Ocean Profiles from Airborne Lidar

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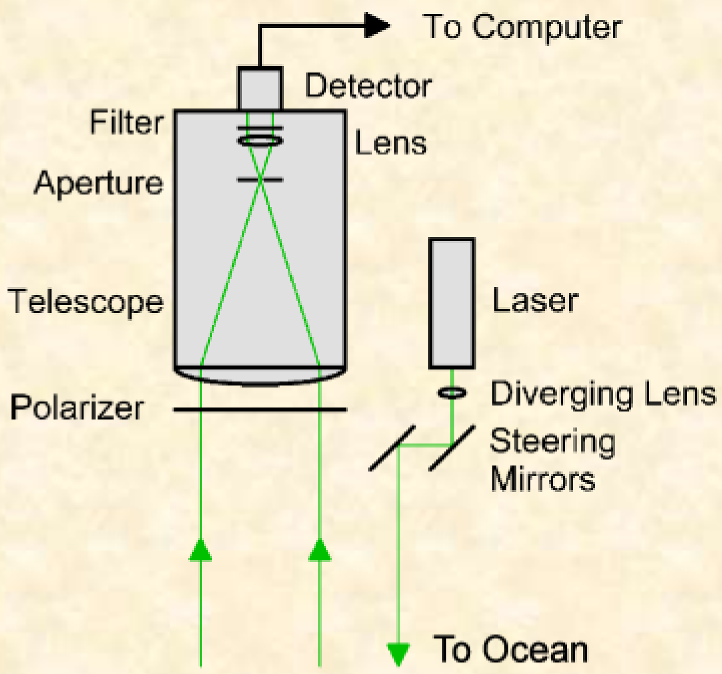
What is a profiling lidar?

- A short pulse of laser light is directed into the sea. As it propagates downward, a small fraction is scattered back toward the lidar, where it is collected by a telescope and converted to an electric signal by a photodetector. Depth is inferred from round-trip propagation time.
- Generally, the beam is not scanned, so the data are backscatter as a function of depth and of distance along the flight track. This is different from a digital elevation mapping lidar or a bathymetric lidar.
- Light penetrates the air/sea interface, so we can operate lidar from an aircraft.
- Light is absorbed by sea water, so we are limited in depth penetration to 50 m or less, depending on water clarity.

Existing Airborne Systems

- NOAA Fish Lidar – 532 nm wavelength; 100 mJ laser pulses at 30 Hz; two polarized receiver channels
- NASA High-Spectral-Resolution Lidar (HSRL) Lidar – 532 nm wavelength; 2.5 mJ laser pulses at 4 kHz; two polarized receiver channels plus one channel with particulate scattering blocked

NOAA Lidar Characteristics



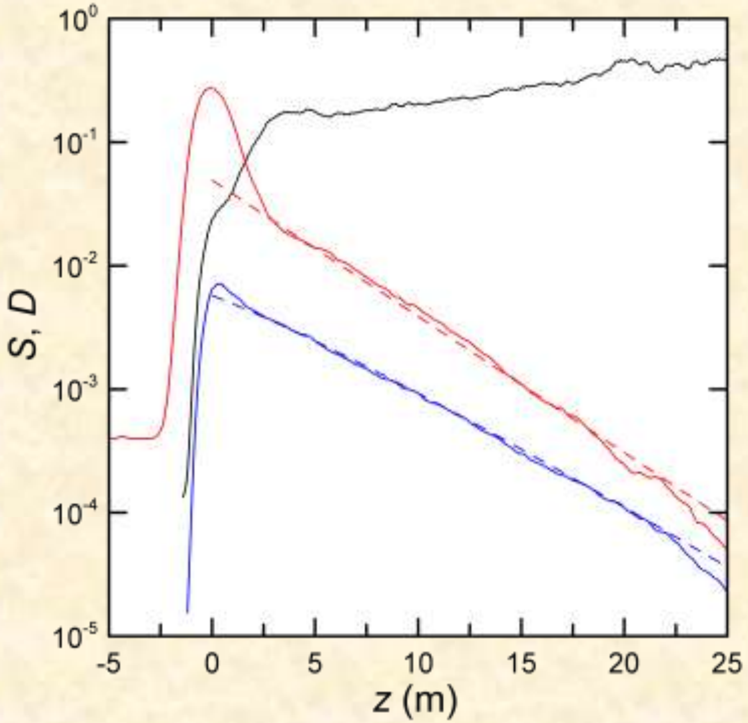
Transmitter

- 532 nm wavelength
- 10 ns pulse length
- 100 mJ pulse energy
- 30 Hz pulse rep. rate
- Linear polarization
- 5 m diameter on surface

Receivers (1 of 2 shown)

- Co- and cross-polarized (separate telescopes)
- 80 dB log-amp
- 1 GHz digitizer

Lidar Profile



- Red line is signal, *S*, for the co-polarized lidar return, along with exponential fit.
- Blue line is cross-polarized return.
- Black line is depolarization ratio, *D*, increasing because of multiple scattering.

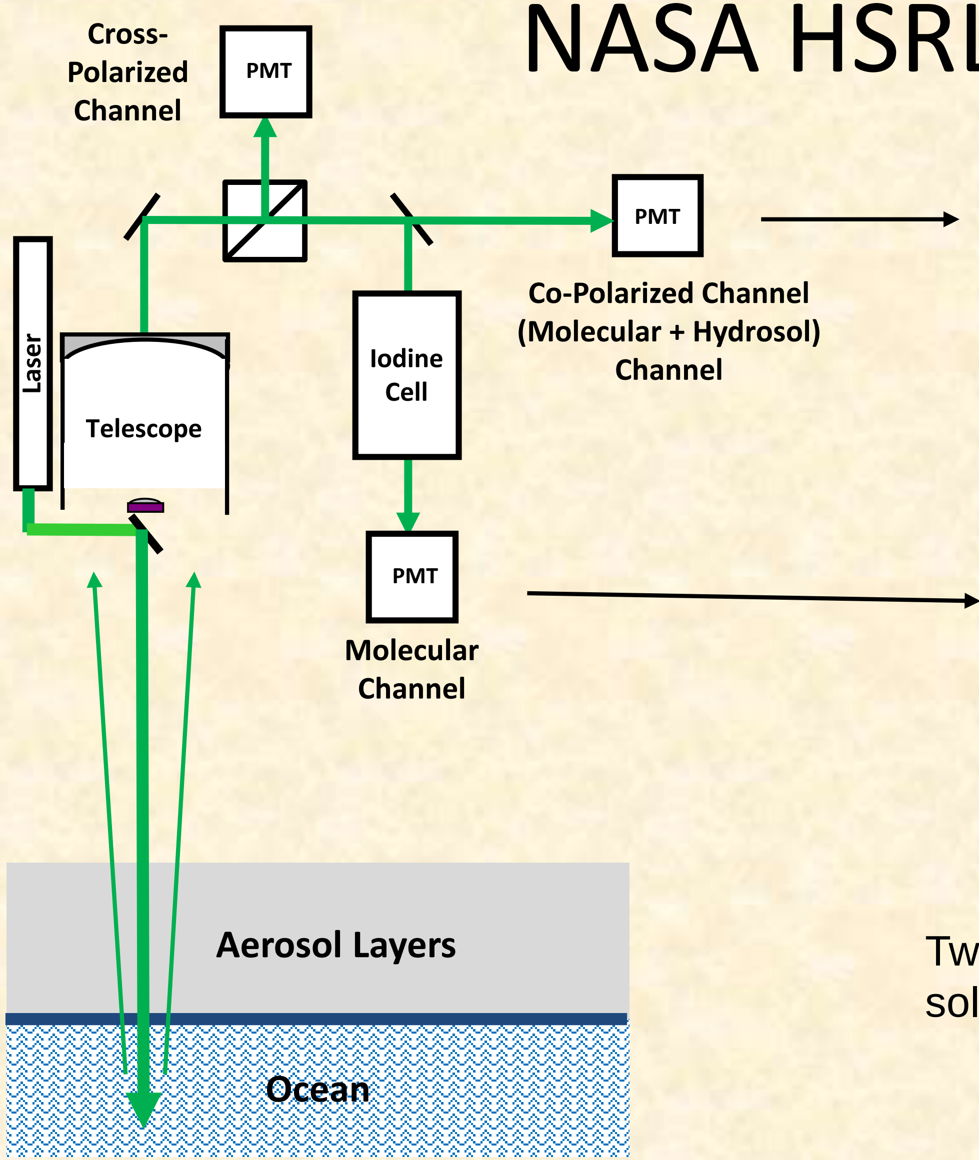
$$S_{\|} = A\beta_{\pi}\left(z\right)\exp\left[-2\int_{0}^{z}\alpha\left(z'\right)dz'\right]$$

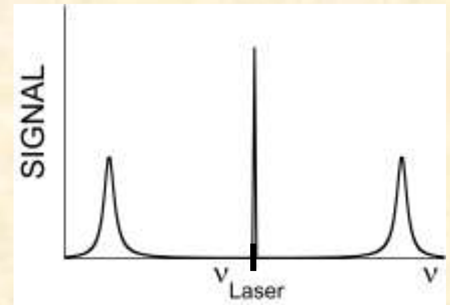
NOAA Lidar

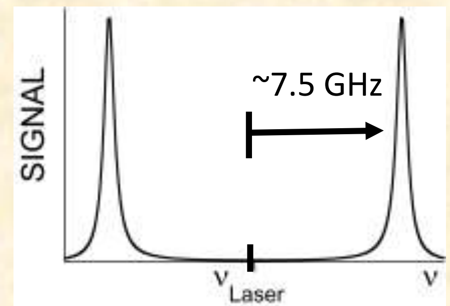
On four seat Cessna

On NOAA Twin Otter

NASA HSRL-1







Two channels give two equations to solve for two unknowns:

– $\beta_p(\pi)$ (converts to b_{bp})
– Attenuation (K_d)

NASA HSRLs

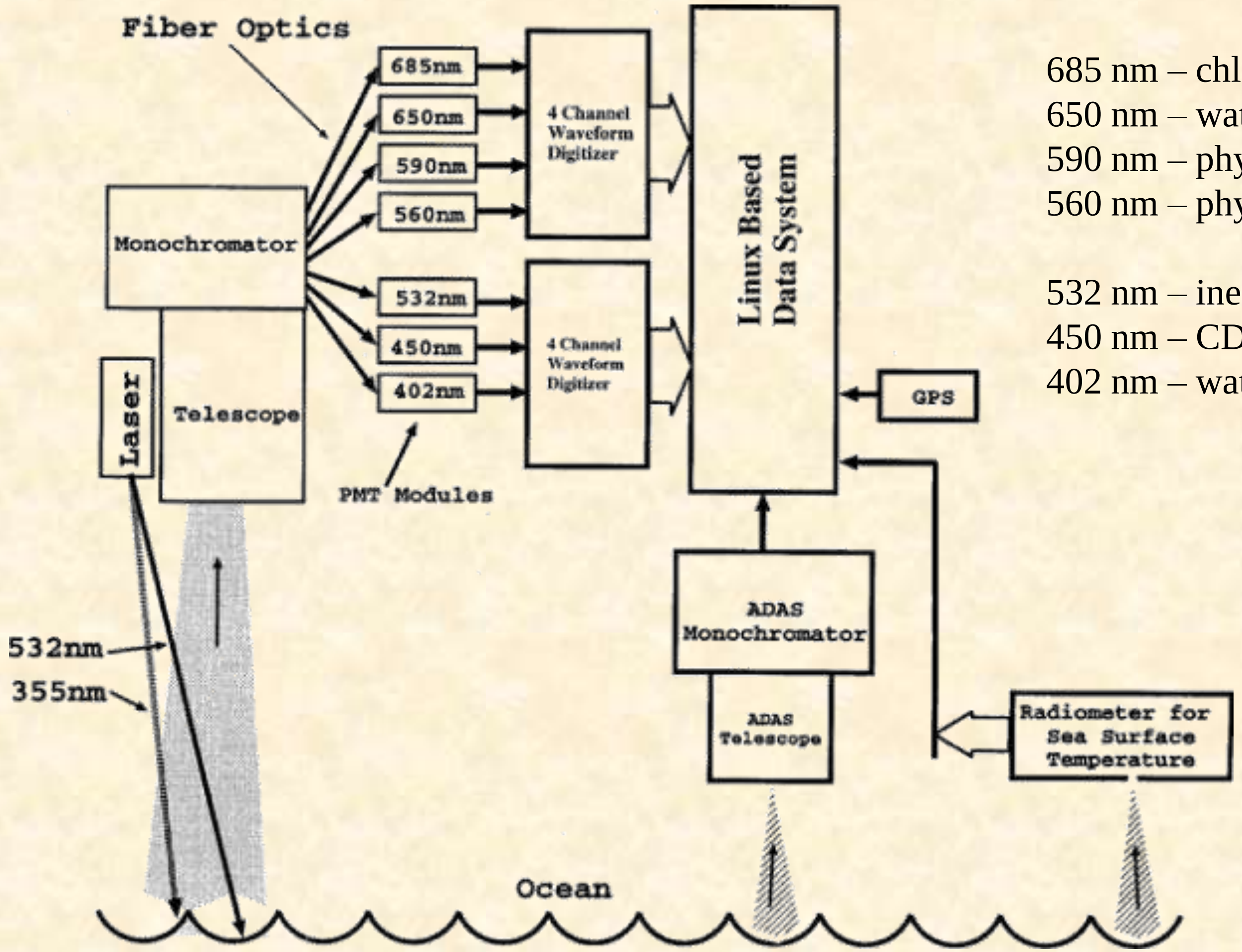
HSRL-1

- Atmosphere: Aerosols and clouds
- Ocean
  - b_{bp} and K_d at 532 nm

HSRL-2

- Atmosphere: Aerosols and clouds
- Ocean upgrade in progress
  - b_{bp} and K_d at 355 nm
  - b_{bp} and K_d at 532 nm
  - CDOM fluorescence at 455 nm
  - Water Raman scattering at 650 nm
  - Chlorophyll fluorescence at 680 nm

NASA Fluorescence Lidar



685 nm – chlorophyll fluorescence
650 nm – water Raman
590 nm – phycoerythrin fluorescence
560 nm – phycoerythrin fluorescence

532 nm – inelastic scattering
450 nm – CDOM fluorescence
402 nm – water Raman

Lidar Inversion

- Lidar signal depends on two parameters: $\beta(\pi) \rightarrow b_b$ and $\alpha \rightarrow K_d$.
- HSRL measures these parameters independently. NOAA lidar depends on an inversion of the signal.
- Various bio-optical models relate K_d and b_b to chlorophyll concentration, *chl*, and b_b to concentration of organic carbon, C.
- Other models relate *chl* and C to primary productivity.

Vertically Generalized Production Model

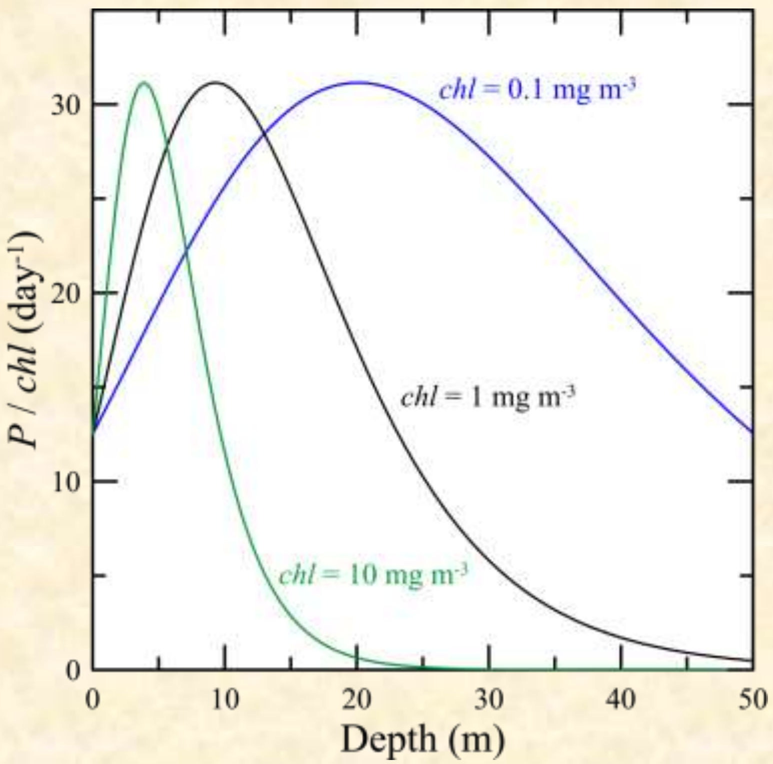
$$P = P_{opt}^{B} D \frac{\left\{1 - \exp\left[-\frac{E(z)}{E_{\max}}\right]\right\} \exp\left[-\beta_p E(z)\right]}{\left\{1 - \exp\left[-\frac{E_{opt}}{E_{\max}}\right]\right\} \exp\left[-\beta_p E_{opt}\right]} chl(z)$$

Need profiles of:

- chlorophyll, *chl*, from lidar inversion.
- photosynthetically-active radiation, *E*, from downwelling irradiance sensor on aircraft and lidar attenuation profile.
- temperature (for maximum fixation rate, P_{opt}^{B}), *T* , from sea-surface temperature radiometer on aircraft.

M.J. Behrenfeld and P.G. Falkowski, "A consumer's guide to phytoplankton primary productivity," *Limnol. Oceanogr.*, vol. 42, pp. 1479-1491, 1997.

Productivity with Constant *chl*

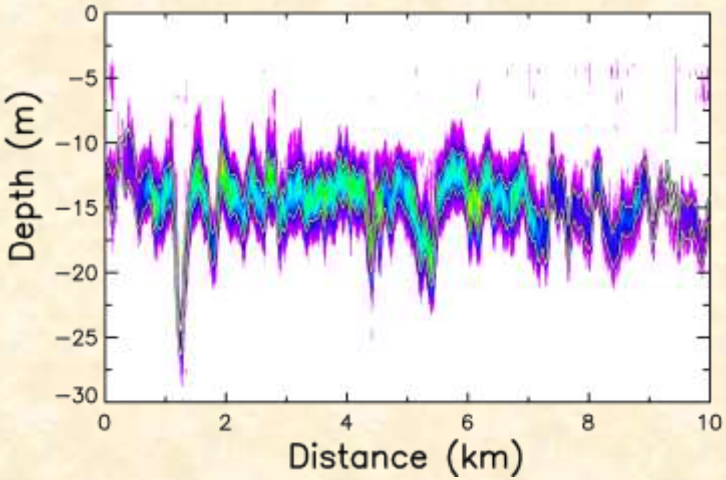


- Primary productivity (mg of carbon m^{-3} day^{-1}) normalized by *chl* (mg m^{-3}) for uniform depth distribution of *chl*.
- MODTRAN irradiance: midsummer, 71° N, clear skies, ice-free surface.
- *T* = 0° C.
- $K_{PAR} = 0.121 chl^{0.428}$.
- Peak productivity is in the range of layer depths observed with the lidar.

Thin Plankton Layers

Airborne lidar profiles

Continental shelf, Portugal →



Deep ocean, Gulf of Alaska

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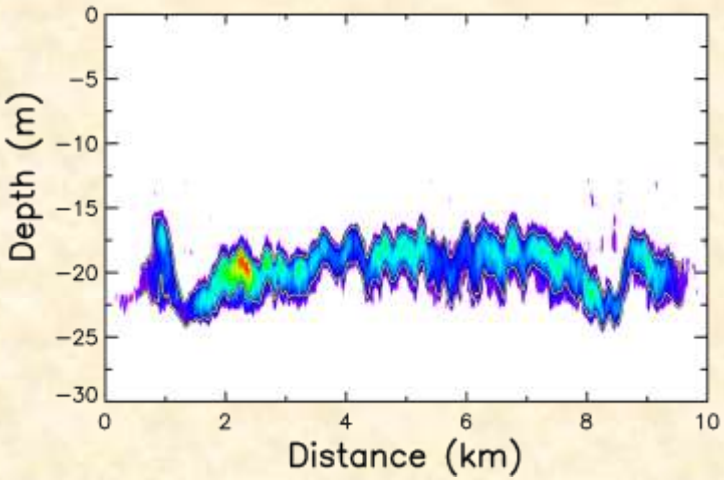
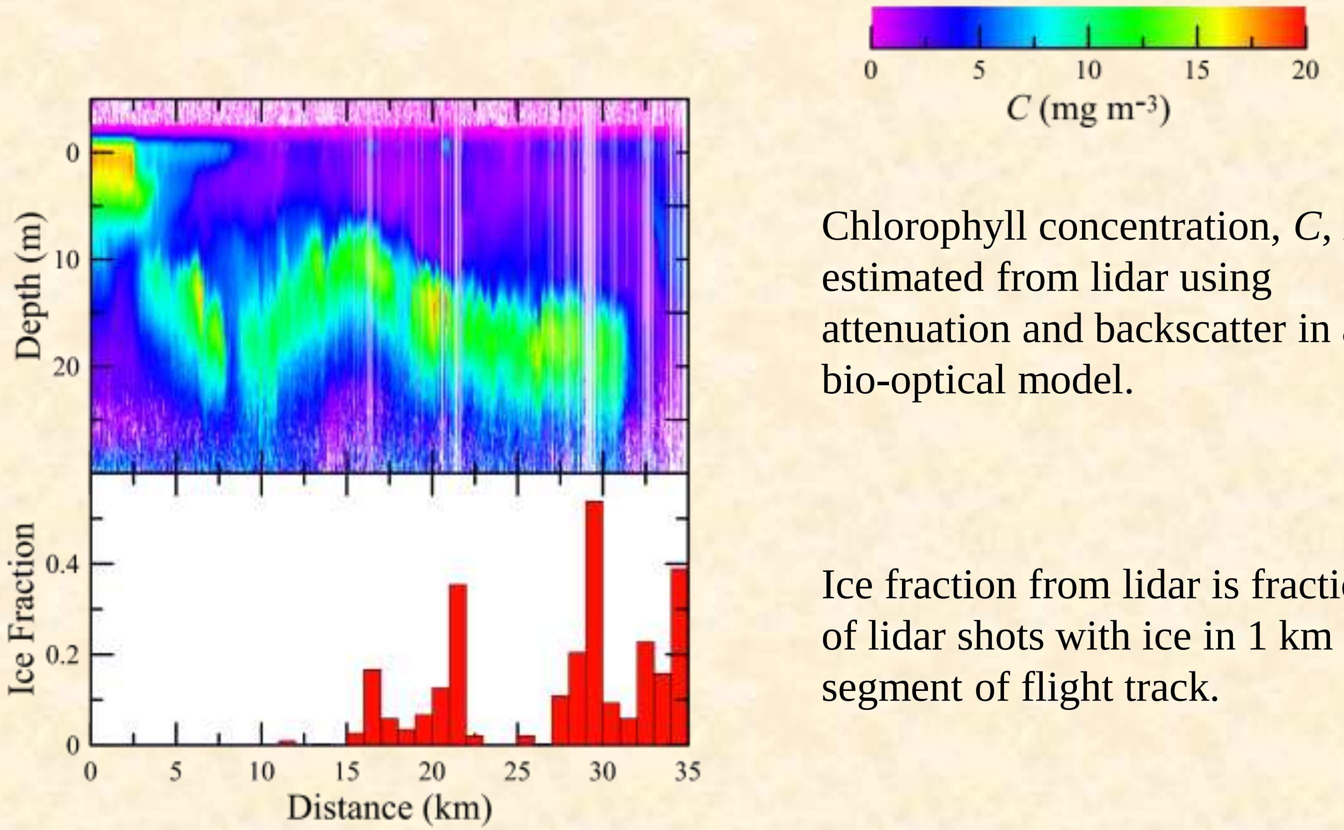


- Thin (< 5 m) phytoplankton layers are associated with the pycnocline.
- Nutrients are quickly depleted above the pycnocline, light levels are lower below, and current shear at the pycnocline acts to further thin layers.

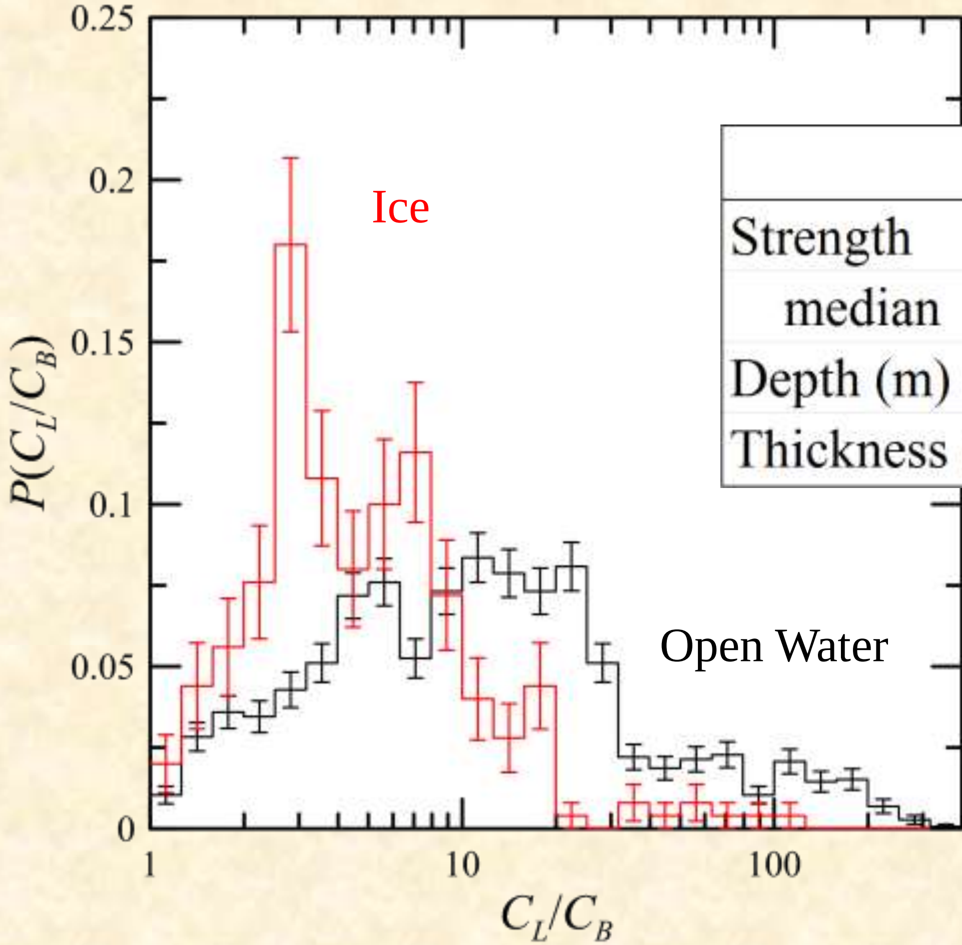
Example Plankton Layer in the Arctic



Chlorophyll concentration, *C*, is estimated from lidar using attenuation and backscatter in a bio-optical model.

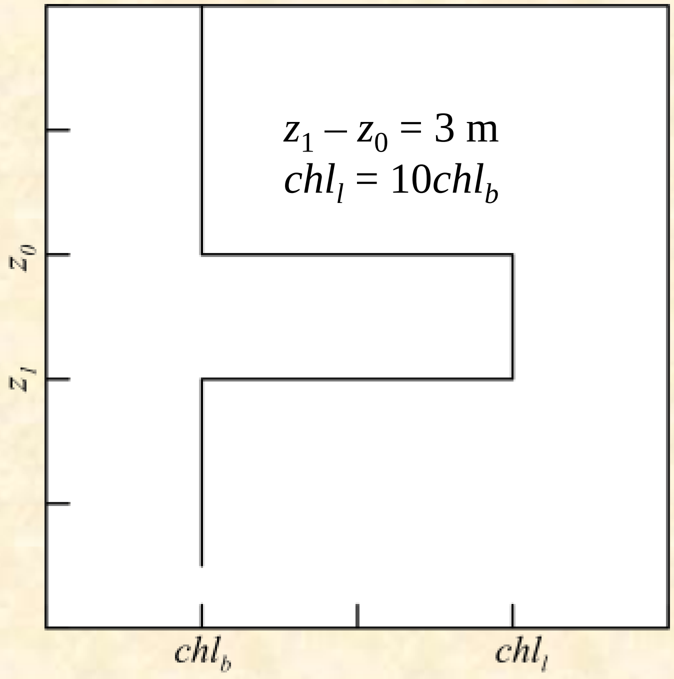
Ice fraction from lidar is fraction of lidar shots with ice in 1 km segment of flight track.

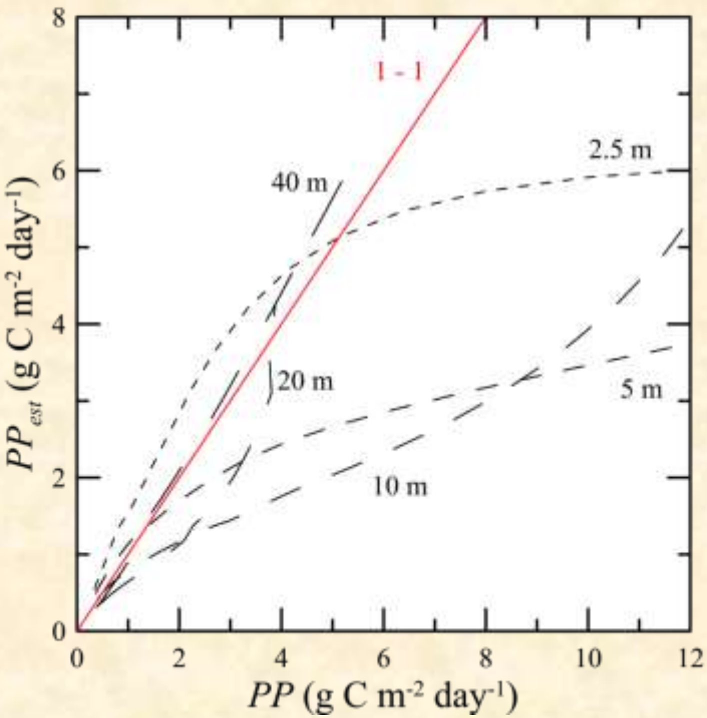
Layer Strength Distribution



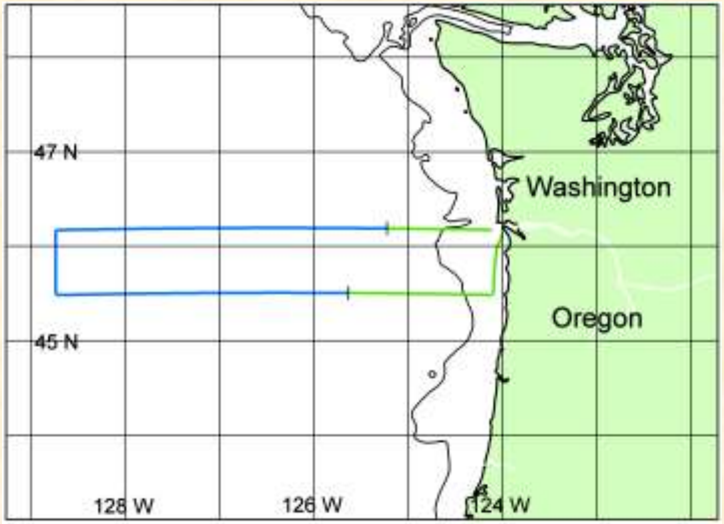
	Open Water	Ice > 0.1
Strength	27.0 ± 44.7	8.9 ± 14.0
median	12.0	5.1
Depth (m)	19.6 ± 6.0	15.6 ± 6.2
Thickness (m)	3.8 ± 1.5	3.4 ± 2.0

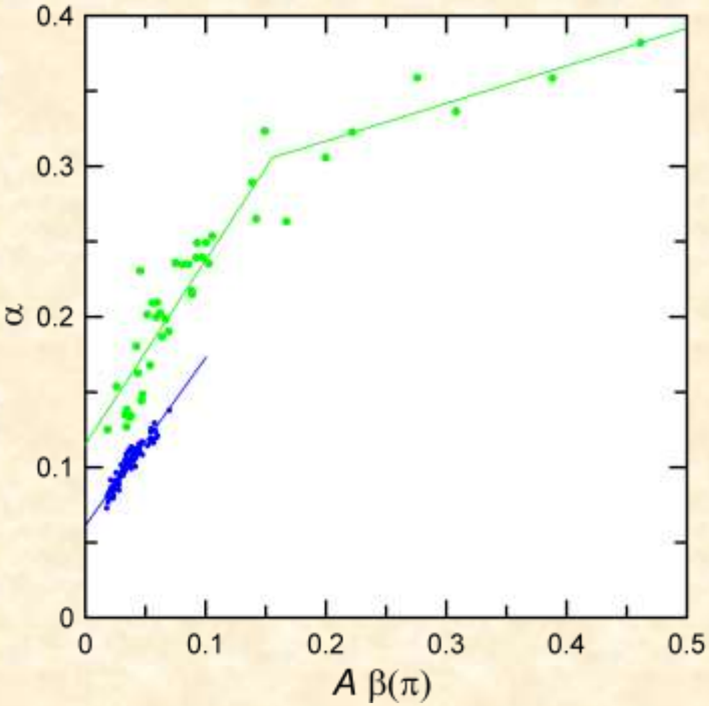
Ocean Color Estimate with Plankton Layer





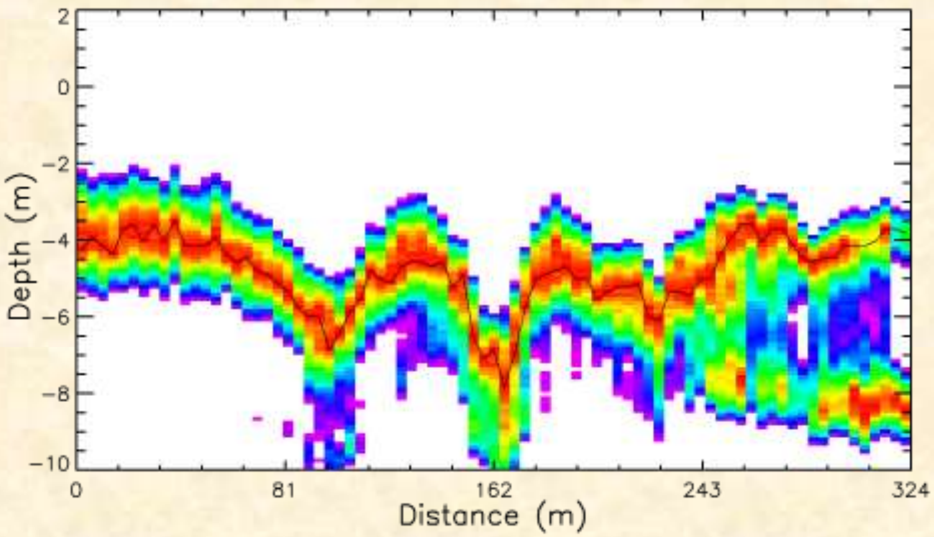
CDOM Absorption





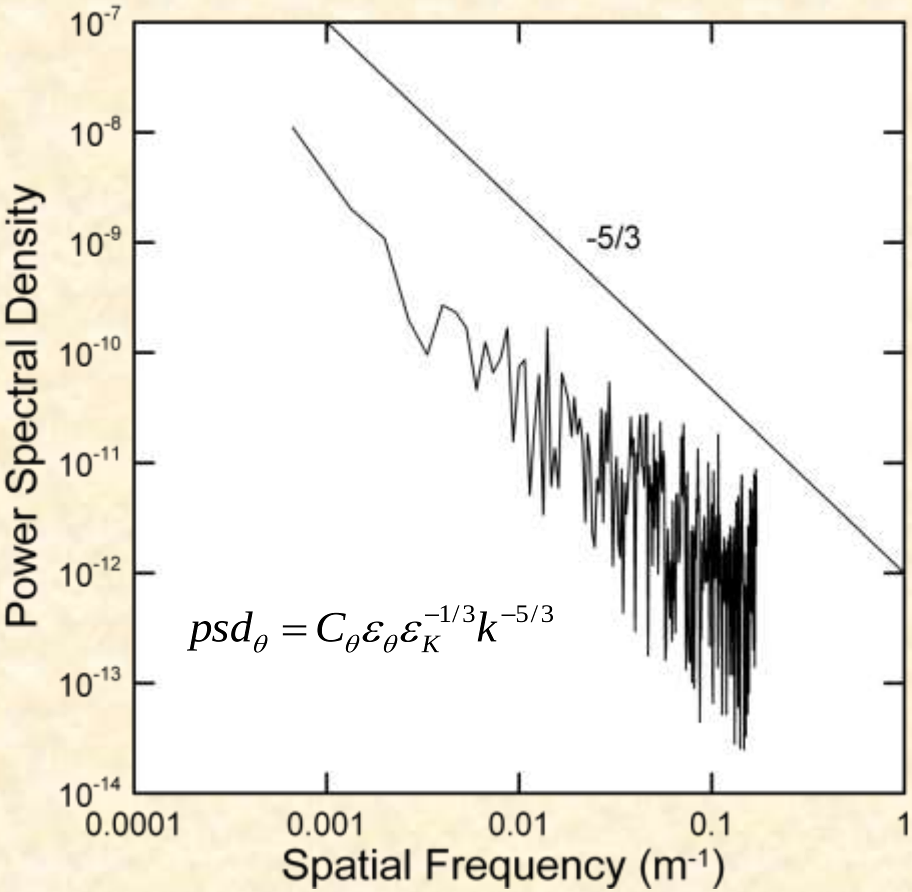
As $\beta(\pi) \rightarrow 0$, $\alpha \rightarrow a_w + a_{CDOM}$

Internal Wave on Layer



Depth of layer = 4 m
Propagation speed = 4.7 cm s^{-1}
Density difference = 0.83 kg m^{-3}
Energy = 9 MJ

Turbulence Measurements

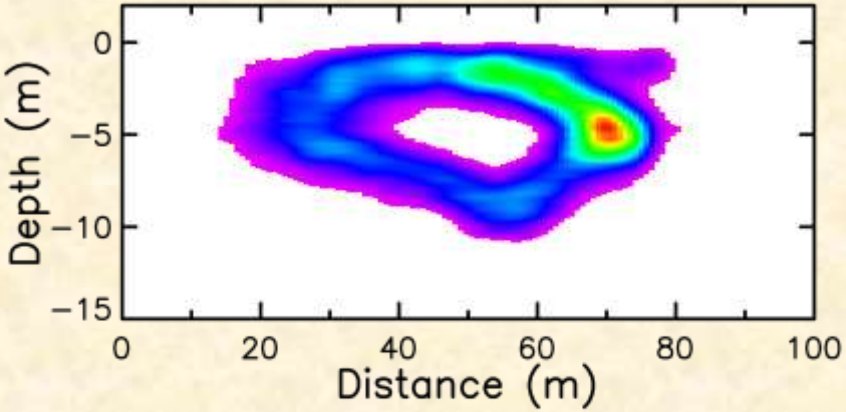


Stratified Turbulence

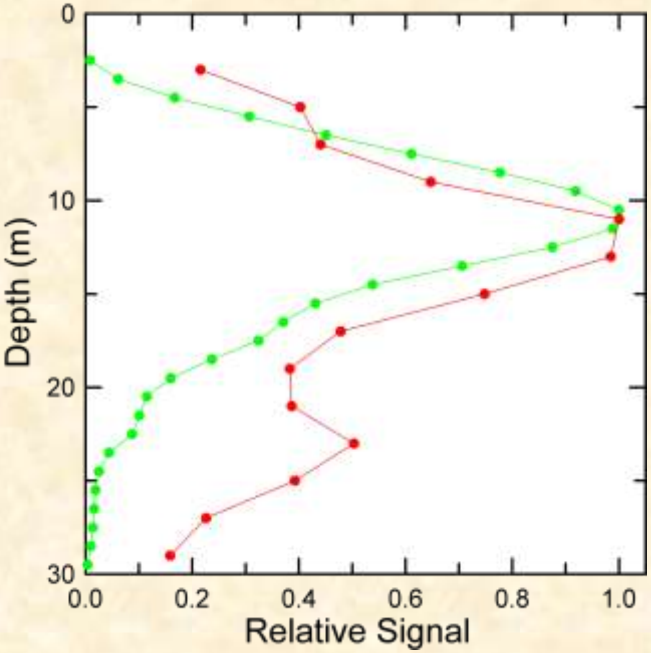
Horizontal power spectrum of optical-scattering fluctuations at center of layer follows a -5/3 power law, even though turbulence is not isotropic. (Lindborg)

Level of spectrum depends on horizontal dissipation rate of something, somehow since plankton are passive additives. Only solved for constant vertical gradient of passive additive.

Zooplankton



Moon Jellyfish - Top of aggregation is at surface; bottom is at pycnocline.



Copepods – Lidar (green) and echosounder (red) profiles in Prince William Sound, AK.

Conclusions

- Lidar can provide profiles of b_b(532 nm) and K_d (532 nm) from aircraft.
- Profiles of derived quantities like *chl*, *C*, CDOM, and primary productivity seem possible.
- Thin plankton layers provide a tracer for internal waves and turbulence measurements.