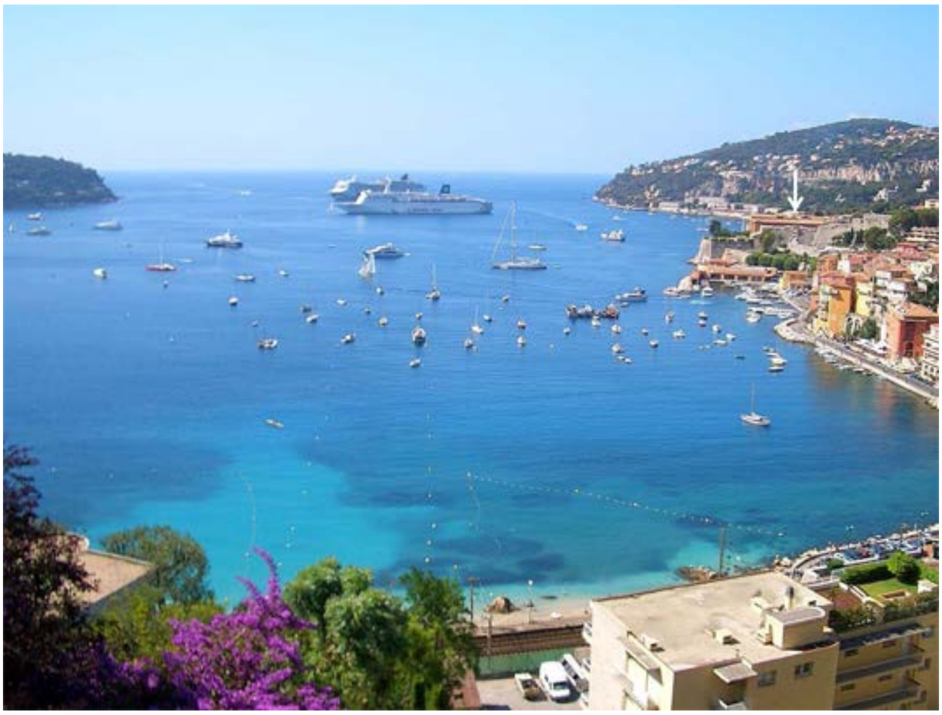
5th IOCCG Summer Lecture Series

Frontiers in Ocean Optics and Ocean Colour Science

https://ioccg.org/what-we-do/training-and-education/ioccg-sls-2022/

Laboratoire d'Océanographie de Villefranche (LOV) /
Institut de la Mer de Villefranche (IMEV),
Villefranche-sur-Mer, 18-29 July 2022



In addition to recurrent support from all IOCCG contributing agencies, specific additional contributions are acknowledged for the 2022 edition, from the following agencies and institutions:

Our hosts

IMEV LOV

Our sponsors

Copernicus — Framework Partnership Agreement for Copernicus User Uptake

cnes — Centre National d'Études Spatiales

IOCCG — International Ocean Colour Coordinating Group

OCB — Ocean Carbon & Biogeochemistry

EUMETSAT

museum — Royal Belgian Institute of Natural Sciences

SEA-BIRD SCIENTIFIC

It is also noted that all lecturers provide their time as in-kind, which is to be credited to their institutions (as listed in Appendix 1 of this report)

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1 Introduction

The Institut de la Mer de Villefranche (IMEV) and the Laboratoire d'Océanographie de Villefranche (LOV), located in Villefranche-sur-Mer, France, hosted the fifth edition of the International Ocean Colour Coordinating Group (IOCCG) Summer Lecture Series (SLS).

The IOCCG-SLS is dedicated to high-level training in the fundamentals of ocean optics, bio-optics, and ocean colour remote sensing. This was a two-week intensive course, delivered by 11 lecturers on the fundamentals of ocean optics as well as cutting edge research (see Appendix 1: List of teaching staff). The main objective was to focus on current critical issues in ocean colour science. 24 students from 14 different countries were selected from a total of 145 applications coming from all around the world (see Appendix 2: List of selected students).

The selection of candidates was based on their motivation statement, knowledge of remote sensing, current area of research, previous training opportunities, and potential to apply the knowledge and skills that they would gain with the SLS to their future research and/or teaching. Most of the trainees were PhD students and post-doctoral researchers, along with early career scientists wanting to gain more experience in the field of ocean colour. The participants came from a broad range of backgrounds but were all familiar with at least some domains of bio-optics and ocean colour science and had a solid understanding of ocean colour remote sensing.

2 Course organisation

The SLS2022 brought together remote sensing specialists from various fields of ocean colour so the course content covered a wide range of topics based on theory, practical sessions and specific applications.

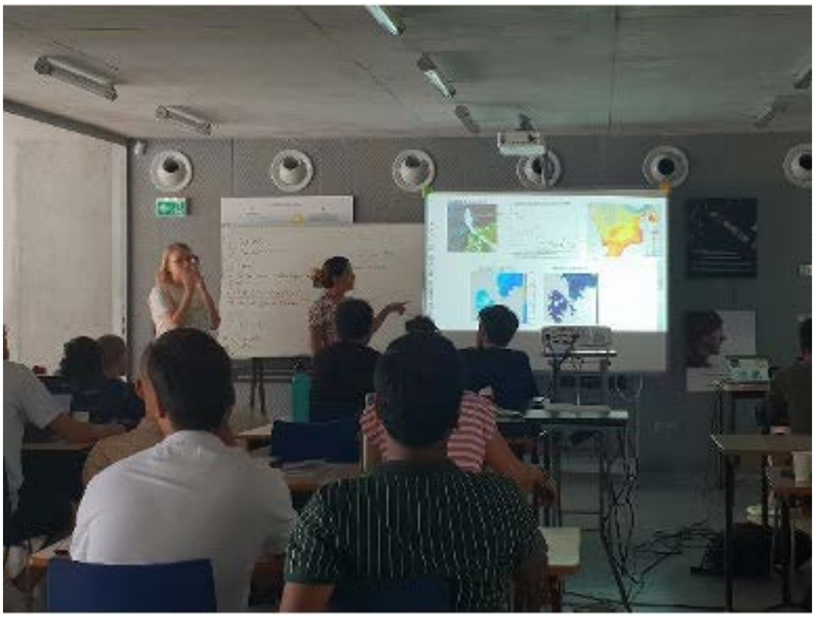
The format of the Summer Lecture Series included a series of lectures as well as hands-on practical sessions and open group discussion sessions on pre-arranged topics to allow interaction between the students and lecturers. The first week of the SLS was dedicated to fundamentals in optics, bio-optics and ocean colour science. It also included hands-on practical sessions. This first week was aimed to make sure that all students would be capable of benefiting from the second week of lectures, which was on different advanced aspects of ocean colour remote sensing, inversion techniques, and applications (see programme in Appendix 3 and lecture synopses in Appendix 4). The objective was to provide opportunities for students to improve their skills and knowledge, which they could then apply to their current and future research.

The course was opened with a welcoming address by the LOV Director, Dr. Rodolphe Lemée. This was followed by a summary of IOCCG activities and a review of the course organization by the SLS2022 coordinator, Prof. David Antoine. After this session the students all introduced themselves by giving a brief presentation on their current area of research (2 slides, 5 minutes). This was an opportunity to get acquainted with the participants' academic backgrounds, their current positions, and their experiences. It was also a chance for the students to make contacts and discuss ideas with people with similar interests and share their work and passion.

Then the programme unfolded as described in Appendix 3. The first week also included a practical AC lab to understand absorption, scattering, and the colour of the ocean. During these practical sessions students learned how to calibrate the AC instrument, and how to measure absorption by Coloured Dissolved Organic Matter (CDOM) and particulate absorption and attenuation, which helped them to understand how to collect high-quality in situ data and how to interpret the measurements. At the end of the week students were also given an introduction to, and an opportunity to use, the HydroLight radiative transfer model. The second week of the course included a discussion of the AC-lab results, an introduction to Matlab codes for semi analytical inversion, as well as lectures on measurement uncertainties, atmospheric corrections, ocean colour remote sensing in shallow and turbid waters, biogeochemical (BGC) modelling and a practical session on Copernicus data (see Appendix 3 - Course Schedule for full details).

For students to be able to prepare for the course, synopses of all lectures and suggestions for further reading were sent in advance to all participants (see Appendix 4).

Students and lecturers during a lesson offered by David Antoine during the first week of the SLS.

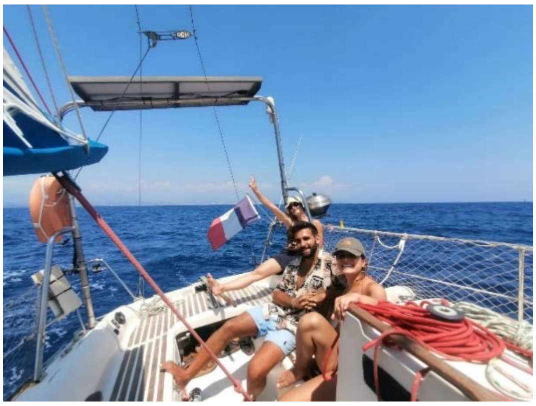


Students presenting their project using satellite data during the last day of the SLS.

Lecture slots included time for interactions with the students. Most lecturers attended the lecture slots of their colleagues, which allowed for guiding the "question time" at the end of each lecture. In addition to the group discussion session, the students were also able to network with the experts in the field on a one-to-one basis during coffee breaks and lunches to discuss and refine aspects of their own research, which most students found immensely helpful.

Many students noted that one of the most important parts of the SLS was being able to make connections with some of the best researchers in the field of ocean optics. Now students know where to start looking for information and who can help them to get answers to their questions. The social events (welcome cocktail and dinner) were additional opportunities of interactions among lecturers and students, along with the free time they had during the first week of the course on Saturday afternoon and Sunday.

For the first time since the beginning of the IOCCG SLS, students were hosted in a new building that was built on the IMEV campus, the Jules Barrois Accommodation Centre. It greatly contributed to their bonding and team spirit building, as well as to facilitate the organization of the courses. Students appreciated being housed on site and sharing social moments apart from the classes.

Students on a boat trip during the weekend (left picture) and eating together at the restaurant (right picture).

3 Course evaluation

At the end of the course, students were given the opportunity to share their experience on various aspects of the lectures and practical course organization via an online anonymous feedback questionnaire.

The responses have been handed over to the IOCCG executive committee. Students' considerations are an opportunity for organisers to improve subsequent editions.

4 Conclusion

The 2022 IOCCG summer lecture series was a success with the students. The journey was an outstanding and enriching experience for them, both on the professional and personal levels. They not only learned technical skills but also built relationships that will last through their careers.

As for the previous SLS sessions, all presentations were audio and video recorded and these recordings, as well as all PowerPoint presentations, are available online at: https://ioccg.org/what-we-do/training-and-education/ioccg-sls-2022/

5 Acknowledgments

The IOCCG thanks all the lecturers and students for their contributions and cooperation, for their enthusiastic knowledge sharing, and for their time during the course. We are grateful to the contributions from all our sponsors, and to all organizations that provided and managed financial support for the participants. They made this training course possible.

The 2022 Summer Lecture Series benefited from the following specific financial or in-kind support from several institutions and agencies:

- **Institut de la Mer, de Villefranche (IMEV)**, France, for providing the lecture room, laboratory facilities and assistance with practicals, and subsidised student accommodation.

- **French National Space Agency (CNES),** for funding the SLS logistic assistant role, student's accommodation, lecturers' travel costs, the audio and video recording of lectures and other operating expenses.
- **Centre National de la Recherche Scientifique (CNRS),** France, for funding and administrative support.
- The **"EU Framework Partnership Agreement for Copernicus Users Uptake" (FP-CUP)**, for funding students' and lecturers' travel costs, the audio and video recording of lectures and other operating expenses.
- **EUMETSAT (European Organisation for the Exploitation of Meteorological Satellites)**, for funding students' travel expenses and full support to EUMETSAT lecturers.
- **International Ocean Colour Coordinating Group (IOCCG[*])**, for administrative support, website maintenance and funding students' and lecturers' travel costs.
- **Laboratoire d'Océanographie de Villefranche (LOV)**, France, for administrative support.
- **Ocean Carbon & Biogeochemistry (OCB)** Project Office, Woods Hole, MA, USA, for funding students' travel costs.
- **Royal Belgian Institute of Natural Sciences (RBINS),** for support to two lecturers.
- **Sea-Bird Scientific**, for providing an AC-S Spectral Absorption and Attenuation Sensor for the practical sessions
- All the IOCCG funding agencies.
- All lecturers' institutions for the lecturers' time provided in-kind (list below).

The organizing team would also like to thank the following key people for their help in the organization and their support during the course:

- David Antoine for motivating, orchestrating and overseeing the 2022 SLS, including developing the agenda and selecting the invited lecturers.
- Louise Janneau, for all aspects of logistical assistance on site, including helping students and lecturers with practical matters related to their stay.
- Raisha Lovindeer, IOCCG Scientific Officer, and Venetia Stuart, IOCCG executive scientist, for the overall organisation and coordination and managing the overall budget and financial support for lecturers.
- The IOCCG Selections Committee (Raisha Lovindeer, Venetia Stuart, Cara Wilson, Frédéric Mélin, David Antoine) for their work in rating and selecting students from the 145 applications.
- Rodolphe Lemée, Director, LOV, for hosting the SLS2022 at the Villefranche Oceanographic Laboratory
- Elisabeth Christians, Director, IMEV, for hosting the SLS2022 at the Institut de la Mer de Villefranche
- Heather Benway, Executive Officer, Ocean Carbon & Biogeochemistry Program, for management of OCB financial support to 5 students
- Linda Féré and Amandine Courtois, LOV secretariat, for management of financial support to students
- Véronique Gourbaud, management of LOV accommodation for students
- The staff of the LOV restaurant and the staff in charge the LOV accommodation and housekeeping

- The LOV IT team
- All the lecturers for their time and support during the course

6 Appendix 1 –Teaching staff

Lecturer	Institution	Country
David Antoine	Curtin University, Perth	Australia
Emmanuel Boss	University of Maine, ME	United States
Collin Roesler	Bowdoin College, ME	United States
Mike Twardowski	Harbor Branch Ocean. Inst. Florida Atlantic University	United States
Dariusz Stramski	Scripps Institution of Oceanography, San Diego, CA	United States
Ali Chase	University of Washington, Seattle, WA	United States
John Hedley	Environmental Computer Science Ltd, Tiverton, Devon	United Kingdom
Kevin Ruddick	Royal Belgian Institute of Natural Sciences	Belgium
Quinten Van Hellemont	Royal Belgian Institute of Natural Sciences	Belgium
Hayley Evers-King	EUMETSAT, Darmstadt	Germany
Ana Ruescas	Brockmann Consult GmbH and Universitat da València	Spain

7 Appendix 2 – Selected students

Lecturer	Institution	Country
Isabel De Sousa Brandão	Royal Netherlands Institute for Sea Research (NIOZ)	Netherlands
Anastasia Papadopoulou	Democritus University of Thrace	Greece
Sejal Pramlall	Spectral Remote Sensing Laboratory, University of Victoria	Canada
Giulia Sent	MARE-ULisboa	Portugal
Esther Patricia Urrego	Laboratory for Earth Observation, Image Processing Laboratory (IPL), University of Valencia	Spain
Masuma Chowdhury	Quasar Science Resources (Madrid) and University of Cadiz	Spain
Chandanlal Parida	Indian Institute of Science (IISc)	India
Premkumar Rameshkumar	Annamalai University	India
Yulun Wu	University of Ottawa	Canada
Shun Bi	Helmholtz-Zentrum Hereon	Germany
Žarko Kovač	Faculty of Science, University of Split	Croatia
Samuel Martin	Laboratoire d'Océanographie de Villefranche (LOV)	France
Flavien Petit	Institut de la Mer de Villefranche (Sorbonne Université)	France
Bastian Raulier	Université Laval, International Research Laboratory Takuvik, Quebec	Canada
Jakob Weis	University of Tasmania and Australian Research Council Centre of Excellence for Climate Extremes	Australia
Muhammad Asim	Department of Physics and Technology, The Arctic University of Norway (UiT), Tromsø	Norway

Kyeong-Sang Lee	Korea Institute of Ocean Science & Technology	South Korea
Elinor Tessin	University of Bergen	Norway
Patrick Clifton Gray	Duke Marine Lab, Nicholas School of the Environment	USA
Anvita Kerkar	Harbor Branch Oceanographic Institute, Florida	USA
Chintan Maniyar	Department of Geography, University of Georgia	USA
Md Masud-Ul-Alam	The University of Georgia, USA and BSMR Maritime University, Bangladesh	Bangladesh and the USA
Anna Elizabeth Windle	University of Maryland Center for Environmental Science, Horn Point Laboratory	USA

8 Appendix 3 – Course Schedule

Fifth IOCCG Summer Lecture Series, Institut de la Mer de Villefranche-sur-Mer, France		
WEEK #1		
Date	**Subject**	**Lecturer(s)**
Sunday 17 July 2022	Participants arrival	
Introductions, Fundamentals		
Monday 18 July 2022		
09h00 - 09h10	Welcome address	Rodolphe Lemée, Director, LOV
09h10 - 09h40	Overview of course content, logistical information, introduction to IOCCG	David Antoine, lectures coordinator
09h40 - 10h40	Brief student presentations (~5 min each) - (12 students)	Students
10h40 - 11h15	Coffee Break	
11h15 - 12h15	Brief student presentations (~5 min each) - (12 students)	Students
12h30 - 14h00	Lunch break	
14h00 - 15h30	The nature and properties of light	Dariusz Stramski
15h30 - 16h00	Coffee Break	
16h00 - 18h00	Practical: playing with light	Emmanuel Boss, Collin Roesler
Inherent optical properties, scattering		
Tuesday 19 July 2022		
09h00 - 10h30	Interaction of light and matter	Dariusz Stramski
10h30 - 11h00	Coffee Break	
11h00 - 12h30	Optics of marine particles	Dariusz Stramski
12h30 - 14h00	Lunch break	
14h00 - 15h30	Introduction to IOPs and their measurement (fundamentals)	Collin Roesler
15h30 - 16h00	Coffee Break	

16h00 - 17h30	Ocean Scattering	Mike Twardowski
18h30 - 20h30	Welcome drink	
Practicals (“AC-labs”), optics of particles		
Wednesday 20 July 2022		
09h00 - 10h30	Practical: AC-lab (1/4)	Mike Twardowski / Collin Roesler / Emmanuel Boss
10h30 - 11h00	Coffee Break	
11h00 - 12h30	Practical: AC-lab (2/4)	Mike Twardowski / Collin Roesler / Emmanuel Boss
12h30 - 14h00	Lunch break	
14h00 - 15h30	Challenges of IOP measurements	Emmanuel Boss
15h30 - 16h00	Coffee Break	
16h00 - 17h30	IOP proxies for biogeochemical properties in the ocean	Collin Roesler
Radiometry, Apparent optical properties and radiative transfer		
Thursday 21 July 2022		
09h00 - 10h30	Radiometry and apparent optical properties (AOPs), fundamentals	David Antoine
10h30 - 11h00	Coffee Break	
11h00 - 12h30	Introduction to Hydrolight	John Hedley
12h30 - 14h00	Lunch break	
14h00 - 15h30	Practical Session - HydroLight Lab	John Hedley
15h30 - 16h00	Coffee Break	
16h00 - 17h30	Practical Session - HydroLight Lab	John Hedley
Practicals (“AC-labs”), IOPs and radiometry continued		
Friday 22 July 2022		
09h00 - 10h30	Practical: AC-lab (3/4)	Mike Twardowski / Collin Roesler / Emmanuel Boss
10h30 - 11h00	Coffee Break	
11h00 - 12h30	Practical: AC-lab (4/4)	Mike Twardowski / Collin Roesler / Emmanuel Boss
12h30 - 13h45	Lunch break	

14h00 - 15h30	Radiometry, apparent optical properties, measurements & uncertainties	David Antoine
15h30 - 16h00	Coffee Break	
16h00 - 17h30	Inexpensive but robust approaches for determining optical and biogeochemical properties	Mike Twardowski / Emmanuel Boss
Measurements: satellite OCR		
Saturday 23 July 2022		
09h00 - 10h30	Past, present and future of satellite OCR	David Antoine
10h30 - 11h00	Coffee Break	
11h00 - 12h30	General discussion feedback on the 1st week lecture, etc	ALL
12h30 - 14h00	Lunch break	
Afternoon	FREE	
Sunday 24 July 2022		
FREE		

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WEEK #2		
Date	**Subject**	**Lecturer(s)**
Atmospheric corrections, water quality from space, hyperspectral remote sensing		
Monday 25 July 2022		
09h00 - 10h30	Atmospheric corrections of satellite OCR observations (1/2)	David Antoine
10h30 - 11h00	Coffee Break	
11h00 - 12h30	Atmospheric corrections of satellite OCR observations (2/2)	David Antoine
12h30 - 14h00	Lunch break	
14h00 - 15h30	Basics on OCR inversion algorithms	Collin Roesler
15h30 - 16h00	Coffee Break	

16h00 - 17h30	Shallow water remote sensing	John Hedley
Tuesday 26 July 2022		
09h00 - 10h30	Perspectives on hyperspectral optics and remote sensing	Alison Chase
10h30 - 11h00	Coffee Break	
11h00 - 12h30	Phytoplankton community composition derived from optics and remote sensing: Approaches, challenges, and next steps	Alison Chase
12h30 - 14h00	Lunch break	
14h00 - 15h30	NPP; Carbon export; climate-driven changes	David Antoine
15h30 - 16h00	Coffee Break	
16h00 - 17h30	HABS, and use of OCR in biogeochemical modelling	Hayley Evers-King
19h00- late	Group diner	
COPERNICUS PRACTICALS		
Wednesday 27 July 2022		
09h00 - 10h30	Practical on Copernicus datasets	Ana Ruescas, Hayley Evers-King, Quinten Van Hellemont, Kevin Ruddick
10h30 - 11h00	Coffee Break	
11h00 - 12h30	Practical on Copernicus datasets	
12h30 - 14h00	Lunch break	
14h00 - 15h30	Practical on Copernicus datasets	
15h30 - 16h00	Coffee Break	
16h00 - 17h30	Practical on Copernicus datasets	
COPERNICUS PRACTICALS		
Thursday 28 July 2022		
09h00 - 10h30	Practical on Copernicus datasets	

10h30 - 11h00	Coffee Break	Ana Ruescas, Hayley Evers-King, Quinten Van Hellemont, Kevin Ruddick
11h00 - 12h30	Practical on Copernicus datasets	
12h30 - 14h00	Lunch break	
14h00 - 15h30	Practical on Copernicus datasets	
15h30 - 16h00	Coffee Break	
16h00 - 17h30	Practical on Copernicus datasets	
COPERNICUS PRACTICALS		
Friday 29 July 2022		
09h00 - 10h30	Students present their work from the practicals	Students, with support from Ana Ruescas, Hayley Evers-King, Quinten Van Hellemont, Kevin Ruddick
10h30 - 11h00	Coffee Break	
11h00 - 12h30	Students present their work from the practicals	
CLOSURE - 5th IOCCG Summer Lecture Series		

9 Appendix 4 – Lectures Synopses

9.1 The nature and properties of light

Lecturer: Dariusz Stramski
Monday 18th July, 2pm.

(1.1) Dual wave-particle nature of light
(1.1.1) Classical electromagnetic-wave description of light (Maxwell equations, wavelength, frequency, phase velocity, radiant energy, Poynting vector)
(1.1.2) Particle-photon description of light (photoelectric effect, photon energy, single-photon interference)
(1.1.3) Electromagnetic-photon spectrum
(1.2) Polarization properties of light
(1.3.) Wave-like optical phenomena: interference, reflection, refraction, diffraction

Useful reading material:
Mobley, C. et al., Ocean Optics Web Book, https://www.oceanopticsbook.info/
Mobley, C. The Oceanic Optics Book, https://ioccg.org/wp-content/uploads/2022/01/mobley-oceanicopticsbook.pdf

Textbooks:
Hecht, E., Physics, Brooks/Cole Publishing Co, 1994.
Hecht, E., Optics, Addison-Wesley, 1998.
Johnsen, S. 2012. The Optics of Life, A Biologist's Guide to Light in Nature. Princeton University Press.
Woźniak, B. and J. Dera. 2007. Light Absorption in Sea Water. Springer.
Jonasz, M. and G. R. Fournier. 2007. Light Scattering by Particles in Water. Theoretical and Experimental Foundations. Academic Press.

9.2 Interaction of light and matter

Lecturer: Dariusz Stramski
Tuesday 19th July, 9 am

(2.1) Emission of light/radiant energy, basic radiation laws (Planck, Stefan-Bolzmann & Wien's laws, solar radiation, Earth radiation)
(2.2) Absorption of light/radiant energy (quantized internal energy of atoms and molecules, basic features of absorption by molecular water and pigments)
(2.3) Scattering of light/radiant energy (oscillating dipole, elastic and inelastic scattering, basic features of molecular and particle scattering)

Useful reading material:
Mobley, C. et al., Ocean Optics Web Book, https://www.oceanopticsbook.info/

Mobley, C. The Oceanic Optics Book, https://ioccg.org/wp-content/uploads/2022/01/mobley-oceanicopticsbook.pdf

Textbooks:
Hecht, E., Physics, Brooks/Cole Publishing Co, 1994.
Hecht, E., Optics, Addison-Wesley, 1998.
Johnsen, S. 2012. The Optics of Life, A Biologist's Guide to Light in Nature. Princeton University Press.
Woźniak, B. and J. Dera. 2007. Light Absorption in Sea Water. Springer.
Jonasz, M. and G. R. Fournier. 2007. Light Scattering by Particles in Water. Theoretical and Experimental Foundations. Academic Press.

9.3 Optics of marine particles

Lecturer: Dariusz Stramski
Tuesday 19th July, 11 am

(3.1) Linkage between the single-particle and bulk optical properties
(3.2) Absorption and scattering properties of individual particles
(3.3) Dependence of particle optical properties on physical and chemical characteristics of particles
(3.4) Optical properties of various types of marine particles
(3.5) Understanding the roles of various types of particles in ocean optics: from rudimentary approaches such as chlorophyll-based approach to higher-level approaches such as reductionist approach

Useful reading material:
Mobley, C. et al., Ocean Optics Web Book, https://www.oceanopticsbook.info/
Mobley, C. The Oceanic Optics Book, https://ioccg.org/wp-content/uploads/2022/01/mobley-oceanicopticsbook.pdf
Morel, A. and A. Bricaud. 1981. Theoretical results concerning light absorption in a discrete medium and application to specific absorption by phytoplankton. Deep-Sea Res., 28, 1375-1393.
Bricaud, A. and A. Morel. 1986. Light attenuation and scattering by phytoplanktonic cells: A theoretical modeling. Appl. Opt., 25, 571-580.
Morel, A. and A. Bricaud. 1986. Inherent optical properties of algal cells including picoplankton: Theoretical and experimental results, p. 521-555. In Photosynthetic picoplankton, Can. Bull. Fish. Aquat. Sci. 214.
Stramski, D., and A. Morel. 1990. Optical properties of photosynthetic picoplankton in different physiological states as affected by growth irradiance. Deep-Sea Res., 37, 245-266.
Morel, A. and Y-H. Ahn. 1991. Optics of heterotrophic nanoflagellates and ciliates. A tentative assessment of their scattering role in oceanic waters compared to those of bacterial and algal cells. J. Mar. Res., 49, 177-202.

Stramski, D., and D. A. Kiefer. 1991. Light scattering by microorganisms in the open ocean. Prog. Oceanogr., 28, 343-383.

Mobley, C. D., and D. Stramski. 1997. Effects of microbial particles on oceanic optics: Methodology for radiative transfer modeling and example simulations. Limnol. Oceanogr., 42, 550-560.

Stramski, D., A. Bricaud, and A. Morel. 2001. Modeling the inherent optical properties of the ocean based on the detailed composition of planktonic community. Appl. Opt., 40, 2929-2945.

Terrill, E. J., W. K. Melville, and D. Stramski. 2001. Bubble entrainment by breaking waves and their influence on optical scattering in the upper ocean. J. Geophys. Res., 106, 16815-16823.

Babin, M. and D. Stramski. 2004. Variations in the mass-specific absorption coefficient of mineral particles suspended in water. Limnol. Oceanogr., 49, 756-767.

Stramski, D., and S. B. Woźniak. 2005. On the role of colloidal particles in light scattering in the ocean. Limnol. Oceanogr., 50, 1581-1591.

9.4 Introduction to IOPs and their measurement (fundamentals)

Lecturer: Collin Roesler, bowdoin College, USA
Tuesday 19th July, 2 pm

After delving into the interaction of light and matter, and optics of marine particles, this lecture will place that theory in the context of what is required for accurate measurement of the inherent optical properties (i.e., what we want from a sensor). Then reality set in and places physical constraints on those specification (i.e., what we settle for). Examples of commonly implemented measurement strategies for in situ measurement of absorption and attenuation, as well as discrete benchtop measurement of particulate absorption will be explored.

In addition to the materials recommended in the preceding lectures, other useful information can be found here:

Kostakis, I., Twardowski, M., Roesler, C., Röttgers, R., Stramski, D., McKee, D., Tonizzo, A. and Drapeau, S. (2021), Hyperspectral optical absorption closure experiment in complex coastal waters. Limnol Oceanogr Methods, 19: 589-625. https://doi.org/10.1002/lom3.10447

Roesler, C. S. and E. Boss, 2008. In situ measurement of the inherent optical properties (IOPs) and potential for harmful algal bloom detection and coastal ecosystem observations. In: Real-Time Coastal Observing Systems for Ecosystem Dynamics and Harmful Algal Bloom, M. Babin, C.S. Roesler and J.J. Cullen, eds. UNESCO Publishing, Paris, France, pp. 153-206. http://misclab.umeoce.maine.edu/boss/classes/SMS_598_2012/Roesler_Boss_final.pdf

Roesler, C. S., D. Stramski, E. D'Sa, R.Röttgers, and R. A. Reynolds. 2018. Chapter 5: Spectrophotometric measurements of particulate absorption using filter pads. IOCCG Protocol Series (2018). Inherent Optical Property Measurements and Protocols: Absorption Coefficient, Neeley, A. R. and Mannino, A. (eds.), IOCCG Ocean Optics and Biogeochemistry Protocols for Satellite Ocean Colour Sensor Validation, Volume 1.0, IOCCG, Dartmouth, NS, Canada https://ioccg.org/wp-content/uploads/2020/09/absorption_protocol_final-incl-cover_rev.pdf

Stramski, D., R. A. Reynolds, S. Kaczmarek, J. Uitz, and G. Zheng. 2015. Correction of pathlength amplification in the filter-pad technique for measurements of particulate absorption coefficient in the visible spectral region," Appl. Opt. 54: 6763-6782. https://doi.org/10.1364/AO.54.006763

9.5 Ocean Scattering

Lecturer: Mike Twardowski, Professor, Harbor Branch Oceanographic Institute, Ft. Pierce, Florida, USA
Tuesday 19th July 4 pm

This lecture will provide more detail on the Inherent Optical Property of Scattering, ranging from theory, to measurement and closure, to interpretation in terms of ocean biogeochemistry. Background material for the lectures can be found in section 3.8 of Mobley (1994) Light and Water, and in Ch. 4 of Kirk (1994) Light and Photosynthesis in Aquatic Ecosystems.

Part 1: Scattering background
Theory, definitions, and sources of scattering in water will be reviewed in this lecture. Angular, spectral, and polarization properties of scattering will be discussed. A detailed examination of aspects involved in measuring scattering will be provided, including technological considerations.

Part 2: Interpretation of scattering
Distributions, variability, and closure for scattering properties will be discussed. State-of-the-art knowledge in measurement of the volume scattering function and the relation of scattering to ocean biogeochemical properties will be presented. Various applications for scattering will be briefly touched on, including passive and active remote sensing, particle field characterization, and imaging. The lecture will conclude with a discussion of current issues and gaps in our understanding of ocean scattering.

References:
Stramski, D., and Kiefer, D. A. 1991. Light scattering by microorganisms in the open ocean. Progress in Oceanography, 28, 343–383.

Stramski, D. E. Boss, D. Bogucki, and K. Voss. 2004. The role of seawater constituents in light backscattering in the ocean. Progress in Oceanography, 61:27–56.

Sullivan, J., M. Twardowski, J.R.V. Zaneveld, and C. Moore. 2013. Measuring optical backscattering in water, In: A. Kokhanovsky (Ed), Light Scattering Reviews 7: Radiative Transfer and Optical Properties of Atmosphere and Underlying Surface, Springer Praxis Books, DOI 10.1007/978-3-642-21907-8_6, pp. 189-224.

Twardowski, M.S., E. Boss, J.B. Macdonald, W.S. Pegau, A.H. Barnard, and J.R.V. Zaneveld. 2001. A model for estimating bulk refractive index from the optical backscattering ratio and the implications for understanding particle composition in Case I and Case II waters. Journal of Geophysical Research, 106(C7):14,129-14,142.

Twardowski, M.S., H. Claustre, S.A. Freeman, D. Stramski, and Y. Huot. 2007. Optical backscattering properties of the "clearest" natural waters. Biogeosciences, 4, 1041–1058, www.biogeosciences.net/4/1041/2007/.

Twardowski, M., X. Zhang, S. Vagle, J. Sullivan, S. Freeman, H. Czerski, Y. You, L. Bi, and G. Kattawar. 2012. The optical volume scattering function in a surf zone inverted to derive sediment and bubble particle subpopulations, Journal of Geophysical Research, 117, C00H17, doi:10.1029/2011JC007347.

9.6 Challenges of IOP measurements

Lecturer: Prof Emmanuel Boss, University of Maine

Wednesday 20th July, 2pm

The premise of this lecture is that we rarely measure the quantity that we are interested in and that the act of measuring can change what we measure. In this lecture I will provide examples of IOP measurements spanning from the beam attenuation via the backscattering coefficients to absorption using varying methods of measurements (from profiling floats to flow-through systems) where significant challenges in obtaining the IOP in question, exist. The different problems associated with different ways of measurement will be discussed. The bottom line emphasized is that w/o using different types of measurements (a process known as closure) we cannot evaluate the likely uncertainty in the data we collect.

References:

IOCCG Protocol Series (2018). Inherent Optical Property Measurements and Protocols: Absorption Coefficient, Neeley, A. R. and Mannino, A. (eds.), IOCCG Ocean Optics and Biogeochemistry Protocols for Satellite Ocean Colour Sensor Validation, Volume 1.0, IOCCG, Dartmouth, NS, Canada. http://dx.doi.org/10.25607/OBP-119

IOCCG Protocol Series (2019). Beam Transmission and Attenuation Coefficients: Instruments, Characterization, Field Measurements and Data Analysis Protocols. Boss, E., Twardowski, M., McKee, D., Cetinić, I. and Slade, W. IOCCG Ocean Optics and Biogeochemistry Protocols for Satellite Ocean Colour Sensor Validation, Volume 2.0, edited by A. Neeley and I. Cetinić, IOCCG, Dartmouth, NS, Canada. http://dx.doi.org/10.25607/OBP-458

IOCCG Protocol Series (2019). Inherent Optical Property Measurements and Protocols: Best Practices for the Collection and Processing of Ship-Based Underway Flow-Through Optical Data. Boss, E., Haëntjens, N., Ackleson, S., Balch, B., Chase, A., Dall'Olmo, G., Freeman, S., Liu, Y., Loftin, J., Neary, W., Nelson, N., Novak, M., Slade, W., Proctor, C., Tortell, P., and Westberry. T. IOCCG Ocean Optics and Biogeochemistry Protocols for Satellite Ocean Colour Sensor Validation, Volume 4.0, edited by A. R. Neeley and A. Mannino, IOCCG, Dartmouth, NS, Canada.

J. Sullivan, M. Twardowski, J. R. V. Zaneveld, and C. Moore, "Measuring optical backscattering in water," in Light Scattering Reviews 7, A. Kokhanovsky, ed. (Springer, 2013), pp. 189–224.

Zhang,X., E. Leymarie, E. Boss, & L. Hu (2021). Deriving the angular response function for backscattering sensors. Applied Optics, 60, 28, 8676-8687

9.7 IOP proxies for biogeochemical properties in the ocean

Lecturer: Collin Roesler, Bowdoin College, USA
Wednesday 20th July, 4pm

Inherent optical properties (IOPs) in the ocean vary substantially with wavelength and across four orders of magnitude as a function of the composition and concentration of particulate and dissolved matter, and water itself. Thus, IOPs provide robust and relatively easy-to-measure proxies for biogeochemical and physical properties that can be challenging, expensive and time consuming to measure. This lecture will explore a range of biogeochemical and physical properties (BGCPs) of interest and link them mechanistically to specific optical proxies. Students are challenged to consider two different approaches to the proxy problem. Approach 1: Tool-based approach. IOP → optical proxy –> BGCP, which contextualizes the question "I can measure X IOP, what information does it contain about which BGCPs?". Approach 2: BCGP-based approach. BGCP → optical proxy → IOP, which contextualizes the question "I want to be able to observe Y BGCP, what optical proxy can help me do so?". Both approaches are tremendously valuable to the field but come from different places and will likely involve different assumptions, simplifications, and compromises.

Some examples of different proxies can be found here:

Boss, E., M. S. Twardowski, and S. Herring (2001), Shape of the particulate beam attenuation spectrum and its inversion to obtain the shape of the particulate size distribution, Applied optics, 40(27), 4885-4893. https://doi.org/10.1364/AO.40.004885

Briggs, N. T., W. H. Slade, E. Boss, and M. J. Perry (2013), Method for estimating mean particle size from high-frequency fluctuations in beam attenuation or scattering measurements, Applied optics, 52(27), 6710-6725. https://doi.org/10.1364/AO.52.006710

Cetinić, I., M. J. Perry, N. T. Briggs, E. Kallin, E. A. D'Asaro, and C. M. Lee (2012), Particulate organic carbon and inherent optical properties during 2008 North Atlantic Bloom Experiment, Journal of Geophysical Research: Oceans, 117(C6). https://doi.org/10.1029/2011JC007771

Chase, A., E. Boss, R. Zaneveld, A. Bricaud, H. Claustre, J. Rasc, G. Dall'Olmo, and T. K. Westberry. 2014. Decomposition of in situ particulate absorption spectra, Methods Oceanogr. 7: 110-124. https://doi.org/10.1016/j.mio.2014.02.002

Reynolds, R. A., Stramski, D. and Neukermans, G. (2016), Optical backscattering by particles in Arctic seawater and relationships to particle mass concentration, size distribution, and bulk composition., Limnol. Oceanogr., 61, 21, https://doi.org/10.1002/lno.10341

Roesler, C. S., and A. H. Barnard (2013), Optical proxy for phytoplankton biomass in the absence of photophysiology: Rethinking the absorption line height, Methods Oceanogr. 7: 79-94. https://doi.org/10.1016/j.mio.2013.12.003

Twardowski, M. S., E. Boss, J. B. Macdonald, W. S. Pegau, A. H. Barnard, and J. R. V. Zaneveld (2001), A model for estimating bulk refractive index from the optical backscattering ratio and the implications for understanding particle composition in case I and case II waters. J. Geophys. Res., 106(C7): 14129-14142. https://doi.org/10.1029/2000JC000404

9.8 Radiometry and apparent optical properties (AOPs), fundamentals

Lecturer: Prof. David Antoine, Curtin University, Perth, Australia
Thursday 21st July, 9 am.

Topics covered:
The "inherent optical properties" (IOPs) will have been defined by Dariusz Stramski and Collin Roesler's lectures before this one.
Here we will define the radiometric quantities, namely the radiance and various irradiances, which describe the light field within the water, and from which the "Apparent optical properties" (AOPs) can be derived (reflectances, diffuse attenuation coefficients etc..).
This lecture will review the radiometric variables and most commonly used AOPs in optical oceanography and ocean colour remote sensing, how they relate to the IOPs and will also illustrate how they vary in the natural environment and how we measure them.
More details on the measurement of these radiometric quantities and the associated protocols and measurement uncertainties will be covered by a second lecture on Friday 22nd July, 2 pm.

Suggested readings:
- Essentially everything can be found in the Light and Radiometry chapter of the Ocean Optics Web Book at www.oceanopticsbook.info/view/light_and_radiometry
- The pages on AOPs, reflectances, and K functions beginning at www.oceanopticsbook.info/view/overview_of_optical_oceanography/apparent_optical_properties

If you have more appetite:
- Mobley CD, 1994. Light and Water: Radiative Transfer in Natural Waters, Academic press.
- https://ioccg.org/wp-content/uploads/2020/09/gordon-book_nov_2019_with_doi.pdf

Also:
- Morel, A. and R.C. Smith (1982) Terminology and units in optical oceanography, Marine Geodesy, 5, 335-349.
- Remote Sensing of Coastal Aquatic Environments, Technologies, Techniques and Applications. Editors: Miller, Richard L., Del Castillo, Carlos E., McKee, Brent A. (Eds). Kluwer Publishing.
  A number of chapters in this book are relevant here

9.9 Introduction to HydroLight

Lecturer: John Hedley, Numerical Optics Ltd.
Thursday 21 June 11.00-12.30

Numerical modelling of the propagation of light in water and the resulting remote-sensing reflectance is an essential component of studies in ocean optics. Radiative transfer models are required for algorithm development, optical closure experiments, and as components of ecosystem models. HydroLight is a well-known commercial product for modelling the propagation of light in water, and has been widely used in the hydrological optics community for nearly 30 years. This lecture will introduce HydroLight, covering both the theoretical structure of the model and the practicalities of the software implementation. The inputs, outputs, functions and limitations of HydroLight will be reviewed. The underlying solution method used in HydroLight is different to the majority of other available models, understanding this is key to understanding the advantages HydroLight provides, but also its limitations. The importance of accurate light calculations in ecosystem models will also be discussed.

References:

https://www.oceanopticsbook.info/view/radiative-transfer-theory/level-2/hydrolight

Mobley CD, Chai F, Xiu P, Sundman LK (2015). Impact of improved light calculations on predicted phytoplankton growth and heating in an idealized upwelling-downwelling channel geometry. J. Geophys. Res: Oceans 120, doi:10.1002/2014JC010588

9.10 Practical Session - HydroLight Lab

Lecturer: John Hedley, Numerical Optics Ltd.
Thursday 21 June 14.00-15.30 and 16.00-17.30

A demo version of HydroLight will be supplied which can be installed on students' laptops (MS Windows or Mac). The software is fully functional but the licence will expire at the end of the course. The session will start with a demonstration of typical HydroLight usage drawing attention to some of the options and available outputs. Students can then run HydroLight on a series of suggested exercises designed to consolidate their understanding of hydrological optics and how AOPs depend on IOPs. Various simulations can be run, using standard bio-optical models for Case 1 waters, Case 2 waters or shallow waters with a given bottom type. Students with experience of HydroLight can also use this opportunity to discuss one-to-one any specific questions they may have. HydroLight can continue to be used after this session until the end of the course and I will be available until Wednesday the 27th to answer any further questions.

References:

HydroLight 6.0 Users' Guide and HydroLight 6.0 Technical Documentation. These can be downloaded at the bottom of this page: https://www.numopt.com/hydrolight.html

9.11 Radiometry, apparent optical properties, measurements & uncertainties

Lecturer: Prof. David Antoine, Curtin University, Perth, Australia
Friday 22nd July, 2 pm.

Topics covered:
This lecture will address the uncertainties that come with measuring radiometric quantities and deriving AOPs from them, covering what comes from the instrument themselves (calibration, characterisation), their deployment in the field (protocols) and the subsequent data processing steps.
Example will be given from current field activities and international programs.

Suggested readings:
Ruddick, K.G.; Voss, K.; Boss, E.; Castagna, A.; Frouin, R.; Gilerson, A.; Hieronymi, M.; Johnson, B.C.; Kuusk, J.; Lee, Z.; Ondrusek, M.; Vabson, V.; Vendt, R. A Review of Protocols for Fiducial Reference Measurements of Water-Leaving Radiance for Validation of Satellite Remote-Sensing Data over Water. Remote Sens. 2019, 11, 2198. https://doi.org/10.3390/rs11192198
Ruddick, K.G.; Voss, K.; Banks, A.C.; Boss, E.; Castagna, A.; Frouin, R.; Hieronymi, M.; Jamet, C.; Johnson, B.C.; Kuusk, J.; Lee, Z.; Ondrusek, M.; Vabson, V.; Vendt, R. A Review of Protocols for Fiducial Reference Measurements of Downwelling Irradiance for the Validation of Satellite Remote Sensing Data over Water. Remote Sens. 2019, 11, 1742. https://doi.org/10.3390/rs11151742
See also other papers on:
https://www.mdpi.com/journal/remotesensing/special_issues/2nd_ocean_color_RS

9.12 Inexpensive but robust approaches for determining optical and biogeochemical properties

Mike Twardowski, Professor, Harbor Branch Oceanographic Institute- Ft. Pierce, Florida, USA
Emmanuel Boss, Professor, University of Maine

Friday 22nd July, 4pm

This lecture will introduce inexpensive approaches to carrying out ocean optics research with acceptable accuracies for many applications. Approaches include viewing a black disk horizontally, using a secchi disk, and using a Forel-Ule color scale. We will discuss ways a cell phone may be used for optics research. Possibilities of developing inexpensive sensors with readily available technologies will also be discussed.

References:
Hou et al. (2007)
Kilroy and Biggs (2002)
Lee et al. (2015)
Leeuw and Boss (2018)
Leeuw et al. (2013)
Pitarch et al. (2019)
Zaneveld and Pegau 2003

9.13 Past, present and future of satellite OCR

Lecturer: Prof. David Antoine, Curtin University, Perth, Australia
Saturday 23rd July, 9 am.

Topics covered:
This lecture will:
- Remind some basics about how ocean colour sensors work.
- Give a historical review of the steps taken towards developing the present day capability, and what the future of passive Ocean Colour Radiometry is made of
- Present complementary solutions to low-Earth orbit passive OCR that have already started to be developed, including sensors on geostationary orbits, polarimeters, and satellite-borne Lidars, and give an overview of the scientific and technical challenges behind developing these new capabilities

Suggested readings:
- Acker J., 2015, "The color of the atmosphere with the ocean below: a history of NASA's ocean color missions". CreateSpace Independent Publishing Platform, USA ©2015, ISBN:1507699220 9781507699225
- Loisel H, L. Duforet, D. Dessailly, M. Chami, and P. Dubuisson, 2008. Investigation of the variations in the water leaving polarized reflectance from the POLDER satellite data over two biogeochemical contrasted oceanic areas," Opt. Express 16(17), 12905–12918.
- Hostetler, CA, et al., 2018. Spaceborne Lidar in the Study of Marine Systems. Annu. Rev. Mar. Sci. 2018. 10:121–47. https://doi.org/10.1146/annurev-marine-121916-063335
- Choi, JK, et al., 2012, GOCI, the world's first geostationary ocean color observation satellite, for the monitoring of temporal variability in coastal water turbidity, JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 117, C09004, doi:10.1029/2012JC008046
- IOCCG (2012). Ocean-Colour Observations from a Geostationary Orbit. Antoine, D. (ed.), Reports of the International Ocean-Colour Coordinating Group, No. 12, IOCCG, Dartmouth, Canada.

9.14 Atmospheric corrections, 1&2

Lecturer: Prof. David Antoine, Curtin University, Perth, Australia
Monday 25th July, 9am and 11am.

Topics covered:
As far as satellite ocean colour is concerned "Atmospheric correction" refers to the process by which most of the recorded signal (~90-95%) has to be estimated before being subtracted so as to access to the remaining part (5-10%), which is the marine signal of interest. The quality (accuracy) of this process is therefore crucial for successful retrieval of the marine reflectances, hence of any product derived from these reflectances.
The lecture will address:

- The accuracy requirements for atmospheric correction of satellite OCR. What an algorithm has to achieve to be qualified for OCR atmospheric correction?
- What the total signal measured by the sensor is made of, and how the various contributions vary spectrally
- Some basic principles of OCR atmospheric corrections
- How OCR atmospheric correction can be performed under simplified assumptions in a number of situations
- How most modern OCR atmospheric correction schemes work
- Alternative approaches to the "aerosol-model-based" schemes
- Under which conditions modern OCR atmospheric correction schemes still fail
- Current issues (turbid waters, absorbing aerosols, high spatial resolution sensors)

Suggested readings:

- Gordon, H. R. (1997), Atmospheric correction of ocean color imagery in the Earth observing system era, J. Geophys. Res., 102, 17081-17106.
- Antoine, D. and A. Morel (1999), A multiple scattering algorithm for atmospheric correction of remotely-sensed ocean colour (MERIS instrument) : principle and implementation for atmospheres carrying various aerosols including absorbing ones, Int. J. Remote Sensing, 20, 1875-1916.
- IOCCG (2010). Atmospheric Correction for Remotely-Sensed Ocean-Colour Products. Wang, M. (ed.), Reports of the International Ocean-Colour Coordinating Group, No. 10, IOCCG, Dartmouth, Canada.
- IOCCG (2012). Mission Requirements for Future Ocean-Colour Sensors. McClain, C. R. and Meister, G. (eds.), Reports of the International Ocean-Colour Coordinating Group, No. 13, IOCCG, Dartmouth, Canada.

9.15 Basics on OCR inversion algorithms

Lecturer: Collin Roesler, Bowdoin College
Monday 25th July 2pm

As you have learned, the color and brightness of radiance exiting the ocean surface is heavily influenced by the inherent optical properties (IOPs) of the particulate and dissolved matter and of water itself. Thus, there is tremendous potential for extracting information about the concentration and composition of seawater constituents from ocean color observations. Preceding lectures have focused on the forward model, whereby knowing the constituents allow for the computation of the light field. This lecture will focus on introducing the inverse model, whereby knowing the light field allows for the estimating of the IOPs, and by use of optical proxies, the biogeochemical and physical properties (BGCPs) of the particulate and dissolved matter in the sea.

Helpful information can be found here:

Clarke, G. L., G. C. Ewing, and C. J. Lorenzen. 1970. Spectra of backscattered light from the sea obtained from aircraft as a measure of chlorophyll concentration. Science 167(3921): 1119-1121. https://doi.org/10.1029/95JC00455

IOCCG. 2006. Report #5: Remote Sensing of Inherent Optical Properties: Fundamentals, Tests of Algorithms, and Applications. [Ed] Z-P. Lee. Dartmouth, NS, Canada, International Ocean-Colour Coordinating Group (IOCCG), 126pp. (Reports of the International Ocean-Colour Coordinating Group, No. 5). DOI: http://dx.doi.org/10.25607/OBP-96

Morel, A. and L. Prieur. 1977. Analysis of variations in ocean color. Limnol. Oceanogr. 22(4): 709-722. https://doi.org/10.4319/lo.1977.22.4.0709

Roesler, C. S., and M. J. Perry. 1995. In situ phytoplankton absorption, fluorescence emission, and particulate backscattering spectra determined from reflectance. J. Geophys. Res: Oceans, 100(C7): 13279-13294. https://doi.org/10.1029/95JC00455

Werdell, P. J., L. I. McKinna, E. Boss, S. G. Ackleson, S. E. Craig, W. W. Gregg, Z. P. Lee, S. Maritorena, C. S. Roesler, C. S. Rousseaux, and D. Stramski. 2018. An overview of approaches and challenges for retrieving marine inherent optical properties from ocean color remote sensing. Prog. Oceanogr. 160: 186-212. https://doi.org/10.1016/j.pocean.2018.01.001

Zaneveld, R., A. Barnard, and Z. P. Lee. 2006. Why are inherent optical properties needed in ocean-colour remote sensing. Pp. 3-11. In IOCCG. 2006. Report #5: Remote Sensing of Inherent Optical Properties: Fundamentals, Tests of Algorithms, and Applications. [Ed] Z-P. Lee. Dartmouth, NS, Canada, International Ocean-Colour Coordinating Group (IOCCG), 126pp. (Reports of the International Ocean-Colour Coordinating Group, No. 5). DOI: http://dx.doi.org/10.25607/OBP-96

9.16 Shallow water remote sensing

Lecturer: John Hedley, Numerical Optics Ltd.
Monday 25th July 11.00 am

This lecture will discuss marine remote sensing applications that depend on the visibility of the bottom, such deriving bathymetry or benthic mapping of coral reefs and seagrasses with high spatial resolution imagery (pixels < 30 m). A wide range of techniques have been applied to these objectives, from fully empirical to those based on radiative transfer models, however many of the challenges and limitations are common to all approaches. Benthic complexity, surface glint, difficulties in atmospheric correction and spatial variability in IOPs all contribute to the challenge of deriving meaningful information. In this lecture I will discuss some of these issues, and give an overview of some of the practical methods used to address these and the limitations of the methods. I will also discuss how uncertainty propagation can be used to give an indication of when these limitations are approached.

References:

Kutser T, Hedley J, Giardino C, Roelfsema C, Brando VE (2020). Remote sensing of shallow waters – A 50 year retrospective and future directions. Remote Sensing of Environment 240, 111619. doi: 10.1016/j.rse.2019.111619

Hedley JD, Roelfsema CM, Chollett I, Harborne AR, Heron SF, Weeks S, et al. (2016) Remote sensing of coral reefs for monitoring and management: A review. Remote Sensing 8: 118-157. doi: 10.3390/rs8020118
Hedley JD, Roelfsema C, Brando V, Giardino C, Kutser T, Phinn S, et al. (2018) Coral reef applications of Sentinel-2: coverage, characteristics, bathymetry and benthic mapping with comparison to Landsat 8. Remote Sensing of Environment 216, 598–614. doi: 10.1016/j.rse.2018.07.014
Dekker A, Phinn S, Lyons M, Roelfsema C, Anstee J, Bissett P, et al. (2011) Intercomparison of methods for physics-based shallow water remote sensing. Limnology and Oceanography Methods 9: 396-425. doi: 10.4319/lom.2011.9.396
Kay S, Hedley JD, Lavender S. (2009) Sun glint correction of high and low spatial resolution images of aquatic scenes: a review of methods for visible and near-infrared wavelengths. Remote Sensing 1, 697-730. doi: 10.3390/rs1040697

9.17 Perspectives on hyperspectral optics and remote sensing

Lecturer: Ali Chase, Applied Physics Laboratory – University of Washington, USA
Tuesday 26th July, 9 am

Summary

Hyperspectral optical measurements provide, by definition, increased information over multispectral data, as an increased number of data points are being collected over the same spectral range. Since the early days of optical oceanography, observation of spectral variations in radiometric measurements have indicated to researchers that the presence of different plankton and particle assemblages influence spectral features due to their absorbing and scattering properties. Hyperspectral measurements have become more ubiquitous in situ and are increasing in remote sensing contexts as well. As a result, the variety of algorithms and methods used to evaluate and extract information from hyperspectral data is extensive.
Hyperspectral absorption and remote-sensing reflectance (Rrs(λ)) spectra are either required, or at least more effective, compared to multispectral data during derivative, spectral decomposition, and/or clustering analyses for phytoplankton pigment assemblage discrimination and size-based phytoplankton community composition assessment. This lecture will cover the history of hyperspectral measurements and the current capabilities of in situ instrumentation and remote sensing platforms. The variety of approaches applied to analyze hyperspectral measurements will be presented, as well as limitation considerations. Finally, the application of hyperspectral data to coastal and complex water type ecosystems will be addressed.

Lecture outline & Key topics

History of hyperspectral optics & remote sensing, and current capabilities
- In situ hyperspectral measurement capabilities (absorption, (back)scattering, radiometry, fluorescence)
- Satellite and suborbital missions, instrumentation on drones
- Linking in situ and remote sensing hyperspectral measurements

Approaches to extracting information from hyperspectral measurements
- Data transformations and retrieval algorithms
- Techniques to move beyond what can be estimated from co-variation with Chlorophyll a
- Degrees of freedom & correlations between wavelengths
Applications to the coastal & complex aquatic ecosystem community
- Challenges and opportunities resulting from both high spectral and spatial resolution requirements
- Case studies re: water quality and ecosystem monitoring

Selected References

Cael, B. B., Alison Chase, and Emmanuel Boss. 2020. "Information Content of Absorption Spectra and Implications for Ocean Color Inversion." Applied Optics 59 (13): 3971. https://doi.org/10.1364/ao.389189

Chase, A. P., E. Boss, I. Cetinić, and W. Slade. 2017. "Estimation of Phytoplankton Accessory Pigments From Hyperspectral Reflectance Spectra: Toward a Global Algorithm." Journal of Geophysical Research: Oceans 122 (12): 9725–43. https://doi.org/10.1002/2017JC012859

Dekker, Arnold G., and Nicole Pinnel (Eds). 2018. "Feasibility Study for an Aquatic Ecosystem Earth Observing System," 195. https://ceos.org/observations/documents/Feasibility-Study-for-an-Aquatic-Ecosystem-EOS-v.2-hi-res_05April2018.pdf

Dierssen, Heidi M, Steven G Ackleson, Karen E Joyce, Erin L Hestir, Alexandre Castagna, Samantha Lavender, and Margaret A. McManus. 2021. "Living up to the Hype of Hyperspectral Aquatic Remote Sensing: Science, Resources and Outlook." Frontiers in Environmental Science 9 (June): 1–26. https://doi.org/10.3389/fenvs.2021.649528

Kramer, Sasha J., David A. Siegel, Stéphane Maritorena, and Dylan Catlett. 2022. "Modeling Surface Ocean Phytoplankton Pigments from Hyperspectral Remote Sensing Reflectance on Global Scales." Remote Sensing of Environment 270 (December 2021). https://doi.org/10.1016/j.rse.2021.112879

Morel, André, and Louis Prieur. 1977. "Analysis of Variations in Ocean Color." Limnology and Oceanography 22 (4): 709–22. https://doi.org/10.4319/lo.1977.22.4.0709

Ryan, John P., Curtiss O. Davis, Nicholas B. Tufillaro, Raphael M. Kudela, and Bo Cai Gao. 2014. "Application of the Hyperspectral Imager for the Coastal Ocean to Phytoplankton Ecology Studies in Monterey Bay, CA, USA." Remote Sensing 6 (2): 1007–25. https://doi.org/10.3390/rs6021007

Uitz, Julia, Dariusz Stramski, Rick A Reynolds, and Jean Dubranna. 2015. "Assessing Phytoplankton Community Composition from Hyperspectral Measurements of Phytoplankton Absorption Coefficient and Remote-Sensing Reflectance in Open-Ocean Environments." Remote Sensing of Environment 171: 58–74. https://doi.org/http://dx.doi.org/10.1016/j.rse.2015.09.027

Vandermeulen, Ryan A., Antonio Mannino, Aimee R. Neeley, P. Jeremy Werdell, and Robert Arnone. 2017. "Determining the Optimal Spectral Sampling Frequency and Uncertainty Thresholds for Hyperspectral Remote Sensing of Ocean Color." Optics Express 25 (16): 785–97. https://doi.org/10.1364/OE.25.00A785

Vandermeulen, Ryan A., Antonio Mannino, Susanne E. Craig, and P. Jeremy Werdell. 2020. "150 Shades of Green: Using the Full Spectrum of Remote Sensing Reflectance to Elucidate

Color Shifts in the Ocean." Remote Sensing of Environment 247 (May): 111900. https://doi.org/10.1016/j.rse.2020.111900
Wolanin, Aleksandra, Mariana Soppa, and Astrid Bracher. 2016. "Investigation of Spectral Band Requirements for Improving Retrievals of Phytoplankton Functional Types." Remote Sensing 8 (10): 871. https://doi.org/10.3390/rs8100871

9.18 Phytoplankton community composition derived from optics and remote sensing: Approaches, challenges, and next steps

Ali Chase, Applied Physics Laboratory – University of Washington, USA
Tuesday 26th July, 11 am

Summary
Phytoplankton are extremely diverse in their taxonomy, size distribution, and ecosystem functional roles. Assessing bulk phytoplankton populations is valuable for many applications, but interest exists and is growing in the assessment of different phytoplankton types and groups. Efforts in this area have been ongoing for nearly two decades, and the methods, understanding of limitations, and terminology have all evolved. The application of different data analysis approaches has impacted our approach to phytoplankton community composition studies (e.g., incorporation of ancillary data, use of machine learning methods, more nuanced understanding of how phytoplankton communities can be defined). Additionally, and importantly, instrumentation has advanced to provide novel datasets that open new doors in algorithm development (e.g., increasing amount of hyperspectral optical measurements, imaging-in-flow cytometry). This lecture will present previous work in phytoplankton community composition detection, the current state-of-the-art, and the opportunities for future work that are enabled by expanding in situ data collection and remote sensing capabilities.

Lecture outline & key points
Previous studies to estimate phytoplankton community composition from optics & remote sensing
- Applications: what have we learned? Limitations: what remains to be strengthened?
- Evaluating algorithms to enable thoughtful future applications

Science is an incremental continuum; we build and grow from past efforts. We should think critically both about what has been done, and what we are currently doing (and why) Recent work and expansion to include new approaches and data types
- Increased attention to the multiple ways phytoplankton community composition can be defined in situ (e.g., plankton imagery data, merged size spectra, genetic information)
- Merging data from multiple platforms, instruments, and models
- Machine learning: what it is (a tool), what it's not (magic)

Where do we go from here? (hint: you tell me!)
- Use of data products at different scales; regional vs. global, tuned/empirical algorithms to address specific needs
- Open science: latest updates, cloud computing, collaborative software & tools

Different questions will have different data needs. Consider when a given data product is applicable, and when it is not. What do you want to know, and why?

Selected References

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Mouw, C. B., N. J. Hardman-Mountford, S. Alvain, A. Bracher, R. J. W. Brewin, A. Bricaud, A. M. Ciotti, et al. 2017. "A Consumer's Guide to Satellite Remote Sensing of Multiple Phytoplankton Groups in the Global Ocean." Frontiers in Marine Science 4 (February). https://doi.org/10.3389/fmars.2017.00041.

Uitz, J., H.Claustre, A. Morel, and S. B. Hooker. 2006. "Vertical Distribution of Phytoplankton Communities in Open Ocean: An Assessment Based on Surface Chlorophyll." Journal of Geophysical Research 111 (C8): C08005. https://doi.org/10.1029/2005JC003207 .

Werdell, P. J., C.. S Roesler, and J. I. Goes. 2014. "Discrimination of Phytoplankton Functional Groups Using an Ocean Reflectance Inversion Model." Applied Optics 53 (22): 4833–49. http://www.ncbi.nlm.nih.gov/pubmed/25090312.

9.19 NPP; Carbon export; climate-driven changes

Lecturer: Prof. David Antoine, Curtin University, Perth, Australia
Tuesday 26th July, 2pm.

Topics covered:
This lecture will cover some aspects of how the phytoplankton primary production can be derived from satellite measurements of ocean colour.
Some fundamentals of this transformation will be reminded, and examples of historical and more recent estimates will be presented.
Some alternative ways of deriving NPP will as well be discussed.

Suggested readings:

Antoine, D. and A. Morel, 1996. Oceanic primary production : I. Adaptation of a spectral light-photosynthesis model in view of application to satellite chlorophyll observations, Global Biogeochemical Cycles 10, 43-55.

Antoine, D., J.M. André, and A. Morel, 1996. Oceanic primary production : II. Estimation at global scale from satellite (Coastal Zone Color Scanner) chlorophyll, Global Biogeochemical Cycles 10, 57-69.

Behrenfeld, M. J. & Falkowski, P. G. Photosynthetic rates derived from satellite-based chlorophyll concentration. Limnol. Oceanogr. 42, 1–20 (1997).

Behrenfeld, M. J., E. Boss, D. A. Siegel, and D. M. Shea. 2005. Carbon-based ocean productivity and phytoplankton physiology from space. Global Biogeochemical Cycles 19: GB1006, doi:10.1029/2004GB002299.

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9.20 Harmful Algal Blooms, and The use of OCR in ocean modelling

Lecturer: Dr Hayley Evers-King (EUMETSAT)
Tuesday 26th July, 4 pm

Harmful Algal Blooms, occurring naturally or as the result of human activities, represent a potential threat to ecosystem and human health in coastal regions. Harm can be caused by blooms through a wide range of mechanisms, including through deoxygenation events, presence of various toxins, as well as physical impacts on other organisms and wider ecosystem dynamics. As a result of these impacts, monitoring HABs is a necessary activity for fishery and aquaculture industries, as well as those managing interactions between the public and our oceans (for tourism and recreation etc). Ocean colour remote sensing offers a cost-effective way to monitor HABs at high spatial and temporal resolution. However, developing appropriate methodologies for using data for these applications, is challenging. High biomass levels are not captured readily by all sensor types, or within the range of many classic algorithm approaches. Similarly, decision making requires more detailed information relating to the potential sources of harm, such as the presence of certain species, cell sizes, and/or risks relating to persistence. This lecture will look at the challenges facing the application of ocean colour remote sensing to HAB monitoring, and share some of the latest research and operational approaches being developed to address these issues.

The use of OCR in ocean modelling

Ocean colour offers views in to both the physical and biogeochemical functioning of the oceans. As such, it represents a wealth of information that can be used in ocean modelling, for parameterisation, assimilation, and validation. Ocean colour data provides information on the light environment of the upper water column, including how much of the incoming energy penetrates into the ocean depths, and from which spectral regions. This has important applications in upper ocean physics and climate modelling, particularly when it comes to heat fluxes. The light environment is also an essential consideration, when modelling oceanic primary production. Beyond the light itself, the ocean colour signal contains information about phytoplankton biomass and characteristics that can be used to inform biogeochemical models. "Phytoplankton functional type(s)" is a concept that particularly lends itself to modelling applications, and ocean colour data can provide information in this regard. Whether considering allometry and phenology and their impacts on ecosystem function, specific biogeochemical function (e.g carbon cycling related to coccolithophores), or the potential of certain species to cause harm, ocean colour data can offer data to information model development and to assess their accuracy. This lecture will summarise the current state of the art in research and operations using ocean colour radiometry in modelling approaches.

9.21 Practical on satellite datasets: coastal and inland waters

Hayley Evers-King, Ben Loveday, Ana Ruescas, Kevin Ruddick and Quinten Vanhellemont

27-28-29 July

The use of optical remote sensing data has increased dramatically over the last ten years, particularly for coastal and inland waters where impacts between the aquatic environment and human activities may be particularly intense. Many of these waters will be turbid because of high concentrations of suspended particulate matter caused by a variety of processes including high biomass algal blooms, sediment resuspension by wind/tide, river plumes, etc. Within this session the specific challenges and opportunities presented by turbid coastal and inland waters will be presented, where "turbid" is understood here to indicate waters with high particulate scattering. We will also consider the complications of dealing with waters where optical properties are highly variable, from turbid to CDOM-rich and occasionally clearer waters.

There are two major additional difficulties for optical remote sensing in turbid waters. Firstly, atmospheric correction is more difficult because it is not possible to assume zero near infrared marine reflectance ("black pixel assumption"), thus complicating the decomposition of top of atmosphere measurements into atmosphere and water reflectances. Secondly, the optical properties of non-algae particles, such as mineral particles from bottom resuspension or from river discharges, need to be considered in addition to algal particles. If the absorption and scattering of non-algae particles is significant compared to that of algal particles it may become difficult or even impossible to distinguish the optical properties of the algal particles. In such conditions the estimation of chlorophyll a may become severely degraded or suffer from a detection limit problem. In turbid waters both the atmospheric correction and the chlorophyll retrieval problems are highly dependent on the technical specification of the remote sensors being used, and in particular on the spectral band set.

This session will take a multi-sensor approach to the challenges of remote sensing in coastal and inland waters, exploring the tradeoffs between spatial, temporal, and spectral resolutions by working with Landsat, Sentinel-2, and Sentinel-3 data. We will also embed practical skills needed for working in these waters, including data access and working with open source software. Participants will be encouraged to take the workflows presented and apply them to an area of interest to share images with the rest of the course.

This topic will be split in to 5 parts:

1) These two key issues facing turbid water remote sensing will be explained in detail, via lectures and via simple python-based modelling exercises. The algorithmic approaches that can be used to deal with these problems will be outlined, based on the current state of the art and with reference to the capabilities of current and future ocean colour sensors such as MODIS, GOCI, OLCI, VIIRS, "land" sensors repurposed for water applications such as Sentinel-2 and Landsat-8/9 and hyperspectral sensors.

2) The atmospheric correction of high resolution (10-60m) satellite imagery from Landsat and Sentinel-2 over turbid waters will be explained and demonstrated with a hands-on practical exercise using ACOLITE. In the exercise, sample imagery will be provided, and different processing settings will be explored. During the practical, the students will also be able to download imagery for their study areas, perform the atmospheric correction using ACOLITE and discuss the results interactively.

3) Sentinel-3 data offers near daily, multispectral measurements of the open ocean and coastal zones at 300m resolution. Designed for ocean remote sensing specifically, it is used in a growing suite of operational water quality monitoring activities. During a practical exercise, students will learn how to download this data routinely, open it in the SNAP software, and learn about the data characteristics that support use in complex waters.

4) Derivation of accurate reflectances and biogeochemical parameters in complex waters is a challenge. Multiple approaches to atmospheric correction and parameter retrieval have been developed, including some simultaneous approaches using machine learning methods. In this part of the practical, we will look at applying the Case 2 Regional CoastColour (C2RCC) processor, through the SNAP software.

5) The colored dissolved organic matter (CDOM) variable is the standard measure of humic substance in waters optics. CDOM is optically characterized by its spectral absorption coefficient, aCDOM at reference wavelength (e.g., ≈ 440 nm). Retrieval of CDOM is traditionally done using bio-optical models. As an alternative, we will derive CDOM using machine learning methods applied to Sentinel-3 simulated reflectance (Rrs) data. Statistics comparison with other well-established polynomial regression algorithms will be used as validation of the methods. Application to an atmospheric corrected OLCI image using the reflectance derived from the alternative neural network (C2RCC) will also be developed.

In addition to aspects of chlorophyll retrieval in turbid waters, other relevant parameters will be discussed, including diffuse attenuation coefficient, euphotic depth, suspended particulate matter, detection of harmful algal blooms etc. The links with applications in aquatic science and coastal and inland water management will be described.

Requirements for the lectures

- A basic knowledge of the definitions of optical properties (scattering, absorption, attenuation) from other lectures from this IOCCG summer school, particularly those of Emmanuel Boss, Collin Roesler, Dariusz Stramski, Mike Twardowski
- An account on the EUMETSAT EO portal for accessing OLCI data (https://eoportal.eumetsat.int/)
- An installation of Python that can be used to run Jupyter Notebooks. Details of the installation requirements, and code that will be used are in the following git repositories. Please follow the README instructions within each git repository. Please make sure to clone both repositories using the commands provided.
  - First install anaconda (further guidance in this video here https://drive.google.com/file/d/1M3gX-BAARFE3y77lqo2ogdK04hIRhE4r/view?usp=sharing).
  - Then clone the repository from your command line prompt (or the anaconda prompt) using the commands in the README.
  - Then install the necessary environment in advance of the lecture series – see the README – this is done using an environment file (.yml) provided in each cloned repository.
  - For any questions, contact hayley.eversking@eumetsat and ben.loveday@external.eumetsat.int
  - Repository for OLCI tutorials: https://gitlab.eumetsat.int/eumetlab/oceans/ocean-training/sensors/learn-olci
  - Repository for forward model tutorials: https://gitlab.com/benloveday/oc_forward_model
- Download and install the latest version of SNAP (https://step.esa.int/main/download/snap-download/), connecting it to your Python executable.

•	Students are encouraged to download ACOLITE binaries from https://github.com/acolite/acolite/releases/latest and Landsat or Sentinel-2 Level 1 images of their interest prior to the lectures (e.g. from USGS EarthExplorer https://earthexplorer.usgs.gov or Copernicus Open Access Hub https://scihub.copernicus.eu/dhus/#/home).
•	The main ACOLITE exercise will use the latest binary release, but students are encouraged to also create an ACOLITE Python environment to be able to run the ACOLITE open source code. Information on dependencies and installation can be found in the GitHub ReadMe file: https://github.com/acolite/acolite/blob/main/README.md

Suitable background reading

- https://www.oceanopticsbook.info/view/remote-sensing/ocean-color
- https://odnature.naturalsciences.be/remsem/software-and-data/acolite
- http://odnature.naturalsciences.be/remsem/acolite-forum/index.php

Sentinel-3 knowledge base:
https://eumetsatspace.atlassian.net/wiki/spaces/SEN3/overview

Prior to the practicals, you may wish to go through the introductory notebooks in the learn-olci repository linked above. We will focus on some advanced examples, but the introductory section provides good background for those not familiar with the data.

- Remote Sens. 2018, 10(5), 786; https://doi.org/10.3390/rs10050786.