A Lidar-based Variable Pathlength Backscattering Transmissometer

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Help Shape Future Ocean Optical Measurements

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Free $\beta(\pi)$ t-shirt!

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To extend the climate record with ocean lidar, we must first illuminate the optical physics that governs it.

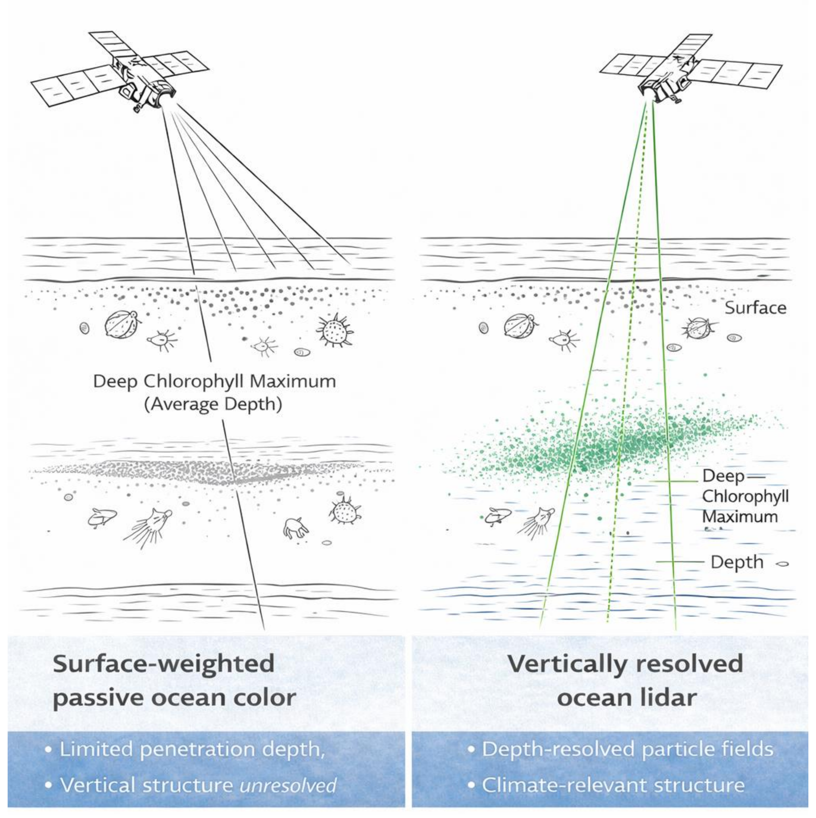
Motivation

Ocean carbon cycling and climate feedbacks depend critically on accurate measurements of inherent optical properties (IOPs). Recent advances in spaceborne and airborne ocean lidar (e.g., Behrenfeld et al., 2023) demonstrate that vertically resolved optical measurements are essential for extending the global climate record. However, next-generation lidar systems require improved in situ calibration of beam attenuation c and volume scattering at 170°-180°, i.e., $\beta(\pi)$.

$2X$ *"Scattering phase function $P_p(180°, 532) = \beta(\pi, 532)/b(532)$ is assumed to be 0.32 following Lu et al. 2002. This value differs from the study of Behrenfeld et al. 2013, where $P_p(180°, 532)$ was set equal to 0.16." (Lacour et al. 2020)*

We present a collaborative effort between Sea-Bird Scientific and Beam-Sea Associates to develop a dual field-of-view (DFOV) variable pathlength beam transmissometer (VPBT) designed specifically for **ocean lidar validation and IOP retrieval** (attenuation $c(z)$ and volume scattering $\beta(\pi, z)$).

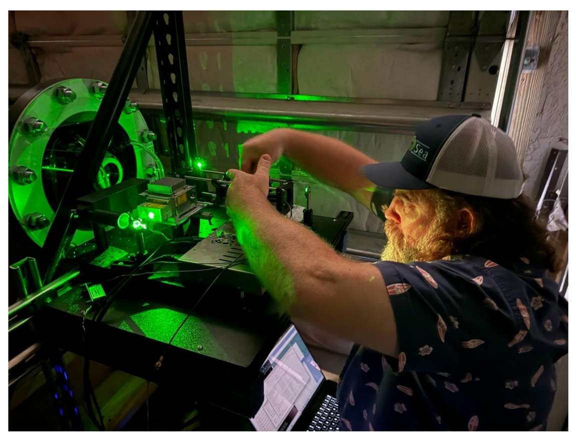
Baseline results demonstrate retrievals of beam attenuation and backscattering at 180°. Improved DFOV-based inversion algorithms are under development.

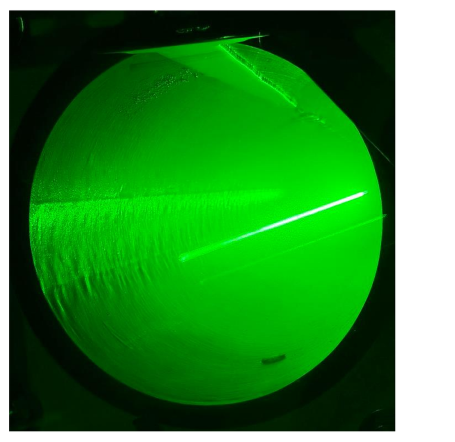


$$P(z) \propto \beta(\pi, z) exp\left[-2\int c(z)dz\right]$$

Monostatic Pulsed Lidar Sensor

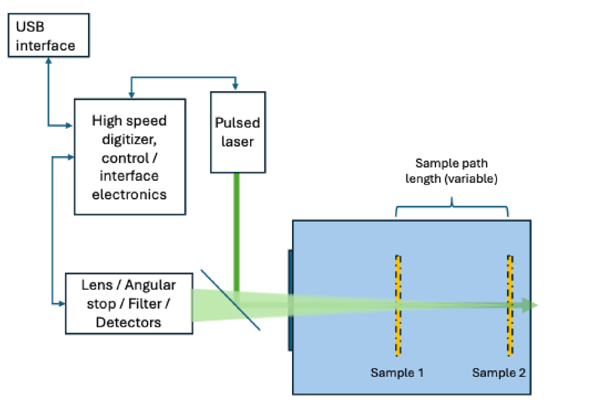
The experimental system integrates a stabilized laser source, custom optical tank, and dual-FOV lidar receiver to characterize beam attenuation (c) and volume scattering (β_π). Controlled additions of polystyrene microspheres enable retrieval validation across known scattering regimes.

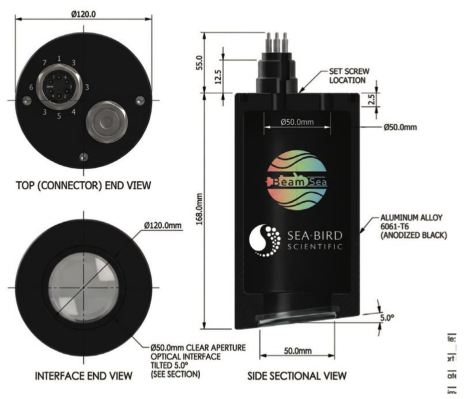




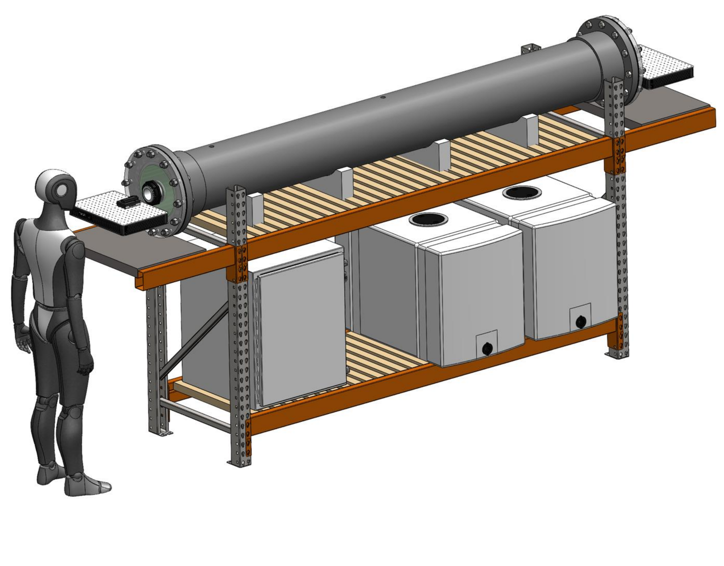
Lidar Test Setup

VPBT Concept





Optical Tank



Optical Tank Main Features:

1. 3 m length
2. 30 cm diameter
3. 212 L volume
4. Coated internally with black waterproof epoxy (99.95% absorbance)
5. Spectralon target portals at 1, 1.5, 2 m
6. Microbeads injected via target portal. $\Delta t_{mix} \approx 30\ minutes$
7. Milli-Q reservoir
8. 1 µm and 0.1 µm filters
9. ac-s hyperspectral absorption and attenuation meter mounted inline: $a(532), c(532)$

Lidar Retrieval: Slope Method

In homogeneous volumes, backscatter and attenuation coefficients can be determined by the inversion of lidar signals using the slope method, i.e., from a linear least-squares fit to the logarithm on the range-compensated lidar return. This long-standing **"baseline method"** (Collis 1966, Kunz 1993) is independent of wavelength.

The generally accepted model for single-scatter lidar signals from a homogeneous volume is given by:

$$P(R) = K_{sys}\frac{\beta(\pi)}{R^2}\exp(-2K_{lidar}R)$$

This equation contains the two terms that influence the lidar signal: lidar attenuation K_{lidar} (m^{-1}) and backscatter at 180° $\beta(\pi)$ $(m^{-1}\ sr^{-1})$. R is range (m), and K_{sys} is a system calibration constant $(W\ m^3 sr)$.

For homogeneous water, backscatter and attenuation coefficients can be inverted from the lidar return by linear regression:

$$\log[P(R)R^2] = \ln[K_{sys}\beta(\pi)] - 2K_{lidar}R \rightarrow y = intercept + slope \cdot x$$

$$K_{lidar} = -\frac{slope}{2}$$

$$\beta(\pi) = \frac{e^{intercept}}{K_{sys}}$$

To make these retrievals, we:

- Measure $a(532)$ and $c(532)$ using ac-s, adjust for pure water absorption and attenuation, and compare to waveform slope retrievals.
- Use scattering particles (polystyrene microspheres) whose phase function $P_{mie}(\theta, 532, \emptyset)$ can be computed from Mie theory (bhmie).
- Compute the reference values for backscattering $\beta_{ref}(\pi, \emptyset)$ as:

$$\beta_{ref}(\pi, \emptyset) = P_{mie}(\pi, 532\ nm, \emptyset) \cdot b(532)$$

  where:

  $\emptyset = 0.1\ \mu m$ or $2.0\ \mu m$

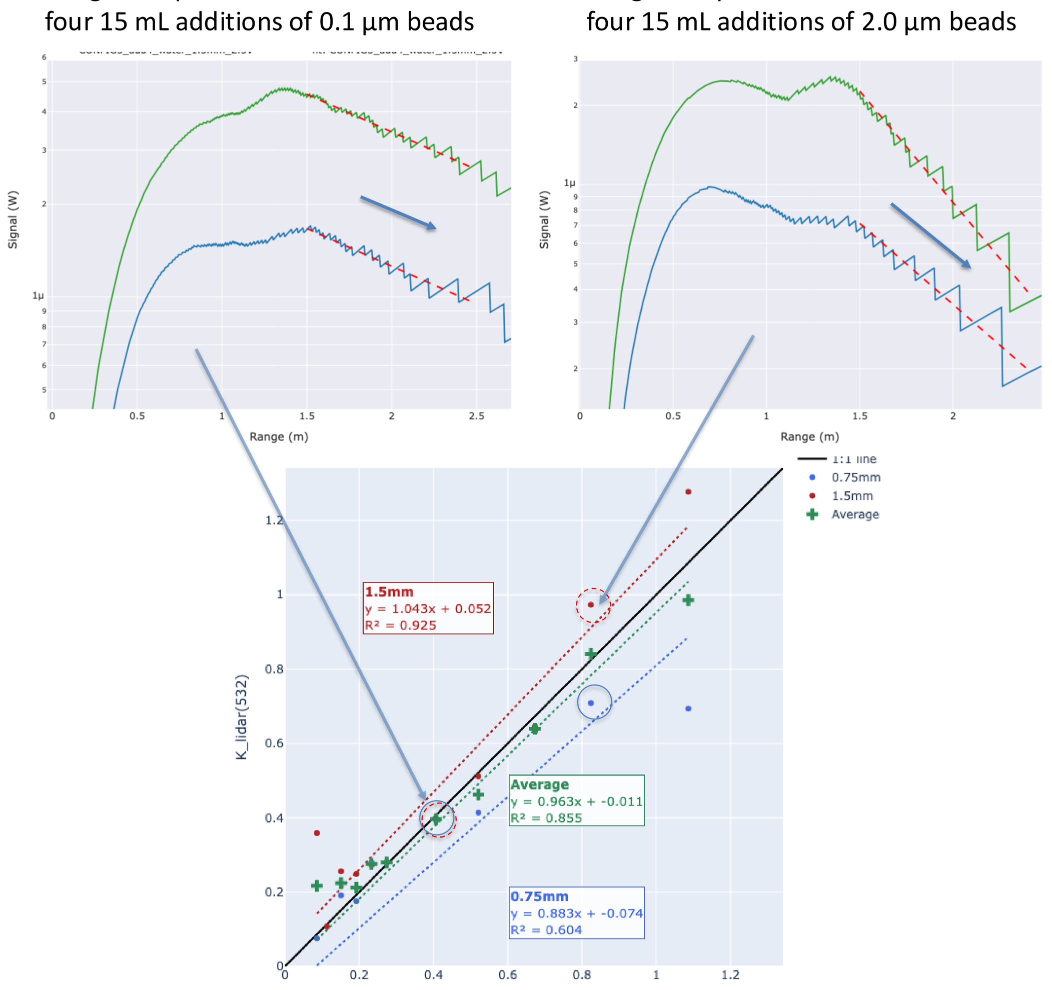
  $b(532) = c(532) - a(532)$ from ac-s measurements
- Use $\beta_{ref}(\pi, \emptyset)$ to determine K_{sys}
- Multiple scattering can and does occur and depends on the field of view (FOV) 180°.

Beam Attenuation Retrieval (c)

Methods: A 532 nm laser, fast-response detector array, and digital storage oscilloscope are used as source, detector, and waveform digitizer, respectively. An adjustable angular stop at or near the Fourier plane creates FOVs of 6.5 and 12.5 mrad. For each trial, 10 laser shots are averaged per FOV. The 3 m optical tank is filled with reverse osmosis purified water. The tank is allowed to circulate, de-bubble, and de-gas for 2-3 hours. Then clear water and bead injection trials are performed with and without a 2% Spectralon target at 2 m. After each bead injection, the tank requires ~30 min to fully mix. Attenuation c_{est} is retrieved from the log slope of each averaged lidar return using an adaptive fitting window.

Range-compensated waveforms after four 15 mL additions of 0.1 µm beads

Range-compensated waveforms after four 15 mL additions of 2.0 µm beads



Trial	FOV	slope	intercpt	R^2	K_{lidar}	$\bar{c}_{est}$	$c_{t,ac-s}$	RPD
CONFIG5_add4_0.1um	N	-0.558	-12.5	0.93	0.279	0.280	0.274	+2.2%
CONFIG5_add4_0.1um	W	-0.561	-11.4	0.96	0.281			
CONFIG5_add8_2.0um	N	-1.417	-12.0	0.88	0.709	0.841	0.824	+2.1%
CONFIG5_add8_2.0um	W	-1.947	-10.1	0.94	0.973			

Conclusion 1

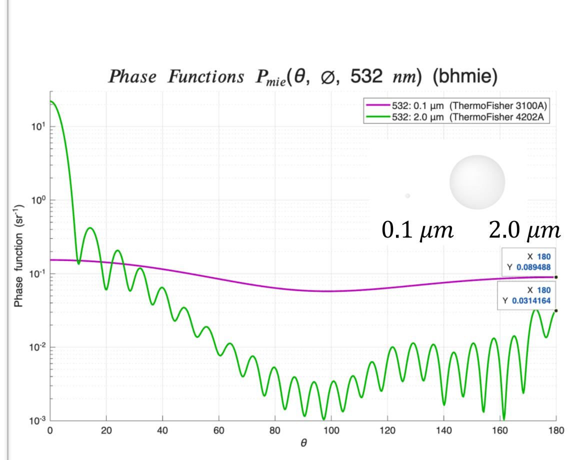
Averaging Collis Method slopes from both FOV's, **we can retrieve attenuation $\bar{c}_{est}(532)$ with matchup slope of 0.96 and a negative bias of 0.01 m^{-1}.**

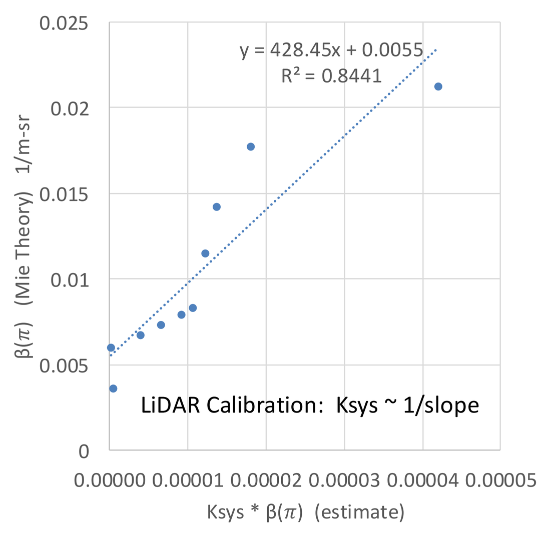
Volume Scattering Retrieval $\beta(\pi)$

Methods: Polystyrene 0.1 µm and 2 µm microspheres provide a controlled and physically well posed test of how monostatic lidar retrievals of $\beta(\pi)$ and c depend on the shape of the volume scattering function (VSF). Because both particle populations are composed of the same material with identical refractive index, these experiments isolate particle size, and therefore VSF shape, as the sole controlled variable.

0.1 µm microspheres @ 532 nm
- Size parameter $x = 2\pi r/\lambda < 1 \rightarrow$ near Rayleigh regime.
- Phase function is broad and smooth.
- Forward/backward contrast is small.
- Angular structure contains little fine information about about size

2 µm microspheres @ 532 nm
- Size parameter $x \gg 1 \rightarrow$ Mie regime
- Multiple internal reflections + phase interference → oscillations
- Scattering is highly forward-directed.
- Backscattering efficiency is reduced relative to total scattering.





Calibrating the Lidar to estimate K_{sys} and $\hat{\beta}(\pi)$:

1. Compute $\beta_{ref}(\pi)$ from Mie theory (P_{mie}) and $b_t = b_{ac-s} + b_w$
   $\beta_{ref}(\pi, \emptyset) = \Sigma[(P_{mie,i}(\pi, \emptyset) \cdot b_{ac-s,i})] + \beta_w(\pi)$
2. Compute $K_{sys}\hat{\beta}(\pi) = e^{intercept}$ from Collis Slope Method
3. Least-squares predictor for $\hat{\beta}(\pi)$:
   Regress $\beta_{ref}(\pi)$ $vs.$ $K_{sys}\hat{\beta}(\pi) \rightarrow \hat{\beta}(\pi) \approx m \cdot K_{sys}\hat{\beta}(\pi) + offset$

Trial	$\emptyset$ (μm)	$P_{mie,i}(\pi, \emptyset)$	b_t	$\beta_{ref}(\pi)$	$K_{sys}\ \hat{\beta}(\pi)$	$\hat{\beta}(\pi)$	RPD
CONFIG5_cw0	0	0	0.0400	0.00358	4.28E-07	0.00364	2%
CONFIG5_cw1	0	0	0.0670	0.00600	1.70E-07	0.00553	-8%
CONFIG5_add1	0.1	0.0895	0.0750	0.00671	3.91E-06	0.00713	6%
CONFIG5_add2	0.1	0.0895	0.0820	0.00734	6.51E-06	0.00824	12%
CONFIG5_add3	0.1	0.0895	0.0880	0.00788	9.06E-06	0.00934	19%
CONFIG5_add4	0.1	0.0895	0.0930	0.00832	1.06E-05	0.00998	20%
CONFIG5_add5	2.0	0.0314	0.1940	0.0115	1.22E-05	0.0107	-7%
CONFIG5_add6	2.0	0.0314	0.2800	0.0142	1.37E-05	0.0113	-20%
CONFIG5_add7	2.0	0.0314	0.3920	0.0177	1.80E-05	0.0132	-26%
CONFIG5_add8	2.0	0.0314	0.5040	0.0212	4.19E-05	0.0234	10%

Conclusion 2

We can predict $\hat{\beta}(\pi)$ within $\pm26\%$ using Wide FOV data. Further calibration and uncertainty analysis methods are being explored.

Discussion & Applications

DFOV methods have strong potential for quantitative IOP lidar retrievals because they isolate angular redistribution caused by multiple scattering (MS), **allowing attenuation and backscattering to be inferred from differential geometry rather than absolute signal amplitude**.

Single Scattering Lidar Equation erroneously assumes single scattering:

$$P(z) \propto \beta(\pi)e^{-2cz}$$

Lidar Equations for DFOV: Add MS terms M_N, M_W : independent (not simply scaled) multiple scattering enhancements to the received signal:

$$R(z) = \frac{P_W(z)}{P_N(z)} = C_0\frac{\beta(\pi)\ e^{-2cz}\ M_W(z)}{\beta(\pi)\ e^{-2cz}\ M_N(z)}, M_i(z) = \int_0^{\theta_{FOV,i}} L(\theta, z)\ W_i(\theta)\ d\theta$$

Various parameter-driven MS transport models $L(\theta, z)$ (e.g., random-walk angular diffusion) and the LiDAR's angular weighting functions $W_i(\theta)$ can be used to model $M_i(z)$ and $R(z)$, calibrated via simulations of particles with known phase functions. These calibrated models can be used operationally to retrieve c and $\beta(\pi)$ from DFOV LiDAR data via non-linear optimization or other ML techniques. (Bissonnette et al., 2002)

Re-imagining Backscattering b_b with VPBT *and* ECO V2

Sea-Bird Scientific has a new generation of backscattering sensors (ECO V2) which measure backscattering $\beta(124°, \lambda)$ with increased resolution and dynamic range. By way of a fixed χ factor, a measurement of $\beta(124°, \lambda)$ can be related to the total backscattering coefficient $b_b(\lambda)$:

$$b_b(\lambda) = 2\pi\chi\beta(\theta, \lambda)$$

However, if we measure $\beta(\pi)$, surprising things may happen. For many plankton, the backward lobe of the VSF near 180° is influenced by internal reflections, interference structure (Mie oscillations), refractive index contrast, surface roughness / non-sphericity; researchers have not found a single χ factor for use with $\beta(\pi)$ (see Churnside et al. 2017). The combination of VPBT (sensitivity to particle size, refractive index) and ECO V2 (reliable, constrained estimates of $b_b(\lambda)$) could be useful in reconciling lidar profiles of carbon from space with in situ profiles of carbon from profiling platforms like Argo floats and gliders.

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