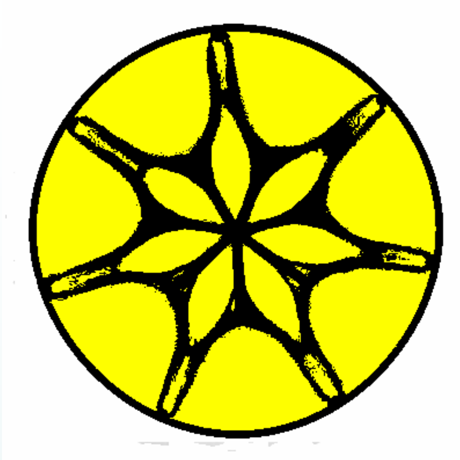
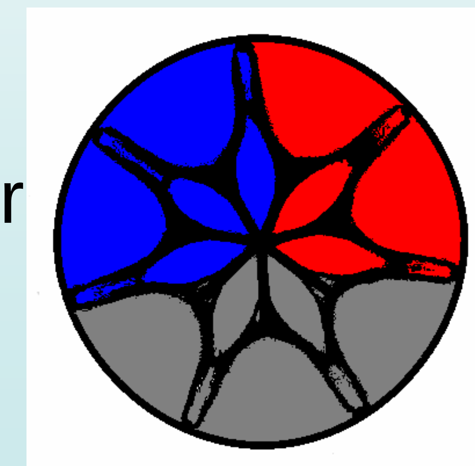


Backscatter and Chlorophyll

Eric Rehm
Ocean Optics 2004
Darling Marine Center
16 July 2004

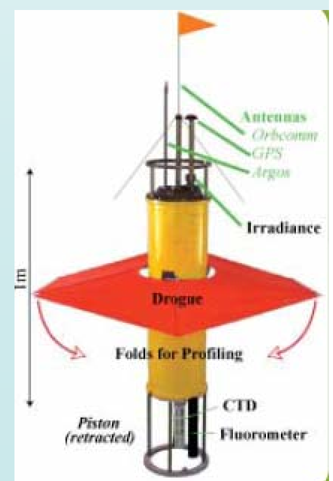


Overview

- Motivation
- Biogeochemical Processes
- Biogeochemical Proxies
- Methods: Measuring the proxies
- Results
- Discussion

Motivation: Lagrangian Observations

- *"The chief source of ideas in oceanography comes, I think, from new observations."*
  Henry Stommel, Oceanography,1989)
- *"The overarching observational problem in oceanography is that of sampling."*
  (Rudnick/Perry, 2003, ALPS Workshop Report)
- Fixed (moored, cabled) observatories
  - Important initiative for the collection of continuous (coastal) time series. But, you can't throw one into a hurricane.
  - Eulerian frame of reference: water parcels go by.
- ALPS: Autonomous and Langrangian Observatories
  - Address time and space scales not covered by cables observatories.
  - Can have a Langrangian frame of reference: follow a water parcel.



Biogeochemical Processes

- In the global carbon cycle, what role does primary production play?
  - Phytoplankton fix 35-65 Gt of carbon into organic molecules
- How can we better estimate primary productivity?
  - In-situ studies of light, biomass, nutrients, physiology, temperature, mixing, species, etc.
  - Estimating net primary productivity

Net primary production (NPP) = *f* [biomass, physiology, light, …]

Some Biogeochemical Proxies… and some possible measurements

Process Component	Proxy	Optical Proxy / Measurement
Light	Irradiance	Irradiance sensors
Biomass	Chlorophyll, Fluorescence	Fluorometer, Spectral fluorometer
Nutrients	Nitrates	Nitrate sensor
Physiology	Absorption, Attenuation Oxygen	a, c O2 sensor
Temperature	Temperature	CTD
Species		
Mixing	T, S, σ, depth	CTD
Composition	Particle size, composition	Beam-c_p Scattering: b_{bp}, b_p ,b_{bp}/b_p

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Helpful Proxy: Chlorophyll

- Chlorophyll Concentration
  - "Buyer beware": May vary from a direct biomass estimate
    - We're really measuring $F = a(\lambda) * E(\lambda) * \Phi_f$
    - Photoadaptation, photoinhibition, quenching
    - Possible simple spectrofluorometer to address this?
  - Can use fluorescence as a proxy for Chl
  - Calibration of fluorometer
    - Important for measurements of both [chl] and *d*[chl]/*d*
- Backup plan?
  - In Case I waters, measure light field: E_d versus Depth
  - Calculate AOP K_d and estimate chlorophyll

Understanding the Particle Proxies

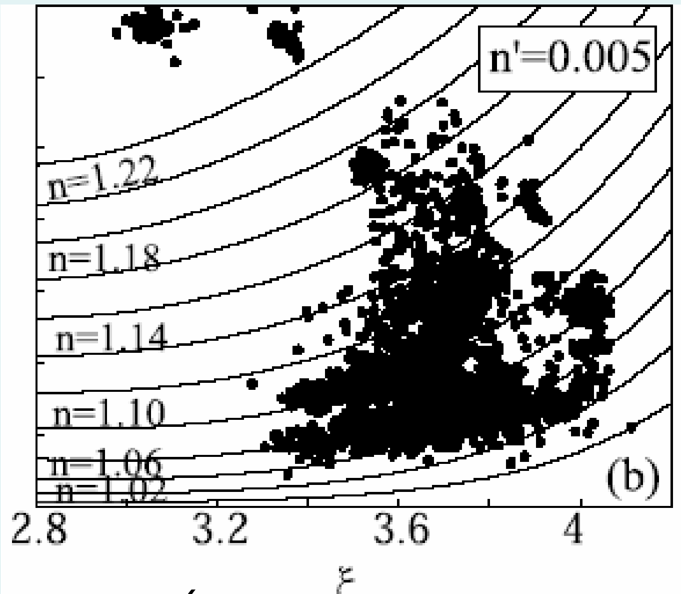
- Composition
  - Is it organic or inorganic?
- Size
  - How big is it?
  - What is size distribution?
- Shape
  - Hard to measure

Helpful Optical Proxy: Scattering

- Composition: Scattering vs. wavelength
  - Diffraction, hence scattering, is wavelength dependent
  - Using wavelength (e.g., BB2F blue vs. red LEDs):
    - Small particles scatter more than large particles in blue vs. red
    - Consider $b_{bblue}:b_{bred}$ ratio
- Particle concentration: Scattering vs. depth
  - Backscattering is distributed with depth very much like particle concentration (Kitchen and Zeneveld, 1990)

Helpful Optical Proxy: Scattering

- Size, shape, composition: Scattering angle (VSF)
  - Ratio of backscattering to total scattering b_{bp}:b_p is a proxy for the bulk index of refraction
  - $n_{inorganic\ particles} > n_{phyto}$ (with some exceptions)
  - $\therefore$ b_{bp}:b_p can help us discriminate phytoplankton from inorganic sediment



(Boss et. al, JGR, 2004)

Helpful Optical Proxy: Scattering

- b_{bp}:b_p can also tell us about size, shape and composition of water *not* dominated by highly refractive materials (Boss et. al, JGR 2004, Twardowski, JGR, 2001)
  - Presence of more highly scattering **coccolithophores**
  - Increased index of refraction in presence of dead organic material and heterotrophs

Helpful Optical Proxy: Scattering

– b_{bp}:b_p can also tell us about chlorophyll concentration

- Statistically significant relationship (Boss et. al, JGR 2004, Twardowski, JGR, 2001)

For example

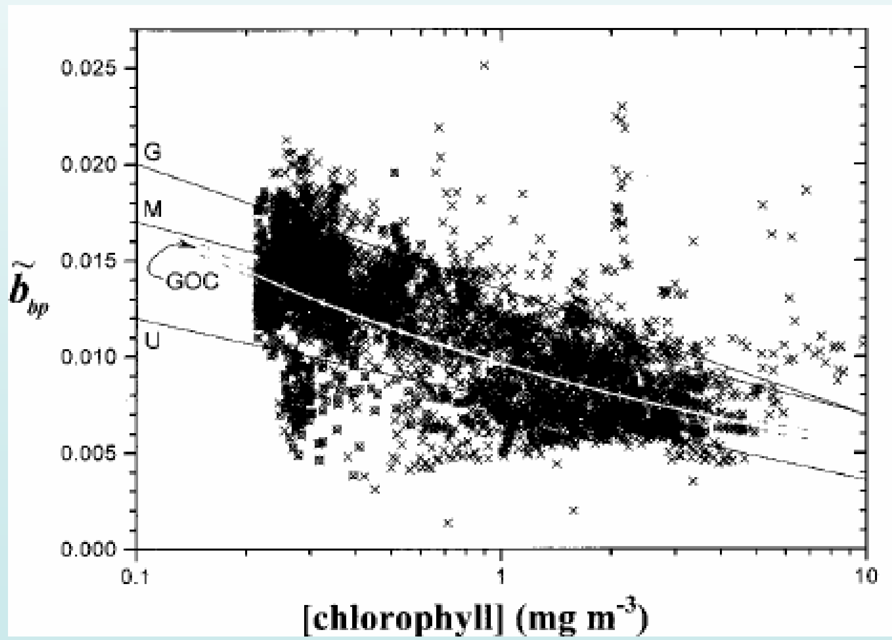
- Hyperbolic model:

  b_{bp}:b_p= 0.0096*[chl]-.253

- Linear model

b_{bp}:b_p=

0.0066*[chl]/c_{p660} +0.0259



Twardowski, JGR, 2001

Helpful Optical Proxy: Scattering

- b_{bp}:b_b *vs. [chl]:*c_p
  - Low *[chl]:*c_p indicative of low [chl] and high fraction of inorganic particles
  - High *[chl]:*c_p indicative of “domination of particulate by phytoplankton”
  - Requires HIGH DyNaMiC Range.
  - (Boss et al., JGR 2004)

Helpful Optical Property: Beam attenuation c_p

- Beam c is dependent on, therefore helps us measure particle size and composition
  - Power law slope of $c_p \alpha$ Particle Size Distribution (aka "Number Size Distribution)
  - Beam c not likely to be affected by chlorophyll packaging (Boss et al., JGR, 2001)
  - $\therefore$Skewed towards refractive particles
- But, beware…
  - Particle and Chlorophyll concentration (hence c*p* and F) are not correlated (Kitchen and Zeneveld, 1990).

Methods:
Measuring the proxies

- Chlorophyll
  - Via lab fluorescence (used here)
    - Turner Fluorometer
  - Via in-situ fluorescence
    - Wetstar flow-through in-situ fluorometer
      - Calibrated to [chl] derived from Turner Fluorometer
      - ([chl] = m*volts + b calibration was blocked by my spam filter.)
    - Wetlabs BB2F fluorometer
      - Used factory Calibrations

Methods: Measuring the proxies

- Backscattering
  - Via active measurement of backscatter
    - Wetlabs ECO-VSF: 100°, 125°, 150° @ 660 nm
      - Correct measure β for attenuation (Zaneveld, year?)
      - Analytically integrate sampled VSF to compute b_{bp}
    - Wetlabs BB2F: 117° @ 470 and 700 nm
      - Factory calibration
      - Use Boss and Pegau χ factor to calculate b from single angle measurement

Methods: Measuring the proxies

- Particulate Attenuation
  - Via in-situ beam attenuation
    - Wetlabs AC-9
      - pure water calibration,
      - corrected for temp and sea water (via .2μ filter)
      - Scattering corrections (λ=715 + spectrally varying correction)

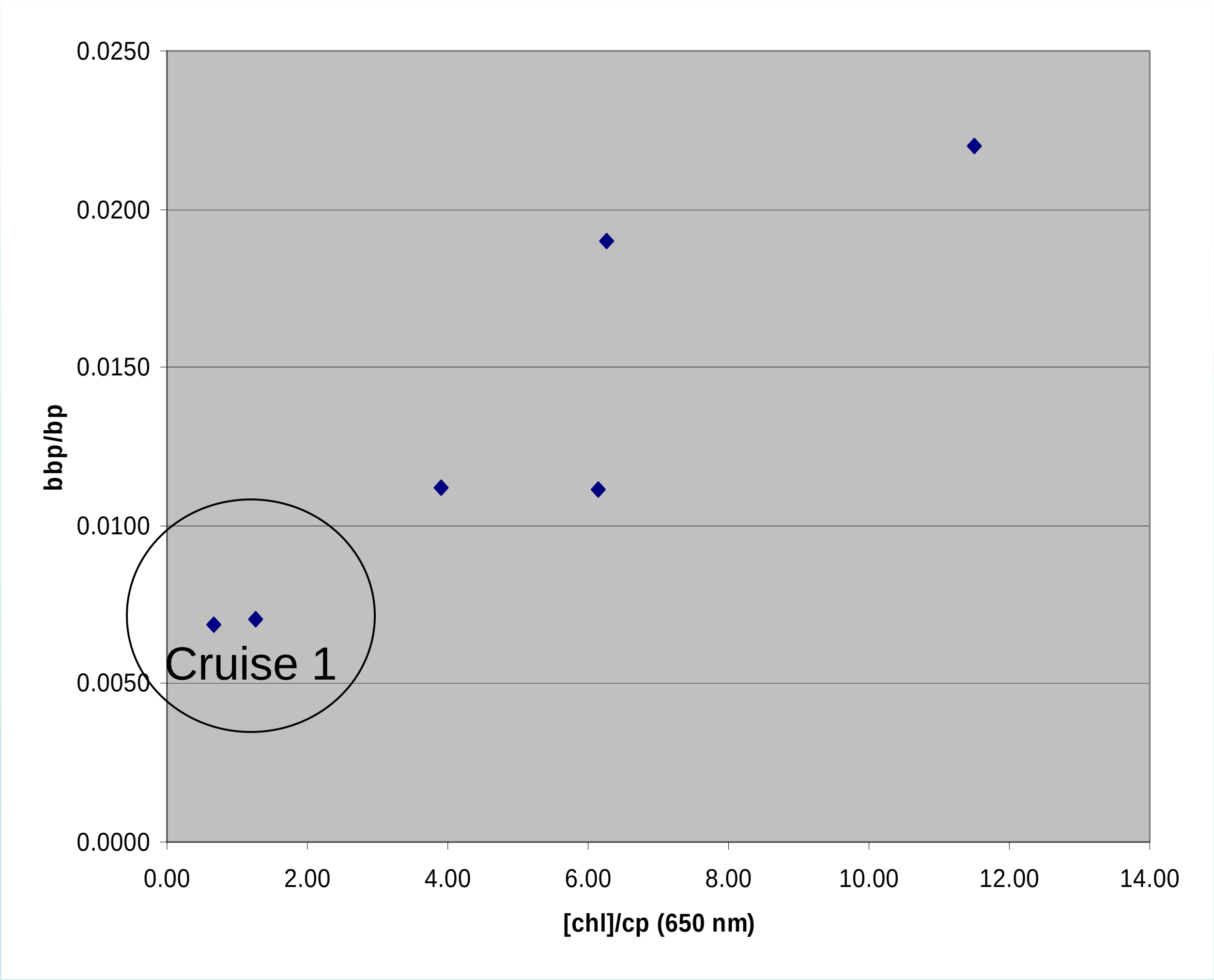
Methods

- Particulate scattering: $b_{p} = c_p - a_p$
- Backscattering ratio: $b_{bp}:b_p$
- Chlorophyll to beam attenuation ratio
- For depth based measurements, used mean +/- .6m of measurements
  - N varied between 3 (profiles) and 70 (holding at depth)
- Decimate and re-grid profiles to combine AC-9 results from one profile with chl, ECOVSF and CTD results of another profile.
  - Re-grid to .5m depths using nearest neighbor
    - Leaves “real” measurements in your data set
  - Better method (but no time): Take mean of values in each .5 m bin

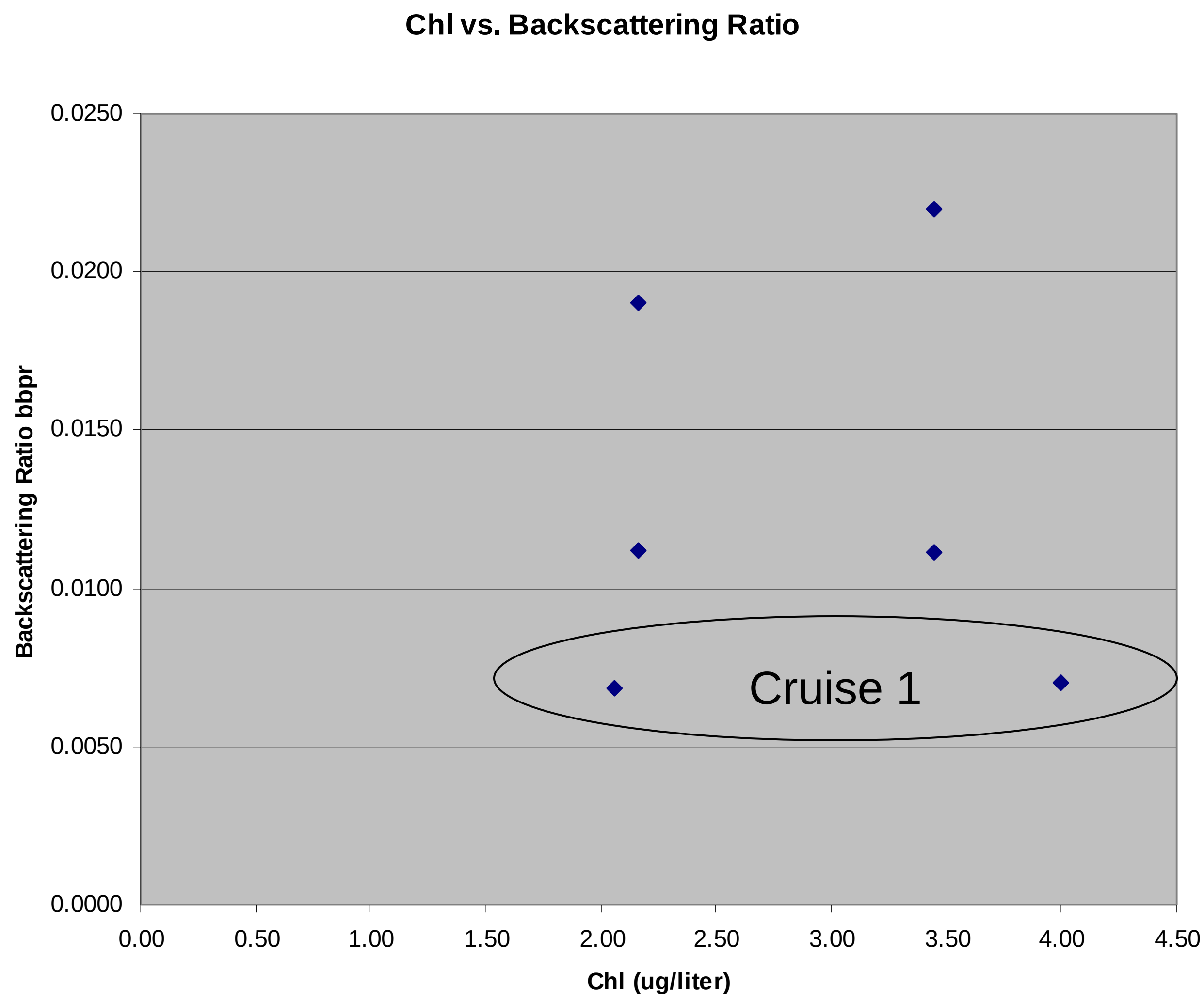
b_{bp}:b_p Results

	Depth (m)	N	chl	cp(660)	chl/c	bbp	bp	bbr
Cruise2_34	4	7	2.16	0.553	3.91	0.0061	0.545	0.0112
Cruise2_63 Profile	4	2	2.16	0.345	6.26	0.0061	0.321	0.0190
Cruise2_36	10	70	3.45	0.561	6.15	0.0061	0.547	0.0112
Cruise2_63 Profile	10	3	3.45	0.300	11.50	0.0060	0.273	0.02198
Cruise1	3	50	2.06	3.100	0.66	0.0210	3.06	0.0069
Cruise1 Profile	11	3	4.00	3.200	1.25	0.0220	3.13	0.00703

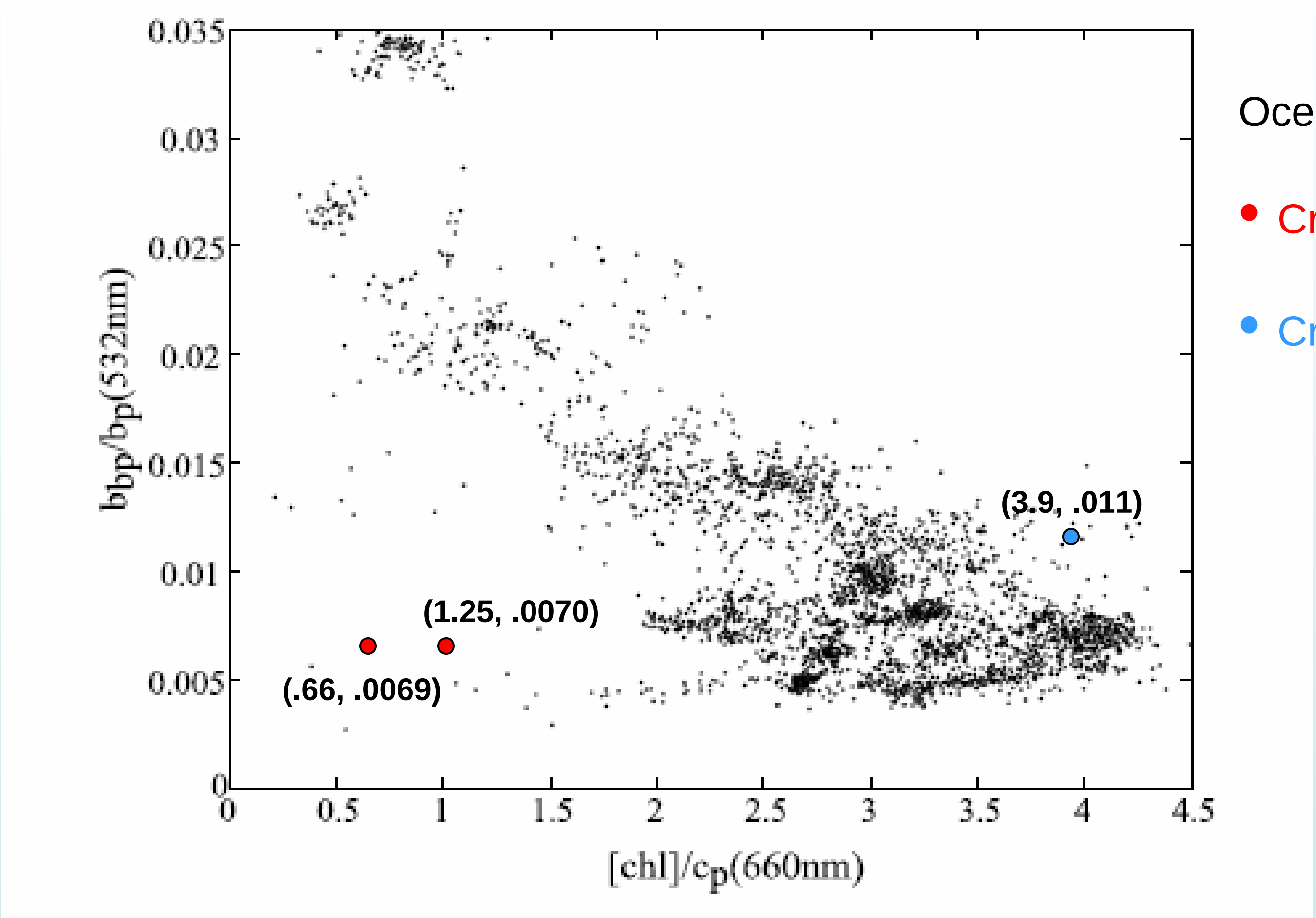
b_{bp}:b_b vs. [chl]:c_p Results

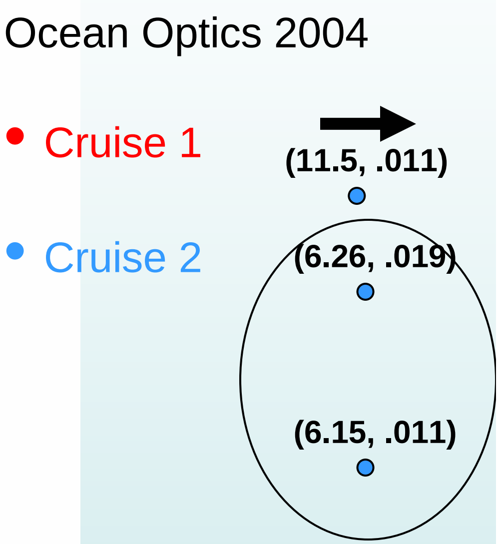


[chl] vs. $b_{bp}:b_b$


Chl vs. Backscattering Ratio
Backscattering Ratio bbpr
0.0250
0.0200
0.0150
0.0100
0.0050
0.0000
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
Chl (ug/liter)
Cruise 1

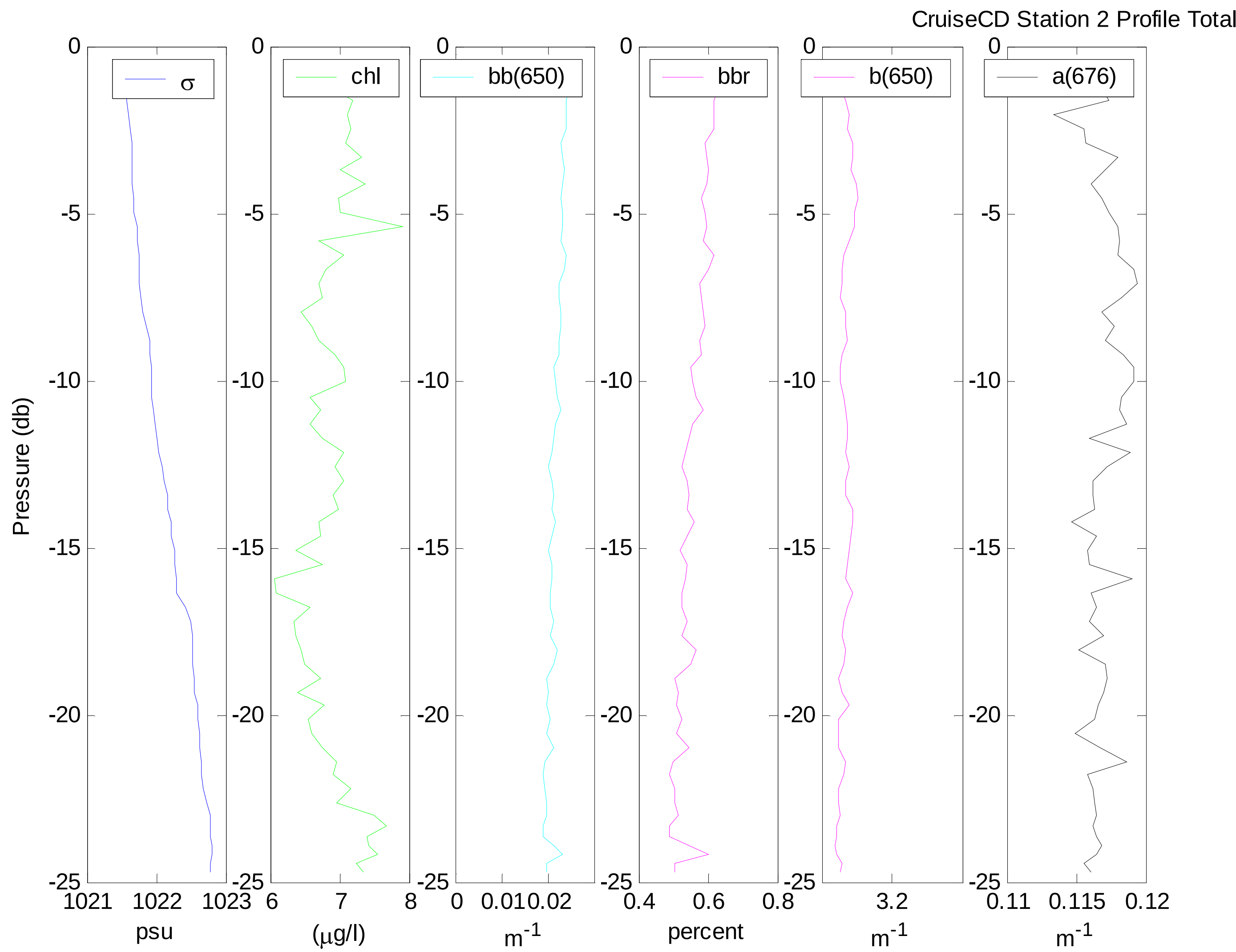
Results in Perspective





Original data: b_b at 632 nm vs. chl:c_p(660) from Boss et al. (JGR, V109/C01014, 2004);

Typical Profile



b_{bp} ~ .02, b(650) ~3.1, 10-20% excursions, ΔPSU ~ 1

Little dynamic Range ➔ Well mixed water

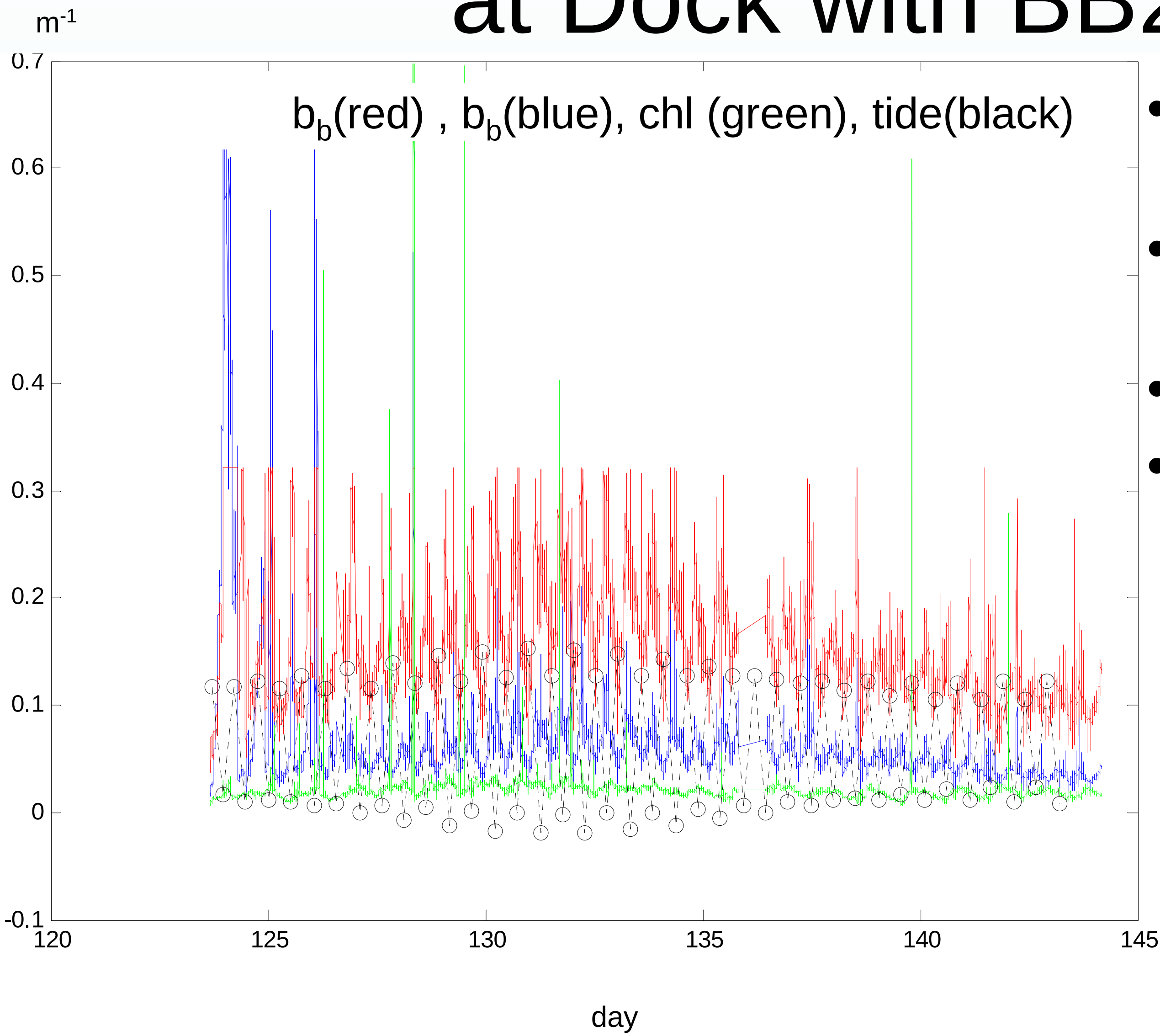
Discussion

- **Scattering b_{bp} , b_p , $b_{bp}:b_p$**
  - **Backscatter**: b_{bp} upriver (.02) > b_{bp} in Gulf of Maine (.006)
  - **Total scatter:** b_p upriver (~3) > b_p in Gulf of Maine (.27-.54)
  - **Backscatter ratio:** upriver (~.007) < backscatter ratio in GoM (~.01-.02)
- **Chlorophyll**
  - Damariscotta River and GoM at output of river are, no surprise, about the same.
- **Backscatter / Chlorophyll Models vs. Data**
  - ***Boss' $b_{bp}:b_b$ vs. [chl]:c_p :*** *a few values fall on the published graph…but I think we're just lucky.*
  - ***Twardowski's $b_{bp}:b_b$ vs. [chl] :*** *Not worth a curve fit…no significant correlation*
  - Both published data sets have 100's – 1000's of data points; We had 6.

Discussion

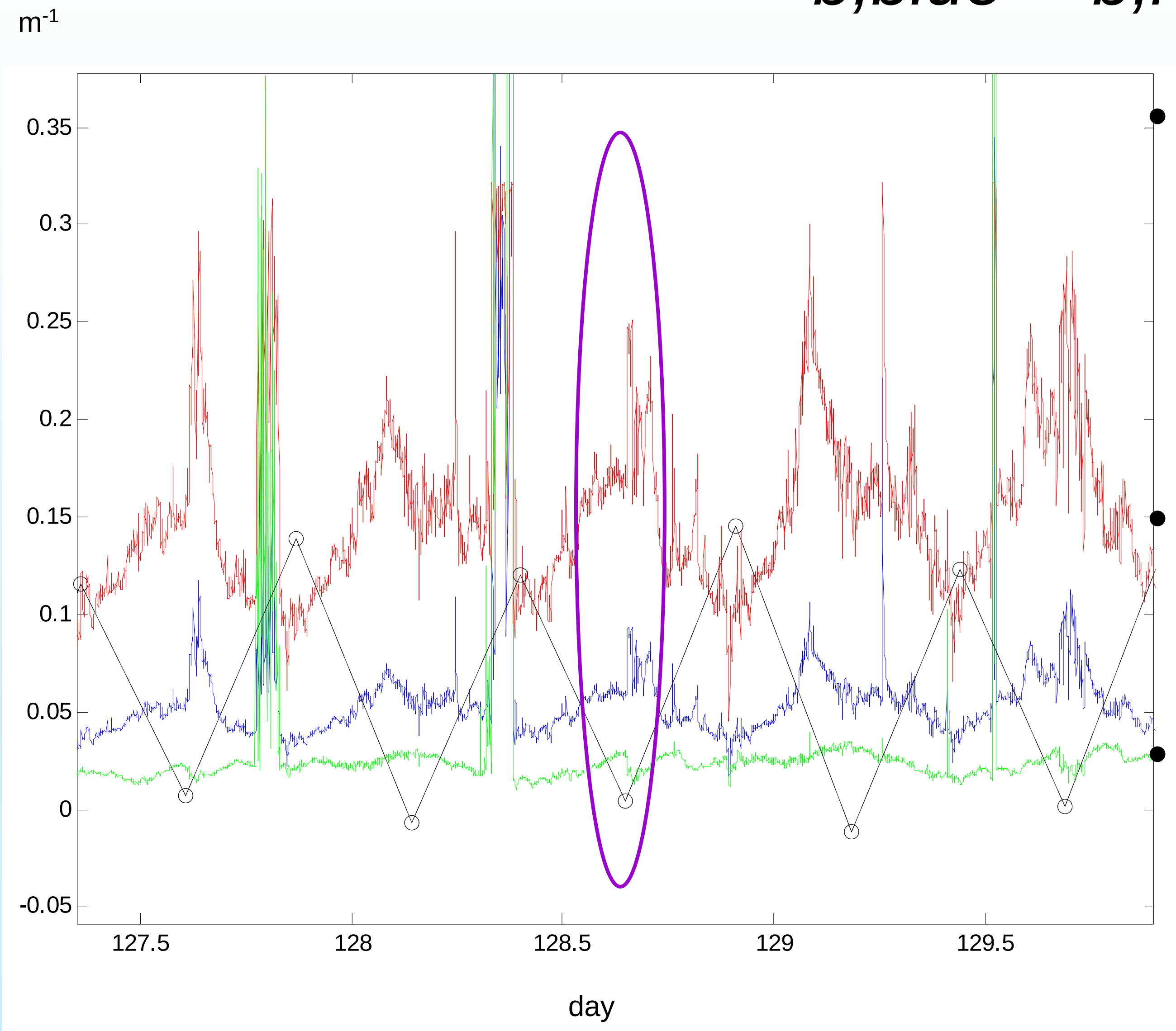
- **Water in Gulf of Maine (Johns Bay) is well mixed**
  - Little stratification
  - Still strong influences of estuary with respect to sediment
- ECO VSF β correction and $b_{p.}$
  - Derived from AC-9 data for a single cast
  - Confidence in $b_p=c_p-a_p$ is low
- Not confident in the factory or class lab calibration of ECOVSF.
  - Only confident in b_{bp} to range of both calibration slopes, i.e., 2x
- In-situ fluorometer calibration from lab fluorescence not completed in time for lab.

Quick Look: $b_{b,blue}$:$b_{b,red}$ ratio at Dock with BB2F



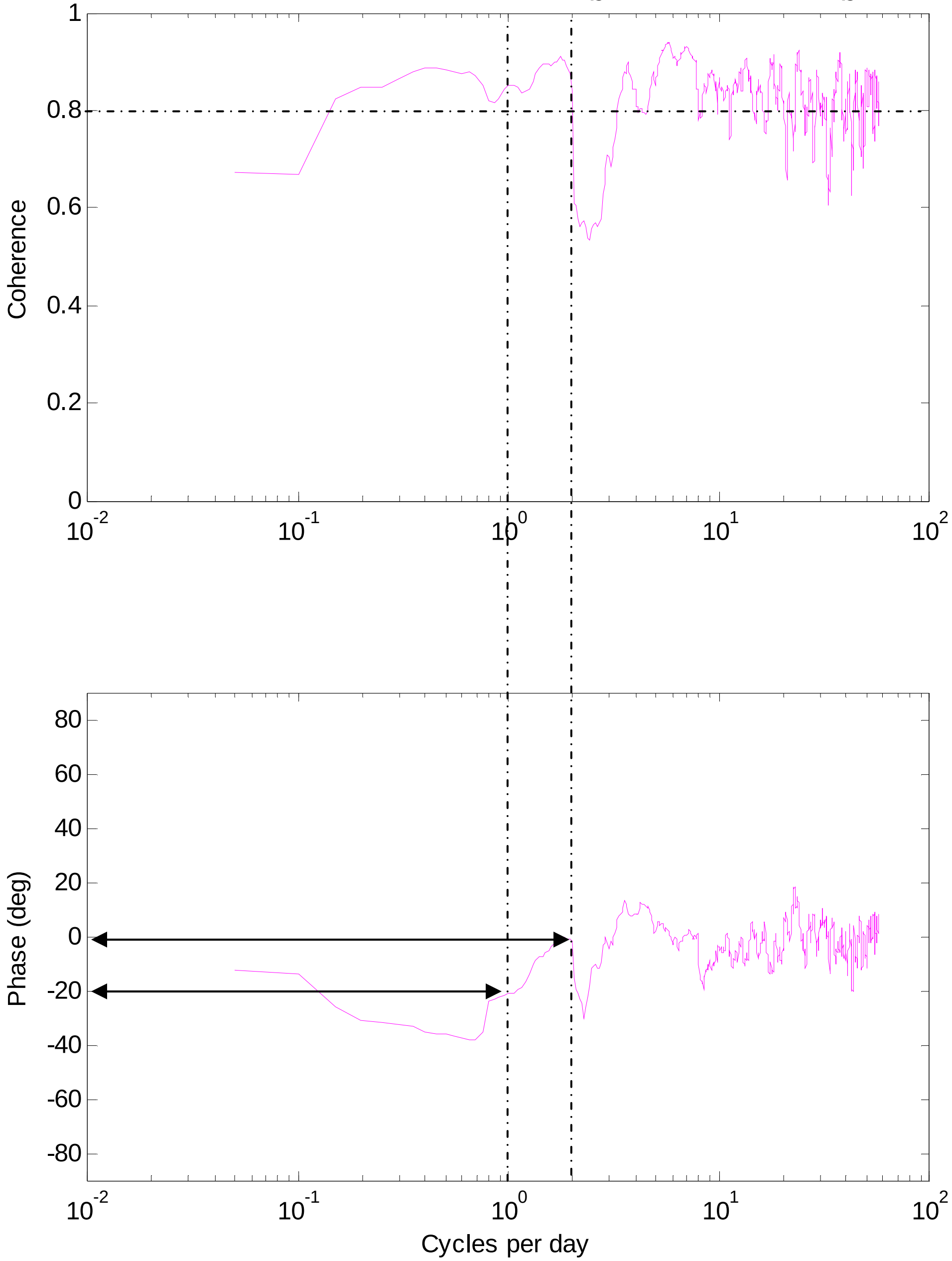
- Diurnal (M2) component
- Lunar tidal (S2) component
- "Stuff"
- Red has less inherent dynamic range than blue

Quick Look: $b_{b,blue}$:$b_{b,red}$ ratio



- There does not appear to be phase difference (time lead or lag) between $b_{b,blue}$ *and* $b_{b,red}$ at the tidal frequency
- But…is there a time lead or lag for a diurnal component?
- Use cross-spectral analysis to find out.

Cross-spectral analysis of b_b(red) and b_b(blue)



- @ f=~2 cycles/day (tide), coherence is large (> .8), i.e., correlation between $b_{b,blue}$ *and* $b_{b,red}$ is significant.
- Phase=0 at f=~2 cycle/day indicates *no* phase difference.

- @ f=~1 cycle/day (sun), coherence is still large (> .8), i.e., correlation between $b_{b,blue}$ *and* $b_{b,red}$ is significant.
- Phase=-20° at f=~1 cycle/day indicates time delay of 20/360*24 hrs/cycle = ~1.33 hours
- Explanation? None yet….

Discussion: $b_{b,blue}$:$b_{b,red}$ ratio

- Red & Blue: Diurnal cycle
  - High tide: bb is low
  - low tide: bb is high
  - Why? Hypotheses: At low tide, Damariscotta River has flushed sediment?
- Red vs. Blue
  - Coherent (Highly correlated) at major frequency (tidal)
  - Coherence at other phase difference indicate there are other frequencies (e.g. 1 cycle/day) where $b_{b,blue}$ *and* $b_{b,red}$ *are shifter in time relative to each other.*
  - Indicates that there may be additional information to mine from the different signals to understand (and subtract) from signal.
  - Can cross-spectral analysis yield additional information about size of scatterers? Tbd….

- Also notice that $b_{b,blue}$ has more slowly decaying "tail" than $b_{b,red}$

Discussion

- Good exercise to understand all of the possibilities …and especially pitfalls of AC-9 scattering measurements
  - CruiseAB was in well-mixed water
  - CruiseCD was in water with more sediment
- Good exercise to understand the value of multiple measurements of the same optical proxy
- Adjust sampling methods
  - More time on water
  - Slower casts
  - More casts
  - Water samples at more depths
    - (Water samples + lab fluorometer backup was important)

Discussion: Future Work

- Particle Attenuation
  - Compute and compare results to $\xi = \gamma + 3$ PSD slope
    - Very useful to have c_p around for PSD
    - And may allow another [chl] check in Case I waters
    - …but an AC-9 may be unwieldy on a Lagrangian float
  - In high inorganic particulate environment, look for scattering correlations
    - PSD from Coulter counter or LISST
    - TSM measurements
  - Simpler & smaller transmissometers possible
    - Even smaller (~10 cm) quite possible (Boss, lab discussion)
  - Spectrofluorometric measurement using a Hydroscat with the “red bug” (red backscatter source stimulates fluorescence)
    - Resolve a_{ϕ} into $a_{PS} + a_{PP}$?
    - Possible special sensor build by Wetlabs?

Discussion: Future Work

- Characterize sensors (esp. BB2F) in an environment with very little inorganic particulate scattering
  - Emmanuel suggests Crater Lake or some quiet waters 15 nm off the Washington coast
  - What about the Arctic or Antarctic? ;-)
- Next Class
  - Learn how b_{bp}:b_b and R_{rs}

Thanks to all of my teachers and classmates for the patient help and support.