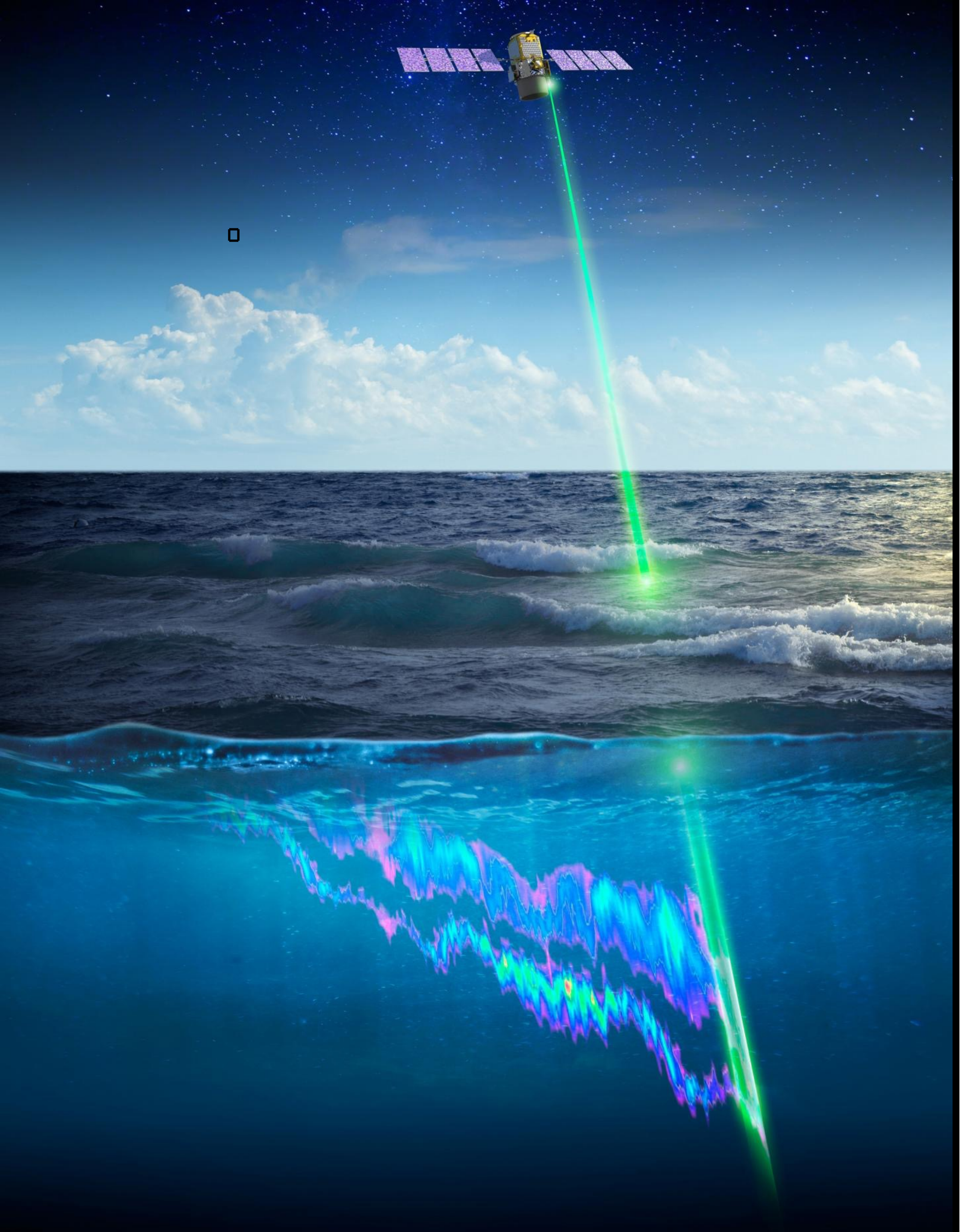
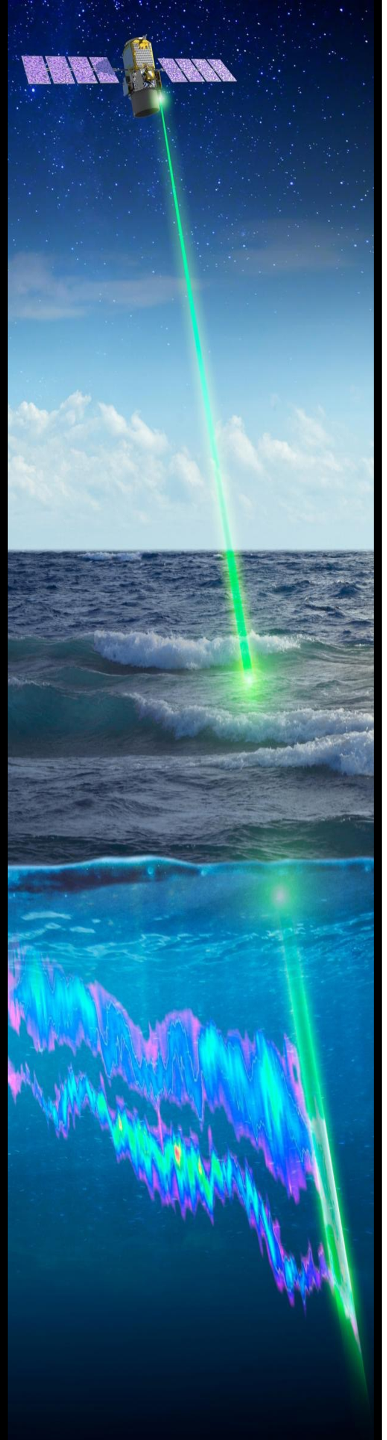


Lidar

for ocean studies

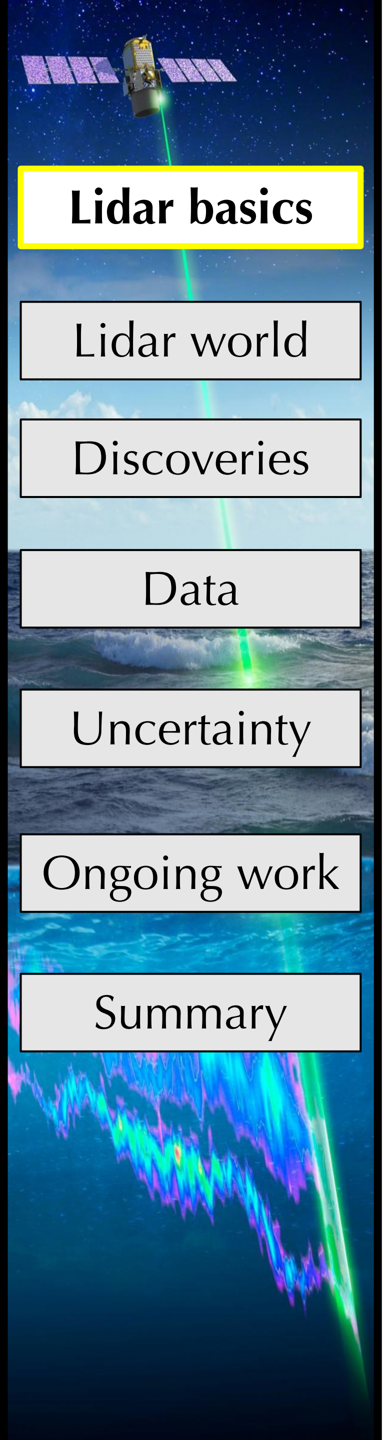
Kelsey Bisson
Assistant Professor Sr Research
Oregon State University

Ocean Optics Class 2023
Ocean Optics 2015 Alumni



Plan for today

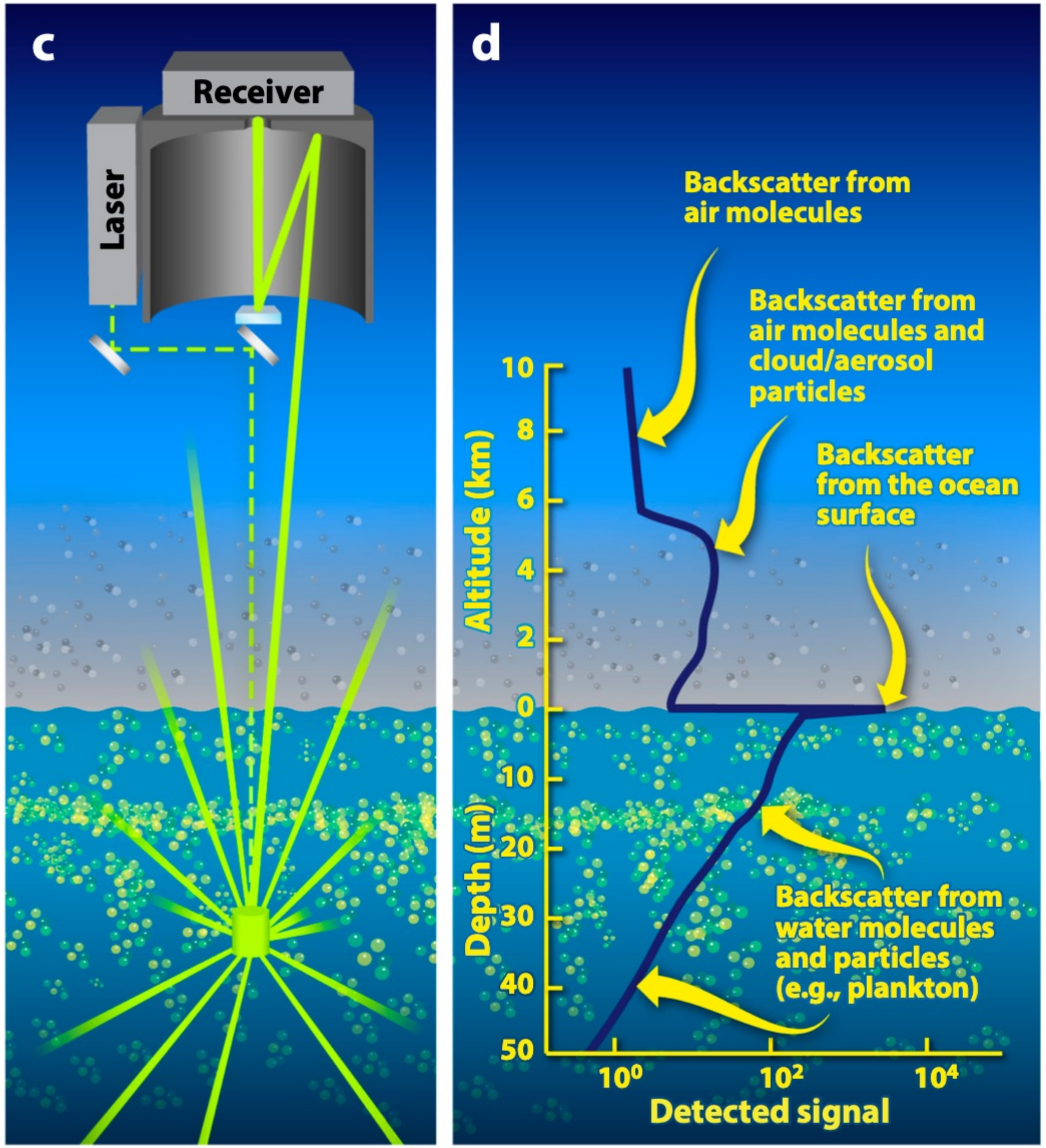
- Lidar basics
- What does our world look like under lidar?
- What discoveries have we made?
- Data availability and processing
- Sources of uncertainty
- Ongoing work
- Summary and advice for future studies



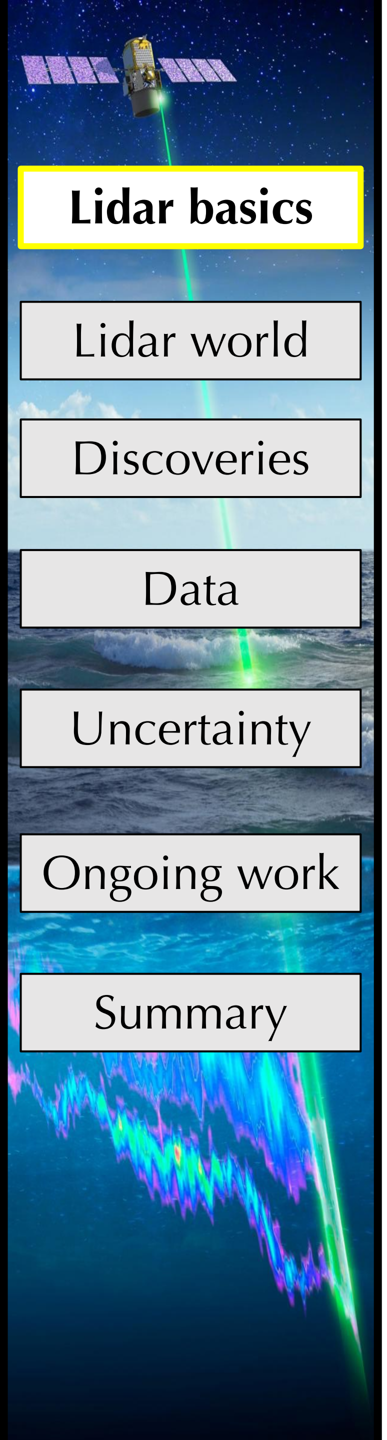
Light Detection And Ranging (LiDAR)

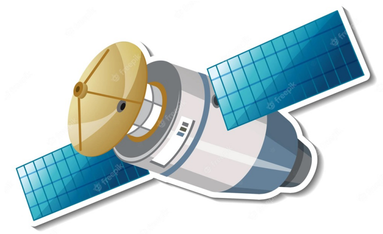
- Active measurement: Emits photons and measures distance (height) using time of travel & speed of light
- Vertical resolution is f(photon frequency)
- b_{bp} in water can be calculated whereafter phytoplankton carbon can be derived (using Cphyto empirical relationships)

No dedicated ocean lidar satellite in orbit (yet!!)



Hostetler et al., 2017

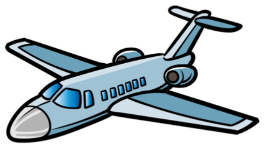




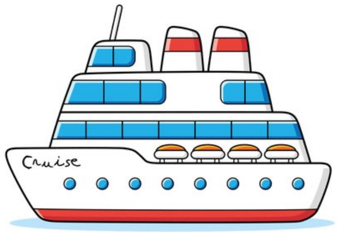
CALIPSO (2006) and ICESat-2 (2018)

Cloud-Aerosol
Lidar and Infrared
Pathfinder
Satellite
Observation

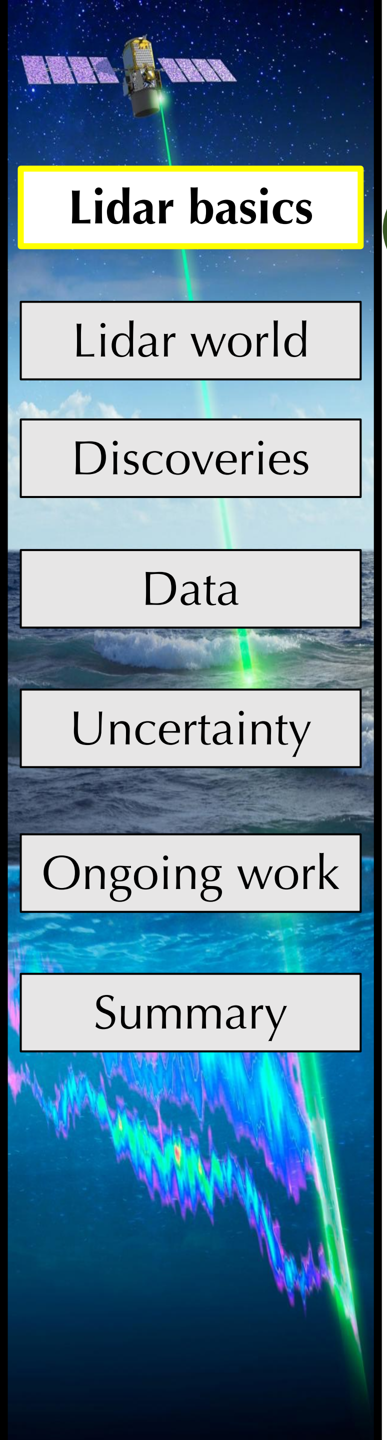
Ice, Cloud and land
Elevation Satellite

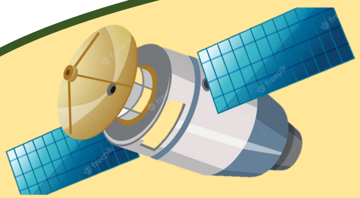


Used for decades to study the oceans (pioneering work by Churnside and others)



Can measure laser induced fluorescence, wavelength shifted Raman scattering, polarization properties



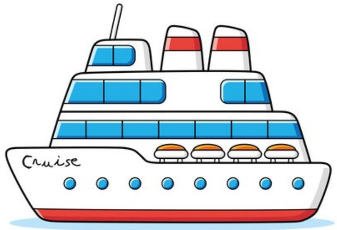


CALIPSO (2006) and ICESat-2 (2018)

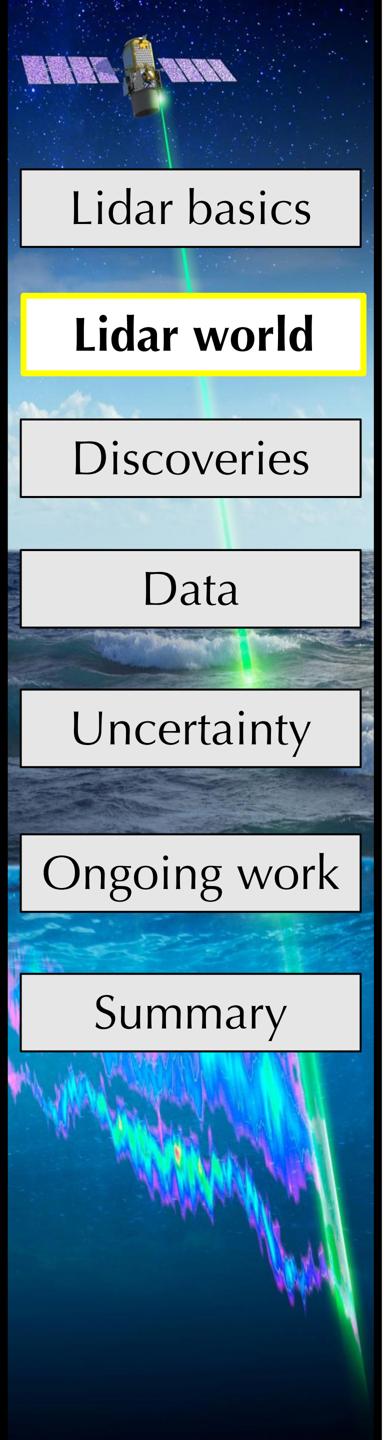
Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation

Ice, Cloud and land Elevation Satellite

Used for decades to study the oceans (pioneering work by Churnside and others)



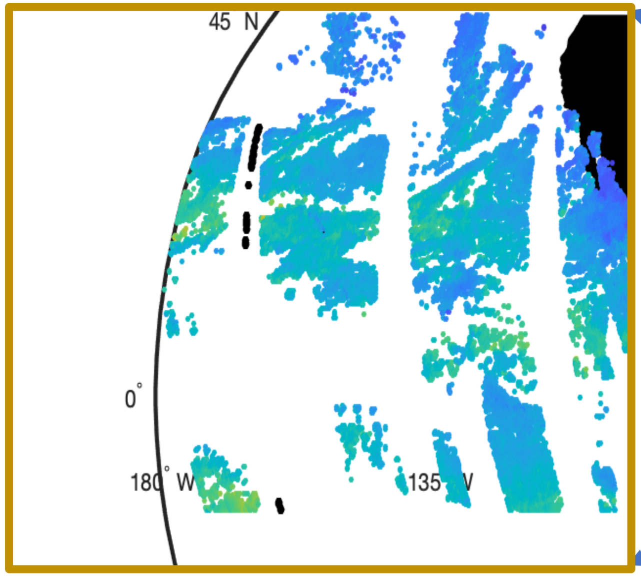
Can measure laser induced fluorescence, wavelength shifted Raman scattering, polarization properties (look for work by Brian Collister and others)

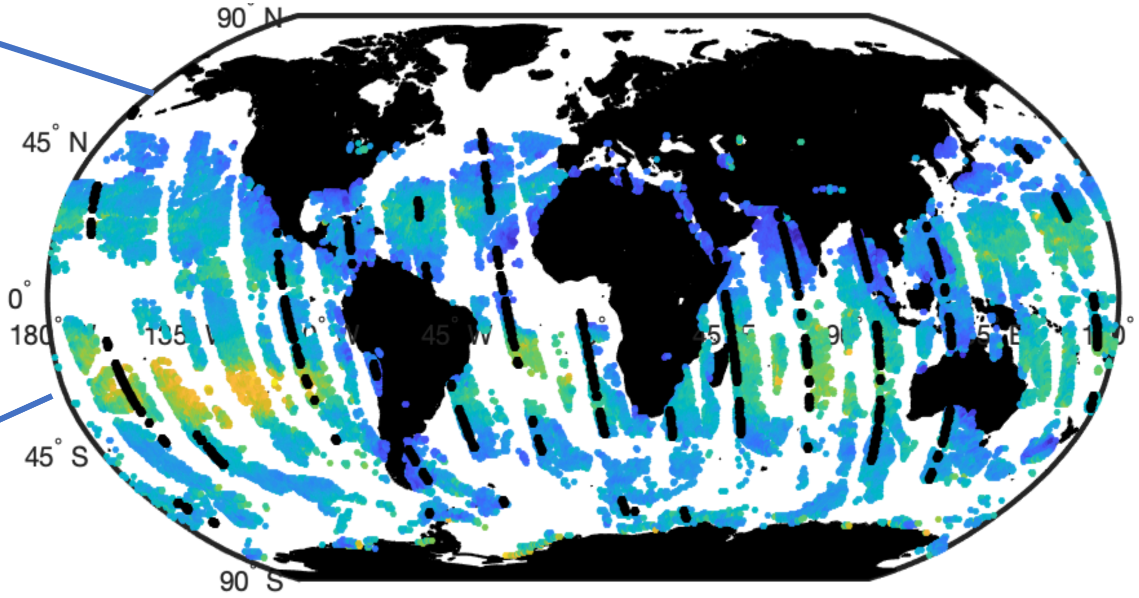


What does the world look like from a lidar perspective?

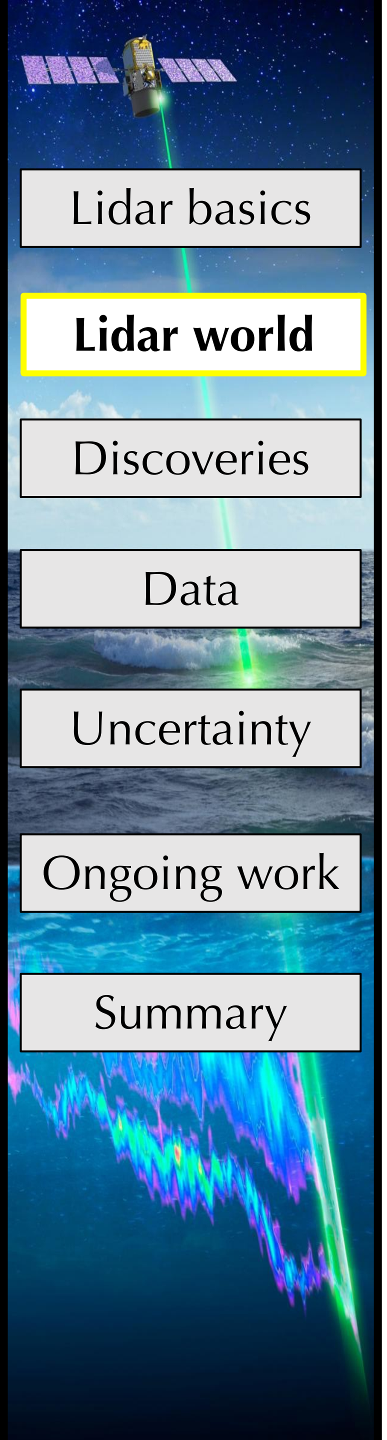
SPATIAL COVERAGE

1 day global coverage comparisons with MODIS-Aqua (passive satellite)



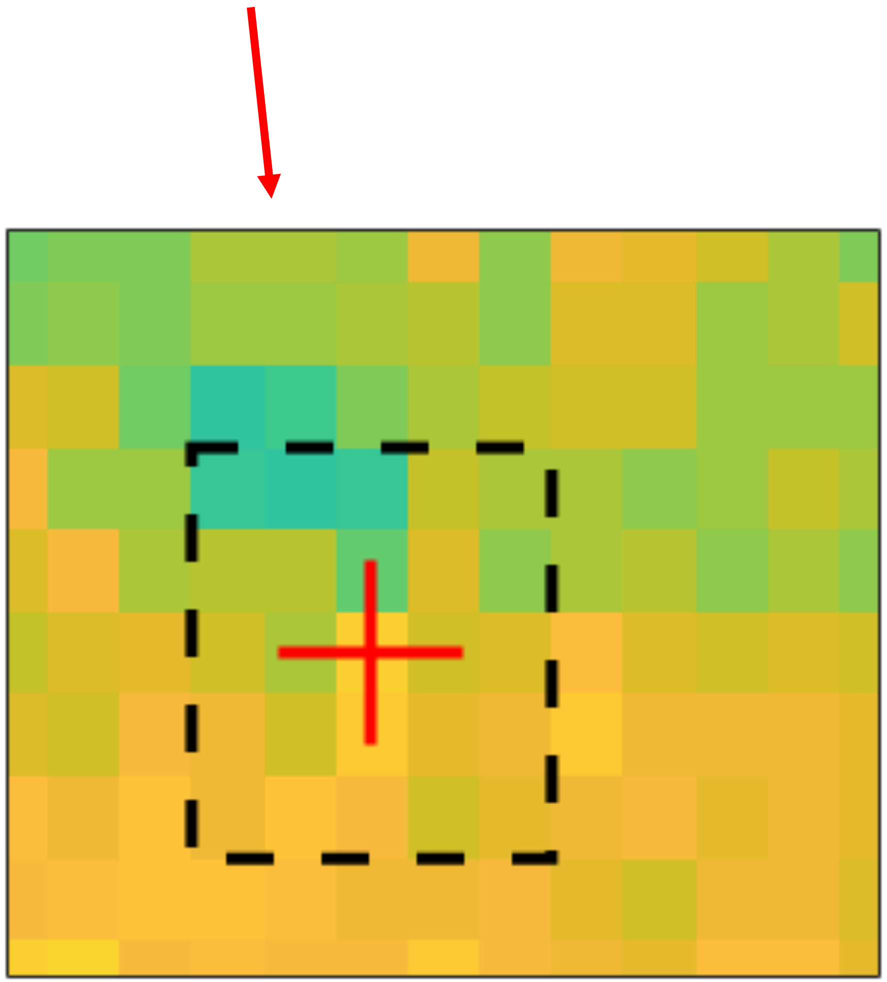


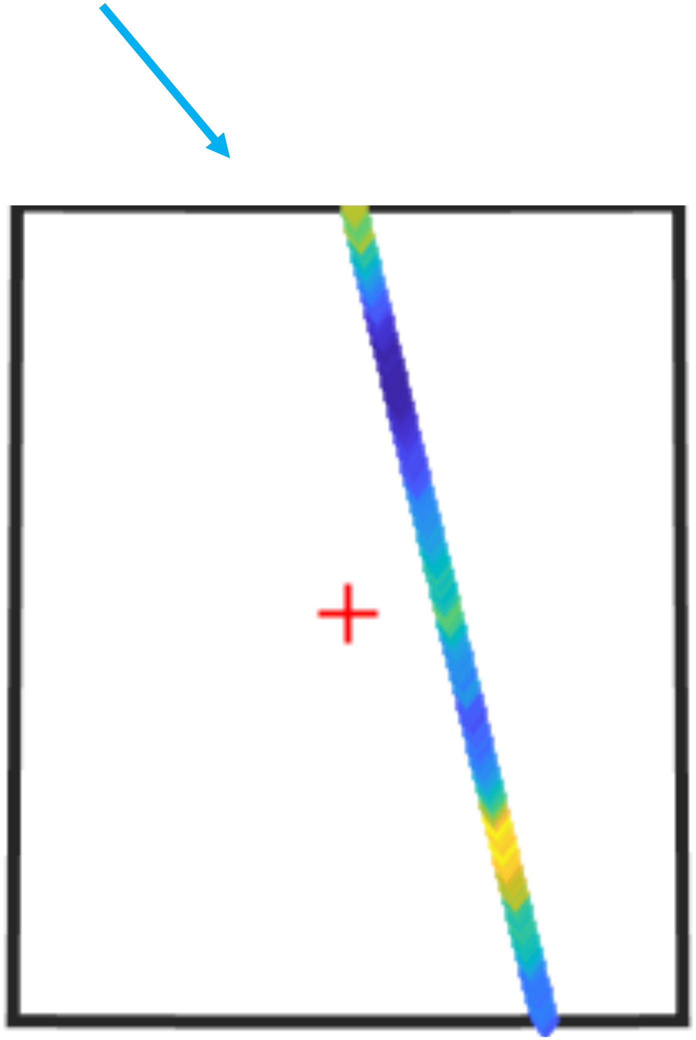
Lidar b_{bp} is in **black**, MODIS b_{bp} is **colored**.

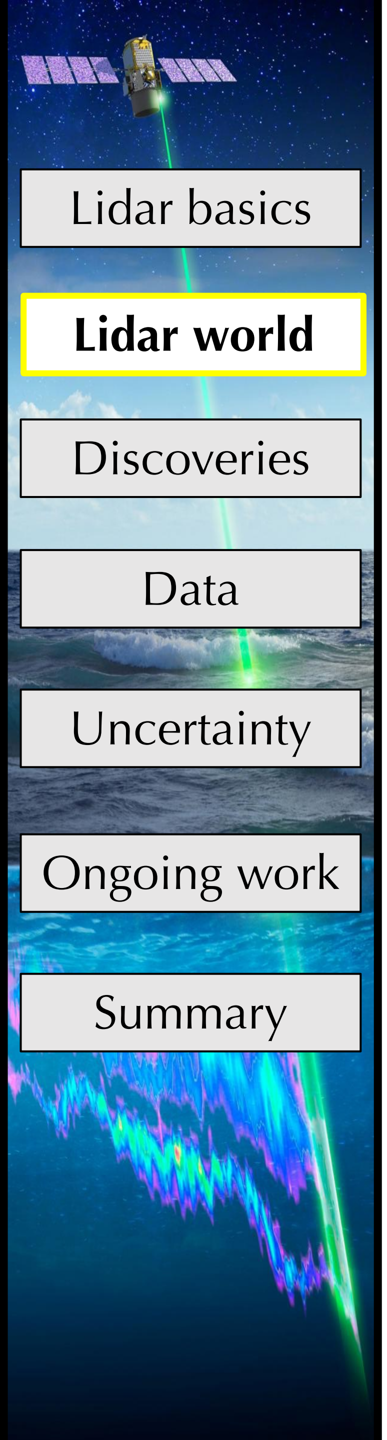


SPATIAL COVERAGE

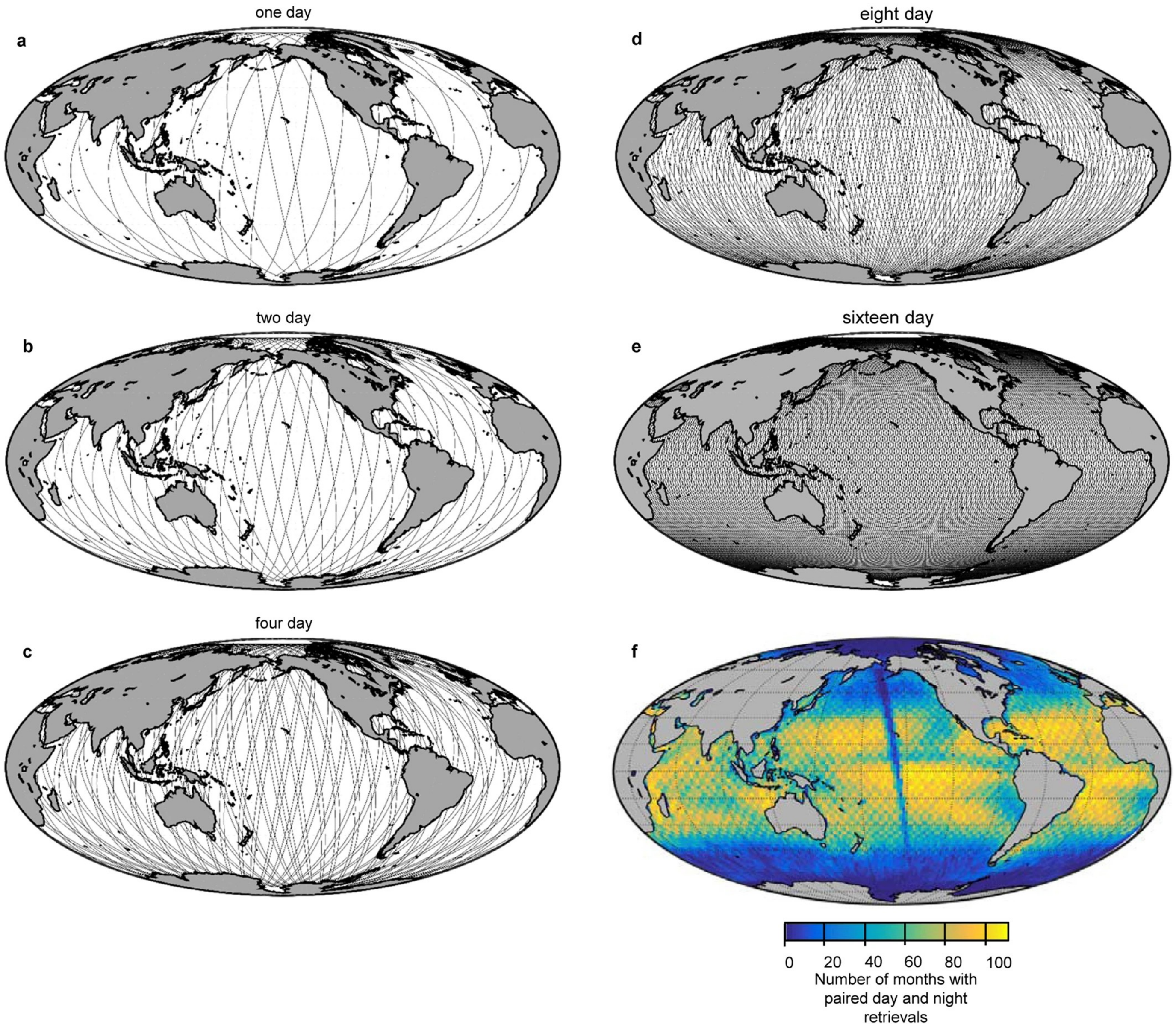
- **MODIS** observes swaths of area while **lidar** provides lines of data.





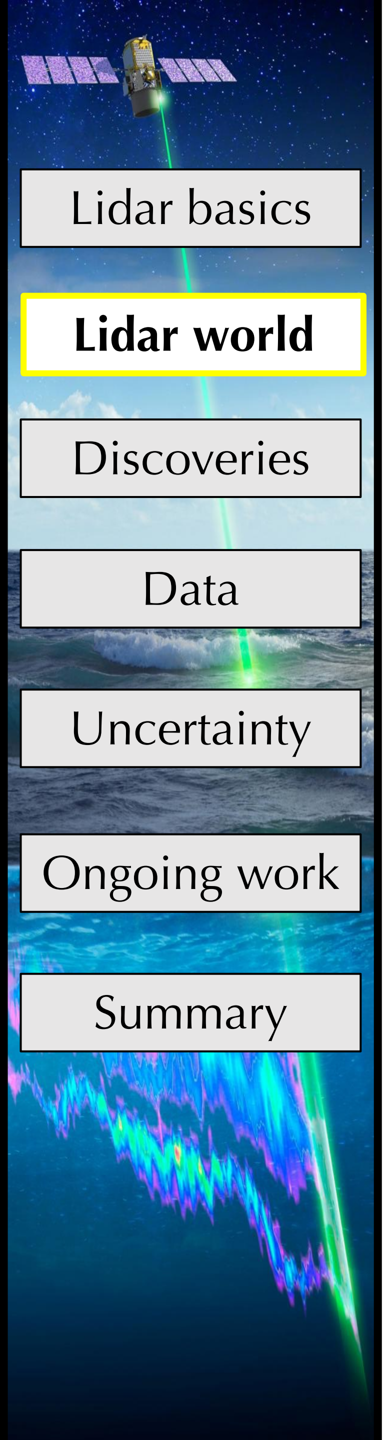


CALIOP (CALIPSO) spatial coverage



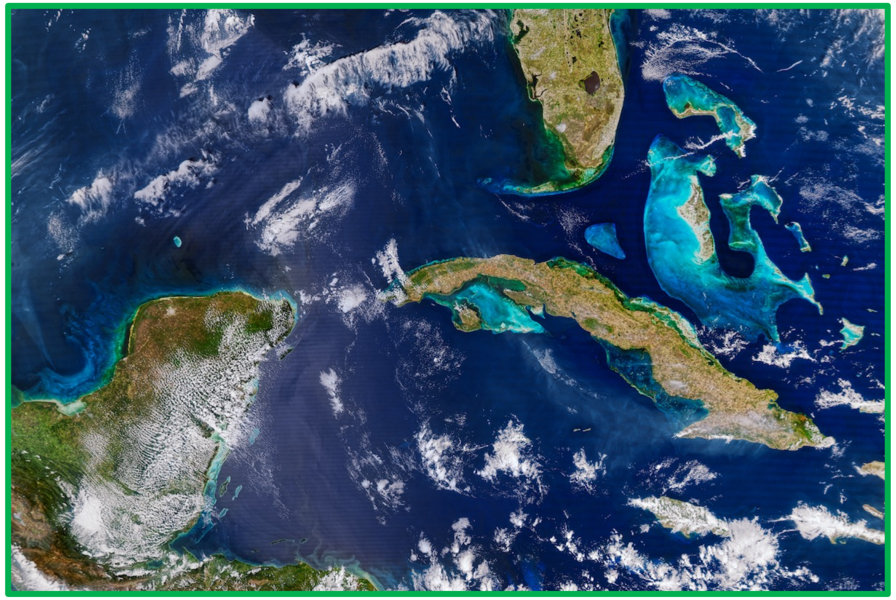
For reference, MODIS-Aqua would be 0 everywhere as there are no nighttime MODIS-Aqua data

Behrenfeld et al 2019



GENERAL DIFFERENCES WITH OCEAN COLOR

- Ocean color measures combined effects of absorption & scattering
- No information during night
- Retrievals are affected by clouds, aerosols, and low solar zenith angle



March 1, 2023 MODIS Aqua - OBPG

r_{rs} Inversion refresher

r_{rs} is ∝ the ratio of scattering to scattering + absorption

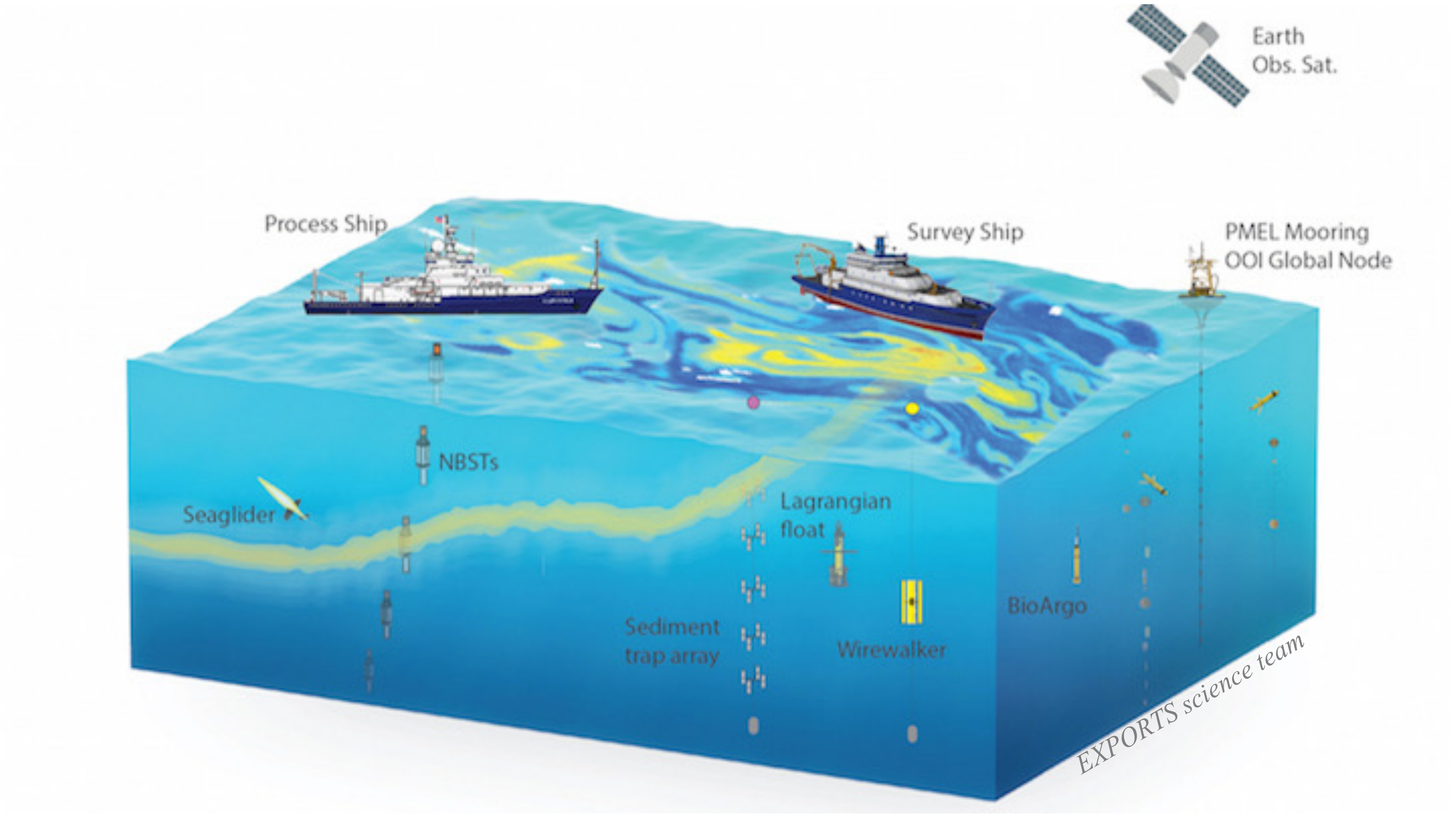
$$r_{rs}(\lambda) = \sum_{i=1}^{2} G_i * \left[\frac{b_b(\lambda)}{a(\lambda) + b_b(\lambda)}\right]^i$$

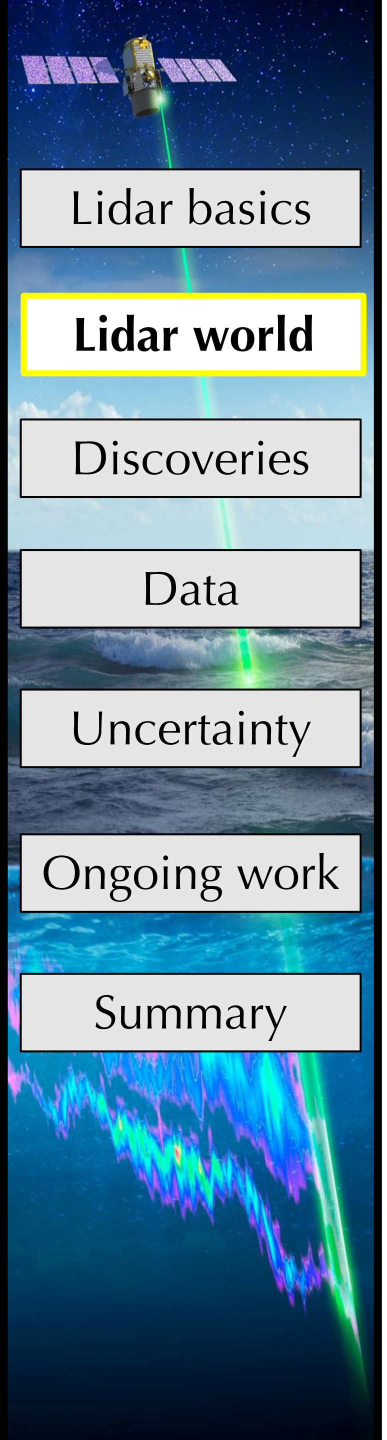
And absorption (a) is the sum of all absorbing constituents (spectrally) and backscattering (b_b) is the sum of backscattering from seawater and from particles.

$$a(\lambda) = a_w(\lambda) + M_{cdm} e^{-S_{cdm}\lambda} + M_{ph} a^*_{ph}(\lambda)$$

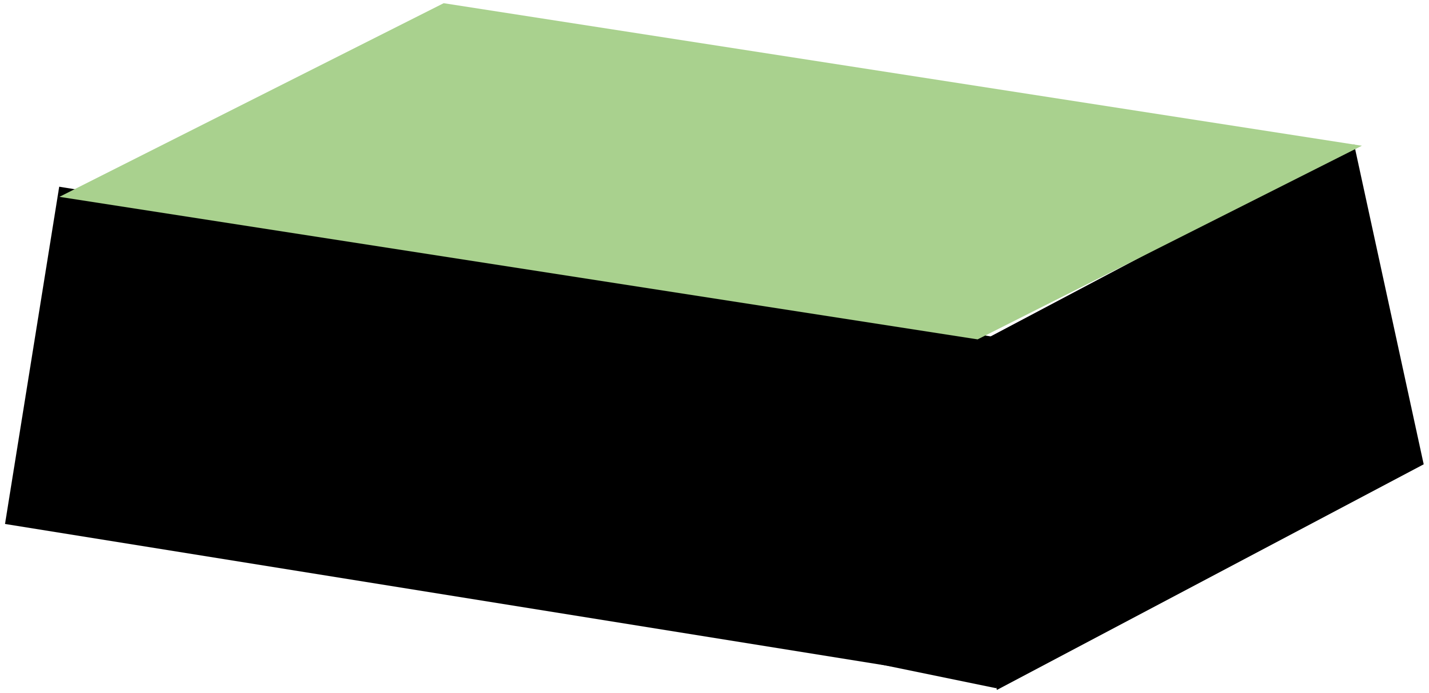
$$b_b(\lambda) = b_{bw}(\lambda) + M_{bp}\, \lambda^{-\gamma},$$

The ocean system is complex & highly variable.





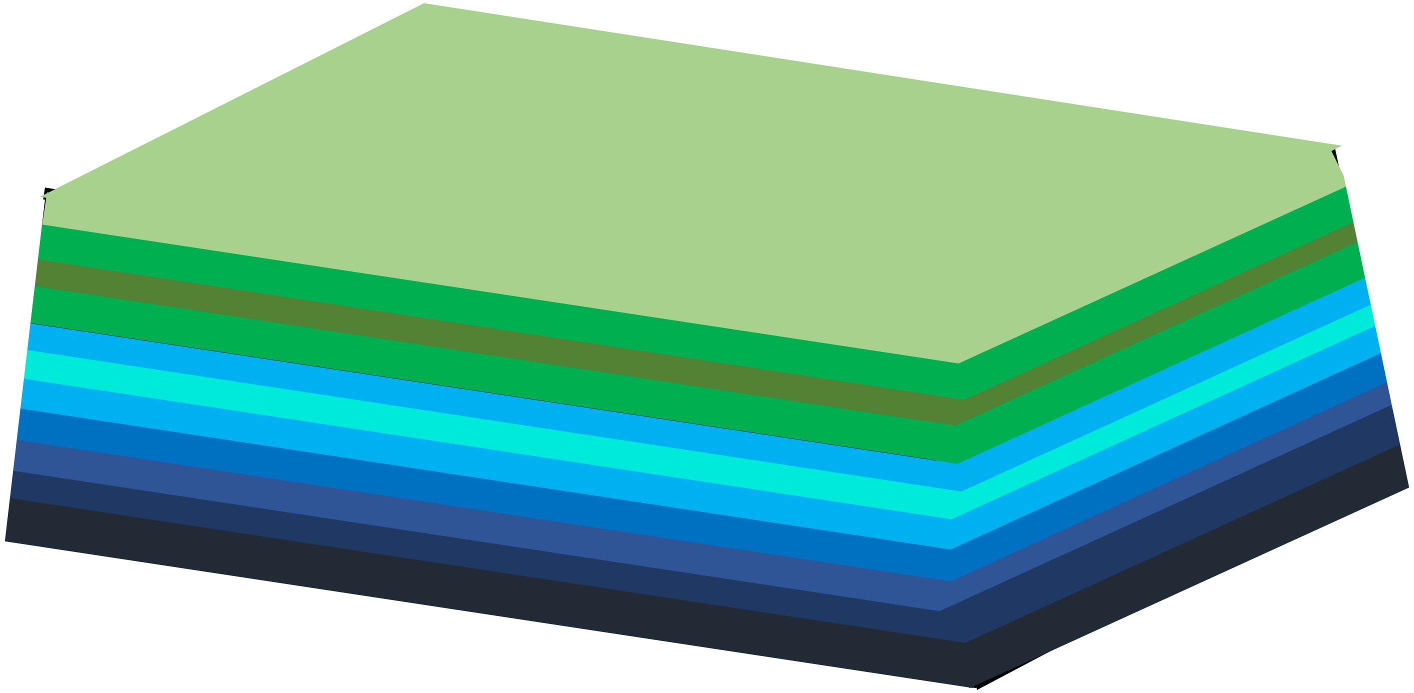
The ocean system is complex & highly variable.



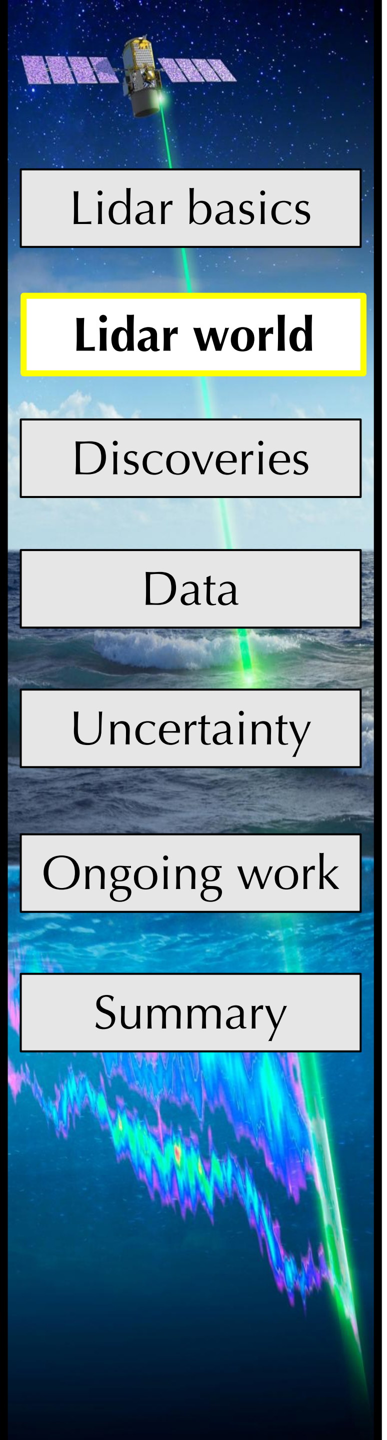
But this is what a pixel of ocean 'looks like' with an ocean color satellite data.

* Conceptual rendering of a 1 degree pixel as seen from space

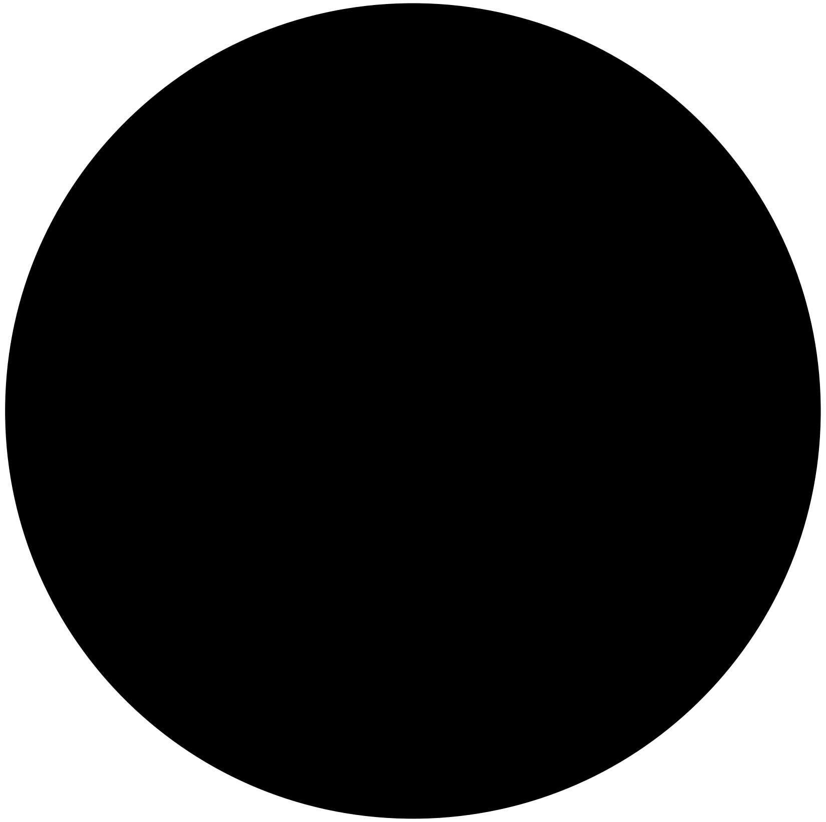
The ocean system is complex & highly variable.



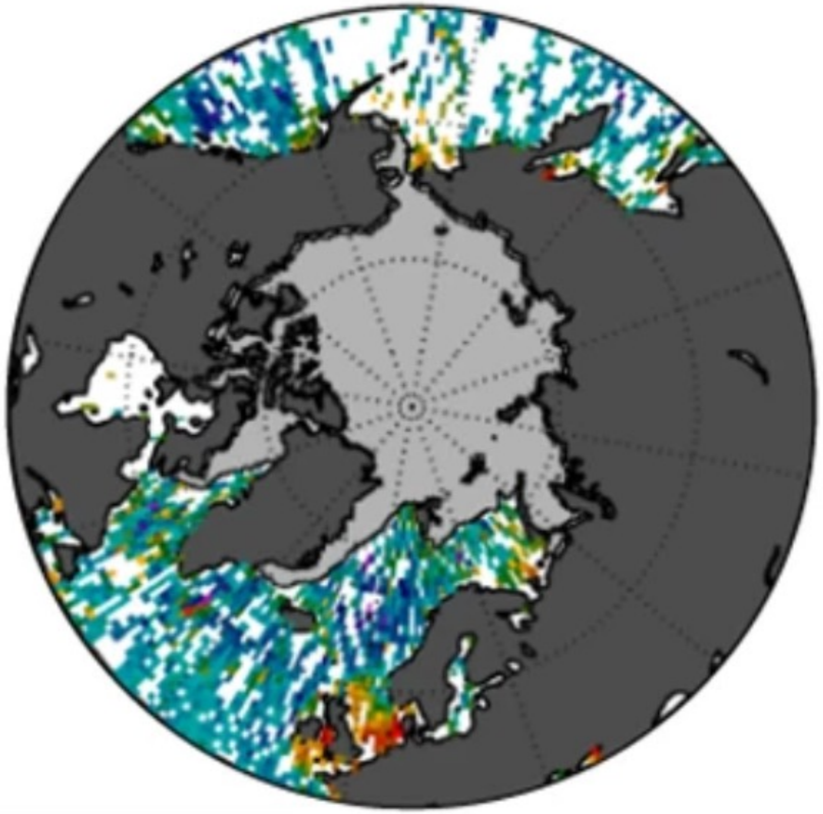
This is what an equivalent 'pixel' of ocean 'looks like' with a lidar



Polar ecosystems

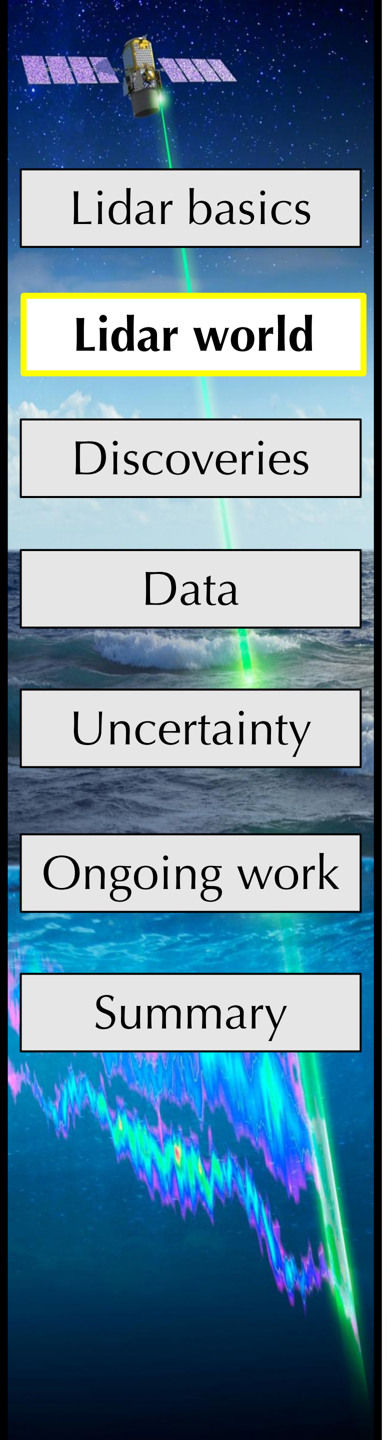


Passive satellite, winter



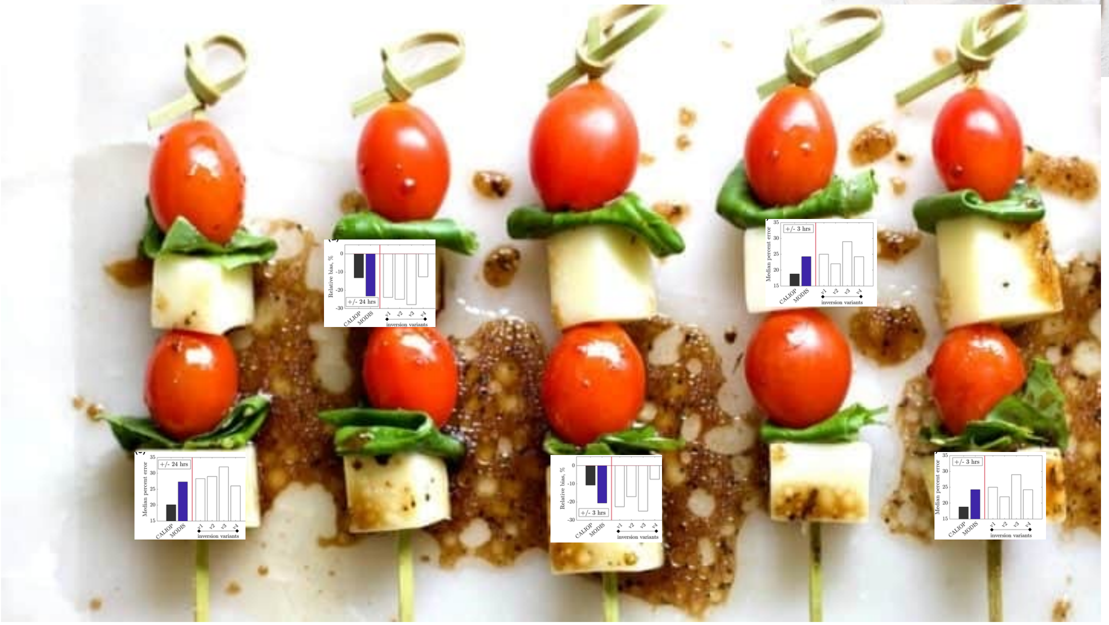
Lidar satellite, winter

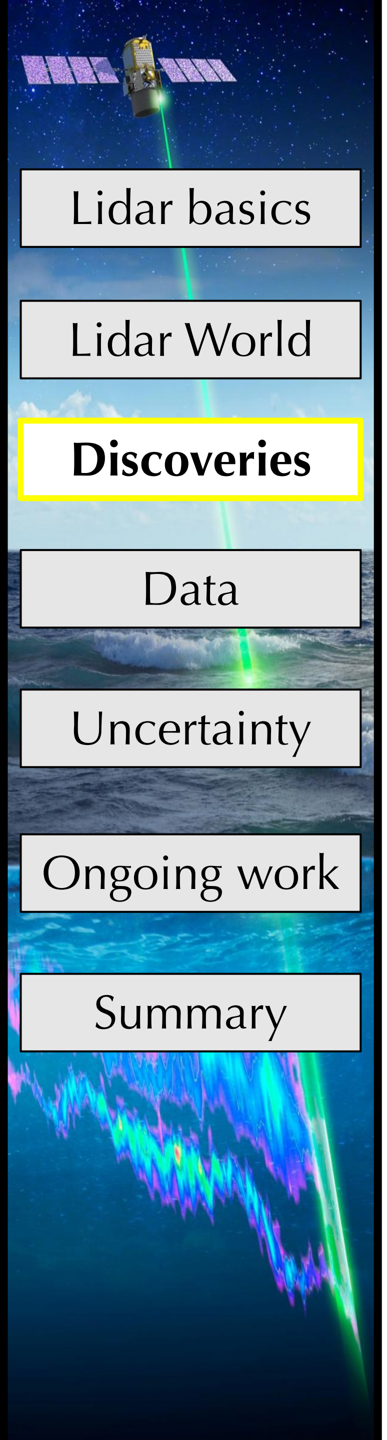
Behrenfeld et al.,2017



What have we discovered with lidar satellites when applied to oceans?

An appetizer….





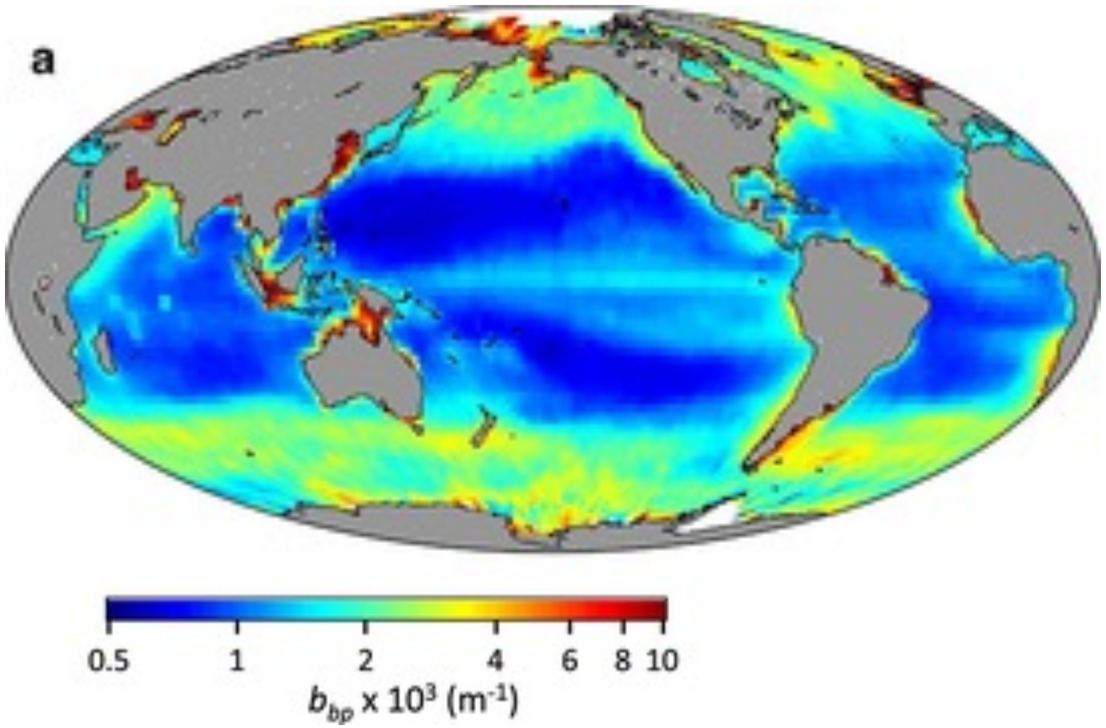
What have we learned so far from CALIPSO and ICESat-2?

GEOPHYSICAL RESEARCH LETTERS, VOL. 40, 4355–4360, doi:10.1002/grl.50816, 2013

Space-based lidar measurements of global ocean carbon stocks

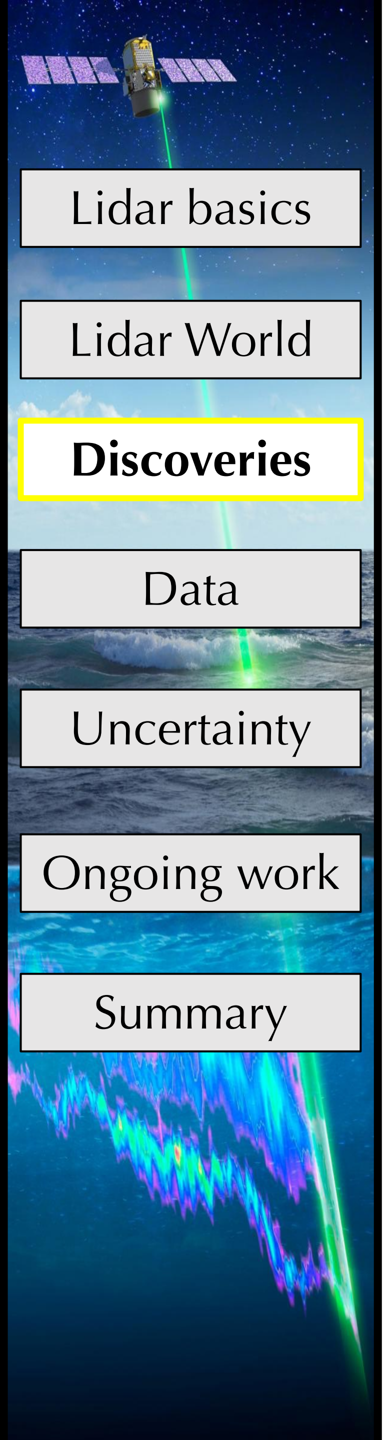
Michael J. Behrenfeld,[1] Yongxiang Hu,[2] Chris A. Hostetler,[2] Giorgio Dall'Olmo,[3] Sharon D. Rodier,[2] John W. Hair,[2] and Charles R. Trepte[2]

Received 31 July 2013; accepted 2 August 2013; published 23 August 2013.



Global aggregated b_{bp} data present independent measurement

b_{bp} data are converted to phytoplankton carbon



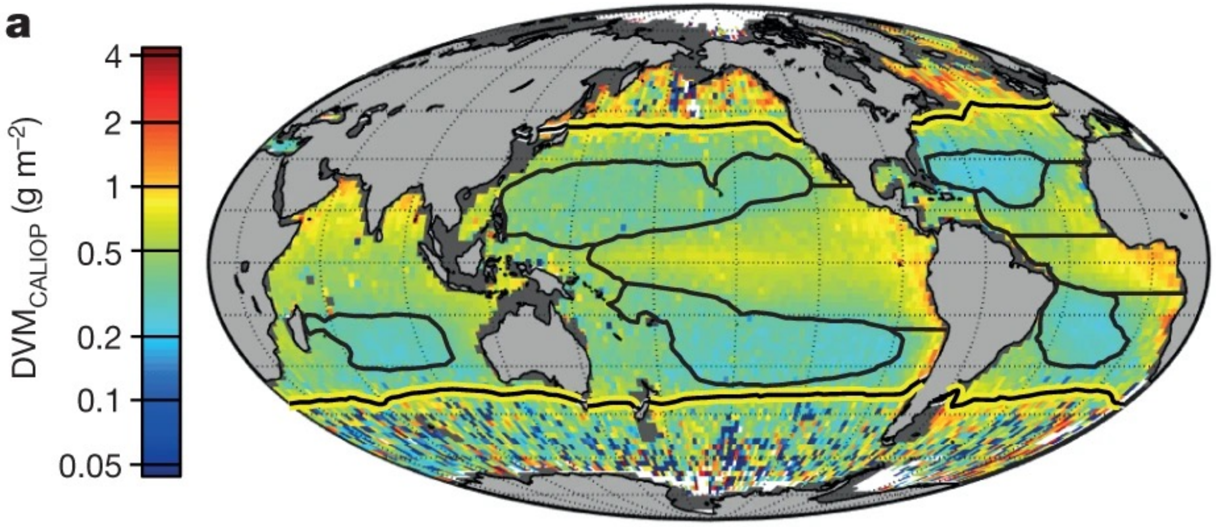
What have we learned so far from CALIPSO and ICESat-2?

Article

Global satellite-observed daily vertical migrations of ocean animals

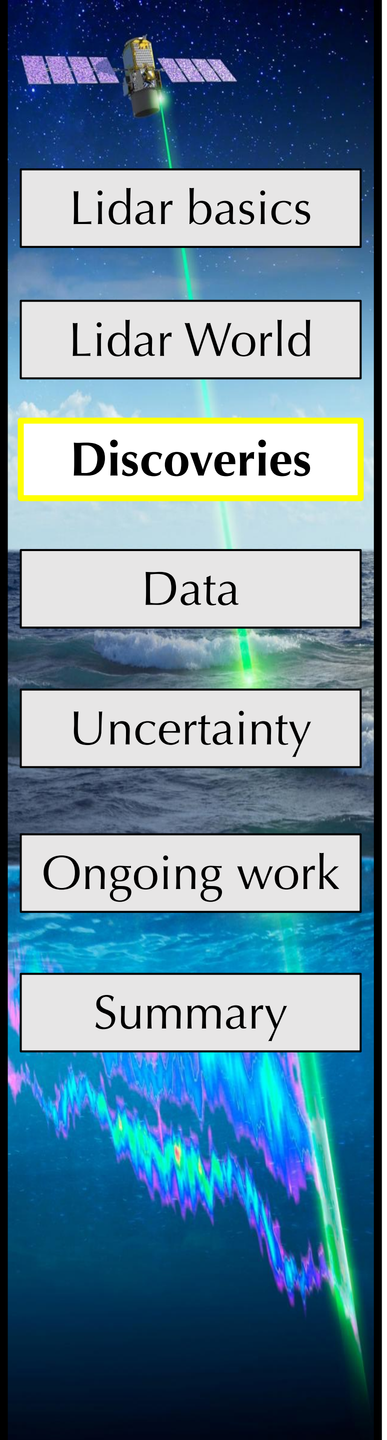
https://doi.org/10.1038/s41586-019-1796-9
Received: 27 September 2018
Accepted: 10 October 2019
Published online: 27 November 2019

Michael J. Behrenfeld[1]*, Peter Gaube[2], Alice Della Penna[2,3], Robert T. O'Malley[1], William J. Burt[4,5], Yongxiang Hu[6], Paula S. Bontempi[7], Deborah K. Steinberg[8], Emmanuel S. Boss[9], David A. Siegel[10,11], Chris A. Hostetler[6], Philippe D. Tortell[4,12] & Scott C. Doney[13]



b_{bp} covaries with all particles, including zooplankton!

Differences in b_{bp} from day to night are attributed to daily migrating zooplankton



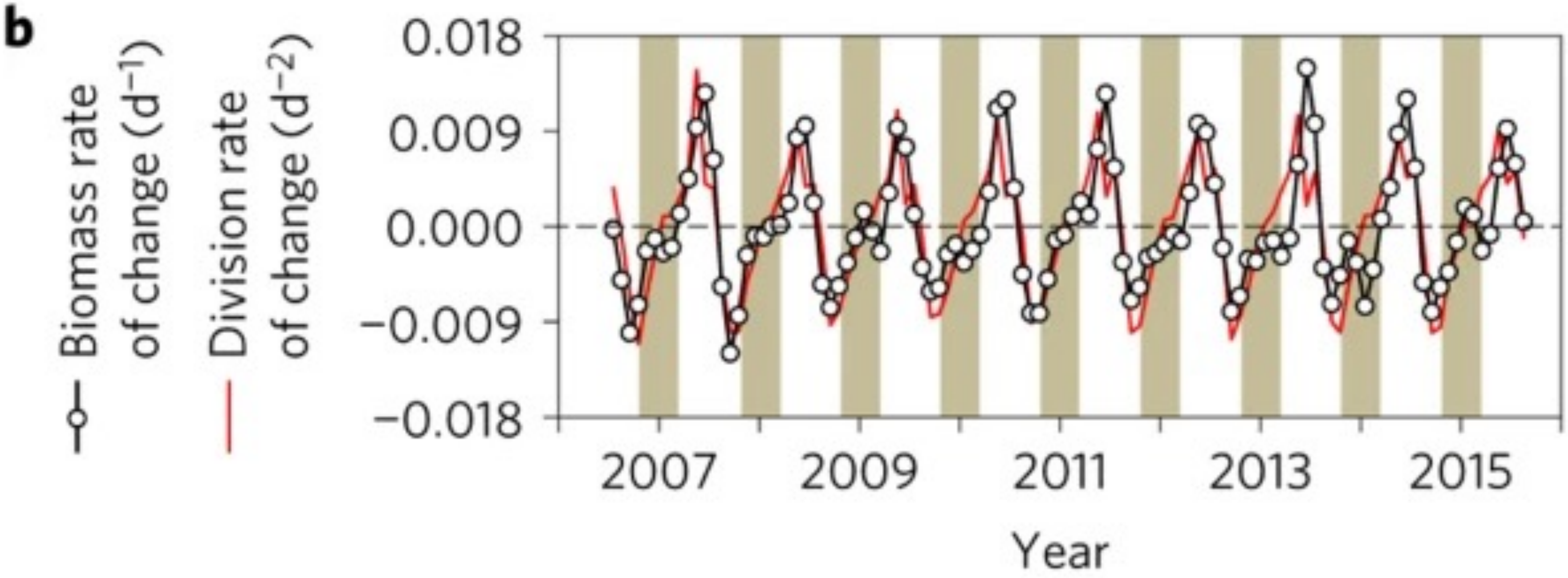
What have we learned so far from CALIPSO and ICESat-2?

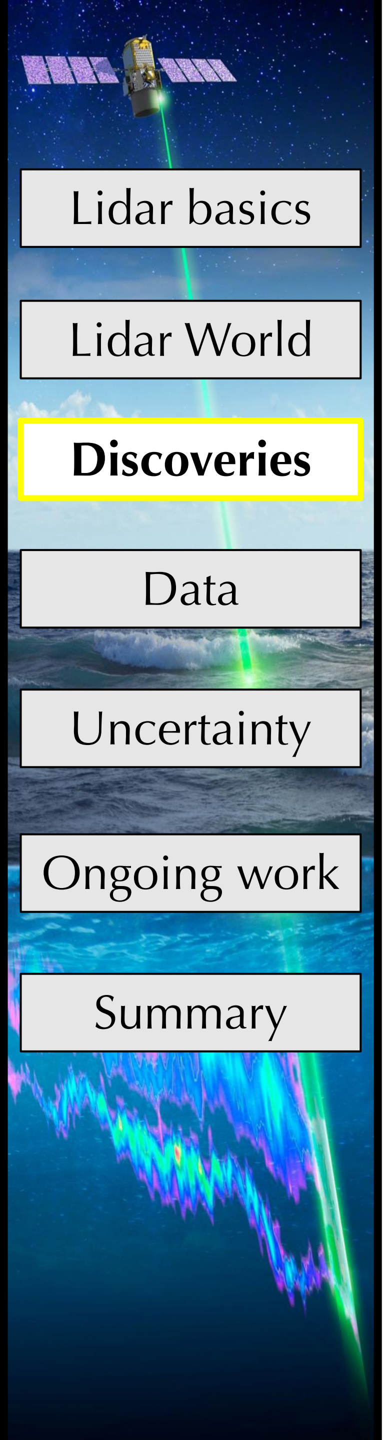
ARTICLES
PUBLISHED ONLINE: 19 DECEMBER 2016 | DOI: 10.1038/NGEO2861
nature geoscience

Annual boom–bust cycles of polar phytoplankton biomass revealed by space-based lidar

Michael J. Behrenfeld[1]*, Yongxiang Hu[2], Robert T. O'Malley[1], Emmanuel S. Boss[3], Chris A. Hostetler[2], David A. Siegel[4], Jorge L. Sarmiento[5], Jennifer Schulien[1], Johnathan W. Hair[2], Xiaomei Lu[2], Sharon Rodier[2] and Amy Jo Scarino[2]

Derivatives of b_{bp}-derived phytoplankton carbon are used to track polar phytoplankton cycles





What have we learned so far from CALIPSO and ICESat-2?

Contents lists available at ScienceDirect

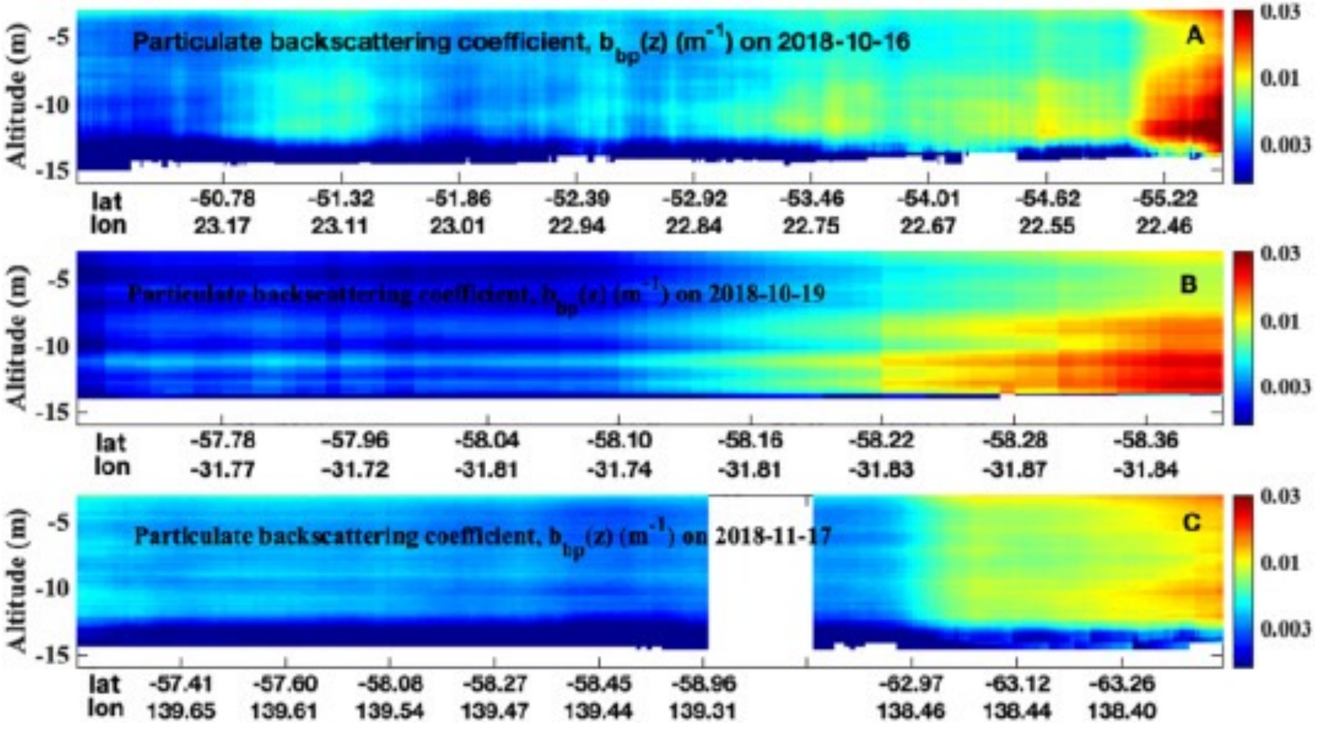
Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Antarctic spring ice-edge blooms observed from space by ICESat-2

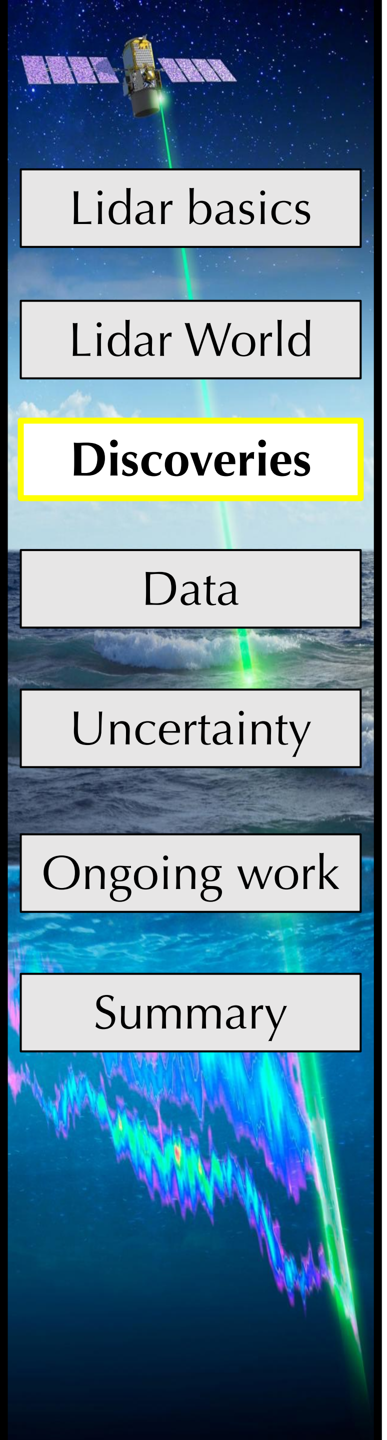
Xiaomei Lu[a,b,*], Yongxiang Hu[b,**], Yuekui Yang[c], Paula Bontempi[d], Ali Omar[b], Rosemary Baize[b]

[a] Science Systems and Applications, Inc., Hampton, VA 23666, USA
[b] NASA Langley Research Center, Hampton, VA 23681, USA
[c] NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
[d] NASA Headquarters, Washington, DC 20546, USA



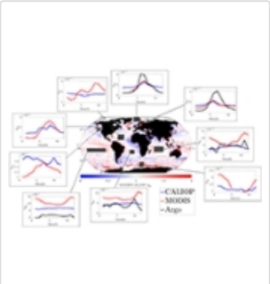
For the first time, cm-scale resolution of the particle field was achieved from ICESat-2 shortly after its launch.

15m is depth limit in open ocean from ICESat-2 due to data downlink restrictions, but the depth could be expanded for ocean optimized lidar



What have we learned so far from CALIPSO and ICESat-2?

Applied Optics Vol. 60, Issue 23, pp. 6978-6988 (2021) • https://doi.org/10.1364/AO.426137

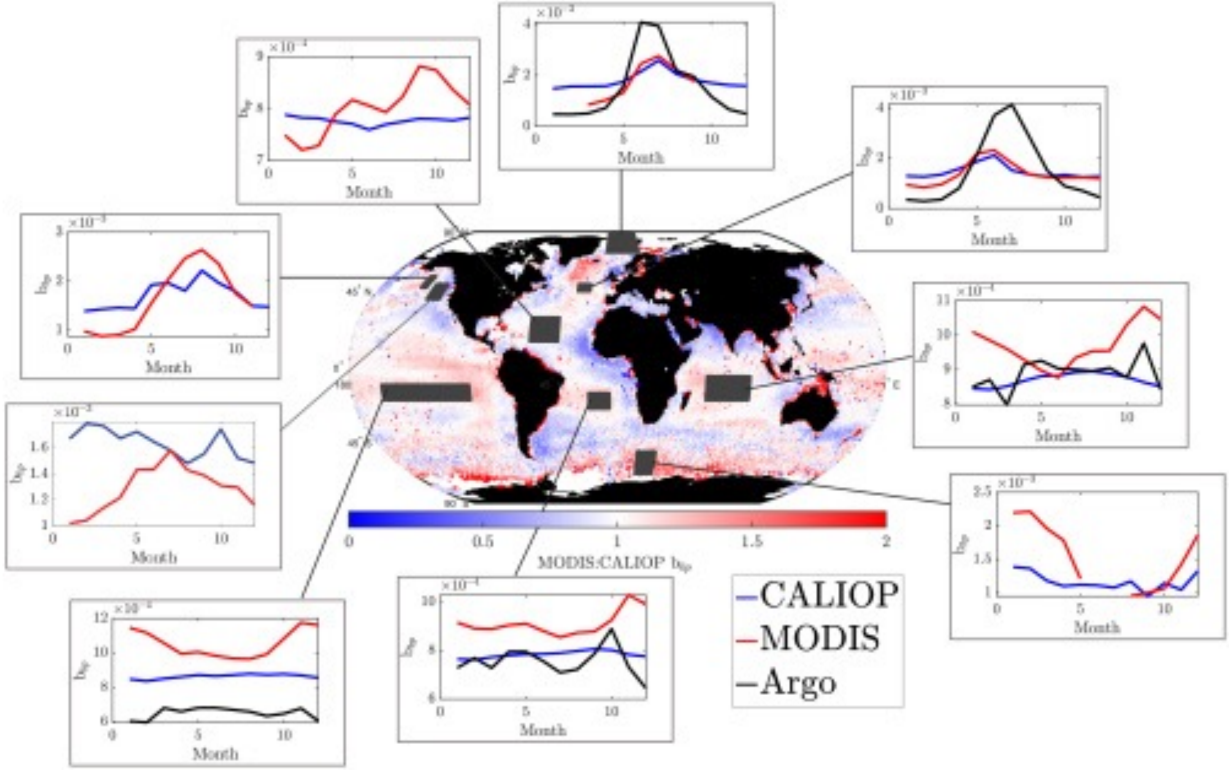


Seasonal bias in global ocean color observations

K. M. Bisson, E. Boss, P. J. Werdell, A. Ibrahim, R. Frouin, and M. J. Behrenfeld

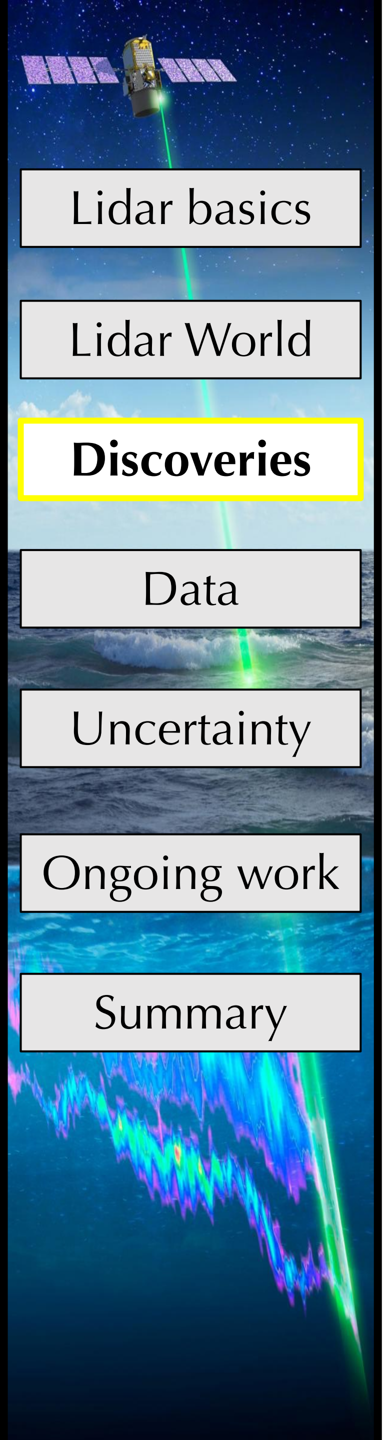
Author Information ▾ Find other works by these authors ▾

CALIPSO

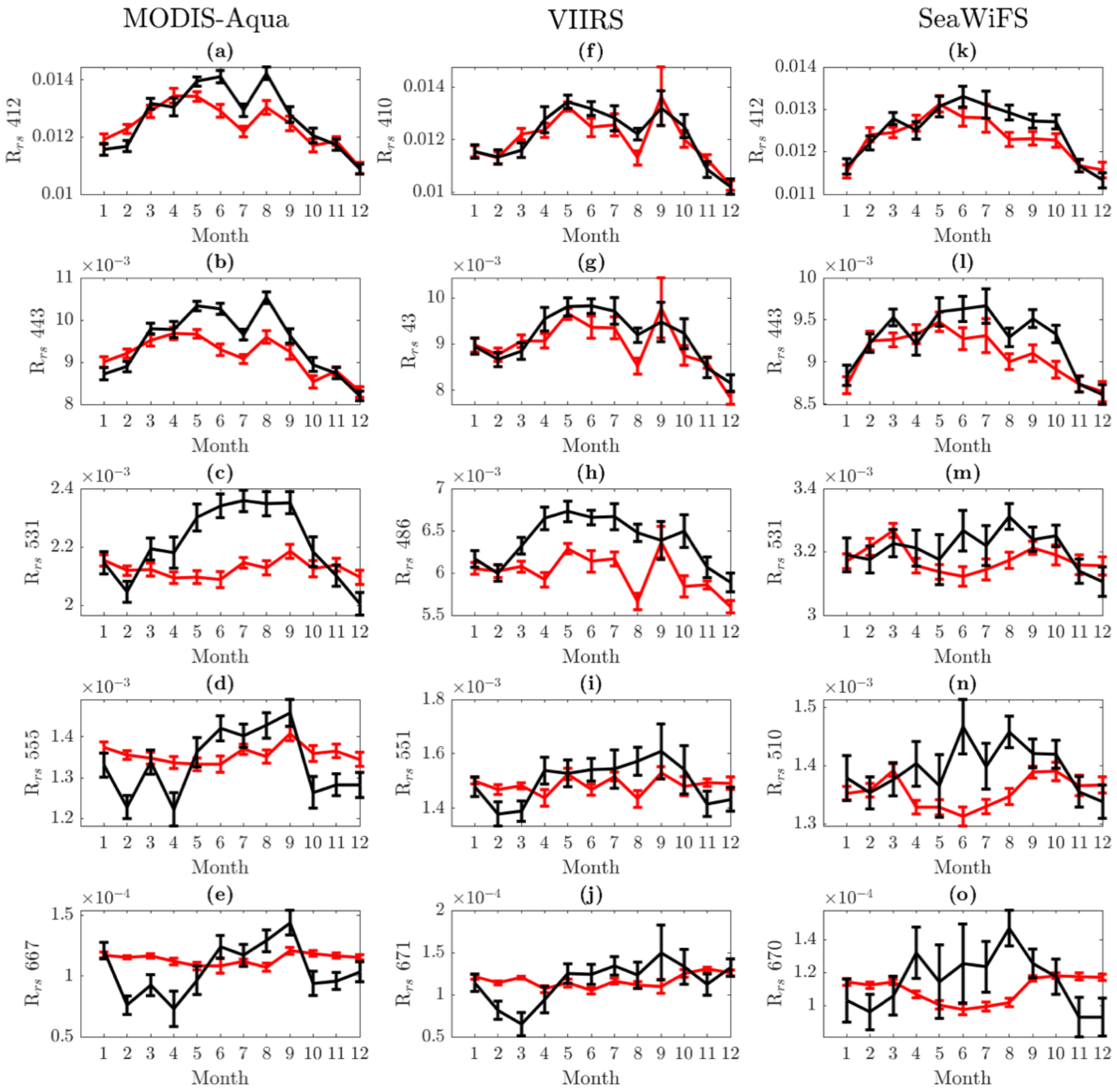


When CALIOP data were compared with MODIS-Aqua data on global scales, weird patterns (not obviously biological) were observed. When looking closer we found systematic biases in MODIS-Aqua data that we did not expect

Bisson et al 2021a



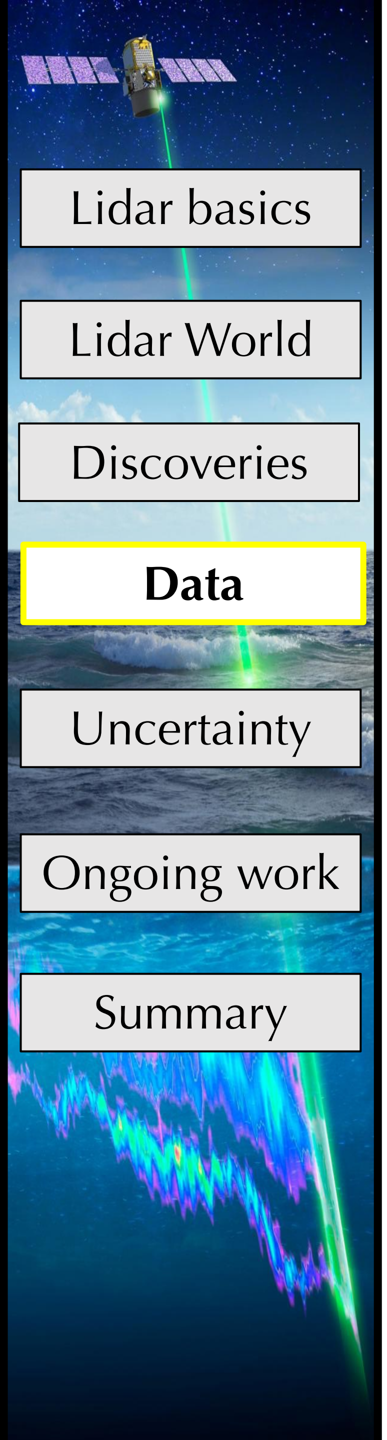
What have we learned so far from CALIPSO and ICESat-2?



Systematic biases in MODIS-Aqua (and other ocean color satellites) data exist in all IOPs and AOPs, even at the ocean color validation site (MOBY)….

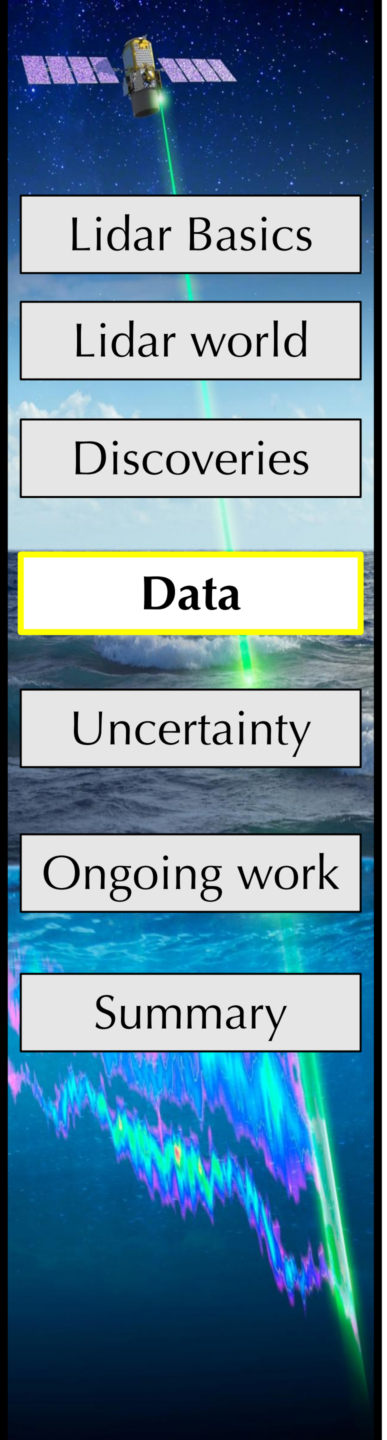
Mismatch in seasonal cycles between in situ observations and satellites at longer wavelengths

Bisson et al 2021a



Lidar for ocean research: We are living off atmospheric & polar satellites!

CALIPSO and ICESat-2 data development has been 'DIY' and very creative, as these satellites were not built for ocean research as a goal.



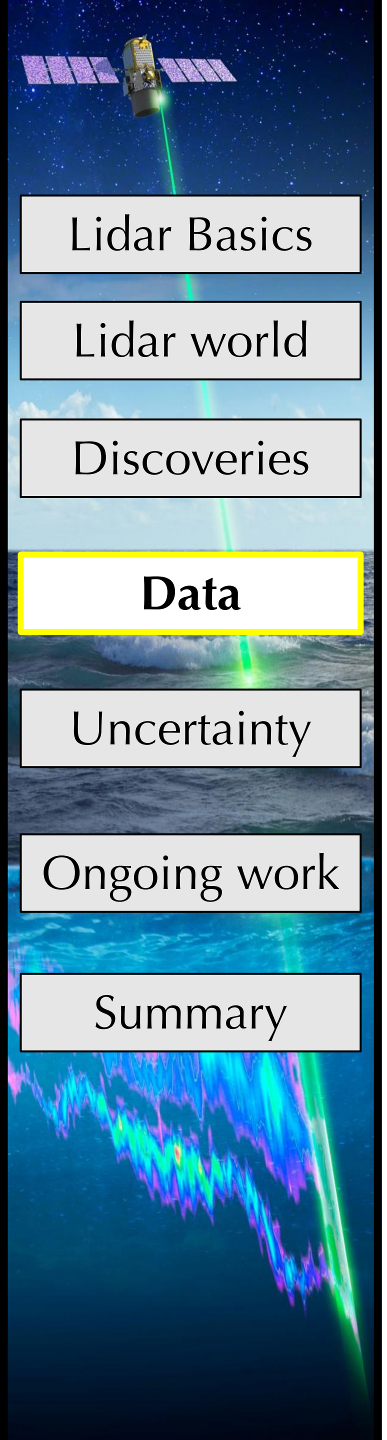
ICESat-2 (ATLAS instrument)

Photon counting altimeter
No polarization information
10 kHz
10 cm vertical resolution in water
11 m footprint

CALIPSO (CALIOP instrument)

Photon counting altimeter
Cross and co parallel polarization channels
20.25 Hz
21 m vertical resolution in water
100 m footprint

image sources: NASA gallery



ICESat-2 (ATLAS instrument)

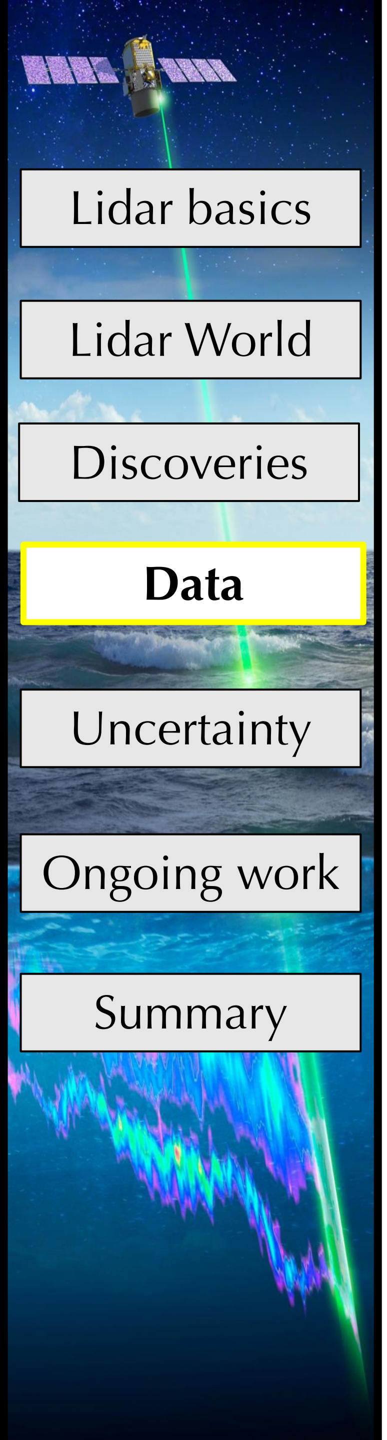
Photon counting altimeter
No polarization information
10 kHz
10 cm vertical resolution in water
11 m footprint

super solid, gets the job done, one of the best

CALIPSO (CALIOP instrument)

Photon counting altimeter
Cross and co parallel polarization channels
20.25 Hz
21 m vertical resolution in water
100 m footprint

more pizazz through polarization channels gives a 'je ne sais quoi' to the mission



CALIOP data processing and access

$$b_{bp}(532) \approx 7.2\, R_{part}$$

$$R_{part} = \beta_{cross-pol} \frac{R_{theory}}{\beta_{co-pol}}\, c_1$$

CALIOP b_{bp}

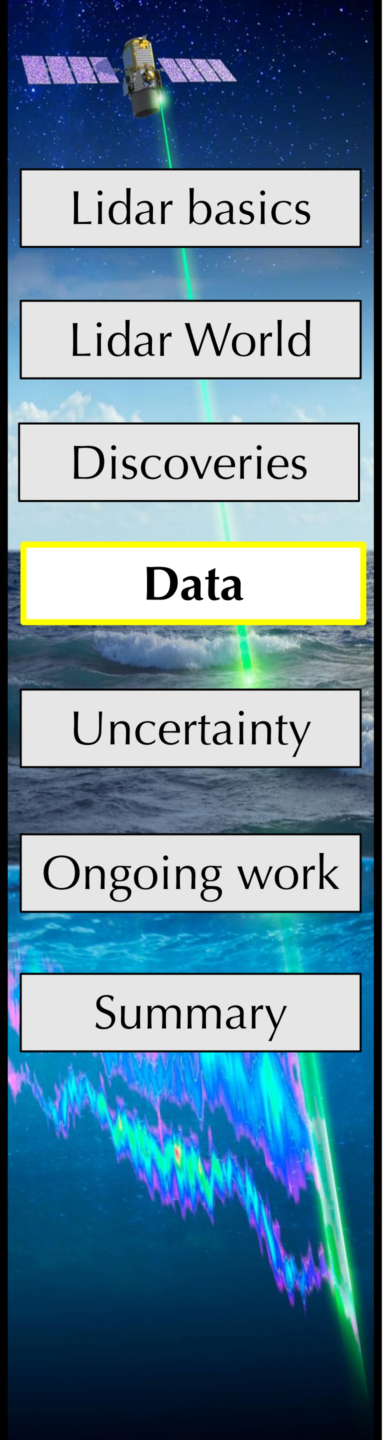
$\beta_{cross\text{-}pol}$ = integrated attenuated backscatter measured with the cross-polarized channels (sr^{-1})

$\beta_{co\text{-}pol}$ = integrated attenuated backscatter measured with the co-polarized channels (sr^{-1})

c_1 = unitless correction for crosstalk between polarization channels (1 – depolarization discrepancy between measured and theoretical molecular depolarization in stratosphere)

R_{theory} = theoretical ocean surface reflectance (sr^{-1}) derived from wind speed, viewing angles, water index of refraction

Behrenfeld et al 2022



Validation status

Geophysical Research Letters

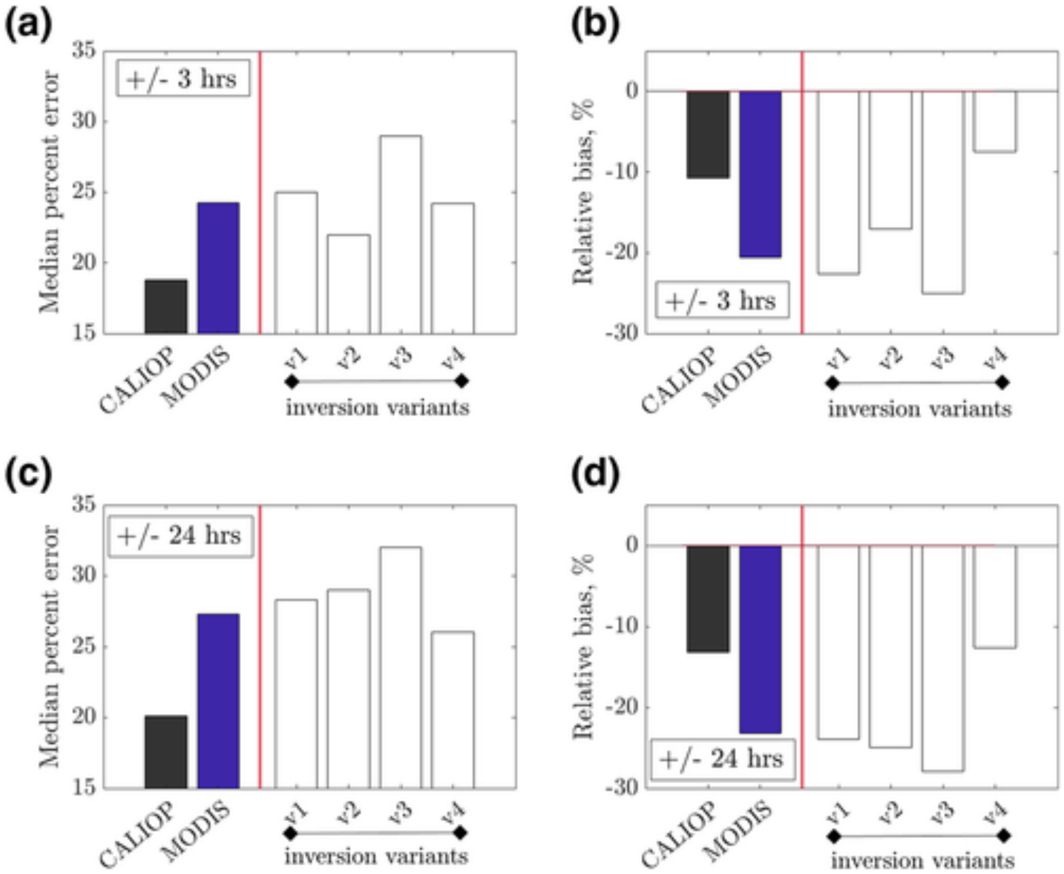
RESEARCH LETTER
10.1029/2020GL090909

Key Points:
- Spatiotemporal correlation scales are quantified between global lidar and in situ observations
- Satellite lidar has lower error and bias compared to ocean color observations of particulate

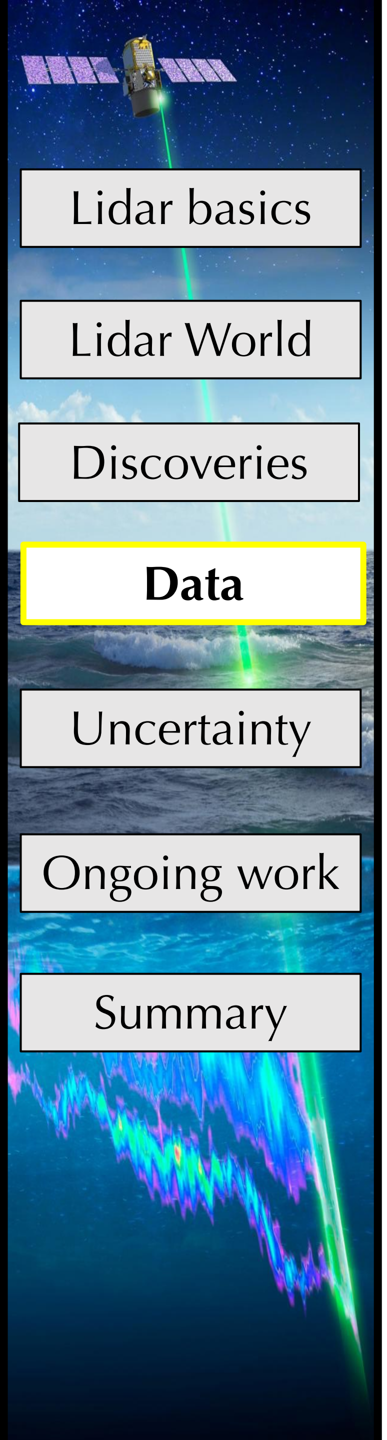
Particulate Backscattering in the Global Ocean: A Comparison of Independent Assessments

K. M. Bisson[1], E. Boss[2], P. J. Werdell[3], A. Ibrahim[3,4], and M. J. Behrenfeld[1]

[1]Department of Botany and Plant Pathology, Oregon State University, Corvallis, OR, USA, [2]School of Marine Sciences, University of Maine, Orono, ME, USA, [3]NASA Goddard Space Flight Center, Ocean Ecology Laboratory, Greenbelt, Maryland, USA, [4]Science Systems and Applications Inc., Lanham, MD, USA



Bisson et al 2021b



Validation status

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RESEARCH LETTER
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Particulate Backscattering in the Global Ocean: A Comparison of Independent Assessments

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[1]Department of Botany and Plant Pathology, Oregon State University, Corvallis, OR, USA, [2]School of Marine Sciences, University of Maine, Orono, ME, USA, [3]NASA Goddard Space Flight Center, Ocean Ecology Laboratory, Greenbelt, Maryland, USA, [4]Science Systems and Applications Inc., Lanham, MD, USA

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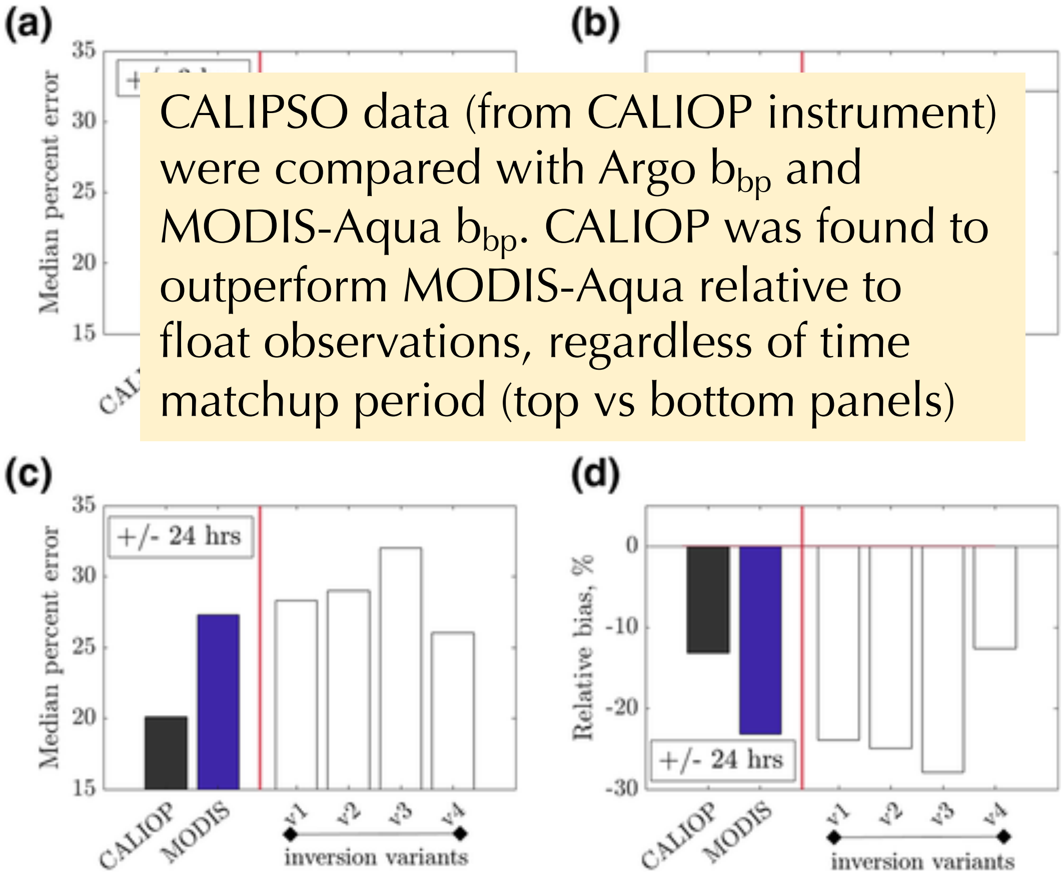
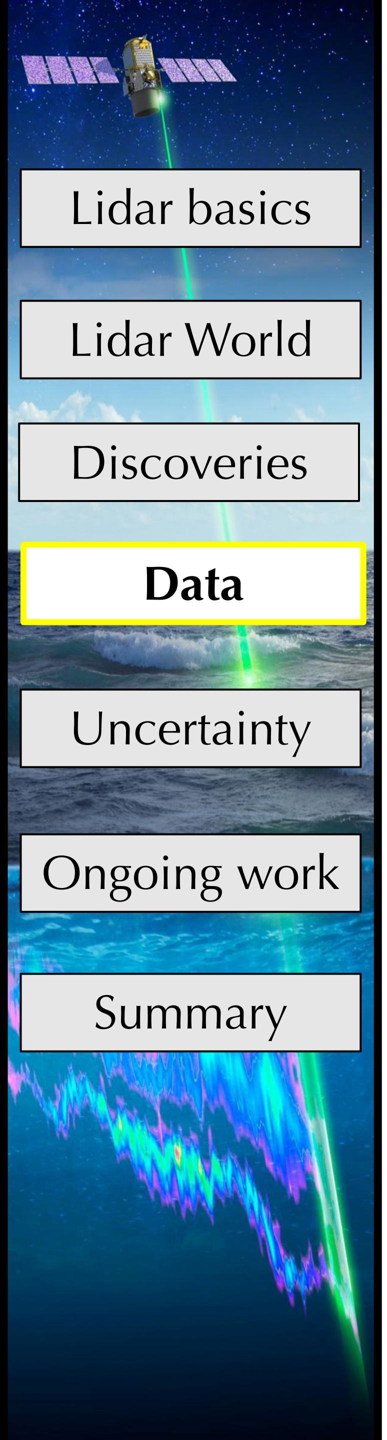


CALIPSO data (from CALIOP instrument) were compared with Argo b_{bp} and MODIS-Aqua b_{bp}. CALIOP was found to outperform MODIS-Aqua relative to float observations, regardless of time matchup period (top vs bottom panels)

Bisson et al 2021b



Validation status

Geophysical Research Letters

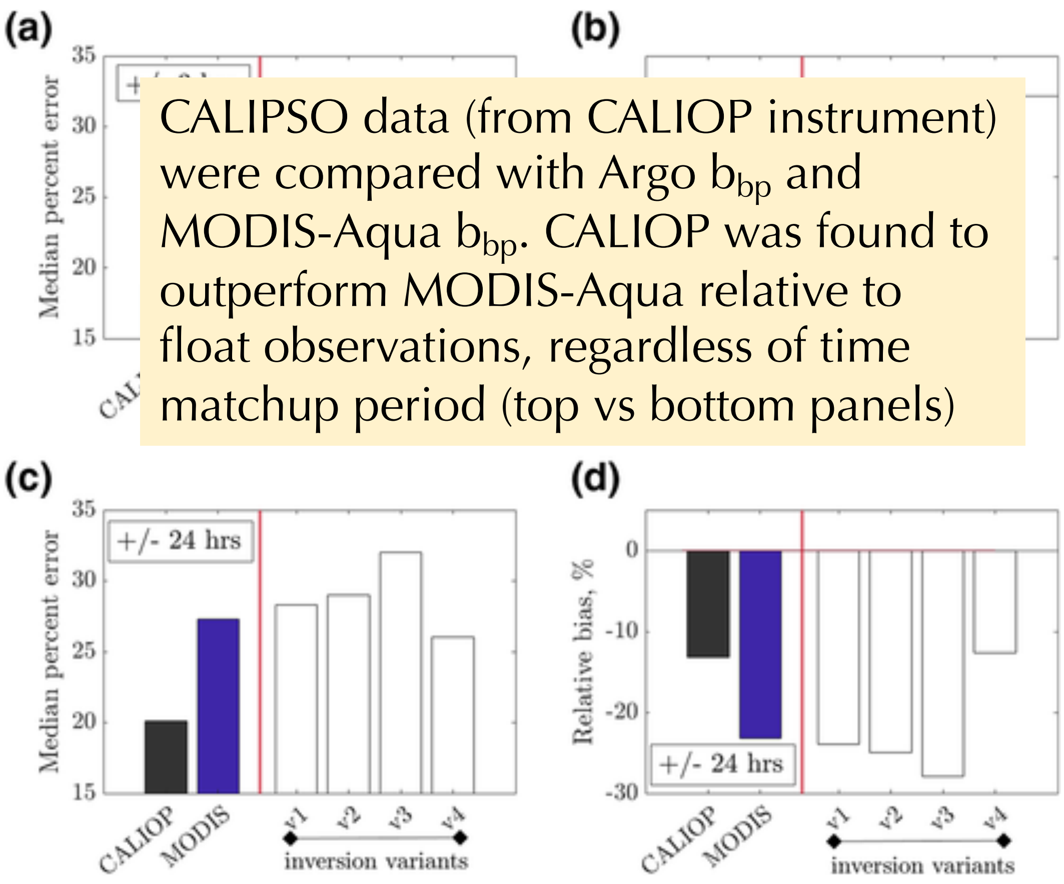
RESEARCH LETTER
10.1029/2020GL090909

Key Points:
- Spatiotemporal correlation scales are quantified between global lidar and in situ observations
- Satellite lidar has lower error and bias compared to ocean color observations of particulate

Particulate Backscattering in the Global Ocean: A Comparison of Independent Assessments

K. M. Bisson[1], E. Boss[2], P. J. Werdell[3], A. Ibrahim[3,4], and M. J. Behrenfeld[1]

[1]Department of Botany and Plant Pathology, Oregon State University, Corvallis, OR, USA, [2]School of Marine Sciences, University of Maine, Orono, ME, USA, [3]NASA Goddard Space Flight Center, Ocean Ecology Laboratory, Greenbelt, Maryland, USA, [4]Science Systems and Applications Inc., Lanham, MD, USA



CALIPSO data (from CALIOP instrument) were compared with Argo b_{bp} and MODIS-Aqua b_{bp}. CALIOP was found to outperform MODIS-Aqua relative to float observations, regardless of time matchup period (top vs bottom panels)

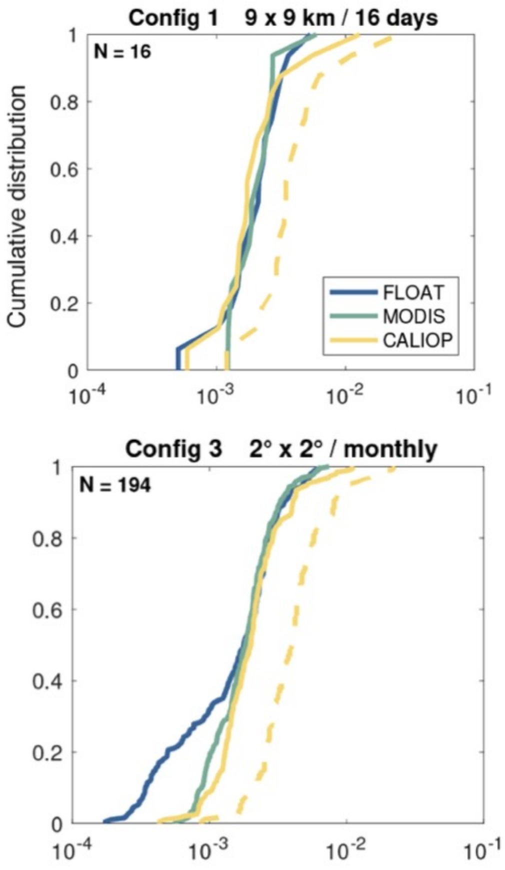
Bisson et al 2021b

Optics EXPRESS

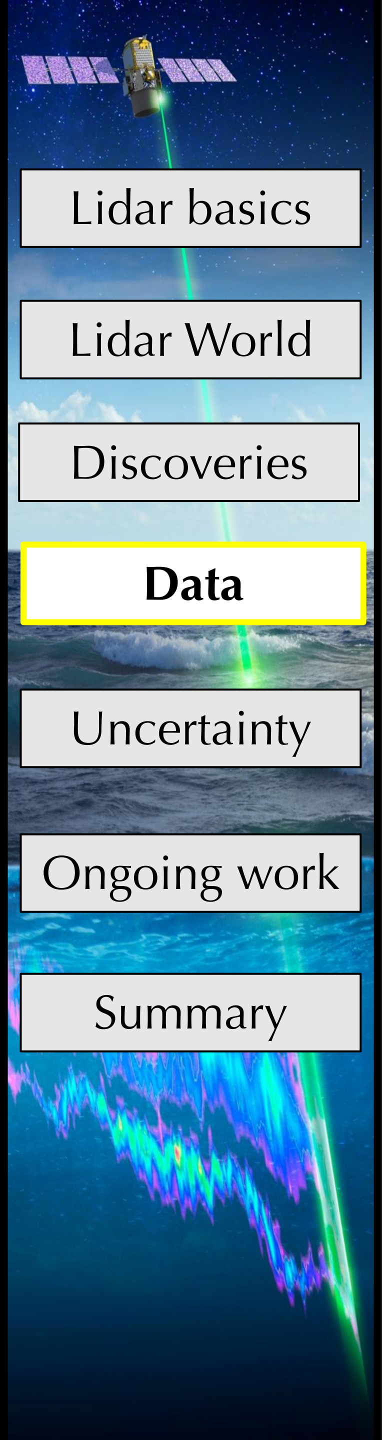
In situ evaluation of spaceborne CALIOP lidar measurements of the upper-ocean particle backscattering coefficient

Léo Lacour,* Raphael Larouche, and Marcel Babin

UMI Takuvik, CNRS/Université Laval, Québec, QC, Canada
*leo.lacour@takuvik.ulaval.ca

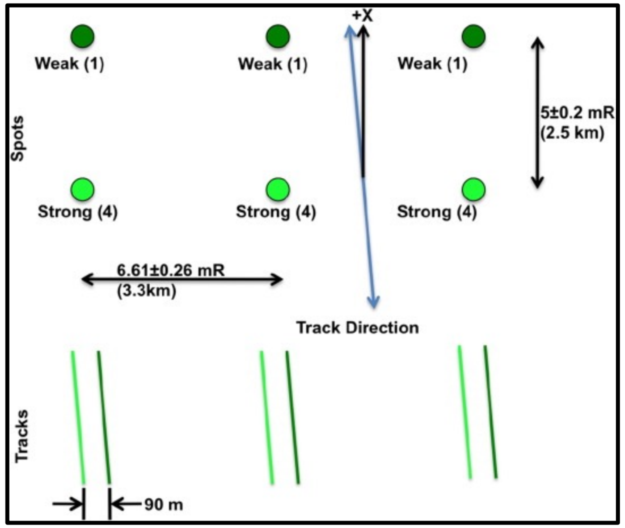


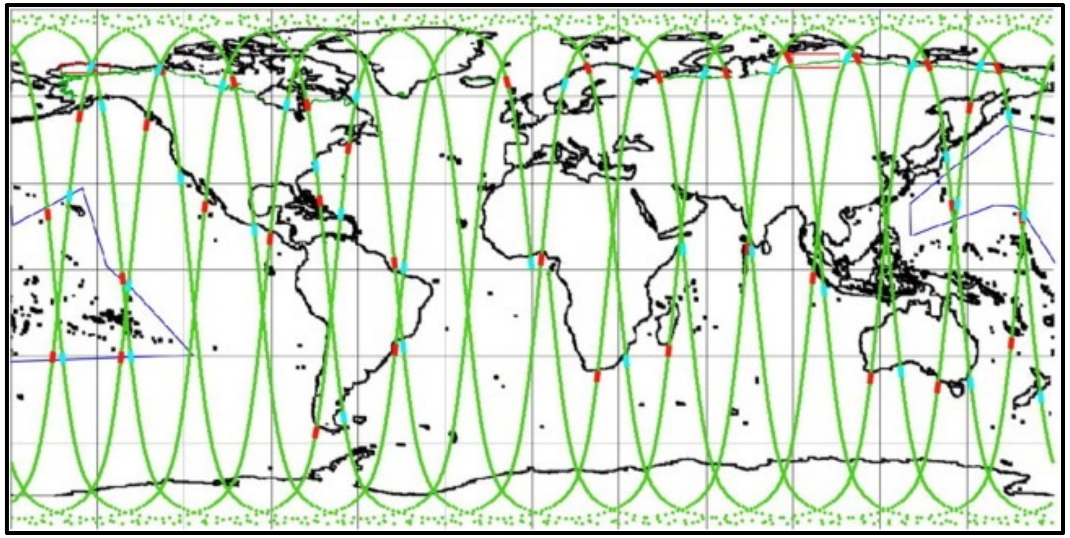
CALIOP (solid yellow) agrees well for the primary processing but not when using doubling a constant parameter in the processing (dashed line)



ICESat-2 data processing and access

Start from raw ATL03 photon height product, distributed in granules and organized into 3 pairs of strong and weak beams

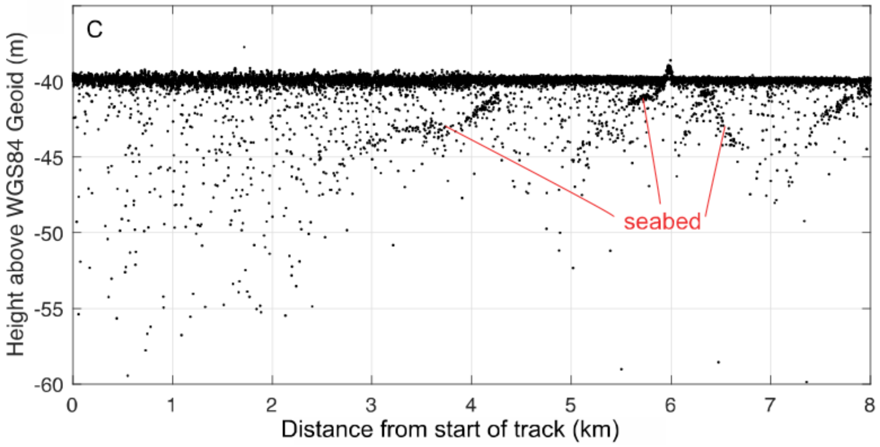


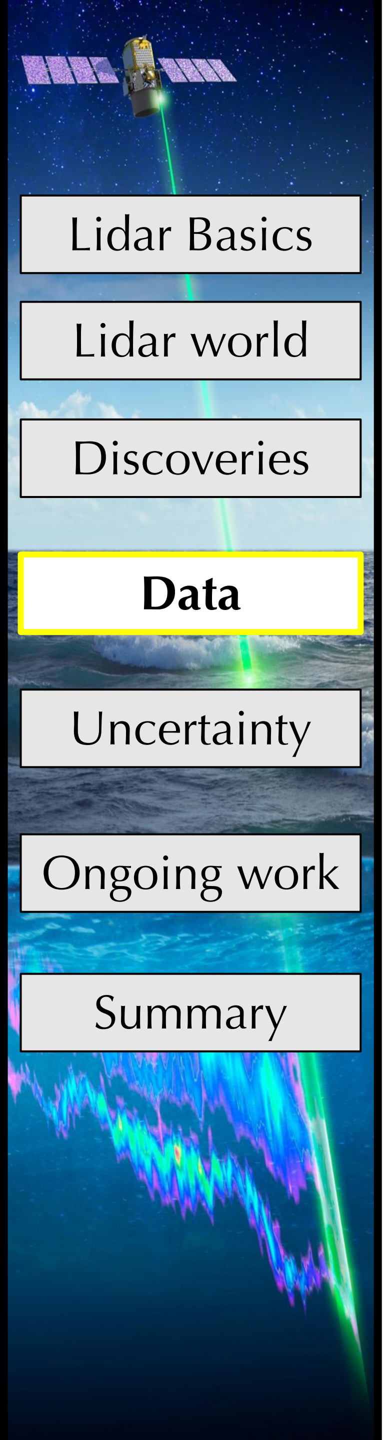


1 day orbit of ICESat-2 data

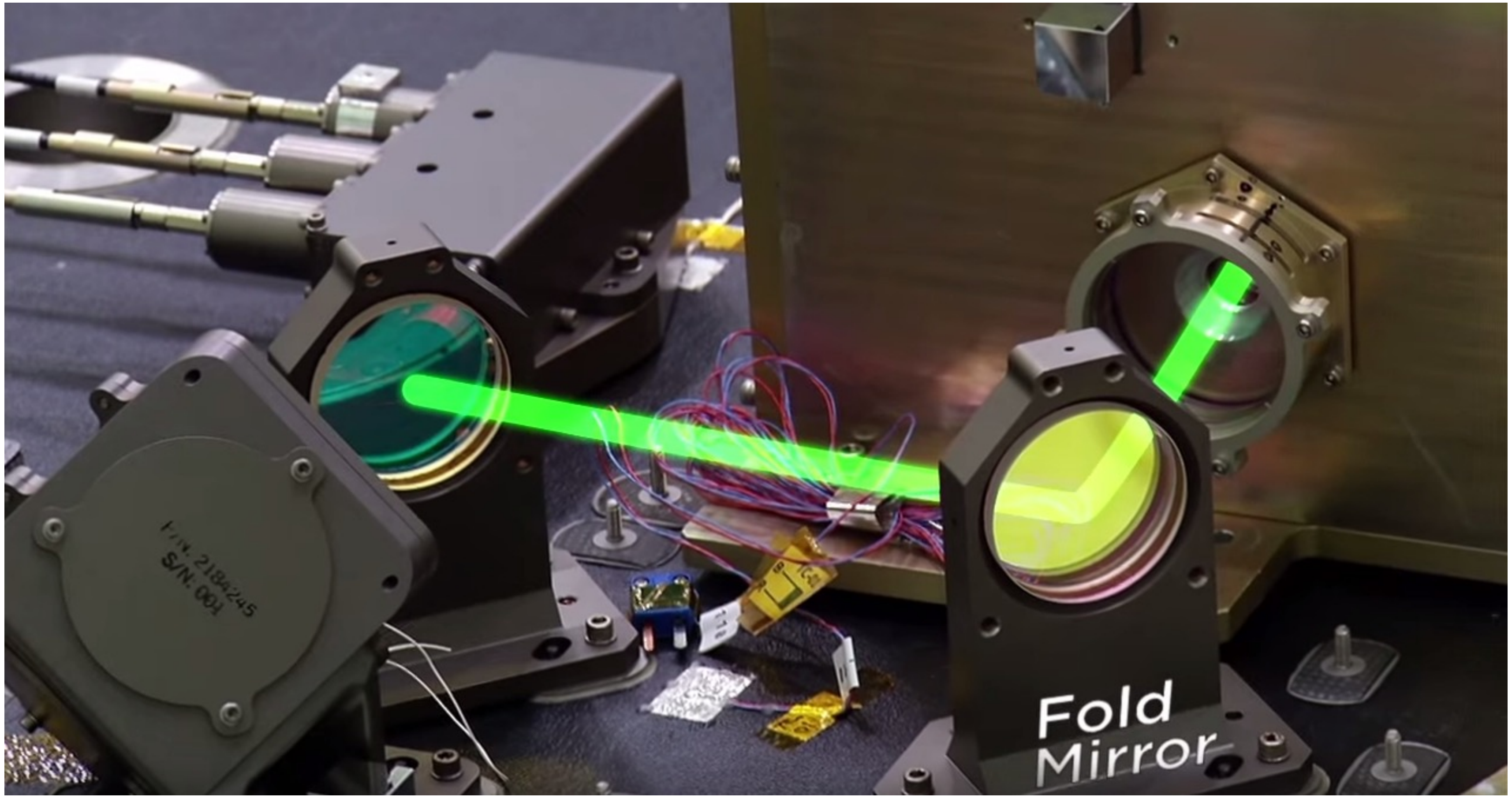
91 day repeat cycle

Photon height product



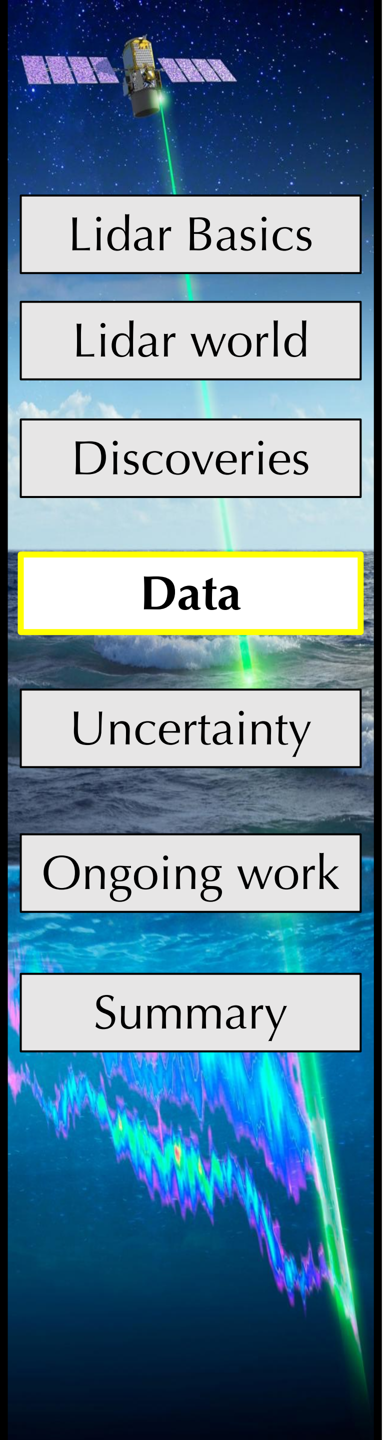


Light Detection And Ranging (LiDAR)



If it flew over a football field, the first ICESat would have taken a measurement outside each end zone; ICESat-2 would take measurements within each yard line.

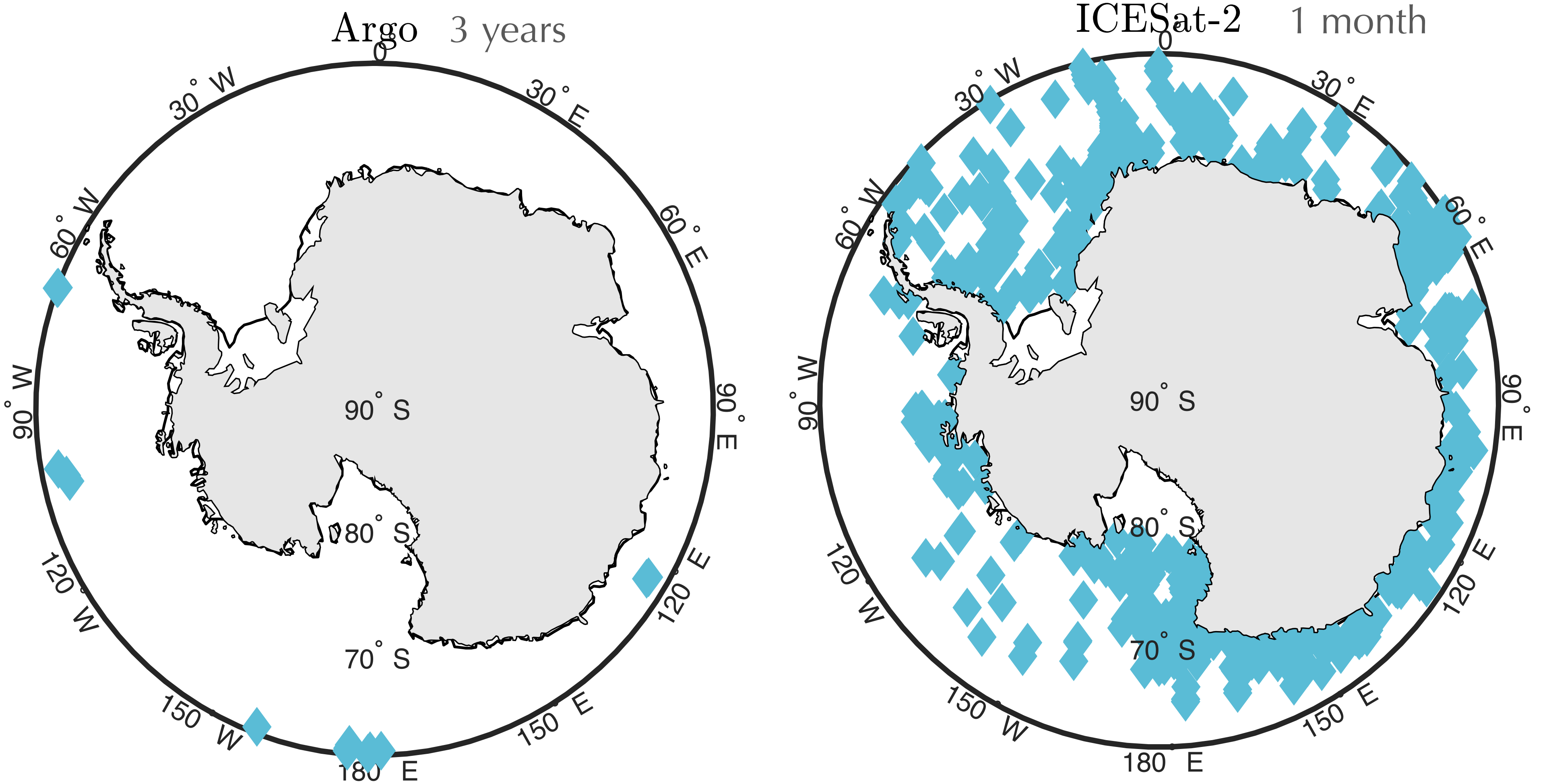
The pulses of light travel through a series of lenses and mirrors before beaming to the ground. This pathway along the optical bench serves to start the stopwatch on the timing mechanism, check the laser's wavelength, set the size of the ground footprint, ensure that the laser and the telescope are perfectly aligned, and split the laser into six beams.



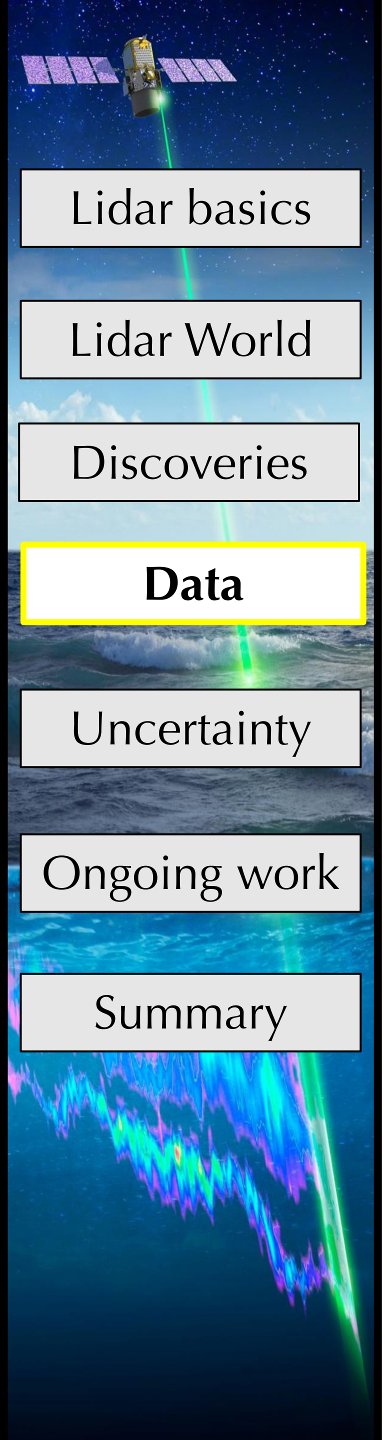
ICESat-2 ocean products

Product	What is it?	Used for?	References (Ocean focus)
ATL03	Global geolocated photon data	• Deriving optical information (Kd, bbp) in coastal and global waters • Bathymetry in shallow waters	Lu et al. 2020, 2021 , Eidam et al, 2022, Babbel et al, 2021, Parrish et al, 2019
ATL07 (ATL20)	Polar sea ice elevation (Gridded sea ice freeboard)	• Sea ice freeboard • Sea ice lead identification	Bisson and Cael, 2021
ATL12 (ATL19)	Ocean Elevation (Gridded sea surface height)	• Sea surface height	Bagnardi et al, 2021

ICESat-2 ocean products



(Left) Under ice Argo float location (approximate within 50km) during October 2018-2021. (Right) Location of sea ice leads longer than 200m during just October 2020 from the ATL10 product. Similar ICESat-2 coverage exists in the Arctic. (unpublished)



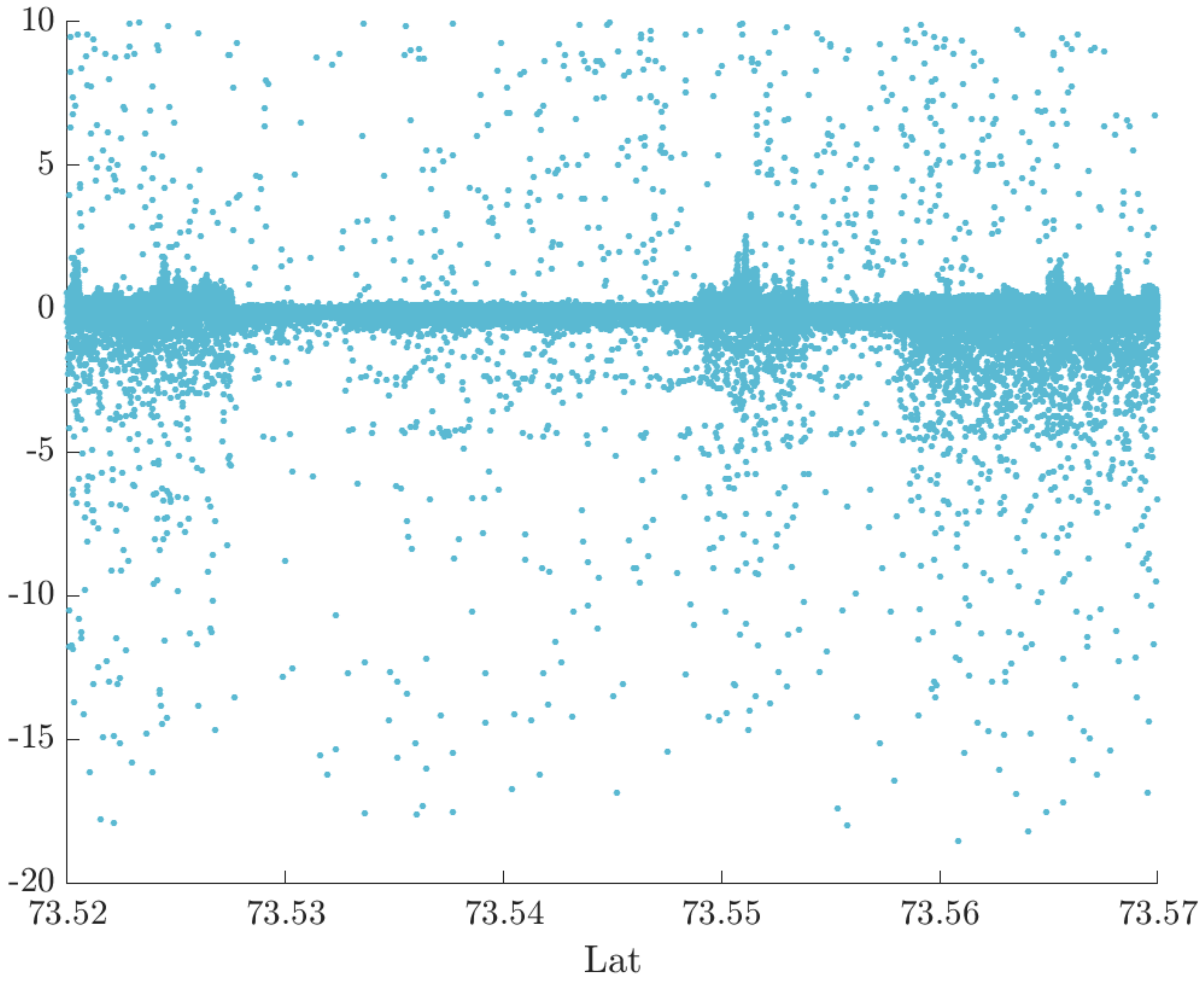
ICESat-2 data processing and access

Start from raw ATL03 photon height product, distributed in granules and organized into 3 pairs of strong and weak beams

$$C = \frac{S(0)}{\beta_s}$$

$$b_b(z) = \frac{m^2 S(z)\exp(2K_d z)}{\beta(\pi) C t^2}$$

m, t, C , β(π) are constants. K_d is calculated from ICESat-2 signal decay, S(z) is the signal.



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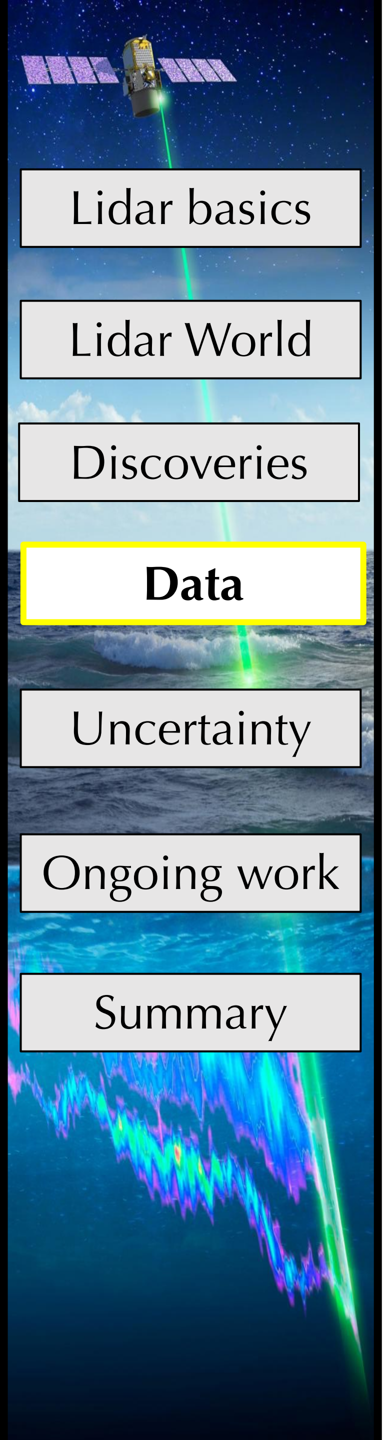
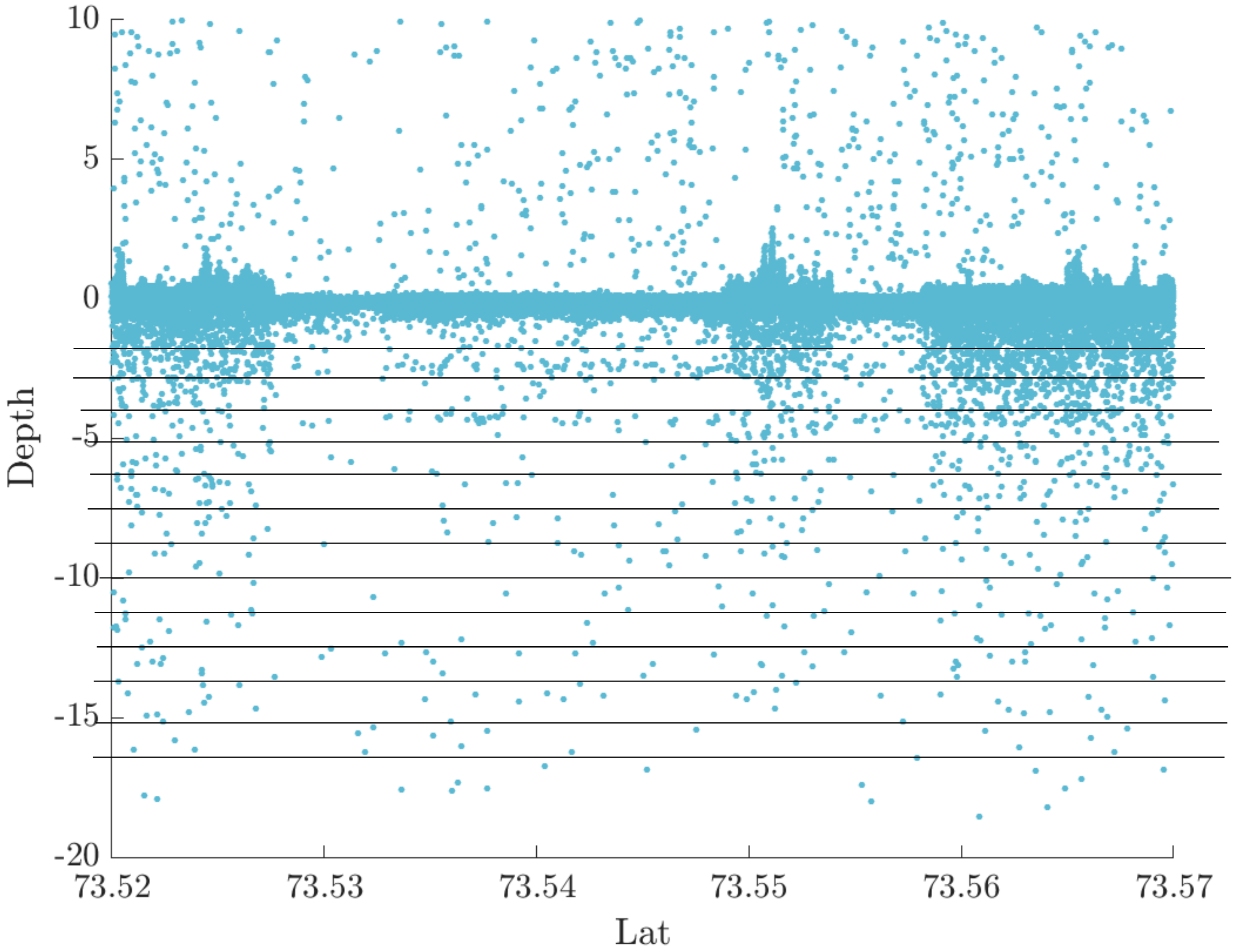
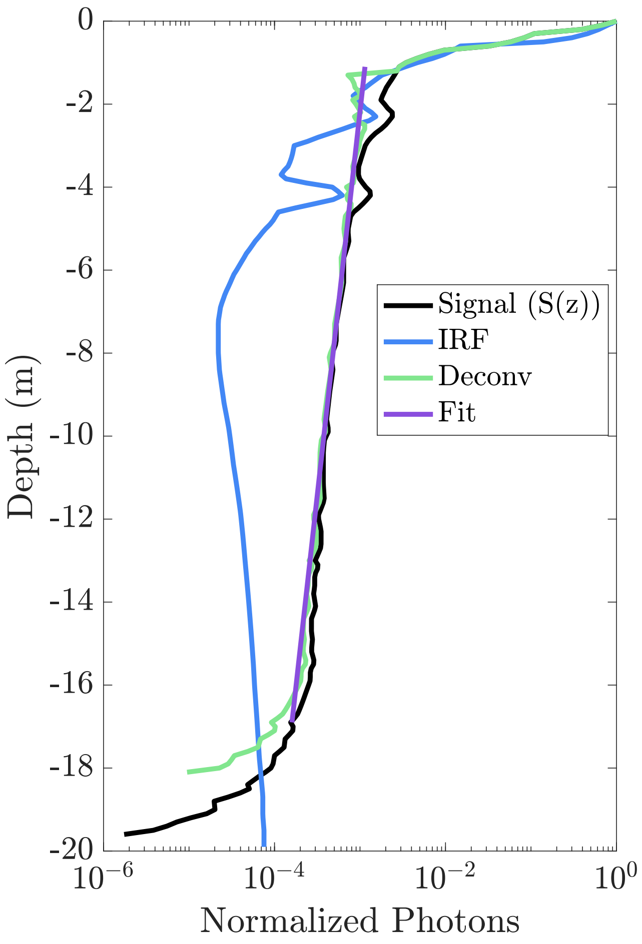
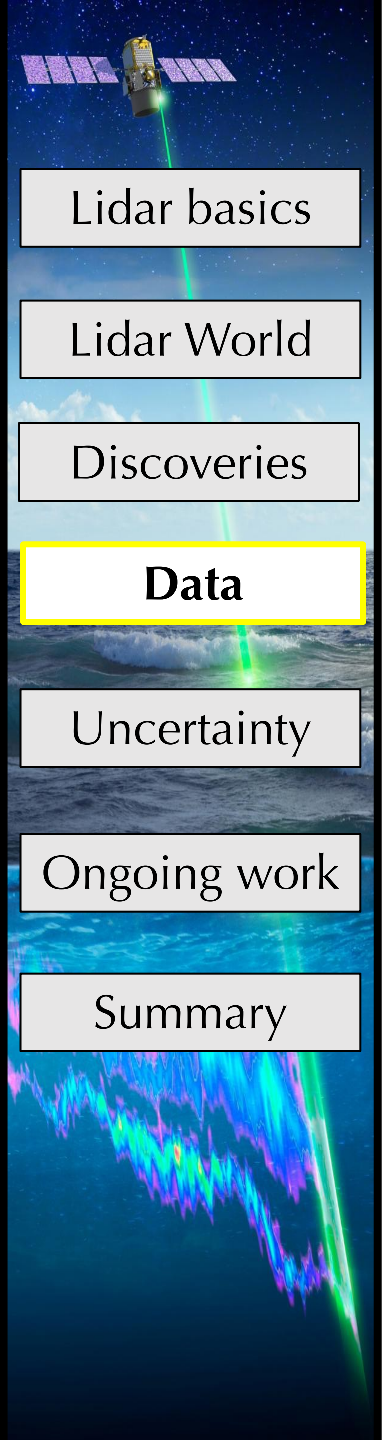


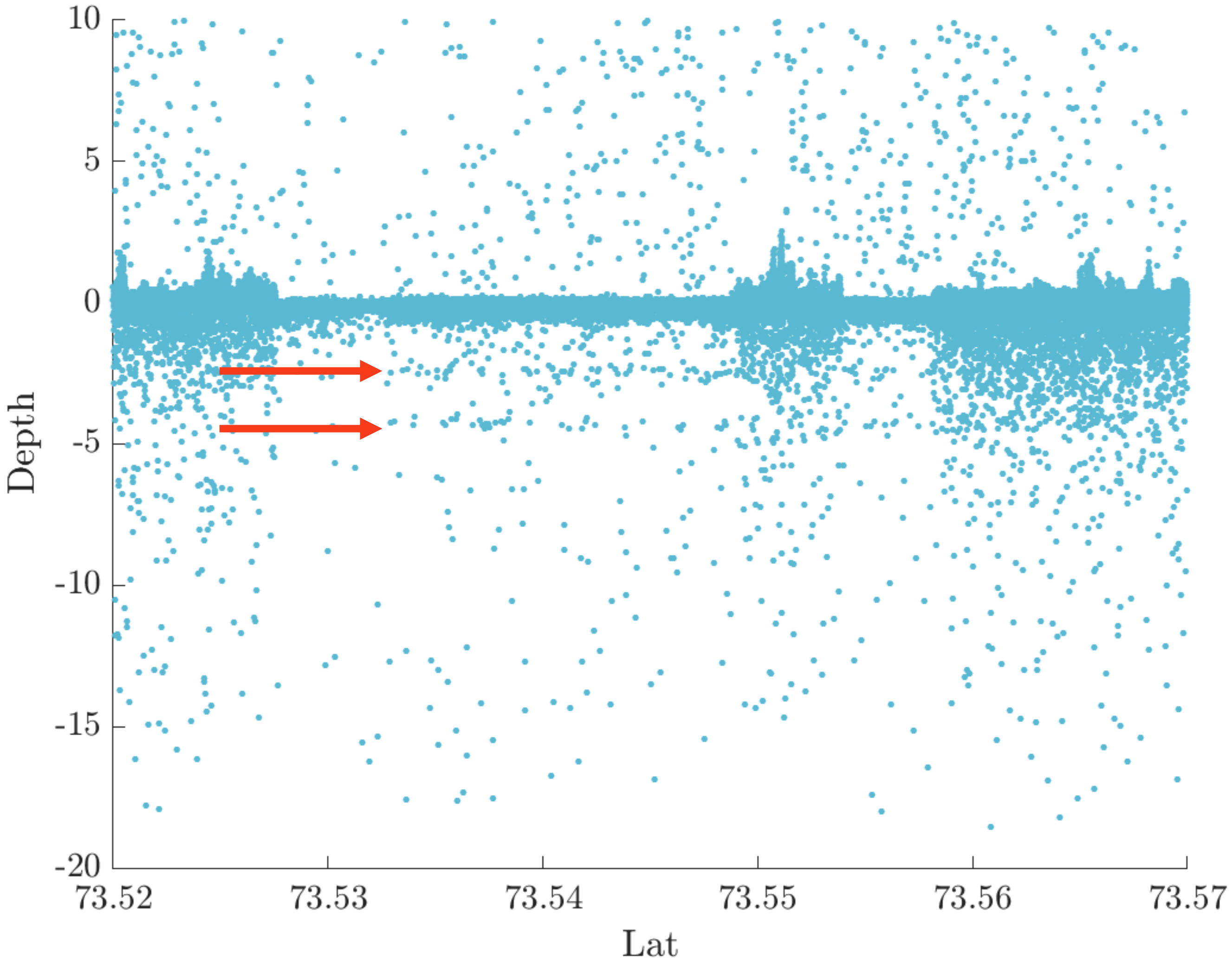


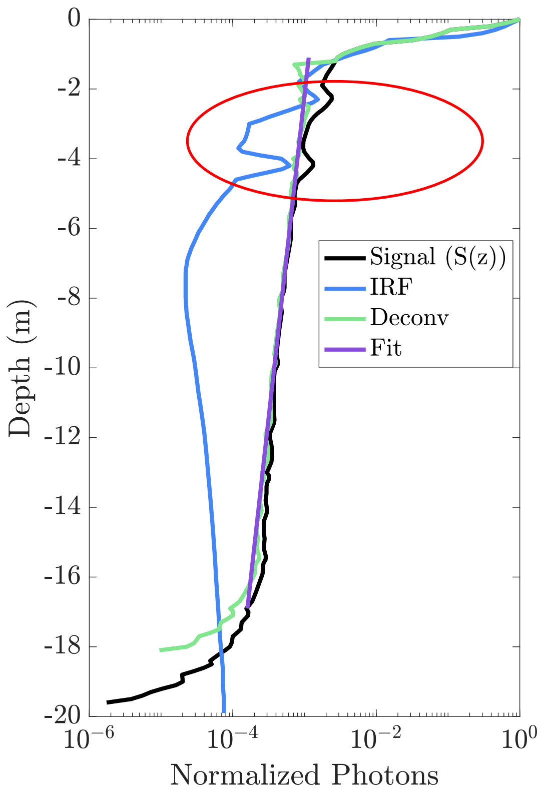




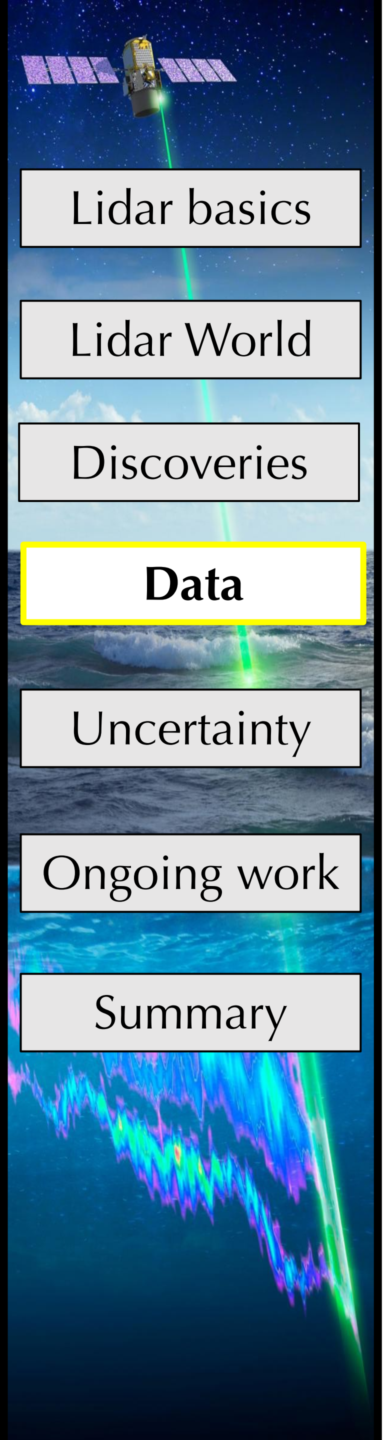
ICESat-2 data processing and access

After pulsing effects (instrument noise, not natural)





Demonstration of method to derive the effective attenuation coefficient from the exponential fit (purple) of the deconvolved signal, where the signal is in black, the impulse response function is blue, and the deconvolved signal with the afterpulse peaks removed is in green.



ICESat-2 data processing and access

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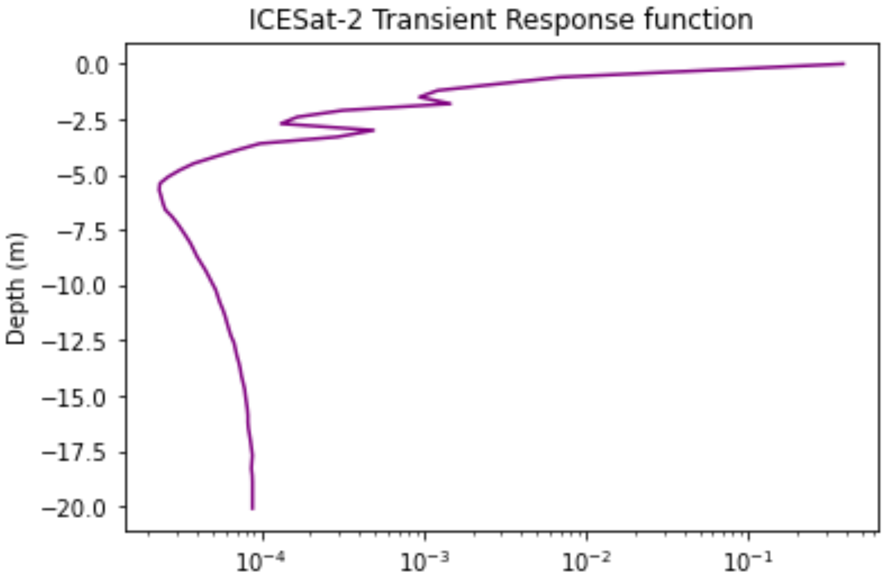
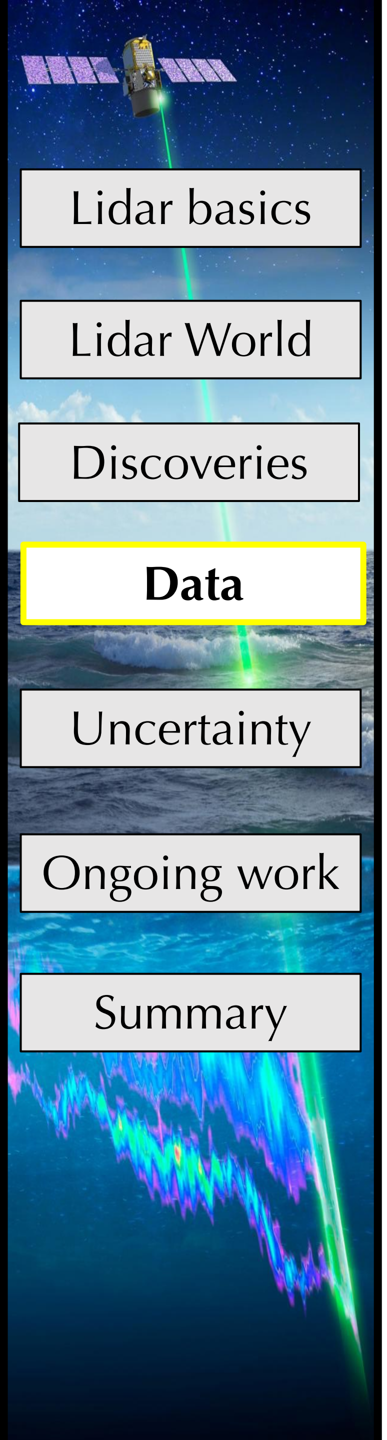


Deconvolution matrix informed by impulse response function

$$\begin{bmatrix} S_m(z_1) \\ S_m(z_2) \\ \dots \\ S_m(z_n) \end{bmatrix} = \begin{bmatrix} F(z_1) & 0 & \dots & 0 \\ F(z_2) & F(z_1) & \dots & 0 \\ \dots & \dots & \dots & \dots \\ F(z_n) & F(z_{n-1}) & \dots & F(z_1) \end{bmatrix} \begin{bmatrix} S(z_1) \\ S(z_2) \\ \dots \\ S(z_n) \end{bmatrix},$$

$$S(z) = \mathrm{F}^{-1}(\mathrm{z})\,\mathrm{S}_m(\mathrm{z})$$

1. Solve for signal by taking the inverse of the function above with the normalized signal previously
2. Then, calculate the effective attenuation coefficient from new signal



ICESat-2 data processing and access

$$S(z) = \mathbf{F}^{-1}(\mathbf{z})\,\mathbf{S}_m(\mathbf{z})$$

1. Solve for signal by taking the inverse of the function above with the normalized signal previously
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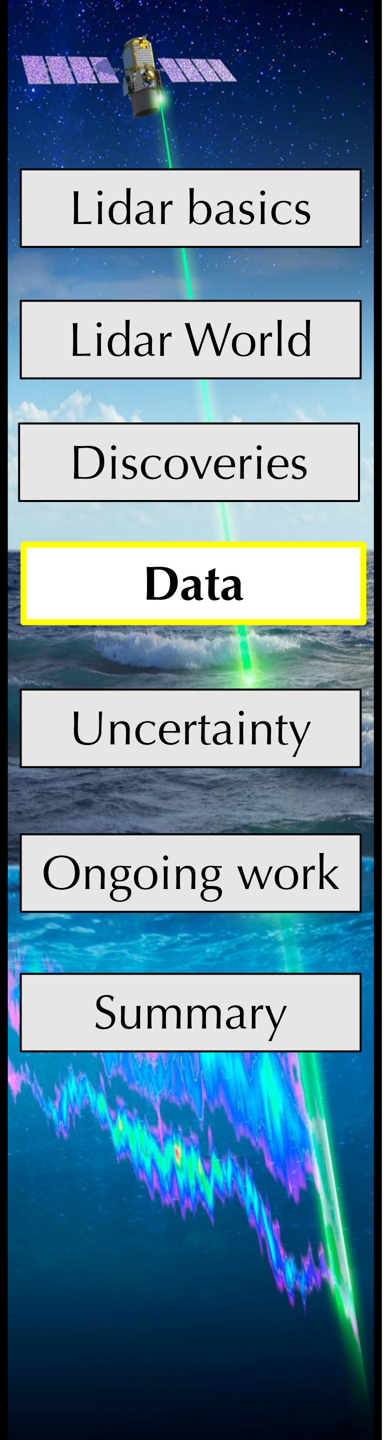
3. Calculate calibration constant from surface photons and theoretical backscatter from wind speed

$$\beta_s = \frac{0.0209}{4\pi\sigma^2 cos^4(\theta)} e^{\left(-\frac{tan^2(\theta)}{2\sigma^2}\right)}$$

σ^2 is the wave slope variance estimated from wind speed, or 0.003 + 0.00512v (v = wind speed in meters per second for winds between 7 and 13 m/s or 0.0146*sqrt(v) for winds < 7 m/s)

And θ is IS2's off nadir pointing angle (a max of 1.8 degrees)

GMAO wind speeds from MERRA-2 1-hourly instantaneous two-dimensional data products are used to compute theoretical estimates of ocean surface backscatter



ICESat-2 data processing and access

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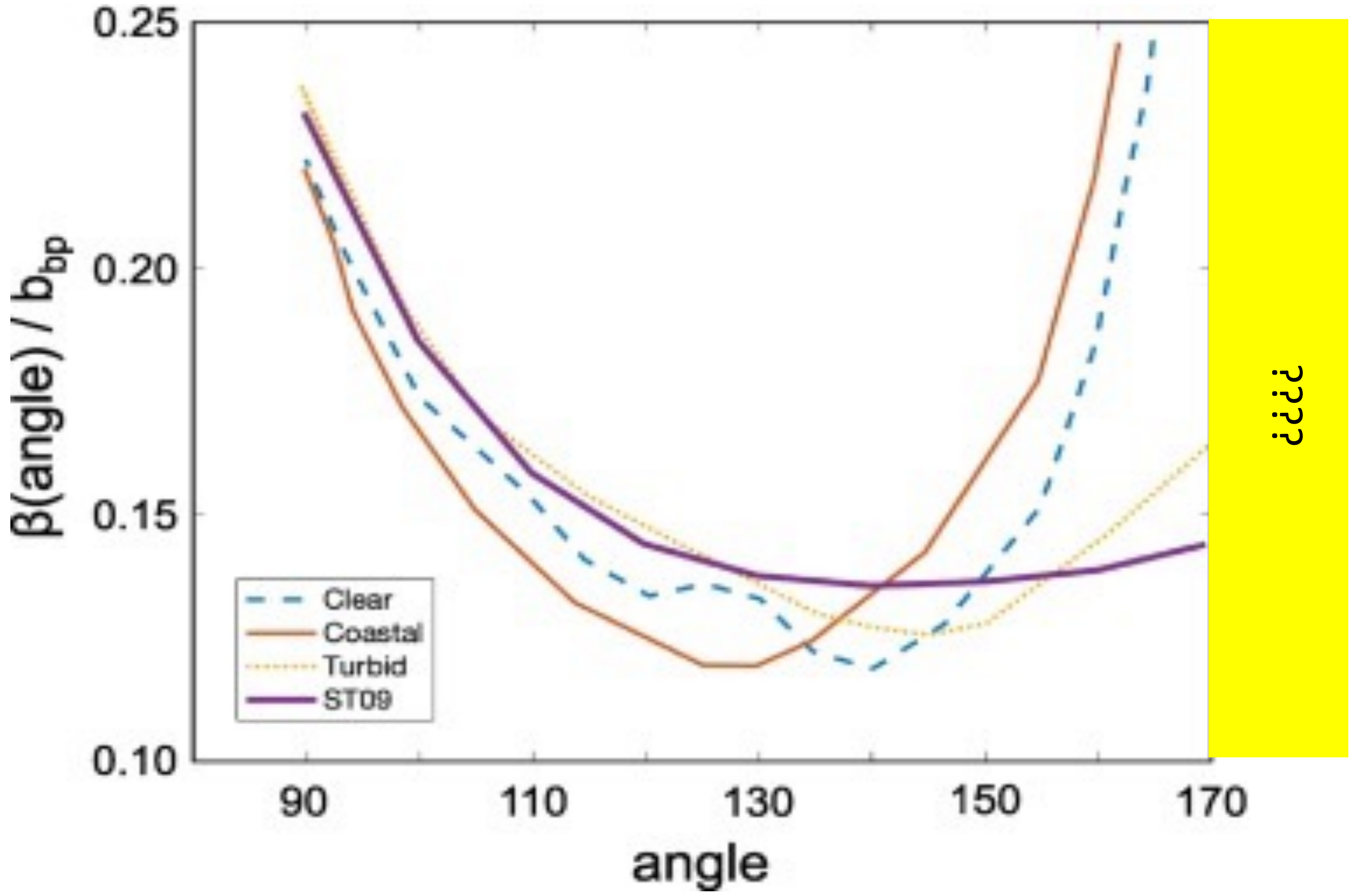
$$C = \frac{S(0)}{\beta_s}$$

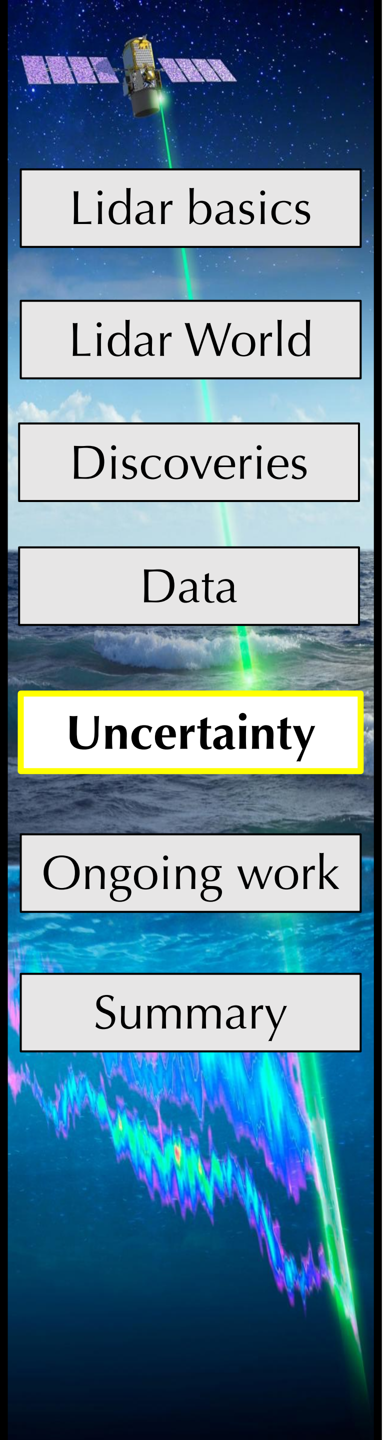
$$b_b(z) = \frac{m^2 S(z)\exp(2Kdz)}{\beta(\pi)Ct^2}$$

ICESat-2 data processing and access: Influence of beta(pi)



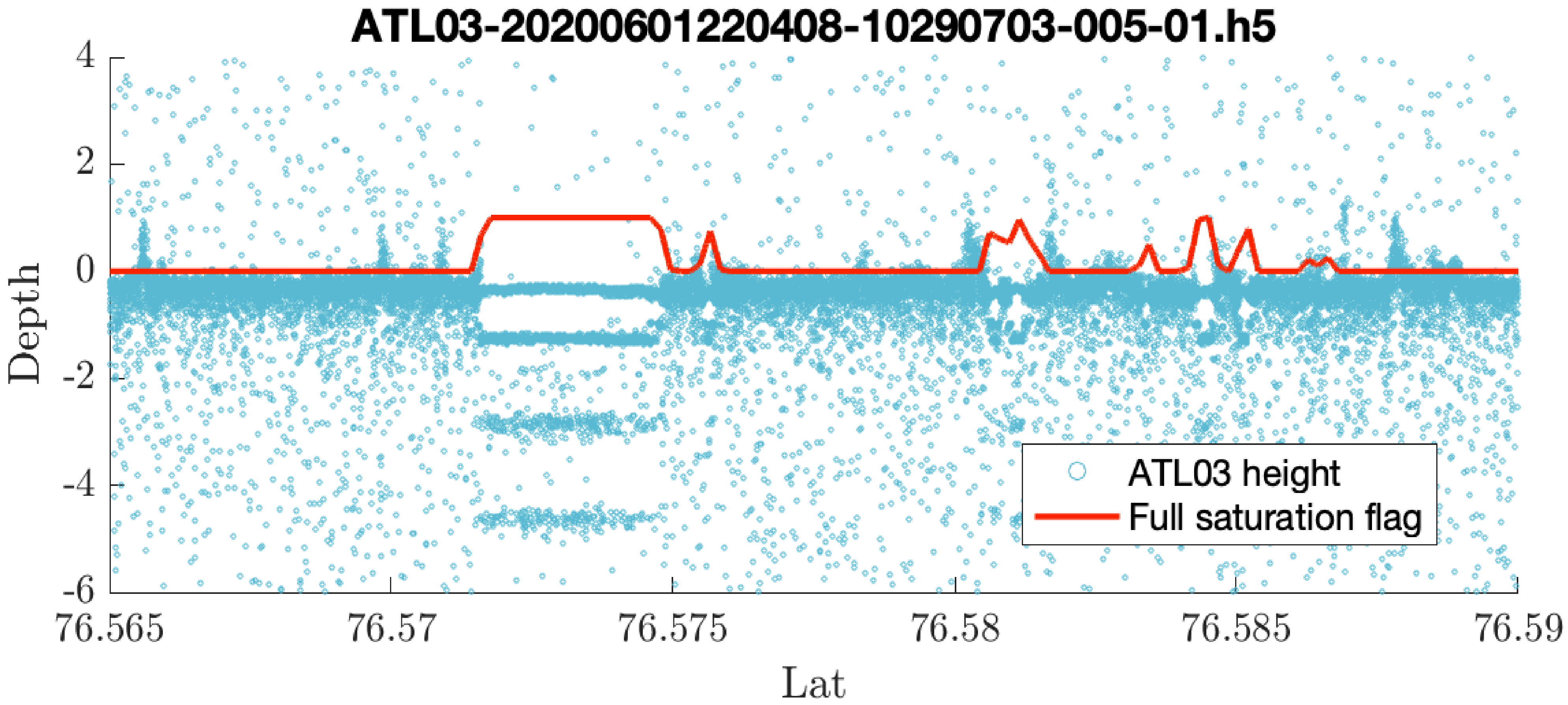
Large variation in this constant and the backscattering is proportional to it!

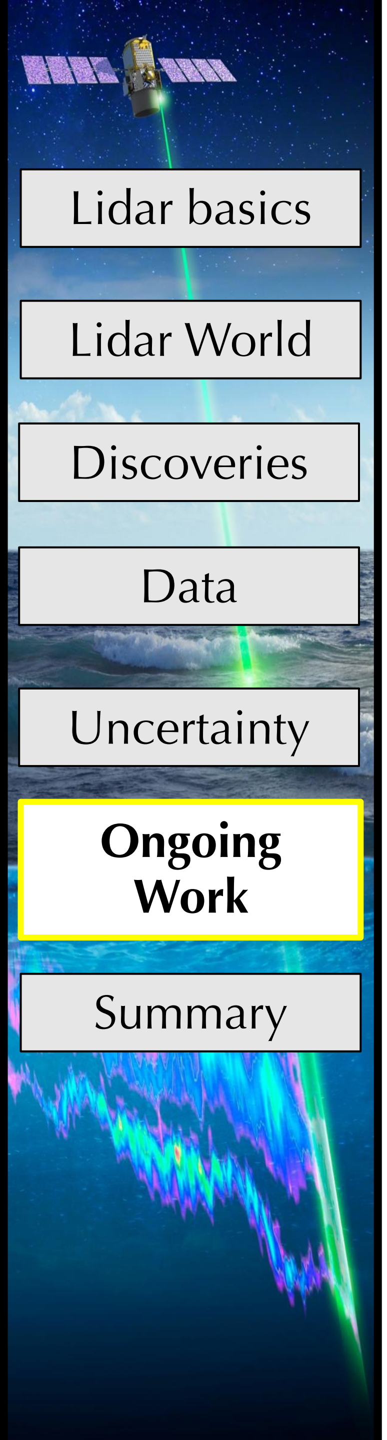
$$b_b(z) = \frac{m^2 S(z)\exp(2Kdz)}{\beta(\pi) C t^2}$$



ICESat-2 data processing, issues

If photon receiving channels are saturated, they stop recording photons … subsurface features will be present but appear unnatural due to dead time effects





Why collaborative open source science?

SCIENCE TEAM

The Science Team is a group of competitively selected scientists who help define and implement ICESat-2's science goals. They provide guidance and advice to the ICESat-2 project to ensure the mission meets its science requirements.

ANDELA, NIELS
Vegetation
NASA Goddard Space Flight Center

BISSON, KELSEY
Oceans
Oregon State University

BORAK, JORDAN
Vegetation
NASA Goddard Space Flight Center

CSATHO, BEA
Land Ice
University of Buffalo

EIDAM, EMILY
Oceanography
University of North Carolina

FARRELL, SINEAD
Sea Ice
University of Maryland

FATOYIMBO, LOLA
Vegetation
NASA GSFC Biospheric Sciences Laboratory

FELIKSON, DENIS
Land Ice
NASA Goddard Space Flight Center

FRICKER, HELEN
Ice sheets
University of California San Diego

GARDNER, ALEX
Ice sheets
NASA Jet Propulsion Lab

HANAN, NIALL
Vegetation
New Mexico State University

HERZFELD, UTE
Land ice
University of Colorado Boulder

HOLSCHUH, NICK
Land ice
Amherst College

HORVAT, CHRIS
Sea ice
Brown University

KWOK, RON
Sea ice
University of Washington Polar Science Center

LIPOVSKY, BRAD
Land ice
Harvard University

LU, XIAOMEI
Atmospheric Science
NASA LaRC/SSAI

MAGRUDER, LORI
Laser altimetry, Science Team Leader
University of Texas

ICESat-2

ICE, CLOUD, AND LAND ELEVATION SATELLITE-2

MAKSYM, TED
Sea ice
Woods Hole Oceanographic Institution

MORISON, JAMES
Arctic oceans
University of Washington

MORLIGHEM, MATHIEU
Land Ice
Dartmouth College

NEREM, STEVE
Oceanography
University of Colorado Boulder

NEUENSCHWANDER, AMY
Vegetation
University of Texas

PADMAN, LAURENCE
Antarctic oceanography
Earth & Space Research

PALM, STEVE
Atmospheric science
Science Systems and Applications, Inc.

POPESCU, SORIN
Vegetation
Texas A&M University

RYAN, JONATHAN
Hydrology
Brown University

SHAPERO, DANIEL
Hydrology
University of Washington

SIEGFRIED, MATTHEW
Land ice
Colorado School of Mines

SMITH, BEN
Ice sheets
University of Washington

STROEVE, JULIENNE
Sea ice
University of Colorado Boulder

THOMPSON, ANDY
Antarctic oceans
California Institute of Technology

TILLING, RACHEL
Sea ice
NASA Goddard Space Flight Center

VELICOGNA, ISABELLA
Ice sheets
University of California Irvine

Collaborative open source science

The Journal of Open Source Software

1Tb per day
Assess simplified in 3 lines of code
Written in object oriented programming
Adaptable, community forward

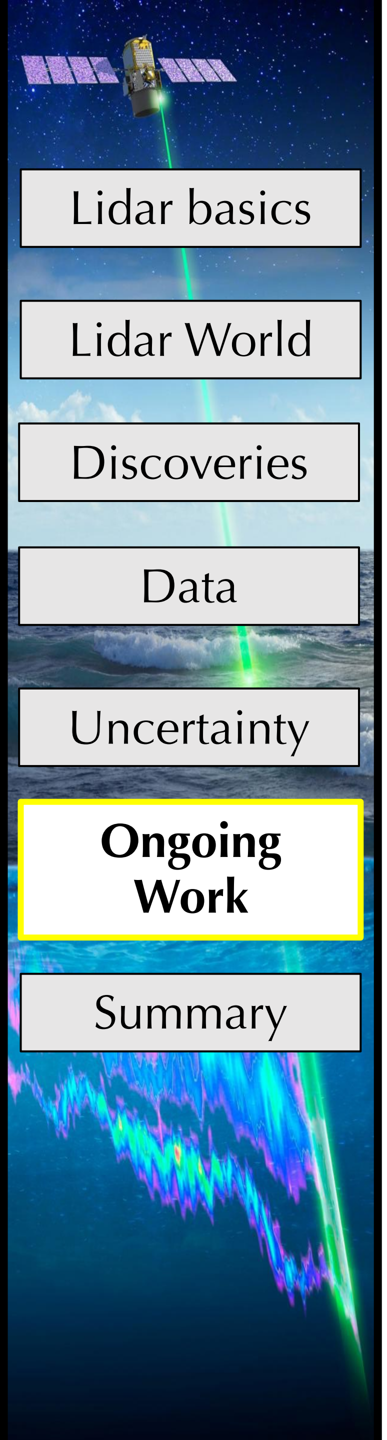
TOPS
TRANSFORM TO OPEN SCIENCE

icepyx: querying, obtaining, analyzing, and manipulating ICESat-2 datasets

Jessica Scheick[1¶], Wei Ji Leong[2], Kelsey Bisson[3], Anthony Arendt[4], Shashank Bhushan[4], Zachary Fair[5], Norland Raphael Hagen[6], Scott Henderson[4], Friedrich Knuth[4], Tian Li[7], Zheng Liu[4], Romina Piunno[8], Nitin Ravinder[9], Landung "Don" Setiawan[4], Tyler Sutterley[4], JP Swinski[5], and Anubhav[10]

1 University of New Hampshire, USA **2** Development Seed, USA **3** Oregon State University, USA **4** University of Washington, USA **5** NASA Goddard Space Flight Center, USA **6** CarbonPlan, USA **7** University of Bristol, UK **8** University of Toronto, Canada **9** University of Leeds, UK **10** University of Maryland, College Park, USA ¶ Corresponding author

DOI: 10.21105/joss.04912



Can lidar and ocean color be combined to get the best of both worlds?

If bb is known from lidar, reduces the amount of parameters to be solved for and possibly constrains solutions more accurately

(assuming bb and Rrs are accurate, as well as Rrs to absorption relationships)

r_{rs} Inversion refresher

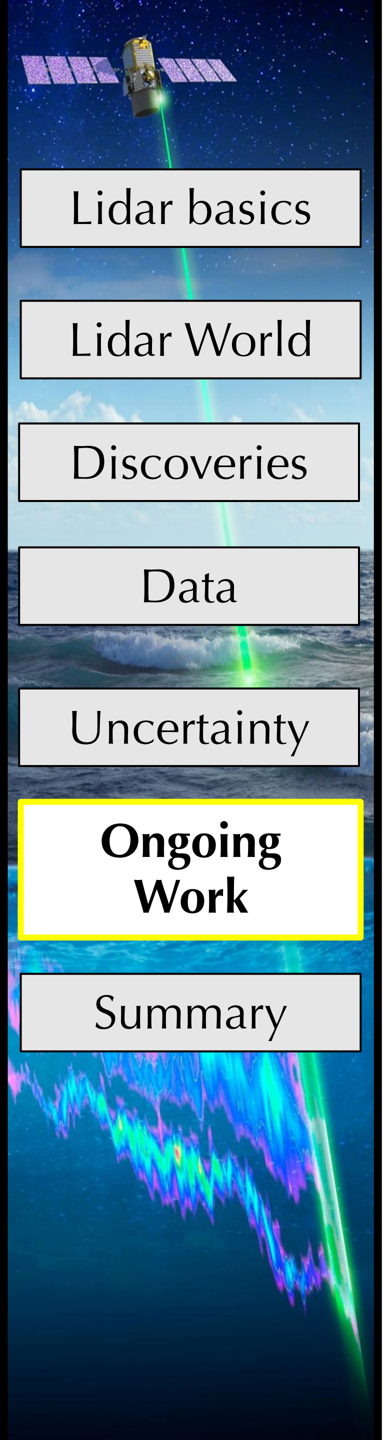
r_{rs} is ∝ the ratio of scattering to scattering + absorption

$$r_{rs}(\lambda) = \sum_{\iota=1}^{2} G_i * [\frac{b_b(\lambda)}{a(\lambda) + b_b(\lambda)}]^i$$

And absorption (a) is the sum of all absorbing constituents (spectrally) and backscattering (b_b) is the sum of backscattering from seawater and from particles.

$$a(\lambda) = a_w(\lambda) + M_{cdm} e^{-S_{cdm}\lambda} + M_{ph} a*_{ph}(\lambda)$$

$$b_b(\lambda) = b_{bw}(\lambda) + M_{bp}\, \lambda^{-\gamma},$$



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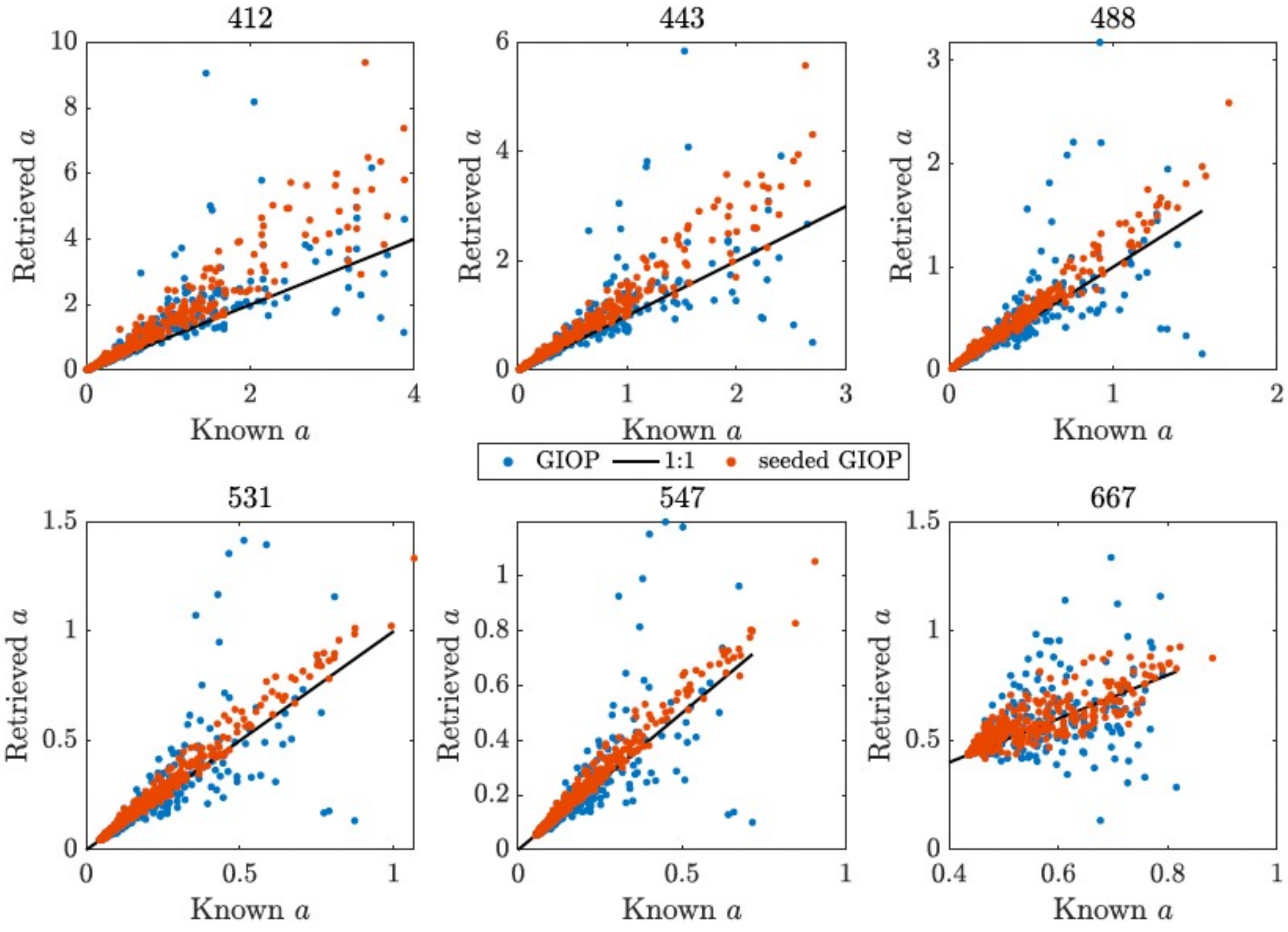
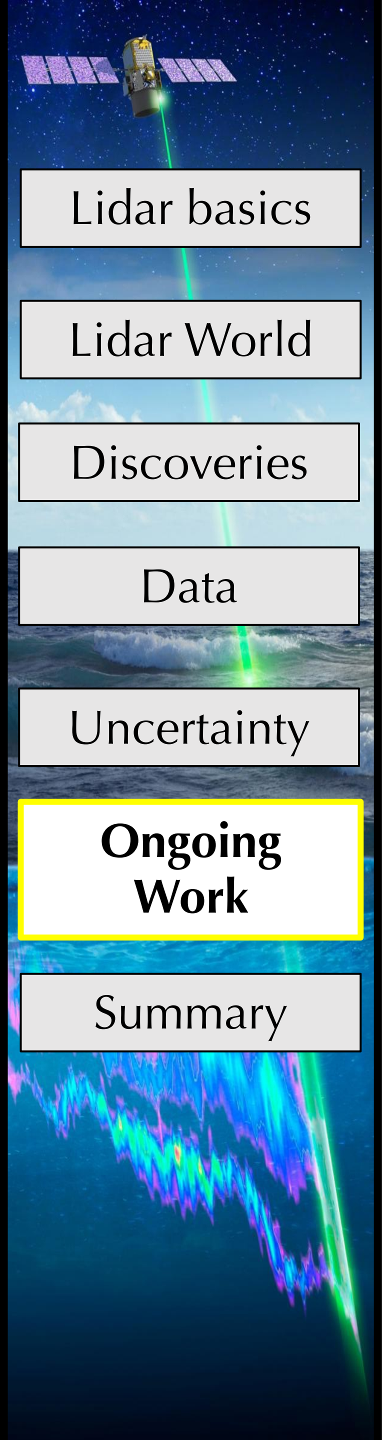


Simulated data case using theoretically derived data shows good proof of concept

(think hydrolight runs!)

Bisson and friends, in review



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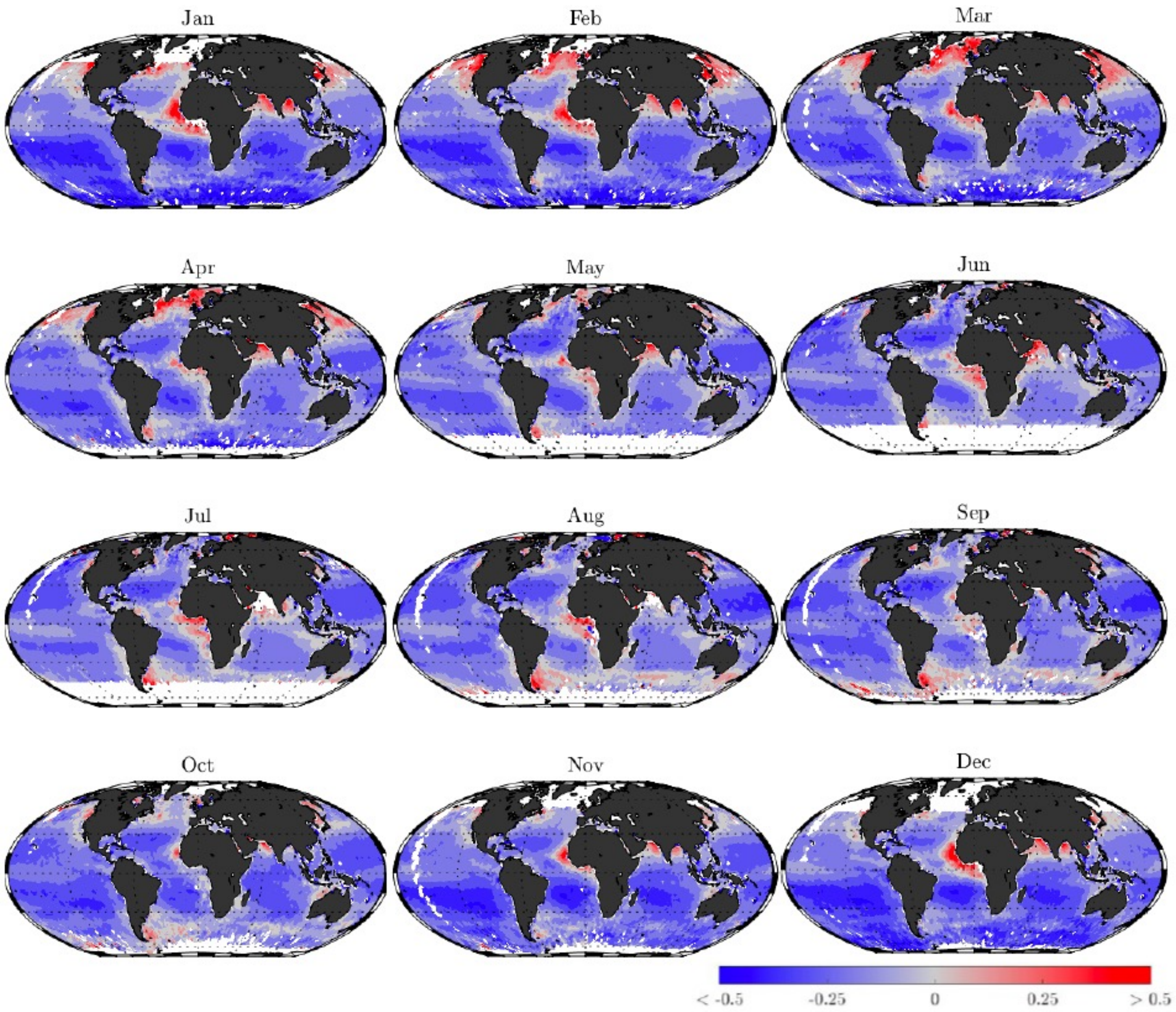
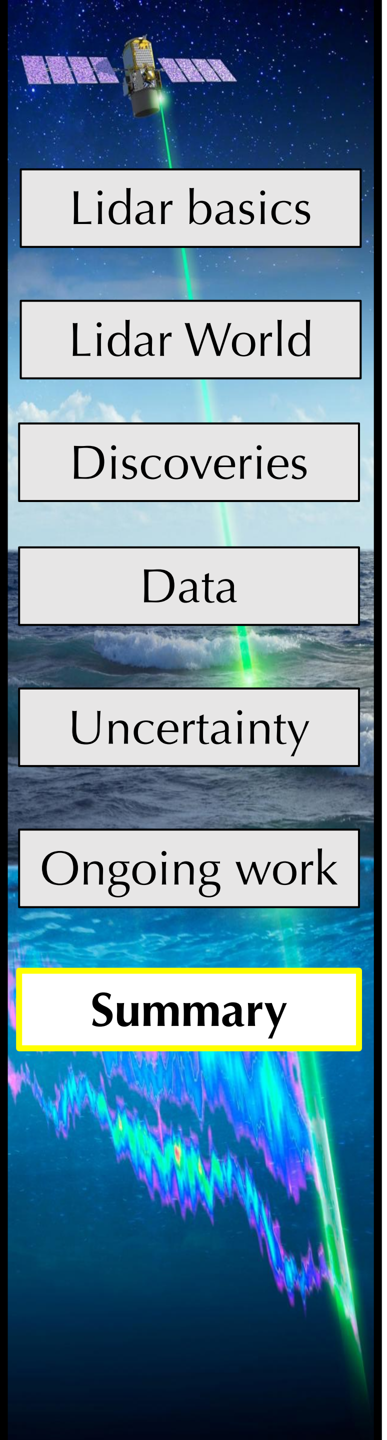


Bisson and friends, in review

Relative differences on global scales between standard absorption and lidar-derived absorption show differences greater than 50% in some places

Need more field absorption data to understand which is more correct…



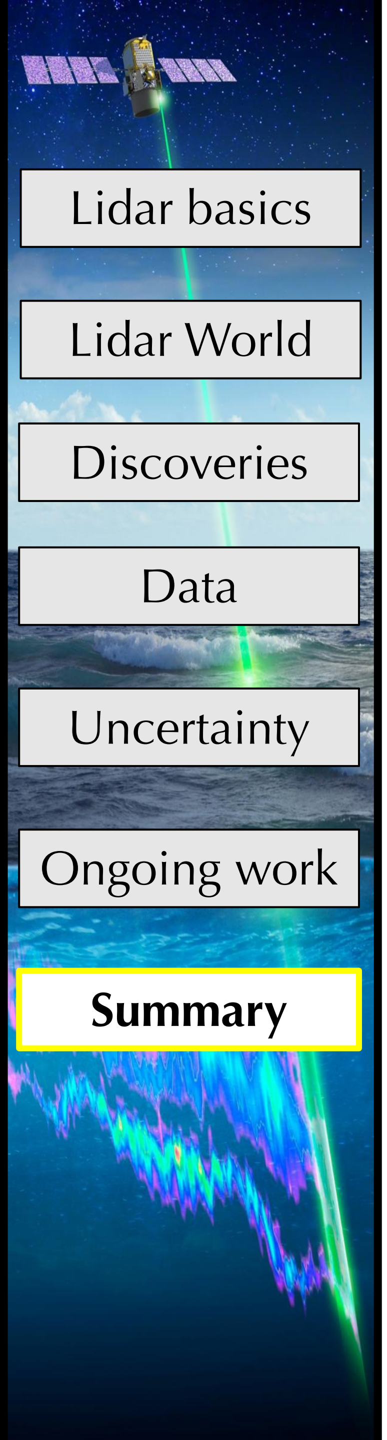
Advantages:

- Lidar provides impendent source of optical properties…closure
- Lidar b_{bp} is more accurate and less temporally biased than ocean color b_{bp}.
- Lidar 'sees' into incredible features like sea ice cracks and subsurface ocean bathymetry, enabling research from polar ecosystems to coral health
- Polarization offers additional data and features to be examined (not discussed today)

Challenges:

Processing is under constant development, no routine centralized route yet
Data require cloud computing or server storage – 1TB per day under ICESat-2
Methods rely on good beta(pi) values, which are uncertain, so field data are needed to confirm realism often

BUT -- this creates ripe opportunities for funding, publications (low fruit), and synergies across disciplines !!!



Spaceborne Lidar in the Study of Marine Systems

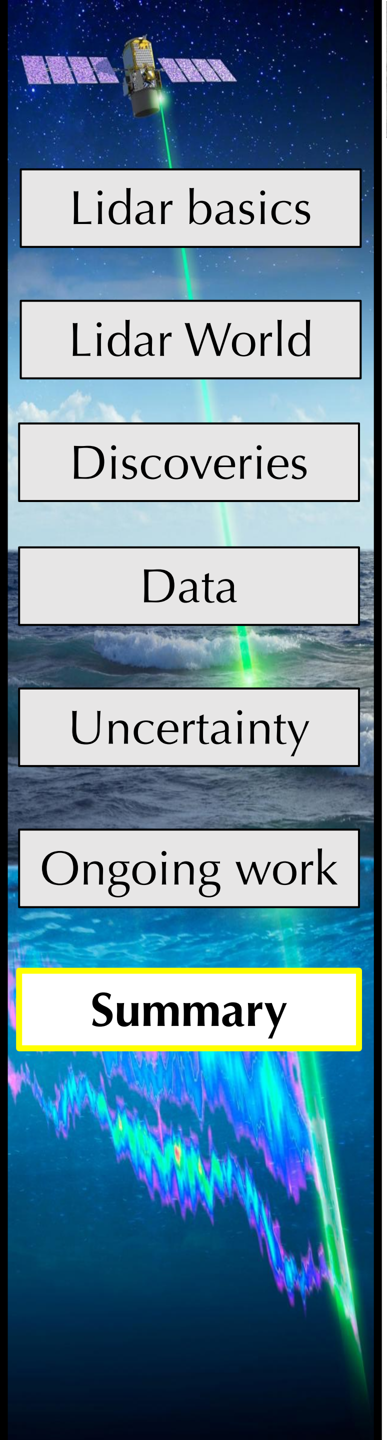
Annual Review of Marine Science
Vol. 10:121-147 (Volume publication date January 2018)
First published as a Review in Advance on September 27, 2017
https://doi.org/10.1146/annurev-marine-121916-063335

Chris A. Hostetler,[1] Michael J. Behrenfeld,[2] Yongxiang Hu,[1] Johnathan W. Hair,[1] and Jennifer A. Schulien[2]
[1]Langley Research Center, National Aeronautics and Space Administration, Hampton, Virginia 23681-2199, USA; email: chris.a.hostetler@nasa.gov
[2]Department of Botany and Plant Pathology, Oregon State University, Corvallis, Oregon 97331-2902, USA

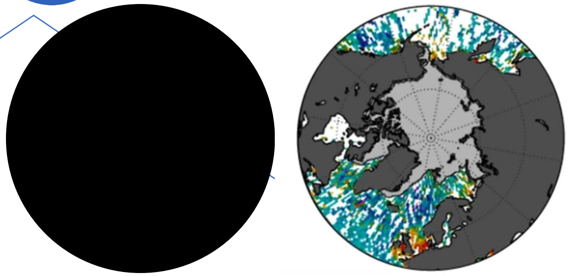
Future reading

Going Beyond Standard Ocean Color Observations: Lidar and Polarimetry

Cédric Jamet[1], Amir Ibrahim[2,3]*, Ziauddin Ahmad[2,4], Federico Angelini[5], Marcel Babin[6], Michael J. Behrenfeld[7], Emmanuel Boss[8], Brian Cairns[9], James Churnside[10], Jacek Chowdhary[9], Anthony B. Davis[11], Davide Dionisi[12], Lucile Duforêt-Gaurier[1], Bryan Franz[2], Robert Frouin[13], Meng Gao[2,3,14], Deric Gray[15], Otto Hasekamp[16], Xianqiang He[17], Chris Hostetler[18], Olga V. Kalashnikova[11], Kirk Knobelspiesse[2], Léo Lacour[6], Hubert Loisel[1], Vanderlei Martins[14], Eric Rehm[6], Lorraine Remer[14], Idriss Sanhaj[19], Knut Stamnes[20], Snorre Stamnes[18], Stéphane Victori[19], Jeremy Werdell[2] and Peng-Wang Zhai[14]*



1 *Lidar observes in polar night*

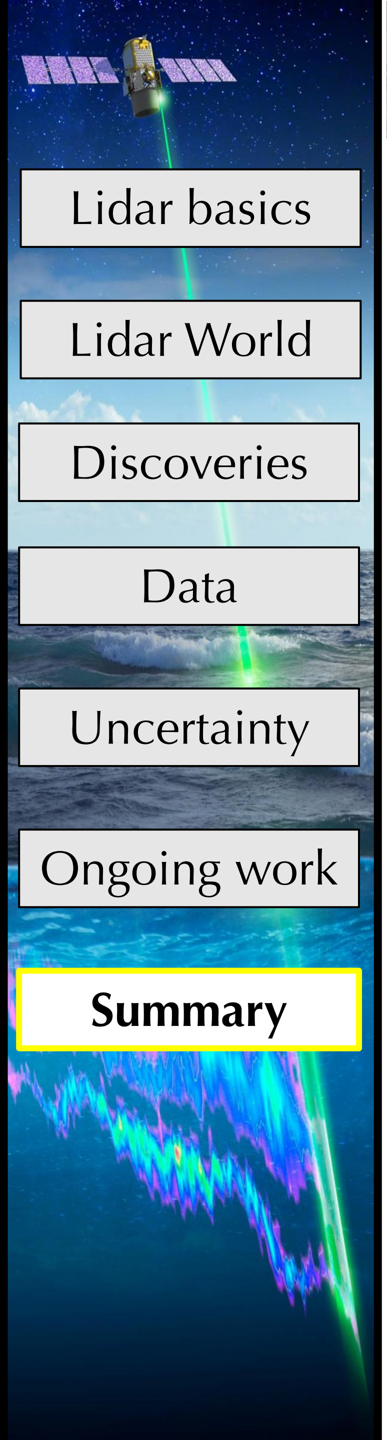


2 *Lidar bbp outperforms ocean color*

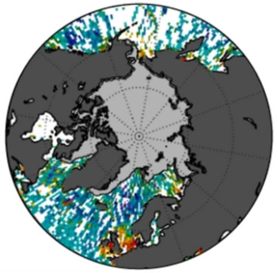
3 *Lidar offers vertical resolution*

4 *Data processing is paramount*

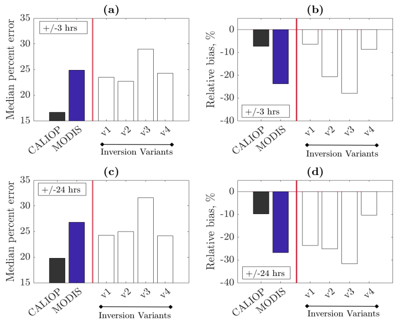
5 *Open source science is > current culture*



1 *Lidar observes in polar night*



2 *Lidar bbp outperforms ocean color*



3 *Lidar offers vertical resolution*

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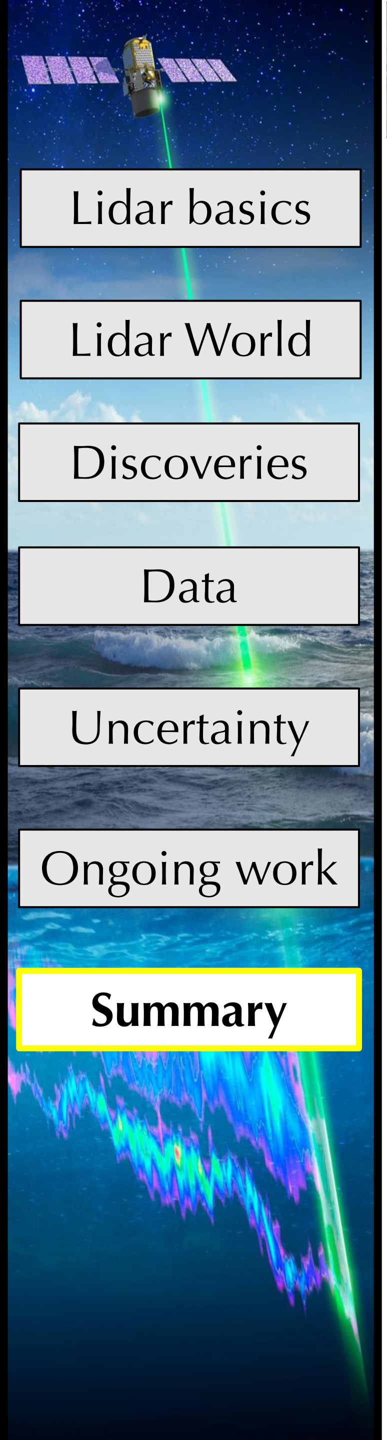

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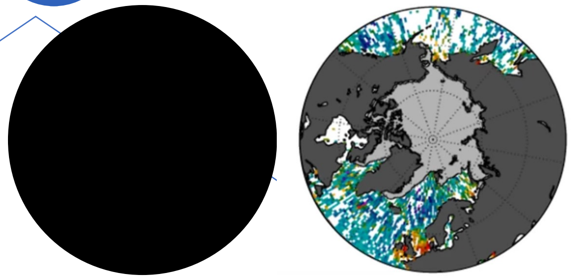

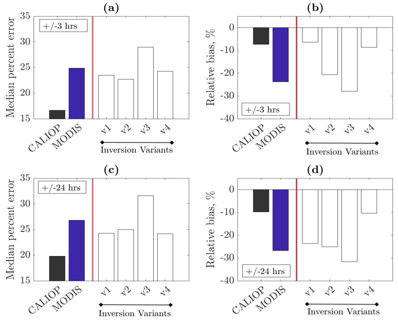

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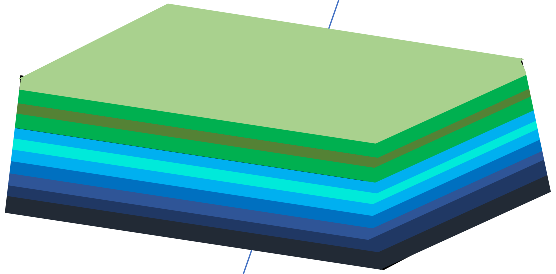

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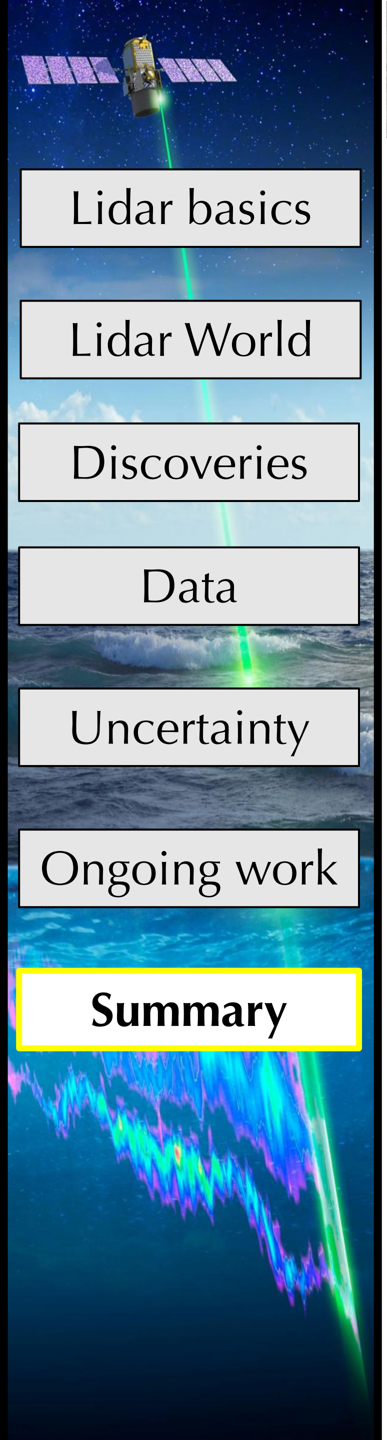

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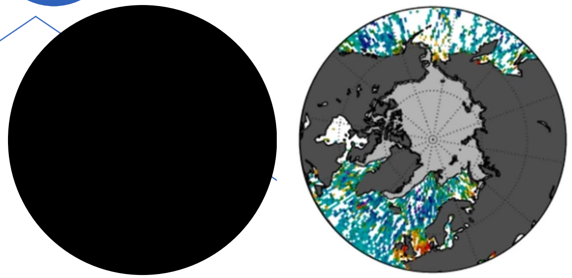

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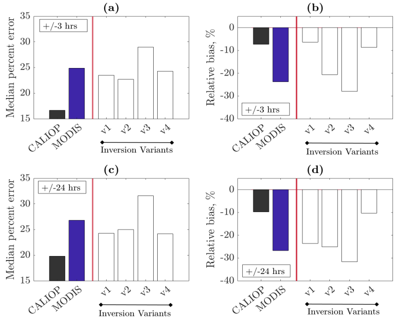

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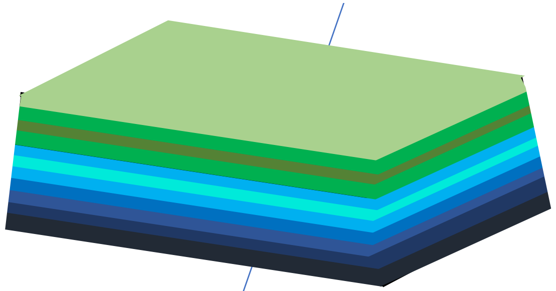

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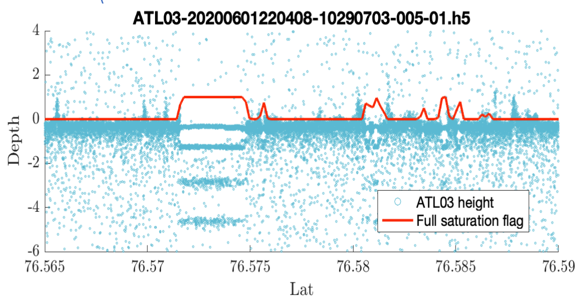

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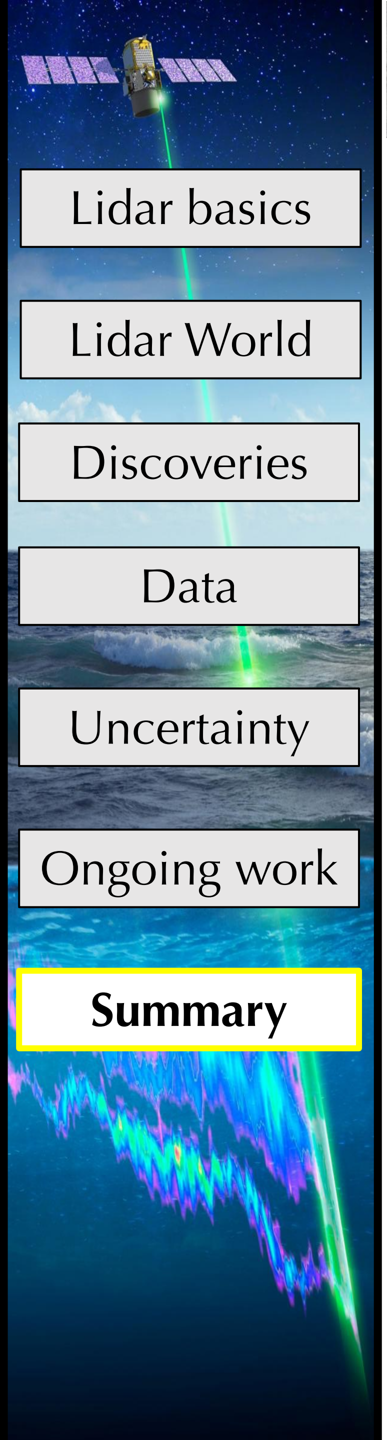

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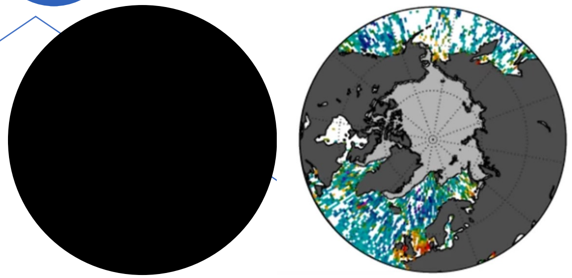

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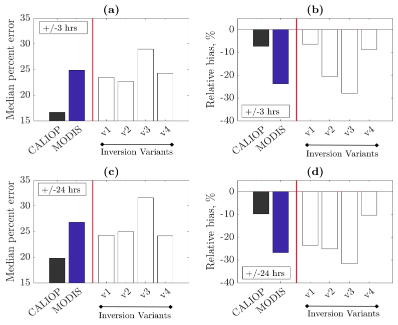

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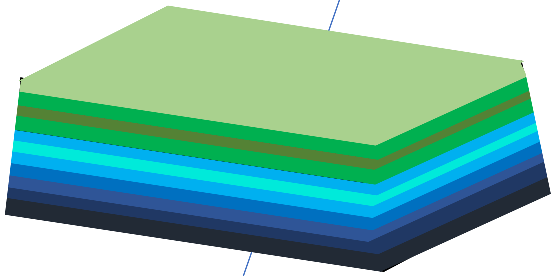

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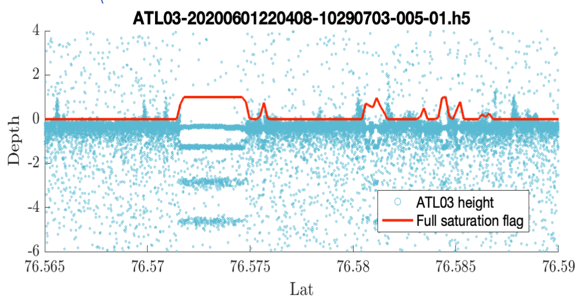

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