COLOR

CDOM-proxy retrieval from aeOLus ObseRvations

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Consortium:
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2 - Serco Italia S.p.A., Frascati, Italy
3 - AEQUORA, Lisbon, Portugal
4 - Università degli Studi della Basilicata, Potenza, Italy

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Spaceborne lidar and OCEAN COLOR

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

Ocean particulate backscatter from Caliop

Behrenfeld et al., 2013

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)

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

Satellite lidars can complement passive ocean color data

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

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

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

New lidar era for oceanic variables (Dionisi et al., 2020)

Satellite lidars can complement passive ocean color data

Behrenfeld et al., 2017

Behrenfeld et al., 2013

Dionisi et al., 2020

Lu et al., 2019

Lu et al., 2014

Lu et al., 2021
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

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 $\theta$.

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

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
**COLOR** (*CDOM-proxy retrieval from aeOLus ObseRvations*) 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 $\beta_{\text{wat}} \rightarrow$ 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 ($\Delta r_{\text{grad}}$)

\[
S_X(\text{grad}) = M_X \left[ \frac{A}{(r_{\text{atm}} + \frac{\Delta r_{\text{atm}}}{n})^2} \right] B_{\text{grad}} T_A^2 (r_{\text{atm}}) + S_{\text{bd}}
\]

\(X = \text{Ray}_{A,B}\)  
\(X = \text{Mie}\)

\[
B_{\text{grad}} = B_{\text{atm}} + B_{\text{surf}} + B_{\text{wat}}(K_L, \beta_{\text{wat}}, \beta_{\text{mol}})
\]

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

This characterization is based on:

a) Radiative transfer numerical modelling  
b) AEOLUS data analysis
General Description

Lidar Equations
AEOLUS Measurement Characteristics
Assumptions/Questions

Input
Numerical
Exp #1

OptimizedRTM

Output
Numerical
Exp #1

Data Pool

Data
Subset #1

Statistical
Analyses

Output
Analyses
Subset #1

Comparison
Interpretation

Answers
Inversion Algorithm Design

MODEL

OBSERVATIONS

Color approach

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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
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

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AEOLUS data analysis

Data filtering procedure

1) **Bathymetry**: sea depth $\geq 100$ 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)
   - $\text{SNR} \geq 5$ and $\text{SNR} \leq \text{SNR}_{\text{FWHMb}}$
   - $\text{SIG} \leq \text{SIG}_{\text{FWHMb}}$

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

*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

**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**

**BGC Argo vs AEOLUS**

**Statistical variable:** Quartiles of the distribution

**Physical variable:** $K_{d,380}$ vs Bin 23 Range Corrected Signal (Mie and Rayleigh) @ 355nm (assuming an inverse dependence -> 1$^{st}$ quartile vs 3$^{rd}$ quartile)
Design and development of OC AEOLUS inversion algorithm

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

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

1) HSRL

$$S_{Mie} = M_{Mie} \left[ \frac{A}{(r_{atm} + \Delta r_{atm} / n)} \right]^2 (C_4 \beta_{wat}^{m} + C_3 \beta_{wat}^{p}) \exp \left[ -2 \int_{0}^{r_{wat}} K_{LID}(r_{wat}') dr_{wat}' \right] T_A^2 (r_{atm})$$

$$S_{Ray} = M_{Ray} \left[ \frac{A}{(r_{atm} + \Delta r_{atm} / n)} \right]^2 (C_1 \beta_{wat}^{m} + C_2 \beta_{wat}^{p}) \exp \left[ -2 \int_{0}^{r_{wat}} K_{LID}(r_{wat}') dr_{wat}' \right] T_A^2 (r_{atm})$$

$$\beta_{wat}^{p} = \beta_{wat}^{m} \left[ \frac{S_{Ray} M_{Mie} C_4 + M_{Ray} C_1}{M_{Ray} C_2 + S_{Ray} M_{Mie} C_3} \right]$$

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**

**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:

\[
S_{23}^* = \frac{C}{n^2} B_{wat} T_s^2 T_A^2 T_{21}^2 T_{22}^2 T_{23}^2 + CB_{23} T_A^2 T_{21}^2 T_{22}^2
\]

\[
S_{22}^* = CB_{22} T_A^2 T_{21}^2
\]

\[
S_{21}^* = CB_{21} T_A^2
\]

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

**Design and development of OC AEOLUS inversion algorithm**  

**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)

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

Design and development of OC AEOLUS inversion algorithm

2) EBL

\[ B_{\text{wat}} \approx \frac{(S^*_2 - S^*_3)}{S^*_1} \frac{B_{21m} n^2}{T_s^2 T_{BLm}^2} e^{2 \rho_0 \sigma_{\text{ext}} \cos \theta} \left( e^{-\frac{z_{21}}{z_s} \Delta z_{21}} + e^{-\frac{z_{22}}{z_s} \Delta z_{22}} + e^{-\frac{z_{23}}{z_s} \Delta z_{23}} \right) \]

Limit of applicability: oligotrophic waters??
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., $v_w < 8 \text{ ms}^{-1}$, Chl-a > $0.1 \text{ mg m}^{-3}$ if $z_b \approx 100 \text{ m}$).

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

➢ 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

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
Thanks for your attention

Contact: davide.dionisi@cnr.it

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

Radiative transfer numerical modelling

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

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

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

- **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

**Tasks**

- **P =** \( P_0 M T_a^2 T_s^2 P_N \)  
  - \( P_0 \) 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

**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 \( \beta_{\pi} = 1.447e-03 \) [m\(^{-1}\) rad\(^{-1}\)]

**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**

- Multiple scattering factor $\delta = \text{footprint radius} \times \text{attenuation}$
- $\delta \rightarrow 0$: single scattering, $K_{\text{lid}} \cong \text{attenuation}$
- $\delta \rightarrow 5$ (or higher) multiple scattering, $K_{\text{lid}} \cong K_d \approx \frac{a+b}{\text{cos}(\theta_{\text{water}})}$
  - Gordon (1982)
  - Sathyendranath et al. (1989)
- Up and cross semi-axis of the ellipse footprint = 3.58, 4.49 [m] $\rightarrow$ 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 $K_{\text{lid}}$
- $K_{\text{lid}}$ can be assumed as known only in the extreme conditions.
- In intermediate optical cases, however, RT estimates of $K_{\text{lid}}$ are necessary to apply the the lidar equation accounting for the Aeolus measurement properties.

**Tasks**

- **AD1**: Development and implementation of the in-water forward model
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