Ocean subsurface study from ICESat-2 mission

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Outline

1. Framework of applying ATL03 for ocean subsurface study (impulse response, after pulses, deconvolution)
2. Ocean phytoplankton examples (validation/comparison)
3. Summary (advantage of using ICESat-2 for ocean biology study)
4. Acknowledgment and References
“Noise” photons are important too!

1. ICESat-2 **high, low, med and even “Noise” photons** are very useful and important!

2. ICESat-2 **impulse response**: the surface returns from **hard surface**, e.g., land surface, No subsurface return because laser at 532nm can not penetrate land surface.

3. ICESat-2 **Transient response**: the waveform of all kinds of lidar surface returns (e.g., ocean, sea ice, snow, etc.) during clear sky conditions (avoid cloud and aerosols impact).
Framework of applying ATL03 for ocean study

ATL03 → Impulse response

Subsurface attenuated backscatter profile → Particulate backscattering coefficient profile ($b_{bp}$, m$^{-1}$)

Particulate organic carbon (POC), and phytoplankton carbon biomass ($C_{phyto}$) analysis etc.

Phytoplankton activities

Lu, et al. (2019, 2020, 2021a, b).
After pulsing effects – Studied regions

Figure S1. The ICESat-2 ATLAS's ground tracks (colored lines) where the photons are studied in this paper. The background color represents the land surface white-Sky albedo in the visible range (300-700 nm) from MODIS acquired between July 7 and July 22, 2019. High albedos are noted as expected over snow covered and desert regions. The missing land surface albedo are due to cloud cover.

Figure S2. ICESat-2 footprints (black lines) on September 3rd (A and B) and 4th (C), 2019. The green line segments indicate the regions where the photon heights were shown in Figure S3. The background colors are the daily sea ice concentration (0-100%) from Nimbus-7 SMMR and DMSP SSM/I-SSMIS passive microwave data on September 3rd, 2019.
After pulses from different surfaces

Red: high confidence photon
The impulse response is important

- No subsurface return.
- No solar background noise (Nighttime).
- No vegetation effect.
- No saturation effect. (Removed saturated cases).
- No low cloud/aerosol effect (clear sky conditions)

Lu, et al. (2021a)
ICESat-2 different surface returns

Different surface returns tell us: ICESat-2 detects subsurface photons below sea ice, snow and ocean surfaces.
## After pulses Summary

<table>
<thead>
<tr>
<th>Afterpulses (AP)</th>
<th>Distance from primary surface to afterpulses</th>
<th>Ratio of afterpulse to surface</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>AP 1s</td>
<td>~ 0.45 m</td>
<td>~ 2e-2</td>
<td>PMT saturation</td>
</tr>
<tr>
<td>AP 2s</td>
<td>~ 0.9 m</td>
<td>~ 4e-3</td>
<td>PMT saturation</td>
</tr>
<tr>
<td>AP 3s</td>
<td>~ 1.35 m</td>
<td>~ 1.9e-3</td>
<td>PMT saturation</td>
</tr>
<tr>
<td>AP 4s</td>
<td>~ 1.8 m</td>
<td>~ 1e-3</td>
<td>PMT saturation</td>
</tr>
</tbody>
</table>

Lu, et al. (2021a)
### Afterpulses due to multiple reflections within ATLAS system

<table>
<thead>
<tr>
<th>Afterpulses (AP) #</th>
<th>Distance from land surface to afterpulses</th>
<th>Ratio of afterpulse to surface</th>
<th>Reason: photons traveled extra times through the fibers due to reflections</th>
</tr>
</thead>
<tbody>
<tr>
<td>AP 1</td>
<td>2.25 m (≈ EOPL of fiber 2)</td>
<td>~ 1.5e-3</td>
<td>Photons traveled through fiber 2 a total of 3 times</td>
</tr>
<tr>
<td>AP 2</td>
<td>4.2 m (≈ EOPL of fiber 1)</td>
<td>~ 7.2e-4</td>
<td>Photons traveled through fiber 1 a total of 3 times</td>
</tr>
<tr>
<td>AP 3</td>
<td>6.45 m (≈ EOPL of fiber 1 + EOPL of fiber 2)</td>
<td>~ 3e-5 - 4e-5</td>
<td>Photons traveled through both fibers a total of 3 times</td>
</tr>
<tr>
<td>AP 4</td>
<td>8.4 m (≈ 2× EOPL of fiber 1)</td>
<td>~ 1.7e-5</td>
<td>Photons traveled through fiber 1 a total of 5 times</td>
</tr>
</tbody>
</table>

### Afterpulses caused by PMT ionization effects

| AP                | ~ 10 - 45 m | ~ 1.3e-5 - 1e-4 | Caused by PMT ionization effects |

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Lu, et al. (2021a)
Ocean subsurface profiles

Smooth surface
Specular and Diffuse Reflection

Rough surface

Reflected light
Incident light

Ocean surface

Refracted light

Particles in water

Normalized surface photon counts

Ocean
Ocean-specular
Land
TEP echo
Model

Altitude after surface (meter)
Ocean subsurface profiles

The subsurface profile indicate how fast the light attenuated through the water.

Lu, et al. (2020, 2021a)
Calibrated Ocean subsurface profiles

ICESat-2 ground track in red

Oct. 16, 2018, Night time measurement.

Attenuated backscatter coefficient on 20190305

$\beta \text{(m}^{-1}\text{sr}^{-1}) \times 10^{-3}$
ICESat-2 global ocean subsurface photons

Subsurface photons directly indicate global phytoplankton distributions

Paper in preparation
Photons indicate ocean biology

ATL03 subsurface photon


Dec Jan Feb


Upwelling region

Sub-Arctic region

Southern Ocean

MODIS ocean color results

Jun Jul Aug

Dec Jan Feb
Global Ocean biology – seasonal distribution

Global phytoplankton distributions - Daytime

Lu, et al. (2021b)
Global Ocean biology – seasonal distribution

Global phytoplankton distributions - Nighttime

Nighttime ocean biology distribution are not available from passive ocean color remote sensing (e.g., MODIS ocean color product)

Nighttime ocean biology distribution are only available from Space lidars: CALIOP and ICESat-2

Lu, et al. (2021b)
Summary

Advantage by combing ICESat-2/CALIOP Space lidar measurements

• Space lidars provide both day and night global ocean biology observations, including measurements underneath aerosols and non-opaque clouds, measurements in polar regions during all seasons.

• Vertical distributions are not available from the traditional passive ocean color records (MODIS, CALIOP) in the upper 30m ocean.
Summary

Great science can be done with ICESat-2/CALIOP lidar results

- Global phytoplankton seasonal and annual climatology.
- Cryosphere – Ocean biology – Cloud interaction.
- The impact of ocean biology on ice-albedo feedback.
- Sea ice vertical structure and light transmittance through sea ice.
- Estimate how much of SW radiation penetrating into the ocean though sea ice.
Acknowledgments

Tom Neumann
Anthony Martino
Christopher Field
For their help on ICESat-2 after pulses
References


PMT Transient Response

• Possible candidates for the cause of the transient response are:
  – PMT afterpulsing (ionization of residual gas). This effect is well documented in the literature for photon counting applications. The time scale of the effect is dependent on PMT voltage, gas species, and PMT internal geometry.
  – Signal induced noise...
ICESat-2 work

- ATL10: Sea ice freeboard
- ATL09: Surface reflectivity, cloud information

**Input**:
- Sentinel ice algae, surface reflectance data
- Sonars sea ice draft data
- CALIOP aerosol, cloud data
- OCO-2&3 CO₂ data
- CERES Solar radiance data

**Set up ICESat-2 system Model**

**ATL03**
- Calibration
- Deconvolution
- Attenuated backscatter profile

**ATL09**
- Over sea ice
- Sea ice backscatter profile, ice algae, blooms below sea ice, analysis etc.

**Impulse response**
- Over ocean
- Diffuse attenuation coefficient (kₐ, /m)
- Particulate backscattering coefficient profile (bₚp, /m)

**Land surface returns**
- Applied on Snow surface
- Snow properties retrieval:
  - Grain size, density, Kd

- Particulate organic carbon (POC) and phytoplankton carbon biomass (Cphyto) analysis etc.