Solutions to protect life

AEOLUS+Innovation
'Ocean sub-surface products and applications'

Aeolus Ocean Colour

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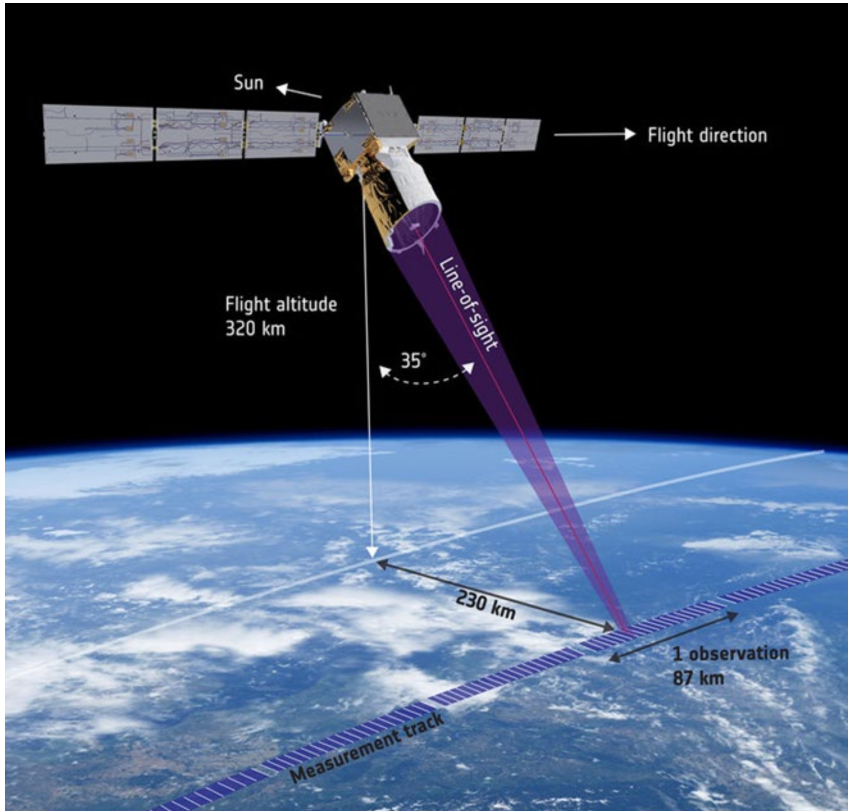
Context & objective

- ADM-Aeolus launched in August 2018
- Initially dedicated to the monitoring of **wind profiles**
- ALADIN LiDAR instrument:
  - › **High-Spectral Resolution LiDAR**: separates the contribution from Molecular (Rayleigh) and Particulate (Mie) backscattering
    - Backscatter and attenuation coefficients can be estimated without the need of ancillary data nor absolute calibration
  - › Screens the atmosphere profile in the UV (355 nm)
    - No measurements / few observations in the UV over **Ocean**
- Assessing the potentials of **Aeolus observations** to provide **ocean colour products**
  - › Provide, **for the first time**, optical ocean properties (b_{bp}) in the UV



Source: ESA

- Derivation of **Ocean Color parameters** from Aeolus
  - LiDAR-derived optical parameters
    - Particulate attenuated backscatter β_p
    - Attenuation coefficient K_L
  - Ocean optical parameters related to **ocean optical properties**
    - Particulate backscattering parameter b_{bp}(355 nm)
    - Diffuse attenuation coefficient K_d(355 nm)
  - Biogeochemical parameters related to **marine biogeochemical cycles**
    - Particulate organic carbon *POC*
    - Phytoplankton carbon C_{phyto}
    - Coloured dissolved organic matter *CDOM*
- Focus on retrieval of $\boldsymbol{\beta_p}$ and $\boldsymbol{b_{bp}}$(355 nm)

Algorithm description

- Estimation approach for the **LiDAR derived optical parameters $\boldsymbol{\beta_P}$**

› Basic of HSRL

$$S_P(z) = K_{Mie}\left[\frac{N_p E_0}{(nH+z)^2}\right]\beta_P\left[exp\left(-\int_0^z K_L(z')dz'\right)\right]^2.(T_A)^2$$

$$S_M(z) = K_{Ray}\left[\frac{N_p E_0}{(nH+z)^2}\right]\beta_M\left[exp\left(-\int_0^z K_L(z')dz'\right)\right]^2.(T_A)^2$$

› ADM-AEOLUS HSRL algorithm

- Taking into account the **cross-talk**

$$S_M(z) = K_{Ray}\left[\frac{N_p E_0}{(nH+z)^2}\right](\boldsymbol{C_1\beta_M + C_2\beta_P})\left[exp\left(-\int_0^z K_L(z')dz'\right)\right]^2.(T_A)^2$$

$$S_P(z) = K_{Mie}\left[\frac{A}{(nH+z)^2}\right](\boldsymbol{C_3\beta_P + C_4\beta_M})\left[exp\left(-\int_0^z K_L(z')dz'\right)\right]^2.(T_A)^2$$

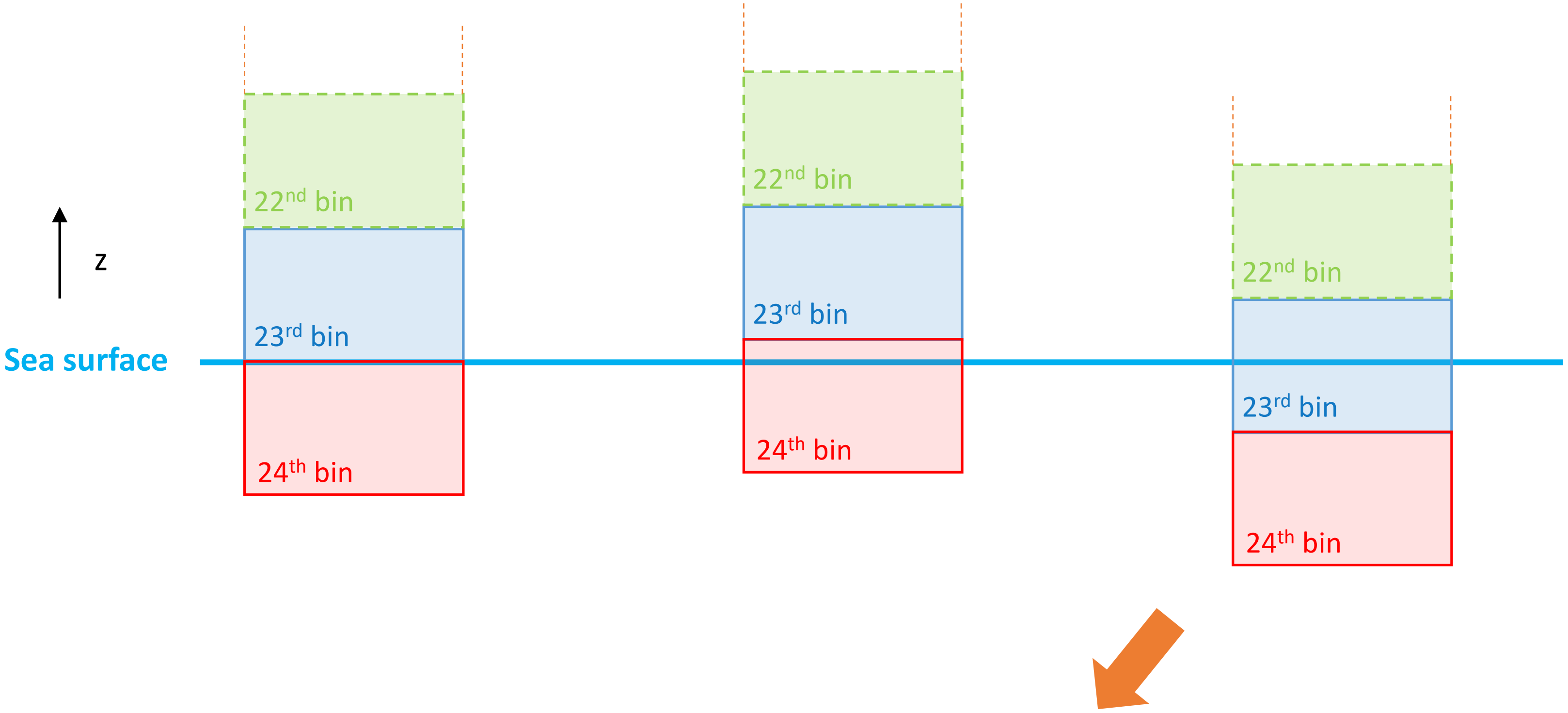
$$\beta_P = \beta_M\frac{(K_{Ray}C_1 - S_R K_{Mie}\,C_4)}{(S_R K_{Mie}\,C_3 - K_{Ray}C_2)}$$

with $\frac{S_M(z)}{S_P(z)} = S_R$

  - C1, C2, C3 and C4 not available for users, and need to be computed for **water spectra**

- Taking into account the **change of temperature of the M1 mirror** introducing a calibration bias
  - The calibration coefficients K_{Ray} and K_{Mie} are not constant
  - Provided in L2A files

- Estimation approach for the **LiDAR derived optical parameters β_P**
  - ADM-AEOLUS HSRL algorithm
    - Taking into account the **altitude of the bins** to get signal from the **ocean**

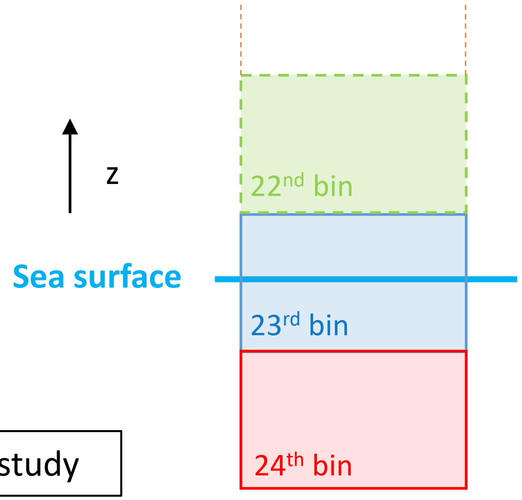


    - SNR of bin #24 is too low -> **choice of bin #23**

- Estimation approach for the **LiDAR derived optical parameters $\boldsymbol{\beta_P}$**

  › ADM-AEOLUS HSRL algorithm

  - Taking into account the **altitude of the bins** to get signal from the **ocean**
  - Decomposition of the LiDAR signal in bin #23 (Li et al., 2007; Josset et al., 2010)



$$\boldsymbol{S}(23) = \boldsymbol{S_{atm}} + \boldsymbol{S_s} + \boldsymbol{S_{wc}} + \boldsymbol{S_o}$$

- S_{atm}: Corrected by using the 22nd bin considering the lower atmosphere homogeneous
- S_s: ≈ 0 as the off-nadir angle of ADM-AEOLUS is 35°
- S_{wc}: ≈ 0 for low surface wind (<3 m.s^{-1})
- S_o: Signal of interest for this study

- S_{atm} is the **contribution of the atmosphere** in the 23rd bin
- The **specular reflection of the LiDAR signal on the sea surface S_s** is a function of the wind speed
- The **whitecaps signal S_{wc}** is a function of the effective reflectance and the surface wind
- **S_0** is the ocean attenuated backscatter signal, i.e. the **signal of interest**

- Estimation approach to derive **ocean optical parameters *bbp***

$$b_{bp} = 2\pi.\chi(180°).\beta_p$$ (Boss and Pegau, 2001)

› $\chi(180°)$, a conversion factor that depends on the size, type and composition of the particles

Validation of b_{bp} parameter

- Comparison of Aeolus derived b_{bp} against *in situ* measurements
  - BGC-ARGO network
  - Sea campaign in Cape Verde

- Aeolus derived b_{bp} vs. BGC-ARGO measured b_{bp}
  - Profiles of **b_{bp}(700)**, **E_d(490)**, ***CDOM***, etc.
  - Processing of BGC-ARGO measurements:

$$b_{bp}(355) = b_{bp}(700)\left(\frac{700}{355}\right)^{\gamma}$$

with γ = 0.78 (Boss et al., 2013)

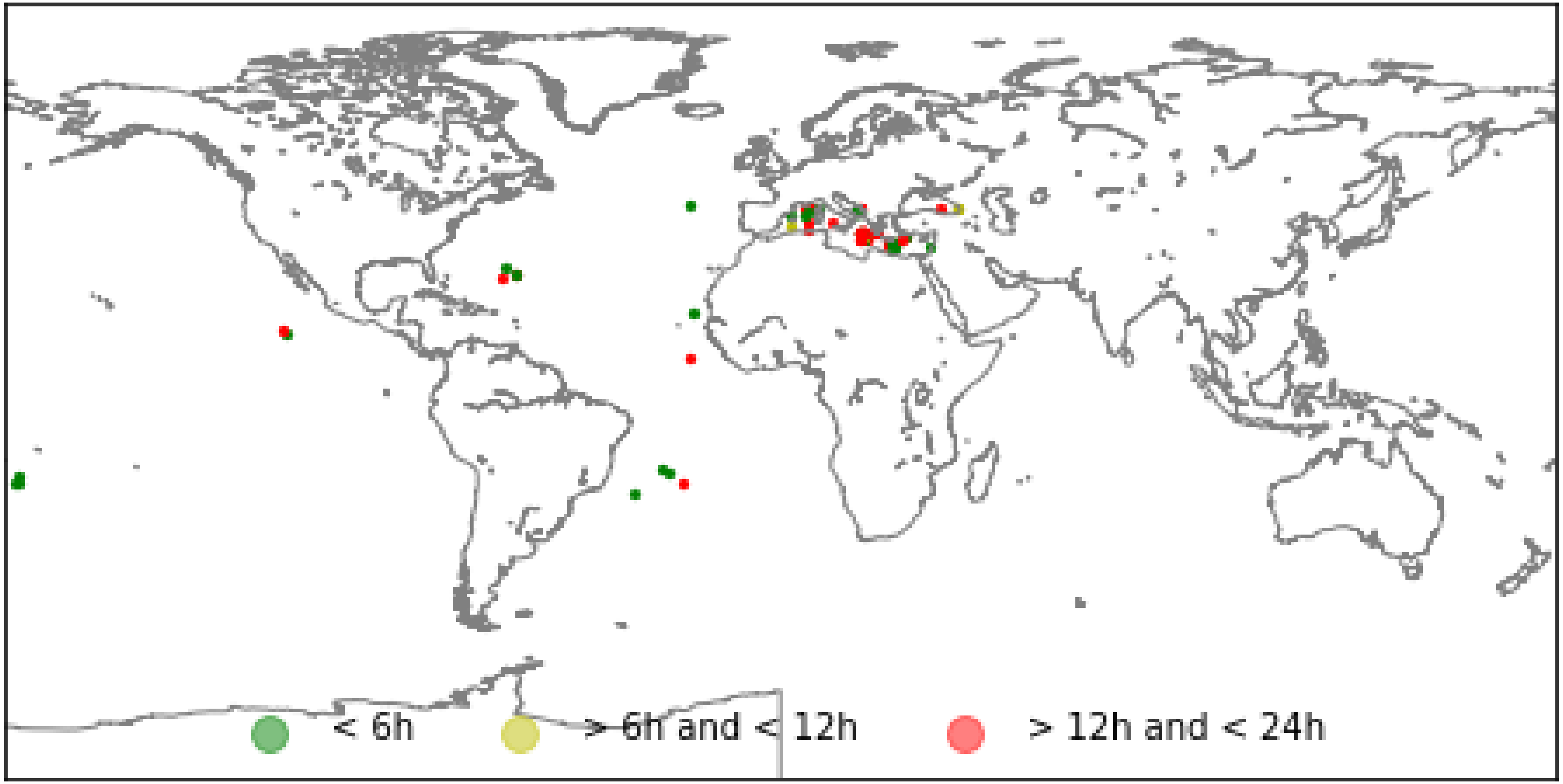
  - **Collocations** between Aeolus observations – BGC ARGO measurements according to Bisson et al., 2020
    - **Distance** threshold: if SST < 15 °C, then distance < 15 km, otherwise, distance < 50 km
    - **Temporal** threshold: < 24 hours
  - Also considered:
    - **Data quality** (for both BGC ARGO and Aeolus data)
    - **Cloud cover** (through scattering ratio in Aeolus L2A products)
  - **Period of interest**: June 28th 2019 to October 10th 2020

Validation of b_{bp} parameter

- Aeolus derived b_{bp} vs. BGC-ARGO measured b_{bp}

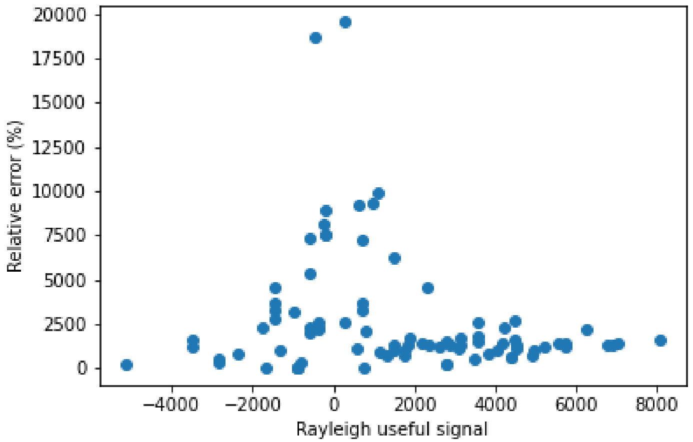
88 collocations

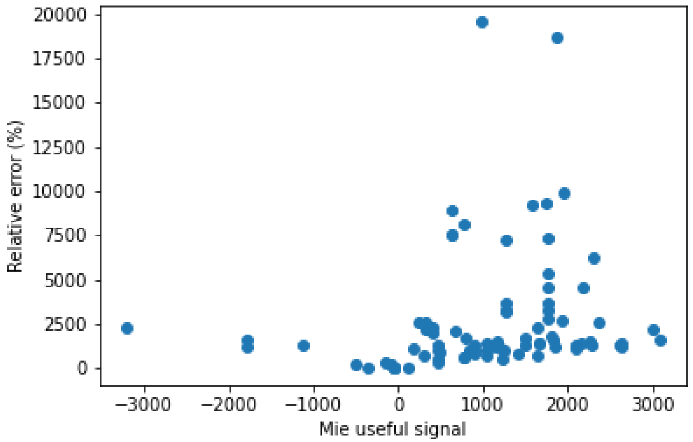
Temporal distance between Aeolus and BGC Argo measurements

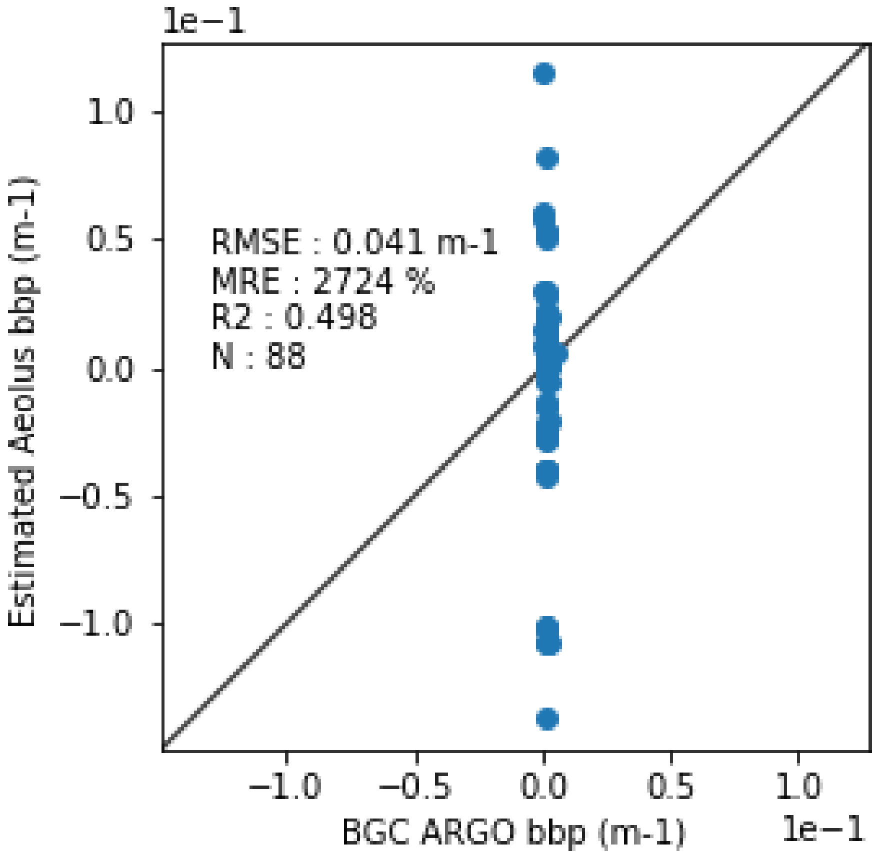


Validation of b_{bp} parameter

- Aeolus derived b_{bp} vs. BGC-ARGO measured b_{bp}
  - $\beta_P = \beta_M \frac{(K_{Ray}C_1 - S_R K_{Mie} C_4)}{(S_R K_{Mie} C_3 - K_{Ray} C_2)}, with\ S_R = {S_M}/{S_P}$
  - $b_{bp} = 2\pi.\chi(180°).\beta_p$
  - $S_{atm}(23) = S(22)$
  - No cross-talk ($C_1 = C_3 = 1, C_2 = C_4 = 0$)







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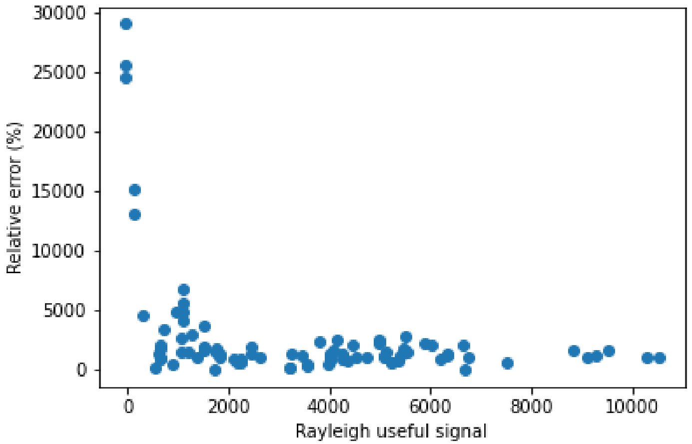
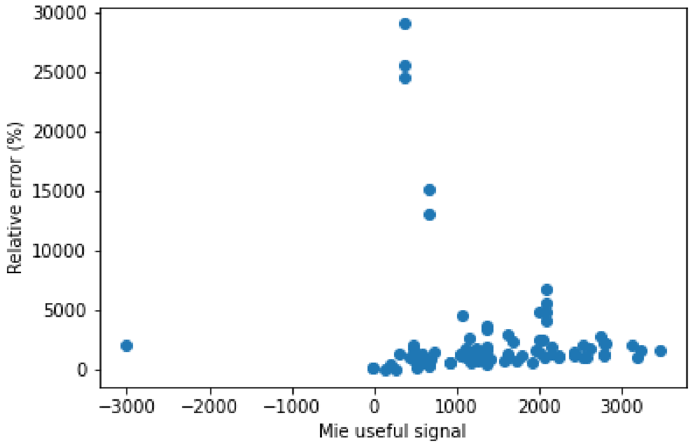
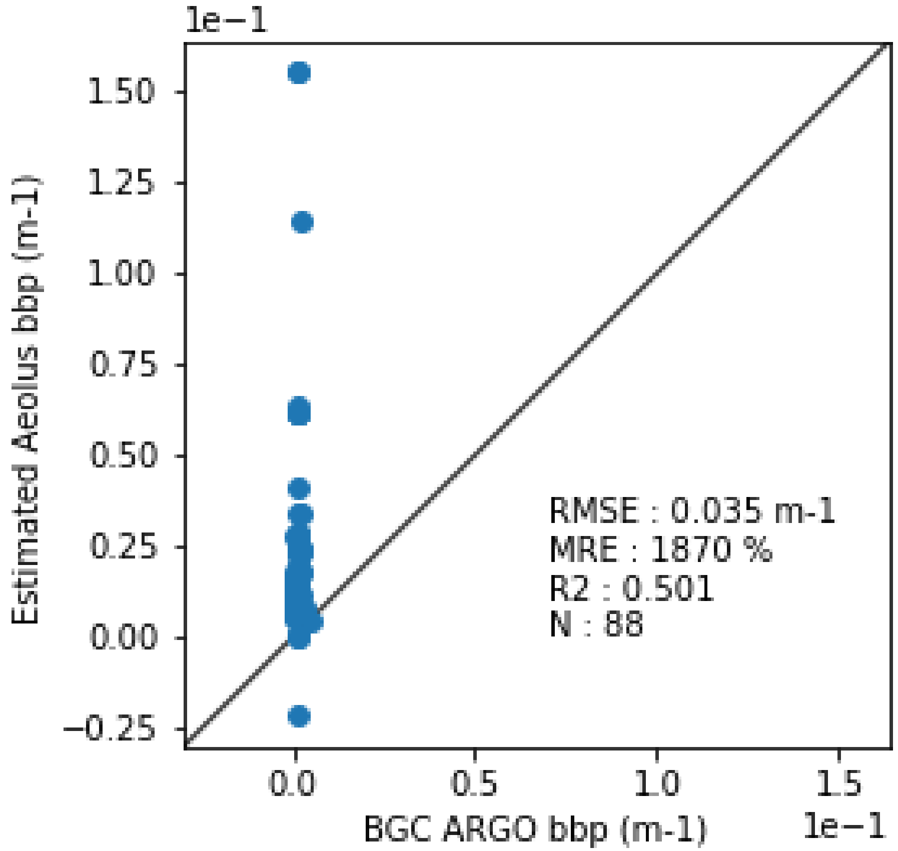
  - $b_{bp} = 2\pi.\chi(180°).\beta_p$
  - $\boldsymbol{S_{atm}(23) = S(22)\frac{altitude\_bin(23)}{height\_bin(23)}}$
  - No cross-talk ($C_1 = C_3 = 1, C_2 = C_4 = 0$)







Validation of b_{bp} parameter

- Aeolus derived b_{bp} vs. BGC-ARGO measured b_{bp}

  › $\beta_P = \beta_M \frac{(K_{Ray} C_1 - S_R K_{Mie}\, C_4)}{(S_R K_{Mie}\, C_3 - K_{Ray} C_2)}, with\ S_R = {}^{S_M}/_{S_P}$

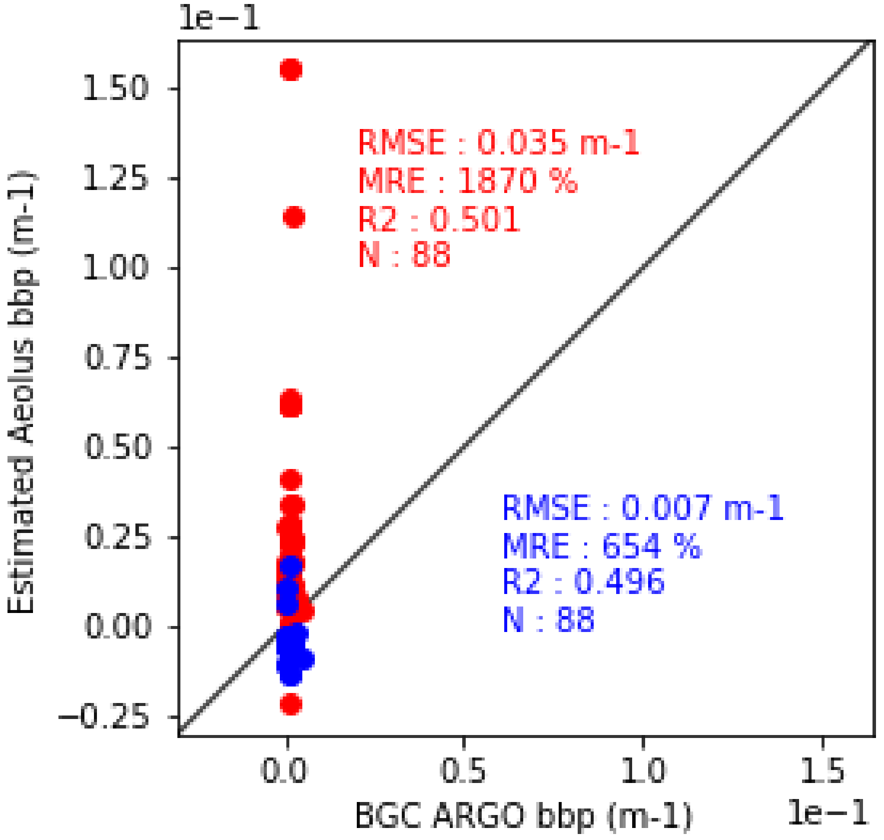
  › $b_{bp} = 2\pi . \chi(180°). \beta_p$

  › $S_{atm}(23) = S(22) \frac{altitude\_bin(23)}{height\_bin(23)}$

  › **Cross-talk** (for **water spectra**,

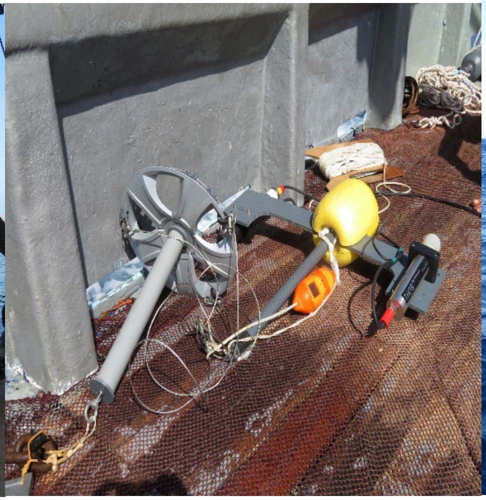
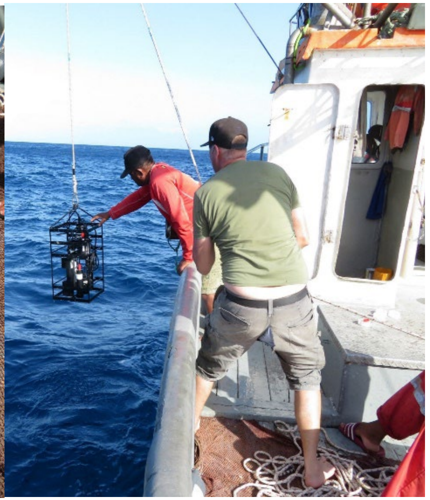
  $C_1 = 1.14,\ C_2 = 1.64,\ C_3 = 1.30,\ C_4 = 1.00)$

  › **Strong impact of C_x**



Validation of b_{bp} parameter

- Aeolus derived b_{bp} vs. Cape Verde measured b_{bp}
  - In the frame of the **ESA JATAC** and **French CADDIWA** campaigns (September 8-22nd 2021)
  - Aeolus overpasses (<100 km) on Sep. 10, 15, 17, 22 -> **9 colocations**
  - Particulate backscattering parameter b_{bp} up to 30 meters
  - Diffuse attenuation coefficient K_d up to 30 meters


Validation of b_{bp} parameter

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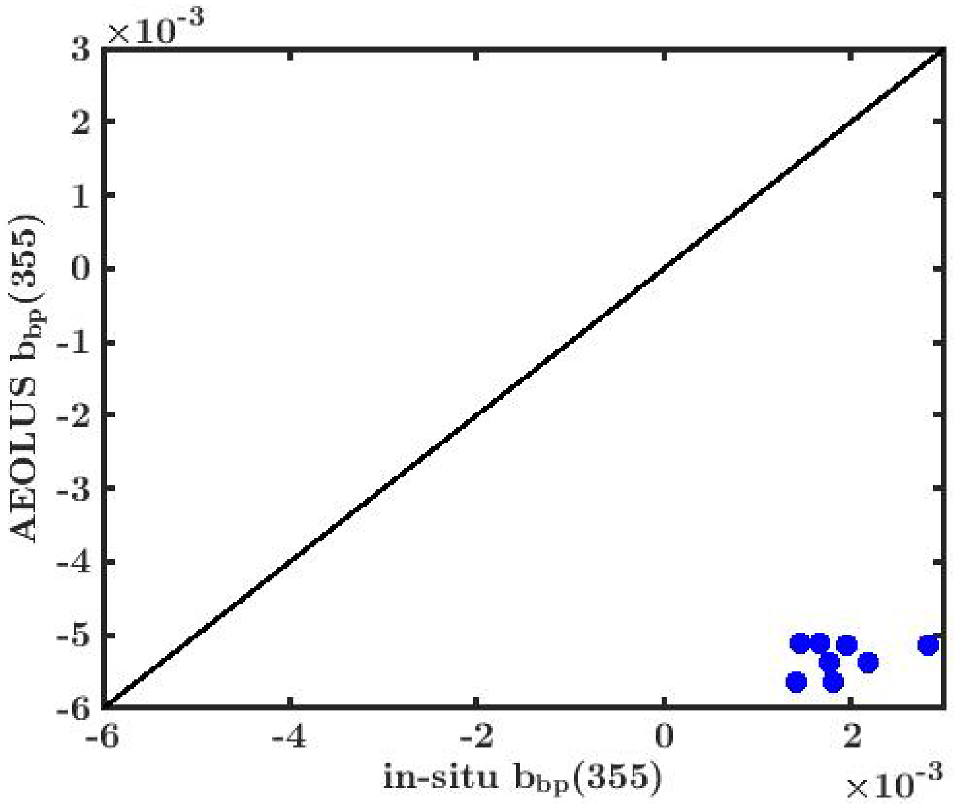
  - $\beta_P = \beta_M \frac{(K_{Ray}C_1 - S_R K_{Mie}\, C_4)}{(S_R K_{Mie}\, C_3 - K_{Ray} C_2)}, with\ S_R = {}^{S_M}/_{S_P}$
  - $b_{bp} = 2\pi.\chi(180°).\beta_p$
  - $S_{atm}(23) = S(22)\frac{altitude\_bin(23)}{height\_bin(23)}$
  - Cross-talk (for water spectra,

$C_1 = 1.14,\ C_2 = 1.64,\ C_3 = 1.30,\ C_4 = 1.00)$

  - **Same trend as for BGC-ARGO**



Conclusion / perspectives

- First tentative to estimate ***b_{bp}* in the UV from ALADIN LiDAR**
    - Need to perform **atmospheric correction** as the bin of interest is both in water and atmosphere
    - Inclusion of **calibration** and **crosstalk** coefficients C_x for water
- High error on b_{bp} retrievals
    - Negative values when including C_x coefficients
    - Impacted by the way to correct the atmosphere
    - No relevant to derive biogeochemical parameters at this stage
- Need to better understand the **ALADIN signal** (threshold on the SNR, binning on more observations)
- **Sensitivity study** on the C_x values
- Need to understand the content of the ground signal → may be useful to correct the contribution of the atmosphere
- Need to consider the surface as a function of the **wind speed**

Acknowledgements

- **ESA** for funding the project through the AEOLUS+ Innovation program
- **CNES** for funding the Cape Verde sea campaign through the TOSCA program
- **Alain Dabas and his team** for providing the C_x values for water and for their valuable comments on this work and the cloud flag
- The **Ocean Science Mindelo Center** (OSCM) for the help to organize the sea campaign and the use of their facilities: Pericles Silva, Ivanice Monteiro and Elizandro Rodrigues
- The **captain** and the **fishermen** of the **Gamboa ship**

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Thank you for your attention!

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- Estimation approach for the **LiDAR derived optical parameters**

  - Basic of HSRL

$$S_M(z) = K_{Ray}\left[\frac{N_p E_0}{(nH+z)^2}\right]\beta_M\left[exp\left(-\int_0^z K_L(z')dz'\right)\right]^2.(T_A)^2$$

$$S_P(z) = K_{Mie}\left[\frac{N_p E_0}{(nH+z)^2}\right]\beta_P\left[exp\left(-\int_0^z K_L(z')dz'\right)\right]^2.(T_A)^2$$

$$\beta_P = \beta_M\left[\frac{K_{Mie}}{K_{Ray}}\right]\left[\frac{S_P(z)}{S_M(z)}\right]$$

β_M is almost constant in the upper-ocean and is equal to 0.001301 at 355 nm (Zhang et al., 2009)

  - Signal the Mie and Rayleigh channels would measure if the HSRL was perfect, i.e. no cross-talk between the Rayleigh and Mie channels

  - ADM-AEOLUS HSRL algorithm (taking into account **cross-talk**)

$$S_M(z) = K_{Ray}\left[\frac{N_p E_0}{(nH+z)^2}\right](\boldsymbol{C_1\beta_M + C_2\beta_P})\left[exp(-\int_0^z K_L(z')dz')\right]^2.(T_A)^2$$

$$S_P(z) = K_{Mie}\left[\frac{A}{(nH+z)^2}\right](\boldsymbol{C_3\beta_P + C_4\beta_M})\left[exp(-\int_0^z K_L(z')dz')\right]^2.(T_A)^2$$

$$\beta_P = \beta_M\frac{(K_{Ray}C_1 - S_R K_{Mie}\,C_4)}{(S_R K_{Mie}\,C_3 - K_{Ray}C_2)}$$

with $\frac{S_M(z)}{S_P(z)} = S_R$

    - C_1, C_2, C_3 and C_4 not available for users, and need to be computed for **water spectra**

- Estimation approach for the **LiDAR derived optical parameters**
  - ADM-AEOLUS HSRL algorithm
    - Taking into account **cross-talk**

$$S_M(z) = K_{Ray}\left[\frac{N_p E_0}{(nH+z)^2}\right](C_1\beta_M + C_2\beta_P)\left[exp\left(-\int_0^z K_L(z')dz'\right)\right]^2.(T_A)^2$$

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$$\beta_P = \beta_M \frac{\left(K_{Ray}C_1 - S_R K_{Mie}\, C_4\right)}{\left(S_R K_{Mie}\, C_3 - K_{Ray}C_2\right)}$$

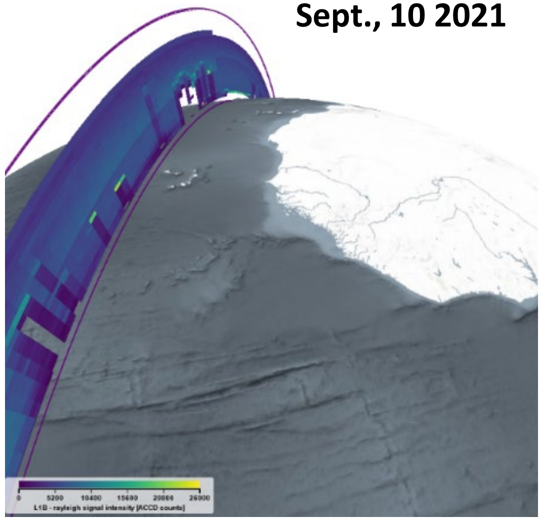
with $\frac{S_M(z)}{S_P(z)} = S_R$

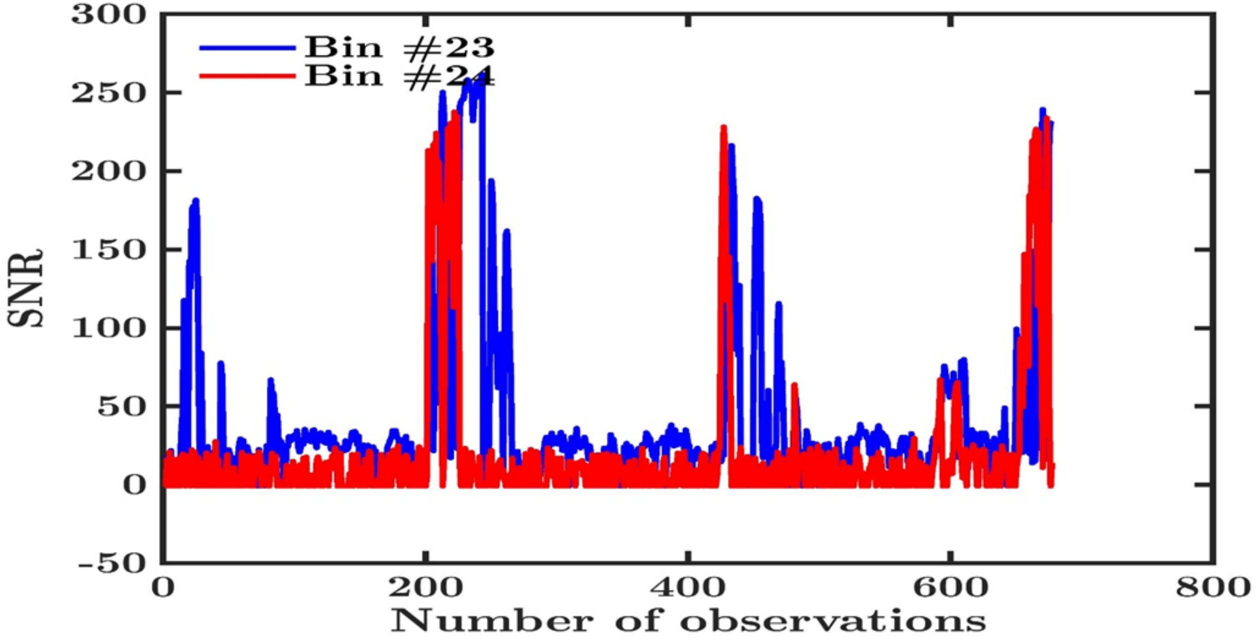
    - Taking into account the **change of temperature of the M1 mirror** introducing a calibration bias
      - The calibration constants K_{Ray} and K_{Mie} are not constants
      - Provided in L2A files

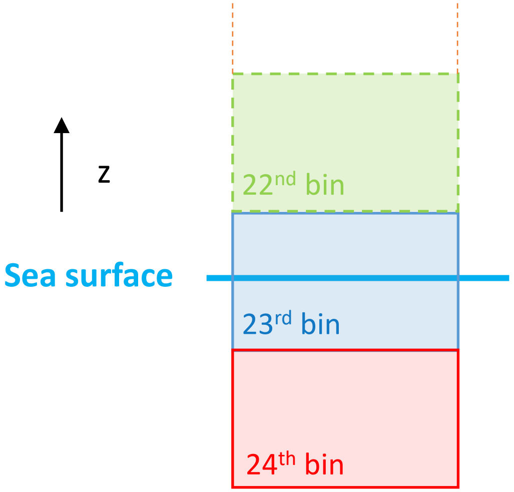
$$K_L(z) = -\frac{1}{2}\frac{d}{dz}\ln\left((nH+z)^2.S_M(z)\right)$$

- Estimation approach for the **LiDAR derived optical parameters**
  - ADM-AEOLUS HSRL algorithm
    - Taking into account the **altitude of the bins** to get signal from the **ocean**

Sept., 10 2021







    - SNR of bin #24 may be too low -> **choice of bin #23**

- Estimation approach for the **LiDAR derived optical parameters**
  - ADM-AEOLUS HSRL algorithm
    - Taking into account **cross-talk**
    - Taking in to account the **change of temperature of the M1 mirror** introducing a calibration bias
    - Taking into account the **altitude of the bins** to get signal from the **ocean**
      - Consider **atmospheric correction** and **wind speed**
    - Taking into account the clouds
      - First assumption: if L1B observation is available, so the scene is free of clouds
      - However, **thin clouds** may still impact the estimation of LiDAR derived optical parameters: **cloud filtering**
      - No cloud information in AEOLUS L1B files…
      - **LiDAR scattering ratio** from L2A or **SNR**

- Estimation approach to derive **ocean optical parameters**

  - Particulate backscattering parameter b_{bp}

    $$b_{bp} = 2\pi . \chi(180°) . \beta_p$$ (Boss and Pegau, 2001)

    - $\chi(180°)$, a conversion factor that depends on the size, type and composition of the particles

  - Diffuse attenuation coefficient K_L

    $$K_d(355) = K_L(355)$$ (Hair et al. 2016)

    - Lidar attenuation coefficient, $K_L(355)$, is a very good approximation of the diffuse attenuation coefficient, $K_d(355)$

- Estimation approach to derive **biogeochemical parameters**

  - Particulate Organic Carbon (*POC*)

$$POC = 53606.7 * b_{bp}(555) + 2.468$$

(Stramski et al., 2008)

$$\text{with } b_{bp}(\lambda) = b_{bp}(355)\left(\frac{355}{\lambda}\right)^{\gamma}$$

γ = 0.78 (Boss et al., 2013), variable value could be investigated (Bisson et al., 2020) .

  - Phytoplankton Carbon (C_{phyto})

$$C_{phyto} = 13{,}128 \times \left(b_{bp}(470) + 0.59\right)$$

(Graff et al., 2015)

  - Coloured dissolved organic matter (*CDOM*)

$$K_{d(355)} = K_{w(355)} + K_{bio}(355)$$

$$K_{bio}(355) \sim CDOM$$

(Organelli and Claustre, 2019)

$$K_{w(355)} = 0{,}0453\ m^{-1}$$

(Austin and Petzold, 1986)

$$CDOM = K_{d(355)} - 0{,}0453$$

- Comparison of Aeolus derived b_{bp} against *in situ* measurements
  - BGC-ARGO network
    - Profiles of ***b_{bp}(700)***, ***E_d(490)***, ***CDOM***, etc.
    - Processing of BGC-ARGO measurements: method based on Lacour et al., 2020
    - b_{bp}(355) computation

$$b_{bp}(355) = b_{bp}(700)\left(\frac{700}{355}\right)^{\gamma}$$

with γ = 0.78 (Boss et al., 2013)

$$b_{bbp}^{float}(355) = \frac{\sum_z \exp(-2K_d(355)z)\, b_{bp}(355,z)}{\sum_z \exp(-2K_d(355)z)}$$

    - K_d(490) computed as the mean slope over the first 50 m of minus the logarithm of a polynomial fit of the measured E_d (490)

$$K_d(355) = 2.0968 \times (K_d(490) - 0.0224) + 0.0453$$

(Austin and Petzold, 1986)