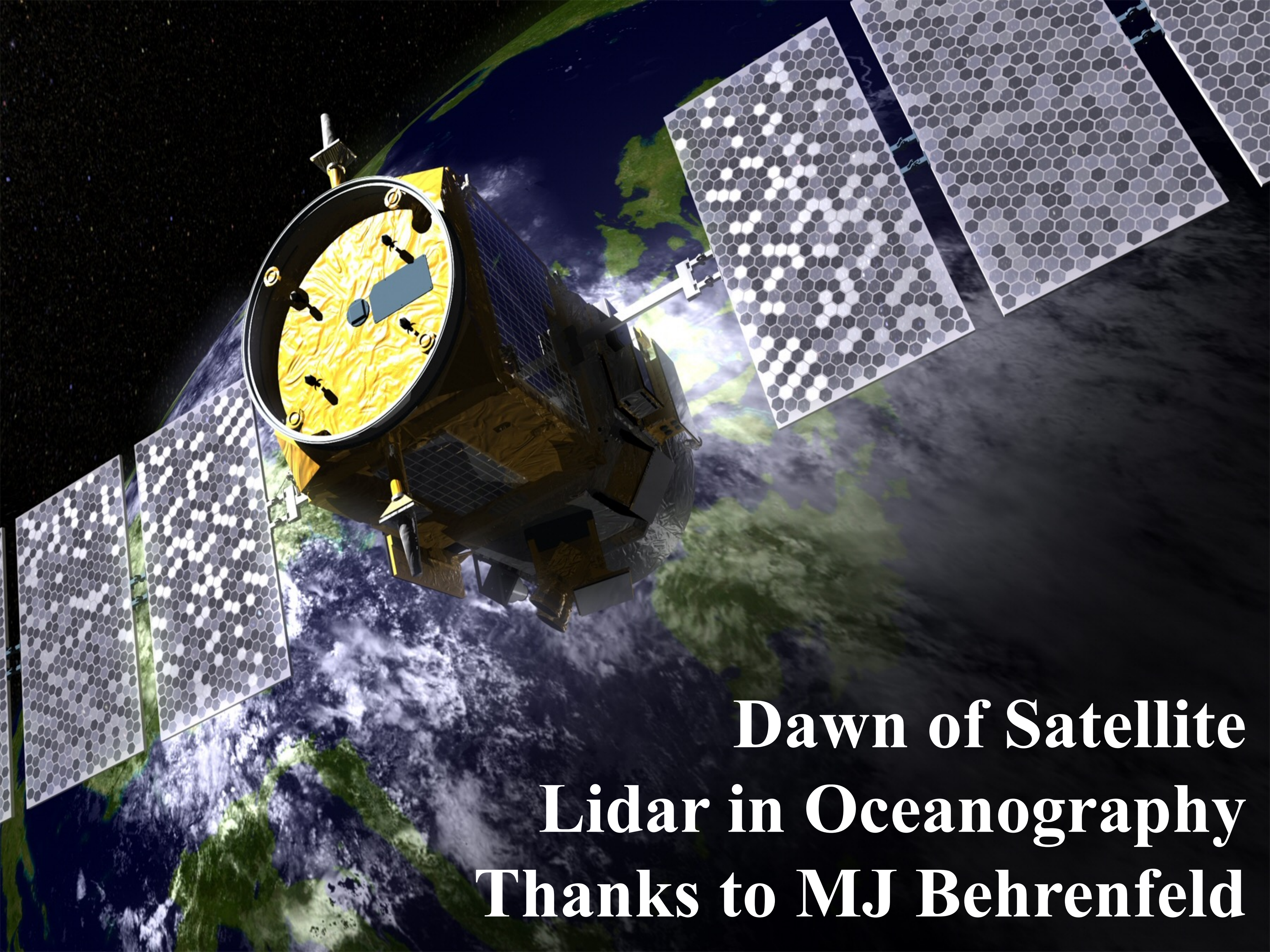
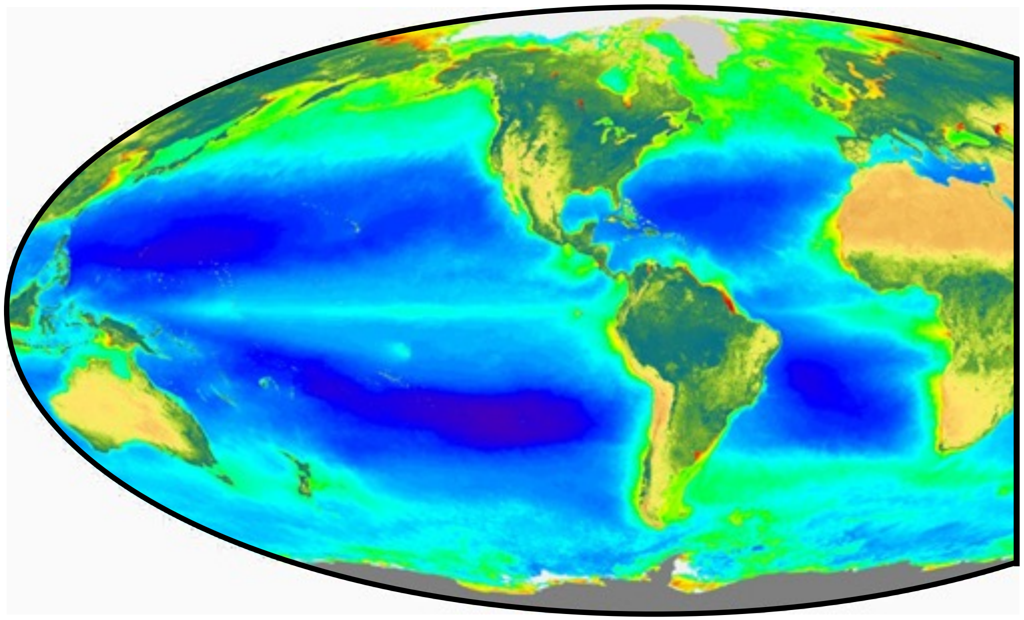

Dawn of Satellite
Lidar in Oceanography
Thanks to MJ Behrenfeld

Limitations of 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

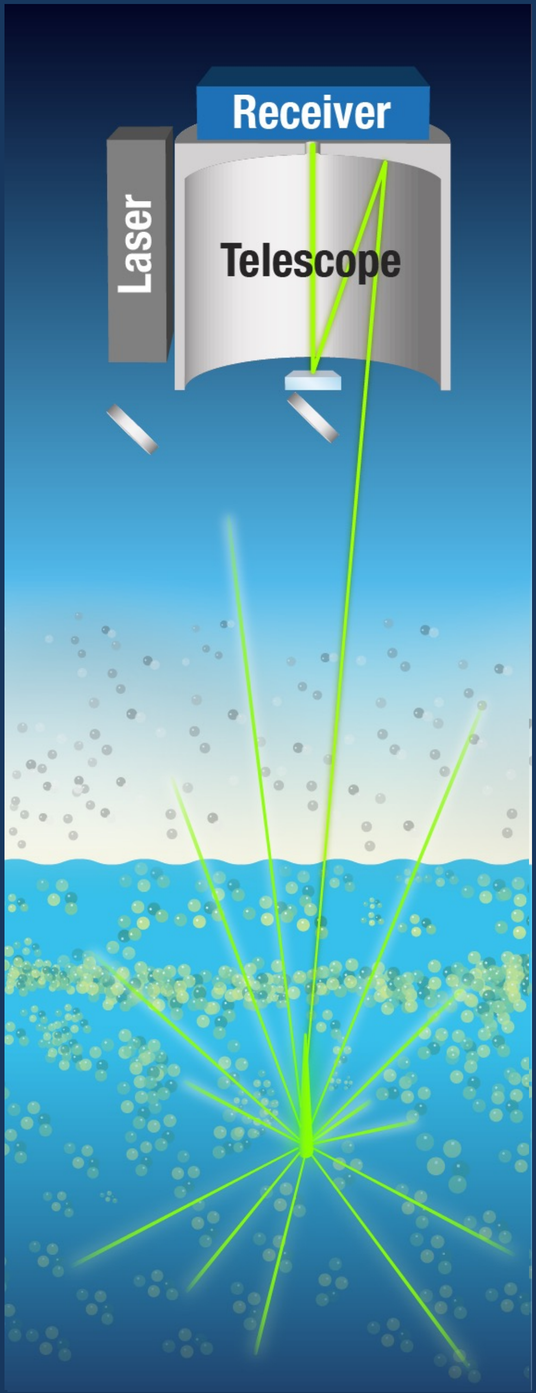
Lidar (Light Detection And Ranging)

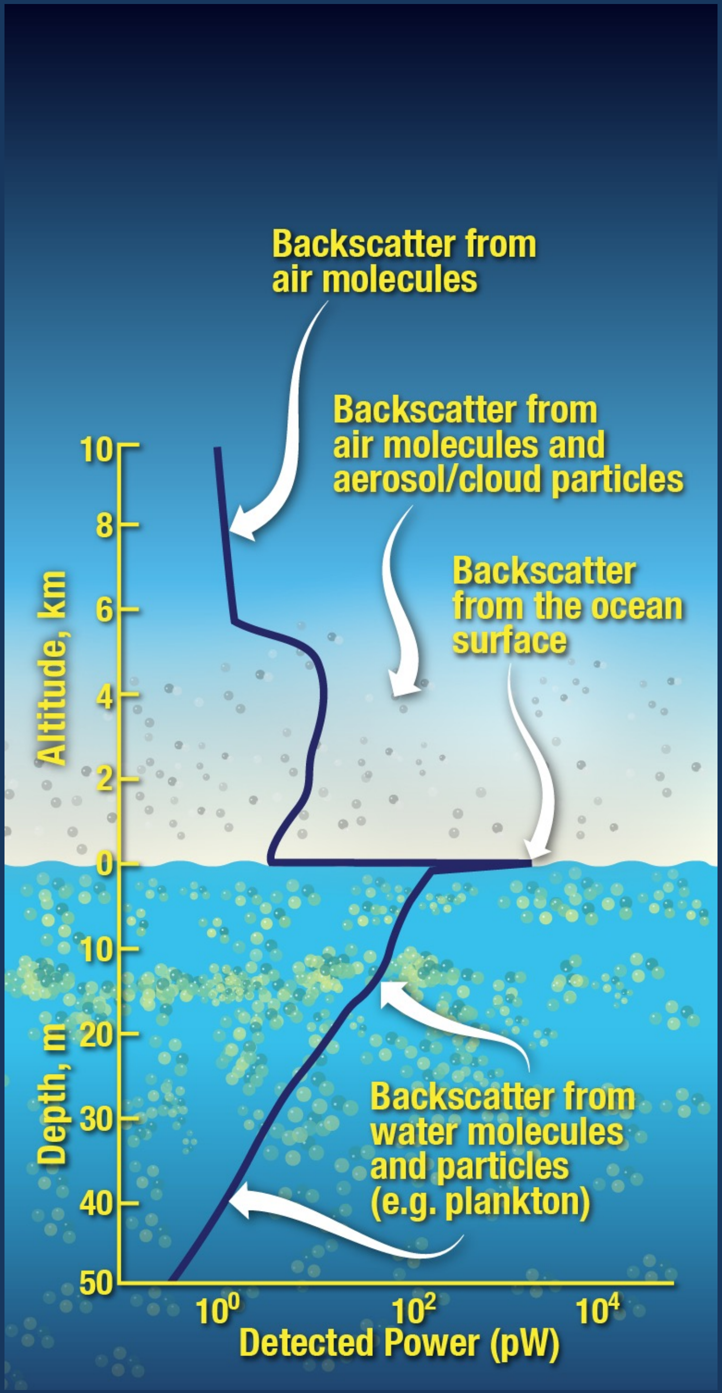
- signal from a known source (laser)
- constant viewing geometry
- minimal atmosphere correction issues
- penetrates deep into photic layer
- resolves vertical structure
- can directly separate absorption and particulate scattering
- retrievals through aerosols/thin clouds & between clouds
- day and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

Roadmap

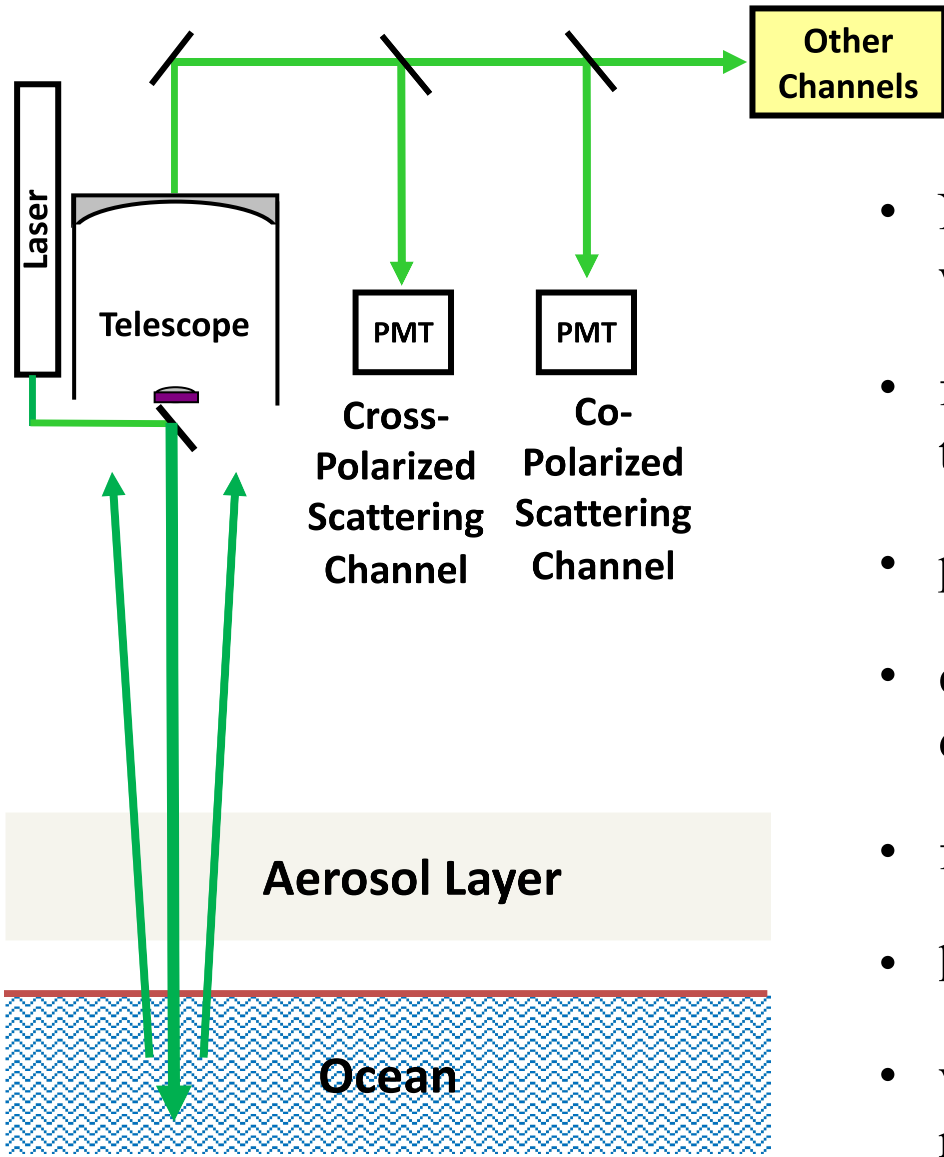
1. How does it work?
2. Notes from the field
3. Going to space
4. Little bit o’ science
5. Solving a problem
6. Looking ahead

Lidar 101: How does it work?



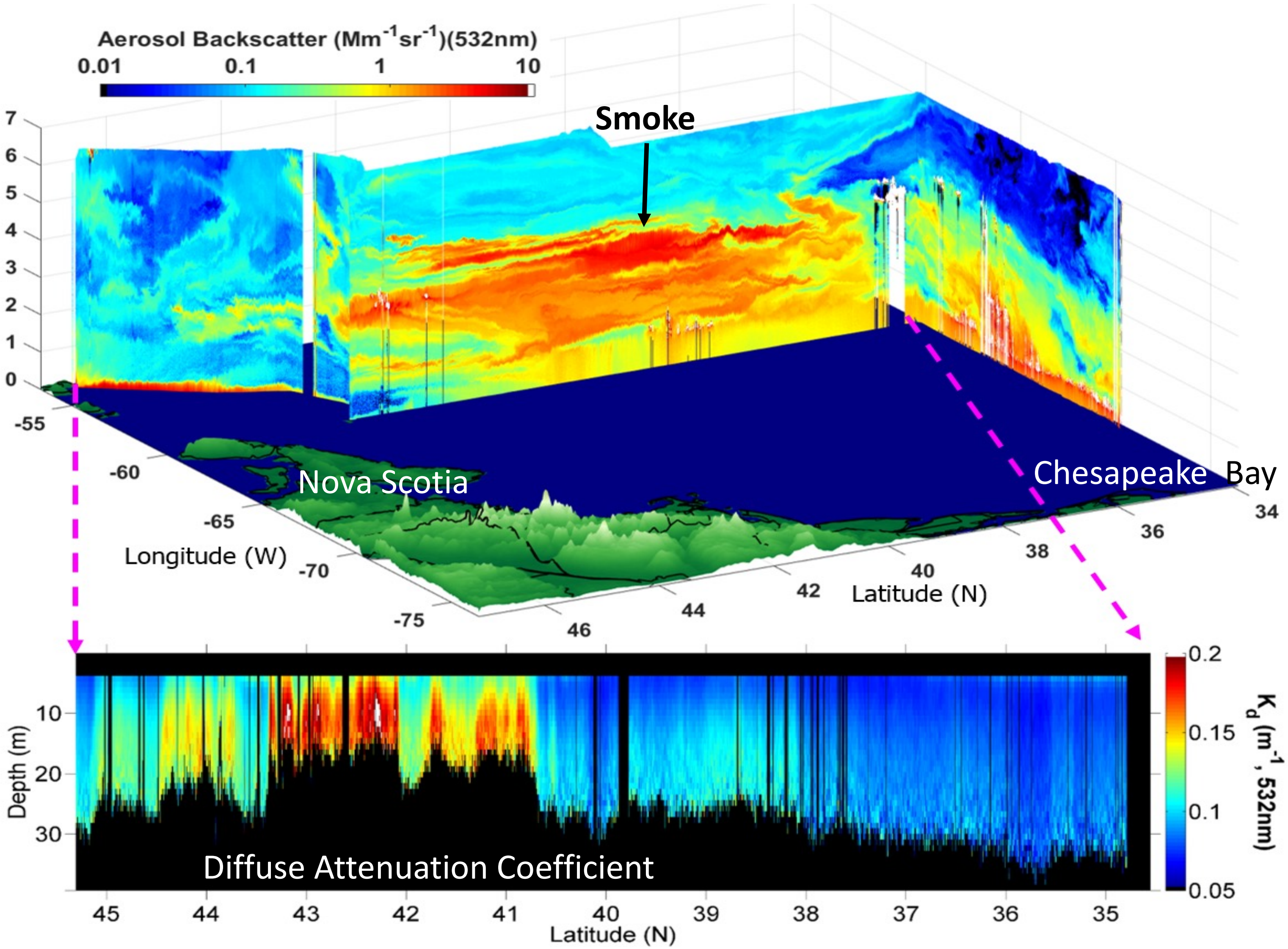


Increasing Information Content



- 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)

The Lidar 'Curtain'

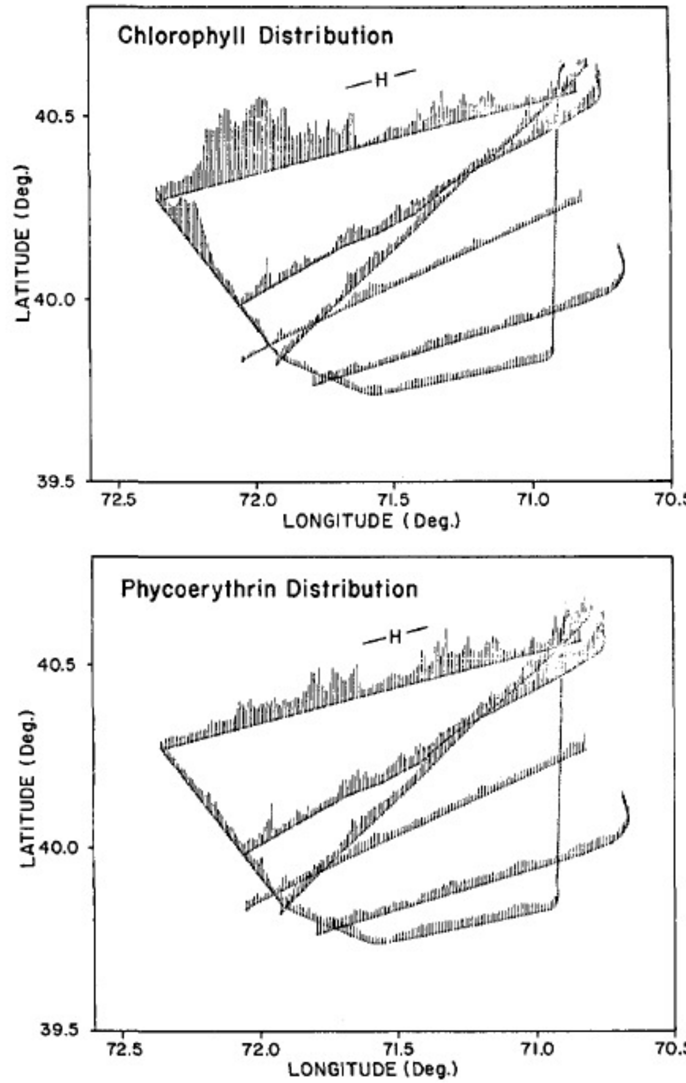


* note, these data are from an advanced airborne lidar system (discussed later)

Notes from the field: Airborne lidar

Early Airborne Measurements

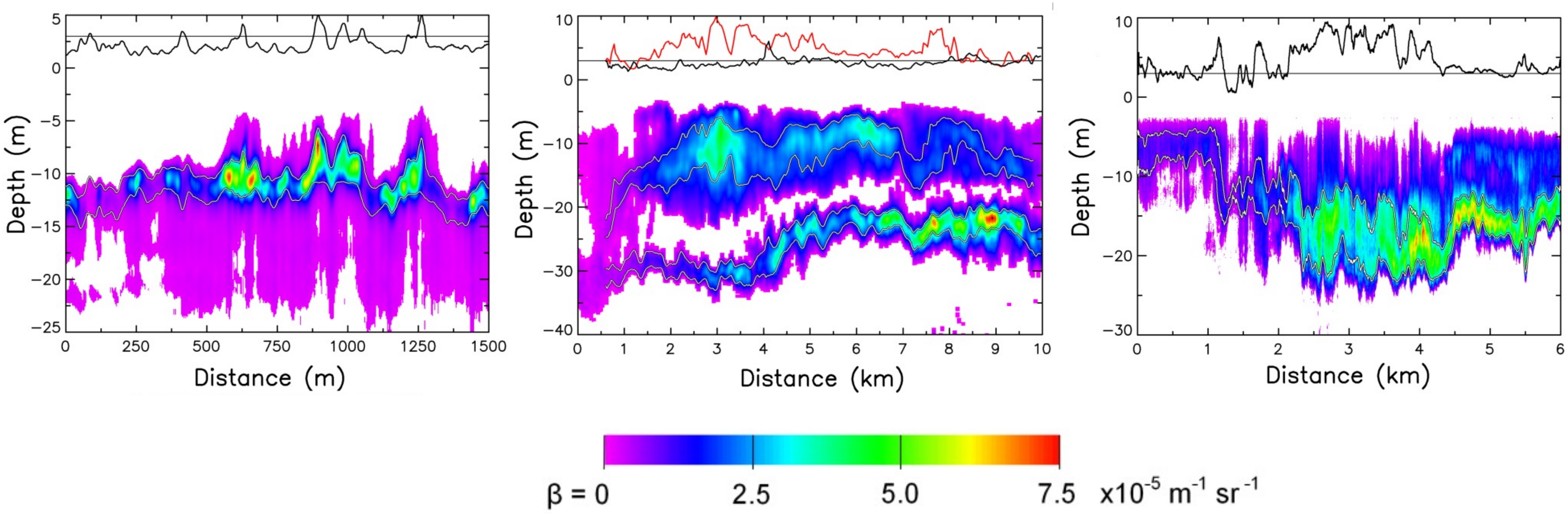
- Kim et al. 1973: Chlorophyll fluorescence
- Bristow et al. 1981, Hoge et al. 1981, 1986: Raman to quantify chlorophyll & phycoerythrin
- Billard et al. 1986, Hoge et al. 1988, Smart & Kwon 1996, Bunkin & Surovegin 1992: Early profiling of (relative) backscattering attenuation
- Hoge et al. 1993, 1995: 355 nm for CDOM
- 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

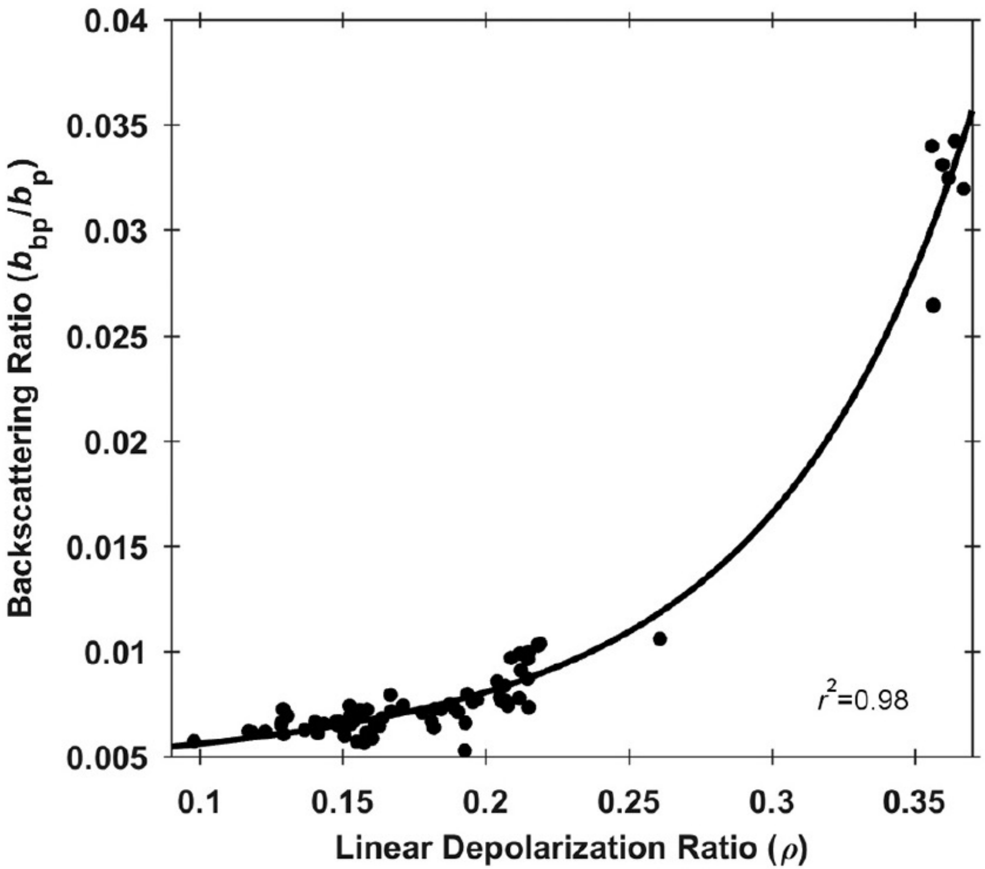
Airborne LiDAR profiling – Jim Churnside

- Churnside et al. 1991, 2001, 2003: Detect/quantify fish schools
- 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



Shipborne LiDAR profiling

- Many papers…
- Collister et al., 2018: Detect/quantify particles and their composition in the upper ocean. Link depolarization ratio to b_{bp}/b_p

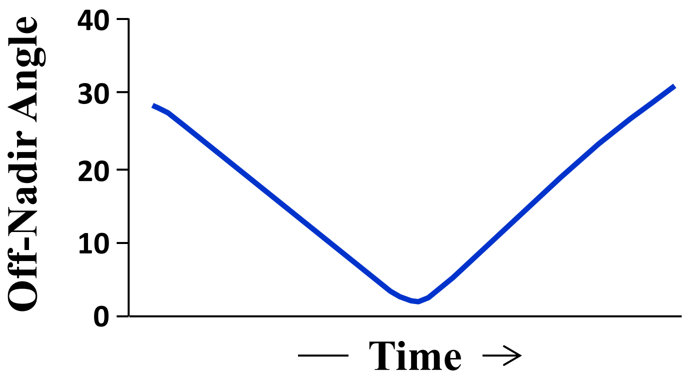


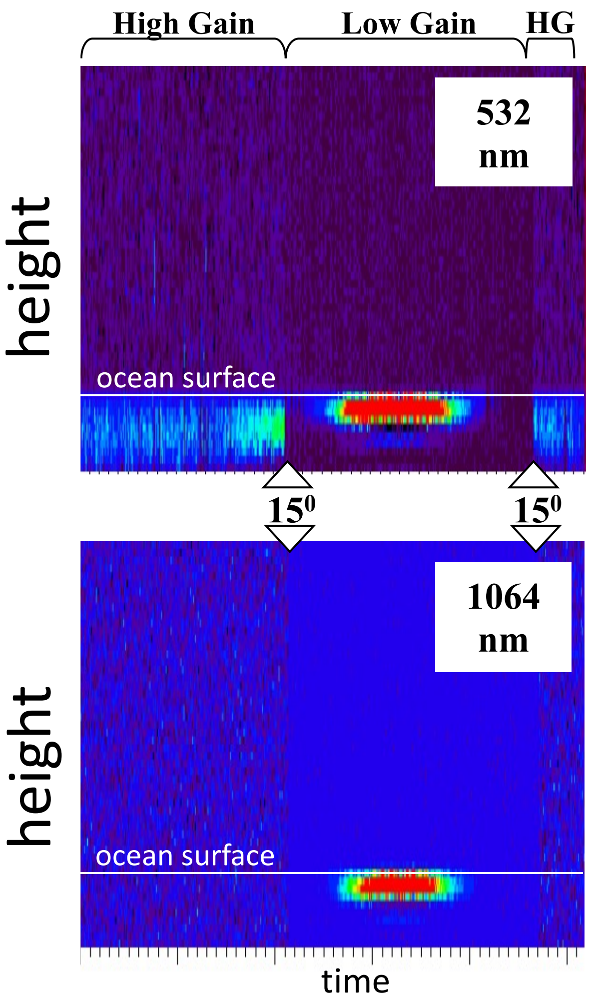
…can we do it from space?

Going to Space

Lidar In-space Technology Experiment (LITE)

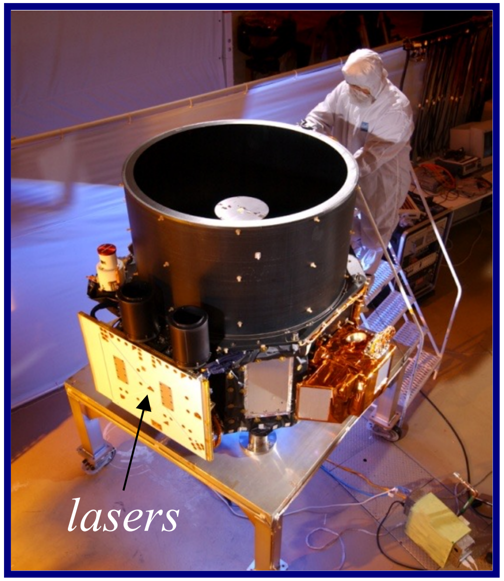
- Discovery Space Shuttle in September 1994
- 3-wavelength Nd-Yg lidar
- 1064 = 486 mJ; 532 = 460 mJ; 355 = 196 mJ
- Multi-angle (+/-30^0) maneuvers over Lake Superior and Gulf of California



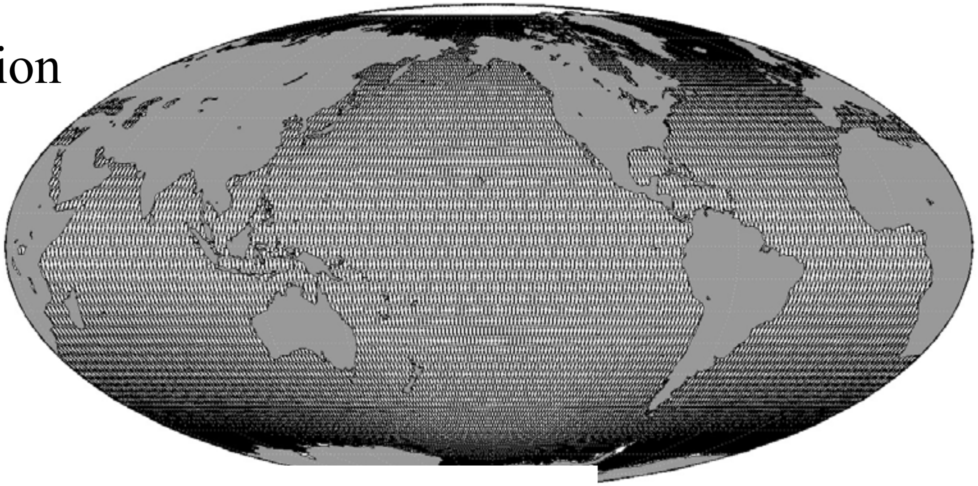


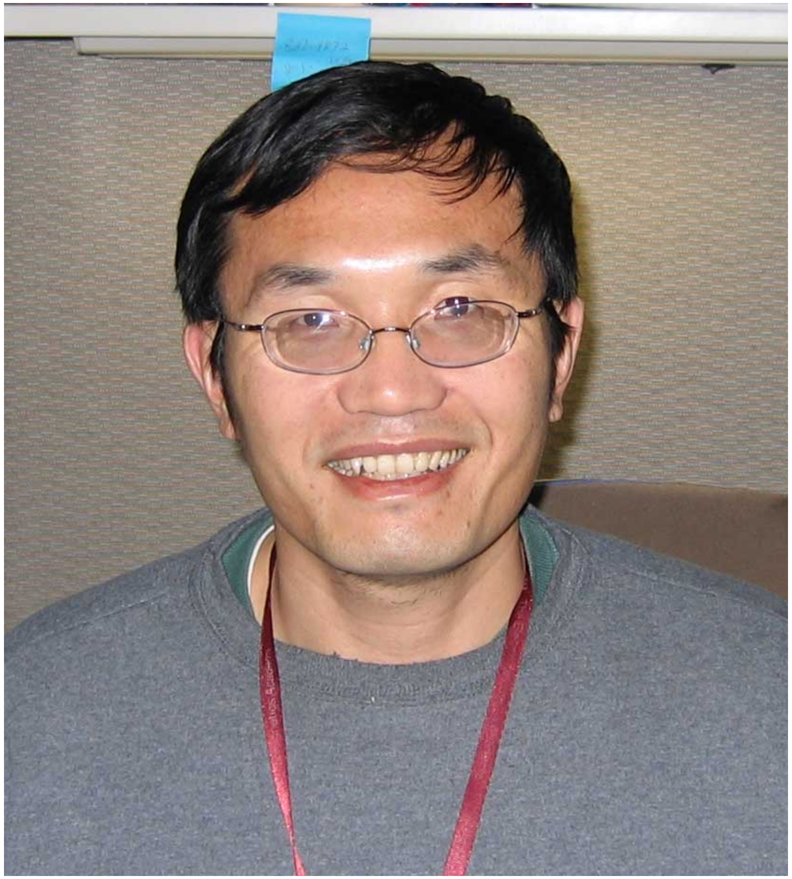
two important things then happened…

#1. Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP)



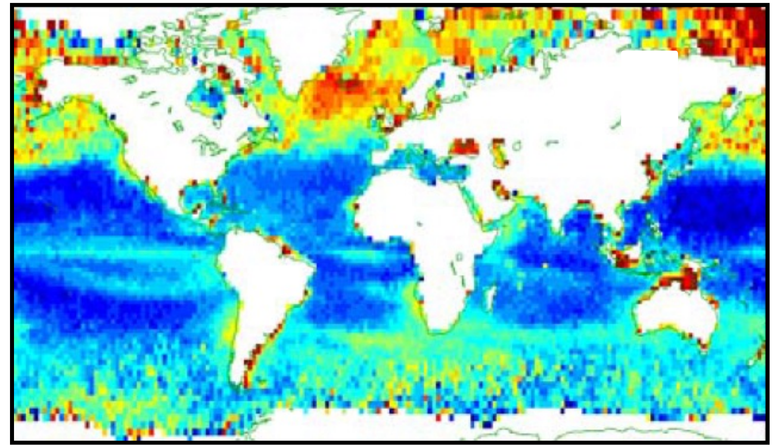
- NASA-CNES partnership
- launched April 28, 2006, still active
- definitively **NOT** designed for ocean applications
- 2-wavelength 110 mJ Nd:Yg laser (532, 1064 nm)
- 3-channel (532$\parallel$, 532 $\perp$, 1064 nm)
- 1 meter telescope
- 100 m footprint
- 30 m air / 23 m water vertical resolution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





#2. Yongxiang ‘Yong’ Hu

- OCRT 2007



$\log_{10} \beta_{W+}$ (sr^{-1})*

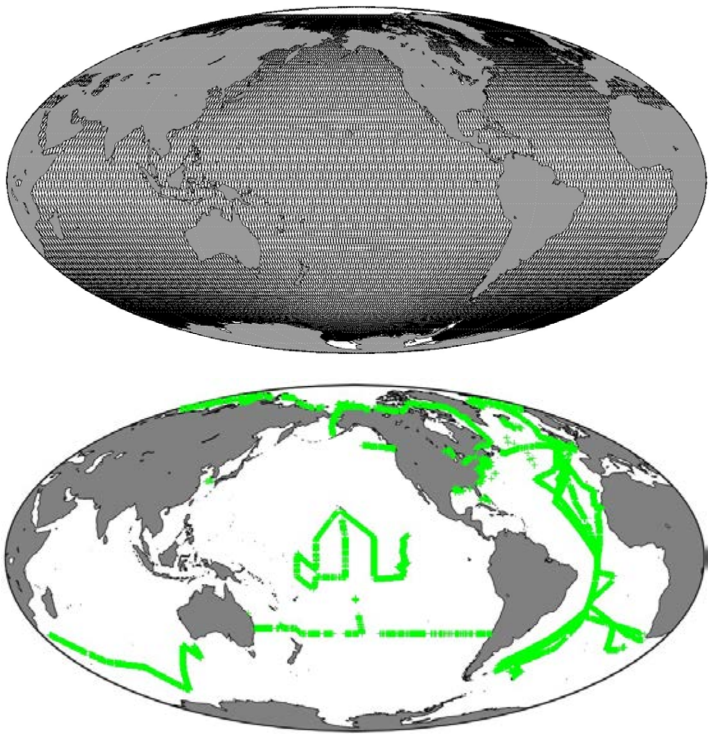
* β_{W+} = column integrated cross polarized ocean lidar backscatter

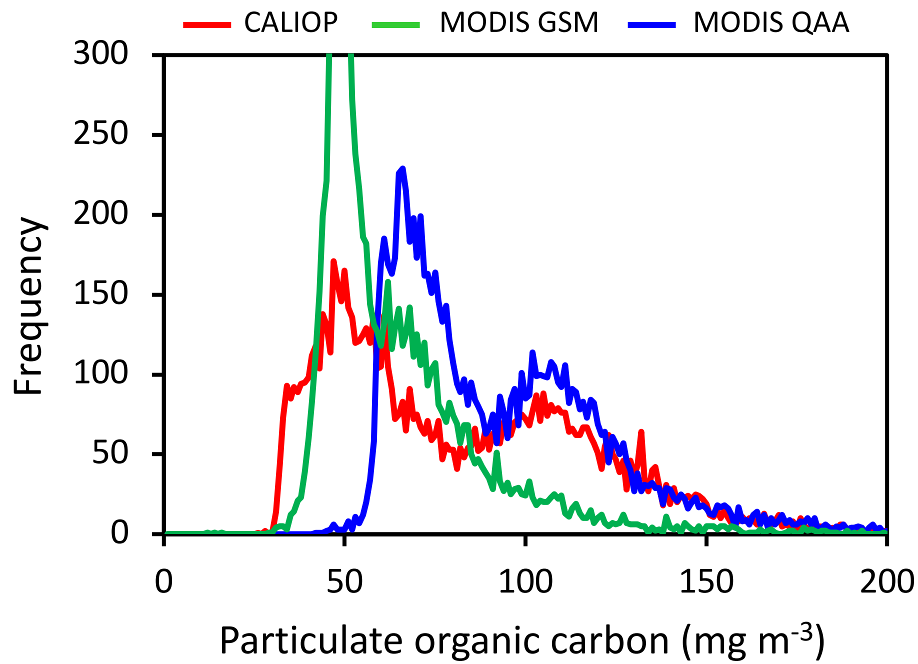
Churnside et al. 2013. *Rem. Sens.* 5:3457-75 (evaluate detection, MODIS comparison)

Behrenfeld et al. 2013 *Geophys. Res. Lett.* 40, 4355-60 (field val, geophysical prod’s)

Little bit o' science

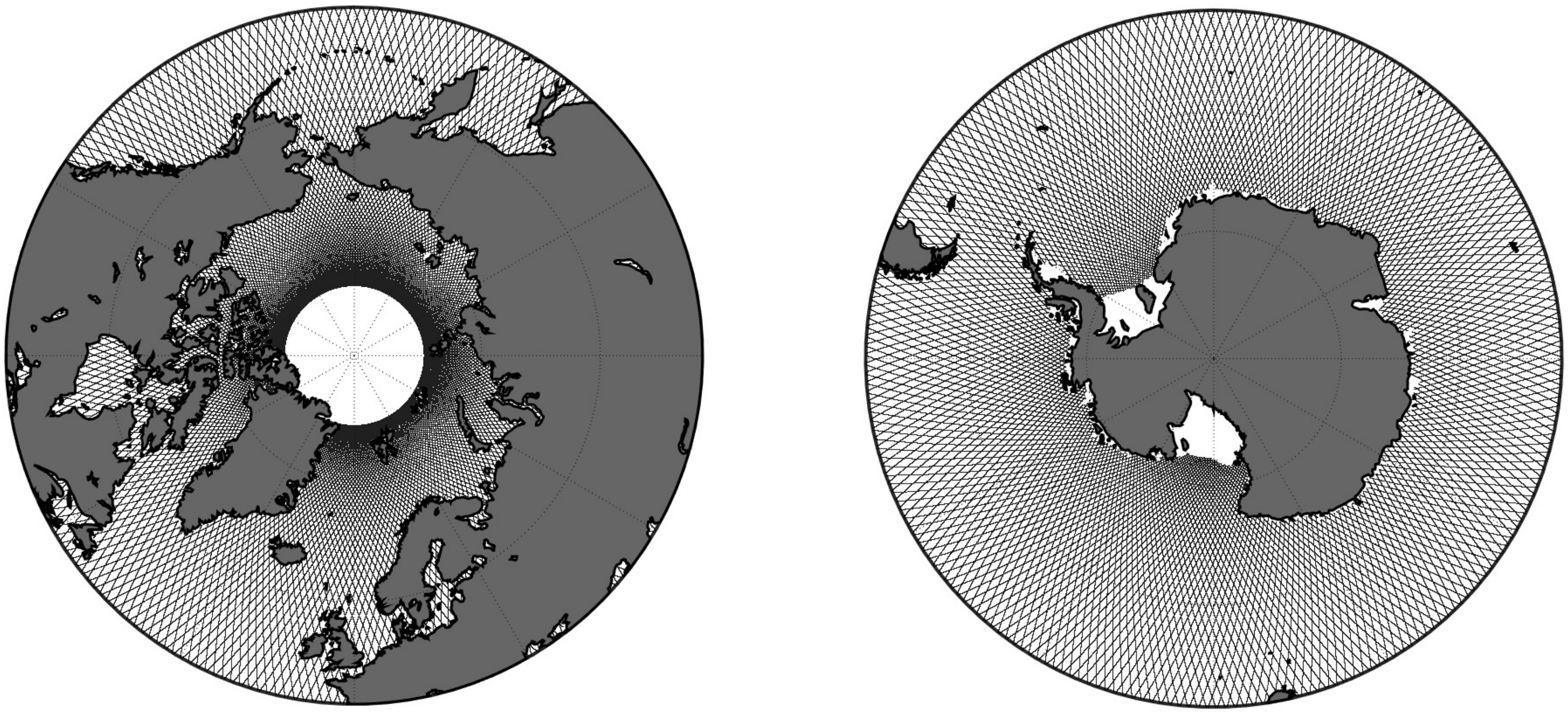
Plankton Stocks with a Satellite Lidar





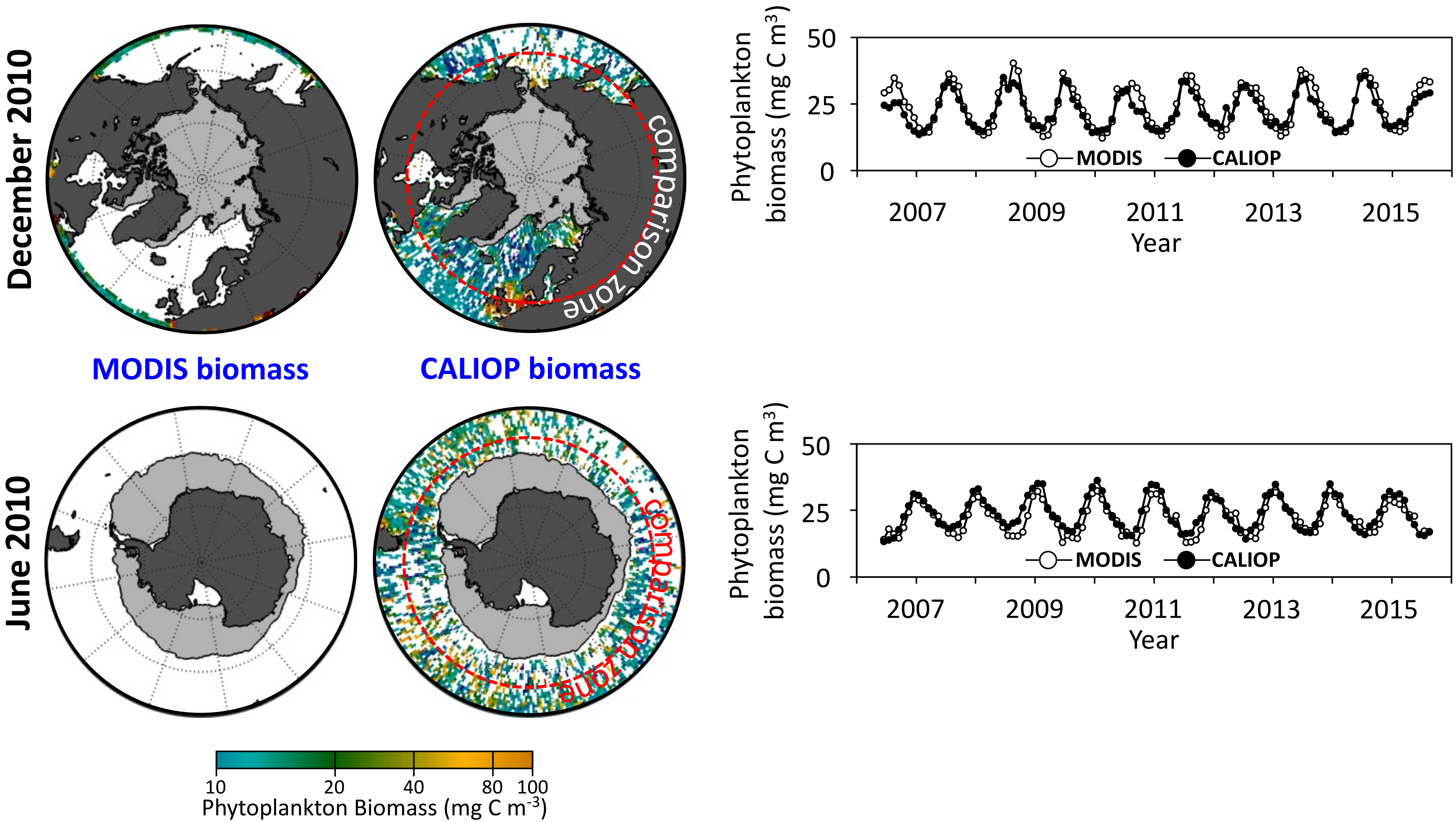
Behrenfeld et al. 2013 Geophys. Res. Lett. 40, 4355-4360

Polar Systems: Where Lidar Really Shines



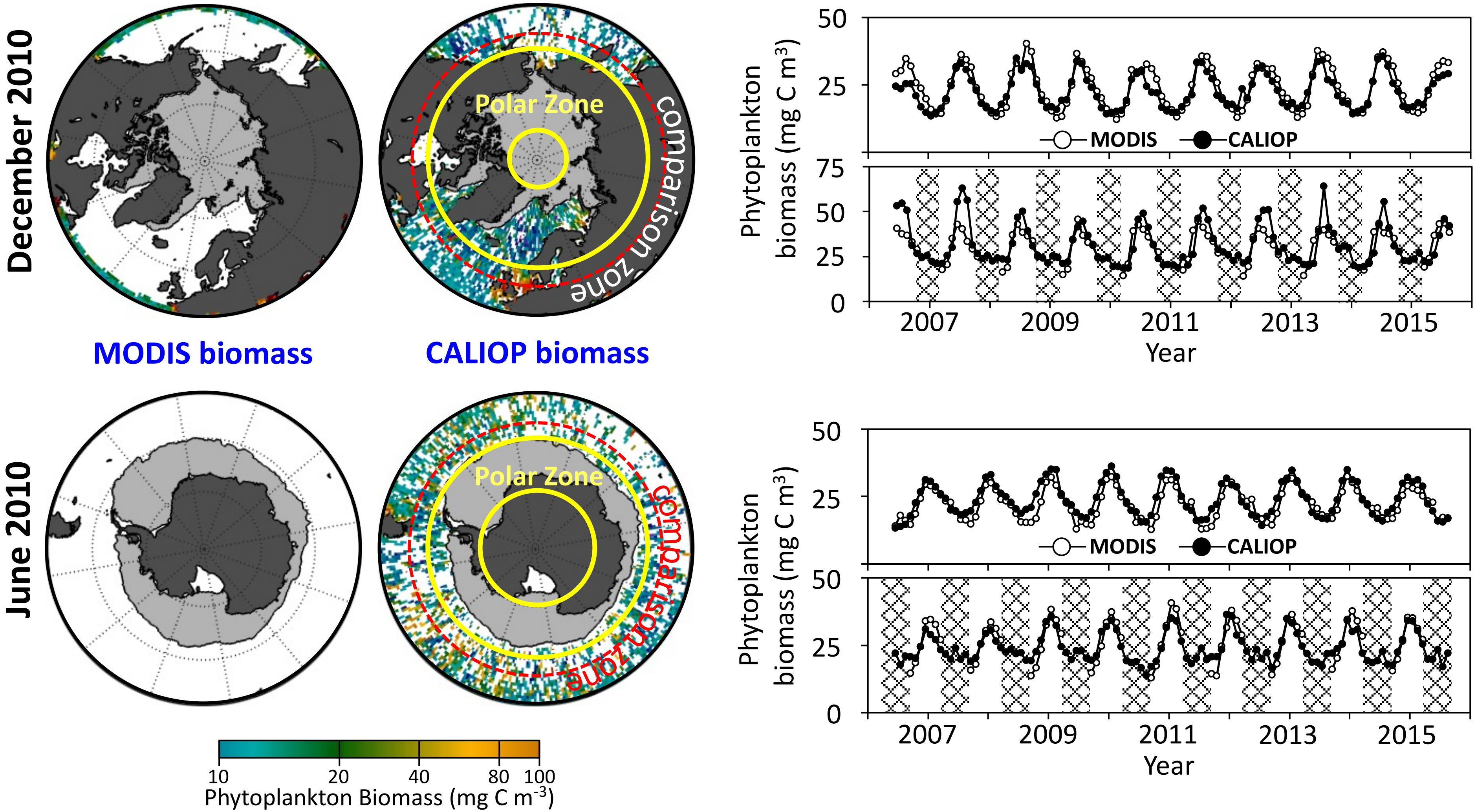
Behrenfeld et al. 2016 Nature Geoscience 19, 118-122

CALIOP Shines on Polar Ecosystems



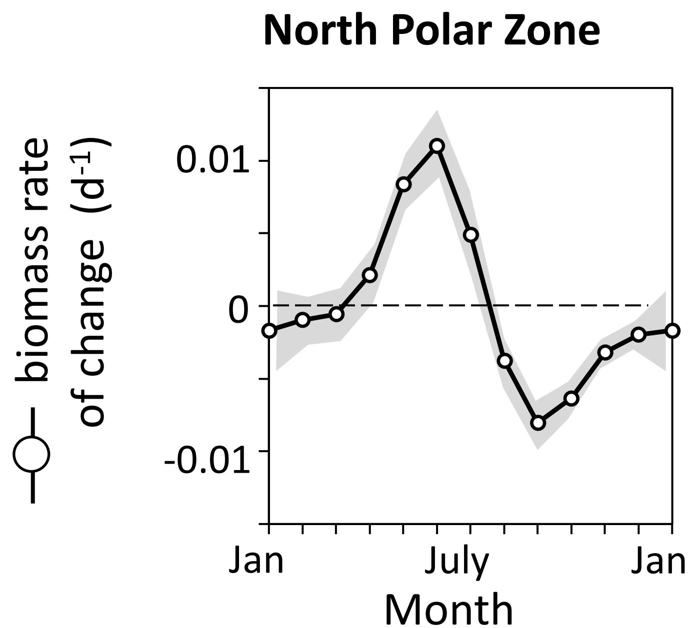
Behrenfeld et al. 2016 Nature Geoscience 19, 118-122

CALIOP Shines on Polar Ecosystems



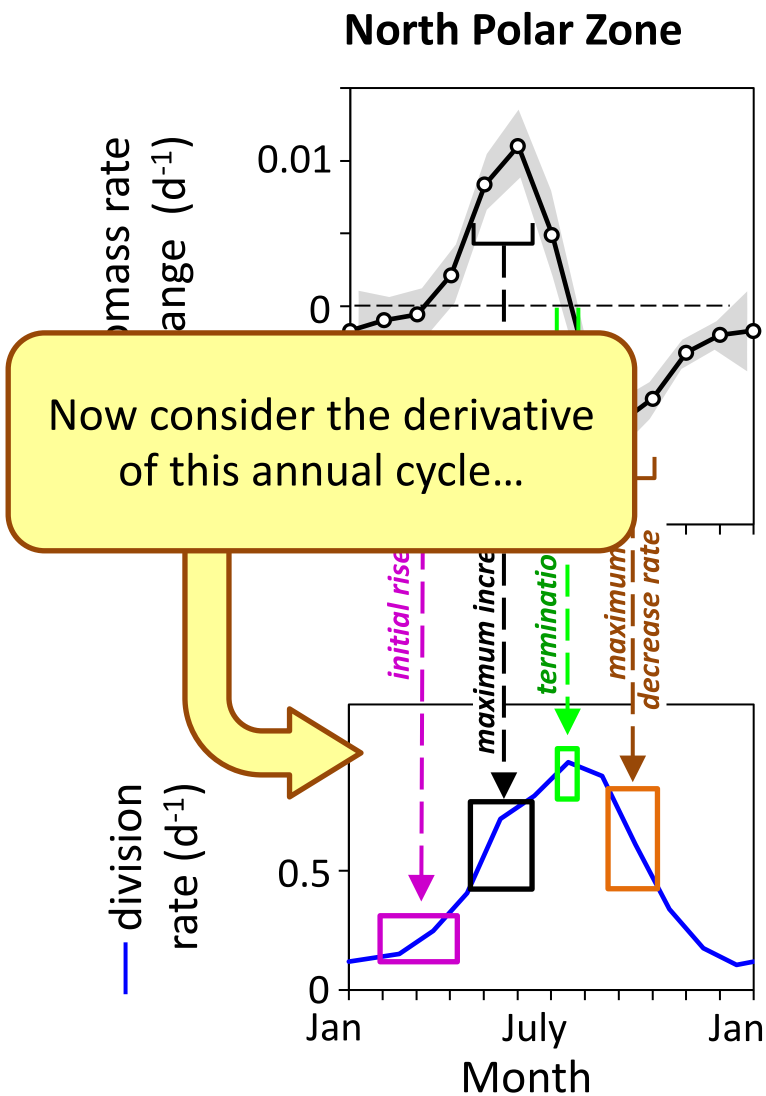
Behrenfeld et al. 2016 Nature Geoscience 19, 118-122

Polar Biomass Dynamics



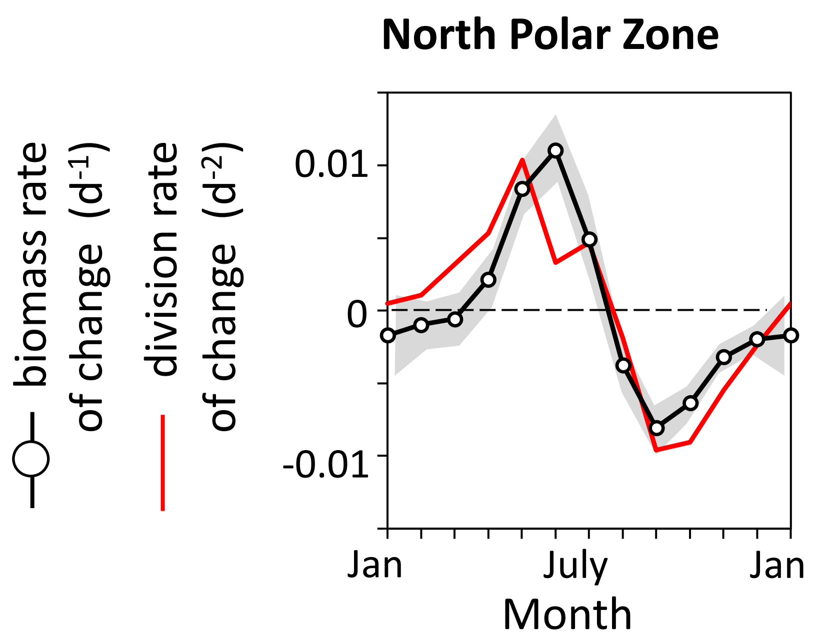
Behrenfeld et al. 2016 Nature Geoscience 19, 118-122

Polar Biomass Dynamics



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

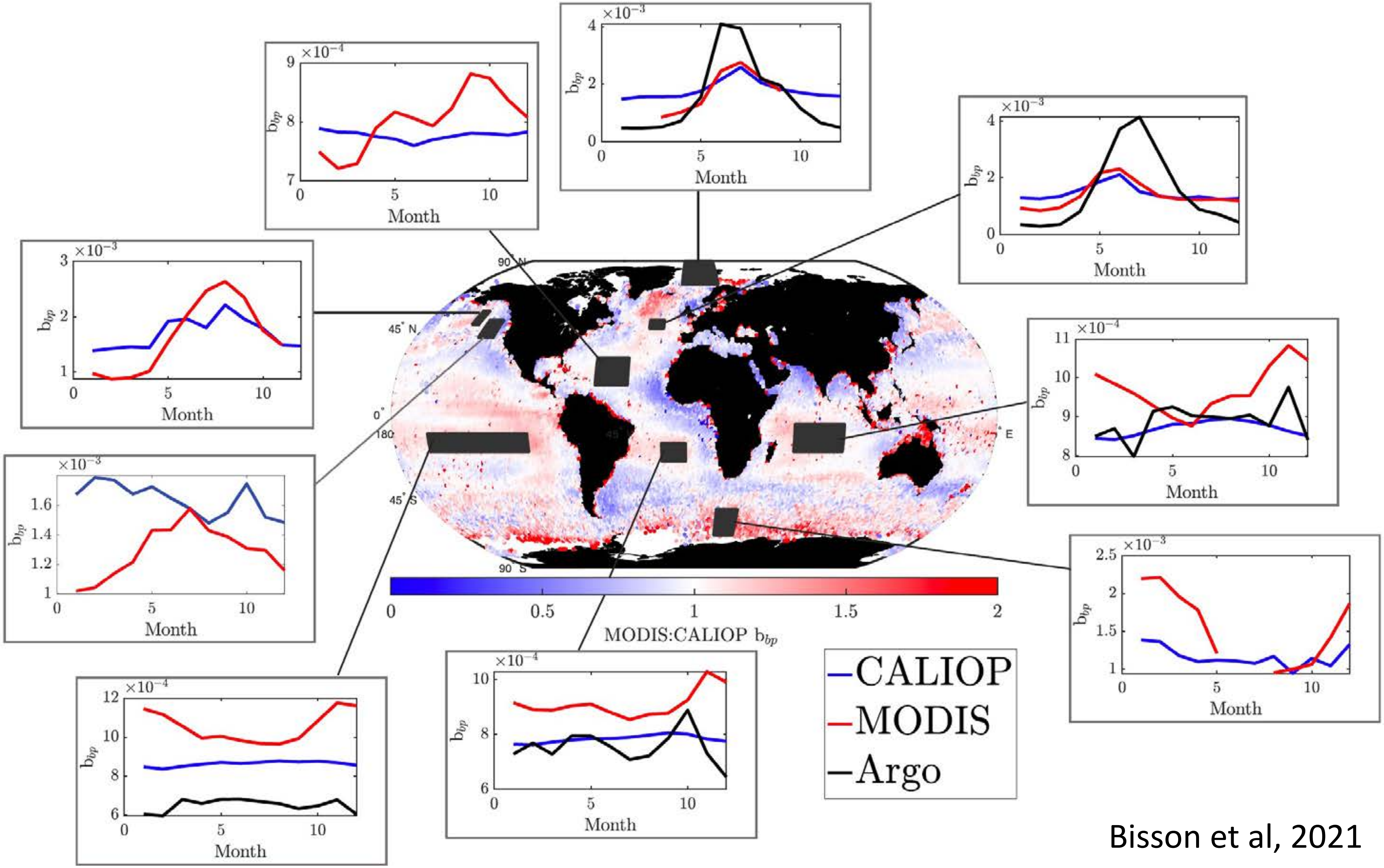
Polar Biomass Dynamics



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

An added value of a lidar – closure with radiometry. Backscattering comparisons (climatology):

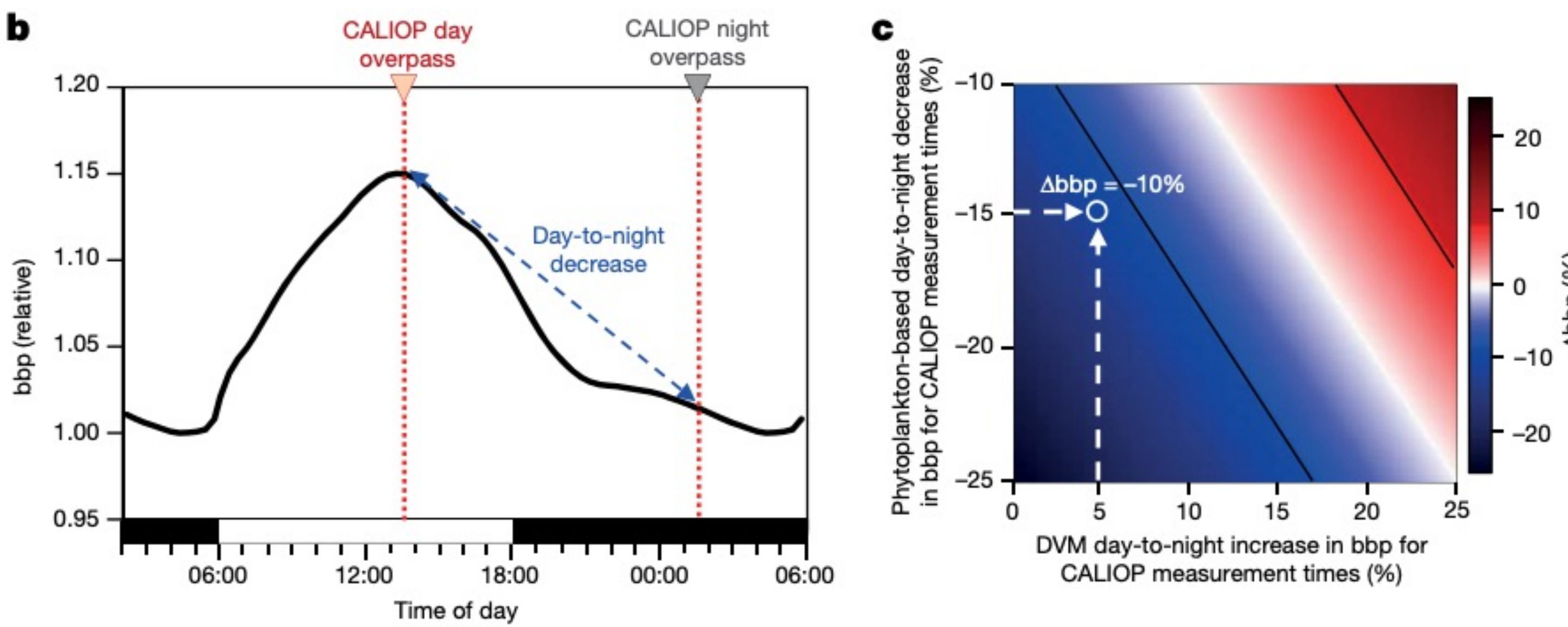


Bisson et al, 2021

From day and night data, one can get information on diel cycles:

Article

Global satellite-observed daily vertical migrations of ocean animals



Behrenfeld et al, 2019

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

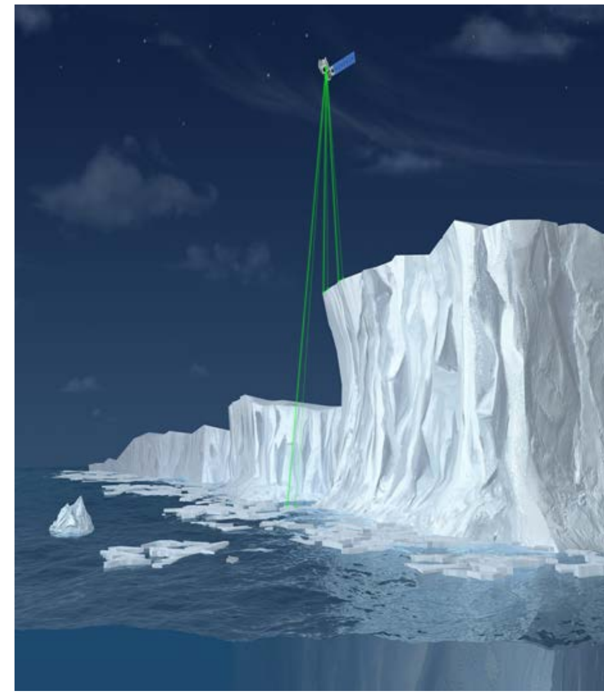
- CALIOP’s day and night data provide constraints on diel cycles.

ICESat-2

ICE, CLOUD, AND LAND ELEVATION SATELLITE-2

For additional questions, contact Kelsey Bisson (bissonk@oregonstate.edu)

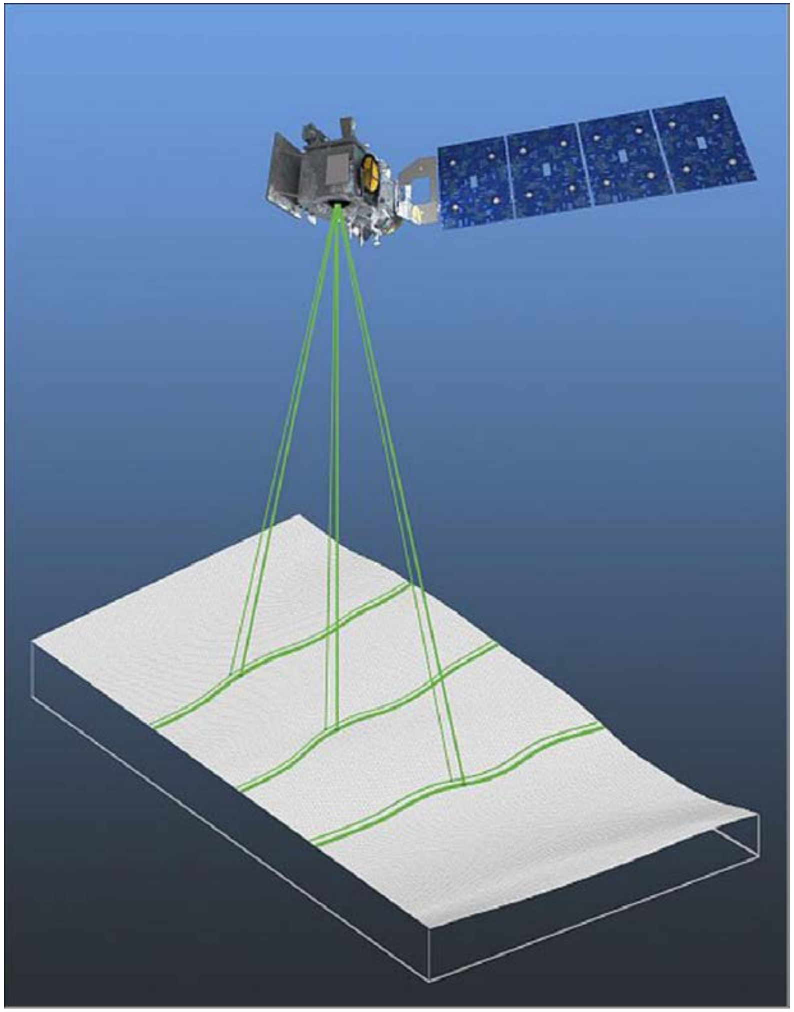
- Launched September 2018 by NASA to measure changes in ice thickness
- 532 nm laser pulses at 10 kHz from the nominal ~500 km fixed orbit.
- ICESat-2/ATLAS uses photomultiplier tubes (PMTs) as detectors in photon counting mode where single photons reflected from the Earth's surface will trigger a detection within the ICESat-2 receiver.
- **Each individual photon is time tagged and geolocated.**

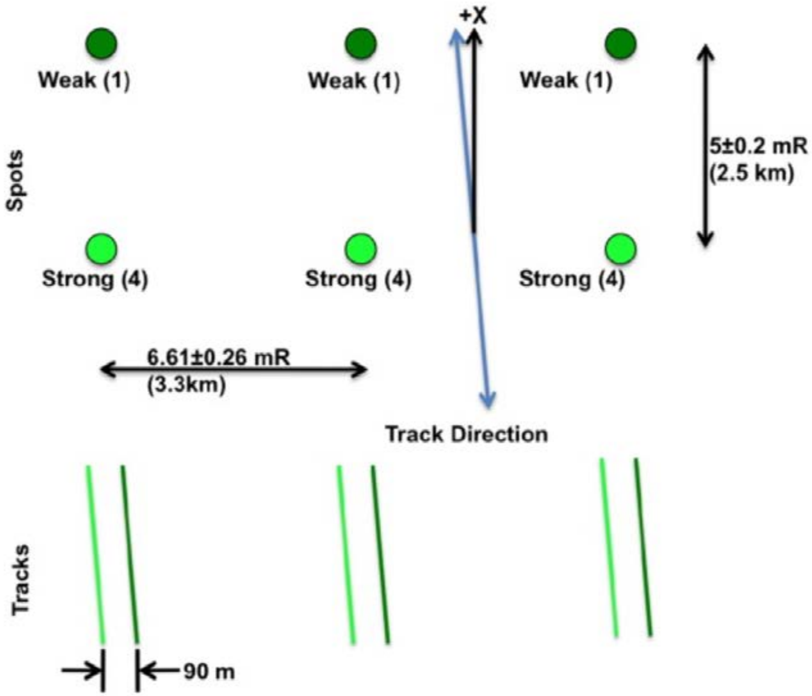


$$S(z) = C\beta'(\pi, z)exp(-2\alpha z)$$

- The subsurface signal in the ocean is given by the basic lidar equation, where C is a calibration constant, α is equal to the attenuation coefficient of photons with depth (z)

ICESat-2 sampling geometry





- The beam pattern is a 3 × 2 array that creates three pairs of beams on the ground.
- Separation for each pair is 90 m but this can be changed on orbit by changing the yaw angle.

Markus et al, 2017

Ocean applications

- **Subsurface blooms & vertical structure**

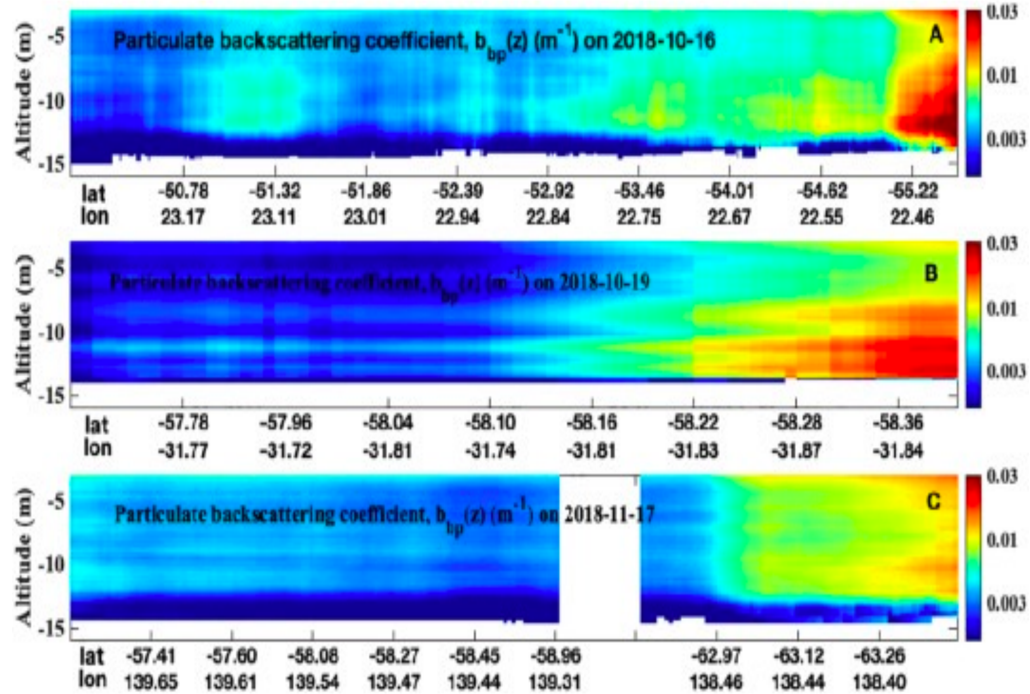
Particulate backscattering (b_{bp}) in the ocean in 3 sites (A,B,C, right) in the Southern Ocean (Lu et al., 2020)

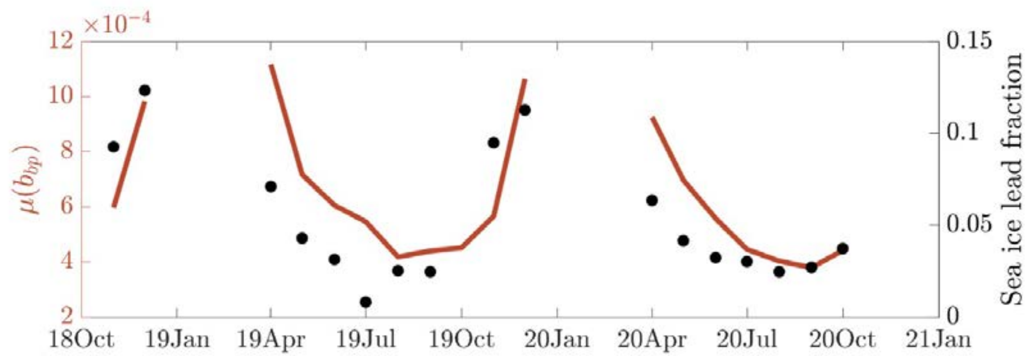
- **Ice/ phytoplankton interactions**

ICESat-2 identifies leads in sea ice, which are compared with monthly under ice b_{bp} from Argo floats to examine the influence of sea ice on phytoplankton characteristics under ice (Bisson and Cael, in review, right bottom)

- **Sea surface height / physical oceanography**

Stay tuned for work & prelim results from Andy Thompson!



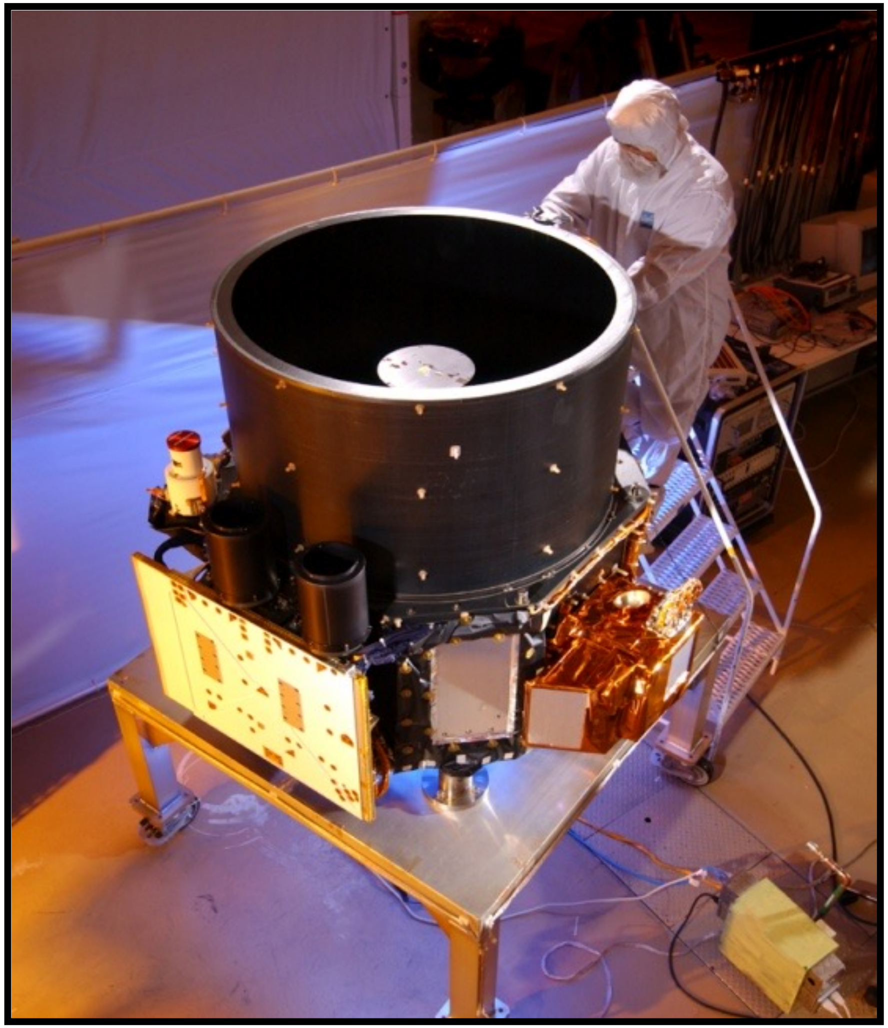


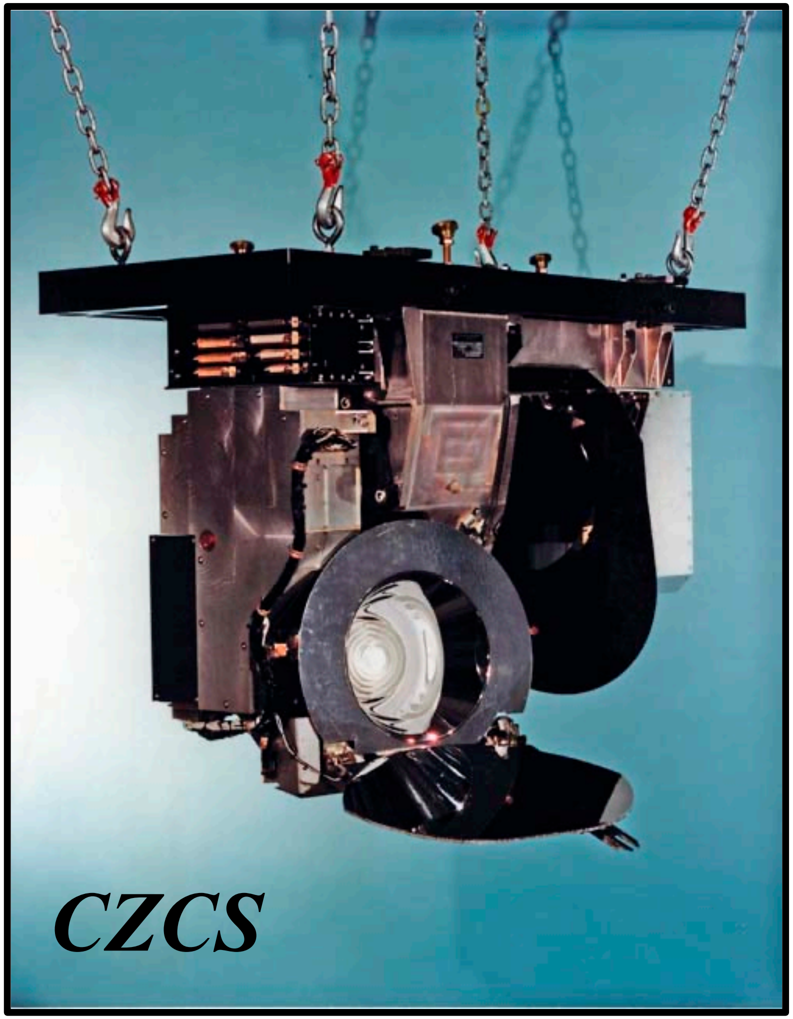
** Note – data are not limited to the poles, and are available everywhere at https://nsidc.org/data/atl03

Open access software to process data: https://github.com/icesat2py/icepyx

But, there is a problem…

'Proof-of-Concept'



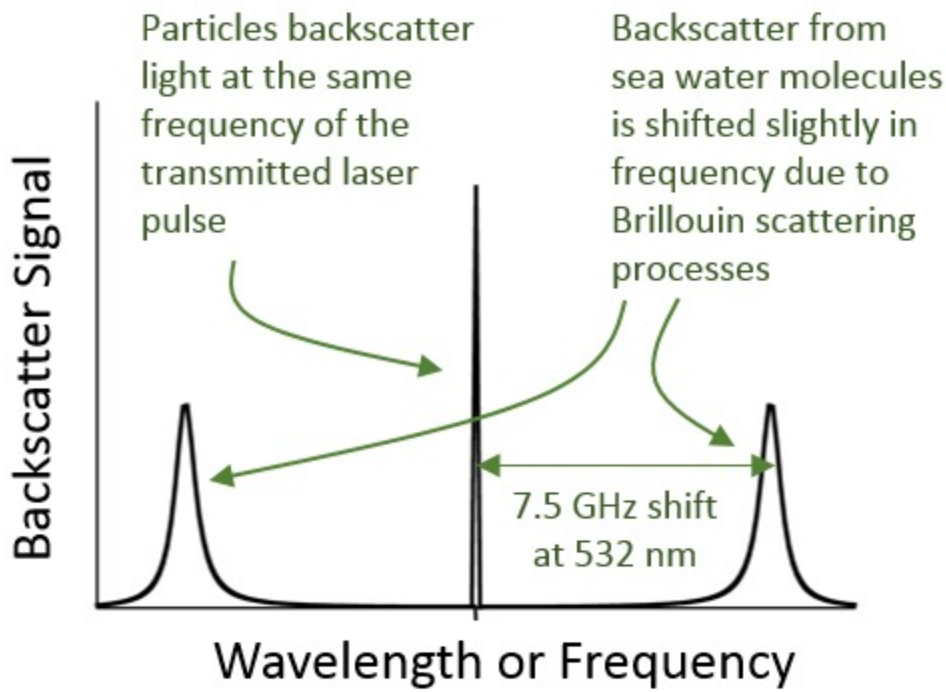


Simple Elastic Backscatter Lidars (e.g., CALIOP)

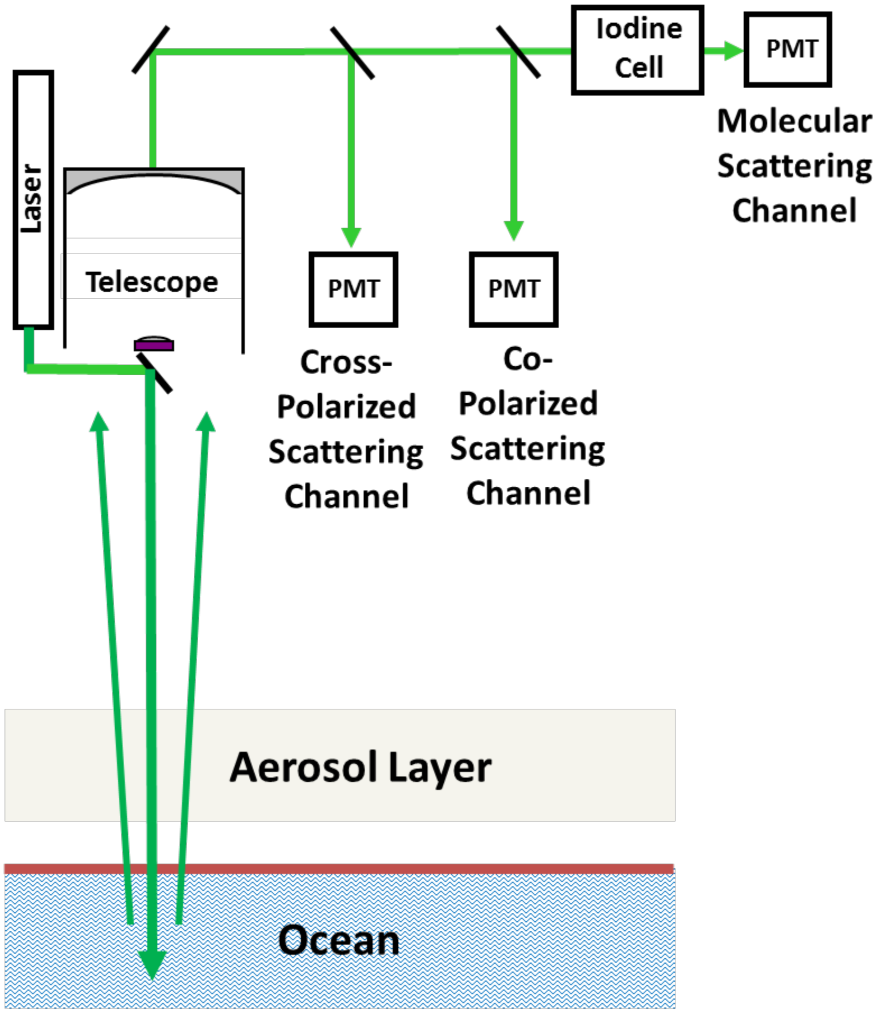
- An ‘ill-posed problem’: 1 measurement (attenuated backscatter), 2 unknowns (b_{bp}, k_d)
- Ancillary data and/or bio-optical assumptions required to solve, with large potential errors
- Retrieval starts from top of profile and attenuation is removed at each level by assuming an extinction-to-backscatter 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 …

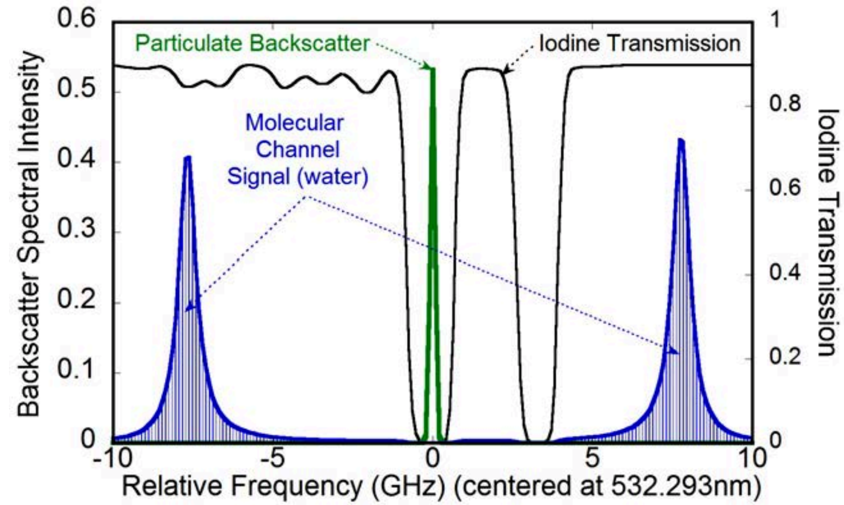
… **can this be done?**

High Spectral Resolution Lidar (HSRL)



High Spectral Resolution Lidar (HSRL)





- Laser tuned to I_2 absorption line
- Can also use interferometer
- Particulate backscatter blocked from “Molecular Channel”

High Spectral Resolution Lidar (HSRL)

- A ‘well-posed problem’: 2 measurement, 2 unknowns (b_{bp}, k_d)

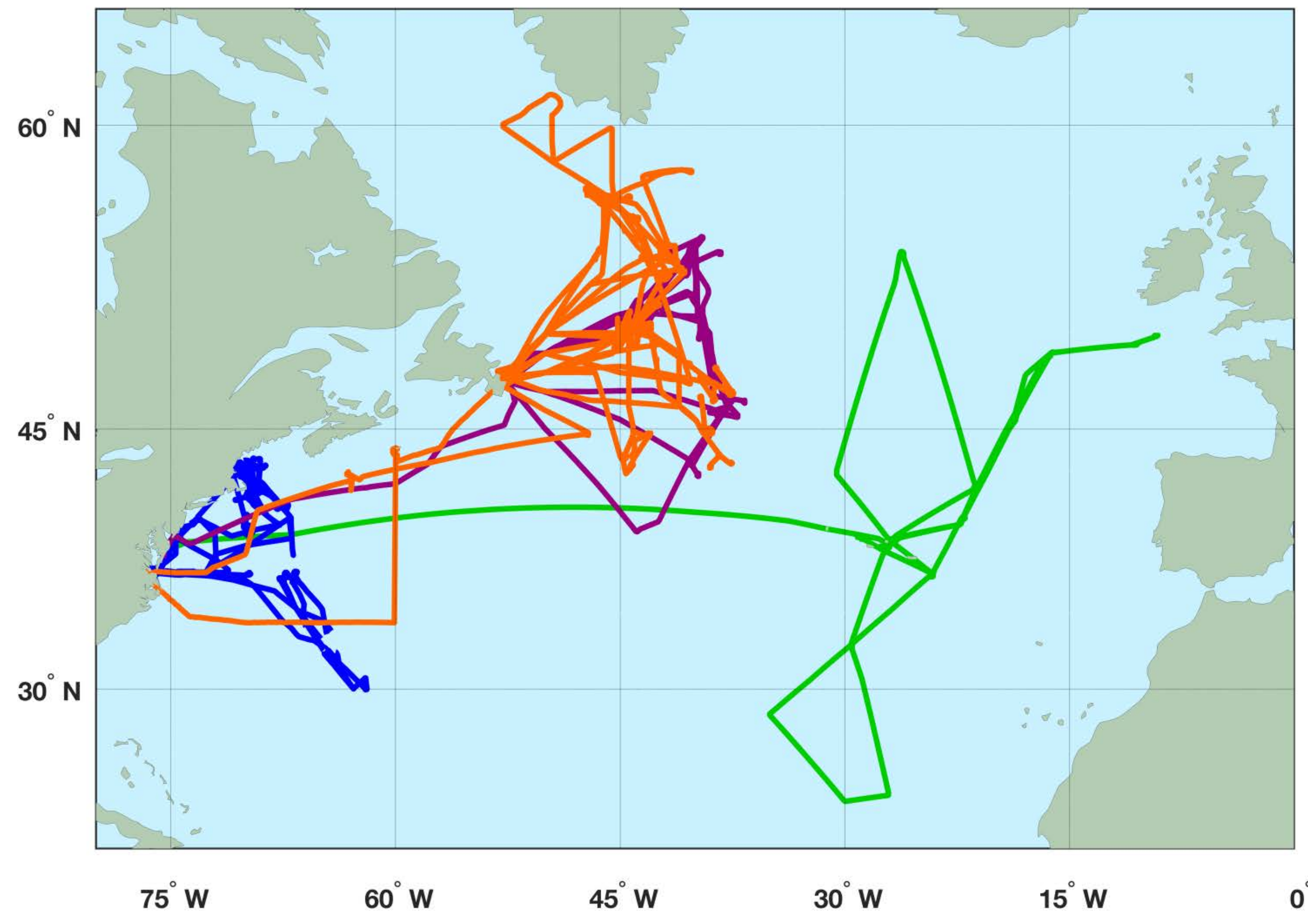
$$S_M(z) = \beta_M \exp\left[-2\int_0^z K_d(z')dz'\right](Atmos.Transmission)^2$$

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

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

$$\beta_P(z) = \beta_M\left[\frac{S_P(z)}{S_M(z)}\right]$$

Ocean Retrievals with HSRL



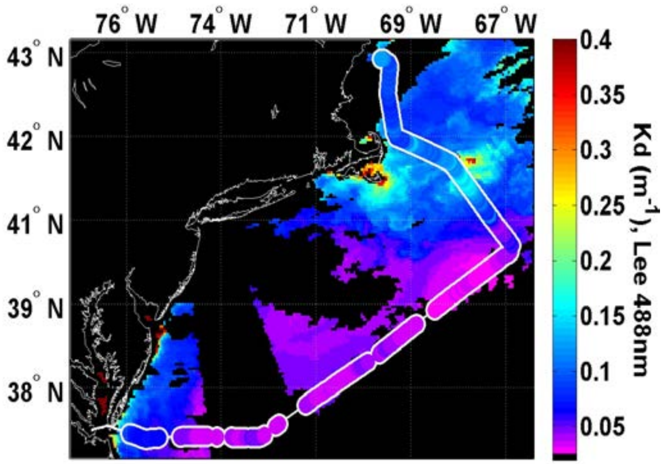
= 2012 Azores/AMT campaign

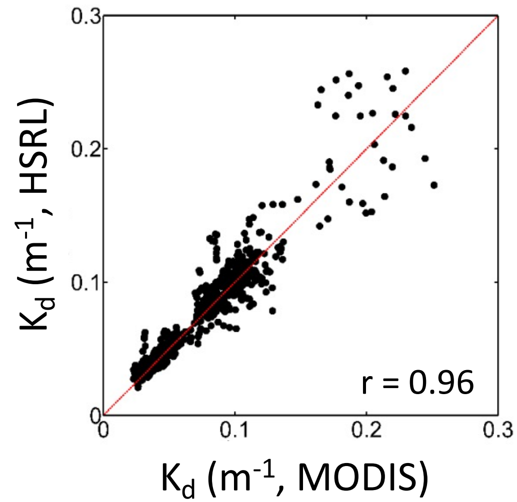
= 2014 NASA SABOR campaign

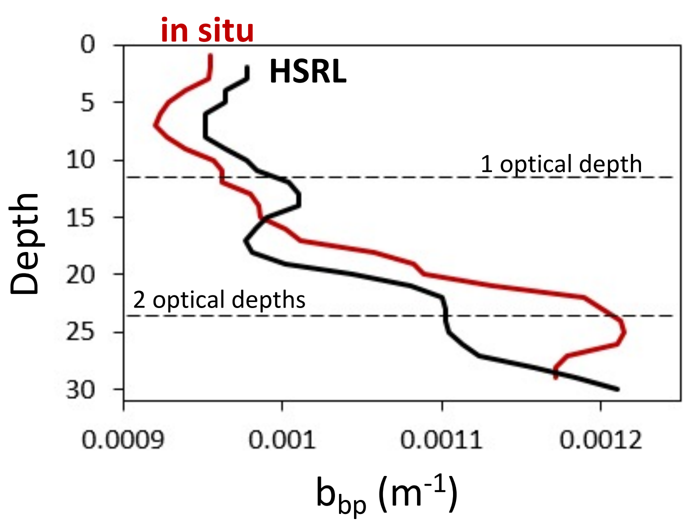
= 2015 NASA NAAMES 1 campaign

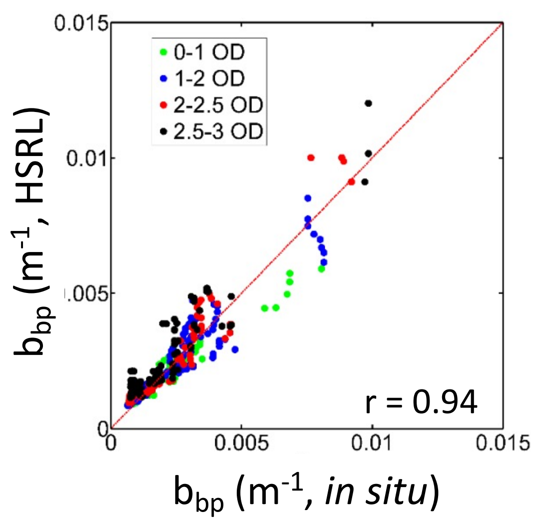
= 2016 NASA NAAMES 1 campaign

Ocean Retrievals with HSRL





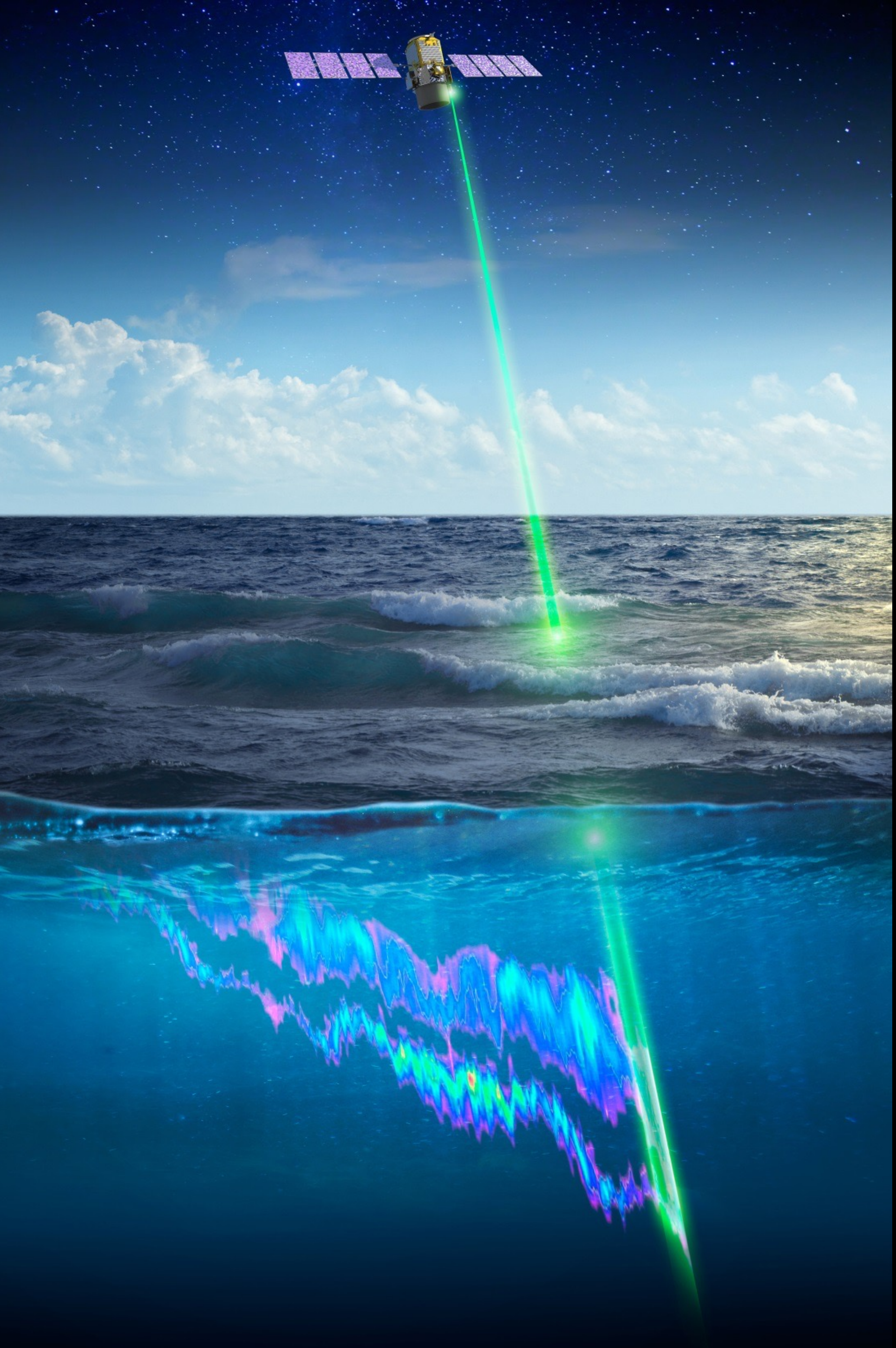




Key Points

- 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 ΣNPP >50% for SABOR (other studies > 100%)

Data from John Hair (NASA LaRC) & *Schulien et al. 2017.*



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)

	Capability	Value to Ocean Science
CALIOP Plus	<3-m vertical resolution	• 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	HSRL at 532 nm Depolarization at 1064 nm	• Calibrated through profile • Well-posed retrieval of b_{bp} & K_d • Improved geophysical products • Independent of ocean color and optical modeling
Plus	Chl Fluorescence	• Chlorophyll concentration (night) • Nonphotochemical Quenching • Iron stress
Plus	HSRL at 355 nm Depolarization at 355 nm	• 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

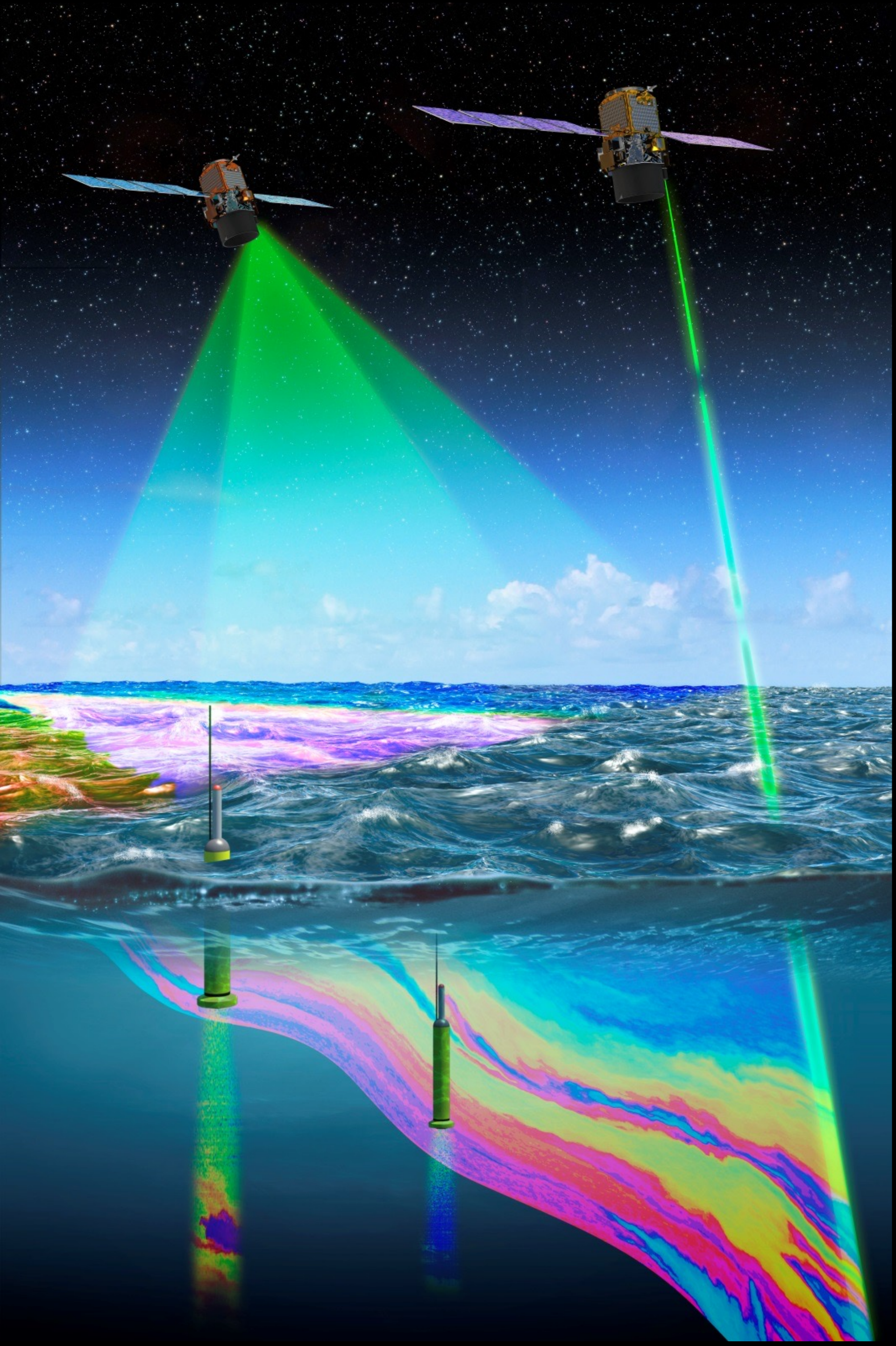
Entry requirement for ocean research (CALIOP Plus)

Minimal additional cost to mission (Plus rows)

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, photo-protection)
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…



Future Constellation

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*