Ocean Subsurface Study from ICESat-2 Mission

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Abstract — NASA has launched the ICESat-2 mission in September 2018 with the primary purpose of monitoring changes in the cryosphere. Fortunately, the measured photons over ocean region provide great opportunity for the ocean subsurface study. We have proposed a novel algorithm to determine ocean subsurface optical properties, such as, diffuse attenuated coefficient, \(k_d\) (/m), total backscattering coefficients \(b_b\) (/m), attenuated backscatter coefficient and particulate backscattering coefficients \(b_{bp}\) (/m) from ICESat-2/ATLAS lidar measurements. Our ICESat-2 ocean subsurface results reveal high vertical resolution of these optical properties through the water column that are hidden from the passive ocean color record. Moreover, we can estimate the particulate organic carbon (POC) and phytoplankton carbon biomass based on the ICESat-2 retrieved particulate backscattering coefficients \(b_{bp}\) results. We will present and discuss the first ICESat-2 ocean subsurface profile results, especially in polar region where passive ocean color measurements are difficult to make. We will also present the multiple scattering effects on the ocean subsurface optical properties retrieval.

1. INTRODUCTION

Water is one of Earth’s most common and important substances. Information concerning its optical properties is of great significance in many areas of science and engineering. Knowledge of its properties is a first step, for example, retrieving diffuse attenuation coefficient \([1, 2]\) and inherent optical properties (IOPs) from NASA ocean color measurements \([3, 4]\). Except passive remote sensing on ocean color studies, Lidar systems have been proposed as an effective tool for oceanic research as demonstrated by a variety of measurements in the upper ocean, including bathymetry \([5]\), ocean surface roughness and backscatter \([6, 7]\), and ocean subsurface studies \([8–12]\).

NASA has launched the ICESat-2 (Ice, Cloud, and land Elevation Satellite-2) laser altimeter in September 2018 \([13]\). The Advanced Topographic Laser Altimeter System (ATLAS) instrument on-board ICESat-2 is a lidar system with detection sensitivities at the photon level; a new technology for laser ranging \([14, 15]\). The ATLAS transmits green (532 nm) laser pulses at 10 kHz from the nominal \(\sim 500\) km fixed orbit. One transmitted laser pulse is emitted every \(\sim 0.7\) m along ground tracks. Each laser pulse emitted is first split by a diffractive optical element in ATLAS to generate six individual beams, arranged in three pairs, as shown in Fig. 1 \([15]\). Each pair of laser beams along the three tracks have different transmission energies referred hereafter as “strong” and “weak”. Light green circles in Fig. 1 indicate “footprints” from the relatively weak beams, and red circles indicate footprints from the strong beams. The pair of beams (strong, weak) are also separated by about 90 m in the cross-track direction. The beam pairs are further separated by about 3.3 km in the cross-track direction, and the strong and weak beams are separated by about 2.5 km in the along-track direction.

The four scientific aims of the ICESat-2 mission are to (1) measure melting ice sheets and investigate how this effects sea level rise, (2) measure and investigate changes in the mass of ice sheets and glaciers, (3) estimate and study sea ice thickness, and (4) measure the height of vegetation in forests and other ecosystems worldwide. While the primary mission goal of ICESat-2 is to monitor changes in the cryosphere, it will also collect data over the ocean region providing opportunity for ocean surface and subsurface studies.

The objective of this study is to estimate the ocean subsurface diffuse attenuated coefficient, \(k_d\) (/m) and total backscattering coefficients, \(b_b\) (/m) from ICESat-2/ATLAS lidar measurements. The effect of ICESat-2/ATLAS impulse response on the photons vertical profile distribution was estimated before the retrieval of the ocean subsurface \(k_d\) and \(b_b\). The passive ocean color remote sensing has the advantage of providing a synoptic view rather than the point footprint (e.g., MODerate-resolution Imaging Spectroradiometer (MODIS) makes ocean images with spatial resolution of 1 km), but the passive remote sensing (e.g., MODIS) can only operate during daylight
hours (optimally between \(\sim 10:00\) and \(14:00\)), is not reliable at low solar angles (e.g., high latitude in winter), and is sensitive to the clouds and atmospheric aerosols [12]. Space-borne lidar systems can operate day or night, and at low solar angles through considerable aerosol loads and thin clouds [11]. Compared with Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) lidar that provide measurements at \(~70\) m footprint every 333 m along the ground track [16], ICESat-2/ATLAS lidar has the advantage of providing measurements from six individual beams (as shown in Fig. 1) with a nominal 17 m diameter footprint with an along track sampling interval of 0.7 m.

Figure 1: ATLAS idealized beams and footprints on the surface showing the 3 laser beam pairs (1 to 6). Each beam pair contains a strong (red) and weak (green) beam. Sub-satellite point is at 7\(^\circ\). Fig. 1 of [15].

2. ICESAT-2/ATLAS IMPULSE RESPONSE

The analysis and results presented in this work use ICESat-2 geolocated photon data (ATL03) [17, 18] and MODIS level 3 global monthly mapped 4 km data products [19]. ICESat-2/ATLAS data is distributed as granules (\(~1/12\) of a complete orbit) and is stored as hdf5 files. Because there are not enough daily \(b_b\) and \(k_d\) measurements co-located with ICESat-2/ATLAS lidar measurements, we used MODIS monthly \(b_b\) products at 531 nm and \(k_d\) products at 490 nm scaled to 532 nm as \(k_d,532 = 0.68(k_d,490 - 0.022) + 0.054\) [10].

2.1. PMT after-pulse

ICESat-2/ATLAS uses photomultiplier Tubes (PMT) as detectors in photon counting mode where single photons reflected from the surface will trigger a detection within the ICESat-2 receiver. Each individual photon will be time tagged and geolocated. This scenario is much different than the full-waveform data collected by avalanche photodiodes (APD) of ICESat [20, 21]. However, one characteristic of PMT is after-pulses, which are pulses with small amplitudes appearing after the primary signal output pulse [22]. The disadvantage of PMT after-pulses is that they can disturb accurate measurements of low level signals following a large amplitude of signal, for example, measurement of ocean subsurface signal beneath ocean surface where the ocean surface signal can be \(~30\) times greater than subsurface signal [10, 23, 24]. There are two types of PMT after-pulses: one is output with a very short delay (several nanoseconds to several tens of nanoseconds) after the signal pulse and the other appears with a longer delay ranging up to several microseconds. After-pulses with a longer delay are caused by the positive ions which are generated by the ionization of residual gases in the photomultiplier tube. These positive ions return to the photocathode (ion feedback) and produce many photoelectrons which result in after-pulses. The time delay with respect to the signal output pulse ranges from several hundred nanoseconds to over a few microseconds [22]. More details about the PMT after-pulses can be found in PMT handbook [22].

The ICESat-2/ATLAS measured photons from land surface will show this after-pulsing effects. ICESat-2 ATL03 provides time, latitude longitude and ellipsoidal height for each photon event downlinked from ATLAS. Height are corrected for several geophysical phenomena, such as effects the atmosphere and solid earth deformation [22]. Fig. 2(a) shows ICESat-2/ATLAS photon height distribution from the ground surface along-track direction during 210 s to 250 s since start of granule on October 16, 2018. The photon counts are then averaged in 15 cm vertical and 0.001 s (\(~7\) m)
along-track bins. The peak normalized photon counts averaged from 220 s to 240 s is shown in Fig. 2(b), with x-axis the normalized photon counts per 15 cm vertical and 0.001 s horizontal bins. The altitude of peak surface return is set to 0 meter in (b).

Note the altitude of land surface return (peak photon counts) is set to 0 meter in Fig. 2 (b). The 532 nm laser pulse cannot penetrate the land surface, the lidar backscatter signal from a land surface goes quickly from a small value to a very large value and then quickly back to zero under ideal conditions [16]. However, from Fig. 2 there are double echoes where the secondary return about 10 m to 45 m below the primary surface return is due to the PMT after-pulses with longer delay time, and the amplitude of the secondary return is more than 10^3 less than the value of primary return. The narrow echoes at ~2.3 m and ~4.2 m below the primary return are due to PMT after-pulses with short delay time.

Another example to show ICESat-2/ATLAS after-pulse effects is shown in Fig. 3. Fig. 3 is same as Fig. 2 but the photons are from ocean surface along-track direction during 150 s to 200 s since start of granule on October 16, 2018. Similar as Fig. 2(b), Fig. 3(b) also shows two small narrow echoes spaced at about 2.3 m and 4.2 m below the primary ocean surface return. Observations indicate that the two small narrow echoes at about 2.3 m and 4.2 m below the primary surface return are due to PMT after-pulses. Because the two small narrow echoes appear after any surface return not matter what the surface reflectance is.

Compared with the land surface return of Fig. 2(b), the signal decay after the ocean surface is much slow than the signal decay from land surface. This is because there are ocean subsurface returns which will be studied in Section 3. Figs. 2 and 3 both indicate that the ICESat2/ATLAS PMT detectors exhibits a non-ideal (slow decay) recovery of the lidar signal after the surface.

![Figure 2](image_url)

Figure 2: Photon distribution from land surface in ICESat-2 along-track direction during 210 s to 250 s since start of granule on October 16, 2018. (a) The photons vertical profile distribution, that is the normalized photon counts averaged from 220 s to 240 s. x-axis is normalized photon counts per 15 cm vertical and 0.001 s horizontal bins. The altitude of peak surface return is set to 0 meter in (b).

2.2. ICESat-2/ATLAS Impulse Response

ICESat-2/ATLAS PMT detectors exhibits a non-ideal (slow decay) recovery of the lidar signal after the surface. The ocean subsurface return will be contaminated by the slowly decaying noise tail of ocean surface return. In order to study the ocean subsurface correctly, first we need to know the ICESat-2/ATLAS impulse response. ATL03 data product contains the ATLAS impulse response as shown in Fig. 4, which is a function of time from laser fire in nanosecond (ns). The blue and red curves are for two of the three strong beams (beam 1 and 3) [18]. The first pulse is the transmit pulse, the second pulse at 44.75 ns is the transmit pulse echo (TEP echo) with two small echoes at 60 ns and 72 ns, which are corresponding to the 2.3 m and 4.2 m small echoes in Fig. 2(b) and Fig. 3(b). The ICESat-2/ATLAS impulse response shown in Fig. 4 is an estimate of the ATLAS impulse-response derived from the transmitter echo path (TEP) photon events [18]. The TEP is an optical path that provides a means to calibrate ATLAS time of flight internally, and is described in detail in ATL02 [25]. Briefly, light following the optical path of the TEP begins at the laser, travels to the laser sampling assembly where part of the transmitted laser pulse is sampled, and then via a fiber optic cable to the optical filter assembly to the detector array assembly. In this
Figure 3: (a) Photon distribution from ocean surface in ICESat-2 along-track direction during 150 s to 200 s since start of granule on October 16, 2018; (b) The averaged normalized signal return from 150 to 200 s, x-axis is normalized photon counts per 15 cm vertical and 0.001 s horizontal bins. The altitude of peak surface return is set to 0 meter in (b).

Figure 4: ICESat-2/ATLAS impulse response from ALT03 data products as a function of time from laser fire. The first pulse is the transmit pulse, the second pulse is the transmit pulse echo [18].

way, photons detected via the TEP traverse part of the transmit optical path, part of the receive optical path, and all of the receiver electronics that all other signal photons traverse.

Here we used the actual signal photons from surface to study the ICESat-2/ATLAS impulse response. ATL03 algorithm is designed to identify likely signal photons [18]. The parameter signal_conf_ph in the /gtx/heights/ group is a two-dimensional array of photon confidence flags. One dimension has five columns corresponding five different surface types (from left to right: land, ocean, sea ice, land ice, and inland water). The values of signal_conf_ph are: −1 type not considered, 0 likely background, 1 likely background, but close to the surface, 2 low confidence signal, 3 medium confidence signal, and 4 high confidence signal. High confidence photons are very likely surface returns. Fig. 5 presents the percentage (0-1) of high confidence (signal_conf_ph = 4) photon counts per 0.15 cm vertical and 0.001 s horizontal bin from land (red), ocean (blue) and snow (black) surface. From Fig. 5, the mean photon is about 30 counts per bin from most of the land surface, while the mean photon is less than 30 counts per bin from most of the ocean surface that can be affected by the wind speed [6] and attenuation of atmospheric cloud and aerosol. The ocean surface
return with photons greater than 80 counts per bin due to water specular reflection is defined as strong signal here, while the ocean surface return with photons from 8 to 40 counts per bin is defined as weak signal. The signals with less than 8 photon counts per bin is not considered here due to the low signal to noise ratio. When there is no wind or very small wind speed, the laser light will be specular over flat water. As a result, nearly no laser energy goes beyond the ocean surface, and the signal after the ocean surface is mostly due to the slowly decaying noise tail of ocean surface return and the subsurface signal can be neglected. The blue curve of Fig. 6 shows the surface response from these ocean strong signals. Note the ocean surface is set to 0 meter. For comparison, the TEP echo (in Fig. 4) is shown in green in Fig. 6. The pink curve is the ICESat-2/ATLAS impulse response model fitting from the land surface return. The ocean surface response from weak signals is in black. It can be seen from Fig. 6 that the ocean surface response from weak signals (black) is different from the strong signals response (blue). That is because the ocean subsurface signal is prominent compared with noise tail of ocean surface return.

![Figure 5: Histogram (percentage: 0-1) of high confidence photon counts per 0.15 cm vertical and 0.001 s horizontal bin.](image1)

![Figure 6: ICESat-2/ATLAS impulse response from ocean, land surface and TEP echo from ATL03. The surface altitude is set to 0 meter. The pink line is the impulse response model.](image2)

3. OCEAN SUBSURFACE STUDY

Results of Section 2 demonstrated that the ocean subsurface signal is prominent and should be considered when the ocean surface return is not specular reflection. In this section, we present the ocean subsurface study from ICESat-2/ATLAS when the ocean surface return has photon from 8 to 20 counts per bin.

The return signal from a nadir-pointing lidar above the homogeneous water can be represented as [26]:

\[ S(z) = A\beta(\pi)b_b(z)\exp(-2\alpha z) \]  

(1)

where \( S(z) \) is the lidar signal at depth \( z \), \( A \) is the calibration constant, which can be accurately derived by comparing ocean surface signal with theory. \( \alpha \) (unit: /m) is the effective attenuation coefficient of lidar volume backscattering that lies between beam attenuation coefficient (unit: /m) and diffuse attenuated coefficient, \( k_d \) (unit: /m), depending on the lidar spot size at the ocean surface [27–29]. For the spot size of the ICESat-2 (\( \sim 42.5 \) m), the lidar attenuation coefficient, \( \alpha \), is equal to the diffuse attenuated coefficient \( k_d \) [27]. \( \beta(\pi) \) is scattering phase function at a scattering angle of \( \pi \) [27]. The total backscattering coefficients \( b_b(z) \) (unit: /m) is the hemispheric total scattering coefficient \( b(z) \). Particulate backscattering coefficient \( b_{bp}(z) \) is obtained by subtracting the backscattering coefficient of seawater \( b_{bw} \) from total backscattering coefficient \( b_b(z) \).

From Eq. (1), the attenuation coefficient can be easily estimated from the exponential decay of the lidar signal, even for an uncalibrated signal. However, ICESat-2/ATLAS PMT detectors exhibit a non-ideal recovery (decaying noise tail) of the lidar signal after both the land (Fig. 2(b)) and ocean surface (Fig. 2(b) and Fig. 6) returns. The slowly decaying noise tail of the ocean surface is present and can be seen over tens of meters. As a result, the ocean subsurface signal is contaminated by the noise tail from the ocean surface return, and is not retrievable directly from ICESat-2/ATLAS lidar measurements, because the vertical profile shown in Fig. 6 does not allow separation of the ocean
surface and subsurface backscatter. As a result, the non-ideal recovery effects on the attenuated backscatter profile should be removed first before retrieving the attenuation coefficient.

A deconvolution method is used here to remove the ICESat-2/ATLAS PMT detectors non-ideal recovery effects and get the correct attenuated backscatter profile [11]. Fig. 7(a) gives an example of the peak normalized profile of ocean surface return $S(z)$ (black curve), the impulse response $h(z)$ (green curve) and the deconvolution result $S_c(z)$ (red curve). Note, the ocean surface is set to be at zero meter, and altitude below sea surface is set to be negative value. Compared with original ocean surface return (black curve of Fig. 7(a)) that has PMT after-pulsing effects, the deconvolution result $S_c(z)$ has no small narrow echoes below ocean surface. The results of Fig. 7(a) demonstrate that the deconvolution method can effectively remove the ICESat-2/ATLAS PMT detectors non-ideal recovery. The attenuation coefficient, $k_d$, is estimated from the exponential decay of the correct ocean subsurface signal (red curve of left panel) between 3.5 m to 11 m below sea surface.

**Figure 7:** (a) Vertical profile of peak normalized ocean surface return signal, $S(z)$ observed by ICESat-2/ATLAS at 532 nm on October 16th, and its corresponding deconvolution result $S_c(z)$ (red curve) with the impulse response $h(z)$ (green curve). (b) The attenuation coefficient, $k_d$, is estimated from the exponential decay of the correct ocean subsurface signal (red curve of left panel) between 3.5 m to 11 m below sea surface. Note, the altitude below sea surface is set to be negative value.

**Figure 8:** ICESat-2/ATLAS observed ocean subsurface attenuated backscatter profile at 532 nm (/m/sr) on October 16 2018. The color is log scale of attenuated backscatter.

GMAO wind speed from MERRA-2 1-hourly instantaneous two-dimensional data products are used to estimate theoretical backscatter of ocean surface for calculating calibration constant $A$. When the detectors non-ideal recovery effects on the attenuated backscatter profile are removed, and the calibration constant is retrieved based on the wind speed, the calibrated ocean subsurface attenuated backscatter along ICESat-2 footprints on October 16th, 2018 are shown in Fig. 8. The color is logarithmic scale of calibrated attenuated backscatter. Figure 9 presents two-dimensional distribution of total backscattering coefficients, $b_b(z)$, obtained from ICESat-2 calibrated ocean
subsurface attenuated backscatter shown in Fig. 8, where $x$-axis is the ICESat-2 ground tracks and $y$-axis is depth in meter. The color is in logarithmic scale of $b_p(z)$. Fig. 10 shows the comparison between ICESat-2 retrieved layer integrated ocean subsurface optical properties and corresponding MODIS results. As shown in Fig. 10, the ICESat-2 retrieved $k_d$ and $b_o$ results compare reasonably well with MODIS results. The mean relative differences between ICESat-2 and MODIS are about 8% and 10% for $k_d$ and $b_o$, respectively. These differences are mainly due to the time offset and different measurements sites. The ICESat-2 measurements were made on October, 16, 2018 while MODIS results were from monthly products of October 2018. The distance between ICESat-2 and MODIS footprints is up to 10 km.

Figure 9: ICESat-2/ATLAS retrieved total backscattering coefficient, $b_o$ (/m) on October 16 2018. The color is log scale of total backscattering coefficient.

Figure 10: Upper panel: ICESat-2/ATLAS retrieved ocean subsurface diffuse attenuation coefficient, $k_d$ (/m) (blue) on October 16 2018 was compared with co-located MODIS diffuse attenuation coefficient at 532 nm (red: monthly data, black: daily data). middle panel: ICESat-2/ATLAS retrieved layer-integrated total backscattering coefficient, $b_o$ (/m) (blue) with colocated MODIS $b_o$ at 531 nm. Lower panel: ICESat-2/ATLAS retrieved layer-integrated ocean subsurface backscatter (/sr) (blue) with co-located MODIS remote sensing reflectance, $Rrs$ at 531 nm.
4. SUMMARY

NASA has launched the ICESat-2 mission in September 2018 with the primary purpose of monitoring changes in the cryosphere. However, the signals over ocean region provide great opportunity for the ocean subsurface study.

Lidar results from both land and ocean surface indicate that the ICESat-2/ATLAS PMT detectors exhibits a non-ideal (slow decay) recovery of the lidar signal after the primary surface return. This slowly decaying noise tail of the ocean surface can be seen over tens of meters. As a result, the ocean subsurface signal is contaminated by the noise tail from the ocean surface return, and is not retrievable directly from ICESat-2/ATLAS lidar measurements, because the ICESat-2/ATLAS lidar profile data do not separate the ocean subsurface backscatter from the noise tail of ocean surface reflectance.

Within this study, we introduce an approach for estimating the diffuse attenuated coefficient, $k_d$ and total backscattering coefficients $b_b$ from ICESat-2/ATLAS lidar measurements. The preliminary ICESat-2 retrieved values compare favorably with results from MODIS ocean color data. The approach will apply to more ICESat-2/ATLAS observations, especially in the high latitude regions where we have limited MODIS passive remote sensing measurements. Moreover, the ICESat-2 retrieved results can be used to study these parameters difference between day and night, where MODIS only has day time results of $k_d$ and $b_b$. This will benefit for the polar phytoplankton biomass cycle study, where the polar plankton communities are among the most productive, seasonally-dynamic and rapidly-changing ecosystems in the global ocean. Our results support the use of space-borne lidar measurements for ocean color studies.

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