Lidar for Ocean Applications: Review of International Efforts

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Abstract: Passive remote sensing of the ocean color has changed our vision of the distribution of the phytoplankton and other optically-active constituents in the ocean. However, these observations have limitations as they cannot be obtained under clouds, under absorbing aerosols, at high latitudes, during the night, or over the vertical in the ocean. To overcome those limitations, lidars have been used, and led to many ocean discoveries despite not having an ocean optimized lidar satellite mission. To increase lidar literacy for the ocean community, it is necessary to provide comprehensive background and training on the technique but also on the ways to process the lidar signal. International efforts have developed lately in the form of an International Team at the International Space Sciences Institute. In this frame, a review of lidar algorithms provides a state-of-art description of the algorithms used to estimate the back-scattering and diffuse attenuation coefficients for elastic backscattering and high-spectral-resolution lidars.

1. Introduction

Remote sensing of ocean color from space has been exploited since the late 1970s with the proof-of-concept satellite mission Coastal Zone Color Sensor [1]. This space mission enabled a new era in the study of the interaction of light with optically-active marine constituents [2, 3]. A continuous record of ocean color from space has existed since 1997. The long-term space observations have been used to study the spatial and temporal distribution of chlorophyll-a, suspended particulate matter, colored dissolved organic carbon, particulate organic carbon, phytoplankton carbon and phytoplankton groups in the open ocean and coastal waters.

However, these measurements are limited to clear sky, daytime-light, high sun elevation angles, ice-free oceans and are exponentially weighted toward the first few meters of the ocean surface. Moreover, the processing of the ocean color images requires the knowledge of the atmospheric components, that contribute to around ninety percent to the total signal measured by the remote sensor over the open ocean. At last, passive ocean color measurements are unable to resolve phytoplankton vertical structure, which can represent a source of error in global estimates of phytoplankton biomass and net primary production. This means that it becomes highly necessary to use complementary remote sensing techniques that provide a 3-D view of the ocean color. For these reasons, the lidar technique is of high interest to the ocean science community.

The lidar technique has yet to be used routinely for studying biological and physical processed in the ocean. The earliest applications of lidar to ocean studies date back to the mid-1970s and early 80s, where it was primarily deployed from airplanes. A resurgence of interest in ocean lidar has prompted the development of several one-off ocean lidar systems deployed from aircraft and ships, as well as the demonstration of algorithms for retrieving ocean optical properties from space-based lidar systems optimized for atmospheric profiling and topographical mapping.

As there is growing interest of the ocean color community to use lidar data but a lack of training in the principles of the technique, we propose to present a review of the algorithms used to retrieve the particulate backscattering b_{bp} and the seawater attenuation, K_d, coefficients from a lidar signal. To do that, an International Team has been created at the International Space Sciences Institute (https://teams.issibern.ch/3doceancolor/). We detail the approaches for two types of lidar: Elastic Backscatter Lidar (EBL) and High-Spectral Resolution Lidar (HSRL). We highlight the specifics of each algorithm.

2. Lidar algorithms for EBL

Algorithms to process lidar signal in the ocean for elastic backscatter lidar are: the slope retrieval technique, the Klett method, the perturbation retrieval [4] and neural networks. Similar to the atmospheric applications, these approaches require assumptions between b_{bp} and K_d, which cannot be retrieved independently. Still, EBL technique is widely used in airborne and shipborne lidar systems [4-7].

3. Lidar algorithms for HSRL

HSRL for ocean applications has been used from airplanes [8-10] and from ships [11]. The advantages of HSRL above EBL is that the absolute calibration of the lidar channels is not needed, just the relative calibration. Moreover, the estimation of the attenuation and backscatter coefficients is direct and require less assumptions.

4. Advantages and limitations

Lidar can provide depth-resolved, day and nighttime, continuous (in-flow) observations on multiple platforms which overcome limitations from passive remote sensed observations of ocean color. To our best knowledge, there are only few published papers showing comparisons between algorithms.

ALGO	**Type of lidar**	**HYPOTHESIS**	**ADVANTAGE/SIMPLICITY TO USE**	**LIMITATIONS**
Slope	EBL	Input: logarithm of the depth-corrected signal Homogeneous waters Derivation of the attenuation through the calculation of the slope: K_L Separation of the backscattering into two components: pure water and particles	Just a slope to estimate High accuracy in well-mixed waters Easy to implement	Ill-posed problem Only well-mixed waters Need correction of multiple-scattering
Klett, Fernald	EBL	Input: logarithm of the depth-corrected signal	Just a slope to estimate Derivative of logarithm of the depth-corrected signal	Ill-posed problem Need absolute

		Stratified and well-mixed waters Separation of the attenuation and backscattering into two components: pure water and particles lidar ratio	Estimate K_L Effective in case of stratified waters	calibration Accumulation of systematic retrieval errors with depth Need lidar ratio Need correction of multiple-scattering
Perturbation	EBL	Linear regression to the logarithm of the depth-corrected signal Split lidar signal into two components: for well-mixed waters and for stratified waters Integral of attenuation perturbation negligible	Determination of the depth profile of scattering More accurate retrievals than the Klett method	Ill-posed problem Need absolute calibration Need correction of multiple-scattering
		Any variations considered as perturbations from the constant scattering		
Standard	HSRL	Need pure water backscatter β_w	Just need ratio of the depth-corrected signal in the two channels Direct estimates of β_P No absolute calibration required No need for lidar ratio	Multiple scattering can introduce errors Strict characterization of the instrument (i.e. molecular and particulate transmittances, relative calibration of the two channels, cross talk)
Multiple-scattering	EBL/HSRL	Assumed phase function	Correction of the molecular scattering impact on K_L	Assumed phase function
NN	EBL/HSRL	No assumptions on lidar ratio Need environmental co-variability Synthetic or in-	Fast to process the data after the training phase	Need a training dataset Long training phase

		situ dataset of lidar signal and β_P and K_L Other datasets including b_{bp} and K_d		

5. Conclusion

This review shows that there is a very high potential in the existing lidar technologies and developed algorithms. There is a lot of efforts made to derive the ocean properties using lidars developed specifically for ocean applications but also lidars that were not initially designed for ocean research. This was possible by applying existing algorithms developed for atmospheric applications but also by adapting those algorithms for ocean applications. Most of the algorithms are mature enough to provide the back-scattering coefficient b_b and the diffuse attenuation coefficient K_d with accuracy with equivalent or better accuracy than the standard ocean color algorithms.

However, efforts are still necessary to improve those algorithms as no round-robin evaluation exist of them. This should be the next step.

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