Dawn of Satellite Lidar in Oceanography
Passive Ocean Color Measurements

- atmosphere dominates measured signal and correction is challenging
- ocean component of signal dominated by upper ½ optical depth
- no direct information on vertical distribution of ocean constituents
- an optically integrated property without a direct signal for separating absorption and scattering fractions
- global sampling is compromised by aerosols, clouds, solar angle (in the extreme, polar night)
- no information on plankton properties at night
Active Lidar Ocean Measurements

Lidar (Light Detection And Ranging)

- signal from a known source (laser)
- constant viewing geometry
- minimal atmosphere correction issues
- penetrates deep into photic layer
- resolves vertical structure
- can directly separate absorption and particulate scattering
- retrievals through aerosols/thin clouds & between clouds
- day and night sampling
Roadmap

1. How does it work?
2. Notes from the field
3. Going to space
4. Little bit o’ science
5. Solving a problem
6. Looking ahead
Lidar 101: How does it work?
Increasing Information Content

- Nd:Yg laser 1064 nm fundamental wavelength
- frequency double to 532 nm & triple to 355 nm
- polarized emission
- co-polarized & cross-polarized detection
- fluorescence detection bands
- high-resolution spectral filtering
- vertical sampling (detector sampling rate, laser temporal pulse width)
*note, these data are from an advanced airborne lidar system (discussed later)
Notes from the field: Airborne lidar
Early Airborne Measurements

- Kim et al. 1973: Chlorophyll fluorescence
- Yoder et al. 1993: Chlorophyll spatial variability during JGOFS North Atlantic Bloom Experiment
- Martin et al. 1994: Chlorophyll fluorescence to map iron stress response during IronExI

From: Hoge et al. 1986
Airborne LiDAR profiling – Jim Churnside

- Churnside & Ostrovsky 2005, Churnside & Donaghay 2009: Detect plankton layers
- Churnside et al. 2014, Churnside & Marchbanks 2015: Bio-optical modeling to separate attenuation and backscatter
- Churnside 2015: Attenuation, backscatter, & chlorophyll
- Churnside 2016: Vertical distribution of net primary productivity
...can we do it from space?
Going to Space
Lidar In-space Technology Experiment (LITE)

- Discovery Space Shuttle in September 1994
- 3-wavelength Nd-Yg lidar
- $1064 = 486 \text{ mJ}; 532 = 460 \text{ mJ}; 355 = 196 \text{ mJ}$
- Multi-angle ($\pm 30^\circ$) maneuvers over Lake Superior and Gulf of California
two important things then happened...
#1. Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP)

- NASA-CNES partnership
- launched April 28, 2006, still active
- definitively **NOT** designed for ocean applications
- 2-wavelength 110 mJ Nd:Yg laser (532, 1064 nm)
- 3-channel (532∥, 532 ┴, 1064 nm)
- 1 meter telescope
- 100 m footprint
- 30 m air / 23 m water vertical resolution
- polar orbiting, 16 day repeat cycle
- measurements both day and night

Behrenfeld et al. 2013 *Geophys. Res. Lett.* 40, 4355-60 (field val, geophysical prod’s)
Little bit o’ science
Field-testing Retrievals

Plankton Stocks with a Satellite Lidar

![Map of global plankton stocks with satellite lidar data](image)

![Frequency distribution of particulate organic carbon (mg m⁻³)](image)

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Polar Systems: Where Lidar Really Shines

Behrenfeld et al. 2016 Nature Geoscience 19, 118-122
CALIOP Shines on Polar Ecosystems

Behrenfeld et al. 2016 Nature Geoscience 19, 118-122
CALIOP Shines on Polar Ecosystems

December 2010

MODIS biomass

CALIOP biomass

June 2010

Phytoplankton Biomass (mg C m⁻³)

0 25 50 75 100

2007 2009 2011 2013 2015 Year

Phytoplankton biomass (mg C m⁻³)

2007 2009 2011 2013 2015 Year

Behrenfeld et al. 2016 Nature Geoscience 19, 118-122
Polar Biomass Dynamics

North Polar Zone

-0.01 -0.005 0 0.005 0.01

biomass rate of change (d\(^{-1}\))

Jan  July  Jan

Month

Behrenfeld et al. 2016 Nature Geoscience 19, 118-122
Now consider the derivative of this annual cycle...
Polar Biomass Dynamics

The temporal lag in predator (zooplankton, viruses, etc.) responses to phytoplankton division rate changes causes the annual cycle in biomass to track accelerations and decelerations in division rate.

Behrenfeld et al. 2016 Nature Geoscience 19, 118-122
Summary

- CALIOP fortuitously circumvented what is the death of many good ideas … proof-of-concept in space

- CALIOP’s global observations provide independent assessments of plankton stocks and new constraints for ocean color algorithms

- CALIOP’s polar observations address major challenges for ocean color sensors, ‘fill in’ missing pieces of plankton annual cycles, and provide new ecological insights on plankton ‘boom-bust’ cycles
The lidar era in satellite oceanography has arrived...
Solving a problem
‘Proof-of-Concept’
Simple Elastic Backscatter Lidars (e.g., CALIOP)

- An ‘ill-posed problem’: 1 measurement (attenuated backscatter), 2 unknowns ($b_{bp}$, $k_d$)

- Ancillary data and/or bio-optical assumptions required to solve, with large potential errors

- Retrieval starts from top of profile and attenuation is removed at each level by assuming an extinction-to-backscatter ratio. Errors accumulate with distance from sensor

- Science value will be far greater for a lidar providing independent, calibrated retrievals of $b_{bp}$ and $k_d$ without propagation of errors … can this be done?
High Spectral Resolution Lidar (HSRL)

Particles backscatter light at the same frequency of the transmitted laser pulse.

Backscatter from sea water molecules is shifted slightly in frequency due to Brillouin scattering processes.

7.5 GHz shift at 532 nm
High Spectral Resolution Lidar (HSRL)

- Laser tuned to I$_2$ absorption line
- Can also use interferometer
- Particulate backscatter blocked from “Molecular Channel”
A ‘well-posed problem’: 2 measurement, 2 unknowns ($b_{bp}$, $k_d$)

\[ S_M(z) = \beta_M \exp\left[-2 \int_0^z K_d(z')dz'\right] (Atmos.\ Transmission)^2 \]

\[ S_P(z) = [\beta_P(z) + \beta_M] \exp\left[-2 \int_0^z K_d(z')dz'\right] (Atmos.\ Transmission)^2 \]

\[ K_d(z) = \left[-\frac{1}{2} \frac{d}{dz} \ln(S_M(z))\right] \]

\[ \beta_P(z) = \beta_M \left[\frac{S_P(z)}{S_M(z)} - 1\right] \]
Ocean Retrievals with HSRL

- 2012 Azores/AMT campaign
- 2014 NASA SABOR campaign
- 2015 NASA NAAMES 1 campaign
- 2016 NASA NAAMES 1 campaign
Ocean Retrievals with HSRL

Key Points

- Accurate retrievals of $b_{bp}$ and $k_d$
- Match-ups have spatial & temporal differences
- Accurate retrieval of vertical structure @ 1m resolution
- Water column profiling to ~3 optical depths
- Improvements in $\Sigma NPP > 50\%$ for SABOR (other studies > 100%)

Data from John Hair (NASA LaRC) & Schulien et al. 2017 Optics Express (in press)
Looking ahead…

… it is time to think about what we can really do with a lidar mission actually designed for ocean retrievals

subsurface data courtesy of Jim Churnside
An Ocean-optimized Lidar
Shopping list additions to CALIOP (1064 ‖ / 532 ‖ / 532 ⊥ / 22 m)

<table>
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<th>Capability</th>
<th>Value to Ocean Science</th>
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| CALIOP Plus | • Profiles of $K_d$, $b_{bp}$, & geophysical properties ($C_{phyto}$, POC, NPP)  
• Calibration error  
• $K_d$-$b_{bp}$ separation error (need ocean color or optical model) |
| Plus <3-m vertical resolution | • Calibrated through profile  
• Well-posed retrieval of $b_{bp}$ & $K_d$  
• Improved geophysical products  
• Independent of ocean color and optical modeling |
| Plus HSRL at 532 nm Depolarization at 1064 nm | • Chlorophyll concentration (night)  
• Nonphotochemical Quenching  
• Iron stress |
| Plus Chl Fluorescence | • Accurate independent profiles of $b_{bp}$ & $K_d$ at 532 and 355 nm  
• Separation of CDOM & pigments  
• Slope of particle size distribution  
• Improved vertically-resolved NPP |

Entry requirement for ocean research

Minimal additional cost to mission
An Ocean-optimized Lidar

1. Better understanding of polar / other problematic regions

2. Major improvements in water column phytoplankton stocks (e.g., biomass) and rates (e.g., primary production)

3. Globally representative data for ocean color algorithm development

4. New information on physiology (e.g., iron stress, photoprotection)

5. Ecological insights from day-night stock changes

6. More accurate ocean color atmospheric corrections

7. Active mixing depth of the ocean surface layer

& much more…
Enabling a 3-dimensional reconstruction of global ocean ecosystems by combining strengths of different approaches

- Optimized ocean-atmosphere lidar
- Advanced ocean color sensor
- Scanning Polarimeter
- Bio-Geo-Argo global array

Achievable in near future (PACE)

MESCAL (Monitoring the Evolving State of Clouds and Aerosol Layers)
- CNES concept study partnering with NASA LaRC
THANK YOU

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NASA Ocean Biology and Biogeochemistry Program
NASA Earth Science Technology Office
NASA Airborne Instrument Technology Transition Program
**Polar Biomass Dynamics**

North Polar Zone

South Polar Zone

Behrenfeld et al. 2016 Nature Geoscience 19, 118-122
Now consider the derivative of this annual cycle...
The temporal lag in predator (zooplankton, viruses, etc) responses to phytoplankton division rate changes causes the annual cycle in biomass to track accelerations and decelerations in division rate.
• Simulated profiling through 70% of the euphotic zone possible with a realizable system
  – 150 mJ at 140 Hz at 532 nm
  – 1.5 m telescope (similar to ADM-Aeolus)
  – Altitude 450 km for these simulations
• Resolution/precision can be increased via changes in instrument parameters
Why do we care about depth-resolved profiles?

- Data from the SABOR mission off East Coast US (2104) demonstrating differences between surface-weighted and depth resolved profiles using in situ and HSRL lidar data.
  - Ocean color style estimates off by as much as 54%
  - Errors can be much larger in other parts of the ocean

Four ocean products from HSRL-1:

- **Attenuation** \( \sim K_d \)
- **Backscatter** \( \beta_p(\pi) \)
- **Depolarization**
- **Attenuation/Backscatter**
Profiles of density $\sigma_\theta$ (solid line) and lidar depolarization $d$ (dashed line).

Lidar (CALIPSO) depolarization after averaging over 100 shots, 33 km and in-situ density profiles.
$1^\circ \times 1^\circ$ latitude bins with valid $b_{bp}$ retrieval.

70% is the theoretical max percentage of MODIS pixels sampled by CALIOP.