ARTEMIS-OC

evaluation of uncertainties in ocean colour products and perspectives

Barbara Bulgarelli

RAMI workshop, 7-9 June 2023

European Commission

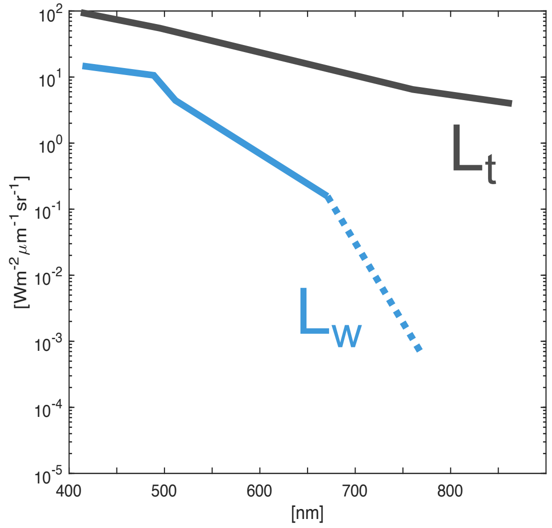
RT for OC applications

The OC scientific community recognizes the important role of RTM [IOCCG, 2006, 2010]:

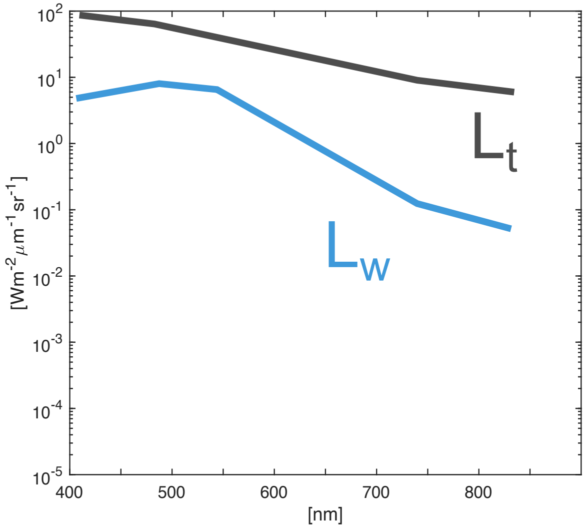
- to evaluate satellite products
- to assess and develop algorithms and correction procedures

RT for OC applications: requirements

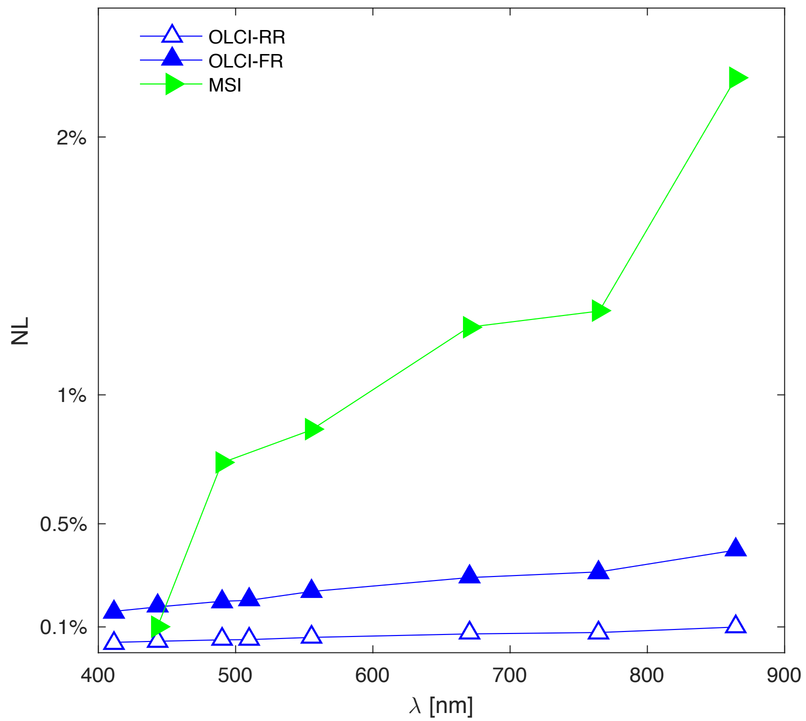
Open Ocean (MOBY)



Coastal Sea (AAOT)



NL= 1/ SNR



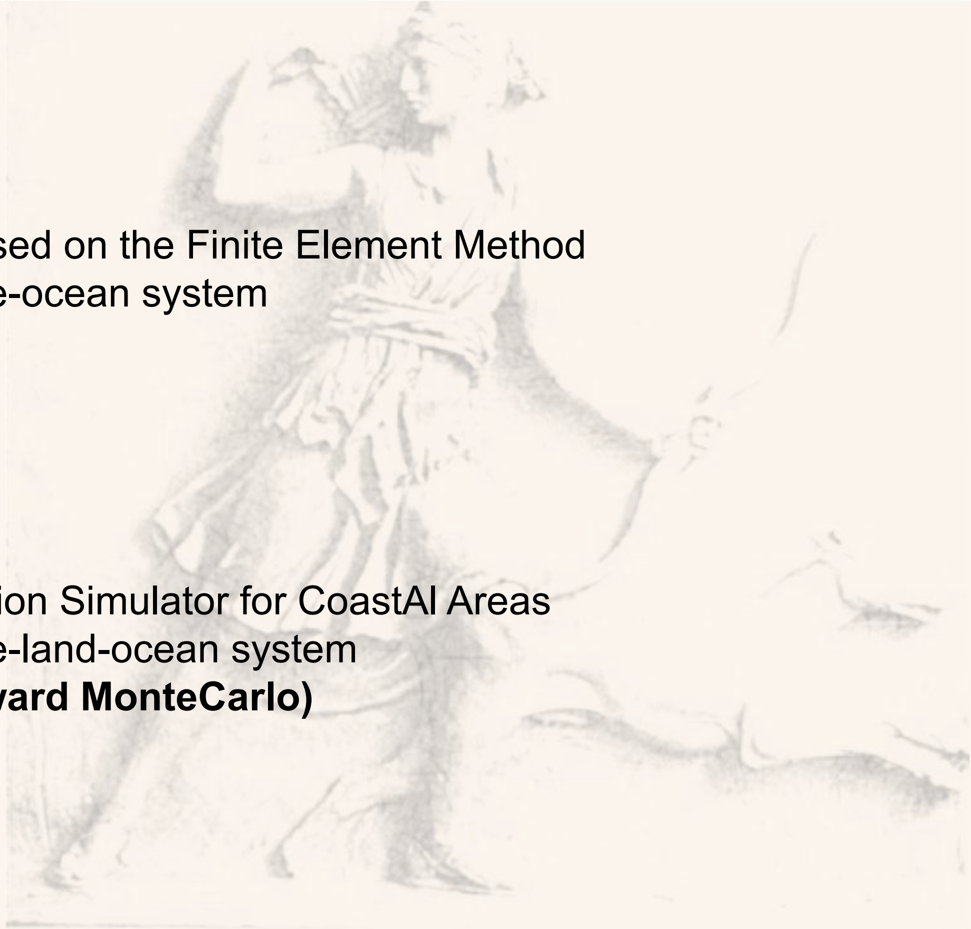
High accuracy is required

Analyses of sources of perturbations require uncertainties in simulated products to be lower than NL

- Accurate numerical solution of the RTE
- Accurate characterization of atmosphere and water

ARTEMIS-OC

Advanced Radiative TransfEr Models for In-situ and Satellite Ocean Color data



FEM
Radiative transfer code based on the Finite Element Method
for the coupled atmosphere-ocean system
numerical method
Plane-parallel

[Bulgarelli et al., AO 1999]

NAUSICAA
Novel Adjacency pertUrbation Simulator for CoastAl Areas
for the coupled atmosphere-land-ocean system
statistical method (backward MonteCarlo)
3D

[Bulgarelli et al., AO 2014]

ARTEMIS-OC: FEM

$$\tilde{\beta}(\tau;\cos\Theta) = \sum_{k=0}^{M} x_k P_k(\cos\Theta)$$

$$L(\tau;\eta,\phi) = \sum_{m=0}^{M} L^m(\tau,\eta)\cos m\phi.$$

$$\eta\frac{dL^m(\tau;\eta)}{d\tau} = -L^m(\tau;\eta) + \frac{\omega_{0l}}{2}\int_{-1}^{1} L^m(\tau;\eta')p^m(\tau;\eta,\eta')d\eta' + Q_l^m(\tau,\eta)$$

$$L^m(\tau,\eta) = \sum_{i=1}^{2N} L_i^m(\tau)b_i^m(\eta)$$

$$b_i^m(\eta) = Y_m^m(\eta)\begin{cases} 1-\frac{|\eta-\eta_i|}{h} & if\ |\eta-\eta_i| < h \\ 0 & elsewhere \end{cases}$$

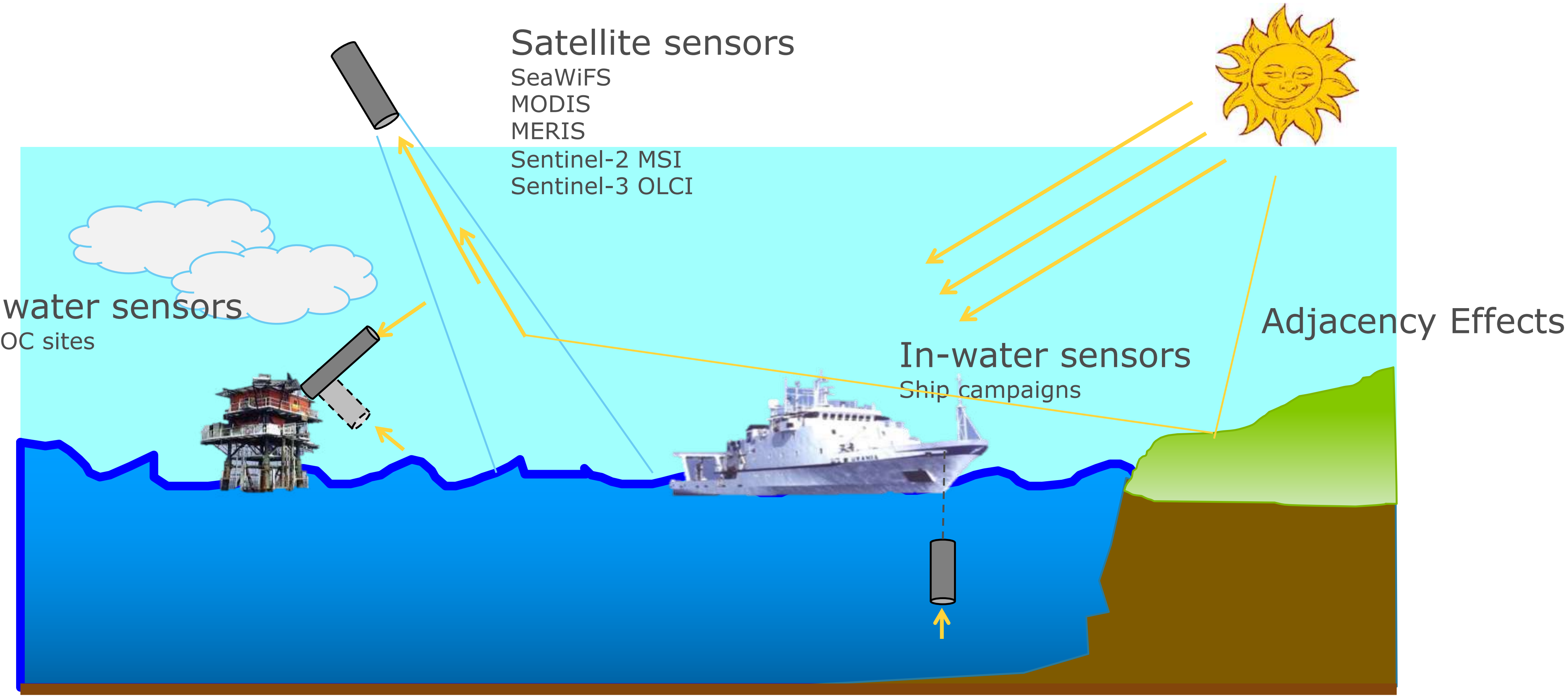
N independent on M

Flux conservation independent on N (N=2 is sufficient)

No need to apply phase function truncation techniques

Particularly suitable for highly asymmetric phase function

ARTEMIS-OC



Satellite sensors

SeaWiFS
MODIS
MERIS
Sentinel-2 MSI
Sentinel-3 OLCI

Above-water sensors

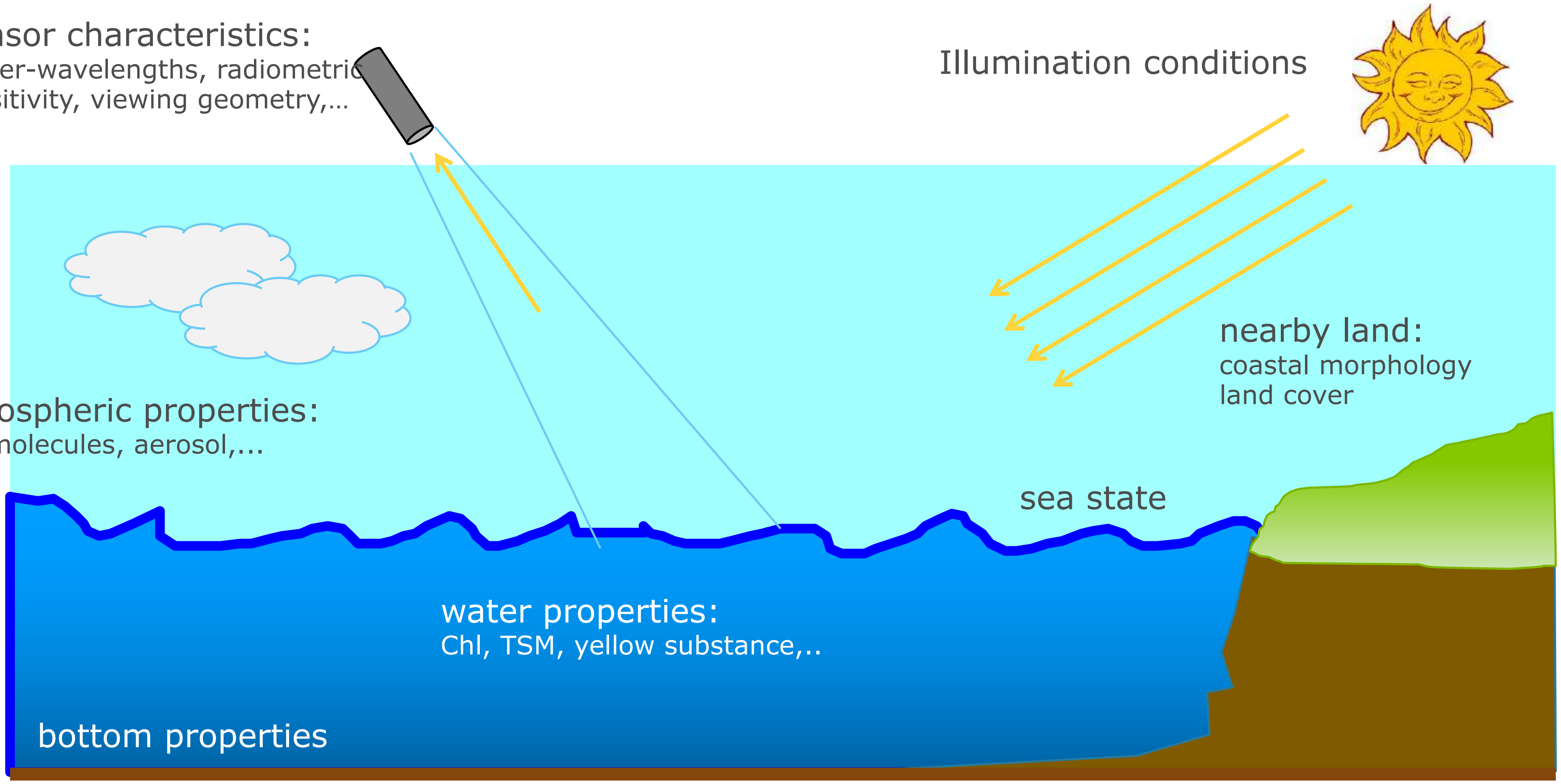
AERONET-OC sites

In-water sensors

Ship campaigns

Adjacency Effects

ARTEMIS-OC



Sensor characteristics:
center-wavelengths, radiometric
sensitivity, viewing geometry,…

Illumination conditions

nearby land:
coastal morphology
land cover

atmospheric properties:
gas molecules, aerosol,...

sea state

water properties:
Chl, TSM, yellow substance,..

bottom properties

ARTEMIS-OC applications: assessment and minimization of uncertainties in

- IN-SITU MEASUREMENTS

Bulgarelli, D’Alimonte, Zibordi, Kajyama, *in preparation*
Kajyama, D’Alimonte,Bulgarelli,Mazeran,Liberti, OO conference 2022
D’Alimonte, Kajiyama, Zibordi, Bulgarelli, AO 2021
Zibordi and Bulgarelli, AO 2007
Bulgarelli, Zibordi, Berthon, AO 2003

- SATELLITE MEASUREMENTS

Bulgarelli and Zibordi, AO 2020
Bulgarelli and Zibordi, RSE 2018
Bulgarelli and Zibordi, GRSL 2018
Bulgarelli, Zibordi, Melin, OpEx 2018
Bulgarelli, Kiselev, Zibordi, AO 2017
Kiselev, Bulgarelli, Heege, RSE 2015
Bulgarelli, Kiselev, Zibordi, AO 2014
Mélin, Clerici, Zibordi, Bulgarelli, JGR 2006
Bulgarelli and Zibordi, IJRS, 2003
Bulgarelli, Zibordi, Melin ,Oceanologia 2003

Uncertainties in in-situ measurements

Sky-radiance Modelling

340 nm 22 center-wavelengths 1020 nm

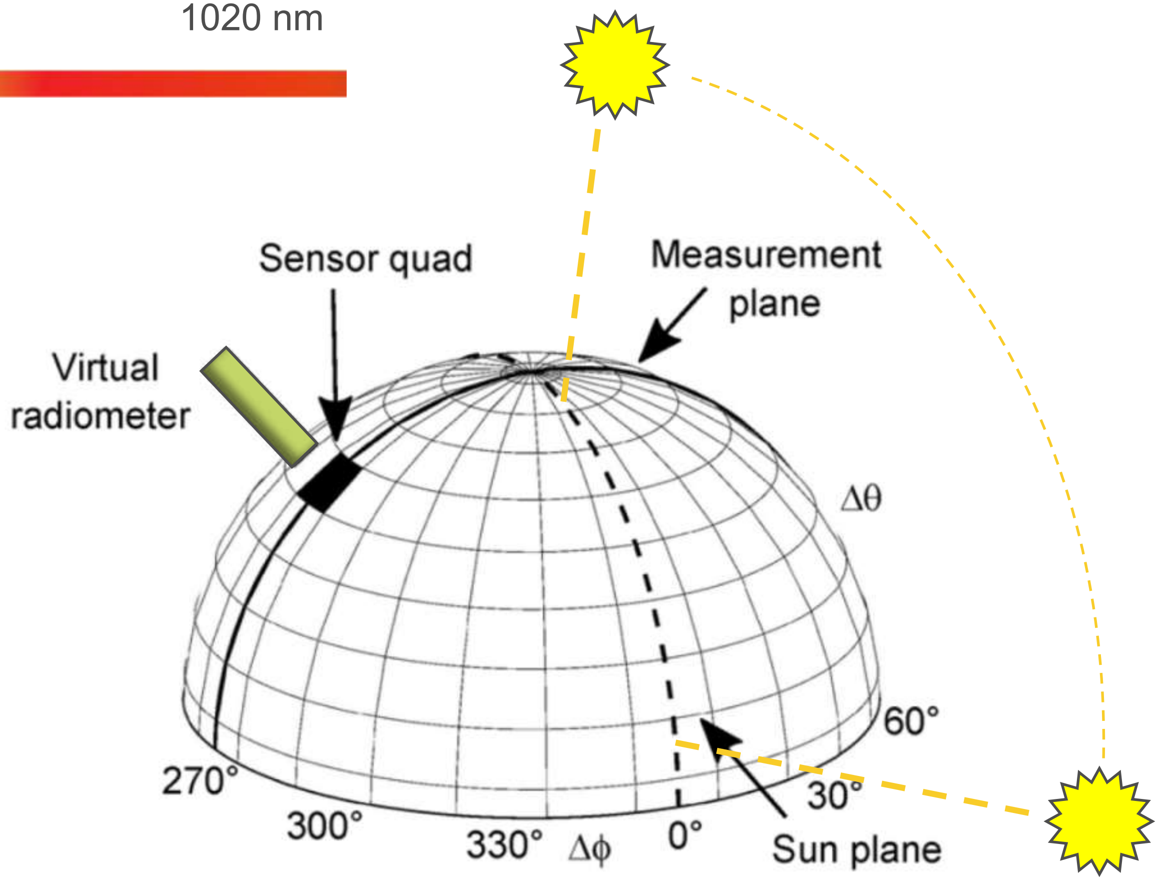
OPAC aerosol models (RH=80% $\alpha = \alpha_{500\text{-}800}$)

MAα0.3 MXα0.6 MXα1.1 COα1.4

[Hesse et al., 1998]

aerosol optical thickness at 500 nm (τ_a^{500})

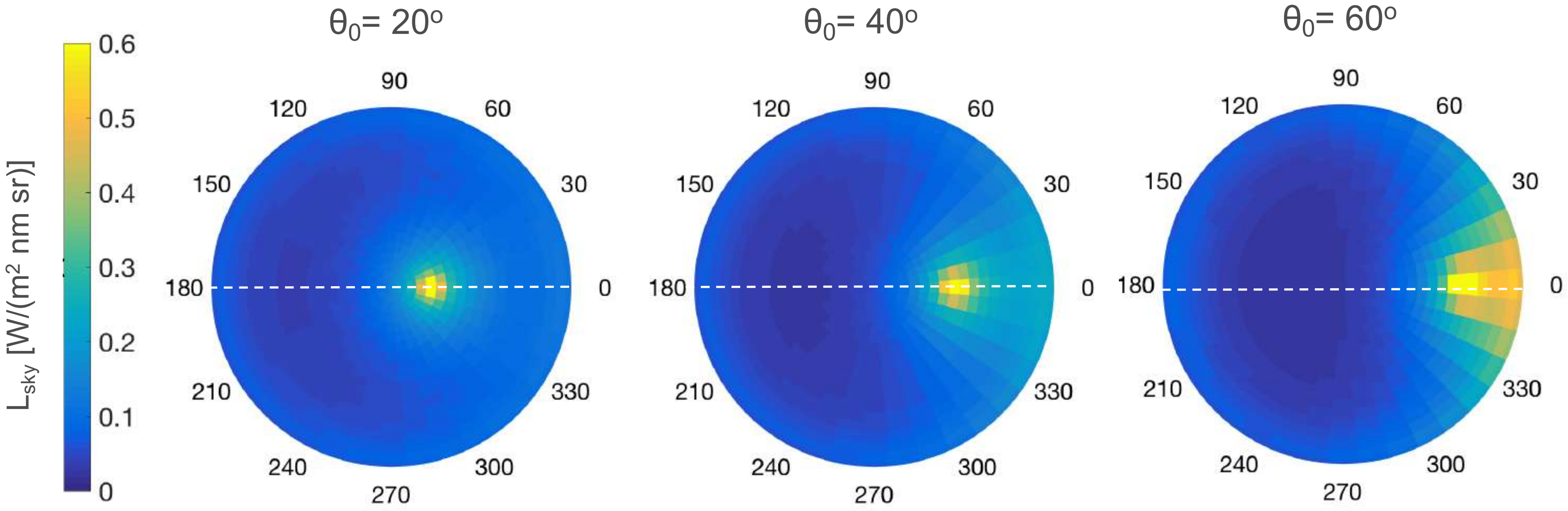
0 0.05 0.1 0.2 0.3 0.5



648 quads

[D’Alimonte et al., 2021; Bulgarelli et al. *in preparation*]

Sky-Radiance Distributions

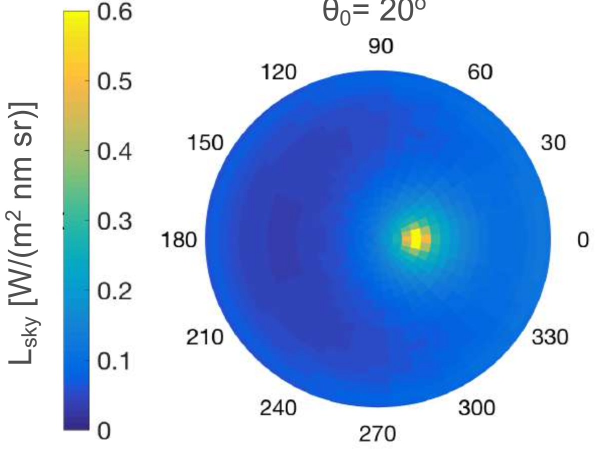


[D'Alimonte et al., 2021; Bulgarelli et al. *in preparation*]

Above-water data reduction

Sky Radiance

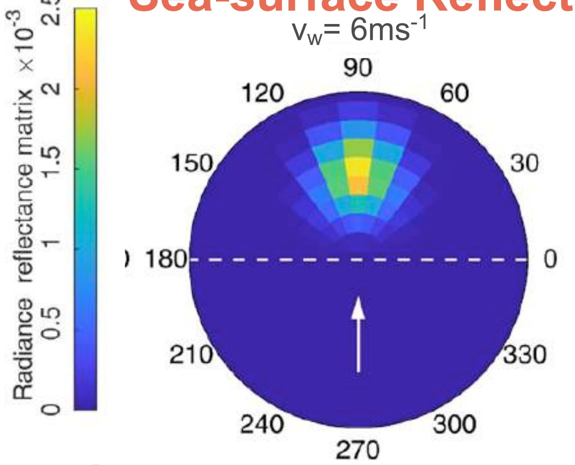
θ_0= 20°



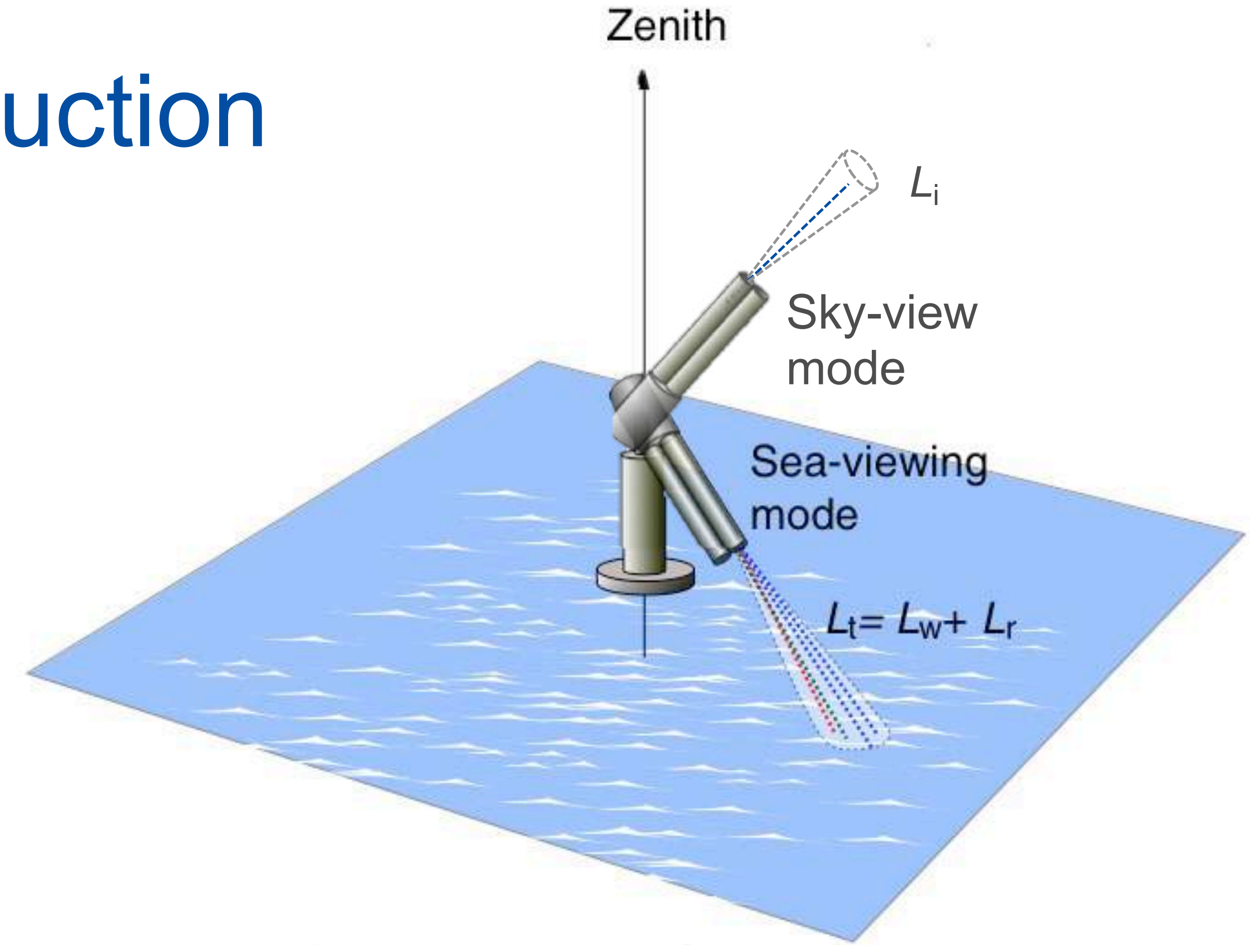
FEM

Sea-surface Reflectance

v_w= 6ms^{-1}



MOX 3D
backward MonteCarlo
[D'Alimonte et al., 2010]



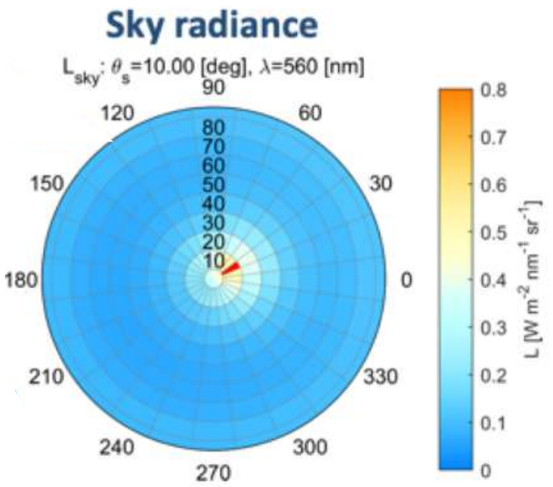
$$L_r(\theta,\phi) = \rho L_i(\theta',\phi)$$

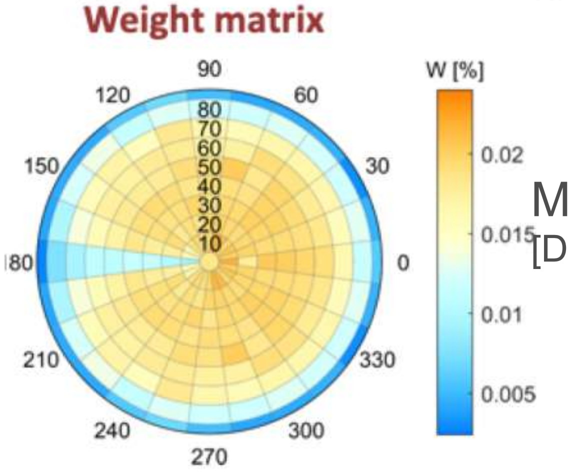
$$\rho = \frac{\int_0^{2\pi}\int_0^{\frac{\pi}{2}} r(\theta^*,\phi^* \rightarrow \theta,\phi) L_{sky}(\theta^*,\phi^*) \sin\theta^* d\theta^* d\phi^*}{L_i(\theta',\phi)}$$

[D'Alimonte et al., 2021; Bulgarelli et al. *in preparation*]

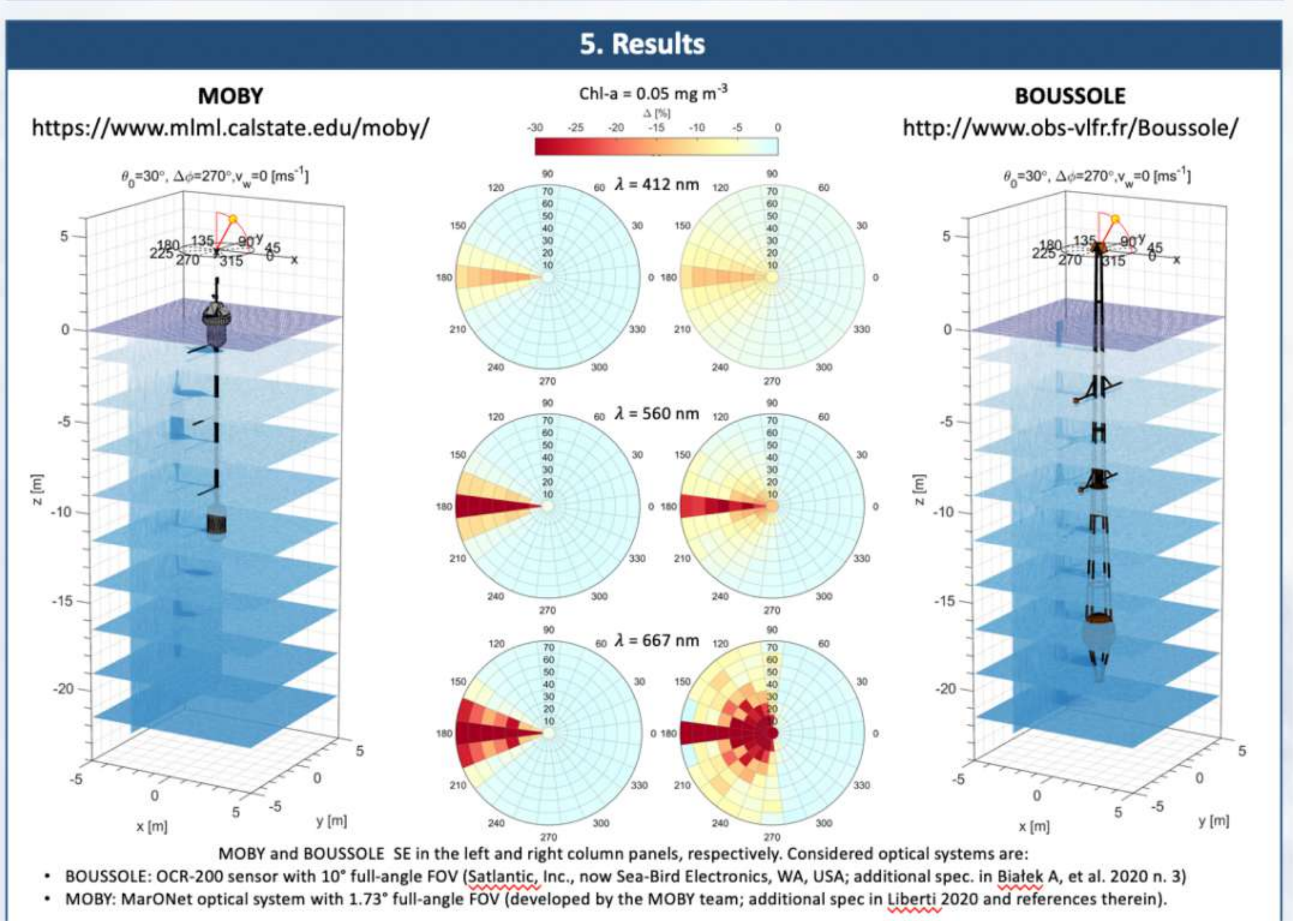
System Vicarious Calibrations

FEM





MOX 3D MC
[D’Alimonte et al., 2010]



5. Results

MOBY
https://www.mlml.calstate.edu/moby/

BOUSSOLE
http://www.obs-vlfr.fr/Boussole/

MOBY and BOUSSOLE SE in the left and right column panels, respectively. Considered optical systems are:

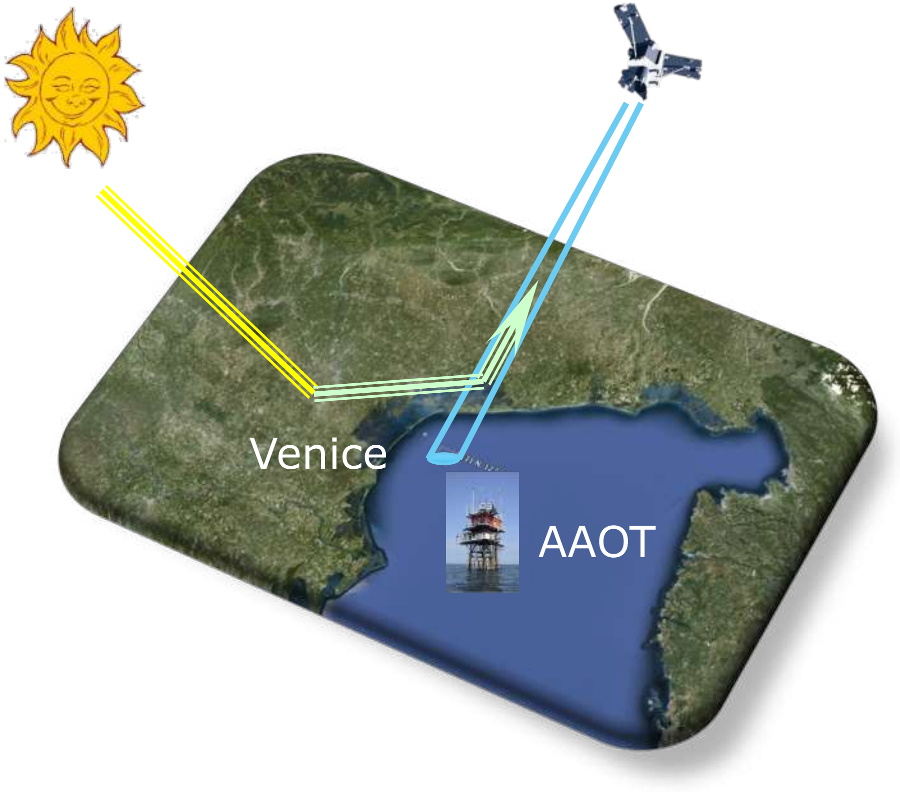
- BOUSSOLE: OCR-200 sensor with 10° full-angle FOV (Satlantic, Inc., now Sea-Bird Electronics, WA, USA; additional spec. in Białek A, et al. 2020 n. 3)
- MOBY: MarONet optical system with 1.73° full-angle FOV (developed by the MOBY team; additional spec in Liberti 2020 and references therein).

OCEAN OPTICS XXV
OCTOBER 2-7, 2022 | QUY NHON, BINH DINH, VIETNAM

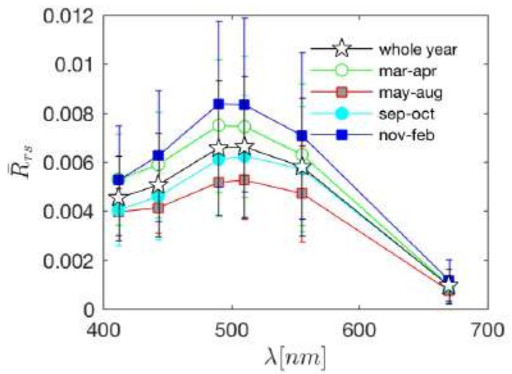
[Kajiyama, D’Alimonte,Bulgarelli,Mazeran,Liberti, OOXXV, 2022]

Uncertainties in satellite data

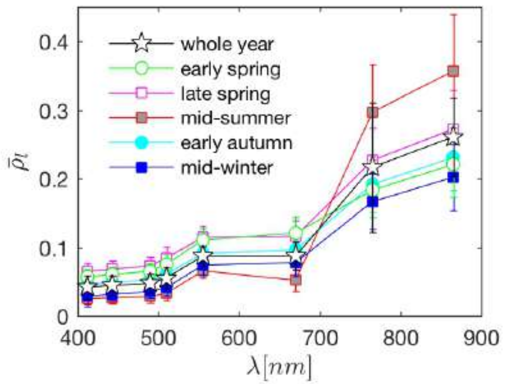
Impact of Adjacency Effects



Aqua Alta Oceanographic Tower (45.31N, 12.51E)
of the AERONET-OC network
comprehensive bio-optical in situ measurements since 1995



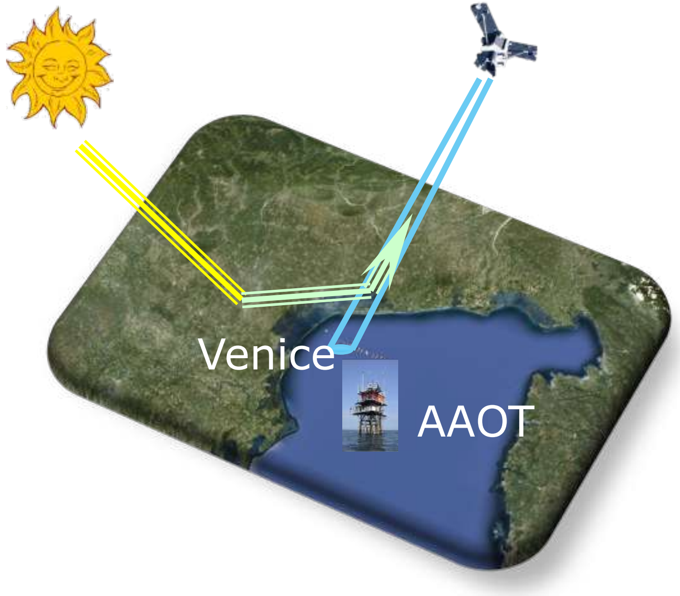
Case-1 to Case-2
moderately turbid waters

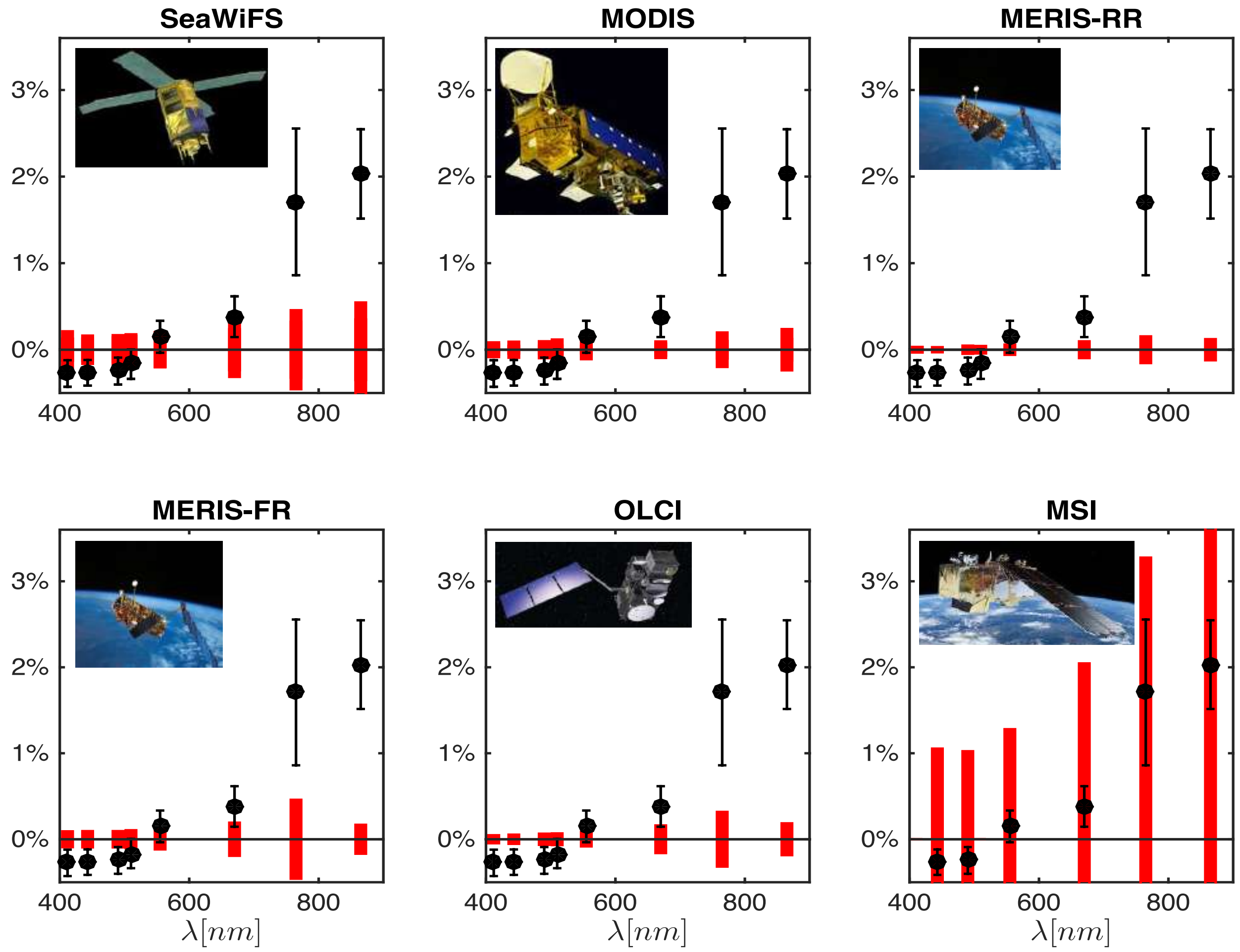


Cropland ecosystem

Bulgarelli et al., AO 2014; AO 2017; OE 2018; IEEE-GRSL 2018; RSE 2018

Impact of AE in OC acquisitions at AAOT





● Percent AE

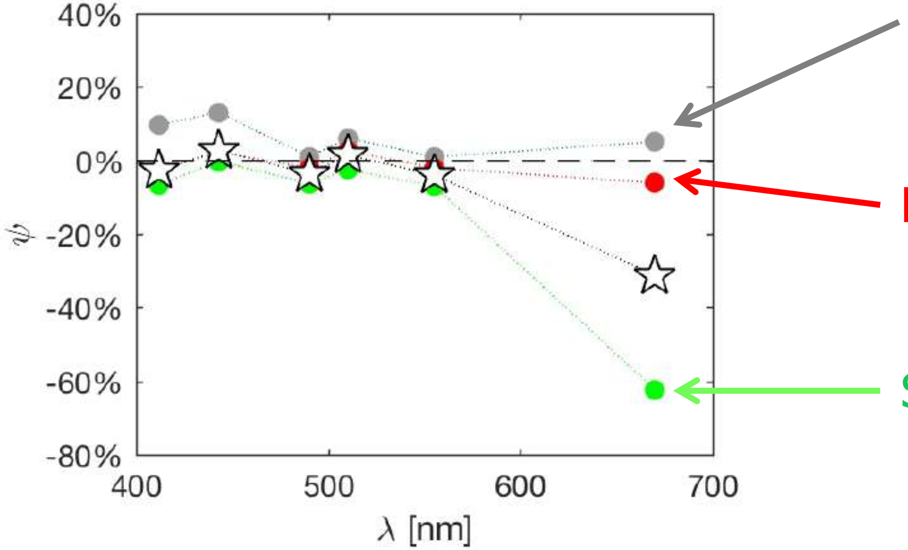
🟥 Sensor NL

Bulgarelli and Zibordi, IEEE-GRSL 2018

Impact of AE on matchups at AAOT

Intra-annual average biases on R_{rs} for 82 cloud-free SeaWiFS images acquired at the AAOT and suitable for match-ups

standard SeaDAS

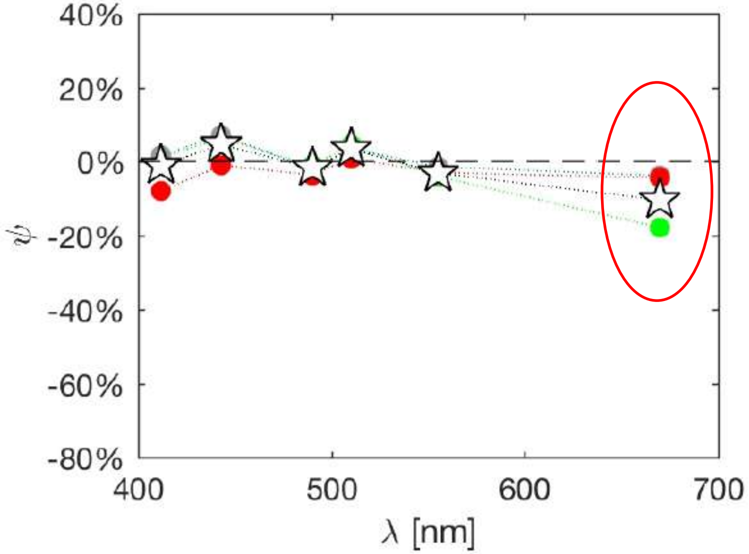


Winter

Mid-seasons

Summer

AE correction



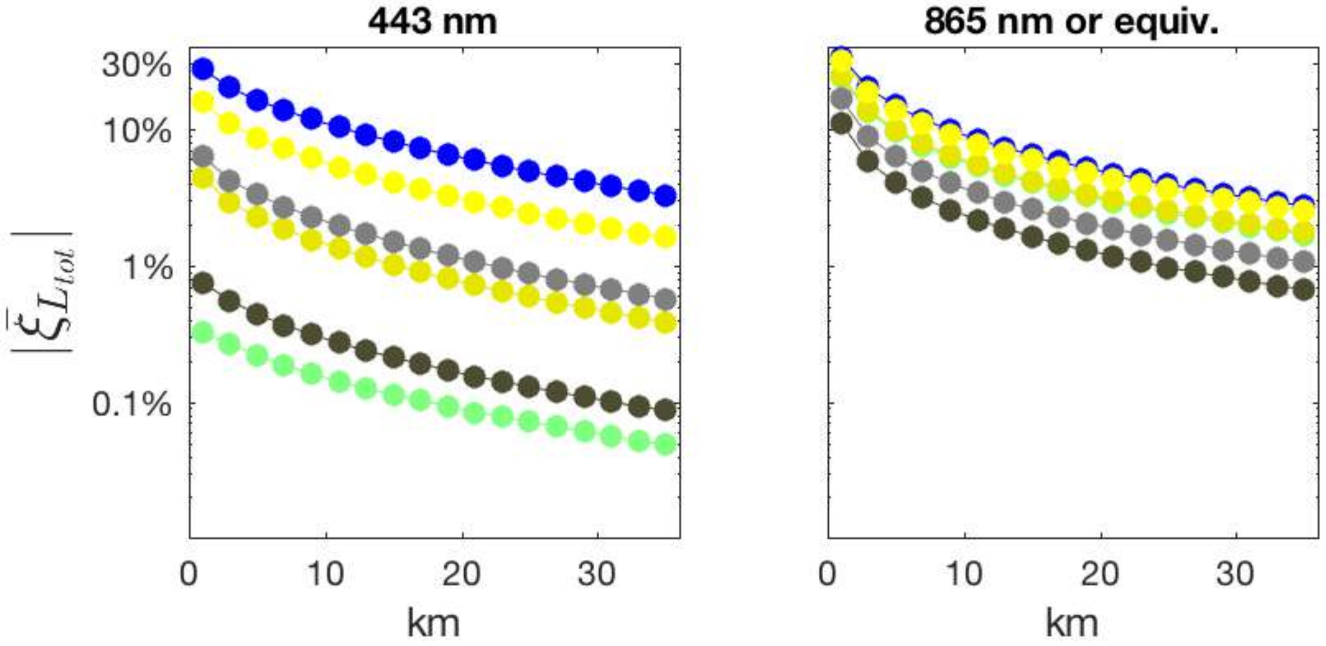
☆ annual average biases

correction for AE reduces annual and intra-annual biases

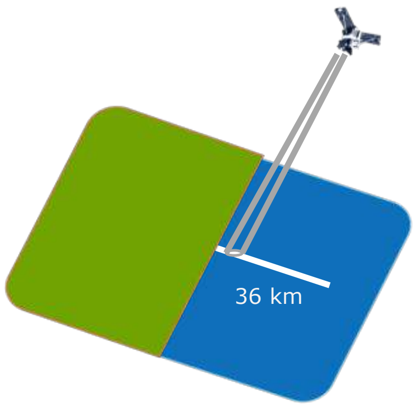
Bulgarelli et al., OE 2018

Analysis of AE spatial extension

Values of percent AE



Snow
White sand
Concrete
Dry grass
Bare soil (brown loam)
Green veg. (dec. trees)



error bars = uncertainties

northern Adriatic Sea waters

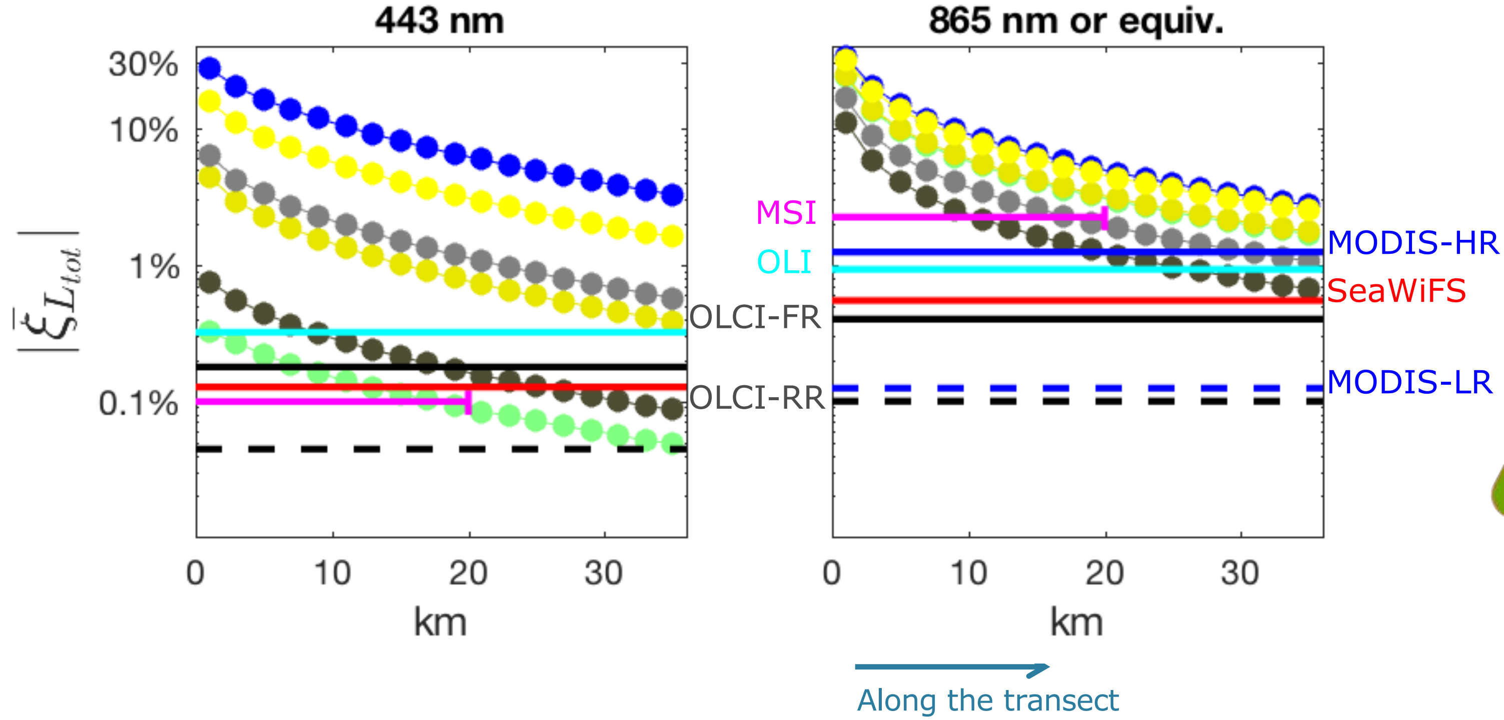
→ Along the transect

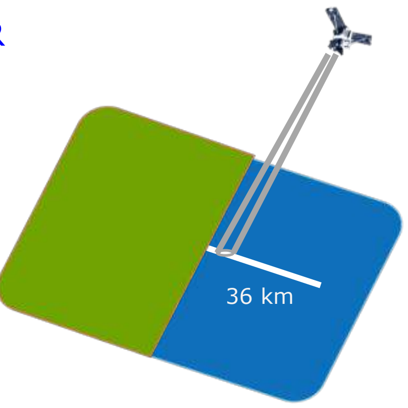
Bulgarelli and Zibordi, RSE 2018

AE spatial extension

Detectability: $\xi_{Ltot} > NL$ (NL=1/SNR)

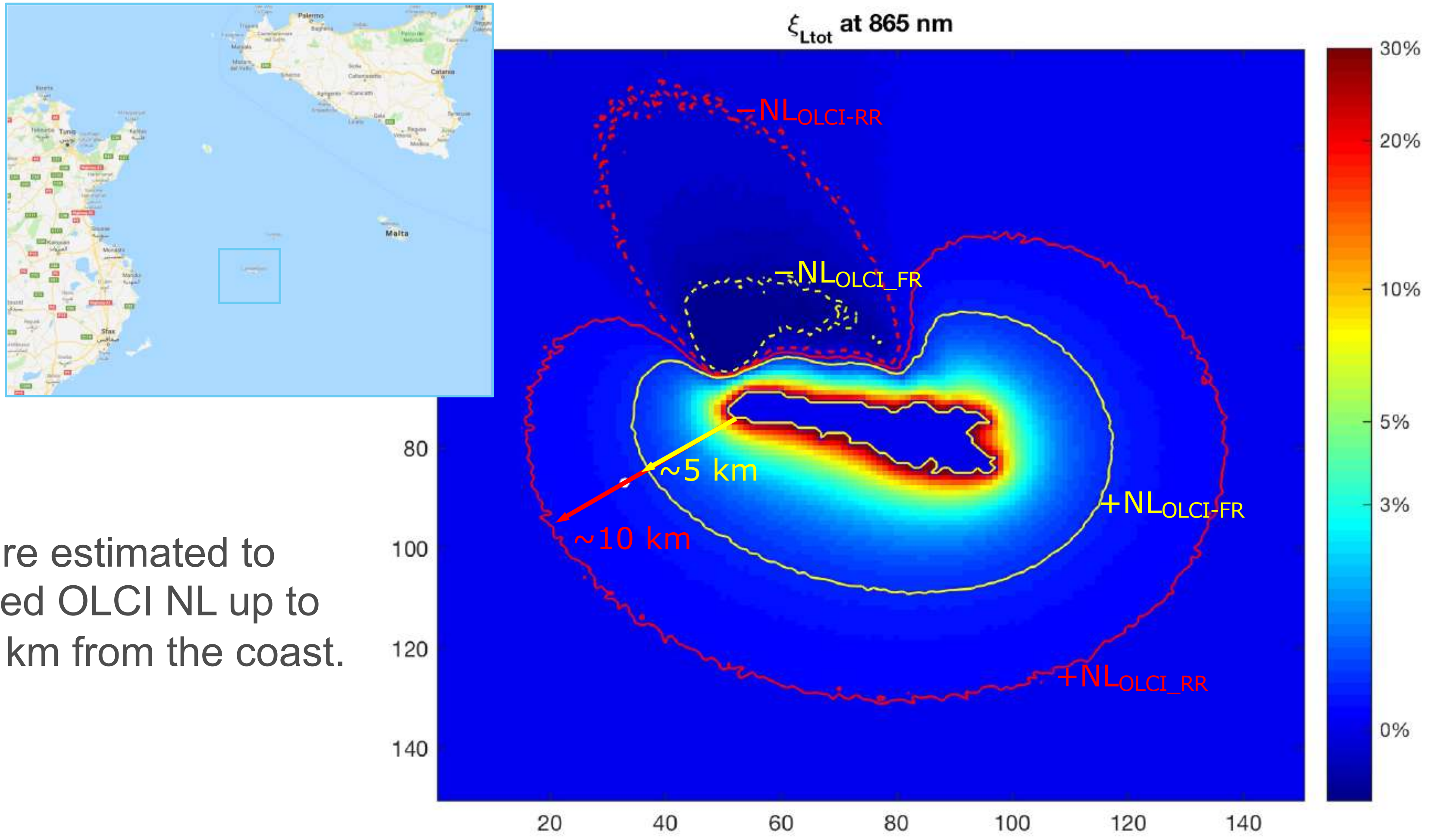
Snow
White sand
Concrete
Dry grass
Bare soil (brown loam)
Green veg. (dec. trees)





Bulgarelli and Zibordi, RSE 2018

AE in OLCI System Vicarious Calibration



865 nm
average atmosphere, land and water
optical conditions

significant AE

$\xi_{Ltot} > NL$

AE are estimated to exceed OLCI NL up to ~ 14 km from the coast.

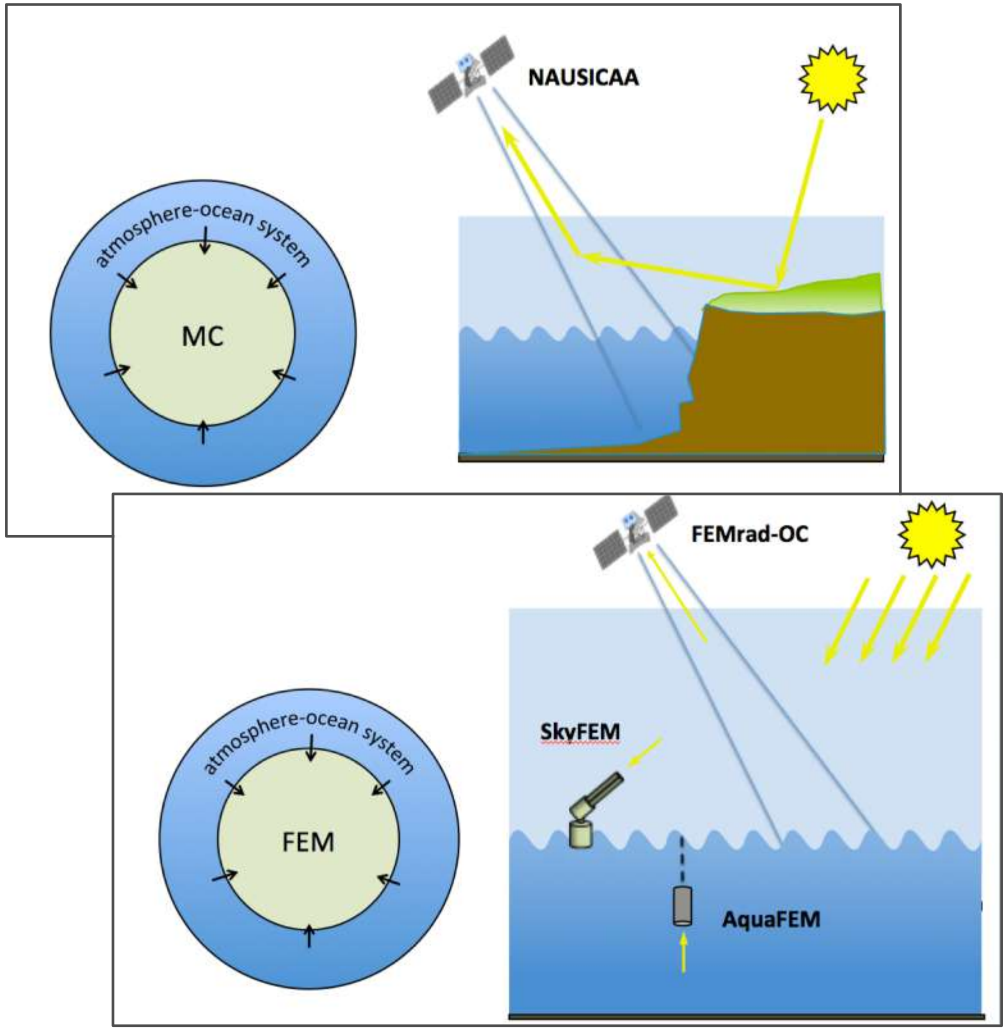
Bulgarelli and Zibordi, AO 2020

Barbara Bulgarelli

ARTEMIS-OC major upgrade

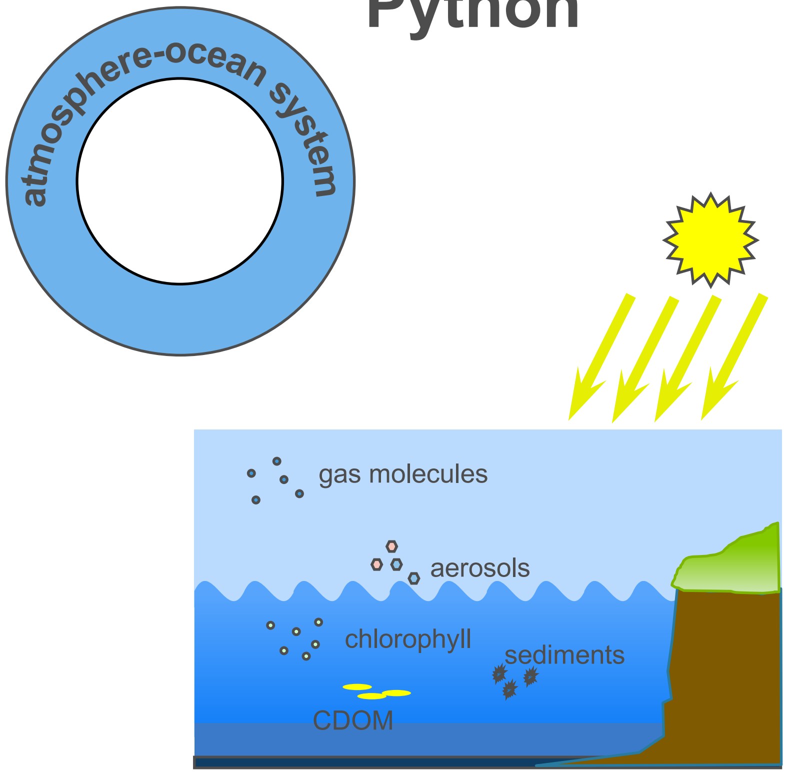
Fortran

MC



FEM

Python



MODTRAN atmosphere
Aerosol from OPAC, S&F, AERONET, etc.
In-situ IOPs
….

Bulgarelli and Vitale, *report in preparation*

Comparison exercises

a reprint from Applied Optics

Comparison of numerical models for computing underwater light fields

Curtis D. Mobley, Bernard Gentili, Howard R. Gordon, Zhonghai Jin, George W.
André Morel, Phillip Reinersman, Knut Stamnes, and Robert H. Stavn

Seven models for computing underwater radiances and irradiances b
transfer equation are compared. The models are applied to the solu
optical oceanography. The problems include highly absorbing and
by molecules and by particulates, stratified water, atmospheric e
effects, and Raman scattering. The models provide consistent outp
Carlo statistical fluctuations) in computed irradiances that are sel
than the experimental errors made in measuring irradiances
instrumentation. Computed radiances display somewhat larger err

1. Introduction

Various numerical models are now in use for computing underwater irradiances and radiance distributions. These models were designed to address a wide range of oceanographic problems. The models are based on various simplifying assumptions, have differing levels of sophistication in their representation of physical processes, and use several different numerical solution techniques.

In spite of the increasingly important roles these numerical models are playing in optical oceanography, the models remain incompletely validated in the sense that their outputs have not been extensively compared with measured values of the quantities they predict. This desirable model–data comparison

is not presently possible
hensive oceanic optical
Such data sets must co
ments of the inherent
water (e.g., the absorpti
and the scattering pha
parameters (e.g., the sk
sea state), and radiomet
plete radiance distribut
The inherent optical pr
tal parameters are need
models; the radiometric
predicted by the models
oceanic optical instrum
methodologies give caus
are adequate for compre
sons will become availab
Meanwhile, our faith
rests on careful debuggi
nal checks such as cons
relations between inhere
erties, simulation of a
tions for which analytic
transfer equation are ava
times indirect) with inc
tional worthwhile check
made by applying them
problems. Such model
identify errors in coding
ematical representation
tify numerical errors pe
tion algorithms, dete
techniques for simulatio

C. D. Mobley is with the Jet Propulsion Laboratory, California Institute of Technology, Mail Stop 300-323, 4800 Oak Grove Drive, Pasadena, California 91109; B. Gentili and A. Morel are with the Laboratoire de Physique et Chimie Marines, Université Pierre et Marie Curie, F06230 Villefranche-sur-Mer, France; H. R. Gordon is with the Department of Physics, University of Miami, Coral Gables, Florida 33124; Z. Jin and K. Stamnes are with the Geophysical Institute, University of Alaska, Fairbanks, Alaska 99701; G. W. Kattawar is with the Department of Physics, Texas A & M University, College Station, Texas 77843; P. Reinersman is with the Department of Marine Science, University of South Florida, St. Petersburg, Florida 33701; and R. H. Stavn is with the Department of Biology, University of North Carolina, Greensboro, North Carolina 27412.

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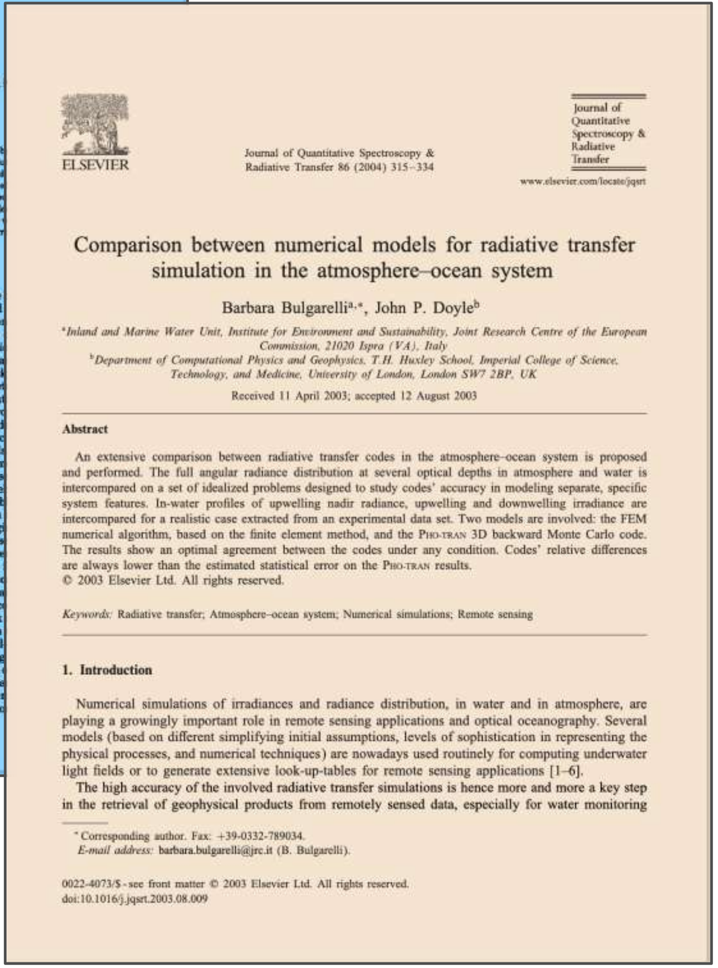

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Journal of Quantitative Spectroscopy & Radiative Transfer 86 (2004) 315–334

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Quantitative
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www.elsevier.com/locate/jqsrt

Comparison between numerical models for radiative transfer simulation in the atmosphere–ocean system

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Received 11 April 2003; accepted 12 August 2003

Abstract

An extensive comparison between radiative transfer codes in the atmosphere–ocean system is proposed and performed. The full angular radiance distribution at several optical depths in atmosphere and water is intercompared on a set of idealized problems designed to study codes' accuracy in modeling separate, specific system features. In-water profiles of upwelling nadir radiance, upwelling and downwelling irradiance are intercompared for a realistic case extracted from an experimental data set. Two models are involved: the FEM numerical algorithm, based on the finite element method, and the Pho-tran 3D backward Monte Carlo code. The results show an optimal agreement between the codes under any condition. Codes' relative differences are always lower than the estimated statistical error on the Pho-tran results.
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Keywords: Radiative transfer; Atmosphere–ocean system; Numerical simulations; Remote sensing

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1. Introduction

Numerical simulations of irradiances and radiance distribution, in water and in atmosphere, are playing a growingly important role in remote sensing applications and optical oceanography. Several models (based on different simplifying initial assumptions, levels of sophistication in representing the physical processes, and numerical techniques) are nowadays used routinely for computing underwater light fields or to generate extensive look-up-tables for remote sensing applications [1–6].

The high accuracy of the involved radiative transfer simulations is hence more and more a key step in the retrieval of geophysical products from remotely sensed data, especially for water monitoring

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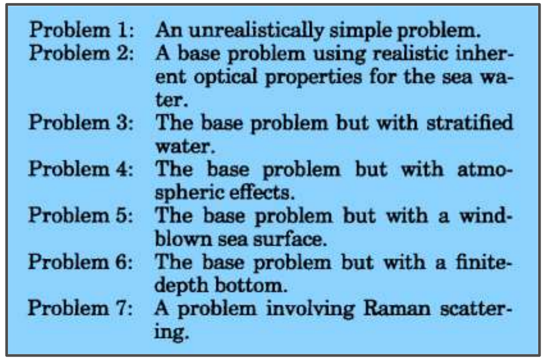
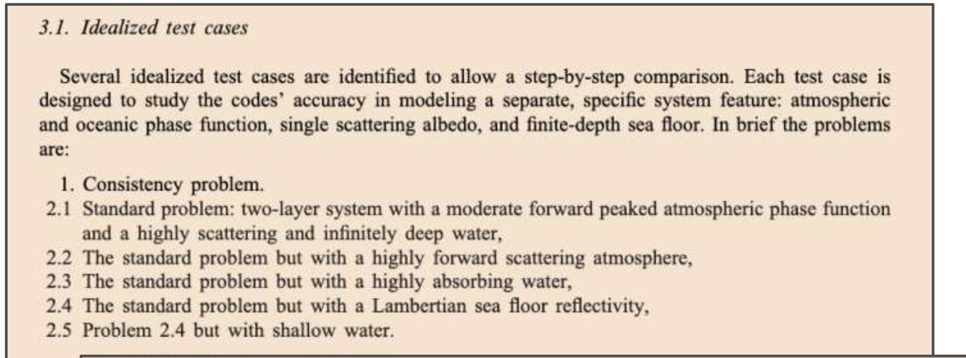
0022-4073/$ - see front matter © 2003 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jqsrt.2003.08.009



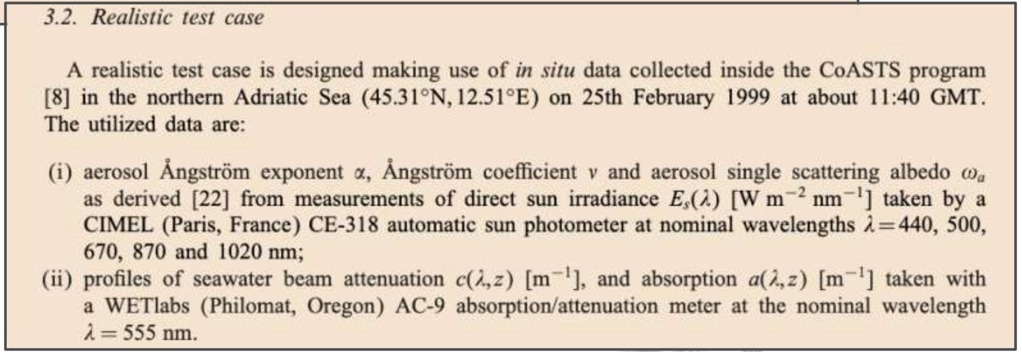
Problem 1: An unrealistically simple problem.
Problem 2: A base problem using realistic inherent optical properties for the sea water.
Problem 3: The base problem but with stratified water.
Problem 4: The base problem but with atmospheric effects.
Problem 5: The base problem but with a wind-blown sea surface.
Problem 6: The base problem but with a finite-depth bottom.
Problem 7: A problem involving Raman scattering.



3.1. *Idealized test cases*

Several idealized test cases are identified to allow a step-by-step comparison. Each test case is designed to study the codes' accuracy in modeling a separate, specific system feature: atmospheric and oceanic phase function, single scattering albedo, and finite-depth sea floor. In brief the problems are:

1. Consistency problem.
2.1 Standard problem: two-layer system with a moderate forward peaked atmospheric phase function and a highly scattering and infinitely deep water,
2.2 The standard problem but with a highly forward scattering atmosphere,
2.3 The standard problem but with a highly absorbing water,
2.4 The standard problem but with a Lambertian sea floor reflectivity,
2.5 Problem 2.4 but with shallow water.



3.2. *Realistic test case*

A realistic test case is designed making use of *in situ* data collected inside the CoASTS program [8] in the northern Adriatic Sea (45.31°N, 12.51°E) on 25th February 1999 at about 11:40 GMT. The utilized data are:

(i) aerosol Ångström exponent α, Ångström coefficient ν and aerosol single scattering albedo ω_a as derived [22] from measurements of direct sun irradiance $E_s(\lambda)$ [W m^{-2} nm^{-1}] taken by a CIMEL (Paris, France) CE-318 automatic sun photometer at nominal wavelengths $\lambda = 440$, 500, 670, 870 and 1020 nm;
(ii) profiles of seawater beam attenuation $c(\lambda, z)$ [m^{-1}], and absorption $a(\lambda, z)$ [m^{-1}] taken with a WETlabs (Philomat, Oregon) AC-9 absorption/attenuation meter at the nominal wavelength $\lambda = 555$ nm.

Thank you

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Any question?