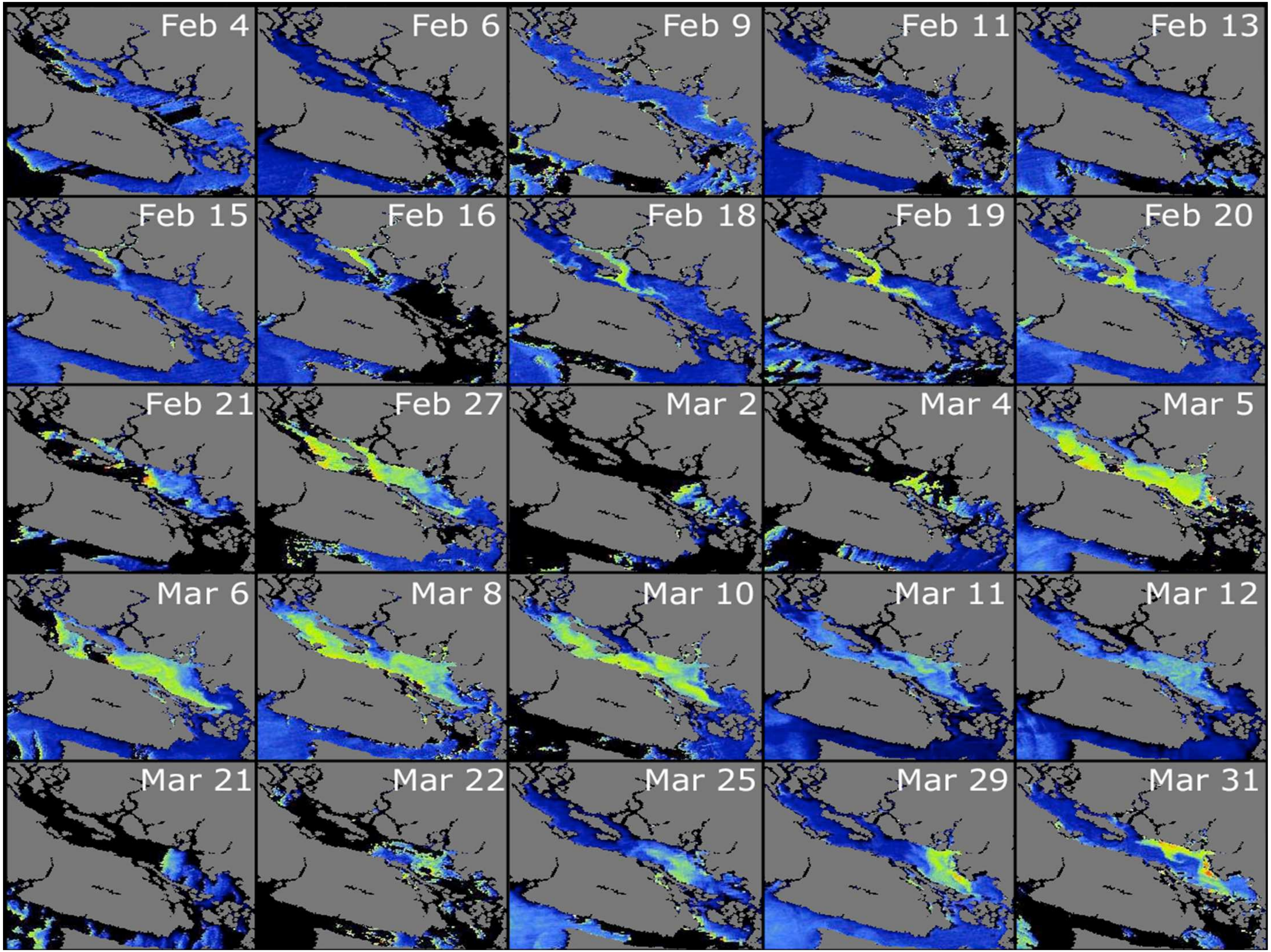
  e.g., Europe: $1.5 \times 10^6 > 1$ ha

  500 000 > 10 ha

- marked space-time variability; implications for representativeness of observations

- costs, lack of resources, inaccessibility





Feb 4
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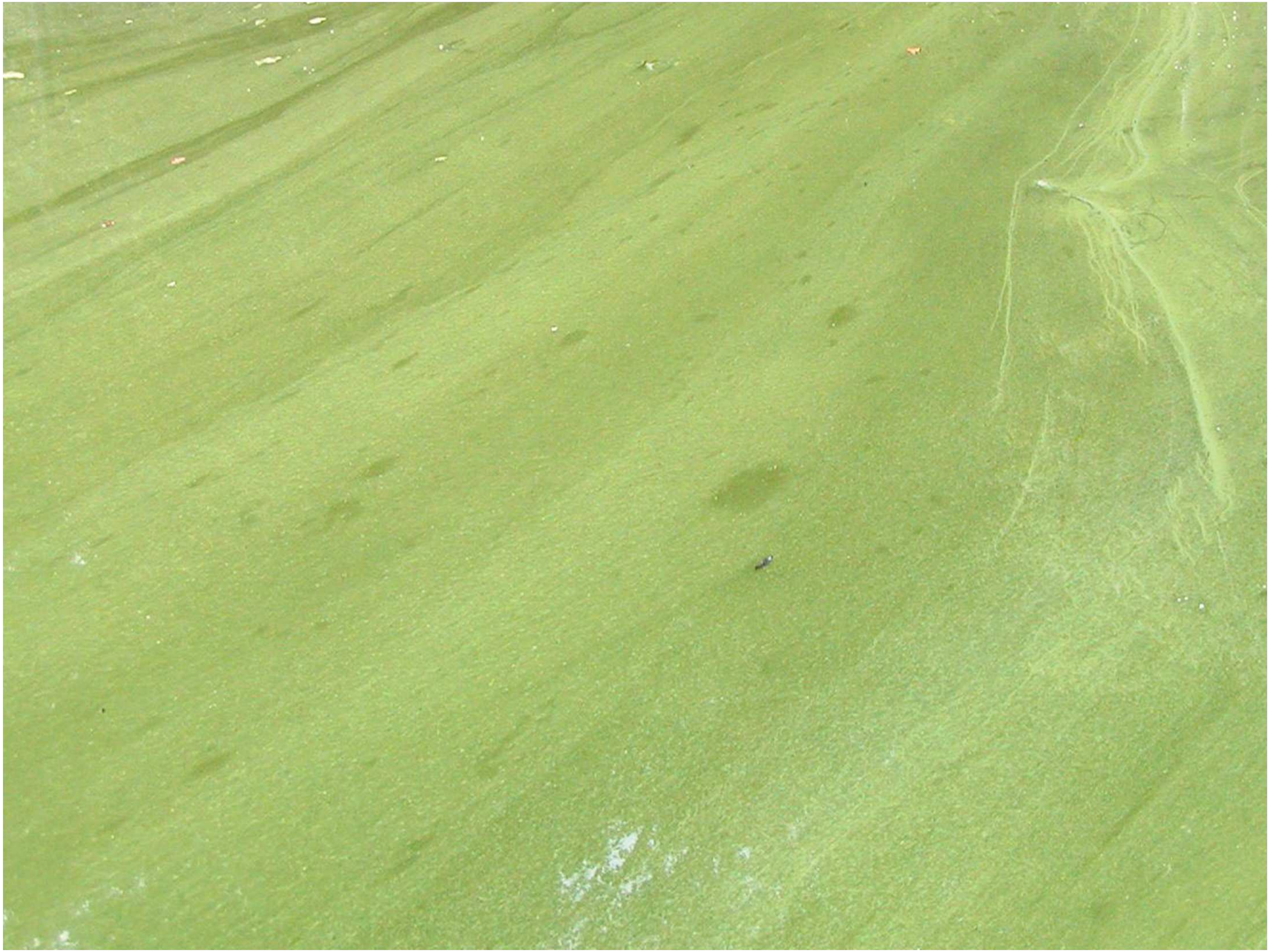
Mar 22
Mar 25
Mar 29
Mar 31

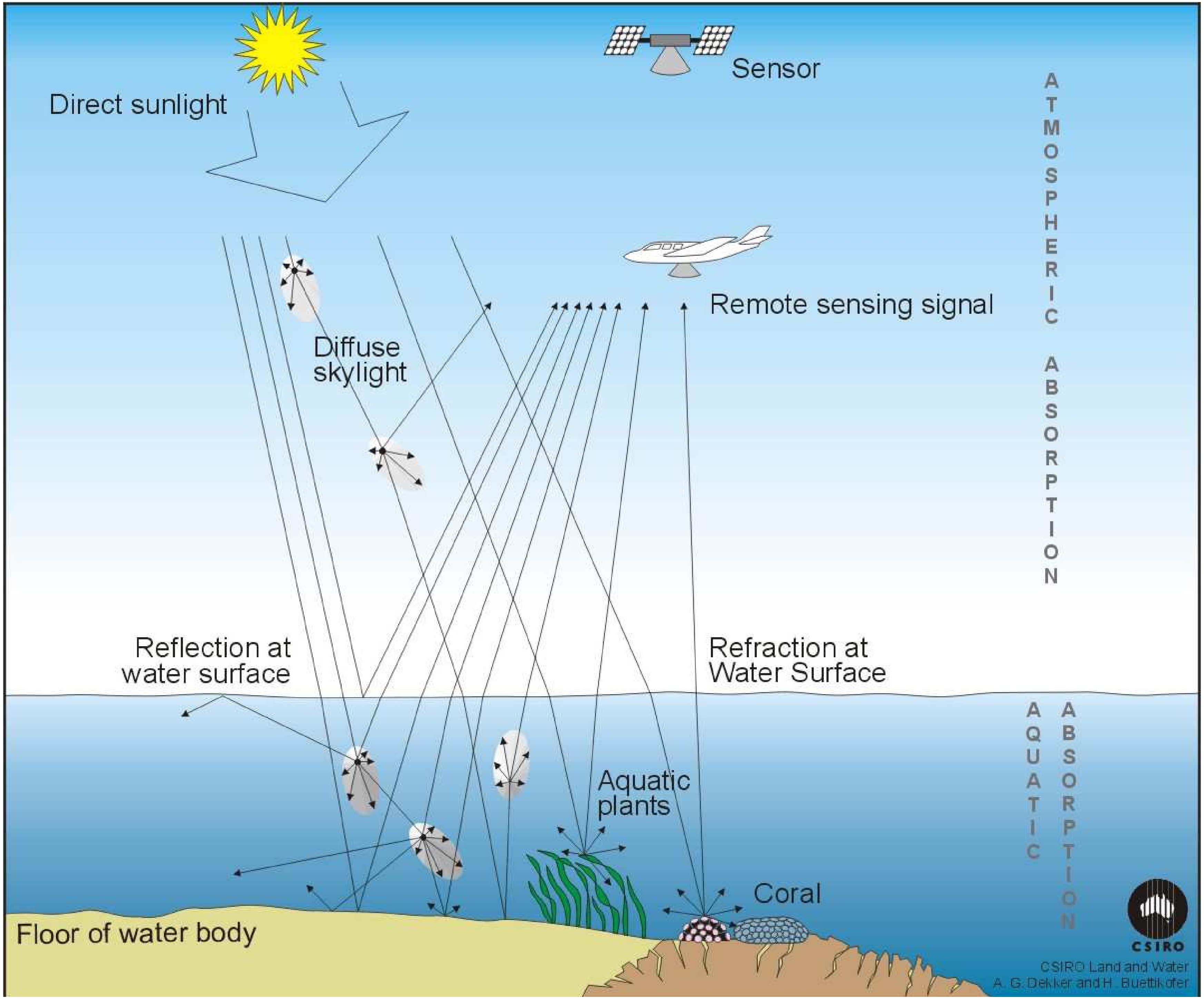
The science in a nutshell…

To develop algorithms (models) to relate the optical properties (colour) of water to its biogeochemical composition…

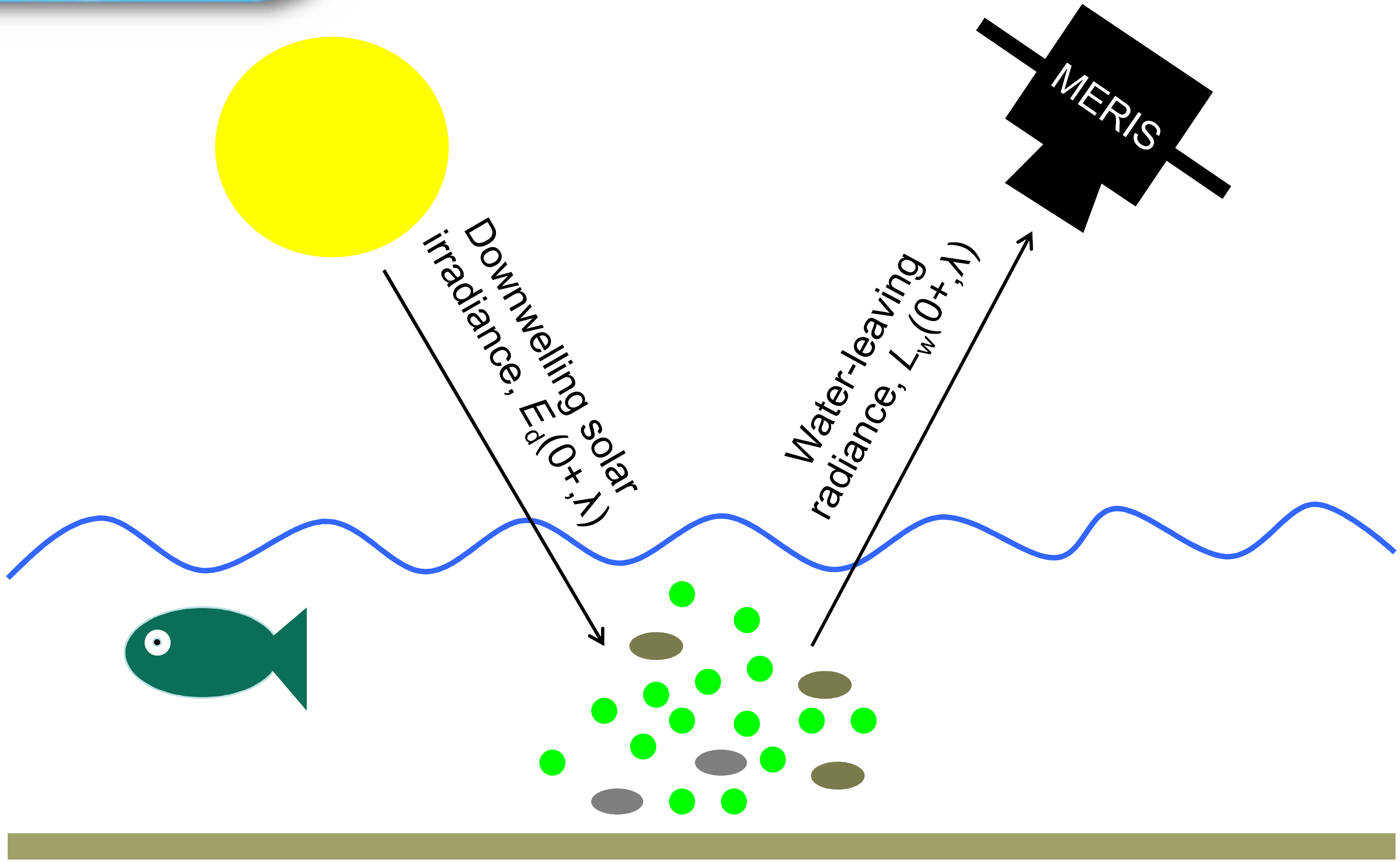
…and use this information to study changes in lake condition and function at high temporal resolution and at global scales

Basic theory: underwater optics




Direct sunlight
Sensor
ATMOSPHERIC ABSORPTION
Remote sensing signal
Diffuse skylight
Reflection at water surface
Refraction at Water Surface
AQUATIC ABSORPTION
Aquatic plants
Coral
Floor of water body
CSIRO
CSIRO Land and Water
A. G. Dekker and H. Buettikofer

Optical properties of waters



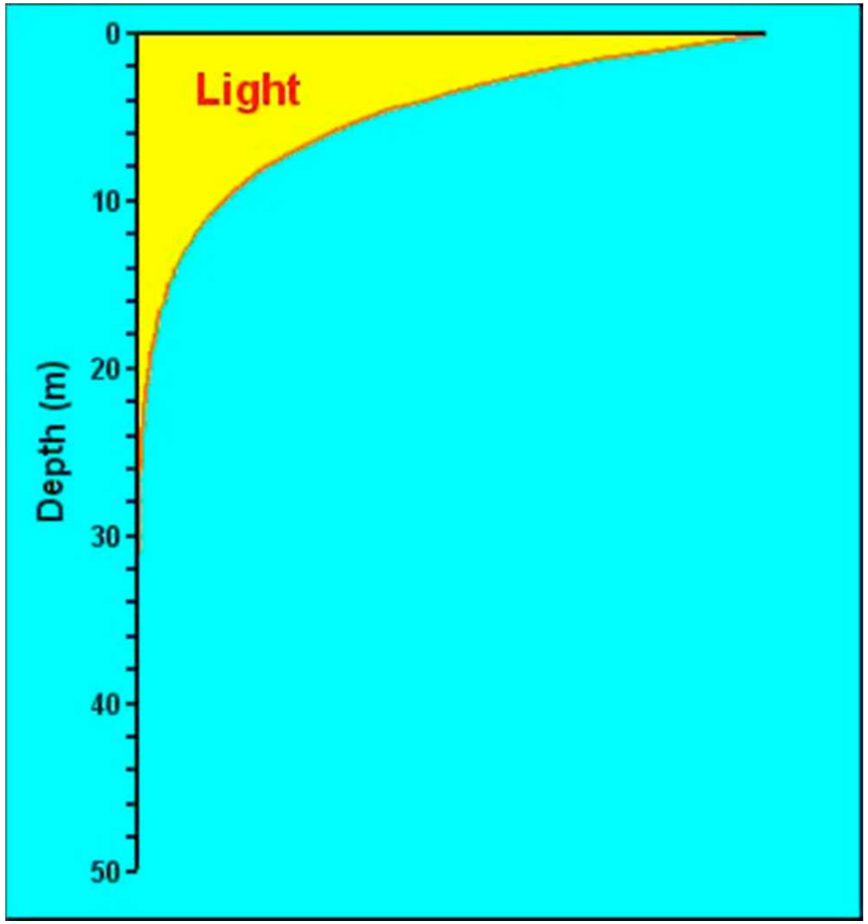
Light penetration

Coefficient of attenuation (K_d, m^{-1})

Rule of thumb: 90% of signal comes from first optical depth

[Optical depth = $1/K_d$ (m)]

Optical depths in Lake Balaton (June 2010) = 0.16-5.95 m



Optical properties of waters

(Specific) Inherent optical properties (IOPs/SIOPs)

absorption (a, m^{-1})
scattering (b, m^{-1})
backscattering (b_b, m^{-1})
beam attenuation (c, m^{-1}) ($c = a + b$)
volume scattering function [$\beta(0)$]

Describe the properties of the medium itself; invariant of the ambient light field

Apparent optical properties (AOPs)

subsurface irradiance reflectance [R(0-)]*
remote sensing reflectance [Rrs(0+)]
coefficient of light attenuation (K_d)
transparency (e.g., Secchi disc depth)
colour

Radiometric quantities that are dependent on the ambient light field and viewing geometry

*considered a quasi-IOP

Optically-active constituents

Absorption (***a*****,** m^{-1}) - removal of light by:

- water itself
- coloured dissolved organic matter
- phytoplankton
- mineral particles and detritus

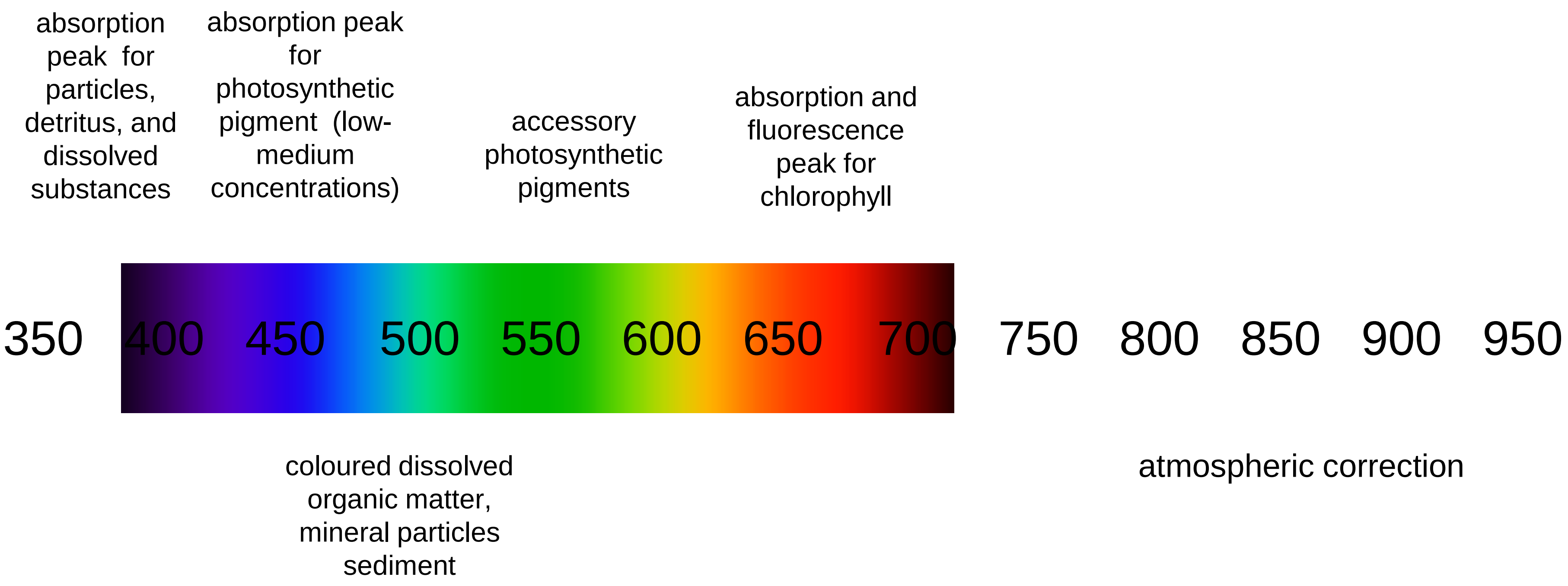
Scattering (***b*****,** m^{-1}) - molecular and particulate; directional:

- water itself
- phytoplankton
- suspended sediments

Beam attenuation (**c**, m^{-1}) – ($c = a + b$)

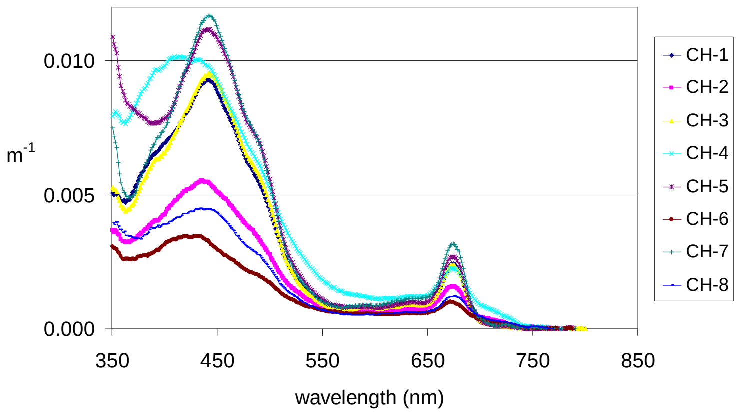
Volume scattering function (***ß***) – directionality of light scattering

Optical properties of waters

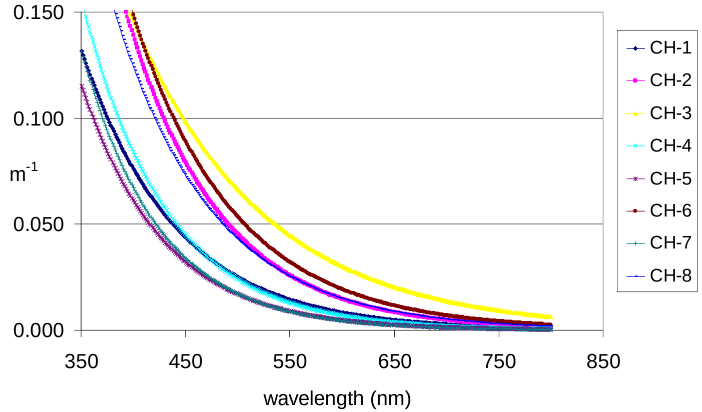


Optical properties of waters

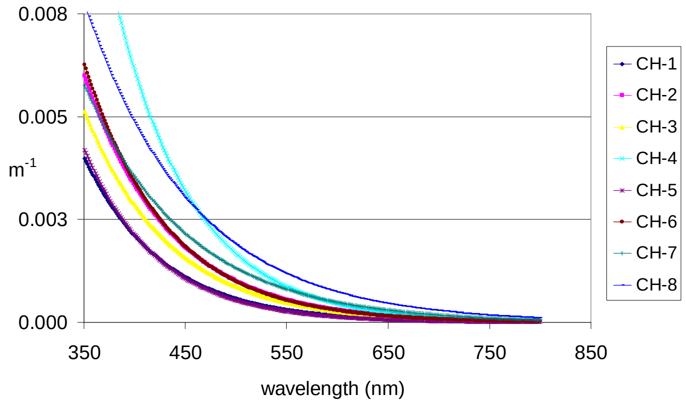
Coringa Herald December 2006
absorption of phytoplankton



Coringa Herald December 2006
absorption of CDOM



Coringa Herald December 2006
absorption of NAP



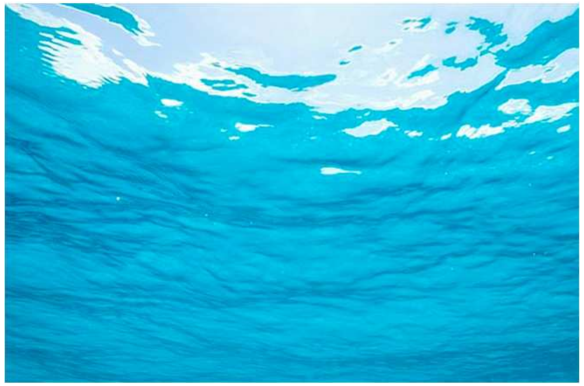
Classification of water types

Case I (open oceans)

3 optically-active components (OACs):

(1) pure water; (2) phytoplankton;

(3) coloured dissolved organic matter.



Case II (coastal and inland waters)

4 *non-covarying* OACs:

(1) pure water; (2) phytoplankton;

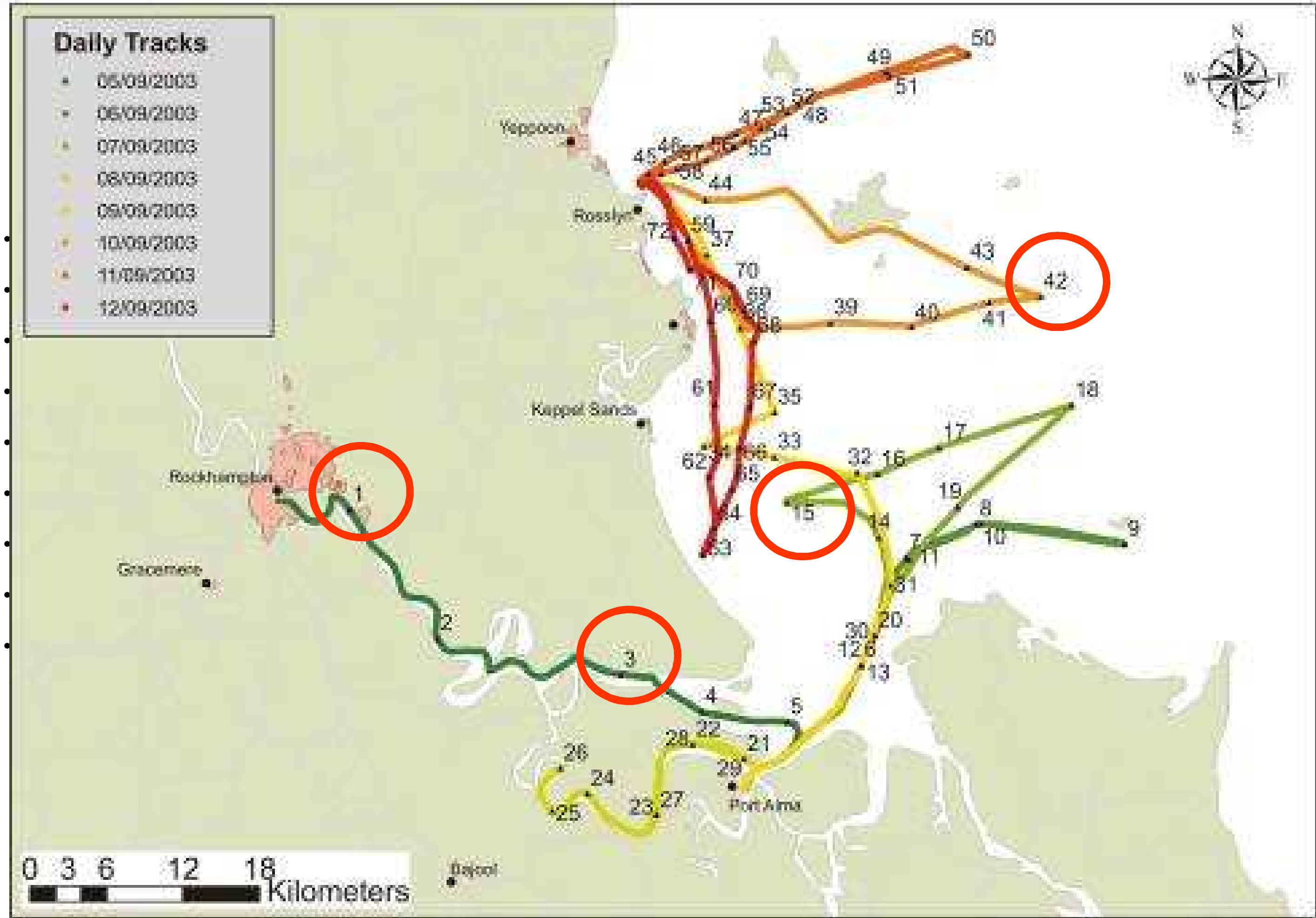
(3) non-algal particles;

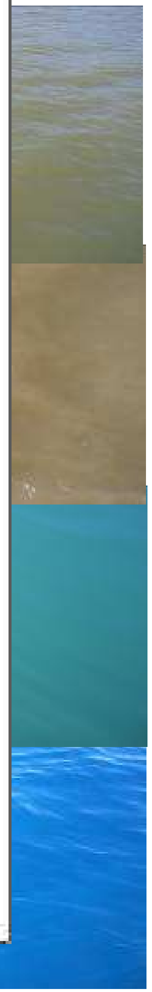
(4) coloured dissolved organic matter.

Variability in water colour

Surface Reflectance

0.
0.
0.
0.
0.
0.
0.
0.
0.





Optical models

Total absorption and backscattering

$$a_t(\lambda) = a_w(\lambda) + a_{ph}(\lambda) + a_{NAP}(\lambda) + a_{CDOM}(\lambda)$$

$$b_{b,t}(\lambda) = b_{b,w}(\lambda) + b_{b,ph}(\lambda) + b_{b,NAP}(\lambda)$$

Subsurface irradiance reflectance (Gordon et al. 1975)

$$R(0-) = E_u/E_d = f * (b_b/a+b_b) \quad \text{where } f \sim 0.33$$

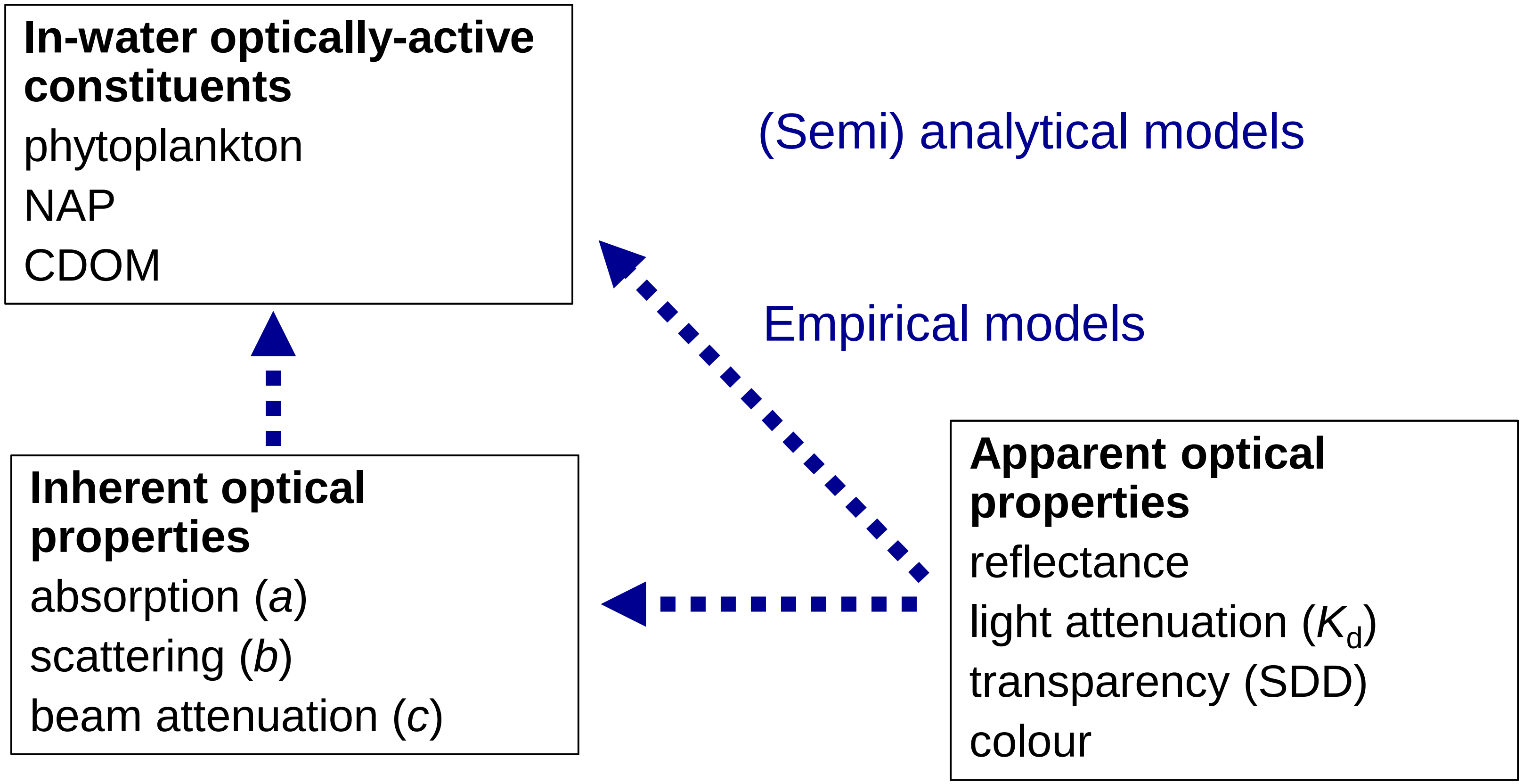
Remote sensing-reflectance

$$R_{rs}(0+) = L_w/E_d = (T*f/Q) * (b_b/a+b_b) \quad \text{where T} \sim 0.54\text{; f/Q} \sim 0.0949$$

Model inversion

Forward model

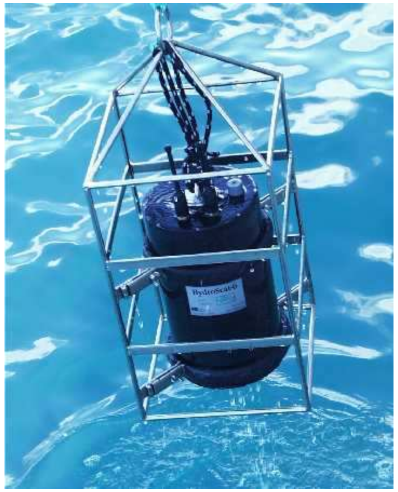
Models for constituent retrieval



In- and above-water optical instruments and measurements

IOPs: active sensors

Wetlabs AC-S: hyperspectral absorption (a) and attenuation (c) [b = c – a]



Wetlabs BB3: spectral backscattering (b_b)

AOPs: passive sensors

Satlantic HyperSAS: above surface water-leaving radiance (L_w) or reflectance (R_{rs})

Satlantic HyperOCRs: subsurface downwelling irradiance and upwelling radiance (subsurface irradiance reflectance)

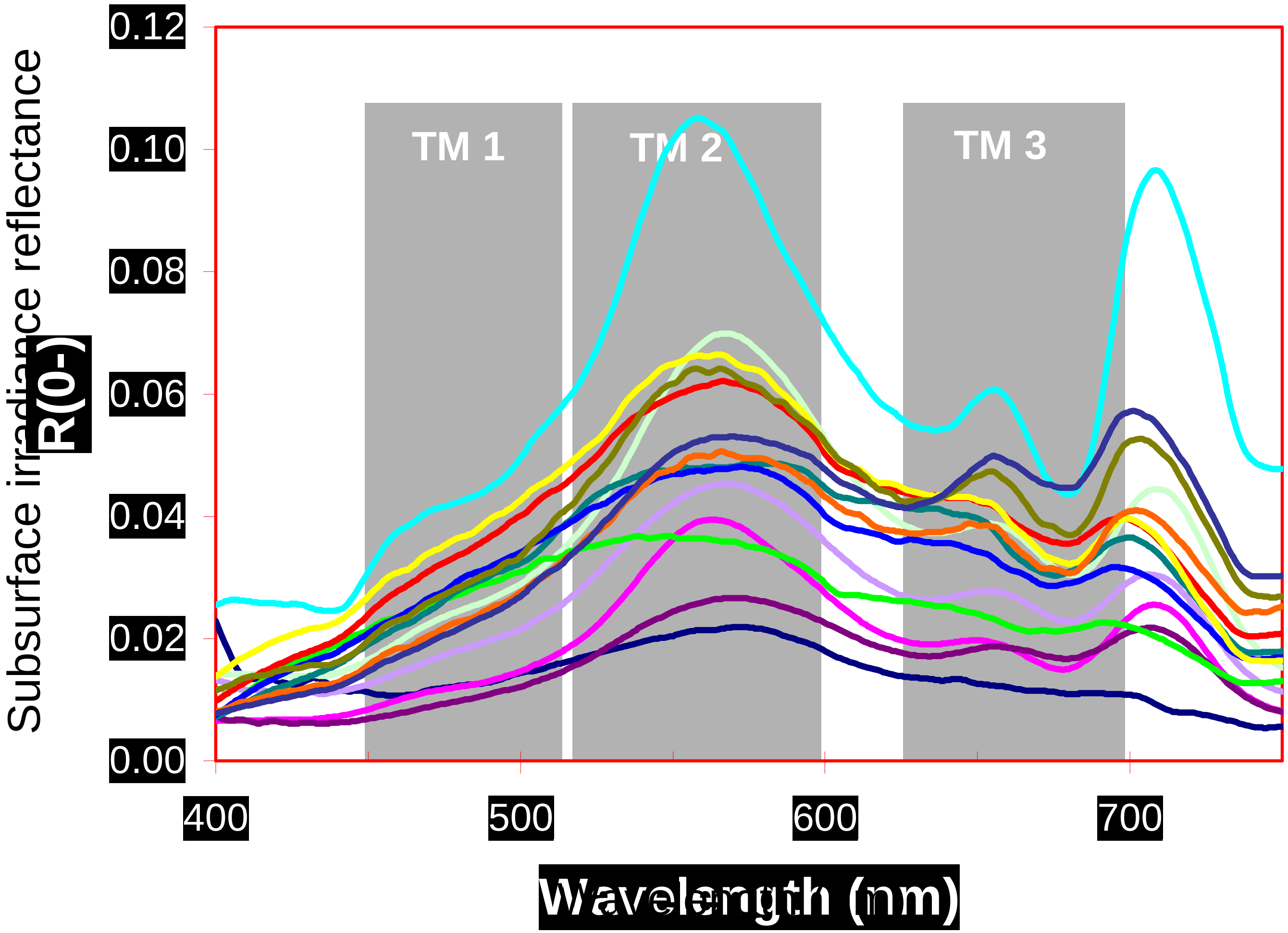
IOP and AOP rigs

Remote sensing platforms

AISA Eagle-Hawk on NERC ARSF Dornier

MERIS on ESA Envisat

Why hyperspectral?



Remote sensing applications

Parameters & processes of interest

Water transparency; light availability (SDD, K_d)

Total (inorganic / organic) suspended solids (TSS)

- concentration
- size spectra

Coloured dissolved organic matter (CDOM)

Phytoplankton

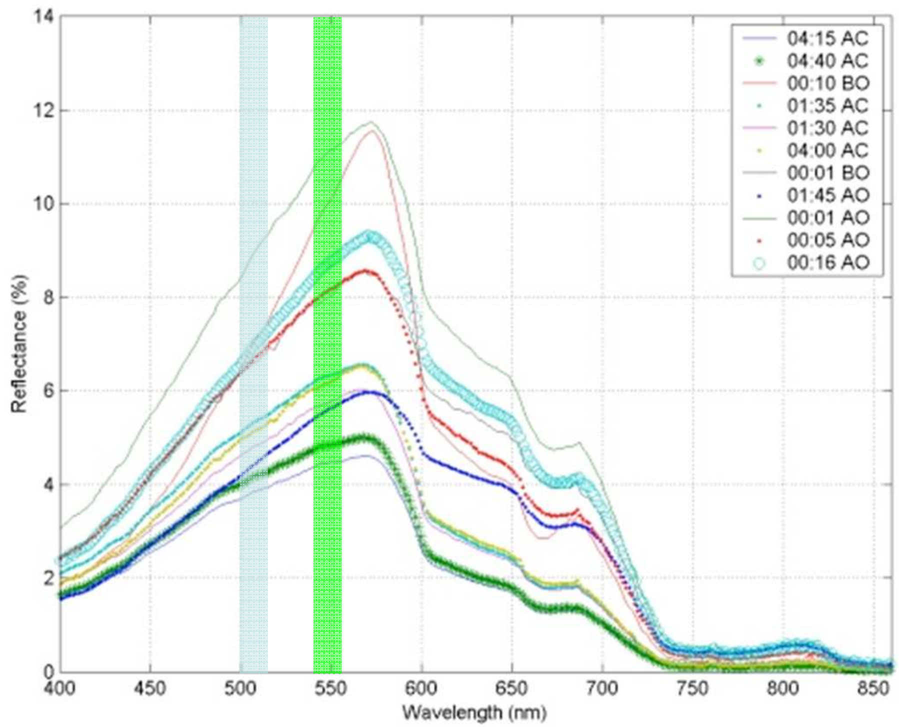
- chlorophyll-a
- phycocyanin & other accessory pigments
- size spectra & functional groups
- harmful algal blooms
- primary productivity

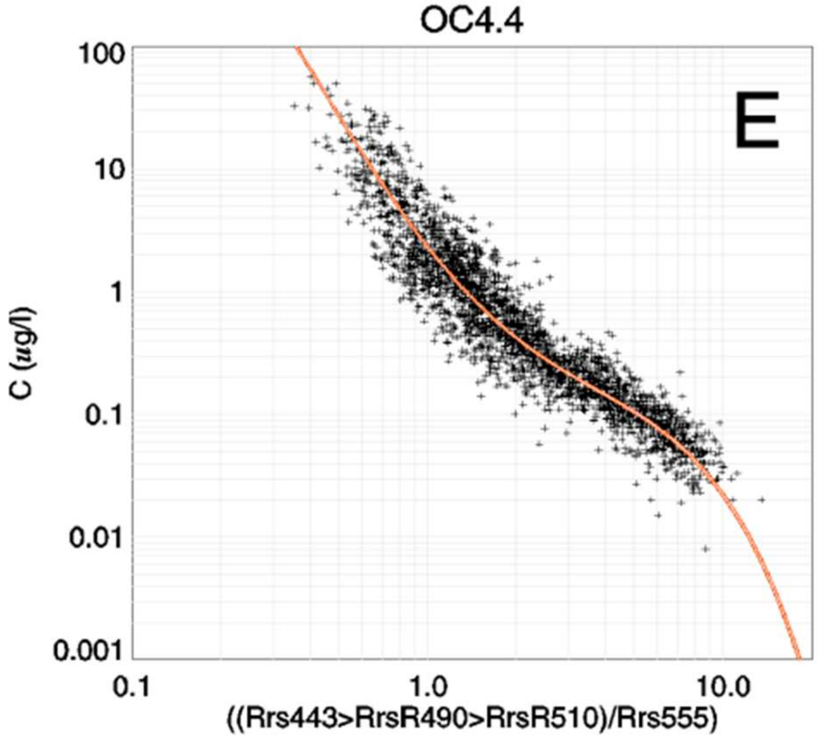
Bottom conditions (if observable)

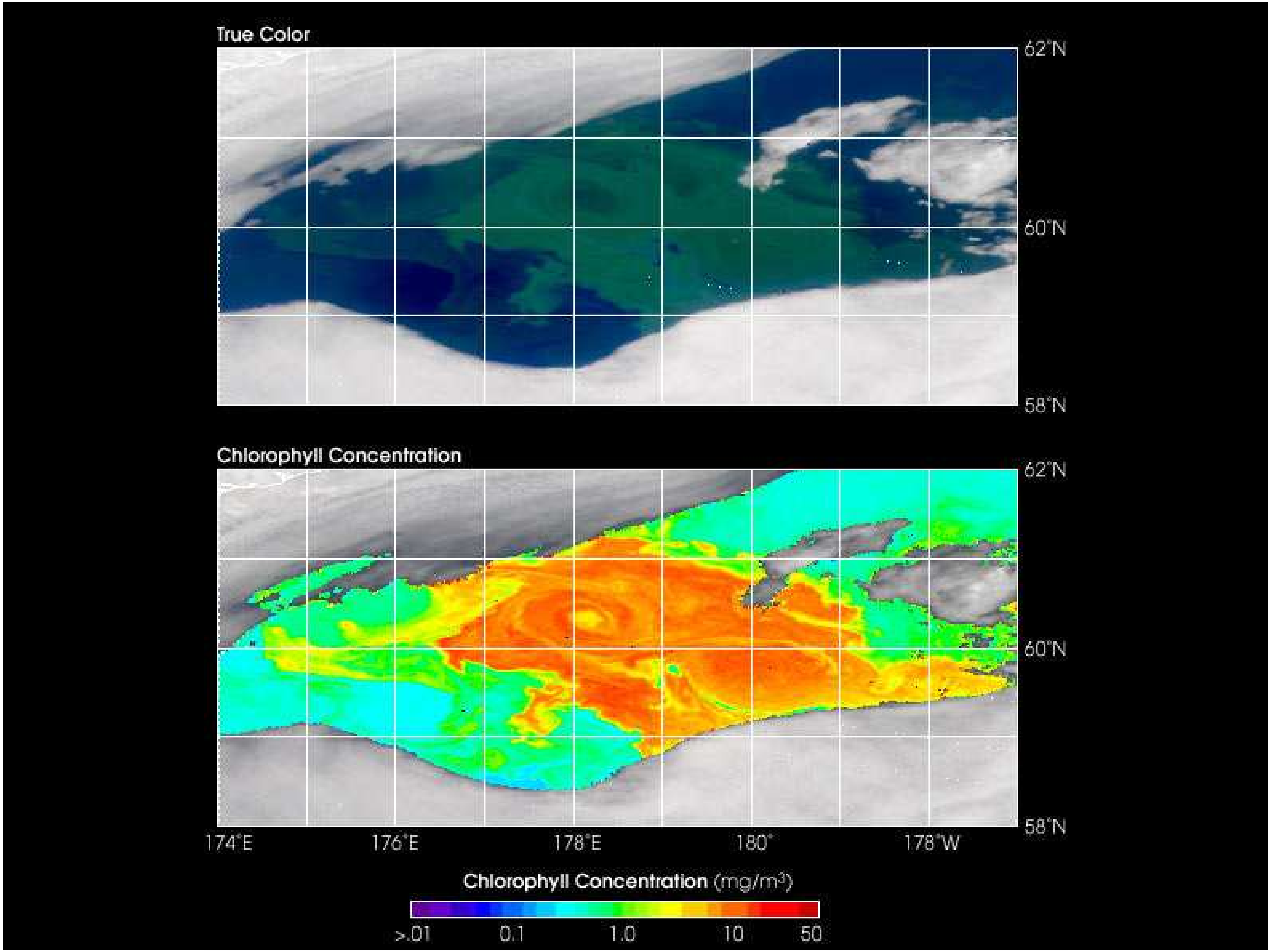
- depth
- submerged habitat

Chlorophyll: Case I waters

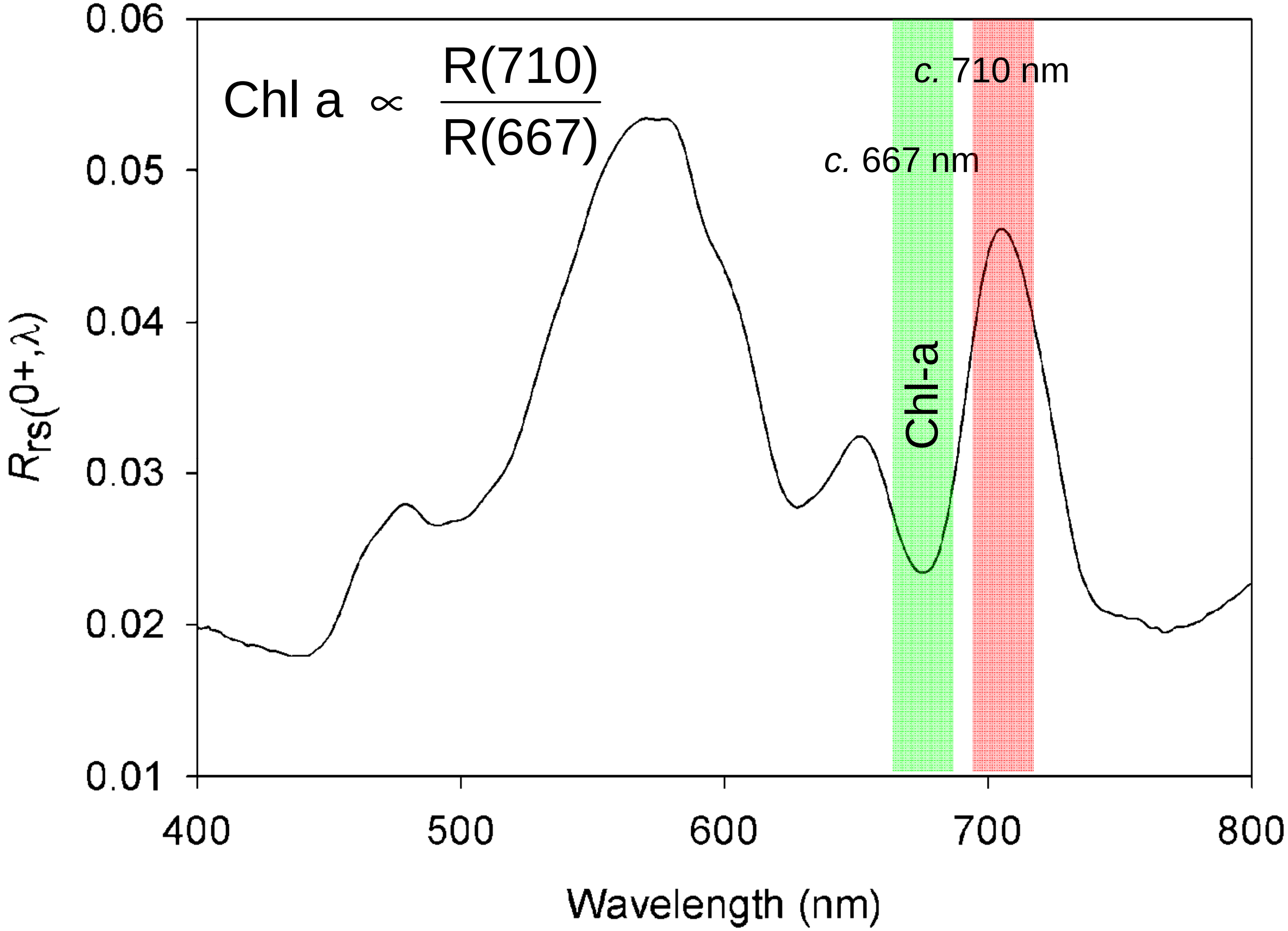
SeaWiFS OC4 algorithm	
R_{MAX}	= Maximum of [R_{rs}-ratio(443/555, 490/555, 510/555)]
R_L	= $\log_{10}(R_{MAX})$
Log_{10}(Chl-a)	= $0.366 - 3.067R_L + 1.930R_L^2 + 0.649R_L^3 - 1.532R_L^4$






True Color
62°N
60°N
58°N
Chlorophyll Concentration
62°N
60°N
58°N
174°E
176°E
178°E
180°
178°W
Chlorophyll Concentration (mg/m³)
>.01
0.1
1.0
10
50

Chlorophyll: Case II waters



Lake Garda: Hyperion

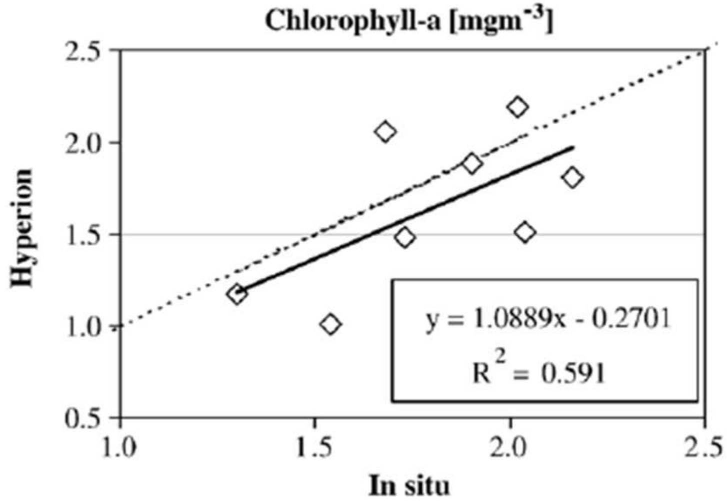
$$[\mathrm{CHL-a}]\left(a^*_{\mathrm{ph}}(\lambda_i)+b^*_{\mathrm{bph}}(\lambda_i)\left(1-\frac{1+\overline{\mu}_{\mathrm{d}}(\lambda_i)/\overline{\mu}_{\mathrm{u}}(\lambda_i)}{R(0-,\,\lambda_i)}\right)\right)$$

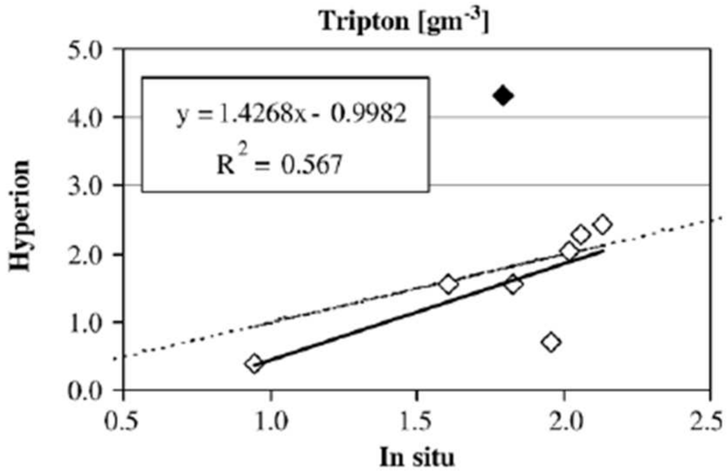
$$+[\mathrm{TR}]\left(a^*_{\mathrm{TR}}(\lambda_i)+b^*_{\mathrm{bTR}}(\lambda_i)\left(1-\frac{1+\overline{\mu}_{\mathrm{d}}(\lambda_i)/\overline{\mu}_{\mathrm{u}}(\lambda_i)}{R(0-,\,\lambda_i)}\right)\right)$$

$$=a_{\mathrm{w}}(\lambda_i)-b_{\mathrm{bw}}(\lambda_i)\left(1-\frac{1+\overline{\mu}_{\mathrm{d}}(\lambda_i)/\overline{\mu}_{\mathrm{u}}(\lambda_i)}{R(0-,\,\lambda_i)}\right)$$

$$-a_{\mathrm{CDOM}}(440)e^{-S_{\mathrm{CDOM}}(\lambda_i-440)}$$

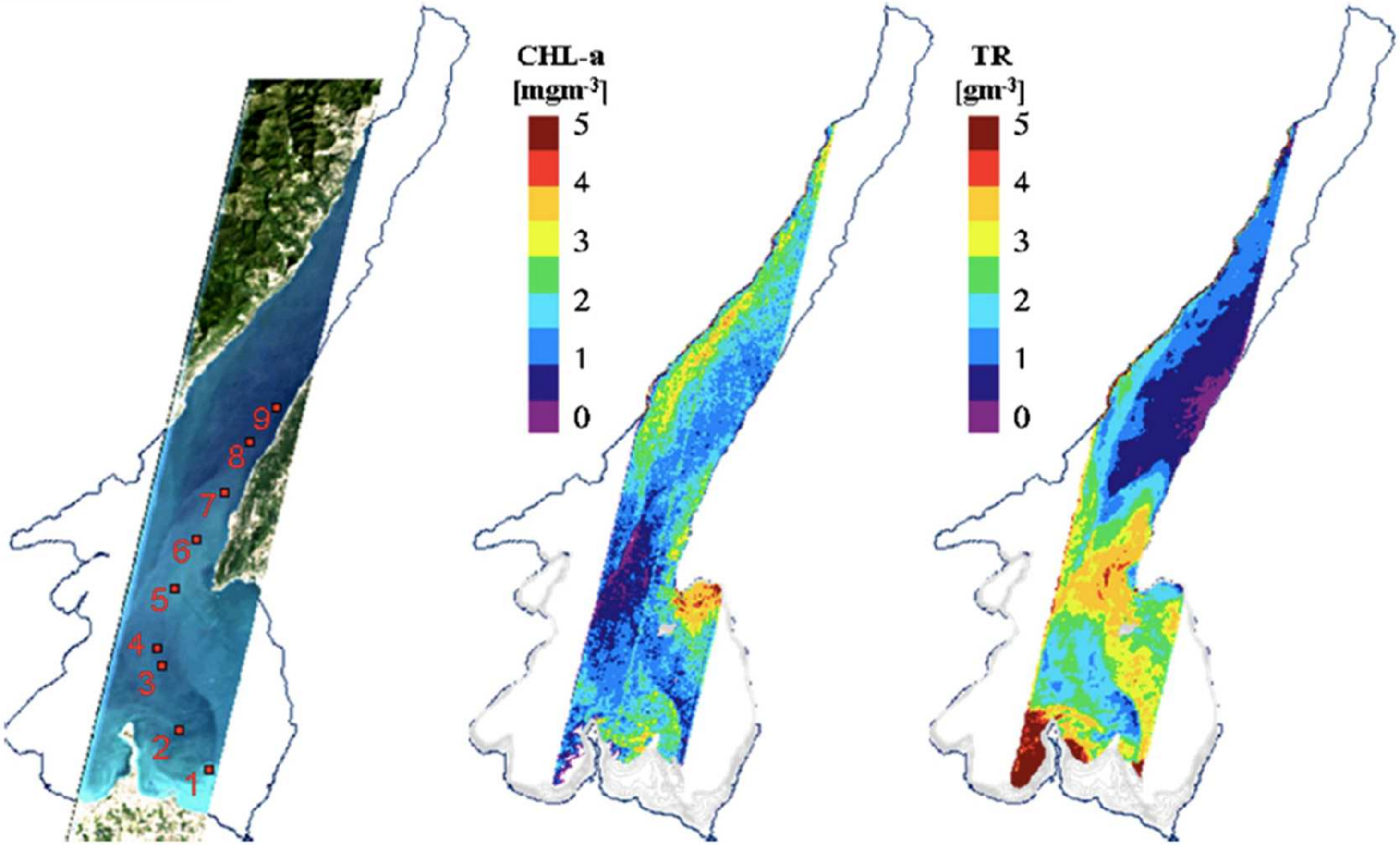
Bio-optical matrix inversion method (MIM)





Giardino et al. (2007) *Remote Sens Environ.* **109**:183-195

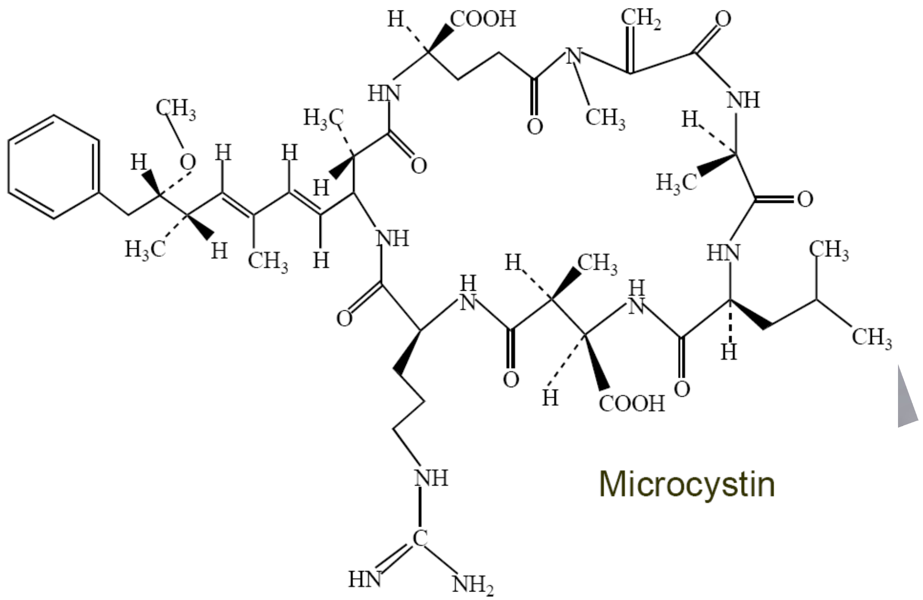
Lake Garda: Hyperion



Giardino et al. (2007) *Remote Sens. Environ.* **109**:183-195

Cyanobacteria

- Natural, ancient and cosmopolitan inhabitants of freshwaters
- Mass populations
- Numerous potent toxins
- Multiple exposure routes

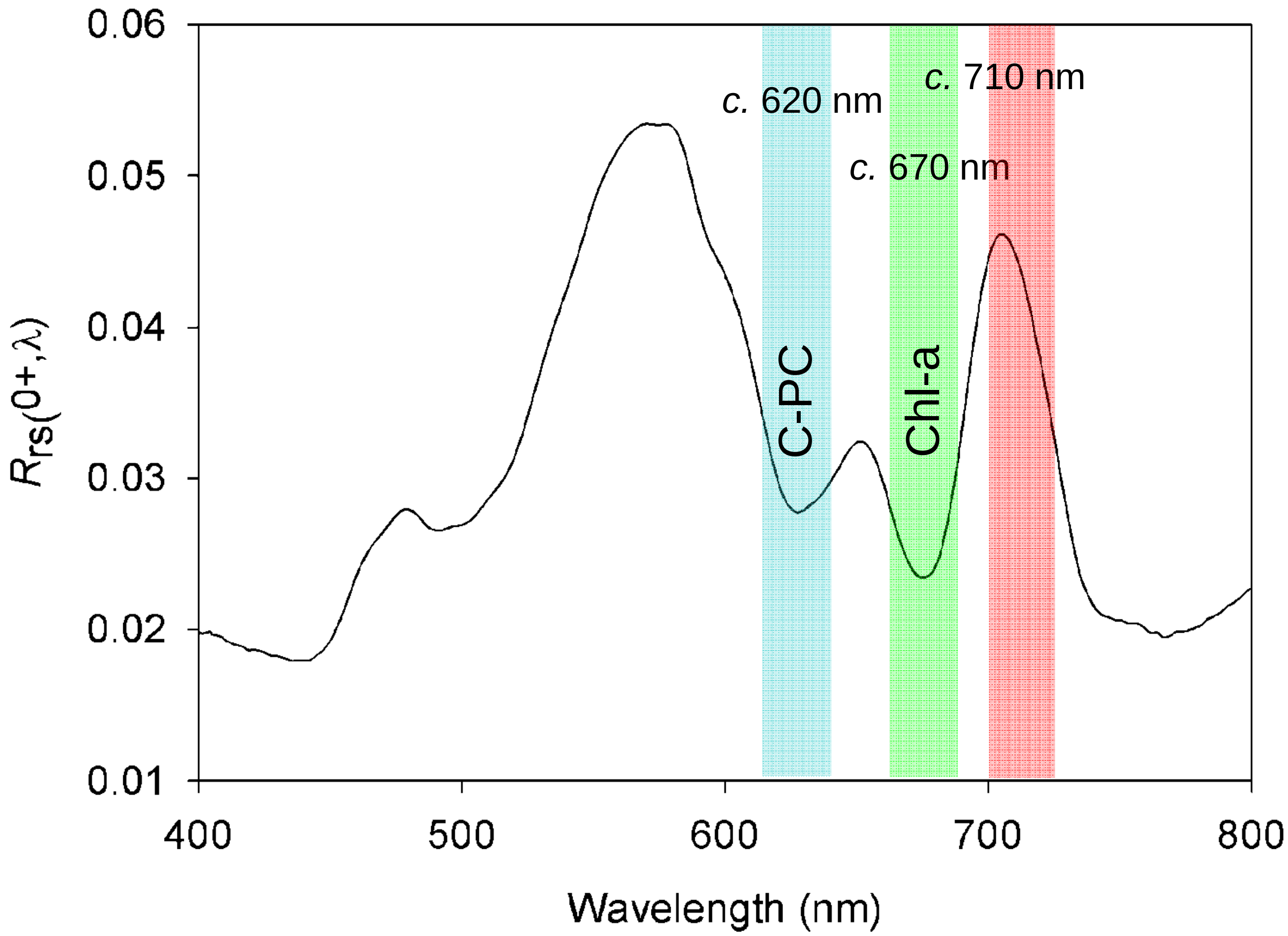


Microcystin

Cyanobacteria

- Inversion algorithms for chlorophyll-a (Chl-a) (total biomass)
- Cannot differentiate cyanobacteria
- New inversion algorithms for C-phycocyanin (C-PC)

C-phycocyanin



Colour groups

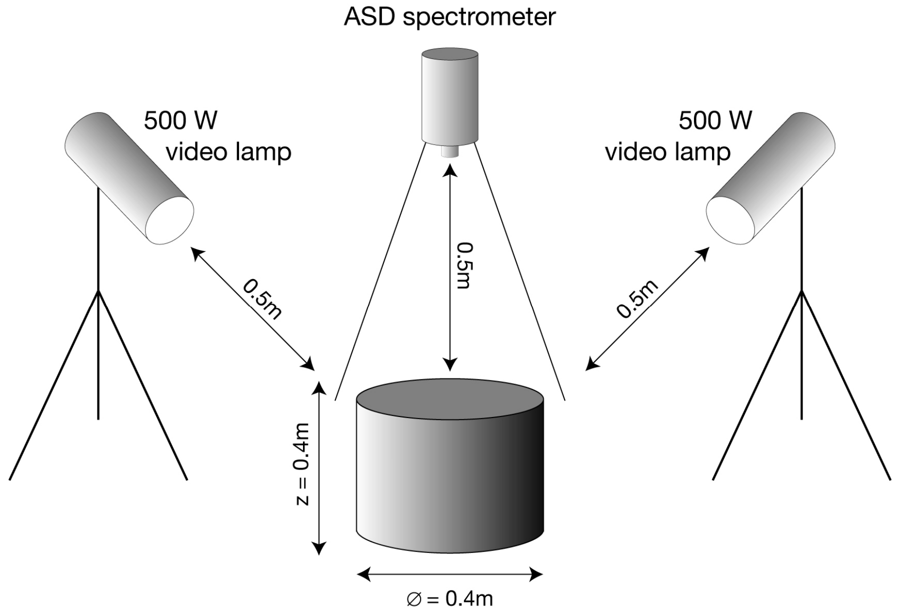
Tank experiments

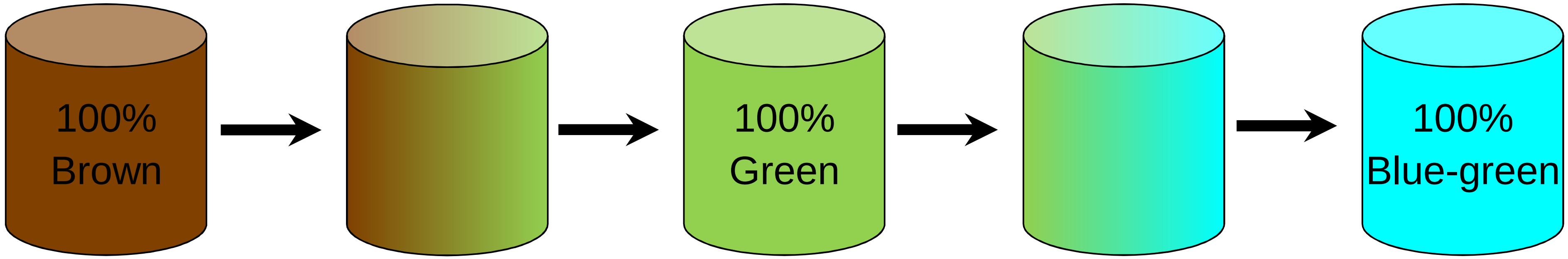
Total Chl *a* ~ 200 mg m^{-3}

Brown: diatom

Green: *Scenedesmus armatus*

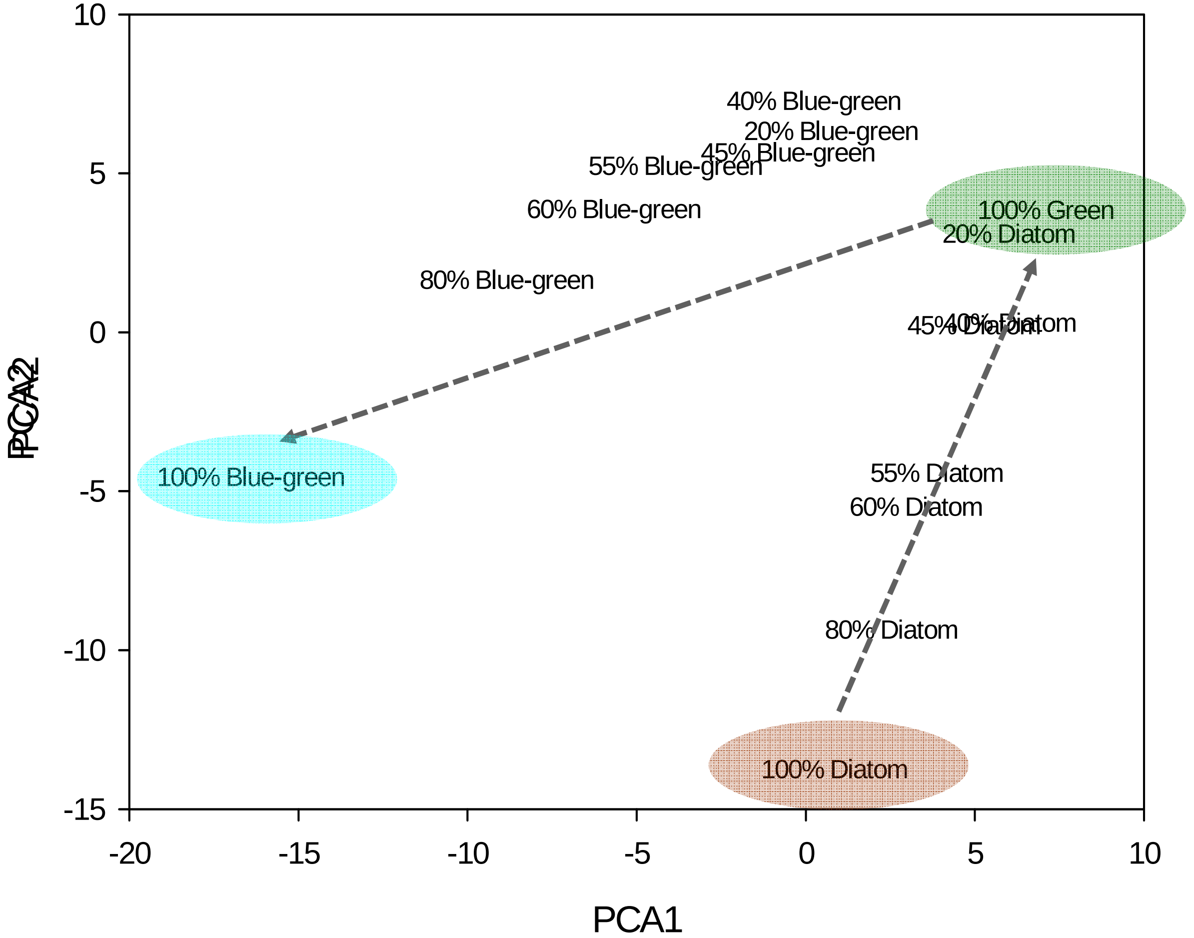
Blue-green: *Cylindrospermopsis raciborskii*





Hunter et al. (2008) *Remote Sens. Environ.* **112**:1527-1544

Colour groups

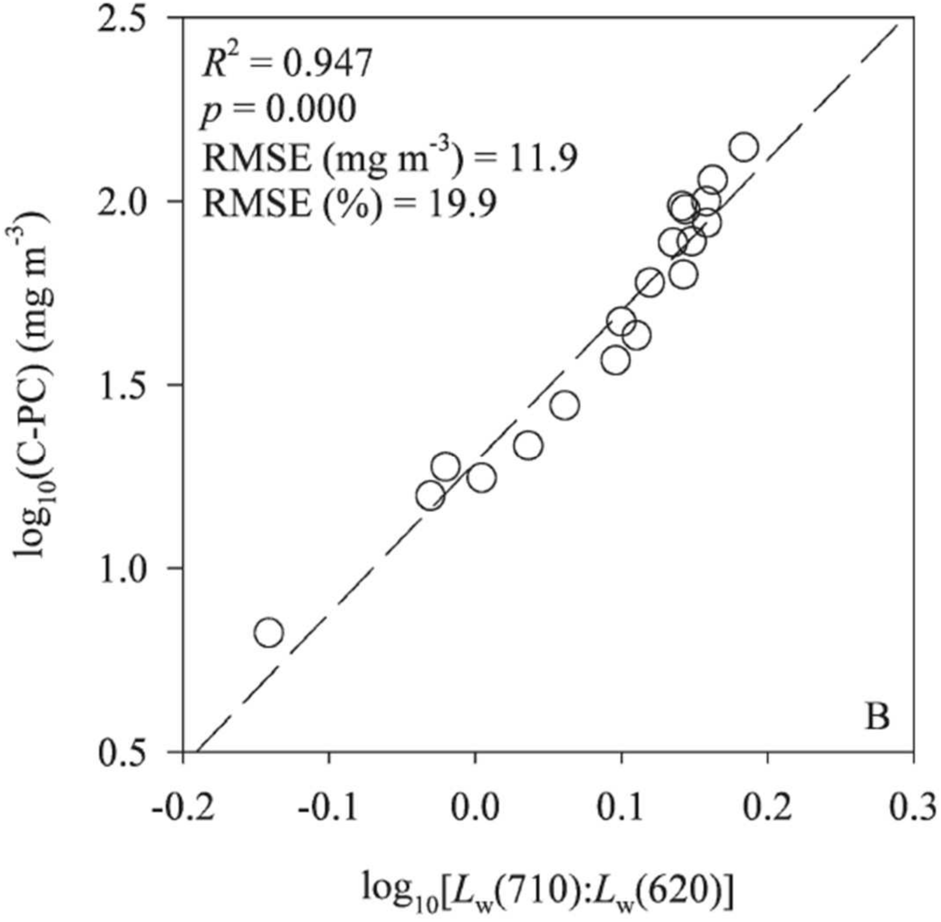


Hunter et al. (2008) *Remote Sens. Environ.* **112**:1527-1544

C-phycocyanin

Empirical algorithm

$\log_{10}(CPC) =$
$1.29 + 4.12 \times \log_{10}(Lw(710):Lw(620))$



Hunter et al. (2008) *Remote Sens. Environ.* **112**:1527-1544

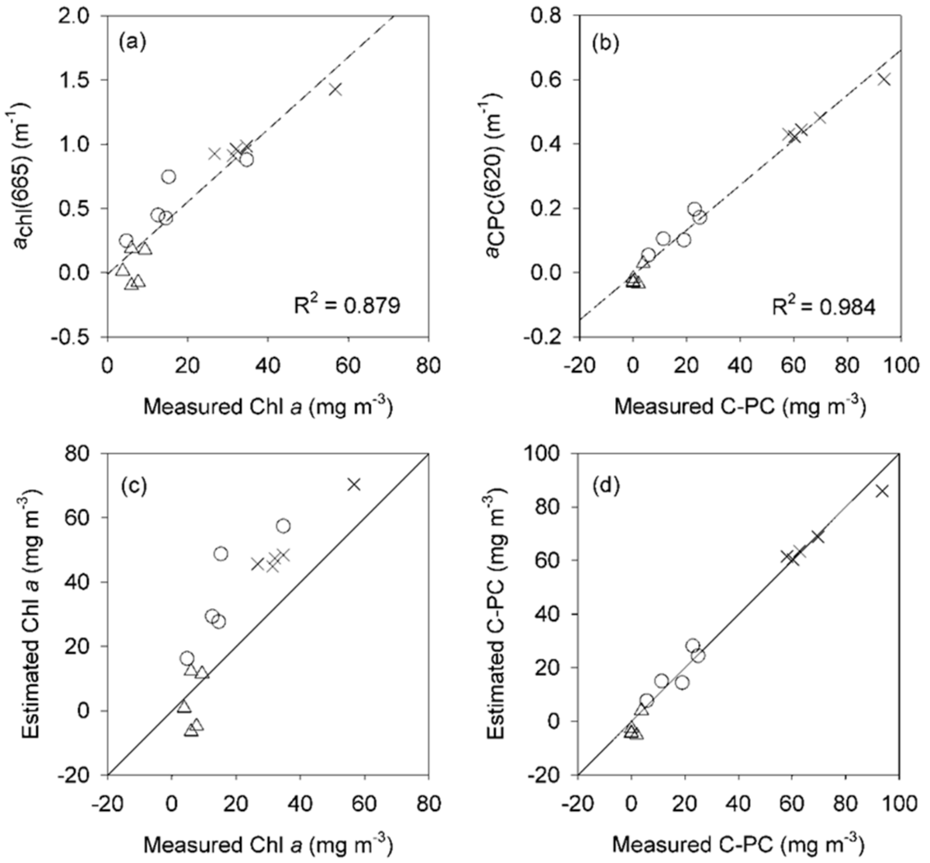
C-phycocyanin

$$a_{\text{chl}}(665) = \left(\left\{[a_w(709) + b_b] \times \left[\frac{R(709)}{R(665)}\right]\right\} - b_b - a_w(665)\right) \times \gamma^{-1}$$

$$a_{\text{CPC}}(620) = \left(\left\{[a_w(709) + b_b] \times \left[\frac{R(709)}{R(620)}\right]\right\} - b_b - a_w(620)\right) \times \delta^{-1} - [\varepsilon \times a_{\text{chl}}(665)]$$

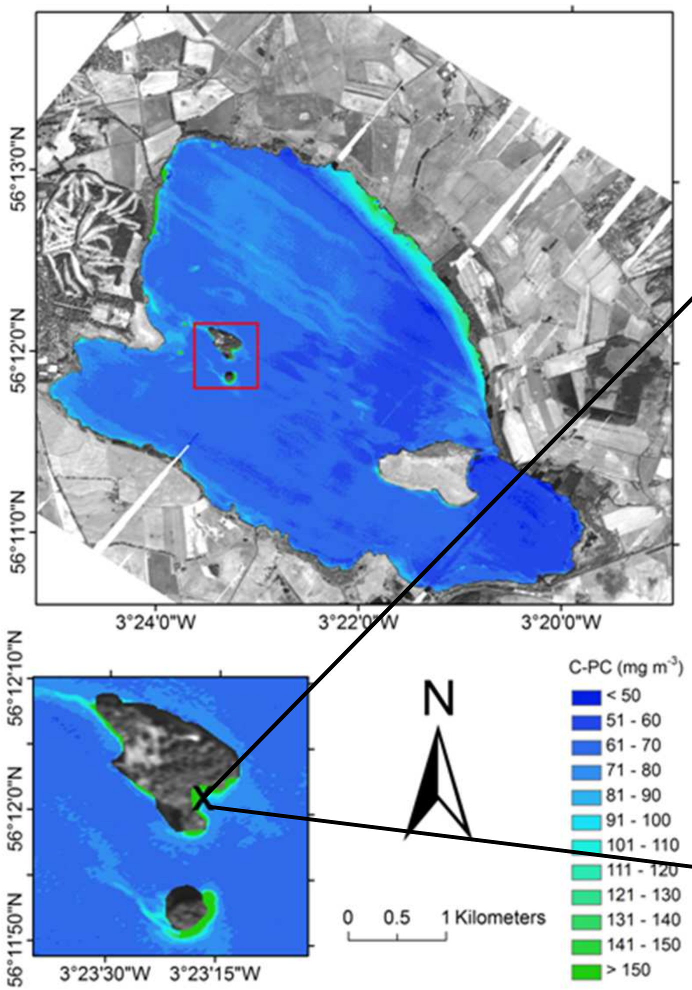
where

$$b_b(779) = \frac{1.61 \times R(779)}{0.082 - 0.6 \times R(779)}.$$



Hunter et al. (2010; in press) *Remote Sens. Environ.*

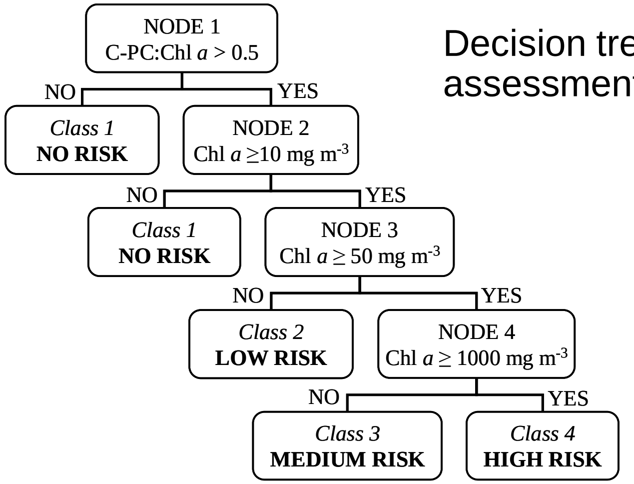
Loch Leven, Scotland

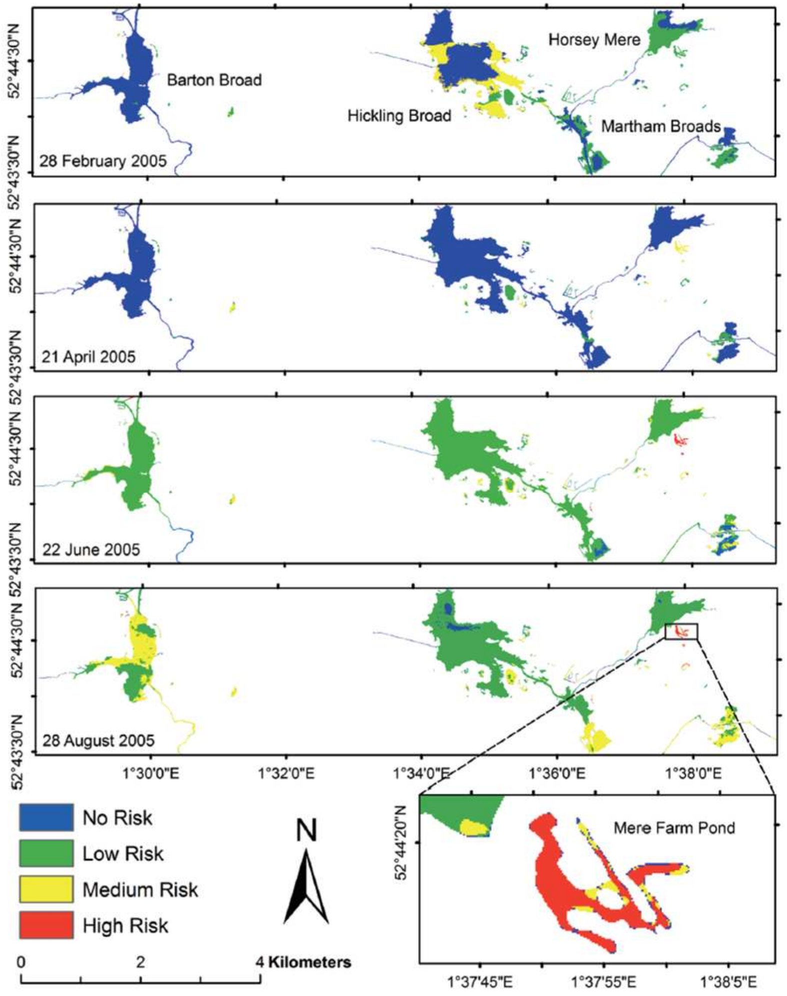


Hunter et al. (2010; in press) *Remote Sens. Environ.*

Health risk monitoring

Decision tree risk assessment model





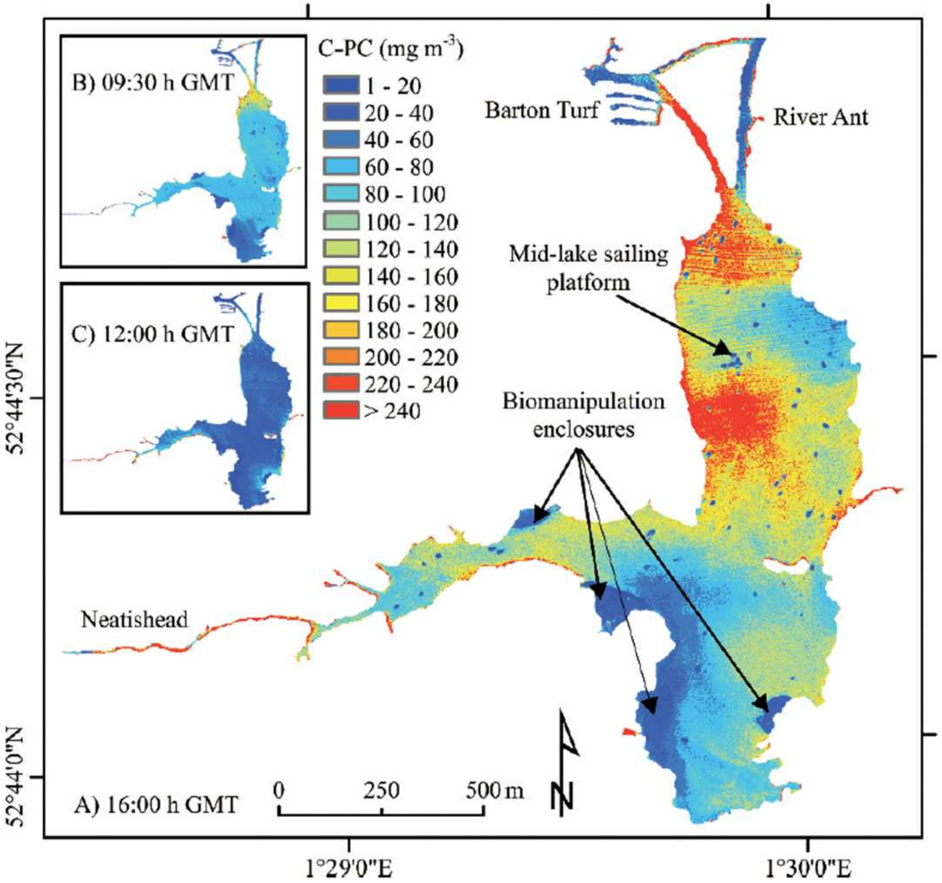
Hunter et al. (2009) *Environ. Sci. Technol.* **43(7)**:2627-2633

Vertical migration

09:30 GMT

12:00 GMT

16:00 GMT

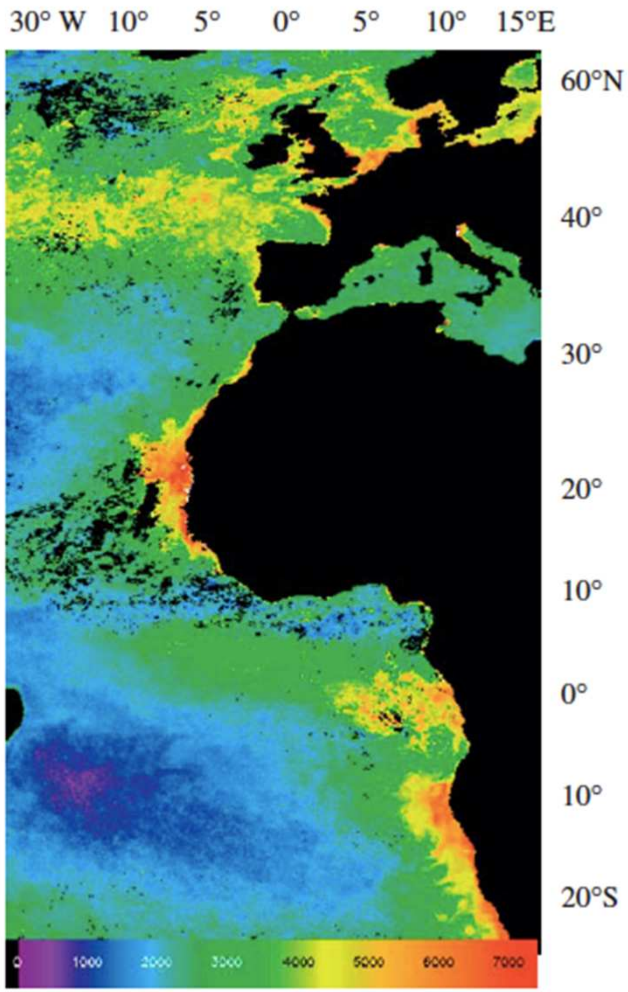


Hunter et al. (2008) *Limnol. & Oceanogr.* **53(6)**:2391-2406

Primary production

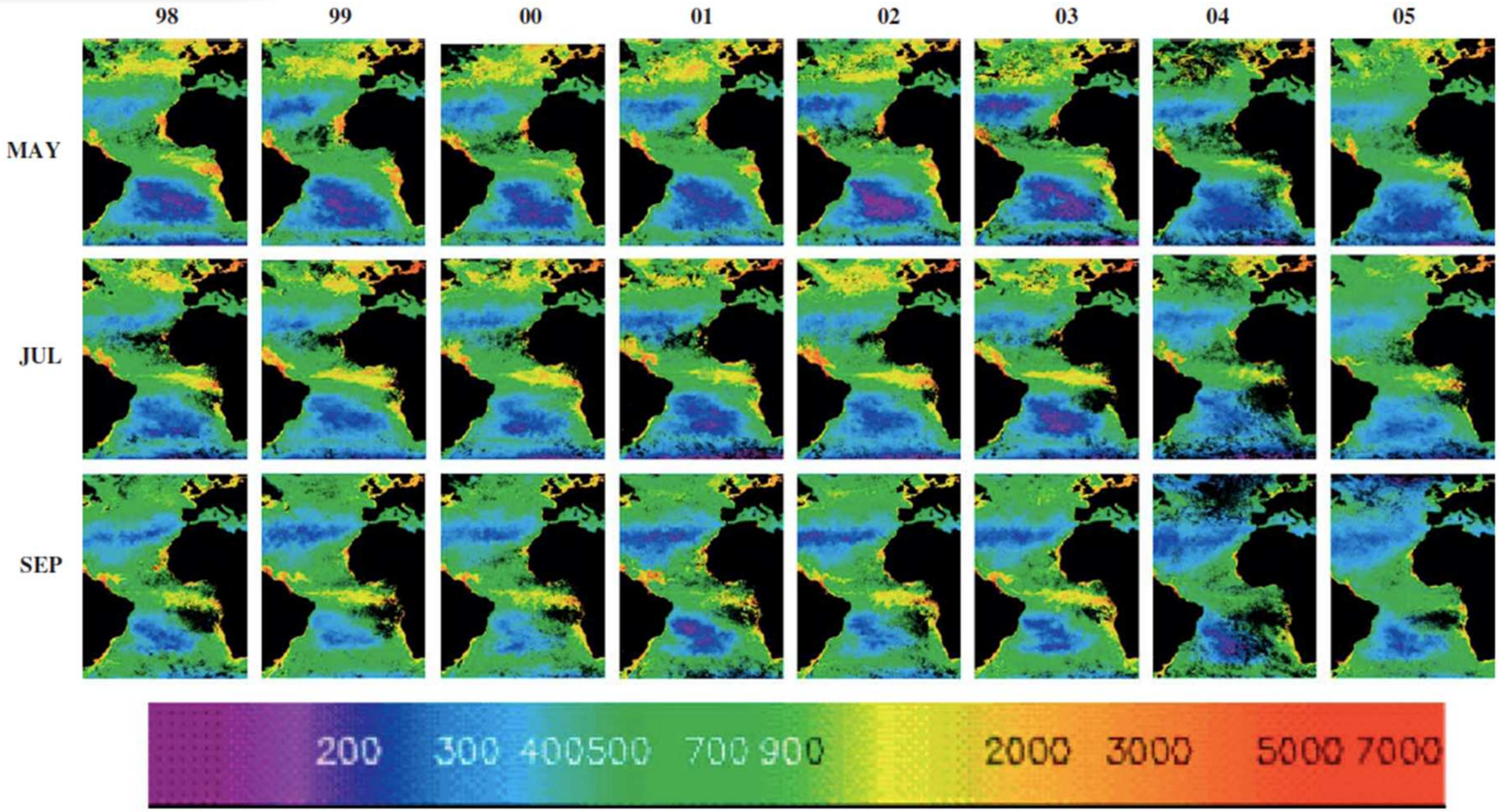
$\log_{10}PP = 0.599 \times \log_{10}Chl\text{-}a + 2.739$
(Behrenfeld et al. 1998)

$PP = f(C_{sat}, Z_{eu}, P^{b}_{opt})$
(Behrenfeld & Falkowski 1997)



Tilstone et al. (2009) *Deep Sea Res. II.* **56:** 918-930

Primary production



Primary production (mg C m^{-2} d^{-1})

Tilstone et al. (2009) *Deep Sea Res. II.* **56:** 918-930

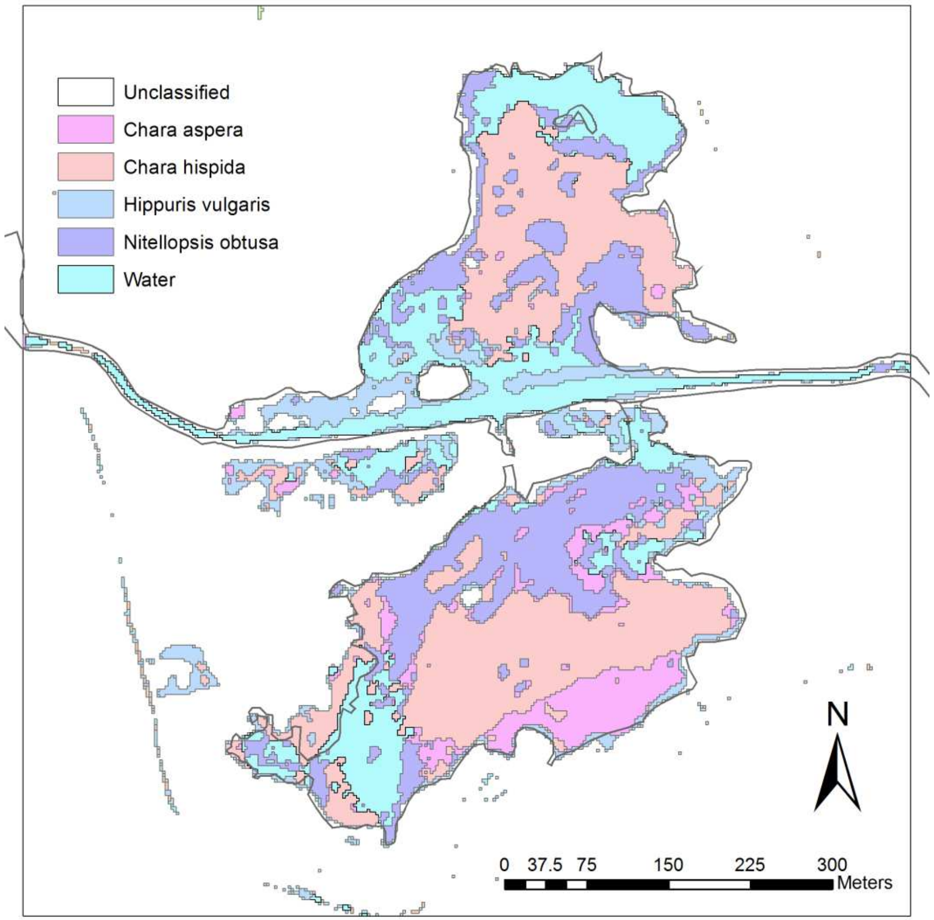
Submerged vegetation

CASI-2 imagery

Support Vector Machine classification of submerged vegetation in the Norfolk Broads

Classification accuracy = 87.3%

Kappa statistic = 0.84



Hunter et al. (2010; in press) *Aquatic Conservation: Marine and Freshwater Ecosystems*

NERC ARSF & EUFAR: Lake Balaton 2010

Peter Hunter, Caitlin Lyman & Andrew Tyler

University of Stirling

Steve Groom & Victor Martinez Vicente

Plymouth Marine Laboratory

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Balaton Limnological Research Institute

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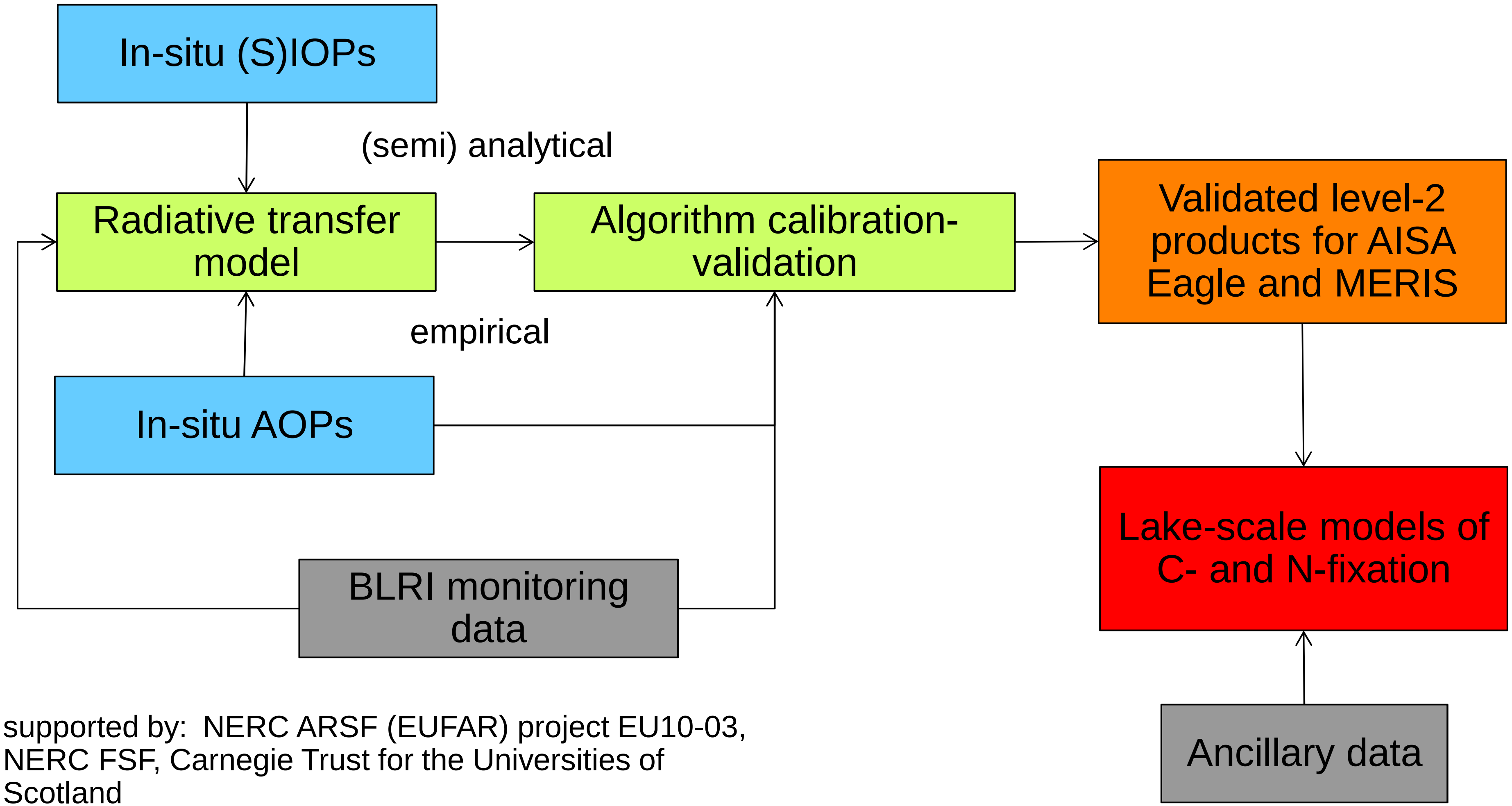
NERC ARSF Lake Balaton 2010

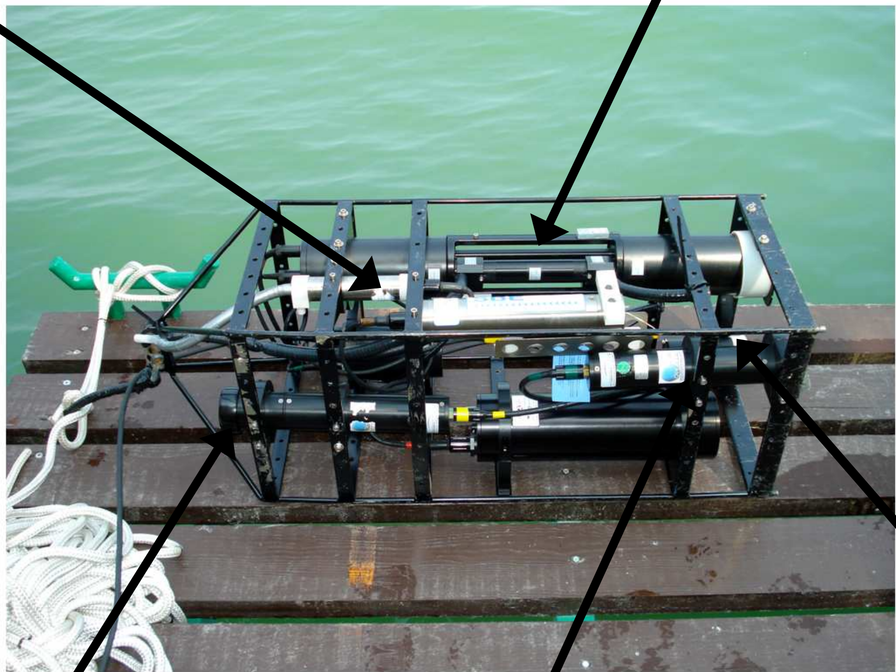


supported by: NERC ARSF (EUFAR) project EU10-03, NERC FSF, Carnegie Trust for the Universities of Scotland

NERC ARSF Lake Balaton 2010

Wetlabs AC-S hyperspectral beam attenuation and absorption meter

Seabird CTD



Satlantic HyperOCR
E_d(0-) radiometer

Satlantic HyperOCR
L_u(0-) radiometer

Wetlabs ECOBB3 backscatter meter

NERC ARSF Lake Balaton 2010

Satlantic HyperSAS $E_d(0+)$ radiometer

Satlantic HyperSAS L_{sky} radiometer

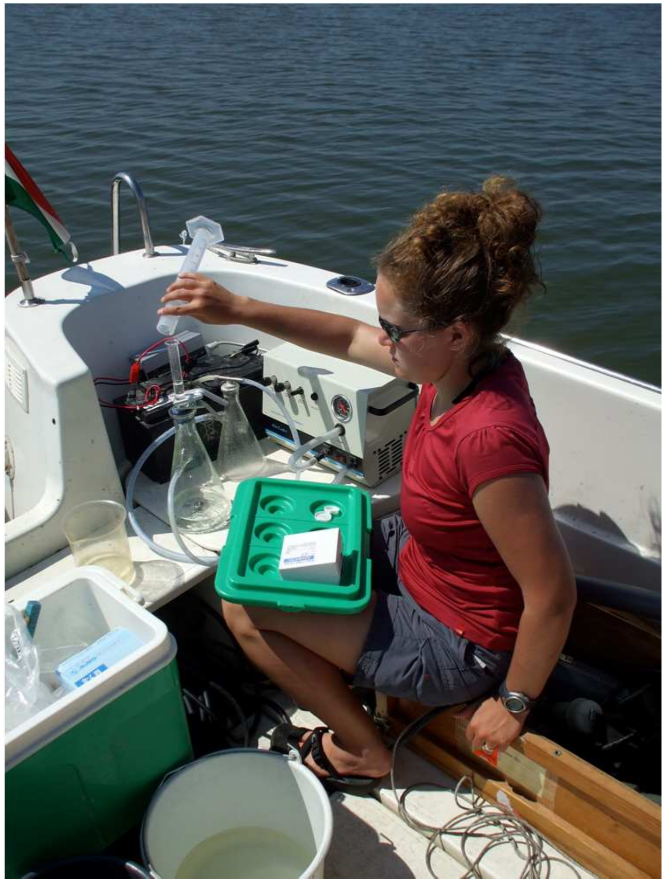
Satlantic HyperSAS L_u radiometer

Satlantic HypeOCR
$E_d(0+)$ radiometer

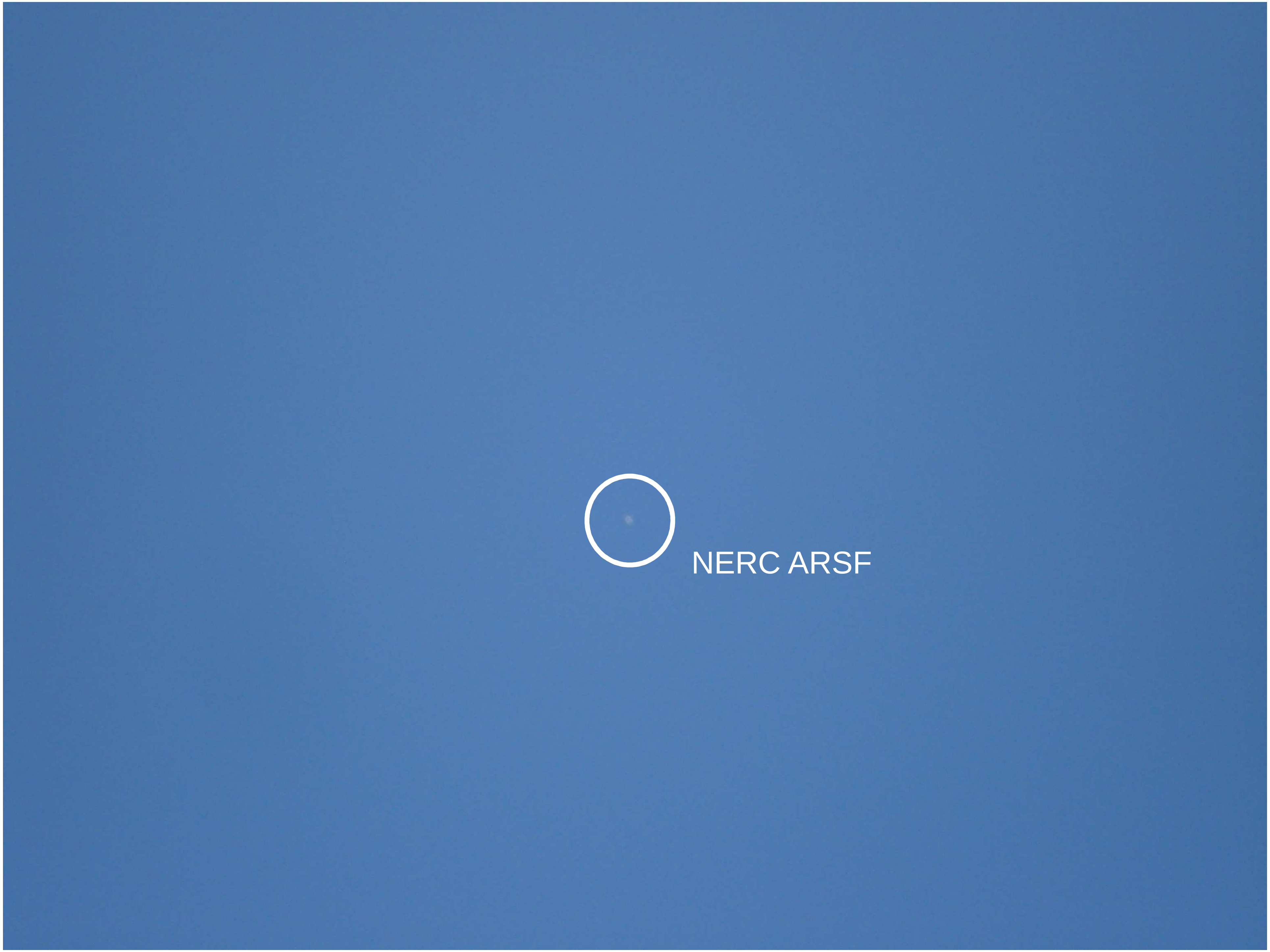
Diffuse shade cap

NERC ARSF Lake Balaton 2010

Ship's winch

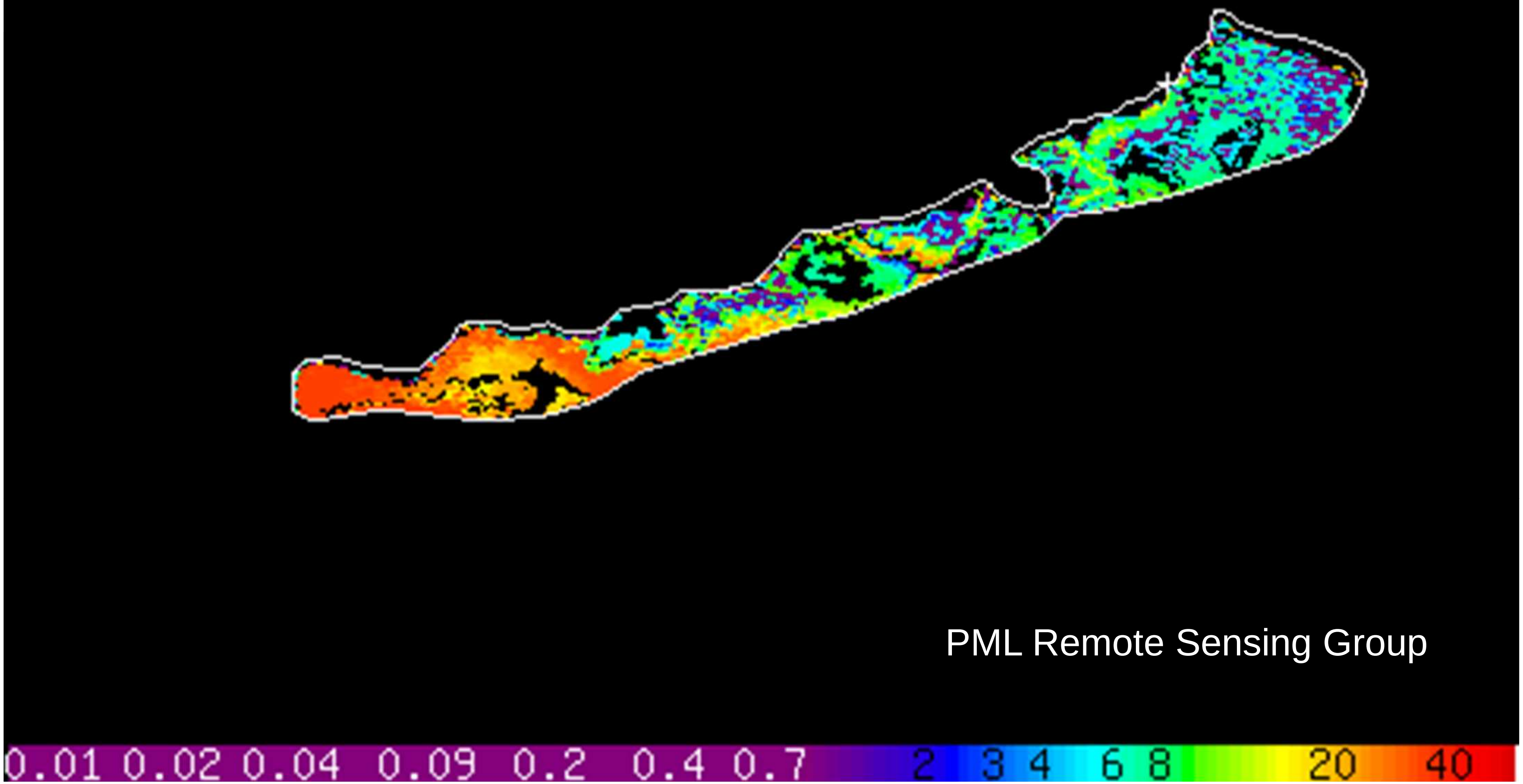


Onboard laboratory


NERC ARSF

MERIS algal_2

Lake Balaton 11 August 2010



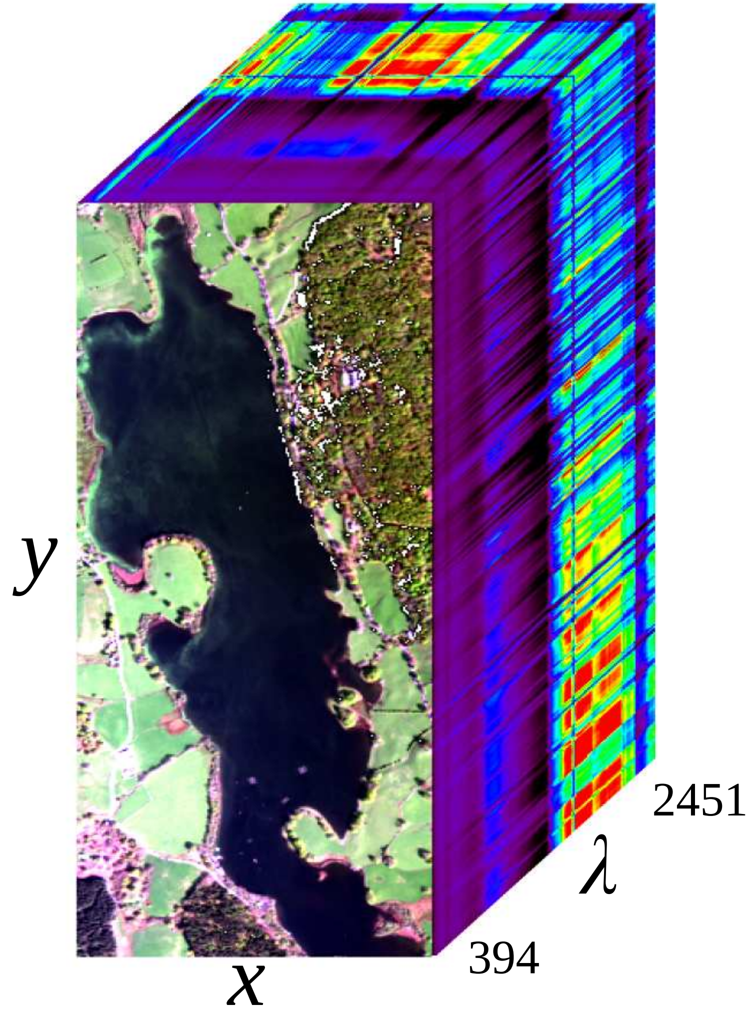
Hands-on practical

Hyperspectral AISA Eagle and Hawk imagery collected over Esthwaite Water in April 2007

- Test an existing empirical Chl-a retrieval algorithm

- Design and apply an empirical algorithm for C-phycocyanin retrieval

- Test a semi-analytical algorithm for Chl-a retrieval (if time permits)



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