WASI Training I: Bio-optical models

Peter Gege

DLR, Earth Observation Center, Remote Sensing Technology Institute, Oberpfaffenhofen, 82234 Wessling, Germany. peter.gege@dlr.de

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DLR

Radiative transfer equation (RTE)
Basic equation for the paths of light and light-matter interaction

$$cos\theta \frac{dL(\lambda, z, \theta, \varphi)}{dz} = -\boldsymbol{c}(\lambda, z) L(\lambda, z, \theta, \varphi) + \int_0^{2\pi} \int_0^{\pi} \boldsymbol{\beta}(\lambda; z, \theta, \varphi; \theta', \varphi')\, L(\lambda, z, \theta', \varphi') sin\theta' d\theta' d\varphi'$$

Simplified RTE for a plane-parallel medium that is homogeneous in x- and y-direction.
Neglected effects: polarization, inelastic scattering (e.g. fluorescence, Raman scattering).

Red: Light
Green: Matter
Blue: Geometry

Light
The source of information in remote sensing

$$\cos\theta \frac{dL(\lambda, z, \theta, \varphi)}{dz} = -\boldsymbol{c}(\lambda, z)L(\lambda, z, \theta, \varphi) + \int_0^{2\pi}\int_0^{\pi} \boldsymbol{\beta}(\lambda; z, \theta, \varphi; \theta', \varphi')\, L(\lambda, z, \theta', \varphi') \sin\theta' d\theta' d\varphi'$$

- **Radiance L.** Units: $W\,m^{-2}sr^{-1}$.

  Definition: $L = \frac{d^2\phi}{dA\,d\Omega}$

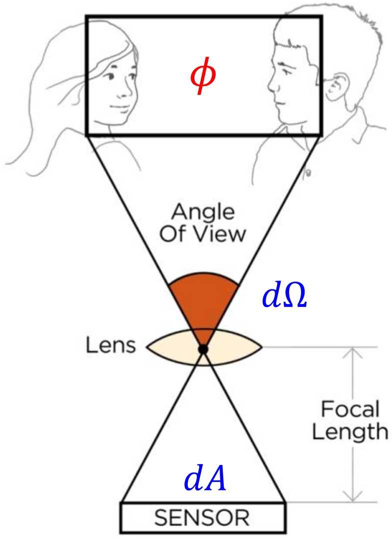
  ϕ: incident flux, dA: sensor area, $d\Omega$: angle of view

  $\phi(\lambda) = \frac{N \cdot E(\lambda)}{t}$

  N: number of photons, *t*: time, *E*: energy of a single photon

- **Wavelength λ.** Units: m.

  The period length of the electromagnetic wave in travel direction.



Picture: http://www.panavision.com/sites/default/files/docs/documentLibrary/2%20Sensor%20Size%20FOV%20(2).pdf

Matter
Its optical properties are accessible to spectroscopy

$$cos\theta \frac{dL(\lambda, z, \theta, \varphi)}{dz} = -c(\lambda, z)L(\lambda, z, \theta, \varphi) + \int_0^{2\pi}\int_0^{\pi} \beta(\lambda; z, \theta, \varphi; \theta', \varphi')\, L(\lambda, z, \theta', \varphi') sin\theta' d\theta' d\varphi'$$

- **Attenuation coefficient (extinction coefficient) c.** Units: m^{-1}.

  Definition: $c = \frac{1}{\phi}\frac{d\phi_a + d\phi_b}{dz}$

  ϕ: incident flux, $d\phi_a$: absorbed flux, $d\phi_b$: scattered flux, dz: thickness of medium

  Reduces the number of photons (beam intensity), not their direction.

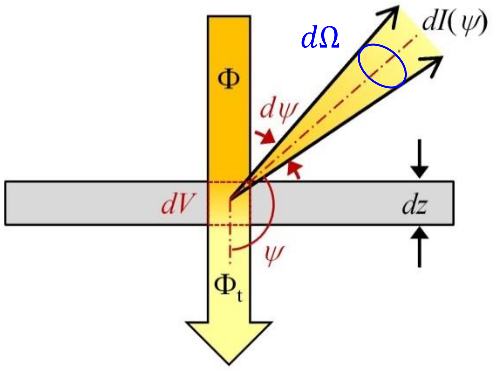
- **Volume scattering function $\beta(z, \theta, \varphi; \theta', \varphi')$.** Units: $m^{-1}\ sr^{-1}$.

  Definition: $\beta(\psi) = \frac{1}{E}\frac{dI(\psi)}{dV} = \frac{1}{E}\frac{d^2\phi(\theta, \varphi; \theta\prime, \varphi\prime)}{dV\, d\Omega}$

  ψ: scattering angle, dI: radiant intensity, E: irradiance, dV: volume

  Alters the flight direction of photons, not their numbers.

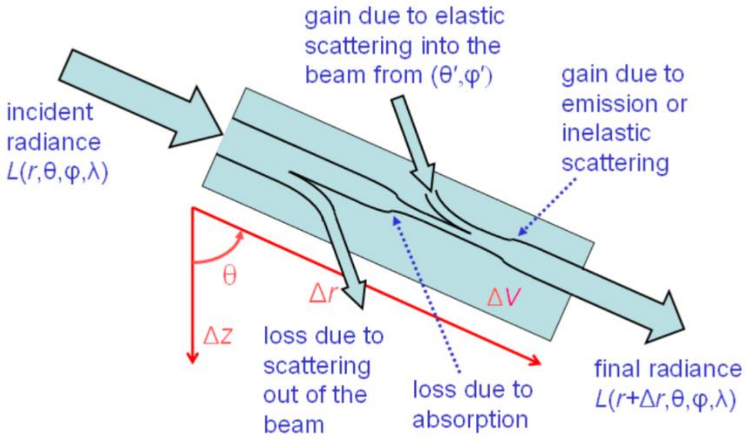
  Related to geometry.



Geometry
The big challenge

$$cos\theta \frac{dL(\lambda,z,\theta,\varphi)}{dz} = -\boldsymbol{c}(\lambda,z)L(\lambda,z,\theta,\varphi) + \int_0^{2\pi}\int_0^{\pi} \boldsymbol{\beta}(\lambda;z,\theta,\varphi;\theta',\varphi')\,L(\lambda,z,\theta',\varphi')sin\theta' d\theta' d\varphi'$$

- **Spatial coordinates** $\vec{r} = (x,y,z)$. Units: m.
- **Angular coordinates** (θ,φ). Units: sr.



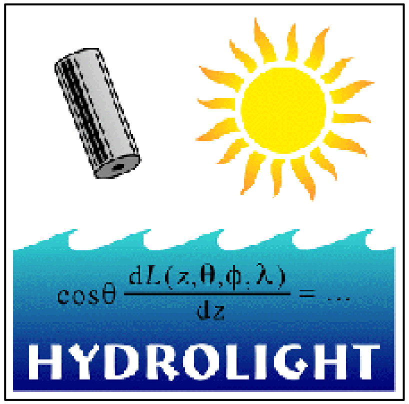
Picture: http://www.oceanopticsbook.info/

Geometric details not known at outdoor conditions

The crux with the RTE
Limited value for practical applications

$$\cos\theta \frac{dL(\lambda, z, \theta, \varphi)}{dz} = -\boldsymbol{c}(\lambda, z) L(\lambda, z, \theta, \varphi) + \int_0^{2\pi} \int_0^{\pi} \boldsymbol{\beta}(\lambda; z, \theta, \varphi; \theta', \varphi')\, L(\lambda, z, \theta', \varphi') \sin\theta'\, d\theta'\, d\varphi'$$

- RTE cannot be solved exactly
  I.e., no analytical equation exists without derivative and integral.
- All calculations are approximations and computationally complex
  See [1] for an overview of the developed methods to solve the RTE and the RT codes currently available for a coupled atmosphere-ocean system.
- **HYDROLIGHT** is the "gold standard" in aquatic optics for accurate RTE modelling
  Commercial software of Sequoia Scientific, Inc.; developed by C. Mobley.
- All methods are too CPU intensive for data analysis
  They are useful for forward simulation and generation of look-up tables.



[1] Zhai, P.-W., Hu, Y., Trepte, C. R., Lucker, P. L., 2009. A vector radiative transfer model for coupled atmosphere and ocean systems based on successive order of scattering method. Opt. Express 17, 2057-2079.

Illumination
Light source is the upper hemisphere

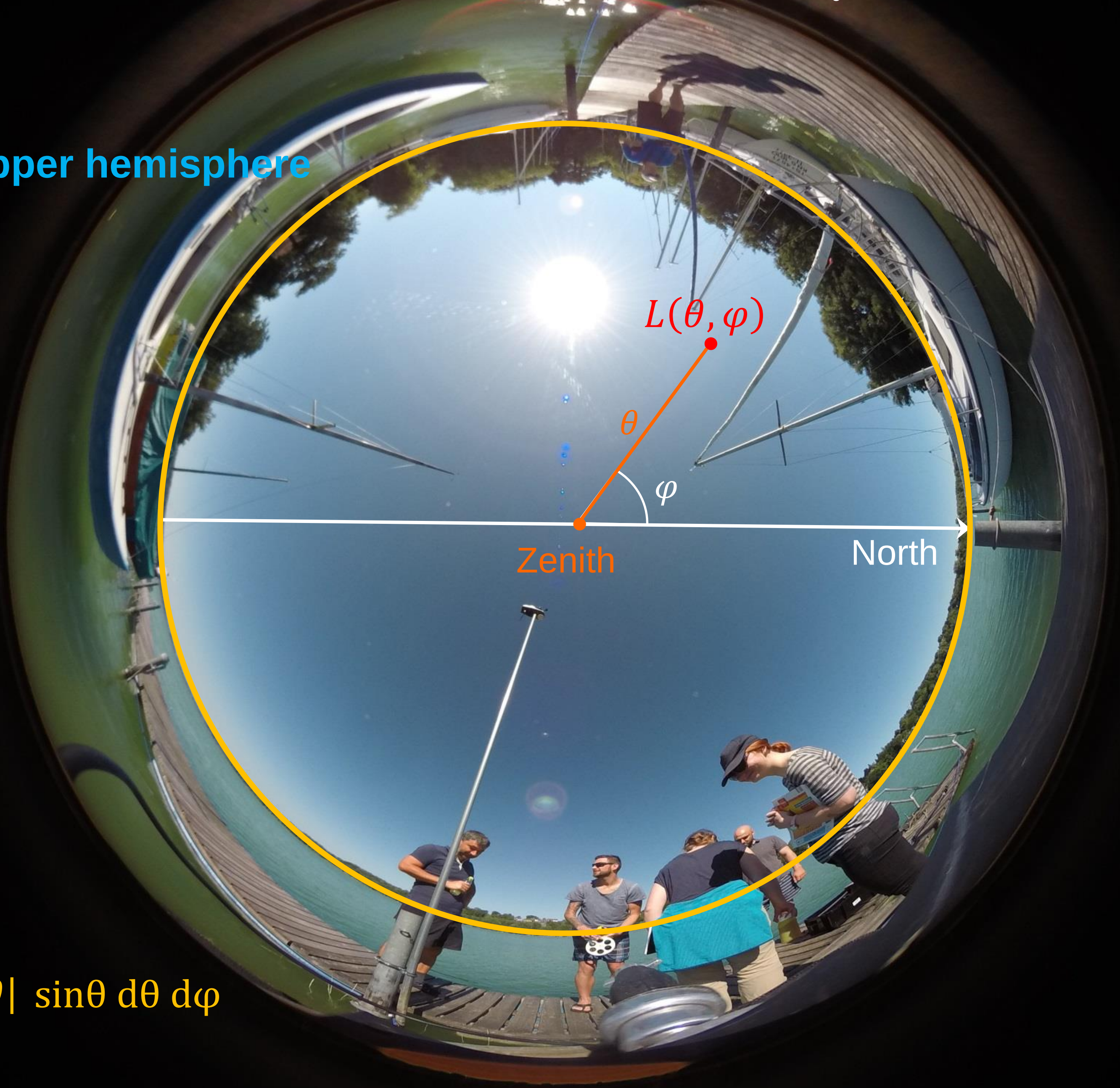
θ: Zenith angle
φ: Azimuth angle

Upper hemisphere:

θ = 0..90° = 0.. $\pi/2$
φ = 0..360° = 0.. 2π

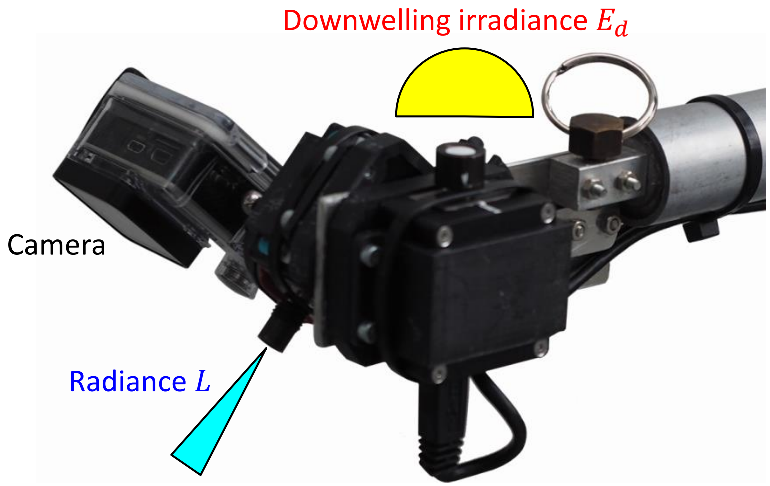
Downwelling irradiance:

$$E_d = \int_0^{2\pi} \int_0^{\pi/2} L(\theta,\varphi) \, |cos\theta| \, \sin\theta \, d\theta \, d\varphi$$



Apparent Optical Properties (AOPs)
Measured at natural illumination conditions

- The downwelling irradiance (E_d) represents the illumination for a plane surface
- Normalization of a measurement with E_d reduces the impact of light source properties (but doesn’t remove it completely)
- Such E_d normalized measurements are called AOPs. Examples:
  - reflectance
  - attenuation coefficient

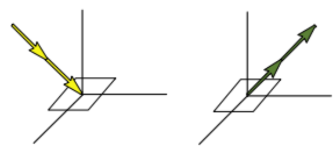
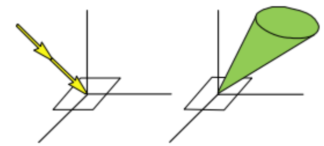
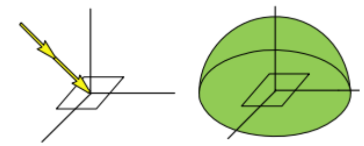
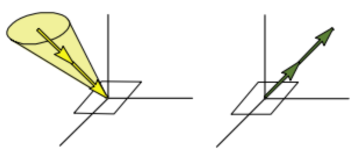
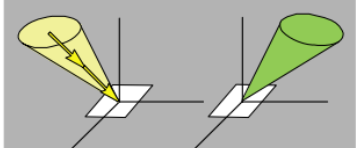
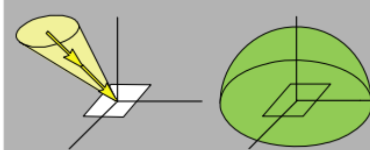
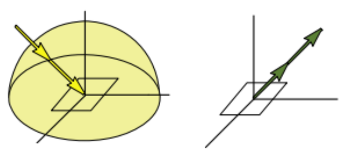
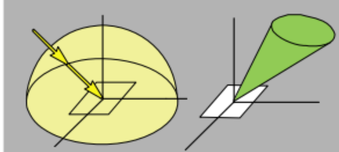
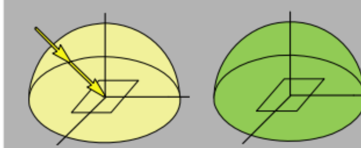


DLR‘s Ocean Optics Sensor System (OOSS) for handheld above-water spectral measurements

Reflectance

Its 9 definitions and terminology in the land and water community

Relation of incoming and reflected radiance terminology used to describe reflectance quantities

Incoming/Reflected	Directional	Conical	Hemispherical
Directional Flux ϕ	BRF Bidirectional CASE 1 	Directional–conical CASE 2 	DHR Directional–hemispherical CASE 3 
Conical Radiance L	Conical–directional CASE 4 	CCRF *in RTE* Biconical CASE 5 	Conical–hemispherical CASE 6 
Hemispherical Irradiance E	HDRF Hemispherical–directional CASE 7 	BRDF R_{rs} Hemispherical–conical CASE 8 	Albedo R Bihemispherical CASE 9 

From: Schaepman-Strub, G., Schaepman, M. E., Painter, T. H., Dangel, S., Martonchik, J. V., 2006. Reflectance quantities in optical remote sensing – definitions and case studies. Remote Sens. Environ. 103, 27-42.

Bio-optical models
Relationships between AOPs, IOPs and concentrations

- Irradiance reflectance (Gordon 1979: i = 1..3; Albert and Mobley 2003: i = 1..4)

$$R(\lambda) = \frac{E_u(\lambda)}{E_d(\lambda)} = \sum_i f_i \left(\frac{b_b(\lambda)}{a(\lambda) + b_b(\lambda)} \right)^i$$

- Remote sensing reflectance (Lee et al. 1998, 1999: i = 1..2; Albert and Mobley 2003: i = 1..4)

$$R_{rs}(\lambda) = \frac{L_u(\lambda)}{E_d(\lambda)} = \sum_i g_i \left(\frac{b_b(\lambda)}{a(\lambda) + b_b(\lambda)} \right)^i$$

- $a(\lambda)$: absorption coefficient of water.
  Depends on type and concentration of water constituents.

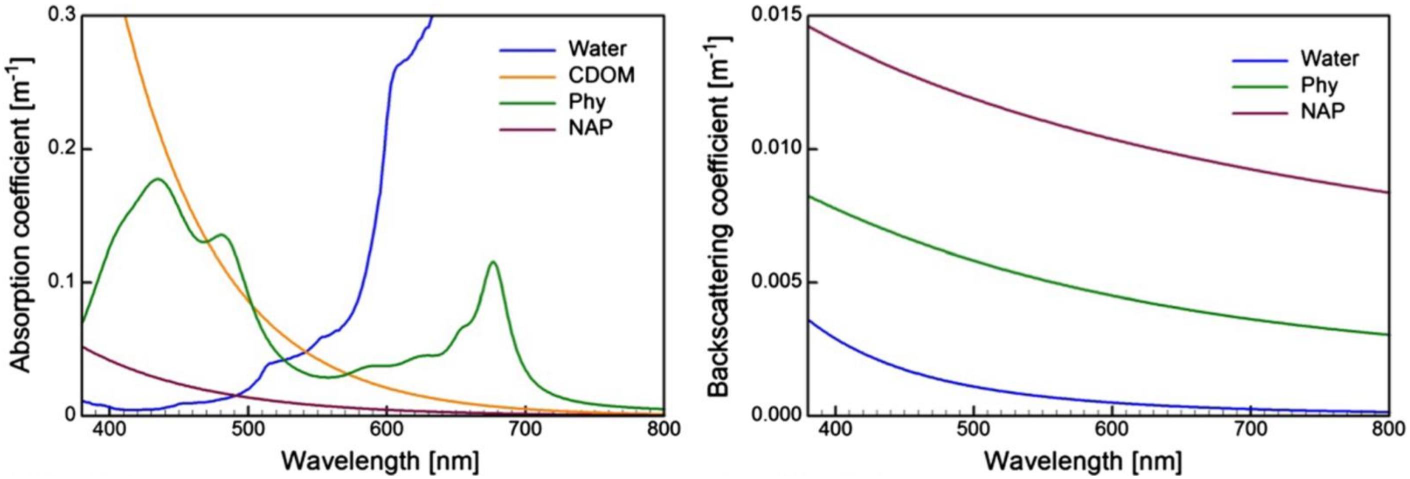
- $b_b(\lambda)$: backscattering coefficient of water.
  Depends on type and concentration of water constituents.

- f_i, g_i: Geometry factors.
  Depend on sun zenith angle, viewing direction, wind speed, $a(\lambda)$ and $b_b(\lambda)$.
  WASI uses the parameterization of Albert and Mobley (2003).

Water constituents
Three main groups

Water contains a huge variety of different molecules and particles.
These are usually grouped into three classes:

- **CDOM:** colored dissolved organic matter. Other names: Gelbstoff, yellow substance, gilvin.
- **Phy:** phytoplankton
- **NAP:** non-algal particles. Other name: detritus.



Examples of optical properties of water and its major constituents.

Picture: C. Giardino et al. (2018): Imaging Spectrometry of Inland and Coastal Waters: State of the Art, Achievements and Perspectives. *Surveys in Geophysics.*

Inherent optical properties (IOPs)
Parameterization in bio-optical models

IOPs are additive:

$$a(\lambda) = a_W(\lambda) + C_{CDOM} \cdot a^*_{CDOM}(\lambda) + C_{phy} \cdot a^*_{phy}(\lambda) + C_{NAP} \cdot a^*_{NAP}(\lambda)$$

$$b_b(\lambda) = b_{b,W}(\lambda) + C_{phy} \cdot b^*_{b,phy}(\lambda) + C_{NAP} \cdot b^*_{b,NAP}(\lambda)$$

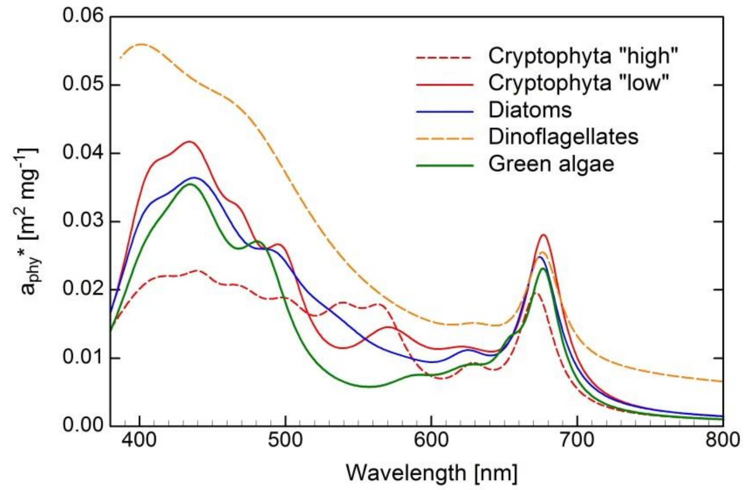
C_x: concentration of component *x*

$a^*_x(\lambda)$: specific absorption coefficient of component *x*

$b^*_{b,x}(\lambda)$: specific backscattering coefficient of component *x*

Concentration normalized IOPs ($a^*_x(\lambda)$, $b^*_{b,x}(\lambda)$) are called **SIOPs** (specific inherent optical properties).

WASI can use up to 6 classes of phytoplankton and 2 classes of NAP simultaneously.



$a^*_{phy}(\lambda)$ from WASI data base

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Albert, A., Mobley, C. D., 2003. An analytical model for subsurface irradiance and remote sensing reflectance in deep and shallow case-2 waters. Opt. Express 11, 2873-2890.

Gordon, H. R., 1979. Diffuse reflectance of the ocean: the theory of its augmentation by chlorophyll a fluorescence. Appl. Opt. 21, 2489-2492.

Lee, Z.-P., Carder, K. L., Mobley, C. D., Steward, R. G., Patch J. S., 1998. Hyperspectral remote sensing for shallow waters: 1. A semianalytical model. Appl. Opt. 37, 6329-6338.

Lee, Z.-P., Carder, K. L., Mobley, C. D., Steward, R. G., Patch, J. S., 1999. Hyperspectral remote sensing for shallow waters: 2. Deriving bottom depths and water properties by optimization. Appl. Opt. 38, 3831-3843.

Schaepman-Strub, G., Schaepman, M. E., Painter, T. H., Dangel, S., Martonchik, J. V., 2006. Reflectance quantities in optical remote sensing – definitions and case studies. Remote Sens. Environ. 103, 27-42.

Zhai, P.-W., Hu, Y., Trepte, C. R., Lucker, P. L., 2009. A vector radiative transfer model for coupled atmosphere and ocean systems based on successive order of scattering method. Opt. Express 17, 2057-2079.

Further reading

P. Gege (2017): Radiative transfer theory for inland waters. In: Mishra D.R., Ogashawara I., Gitelson A.A. (Eds.), Bio-Optical Modelling and Remote Sensing of Inland Waters. Elsevier, p. 27-69. ISBN: 978-0-12-804644-9. DOI: http://dx.doi.org/10.1016/B978-0-12-804644-9.00002-1

C. Giardino, Brando V.E., Gege P., Pinnel N., Hochberg E., Knaeps E., Reusen I., Doerffer R., Bresciani M., Braga F., Foerster S., Champollion N., Dekker A. (2018): Imaging Spectrometry of Inland and Coastal Waters: State of the Art, Achievements and Perspectives. *Surveys in Geophysics.* https://doi.org/10.1007/s10712-018-9476-0

Mobley, C. D., Boss, E., Roesler, C., 2018. Ocean Optics Web Book. http://www.oceanopticsbook.info/

WASI
Water color simulator

- ✓ Simulation and analysis of spectral measurements in water ($a, R_{rs}, E_d, L_u, \ldots$)
- ✓ Bio-optical models for deep water [1] and shallow water [2]
- ✓ Analytical model of downwelling irradiance
- ✓ Elementary data base of SIOPs, bottom substrates, atmospheric absorbers
- ✓ Physically traceable and transparent calculation steps

[1] P. Gege (2004): The water colour simulator WASI: An integrating software tool for analysis and simulation of optical in-situ spectra. *Computers & Geosciences 30, 523–532.*

[2] P. Gege, A. Albert (2006): A tool for inverse modeling of spectral measurements in deep and shallow waters. *In: L.L. Richardson and E.F. LeDrew (Eds): "Remote Sensing of Aquatic Coastal Ecosystem Processes: Science and Management Applications", Kluwer book series: Remote Sensing and Digital Image Processing, Springer, ISBN 1-4020-3967-0, pp. 81-109.*

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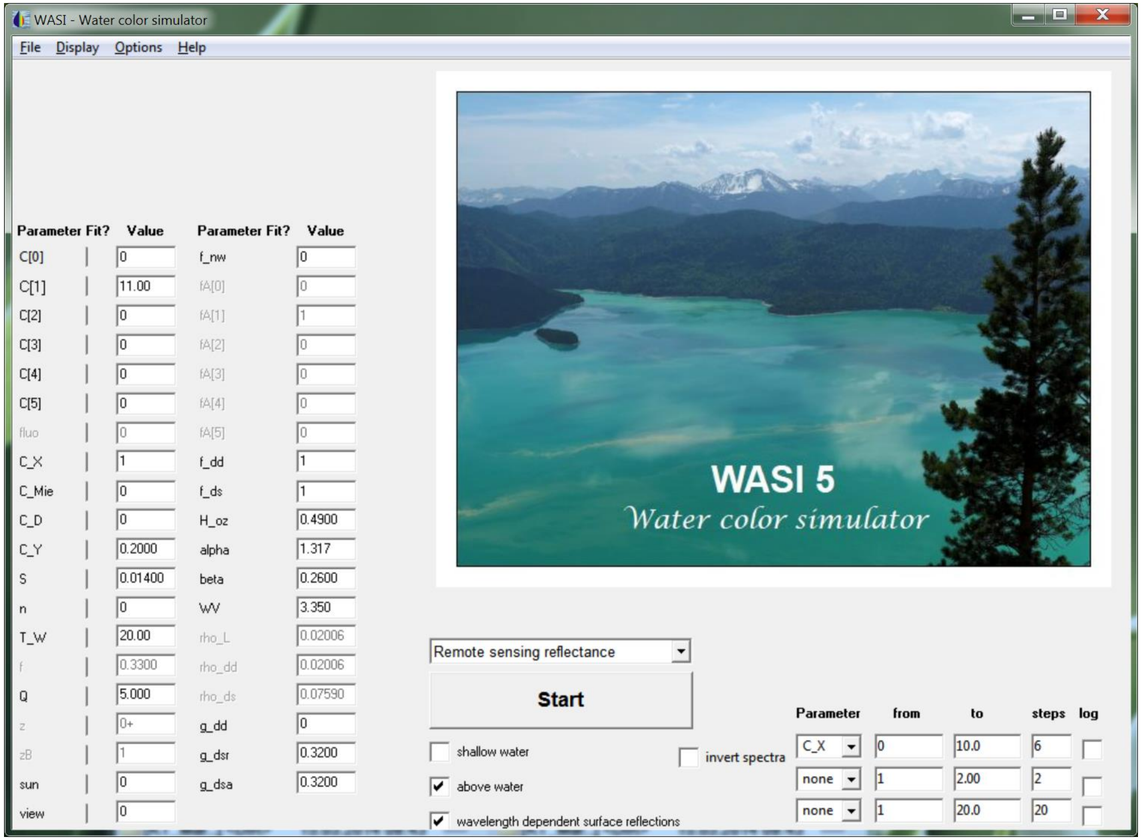
WASI exercise
Forward modelling



- Data base: structure, visualization, local adaptation
- Implemented models
- Model parameters and constants
- Forward simulation: initialization, visualization, loops, export

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