ESA AO/1-9544/20/I/NS

COLOR
CDOM-proxy retrieval from aeOLus ObseRvations

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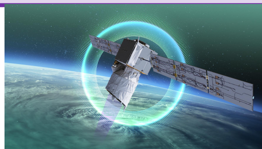
Consortium:

1 - Consiglio Nazionale delle Ricerche, Istituto di Scienze Marine, Rome, Italy
2 - Serco Italia S.p.A., Frascati, Italy
3 - AEQUORA, Lisbon, Portugal
4 - Università degli Studi della Basilicata, Potenza, Italy



Introduction

Spaceborne lidar and OCEAN COLOR

2008 2010 2012 2014 2016 2018 2020

CALIOP Integrated **subsurface backscatter vs chlorophyll-a concentration** (Lu et al., 2014)

Going beyond standard ocean color observation: Lidar and Polarimetry (Jamet et al., 2019)

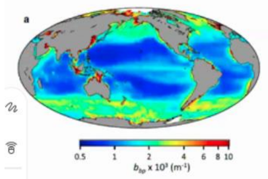
Demonstrated opportunity for future ocean colour applications (IOCS, 2019)

Assessment of the oceanic surface layer's optical properties through CALIOP

GUANLAN mission for space oceanography (S. Wu, Aeolus cal/val meeting,2020)

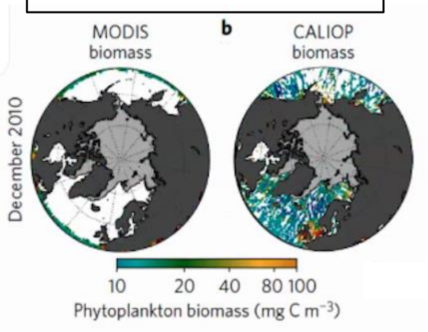
First investigations on **CALIOP subsurface bins** (Shi and Wang, 2008)

Ocean particulate backscatter from Caliop

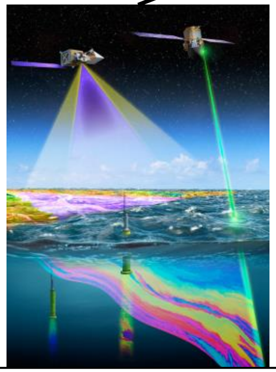


Behrenfeld et al., 2013

Annual cycle of polar phytoplankton **biomass**



Behrenfeld et al., 2017



New ***lidar era*** in satellite oceanography (Hostetler et al., 2018)

Ocean subsurface observations through ICEsat-2 (Lu et., 2019)

CALIOP δ_T used as an oceanic variable for the ocean particulate optical properties (Dionisi et al., 2020)

Vertical distribution of phytoplankton optical properties through CALIOP and ICEsat-2 measurements (Lu et al., 2021)

Satellite lidars can complement passive ocean color data

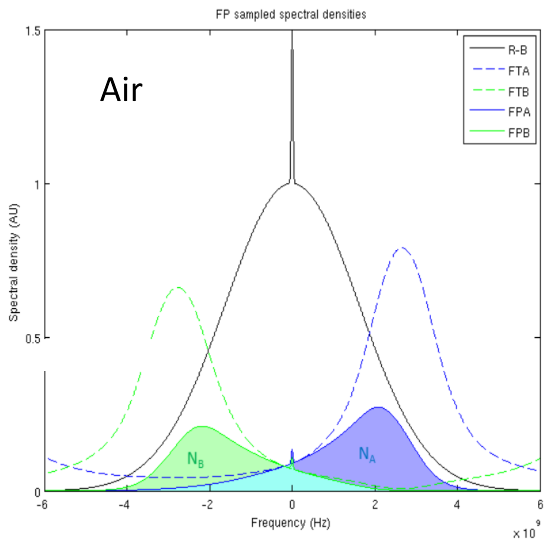
CDOM-proxy retrieval from aeOLus ObseRvations

Introduction

Motivation

Being the first orbiting HSRL lidar in the UV, AEOLUS gives the opportunity to investigate the signal backscattered by the ocean sub-surface:

- Separation of water and particulate backscatter contributions
- Ocean subsurface information content in the UV

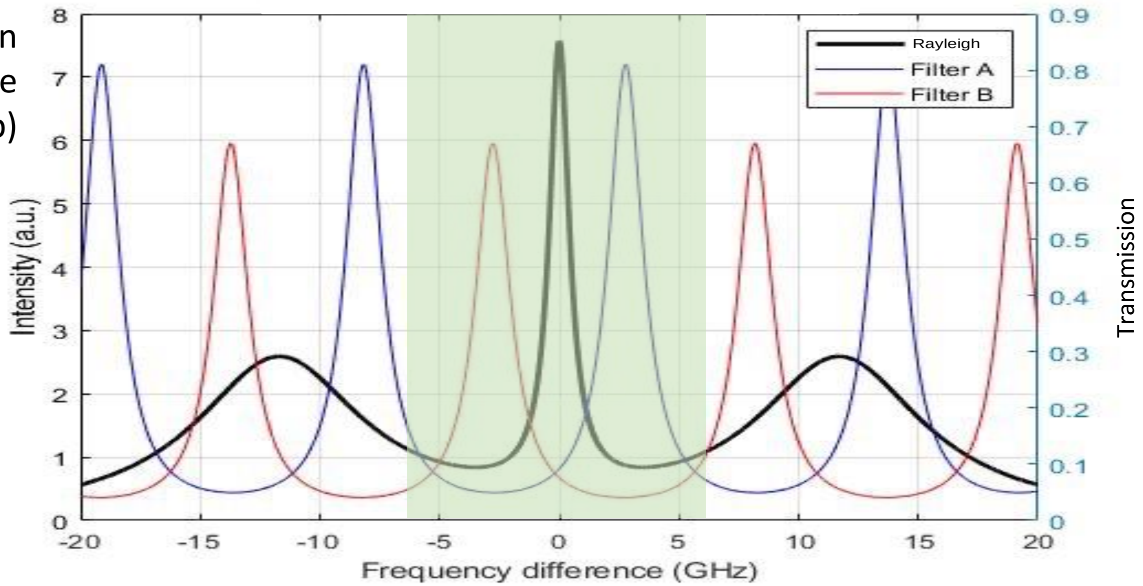


Flamant et al., 2020

Estimation of the Rayleigh spectrum in the water

The Brillouin frequency shift depends on the speed of sound $v_s = v_s(T, S, p)$, the refractive index of seawater $n = n(T, S, p)$ and the scattering angle θ.

$$v_B = \pm \frac{2nv_s}{\lambda} \sin\left(\frac{\theta}{2}\right)$$



FWHM	1,78 GHz
FSR	10,95 GHz
Spacing between A and B	5,5 GHz
Filter A Peak Transmission	81 %
Filter B Peak Transmission	67 %

Introduction

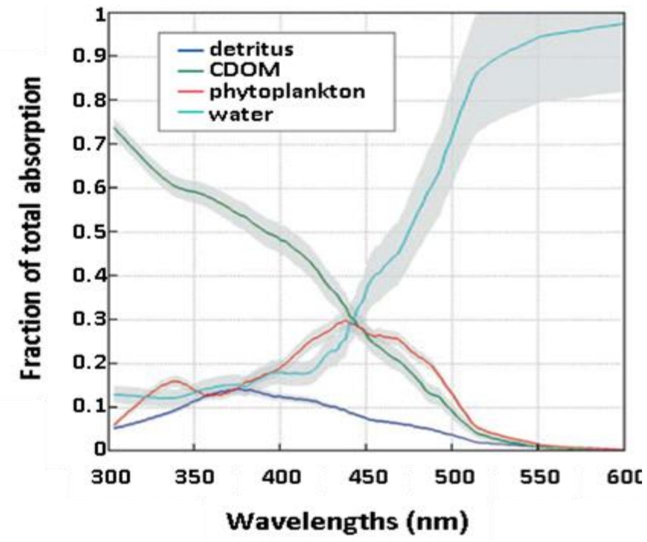
CDOM-proxy retrieval from aeOLus ObseRvations

Motivation

In the **ocean**, at 355 nm:

- b_{bp} (sub-surface hemispheric particulate backscatter coefficient) is dominated by the contribution due to **water molecules**
- K_d (diffuse attenuation coefficient for downwelling irradiance) is dominated by light absorption of optically-significant water constituents (water, particles and Chromophoric Dissolved Organic Matter, **CDOM**)

CDOM is the most relevant contributor to the light absorption at 355 nm. In the UV, K_d is used as a proxy of CDOM light absorption



Introduction

COLOR
CDOM-proxy retrieval from aeOLus ObseRvations

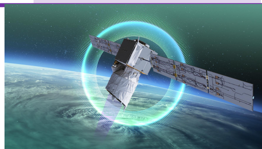
COLOR (*CDOM-proxy retrieval from ae**OL**us Obse**R**vations)* is an on-going 18 month feasibility study approved by **ESA** within the **Aeolus+ Innovation program** (ESA AO/1-9544/20/I/NS). **Kick-off: 10 march 2021.**

Objective

COLOR proposes to evaluate and document the **feasibility** of deriving an **in-water AEOLUS product** at 355 nm (lidar attenuation coefficient K_L, in-water particle backscattering β_{wat} ➔ ocean color parameters, e.g. K_d, Chl-a, CDOM)

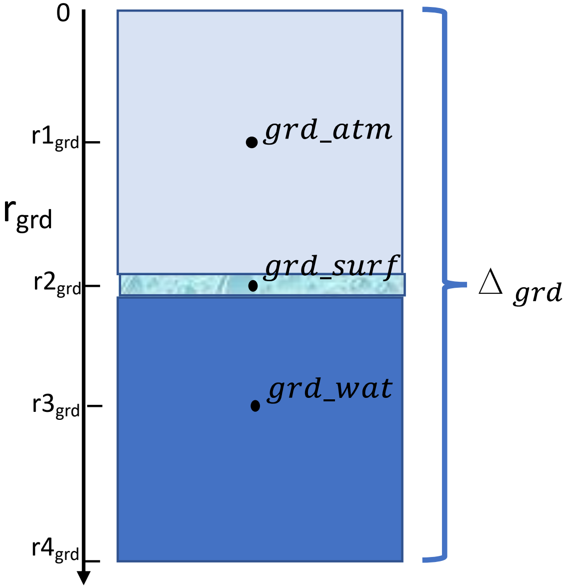
Consortium

Institute of Marine Sciences (ISMAR) - CNR	University of Basilicata	Aequora	Serco Italia SpA



Ground bin signal characterization

The potential information on ocean subsurface optical properties is contained in the AEOLUS ground bin volume (**Δr_{grd}**)



$$S_X(grd) = M_X \left[\frac{A}{\left(r_{atm} + \frac{\Delta r_{atm}}{n} \right)^2} \right] \boxed{B_{grd}} T_A^2(r_{atm}) + S_{bkd} \qquad (1)$$

X= $Ray_{A,B}$
X= Mie

$$B_{grd} = B_{atm} + B_{srf} + B_{wat}(K_L, \beta_{wat}^{par}, \beta_{wat}^{mol}) \qquad (2)$$

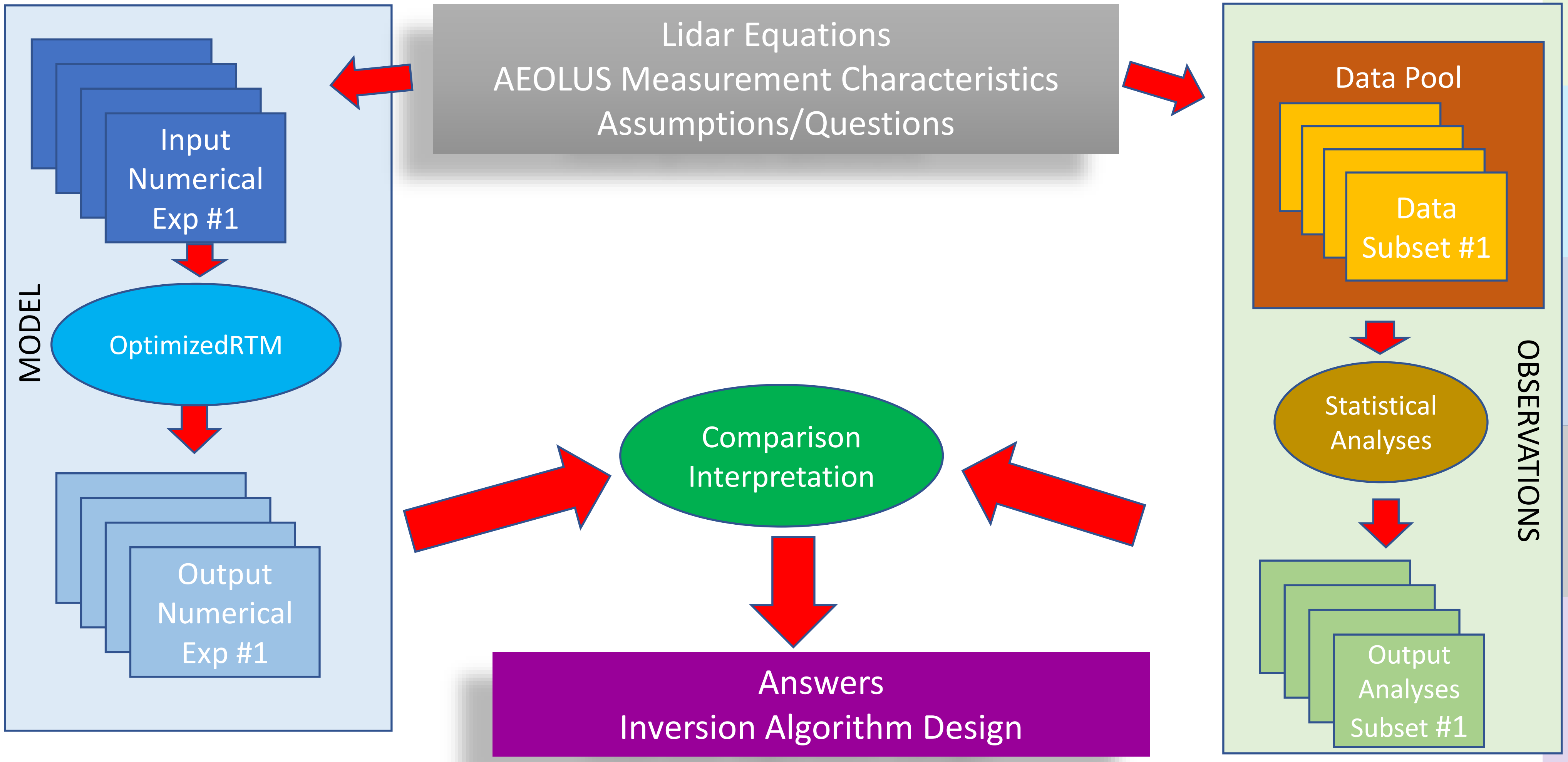
$$B_{wat} = \int_0^{r_{wat}} \beta_{wat}(\pi, r'_{wat})\, exp\left[-2 \int_0^{r'_{wat}} K_{LID}(r''_{wat}) dr''_{wat} \right] dr'_{wat} \qquad (3)$$

This characterization is based on:

a) **Radiative transfer numerical modelling**
b) **AEOLUS data analysis**

Color approach

General Description



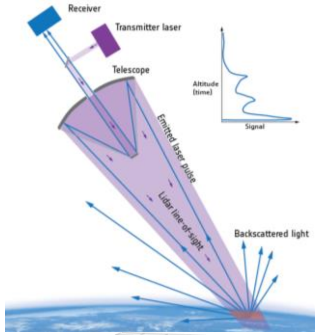
Preliminary results

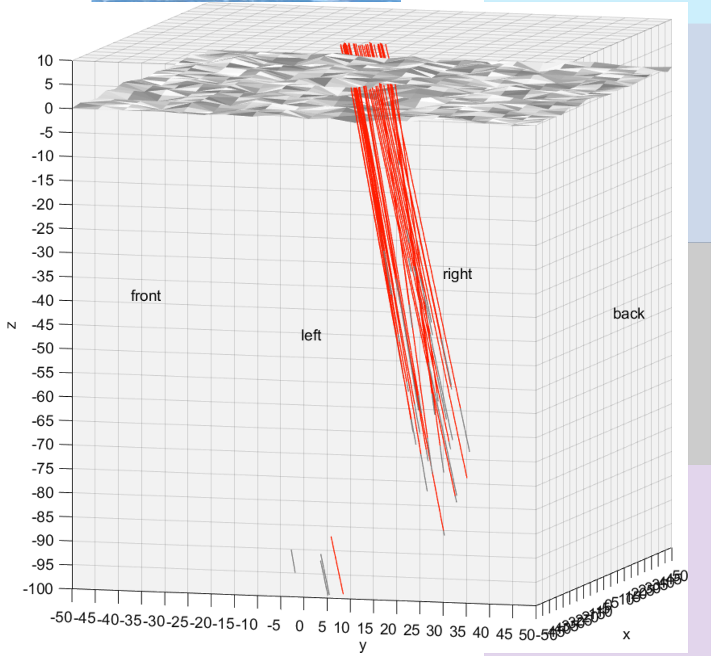
CDOM-proxy retrieval from aeOLus ObseRvations

Radiative transfer numerical modelling

- **Aim:** Development and validation of a RTM to simulate AEOLUS signal propagation in ocean.
- **Features**:
  - 3D Monte Carlo
  - surface reflection, absorption and multiple scattering
  - implementation and testing of missed components/functions
  - Fully accounting for ALADIN characteristics
- **Input:** wind, T, Chl, CDOM, …
- **Output:** b_{bp}, K_d, ratio between incident and transmitted signal, photons counts at the receiver (estimate)

- **Activities:**
  - Analysis of requirements for the Forward Modeling Tools;
  - Optimization of the Forward Modeling Tools;
  - Definition of numerical experiments

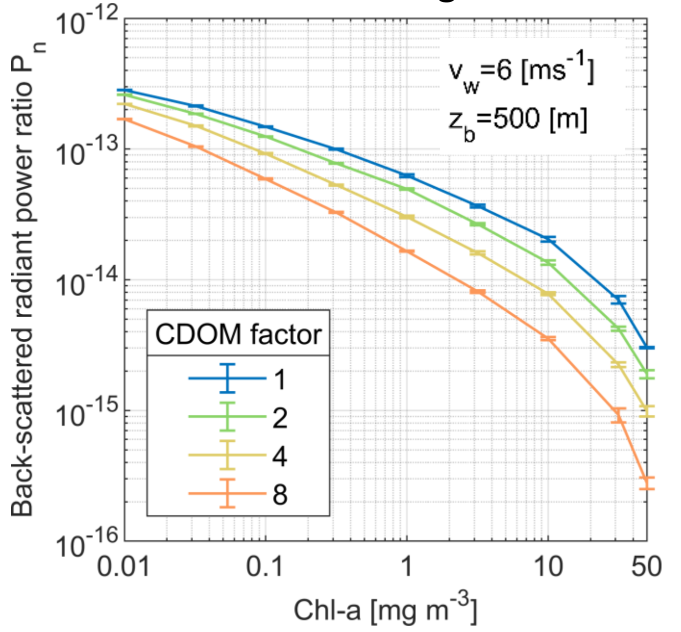




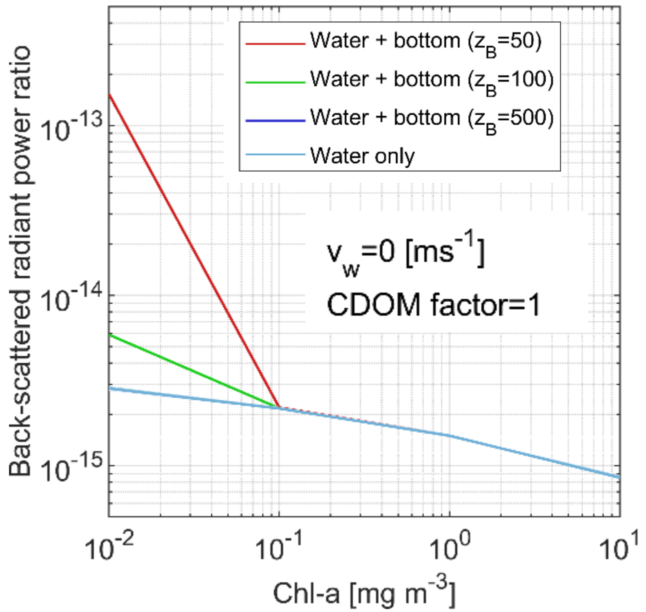
CDOM-proxy retrieval from aeOLus ObseRvations

Radiative transfer numerical modelling

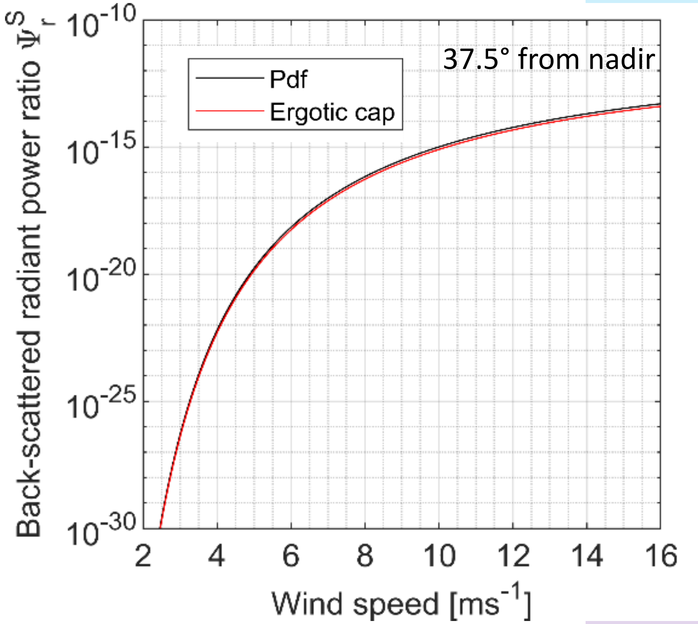
Contribution of the water bin to the retrieved signal



Reflection at the sea bottom



Sea-surface back-scattering contribution



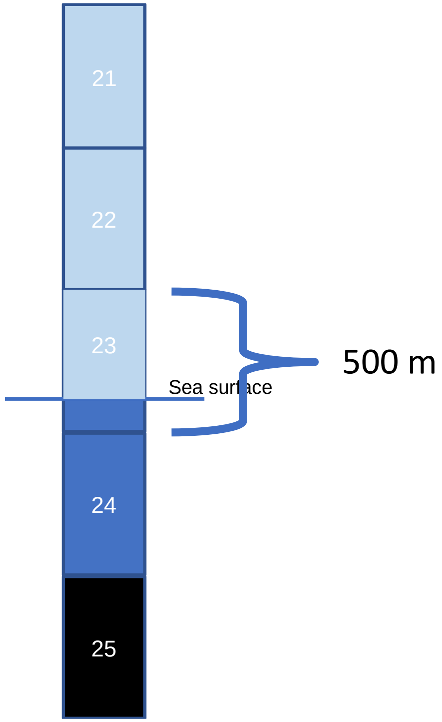
Simulations identified "**expected**" **conditions** where the **echoed lidar signal** can be informative of **optically active sea-water constituents** (e.g., v_w<8 ms^{-1}, Chl-a > 0.1 mg m^{-3} if $z_b \approx 100$ m).

Ocean color radiometry with space-borne lidar: the AEOLUS case study, IN PREPARATION

Preliminary results

AEOLUS data analysis

AEOLUS acquisition bins

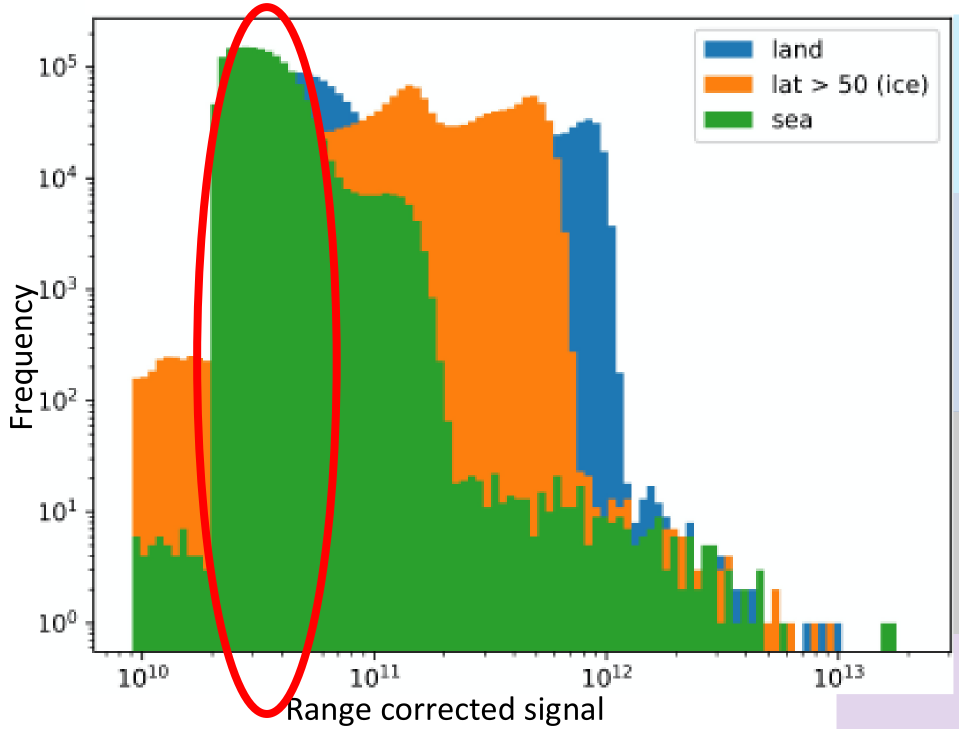


- Bin #23 contains the atmosphere-ocean interface (more than 95% of the cases). Water portion is around 20% of the bin.

- Analysis of the different contributions of the ground bin (#23) signal

BIN #23

Mie Channel – L1B -B11 - JJA 2020 – L1B dataset - measurement



Preliminary results

AEOLUS data analysis

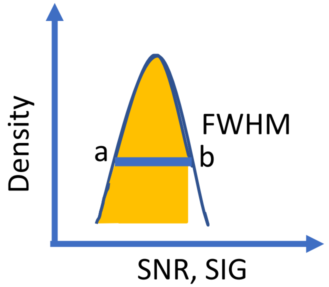
Data filtering procedure

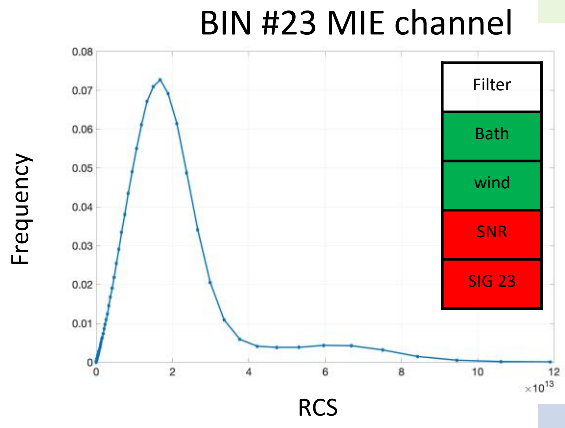
1) Bathymetry*: sea depth ≥ 100 m; lower edge of BIN #23 < -70 m

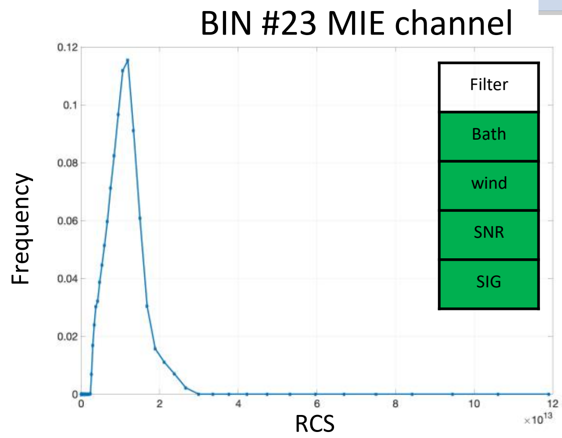
2) Wind at the surface**: < 8 m/s

3) Cloud/aerosols contamination (BIN #23, #22 and #21 of Mie channel)

- SNR ≥ 5 and SNR ≤ SNR_{FWHMb}
- SIG ≤ SIG_{FWHMb}







<u>This procedure removes the majority of cloud contaminated bins but filters out around 70% of the original data sample. Residual contaminated bins are present.</u>

*GEBCO (General Bathymetric Chart of the Oceans) Gridded Bathymetry Data (https://www.gebco.net/)

**ERA5 dataset (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5)

Preliminary results

COLOR

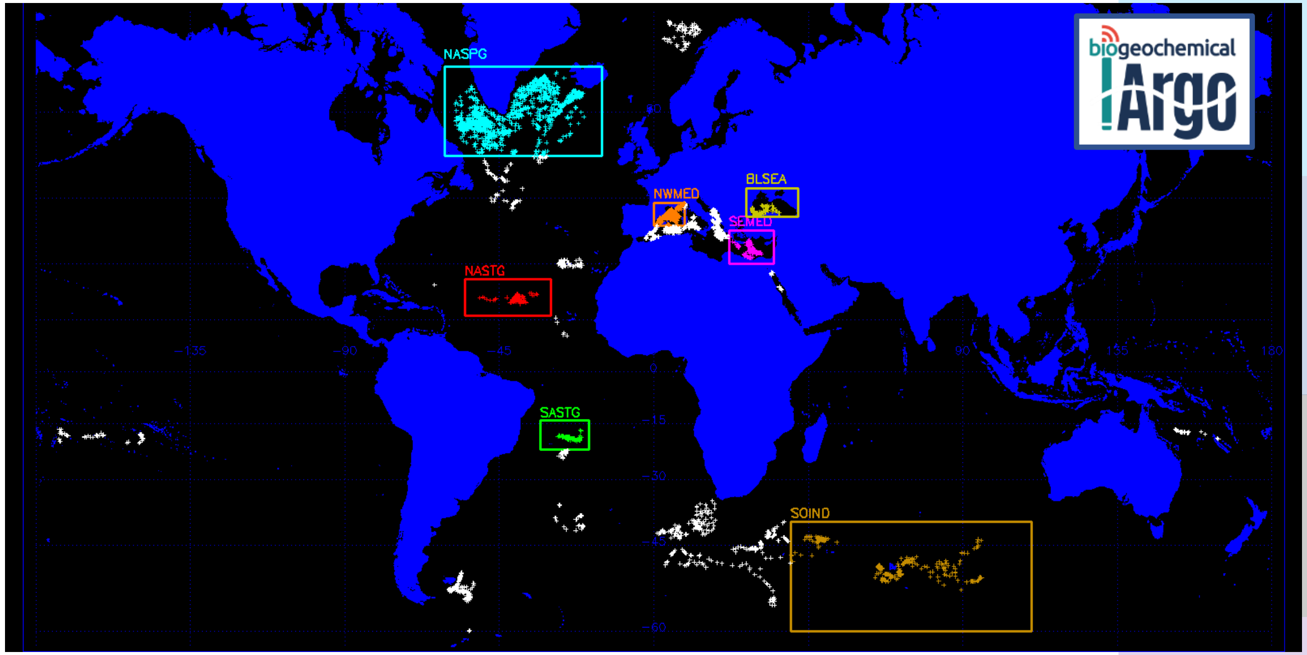
CDOM-proxy retrieval from aeOLus ObseRvations

CAL/VAL activities: testing the capability to reproduce expected behaviours

Statistical comparison between **AEOLUS** observations and reference datasets**: BGC-Argo (K_d at 380 nm)**.

Areas of interest:

1) North Atlantic subpolar gyre;
2) North Atlantic subtropical gyre;
3) South Atlantic subtropical gyre;
4) Black Sea;
5) North Western Mediterranean Sea;
6) Levantine Sea (Mediterranean Sea);
7) Southern Ocean – Indian sector.

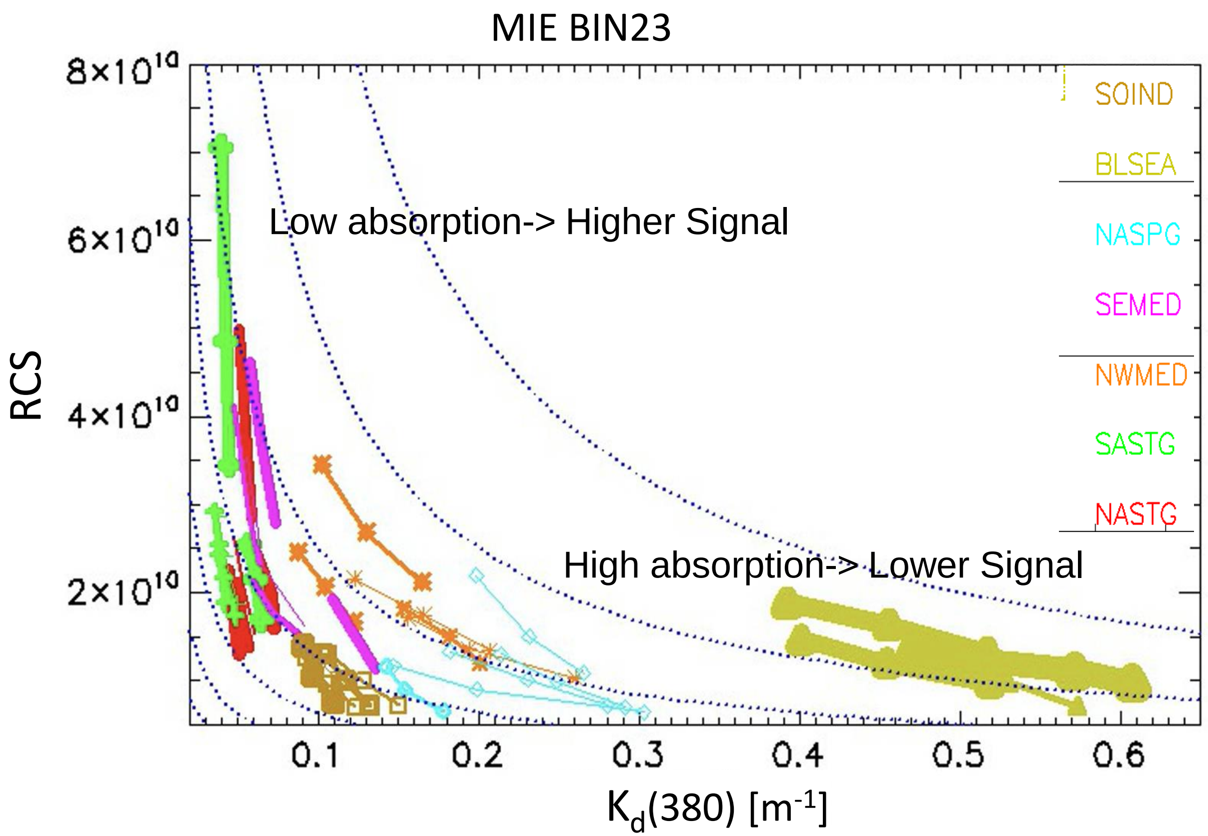


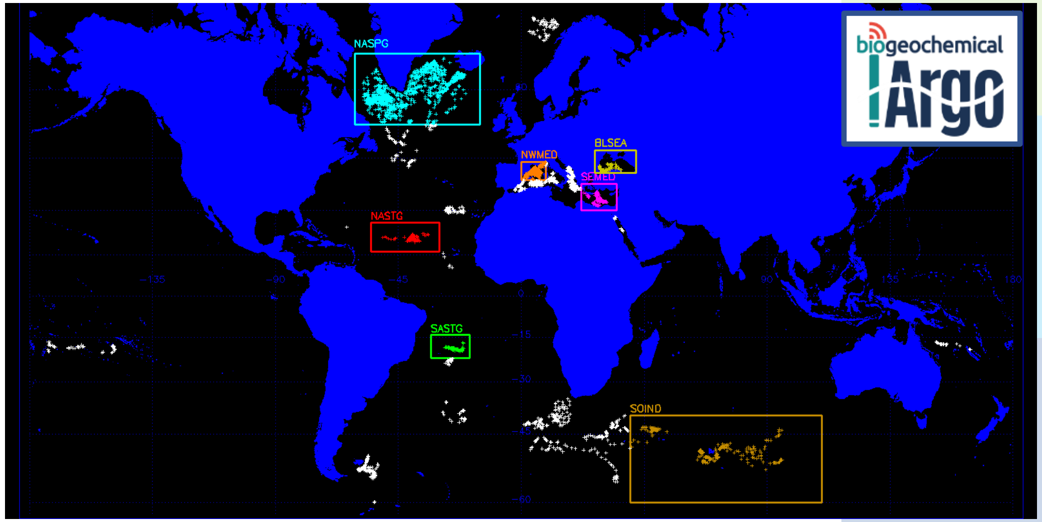
B11 L1B dataset at measurement scale: JJA, SON 2020, DJF, MAM 2021

Preliminary results

CDOM-proxy retrieval from aeOLus ObseRvations

BGC Argo vs AEOLUS





Statistical variable: Quartiles of the distribution

Physical variable: Kd_{380} vs Bin 23 Range Corrected Signal (Mie and Rayleigh) @ 355nm (assuming an inverse dependence -> 1st quartile vs 3rd quartile)

On-going activities

COLOR
CDOM-proxy retrieval from aeOLus ObseRvations

Design and development of OC AEOLUS inversion algorithm

-1) High Spectral Resolution Lidar (HSRL) AEOLUS-adapted algorithm
Separation of β_{wat}^{par} and β_{wat}^{mol}, using both the equations of Mie and Rayleigh channels.

-2) Elastic Backscattering Lidar (EBL) AEOLUS-adapted algorithm
Assumptions needed to derive one or both β_{wat}^{par} and β_{wat}^{mol}, using Mie channel.

1) HSRL

$$\left.\begin{aligned}
S_{Mie} &= M_{Mie}\left[\frac{A}{\left(r_{atm}+\frac{\Delta r_{atm}}{n}\right)^{2}}\right]\left(C_4\beta_{wat}^{m}+C_3\beta_{wat}^{p}\right)exp\left[-2\int_0^{r_{wat}}K_{LID}(r'_{wat})dr'_{wat}\right]T_A^2(r_{atm}) \\
S_{Ray} &= M_{Ray}\left[\frac{A}{\left(r_{atm}+\frac{\Delta r_{atm}}{n}\right)^{2}}\right]\left(C_1\beta_{wat}^{m}+C_2\beta_{wat}^{p}\right)exp\left[-2\int_0^{r_{wat}}K_{LID}(r'_{wat})dr'_{wat}\right]T_A^2(r_{atm})
\end{aligned}\right\}\quad \beta_{wat}^{p}=\beta_{wat}^{m}\left[\frac{S_R M_{Mie}C_4-M_{Ray}C_1}{M_{Ray}C_2-S_R M_{Mie}C_3}\right]$$

Cross-talk and calibration coefficients are not available for L1B dataset
High variability of the Rayleigh ground bin signal

On-going activities

Design and development of OC AEOLUS inversion algorithm

2) EBL

INPUTS: (Mie channel) Range Corrected Signals (S^*_{xx}) and geometry of bins 21, 22, 23 ($z_{xx}, \Delta z_{xx}$)
ANCILLARY: Atmospheric density profile, surface wind (T_s^2), sea temperature and salinity, aerosols scale height (z_s) .
OUTPUT: sea water contribution (backscattering+extinction) to ground bin signal (B_{wat})

Assuming the surface return contribution negligible:

$$S^*_{23} = \frac{C}{n^2} B_{wat} T_s^2 T_A^2 T_{21}^2 T_{22}^2 T_{23}^2 + C B_{23} T_A^2 T_{21}^2 T_{22}^2$$

$$S^*_{22} = C B_{22} T_A^2 T_{21}^2$$

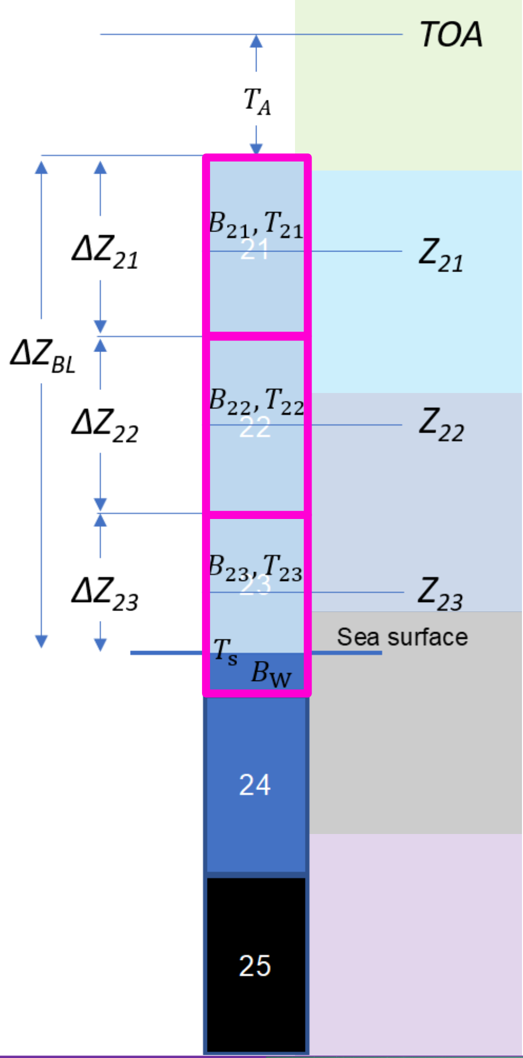
$$S^*_{21} = C B_{21} T_A^2$$

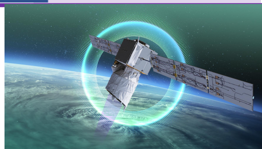
Where:

$$T_X^2 = T_{Xa}^2 \, T_{Xm}^2$$

$$B_X^2 = B_{Xa}^2 + B_{Xm}^2$$

X= 21, 22, 23





On-going activities

COLOR
CDOM-proxy retrieval from aeOLus ObseRvations

Design development of OC AEOLUS inversion algorithm

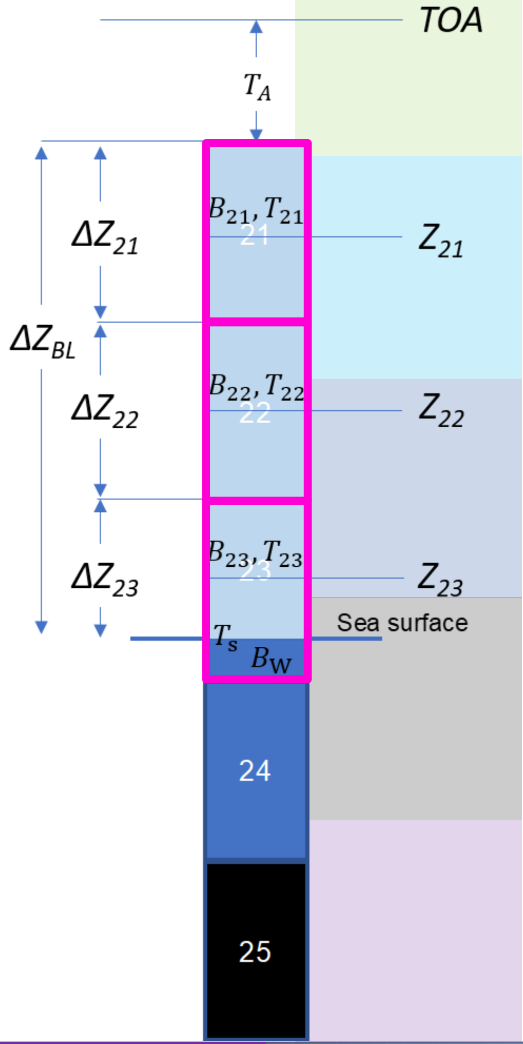
2) EBL

INPUTS: (Mie channel) Range Corrected Signals (S^*_{xx}) and geometry of bins 21, 22, 23 ($z_{xx}, \Delta z_{xx}$)
ANCILLARY: Atmospheric density profile, surface wind (T_s^2), sea temperature and salinity, aerosols scale height (z_s) .
OUTPUT: sea water contribution (backscattering+extinction) to ground bin signal (B_w)

ASSUMPTIONS:

- Contribution of Sea surface reflection negligible.
- Aerosols Backscattering negligible compared to Molecular Backscattering
- **Difference** between atmospheric backscattering of bin 23 and 22 negligible with respect to contribution to the signal of bin 23
- Homogeneous aerosols type in bins 21,22,23
- Known vertical distribution of aerosols (e.g. exponential)

$$\boldsymbol{B_{wat}} \approx \frac{(S^*_{23} - S^*_{22})}{S^*_{21}} \frac{B_{21m} n^2}{T_s^2 T_{BLm}^2} e^{+\left(\frac{2\rho_0\,\sigma_{ext}}{\cos\theta}\left(e^{\frac{-z_{21}}{z_s}}\Delta z_{21} + e^{\frac{-z_{22}}{z_s}}\Delta z_{22} + e^{\frac{-z_{23}}{z_s}}\Delta z_{23}\right)\right)}$$

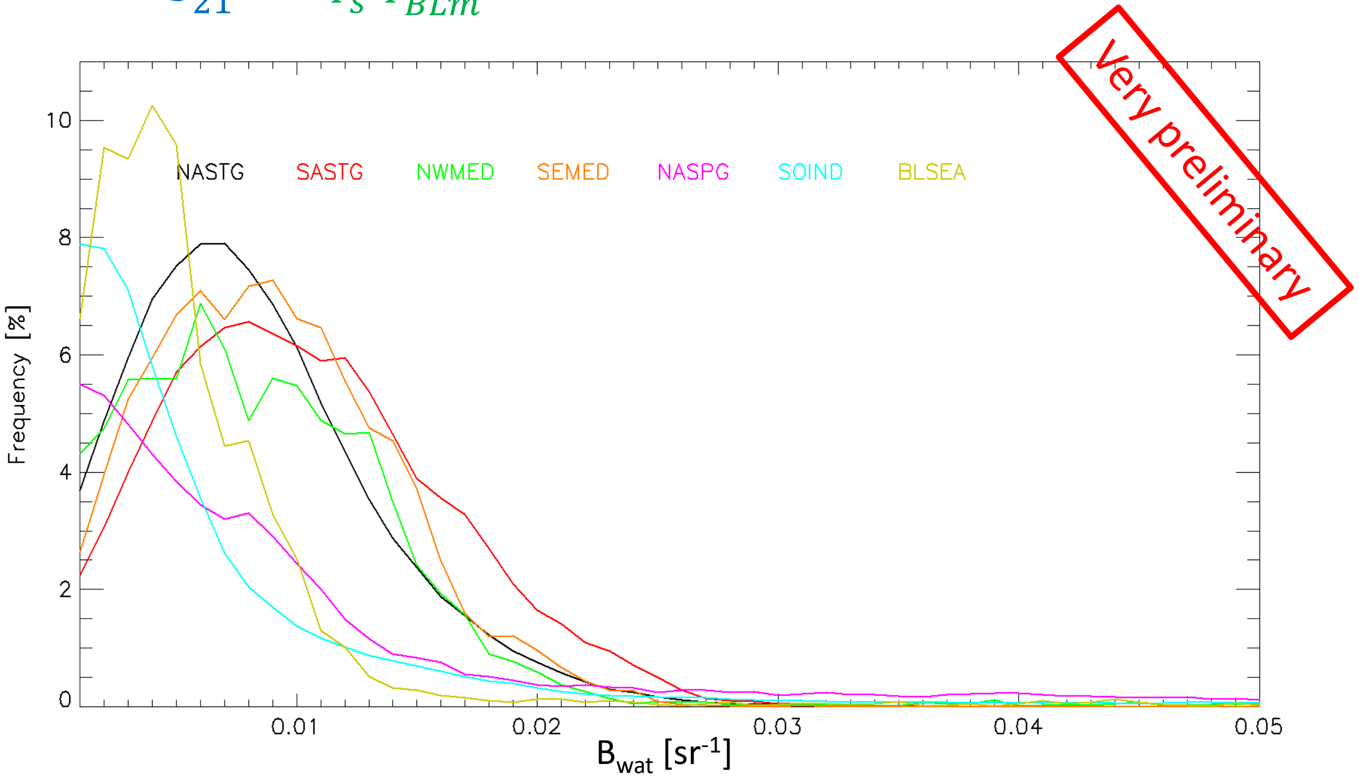


On-going activities

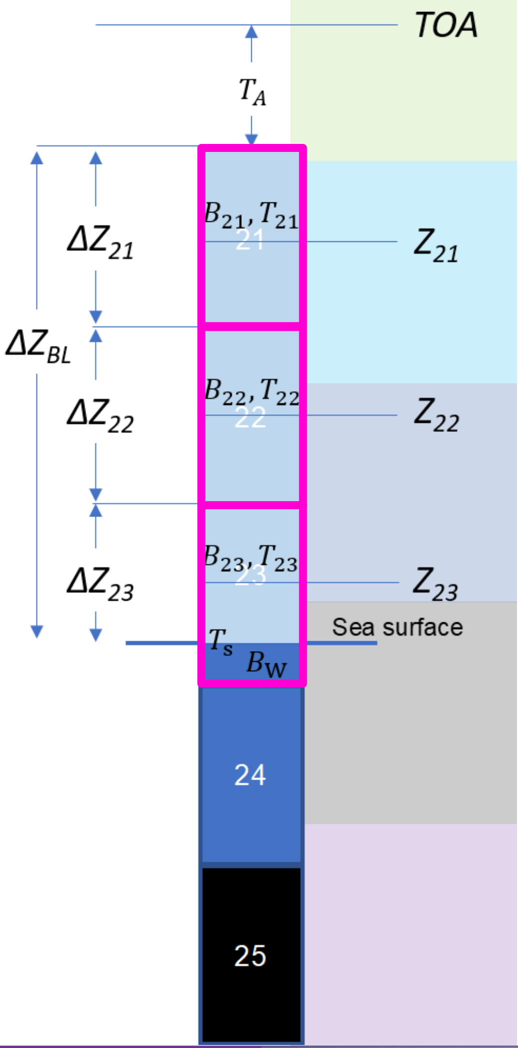
Design and development of OC AEOLUS inversion algorithm

2) EBL

$$B_{wat} \approx \frac{(S^*_{23} - S^*_{22})}{S^*_{21}} \frac{B_{21m} n^2}{T_s^2 T_{BLm}^2} e^{+\left(\frac{2\rho_0 \sigma_{ext}}{\cos\theta}\left(e^{\frac{-z_{21}}{z_s}}\Delta z_{21} + e^{\frac{-z_{22}}{z_s}}\Delta z_{22} + e^{\frac{-z_{23}}{z_s}}\Delta z_{23}\right)\right)}$$



limit of applicability: oligotrophic waters??



Summary

CDOM-proxy retrieval from aeOLus ObseRvations

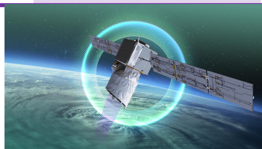
- COLOR (CDOM-proxy retrieval from aeOLus ObseRvations) has the objective to evaluate and document the **feasibility** of deriving an **in-water AEOLUS prototype.** Kick-off: 10 march 2021.

- COLOR core approach is the characterization of the AEOLUS ground bin signal coupling radiative transfer modeling and data analysis

- Development of RTM to simulate AEOLUS signal propagation in ocean.
  Simulation results allowed to identify "expected" conditions where the echoed lidar signal can be informative of optically active sea-water constituents (e.g., v_w<8 ms^{-1}, Chl-a > 0.1 mg m^{-3} if $z_b \approx 100$ m).

- Preliminary analysis on AEOLUS signal:
  - For the large majority of the cases, bin #23 is the one containing the atmosphere-ocean interface
  - Data filtering procedure on #23,22,21 bin of Mie channel removes the majority of cloud/aerosol contaminated bins
  - Statistical comparison between K_d derived by BGC-Argo and AEOLUS RCS seems to confirm RTM results

- A potential inversion algorithm using only Mie channel was designed ➔ Need to be validated and assessed.



On-going activities

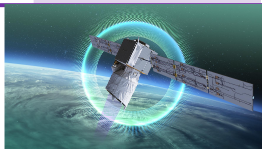
CDOM-proxy retrieval from aeOLus ObseRvations

Data issues

- Removal of residual ice/low level clouds/aerosol signal in the ground bin
- Large variability of Rayleigh ground bin signal
- Estimation of Rayleigh/Mie efficiencies and cross talk coefficients
- Definition of surface range bin.

On-going data analysis

- Improvement of Q/C tests
- Specific data integration strategy to increase SNR
- Use of L2A dataset
- ELB retrieval: 1) Refinement of the analytic solution; 2) Development of three equation inversion
- Design and development HSRL retrieval inversion



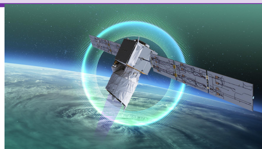
COLOR

CDOM-proxy retrieval from aeOLus ObseRvations

Thanks for your attention

Contact: davide.dionisi@cnr.it

COLOR website: http://ricerca.ismar.cnr.it/color/

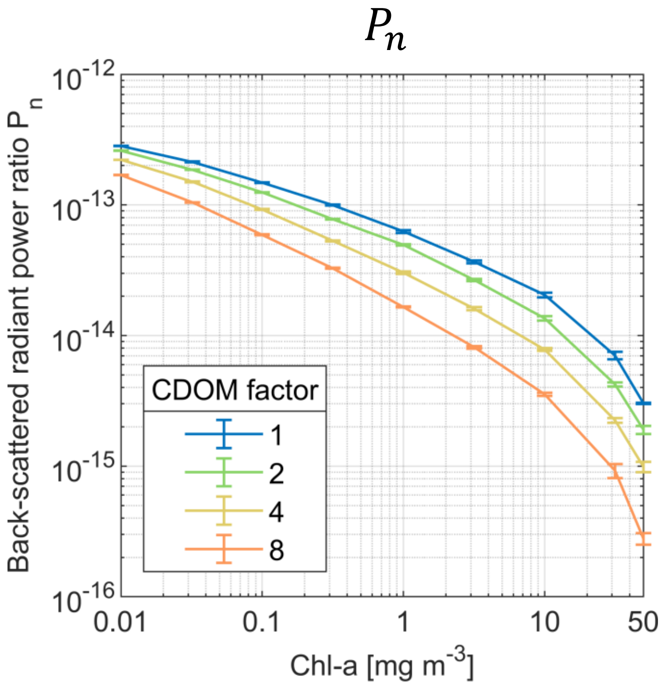


Preliminary results

Radiative transfer numerical modelling

CDOM-proxy retrieval from aeOLus ObseRvations

Estimation of the expected number of photons due to the water bin



$$P_r = P_0 M\, T_a^2 T_s^2 P_N$$

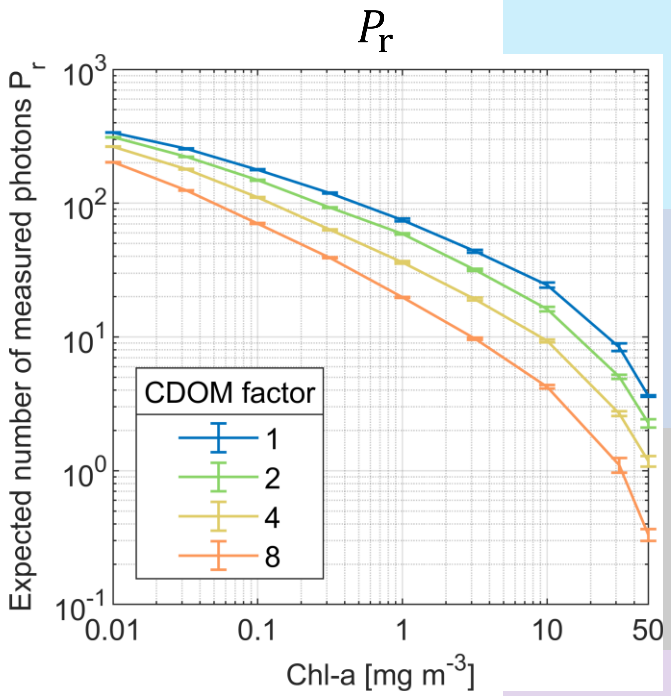
P_0: number of emitted photons

M is the instrument efficiency

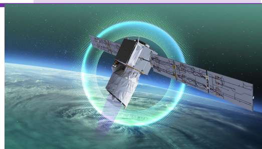
T_a^2 is the transmittance of the atmosphere

T_s^2 is the sea−surface transmittance

$$P_N = \frac{\Delta\, \Omega_r\, \beta_{wat}}{2K_{\mathrm{Lid}}}\left[1 - e^{-2K_{\mathrm{Lid}} z_{\max}}\right]$$



Ocean color radiometry with space-borne lidar: the AEOLUS case study, IN PREPARATION



Objective:

Analytical (based on simulated K_{lid}) vs fully statistical results (Chla=0.1 mg m^{-3})

Tasks

- **AD1: Development and implementation of the in-water forward model**
- AD2: Development of the AEOLUS inverse model and assessment of the retrieval performances
- AD3: Algorithm implementation and Prototype product testing
- DV: Validation and assessment of the retrieval performances

Seawater factors

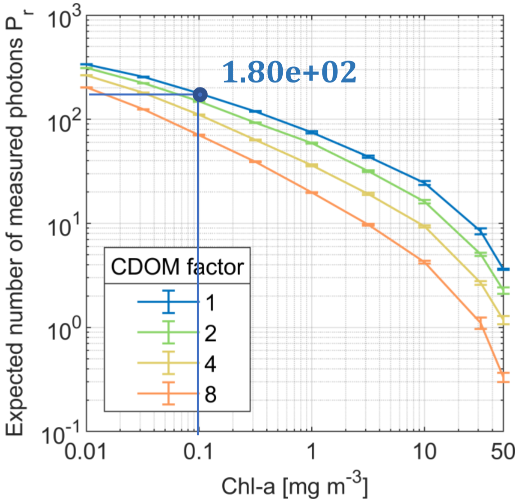
- Total absorption coefficient a = 1.801e-02 [m^{-1}]
- Total scattering coefficient b = 1.020e-01 [m^{-1}]
- Total attenuation coefficient c = 1.200e-01 [m^{-1}]
- Water absorption coefficient a_w = 9.735e-04 [m^{-1}]
- Water scattering coefficient b_w = 1.120e-02 [m^{-1}]
- Water attenuation coefficient c_w = 1.217e-02 [m^{-1}]
- Surface transmittance T_s = 9.7e-01
- Telescope solid angle (water) $\Delta\Omega_r$= 1.246e-10 [rad]
- Volume scattering function β_π = 1.447e-03 [m^{-1} rad^{-1}]

$P_r = P_0 M\, T_a^2 T_s^2 P_N$ P_0 is the emitted signal (e.g., number of photons) M is the instrument efficiency (or response) T_a is the transmittance of the atmosphere T_s is the sea−surface transmittance

$$P_N = \frac{\Delta\,\Omega_r\,\beta_\pi}{2K_{\mathrm{Lid}}}\left[1 - e^{-2K_{\mathrm{Lid}}z_{\max}}\right] \text{ if } K_{\mathrm{Lid}} \text{ known}$$

Lidar equation factors

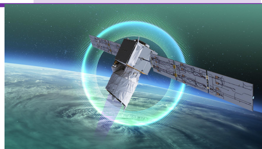
- Emitted photons P_0 = 2.1699e+18
- Instrument efficiency M = 6.0350e-03
- Atmospheric transmittance (two-ways) T_a^2 = 2.0000e-01
- Lidar attenuation coefficient (RTMT simulation) K_{Lid} = 6.3925e-02
- Signal fraction K_{Lid} based returned by the water column P_N^{sim} = 1.28e-13



Received photons

- Received photons based on the lidar equation and simulated K_{Lid} P_r = **1.57e+02**

Difference due to K_{lid} changes with depth?



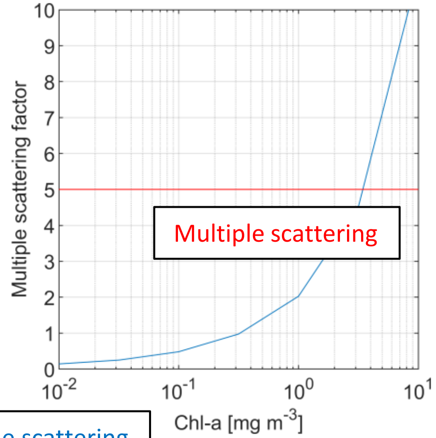
Single vs multiple scattering contribution

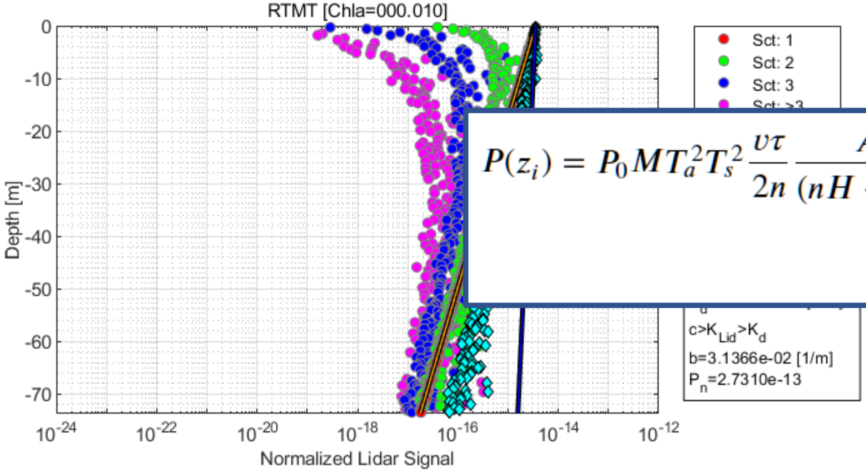
Tasks

- **AD1: Development and implementation of the in-water forward model**
- AD2: Development of the AEOLUS inverse model and assessment of the retrieval performances
- AD3: Algorithm implementation and Prototype product testing
- DV: Validation and assessment of the retrieval performances

- Multiple scattering factor **δ= footprint radius * attenuation**
- $\delta \to 0$: single scattering, $K_{lid} \cong$ attenuation
- $\delta \to 5$ (or higher) multiple scattering, $K_{\text{lid}} \cong K_{\text{d}} \cong \frac{a+b_b}{\cos(\theta_{\text{water}})}$

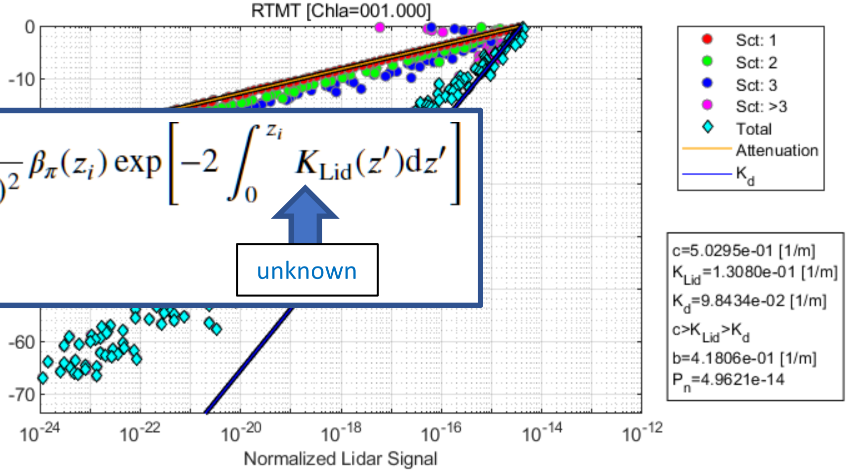
  Gordon (1982)
  Sathyendranath et al. (1989)
- Up and cross semi-axis of the of the ellipse footprint = 3.58, 4.49 [m] →Mean radius = 4.03 [m]
- Attenuation in the range 0.04 to 2.7 [m^{-1}] (for Chla equal to 0.01 to 10 [mg m^{-3}], respectively)
- The lidar response varies between single- and multiple-scattering regime, depending on Chl-a and CDOM; this affects K_{lid}
- K_{lid} can be assumed as known only in the extreme conditions.
- **In intermediate optical cases, however, RT estimates of K_{lid} are necessary to apply the the lidar equation accounting for the Aeolus measurement properties.**





$$P(z_i) = P_0 M T_a^2 T_s^2 \frac{\upsilon\tau}{2n} \frac{A_r}{(nH+z_i)^2} \beta_\pi(z_i) \exp\left[-2\int_0^{z_i} K_{\text{Lid}}(z')\mathrm{d}z'\right]$$

unknown



COLOR
CDOM-proxy retrieval from aeOLus ObseRvations