

Lectures on  
Optical Oceanography and  
Ocean Color Remote Sensing

Closure and Experiment Design

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2021

# Closure

“Closure” is just a fancy word for “getting everything to agree”

**Scale closure:** Do measurements made at different spatial or temporal scales agree? (e.g., Chl from MODIS vs in situ)

**Instrument closure:** Do different instruments or methodologies that measure the same quantity give the same values? (bb-9 vs HydroScat-6 vs Hyper-bb)

**Model closure:** Do different models give the same answers? (HydroLight vs Monte Carlo vs Gordon vs...)

**Model-data closure:** Do model predictions agree with measurements (HydroLight  $R_{rs}$  vs measured  $R_{rs}$ ?)

# Today

- Show several examples of output from advanced HydroLight simulations to show what is necessary to achieve model-data closure, i.e., getting all of your inputs to H and outputs from H to agree with your measurements
- Thoughts on the design of field experiments



# Measurements Necessary for Model-Data Closure

## HydroLight inputs

- absorption coef  $a(z,\lambda)$  (e.g., from ac-s or spectrophotometer)
- scattering coef  $b(z,\lambda)$  (e.g., from ac-s)
- scattering phase function  $\tilde{\beta}(z,\lambda,\psi)$  (almost never measured, but may have backscatter fraction  $B = b_b/b$  from  $b_b$  (e.g. Hyper-bb) and  $b$  (ac-s))
- boundary conditions: sea state (wind speed); sun location and sky conditions (usually model), bottom reflectance (in shallow water)

## HydroLight outputs

- radiometric variables (radiances and irradiances; usually measure  $L_u(z,\lambda)$  and  $E_d(z,\lambda)$  at a minimum)
- apparent optical properties ( $K_d$ ,  $R$ ,  $R_{rs}$  etc. obtained from radiometric measurements). The most common for remote sensing is remote sensing reflectance  $R_{rs}$  (often measure  $E_d(\text{air})$  and  $L_u(z)$  and extrapolate upward from underwater  $L_u$ , or estimate  $R_{rs}$  using above-surface techniques)

# Comprehensive Data Sets Are Extremely Scarce

Data set from ONR HyCODE (Hyperspectral Coastal Ocean Dynamics Experiment) 2000 off the coast of New Jersey (LEO-15 site)

measurements taken near local noon on 24 July 2000 at 39° 24.91' N, 74°, 11.78' W (station 19); cloudy sky, wind = 6 m/s

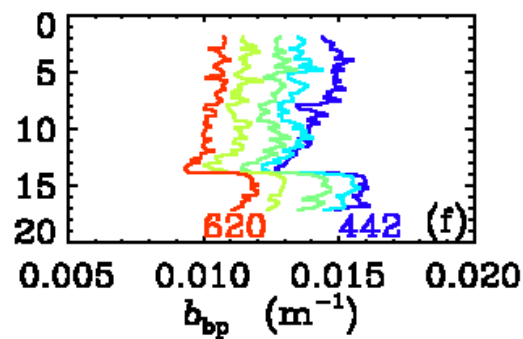
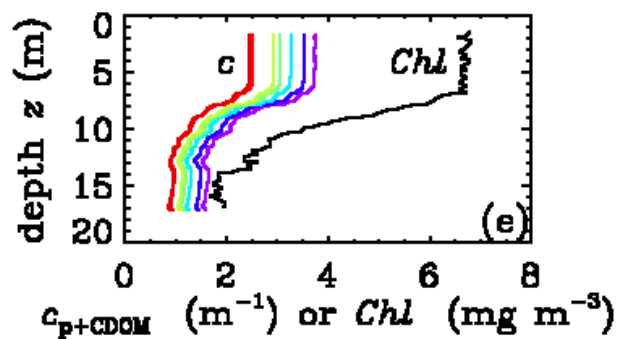
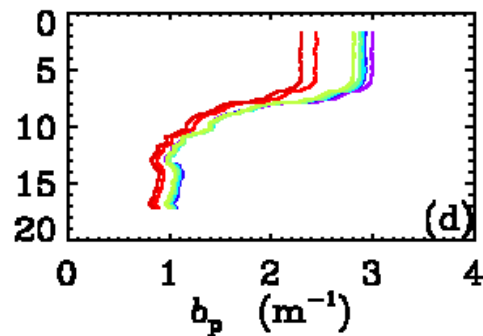
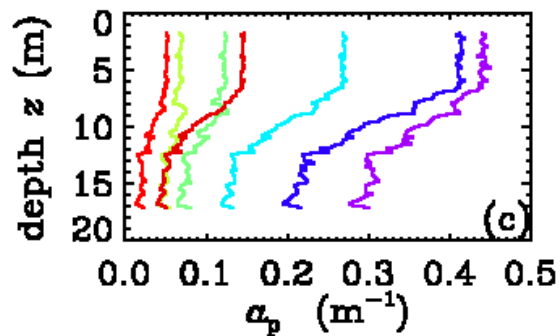
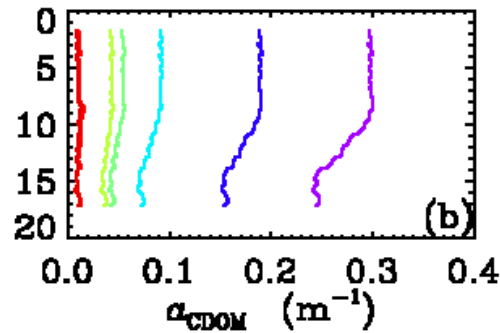
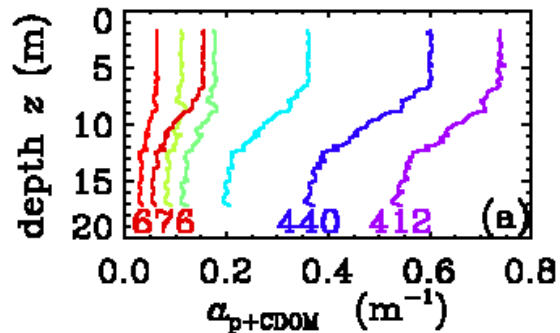
See Mobley et al, 2002, *Applied Optics* 41(6), 1035-1050 for details

Table 4. Data Taken at the LEO-15 Site as Used to Model the In-Water Light Field<sup>a</sup>

Quantity Measured	Instrument	Nominal Wavelength (nm)
Total $a(z, \lambda)$ , total $c(z, \lambda)$	Unfiltered ac-9	412, 440, 488, 532, 555, 650, 676, 715
Dissolved $a(z, \lambda)$	Filtered ac-9	412, 440, 488, 532, 555, 650, 676, 715
Backscatter $b(z, \lambda)$ derived from VSF at $\psi = 140$ deg	HydroScat-6	442, 488, 532, 555, 620
Backscatter $b(z, \lambda)$ derived from VSF at $\psi = 100, 125,$ and $150$ deg	ECO-VSF	530
VSF ( $\psi = 0.6$ – $179.6$ deg)	VSM	530
$E_d(z, \lambda)$ and $L_u(z, \lambda)$	OCP	412, 443, 489, 533, 555, 591, 683
Sky $E_d(\lambda)$	Multichannel visible detector system	412, 443, 489, 533, 555, 591, 683
Sky $E_d(\lambda)$ and $L_u(z = 0.6 \text{ m}, \lambda)$	Hyper-TSRB	123 wavelengths between 396 and 798

<sup>a</sup>Most instruments have a nominal 10-nm bandwidth centered on the listed wavelengths.

# HyCODE Data



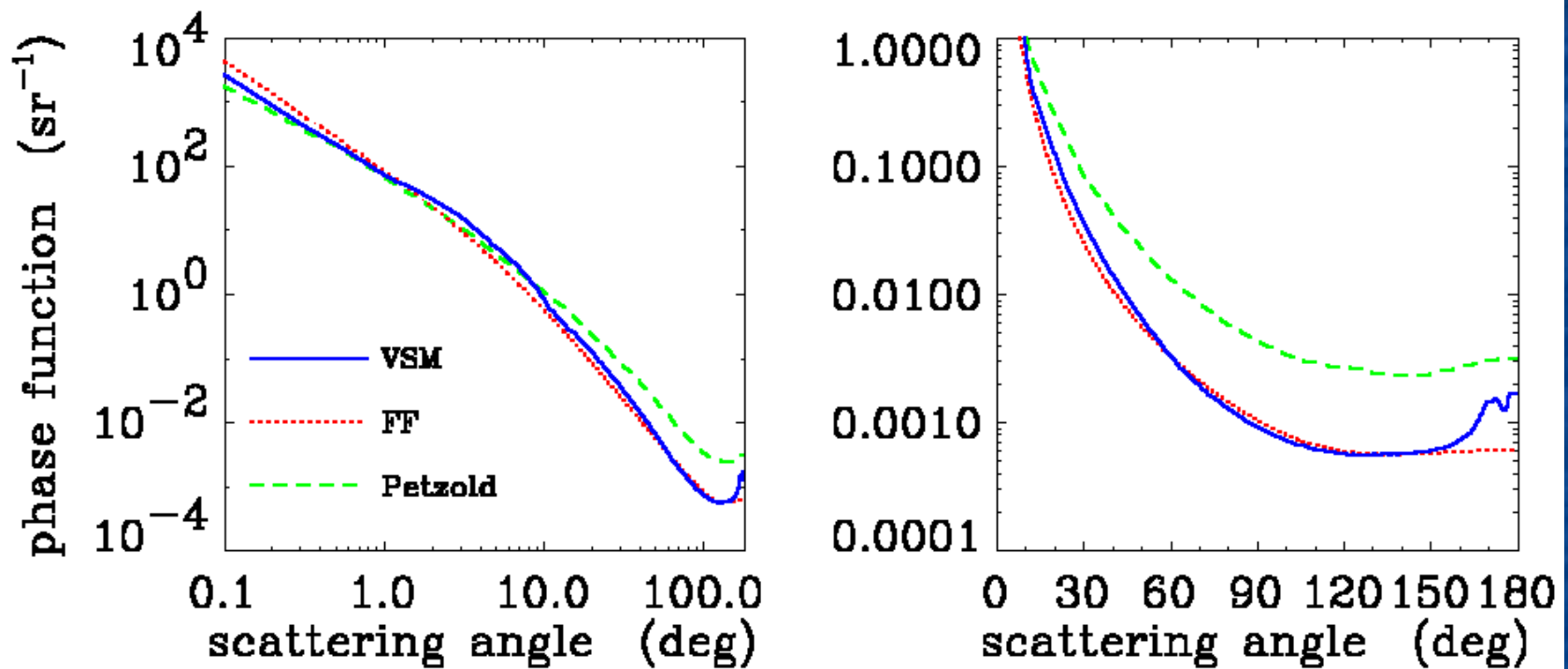
ac-9, both filtered (CDOM absorption) and unfiltered (total  $a$  and  $b$ )

HydroScat-6 ( $b_p$ )

can get  $B_p$  from measured  $b_{bp}/b_p$

can then use  $B_p$  to define a Fournier-Forand phase function with the same backscatter fraction (Mobley, 2002. AO 41(6), 1035-1050)

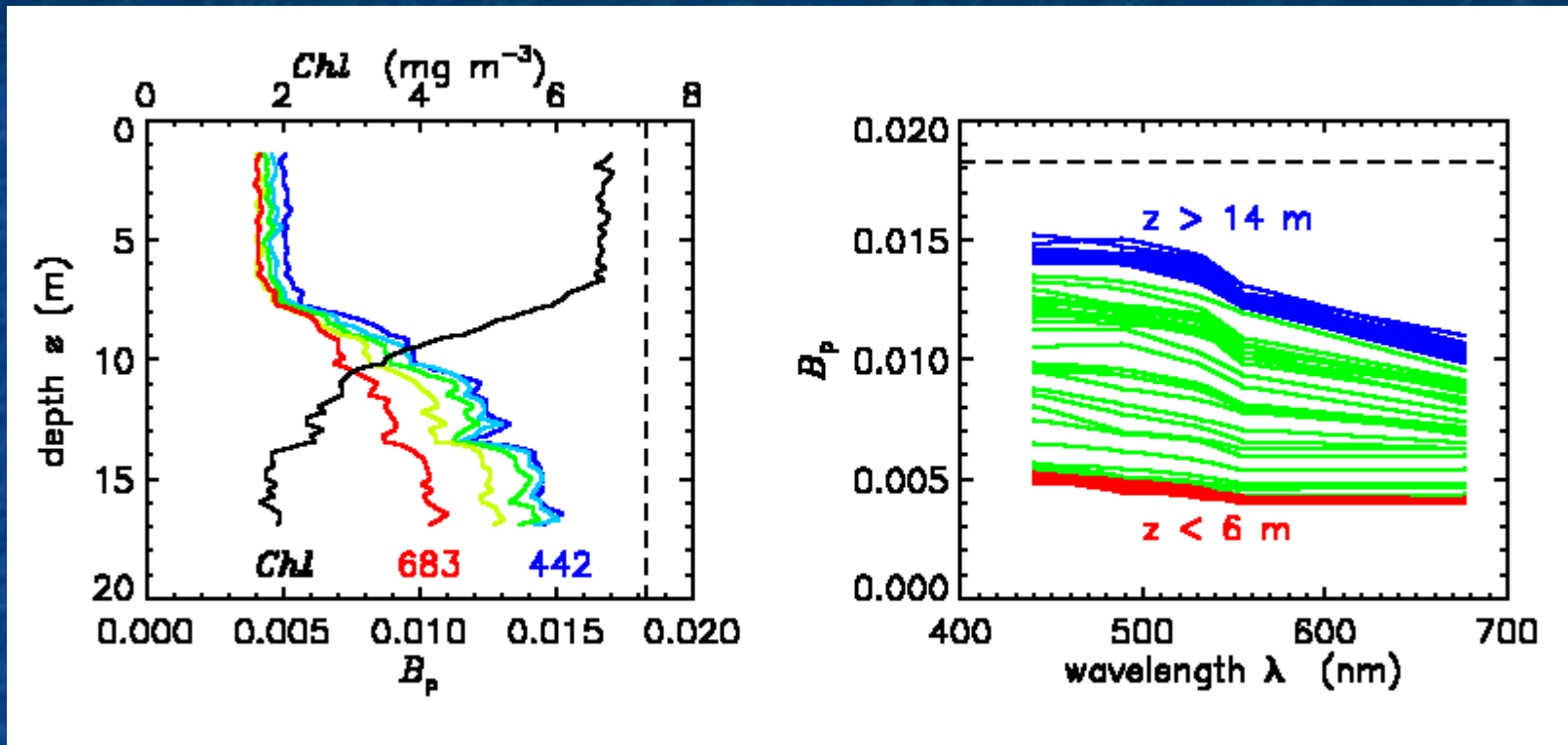
# HyCODE Data



Also have VSF measurements (extremely rare) at 2 m depth at 530 nm from a novel Ukrainian instrument (Lee and Lewis, 2003. *J Atmos Ocean Tech* 20(4), 563-571)



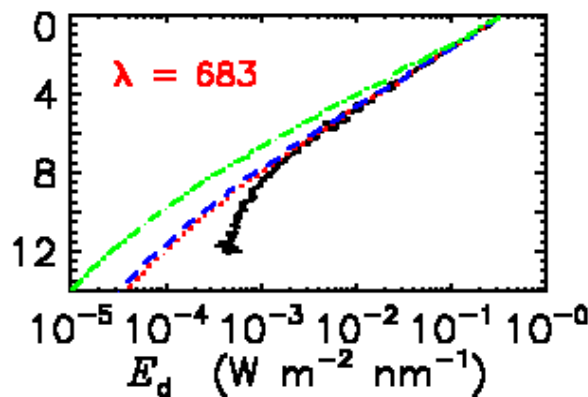
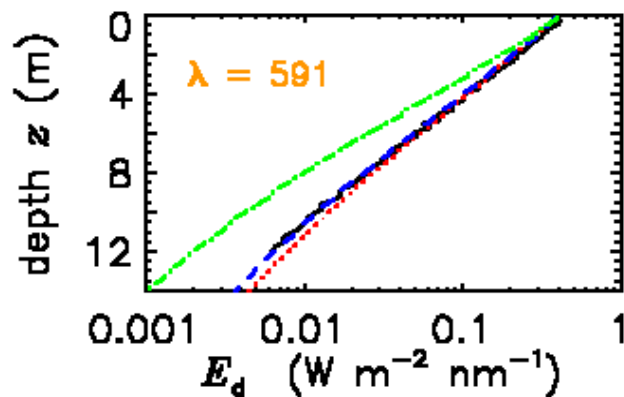
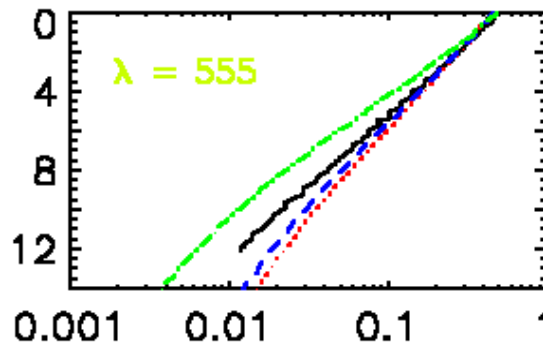
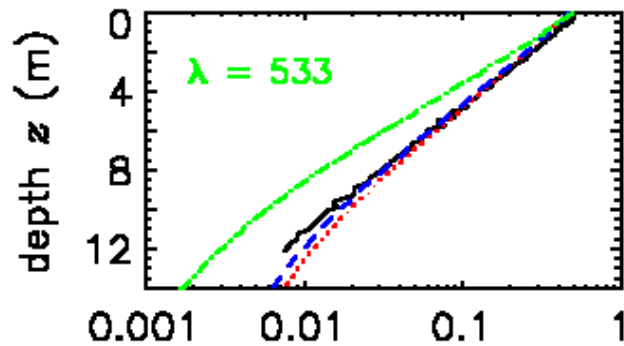
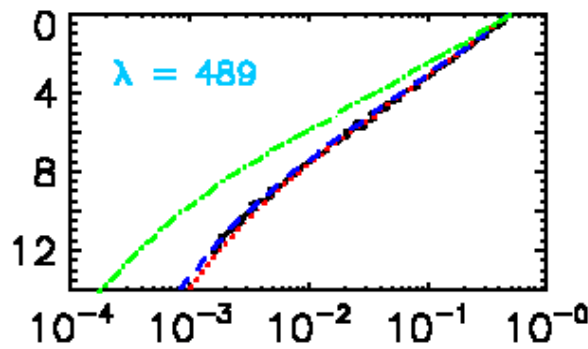
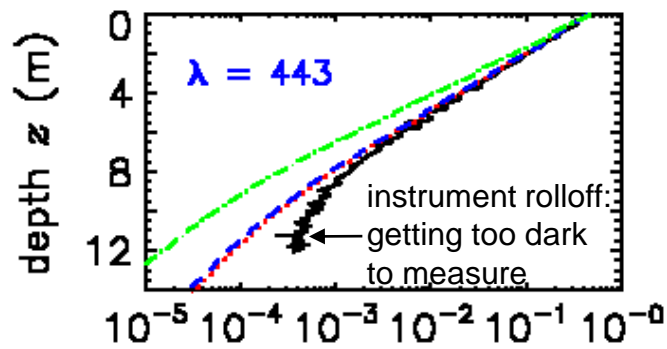
# HyCODE Data



Note that the measured  $B_p$  is much less than for the commonly used Petzold “average particle” phase function (0.0183), and  $B_p$  varies with depth and wavelength; value depends on type of particles: predominately phytoplankton near surface vs resuspended sediments near the bottom (18 m depth)



# HyCODE Data: HydroLight vs $E_d$ Measurements



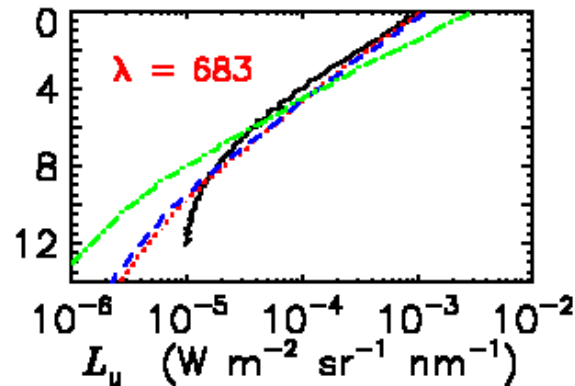
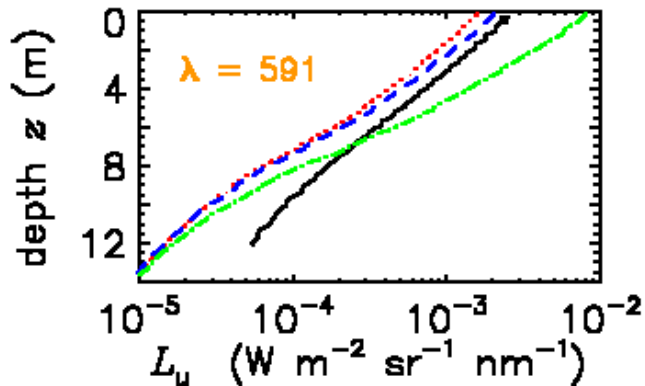
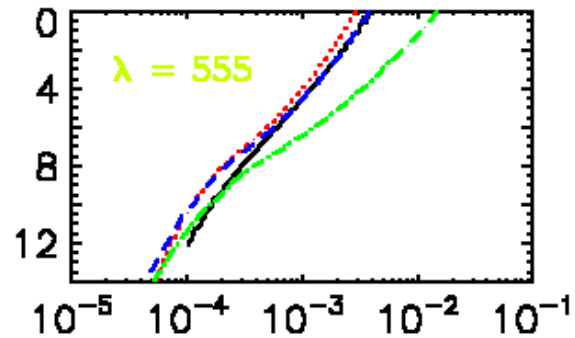
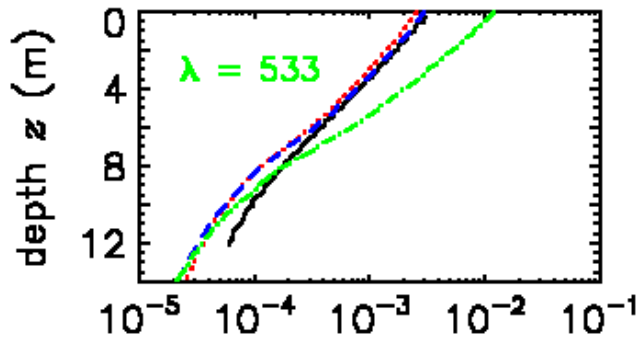
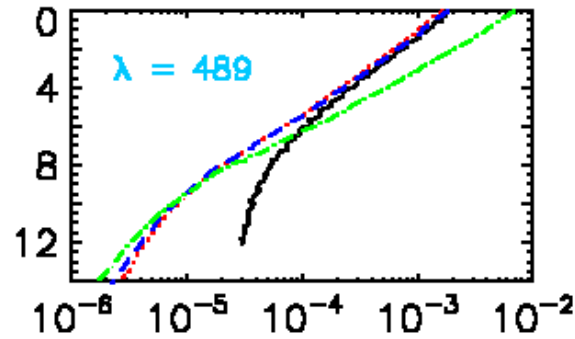
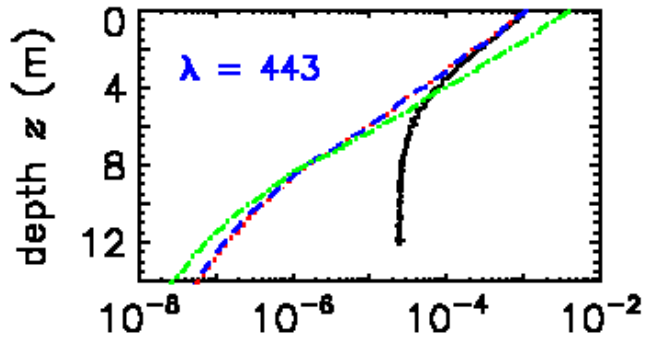
black:  
measurements

green: H with  
Petzold phase  
function

red: H with FF  
phase function  
determined from  
measured  $b_p/b$

blue: H with  
measured pf

# HyCODE Data: HydroLight vs $L_u$ Measurements



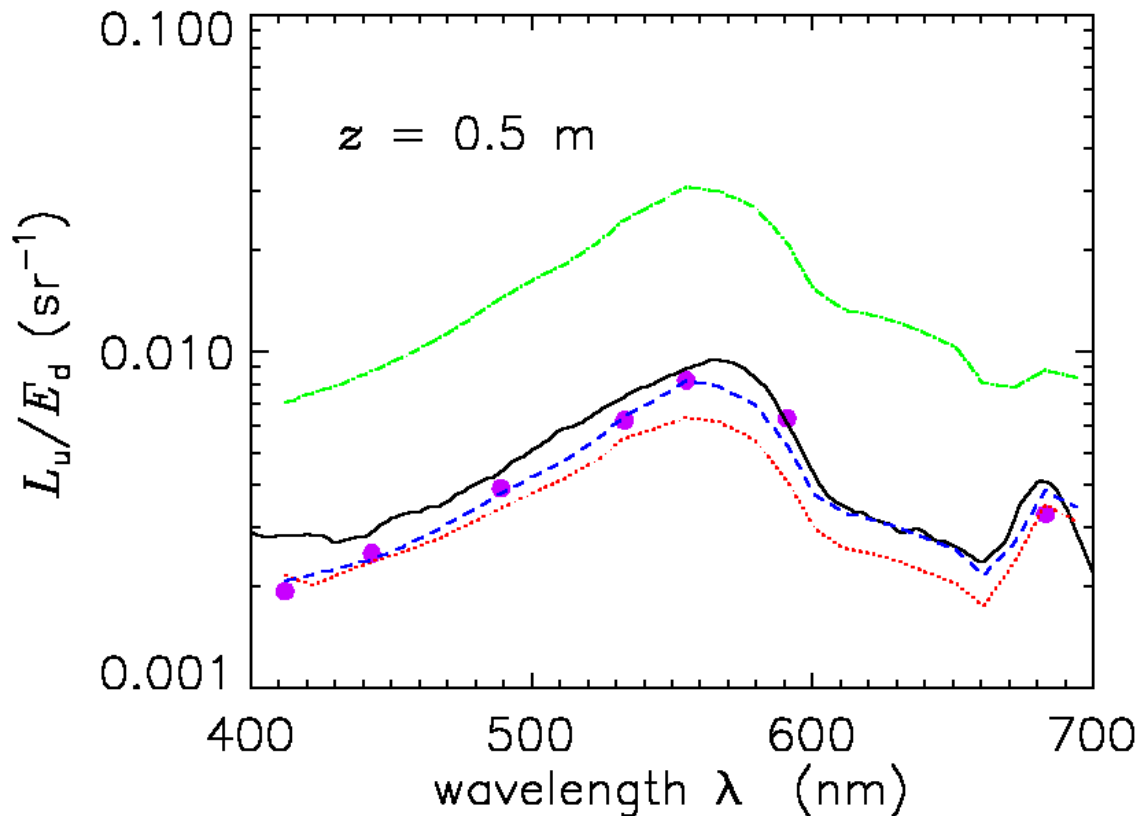
black:  
measurements

green: H with  
Petzold phase  
function

red: H with FF  
phase function  
determined from  
measured  $b_p/b$

blue: H with  
measured pf

# HyCODE Data: HydroLight vs $L_u/E_d$ Measurements



black: measured by  
Hyper-TSRB  
(Satlantic)

purple dots:  
measured by OCP  
(Ocean Color  
Profiler; Satlantic)

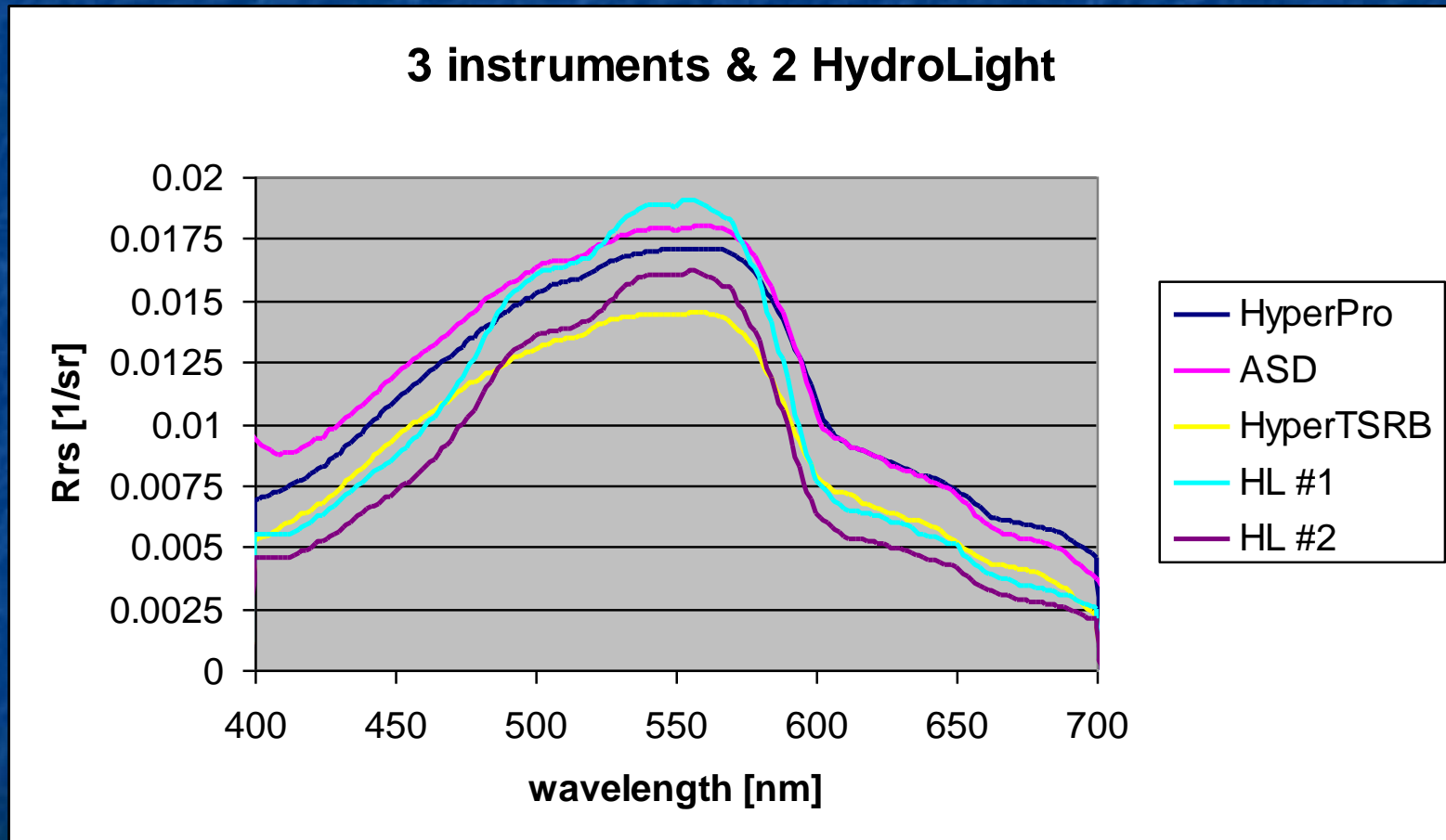
green: H with  
Petzold phase func.

red: H with FF pf  
determined from  
measured  $b_b/b$

blue: H with  
measured pf

# Measured vs HydroLight for CICORE Station ER01

CICORE data and analysis by Heidi Dierssen, Univ. Conn.; used measured ac-9 *a* and *b*; best-guess Fournier-Forand phase function, etc.]



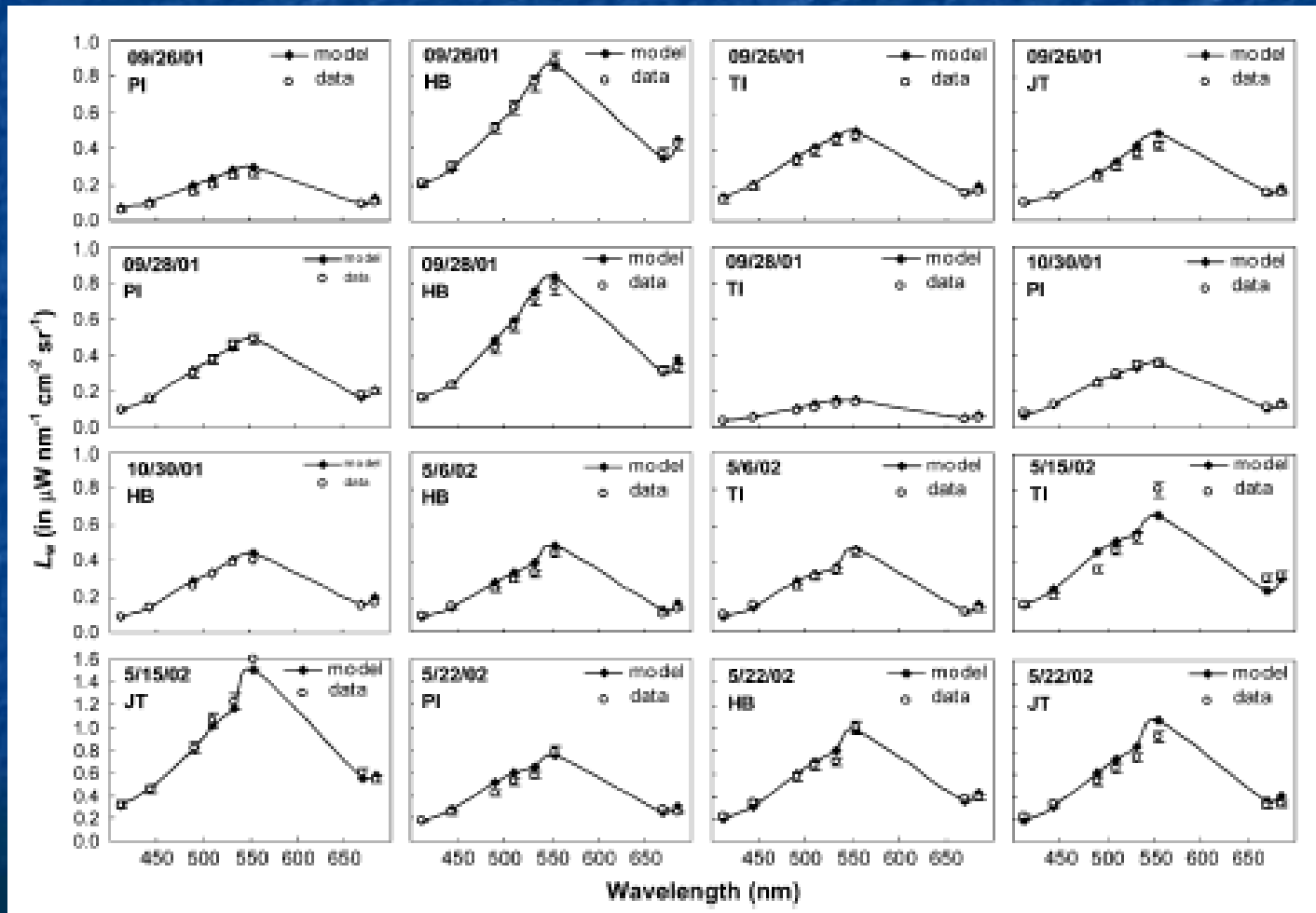
Note that the 3 instruments disagree by about the same amount as the two H simulations (using different guesses for the phase function)



# Measured vs HydroLight for Chesapeake Bay

**Case 2 water.** From Tzortziou et al, Estuarine & Coastal Syst. Sci. (2006). She shows how to “do it right” in taking and processing data, and modeling it with HydroLight.

$L_w$  ( $\mu\text{W cm}^{-2} \text{sr}^{-1} \text{nm}^{-1}$ )



wavelength (nm)

# Measured vs HydroLight for Chesapeake Bay

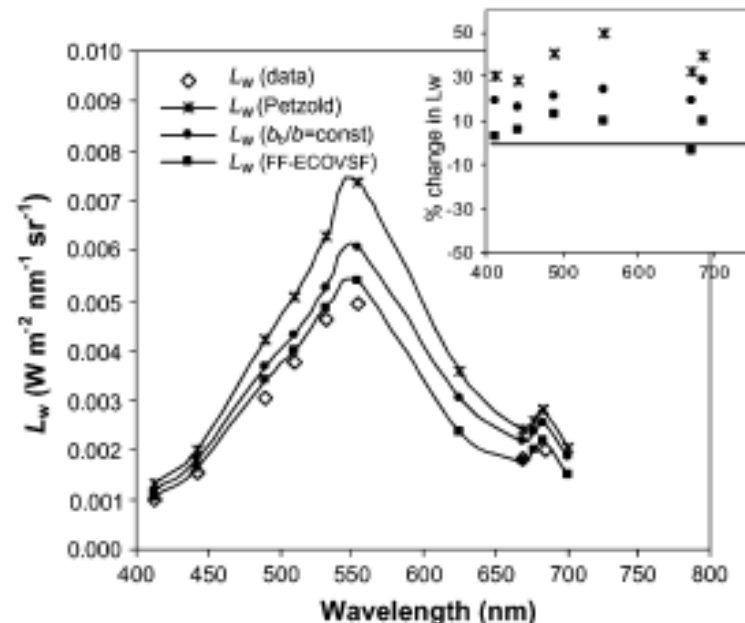
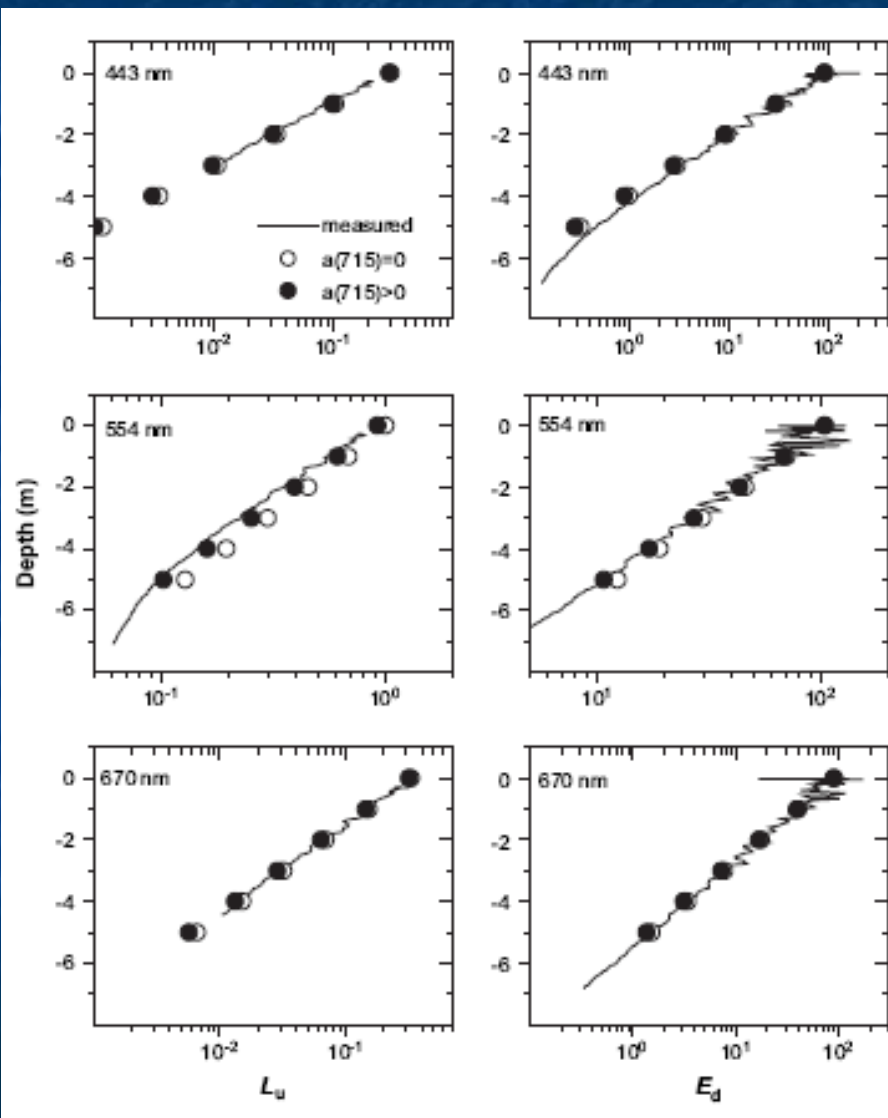


Fig. 3.  $L_w$  spectra estimated using: (1) a Petzold "average particle" scattering phase function (stars), (2) an FF scattering phase function with a constant backscattering ratio,  $b_b/b = 0.015$  (filled circles); and (3) an FF scattering phase function as determined by measured wavelength- and depth-dependent  $b_b/b$  (filled squares). Measured  $L_w$  are shown as open diamonds. Percent differences in  $L_w$  between measurements and model estimations are shown in the inset figure (percent differences estimated as  $(L_{w(model)} - L_{w(data)})/L_{w(data)}$ ).

other examples from  
Tzortziou et al. 2001

# Measured vs HydroLight $R_{rs}$

Tonizzo et al. (2017) compared measured and HydroLight-computed  $R_{rs}$  at 5 locations including Case 1 and Case 2 water

Compared results for 3 different scattering corrections for their ac9 absorptions

Compared results for measured VSFs and modeled VSFs based on Fourier-Forand phase functions determined by the backscatter fraction

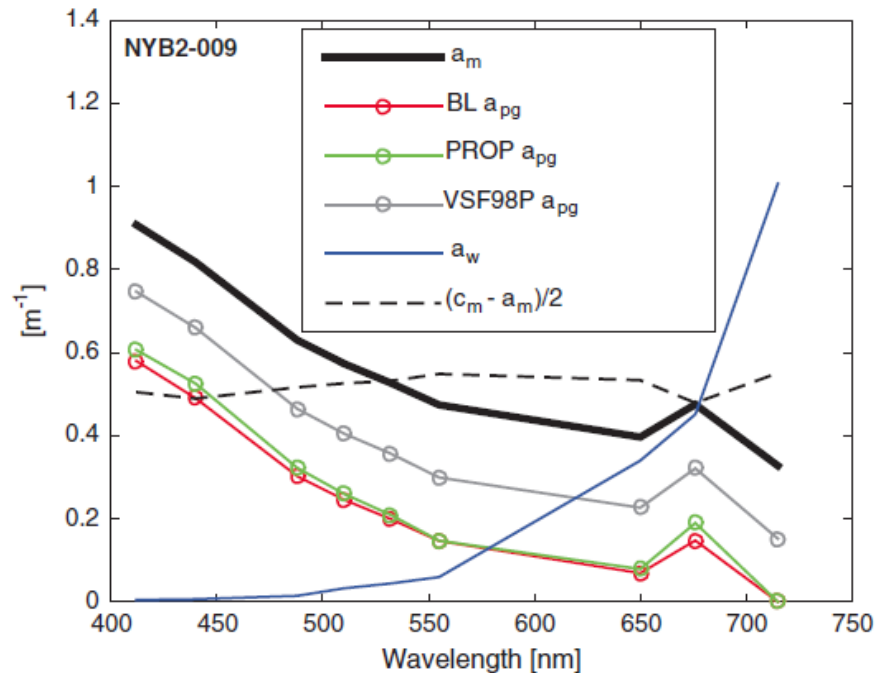
# Compared Three Different Scattering Corrections for ac9

**Table 2. Descriptions of Scattering Error Corrections Applied for WET Labs ac Device Absorption Measurements<sup>a</sup>**

Label	Description	Formula for Scattering Error, $\epsilon(\lambda)$
BL	Measured absorption at 715 nm reference wavelength assumed to be 100% scattering error (i.e., assumes no real absorption in the near-R). Error assumed spectrally constant.	$a_m(715)$
PROP	Measured absorption at 715 nm reference wavelength assumed to be 100% scattering error. Error is scaled spectrally by the ratio of measured total scattering ( $c - a$ ) (i.e., assuming that the ratio of scattering error to total scattering is constant spectrally).	$a_m(715) \frac{c_m(\lambda) - a_m(\lambda)}{c_m(715) - a_m(715)}$
VSF98P	Scattering error is independently derived by convolving measured VSF $\beta$ with angular weighting function $W_e$ of the scattering error for WET Labs ac device reflective tube modeled in McKee <i>et al.</i> [15]. Weighting function associated with 98% tube reflectivity is applied after Stockley <i>et al.</i> [13]. Error is scaled spectrally according to the PROP method.	$2\pi \int_0^\pi \sin(\theta) W_e(\theta) \beta(\theta, 658) d\theta \frac{c_m(\lambda) - a_m(\lambda)}{c_m(650) - a_m(650)}$

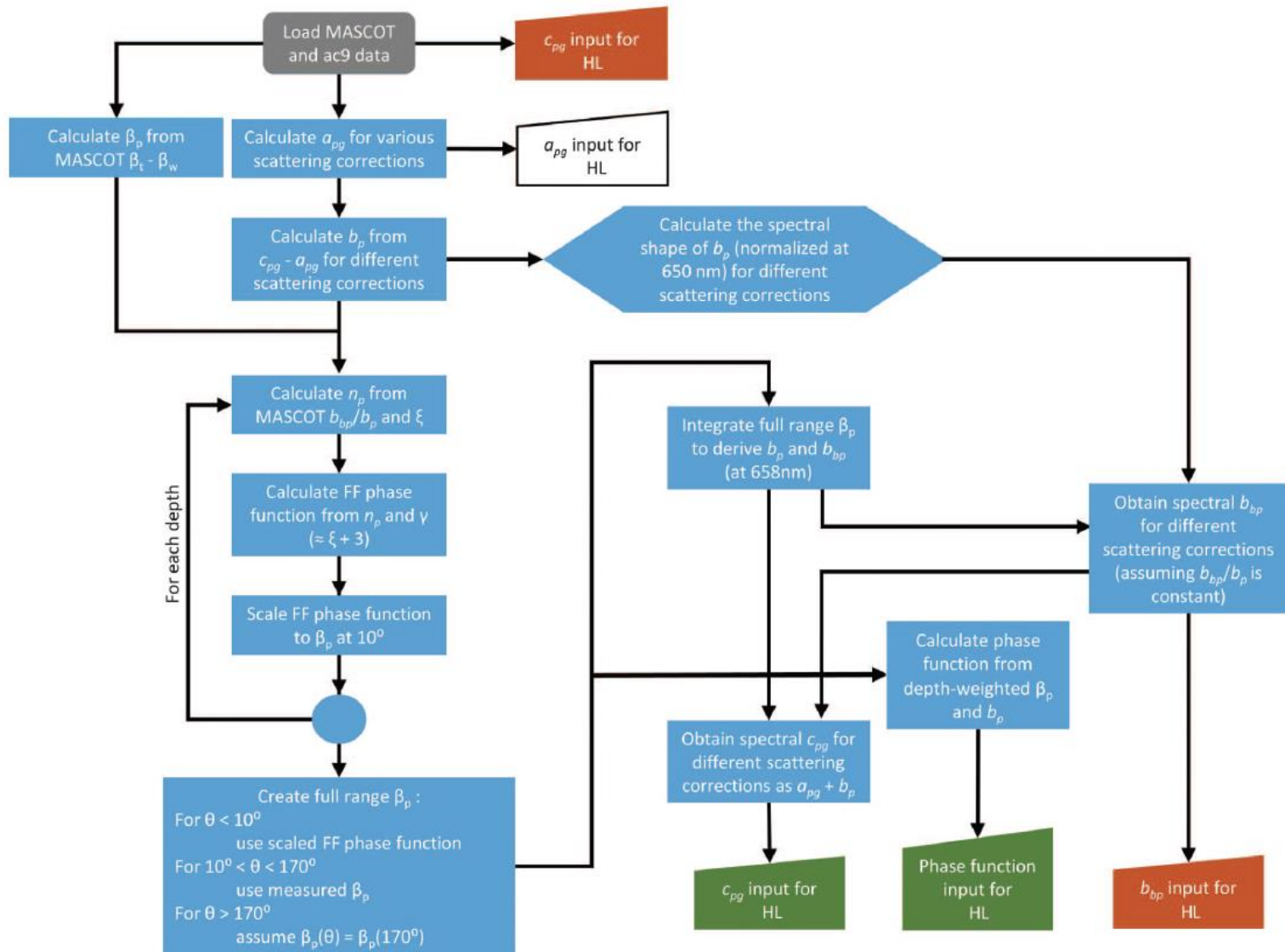
<sup>a</sup>Scattering errors are subtracted from measured absorption  $a_m$ .

absorp coef [1/m]



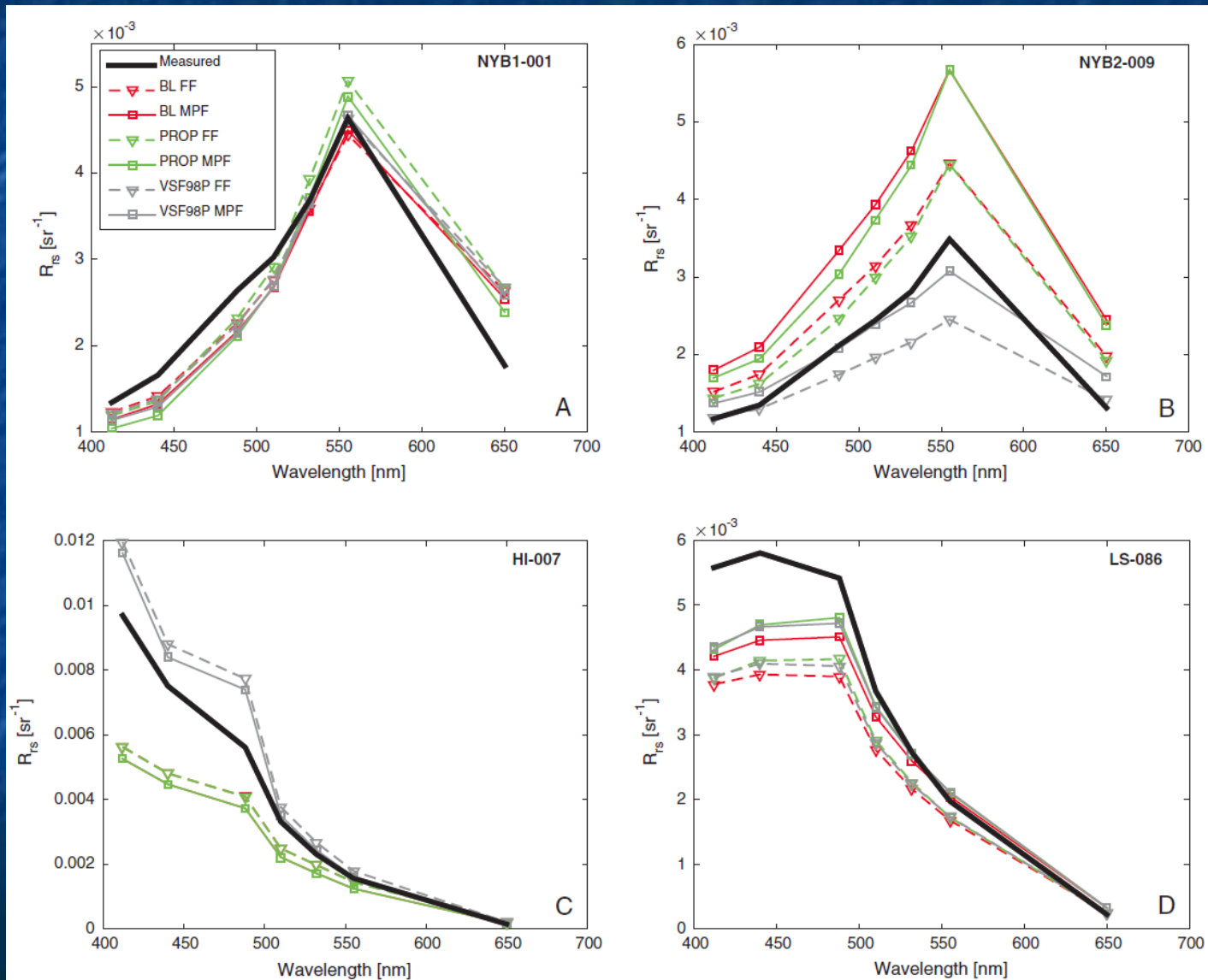


# Preparation of HydroLight Inputs



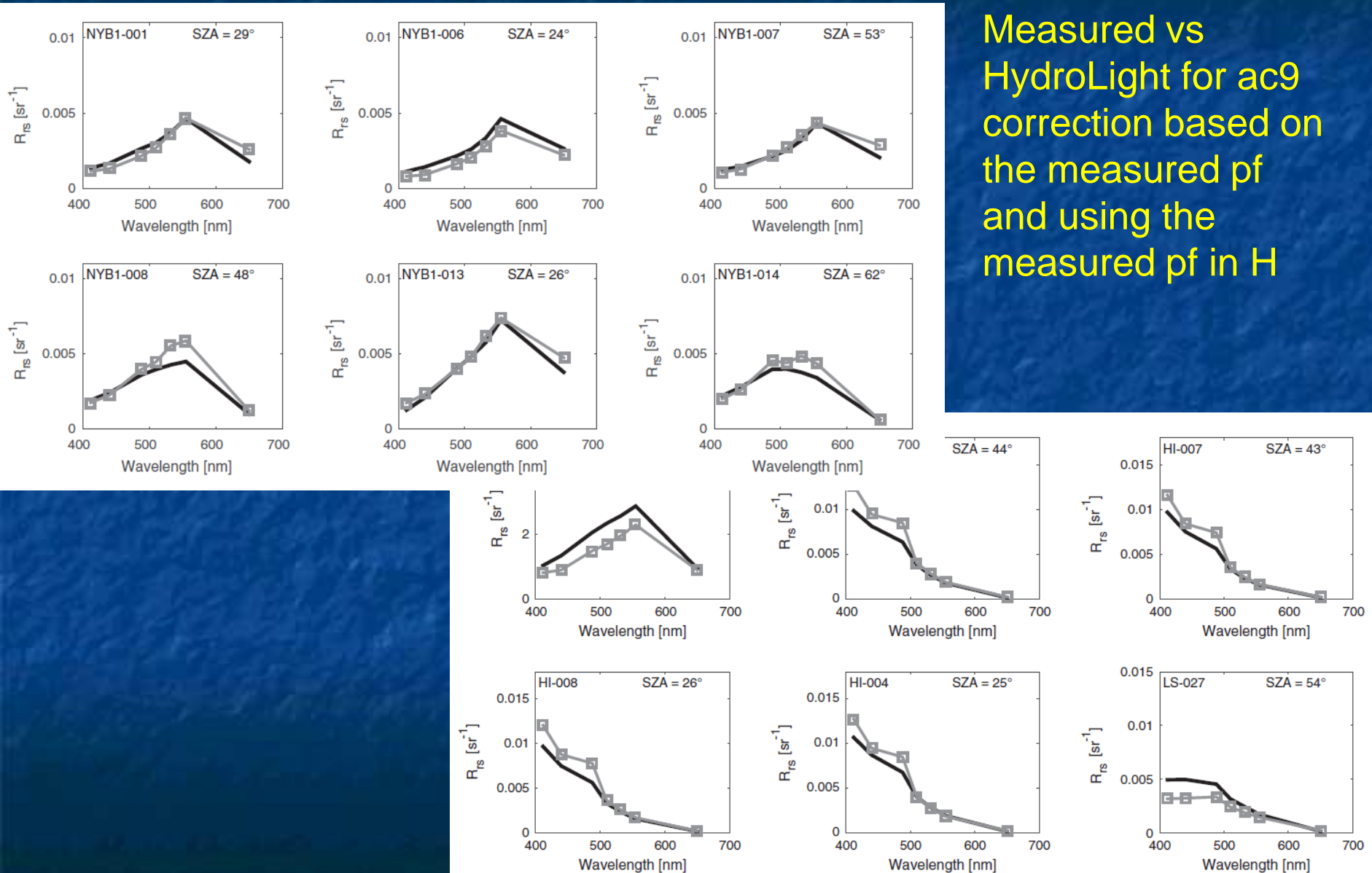
**Fig. 2.** Summary flow chart of preparation of IOPs for HL input. Orange HL input boxes correspond to FF phase function protocol; green HL input boxes correspond to protocol with measured VSFs; the white input box is common to both paths of data input. See text for details.

# Example Model-Data Comparison of $R_{rs}$



# Example Model-Data Comparison of $R_{rs}$

Measured vs HydroLight for ac9 correction based on the measured pf and using the measured pf in H



## Tonizzo et al. Conclusions

Average errors in  $R_{rs}$  were ~20%

½ of error came from  $R_{rs}$  measurement (radiometric calibration, etc.)

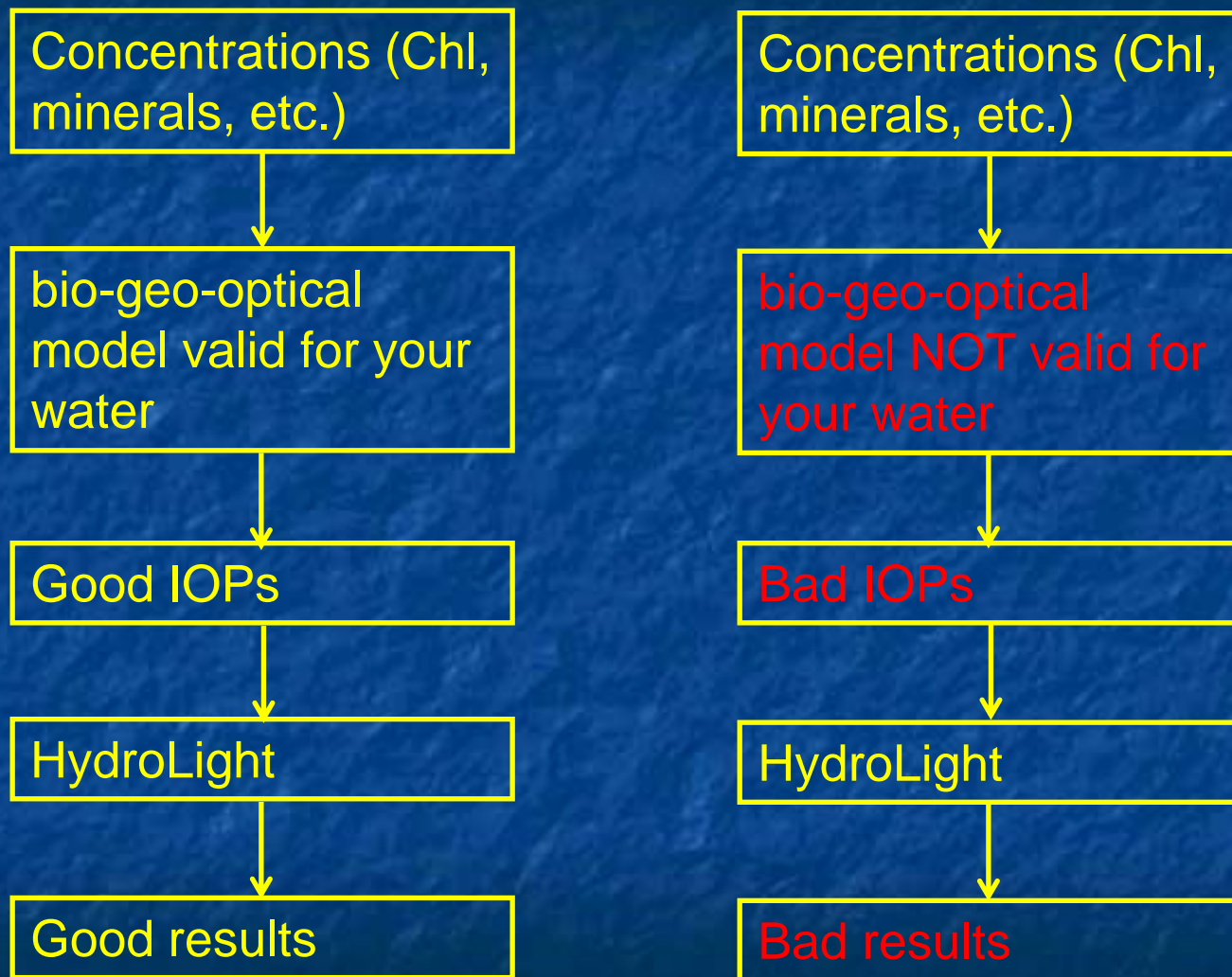
½ of error came from IOP measurement (ac9 scattering correction) and model assumptions (ignoring polarization in HydroLight)

Using a Fournier-Forand phase function determined by the backscatter fraction (a standard option in HydroLight) gave results almost as good (23% avg error) as using a measured phase function (20% avg error)

Read the Tzortziou et al. and Tonizzo et al. papers to see how difficult it is to get good model-data comparisons. They show “how to do things right.”



# The Main Cause of Bad HydroLight Results



## To Get Good Agreement Between HydroLight and Measurements:

You **MUST** have good IOPs, which means you almost always **MUST MEASURE** the IOPs and other inputs for **YOUR** water body.

You can **NOT** use simple bio-optical models based on data from other ocean waters to simulate the Yellow Sea or the Gulf of Maine or ....

Bio-optical models are fine on average, and for generic studies, but they should **NOT** be used to simulate specific water bodies.

## You Get the Idea

You do the best you can with the data you have. Sometimes very good, sometimes not so good, sometimes completely useless. That's science.

If you didn't measure the VSF, can you get the backscatter fraction from  $b_b/b$ ? If not, treat  $b_b/b$  as a "fitting parameter" and adjust to get the best fit for  $R_{rs}$ , for example.

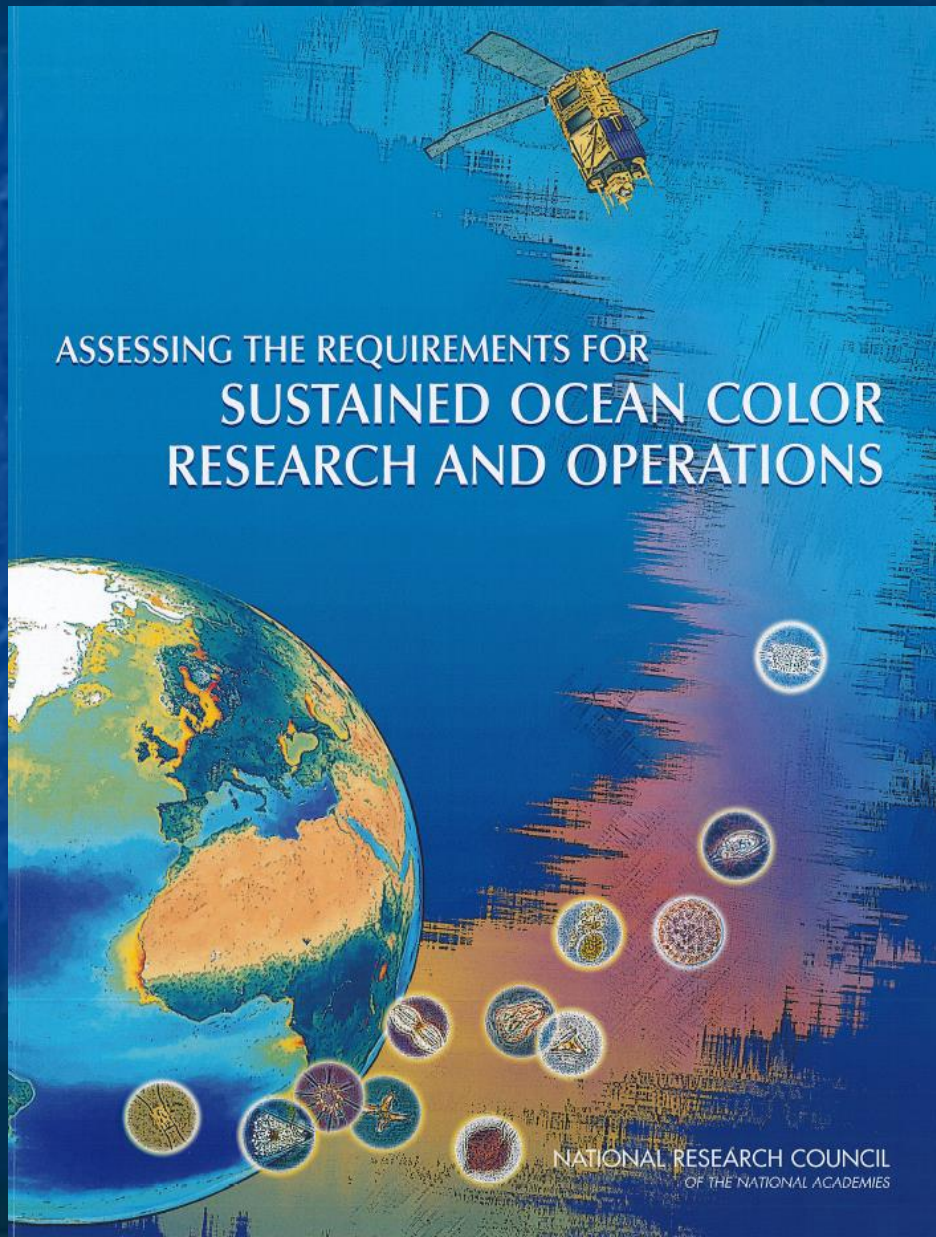
Even if you can't get agreement between measured and modeled  $E_d$  and  $L_u$ , for example, can you get agreement with  $L_u/E_d$  or with  $K_d$ ?

Compare as many things as possible, e.g., the measured  $E_d$  from the HyperPro and from the ship deck cell and with H's default sky irradiance model.

The disagreements are often where you learn the most.



# Designing the Perfect Field Experiment



## The Problem:

Data collection campaigns are designed to answer specific questions or to validate specific products, instruments, or models, without regard for subsequent possible uses and long-term value of the data.

This results in a partial dataset, which, when later examined for other purposes, lacks one or more crucial “missing pieces” that preclude its use.

see Appendix C



# Comprehensive Data Sets

## Guiding Principle:

A truly comprehensive dataset would have all of the information necessary for a complete radiative transfer (RT) calculation to propagate sunlight from the top of the atmosphere (TOA), through the atmosphere to the sea surface, through the sea surface into the water, and then from the water back to the atmosphere, and finally through the atmosphere to the sensor. This RT process is the physical basis for all optical oceanography and ocean color remote sensing.

No such data set has ever been collected, and probably never will be.

# Comprehensive Data Sets

In remote sensing, to validate an environmental parameter or ocean color product (such as the chlorophyll concentration, or depth and bottom type in shallow water):

- It is first necessary to validate the atmospheric correction algorithm, which requires knowing the absorbing and scattering properties of the atmosphere.
- Then, to validate the bio-optical inversion algorithm that retrieves an ocean color product from the sea-level remote sensing reflectance, it is necessary to know both the value of the product and the water-leaving radiance.
- Finally, to understand how the product influences the water-leaving radiance, it is necessary to know the water absorbing and scattering properties (the inherent optical properties [IOPs]) and the in-water radiance distribution.

# Comprehensive Data Sets

If everyone wants them, why are there no comprehensive data sets?

- Funding constraints for personnel, instrumentation, and ship time.
- Data collection for its own sake is almost never viewed as fundable science, even though model and algorithm development and validation always need comprehensive datasets.
- Instrument limitations for measurement of some needed parameters.
- Narrow scientific focus on specific problems.

You just do the best you can with the resources you have.



# Oceanic Measurements: IOPs

Ideally, measure

- absorption coefficient  $a(z,\lambda)$ , measured as a function of depth  $z$  and wavelength  $\lambda$ .
- volume scattering function  $VSF(z,\lambda,\psi)$ ;  $\psi$  is the scattering angle, 0-180 deg.

What can be measured with commercial instruments:

- $a(z,\lambda)$  and  $c(z,\lambda)$  [e.g., WETLabs ac-9 or ac-s]; get  $b(z,\lambda) = c(z,\lambda) - a(z,\lambda)$
- $b_b(z,\lambda)$  [e.g., WETLabs bb-9 or Sequoia Hyper-bb]

Only one newly available commercial instrument (LISST-VSF, <http://www.sequoiasci.com/product/lisst-vsrf/>) for measuring the full VSF, so use  $b_b(z,\lambda) / b(z,\lambda)$  to estimate the shape of the phase function when modeling.



# Oceanic Measurements: Boundary Conditions

Ideally, measure

- in-air, sea-level downwelling (sun + sky) radiance  $L_{\text{sky}}(\theta, \varphi, \lambda)$
- sea-surface wave spectrum
- BRDF( $\theta', \varphi', \theta, \varphi, \lambda$ ) of the bottom (if shallow water) for all incident ( $\theta', \varphi'$ ) and reflected ( $\theta, \varphi$ ) directions

What can be measured with commercial instruments:

- in-air, sea-level downwelling irradiance  $E_d(\lambda)$  direct and diffuse components
- sun zenith angle (or time and location)
- cloud conditions
- wind speed
- bottom irradiance reflectance  $R_b(\lambda) = E_u(\lambda) / E_d(\lambda)$

Then use atmospheric RT models to estimate  $L_{\text{sky}}(\theta, \varphi, \lambda)$  (e.g., when running HydroLight).

Assume a Lambertian bottom to get  $\text{BRDF}(\theta', \varphi', \theta, \varphi, \lambda) = R_b(\lambda) / \pi$

# Oceanic Measurements: Light

Ideally, measure

- in-water radiance  $L(z, \theta, \phi, \lambda)$
- upwelling radiance above the sea surface  $L_u(z, \theta, \phi, \lambda)$

What can be measured with commercial instruments:

- plane irradiances  $E_u(z, \lambda)$ ,  $E_d(z, \lambda)$
- scalar irradiance  $E_o(z, \lambda)$  [for PAR calculations]
- upwelling, nadir-viewing irradiance  $L_u(z, \lambda)$
- above-surface upwelling radiance in one direction,  $L_u(\theta=40, \phi=135, \lambda)$ , plus sky and gray-card measurements needed to estimate  $R_{rs}$  (via the Carder method; Mobley 1999)

# Oceanic Measurements: Ancillary

These measurements are not needed to solve the RTE, but they are needed to validate bio-optical models for Chl, CDOM, TSM, etc., and to understand the fundamental connections between water constituents and optical properties.

Ideally, measure

- phytoplankton pigments
- IOPs partitioned into contributions by phyto, CDOM, organic (detritus) and inorganic (mineral) particles

What can be measured with commercial instruments:

- the chlorophyll concentration  $\text{Chl}(z)$
- total and dissolved  $a(z,\lambda)$  and  $c(z,\lambda)$  [e.g., unfiltered and filtered ac9]
- TSM or SPM (dry weight)



# Atmospheric Measurements

To solve the RTE in the atmosphere and to validate the computations, you need the same things as for the ocean: IOPs, constituents, and radiance

What can be measured with commercial instruments:

- sea-level pressure, temperature, humidity, wind speed [for simple RT modeling, and for computing the Rayleigh scattering contribution to atmospheric path radiance]
- aerosol concentration, size distribution, and optical properties are highly variable and are the biggest uncertainty in atmospheric correction of airborne and satellite imagery. Can use sun photometer measurements to extract aerosol optical depth, scattering phase function, and albedo of single scattering
- if highly accurate atmos RT calculations are to be done, need vertical profiles of temperature, moisture, cloud type [from balloon-borne instruments or ground-based LIDAR). Ozone from TOMS satellite data.



# Polarization

Polarization is an inherent feature of all electromagnetic radiation.

The ocean color community has usually ignored polarization (with a few exceptions such as the POLDER satellite, and some studies of underwater imaging). This is both because of measurement difficulties and because unpolarized measurements can yield acceptably accurate answers for many (but not all) problems of interest.

However, polarization carries information that can be exploited to improve ocean color product retrievals. For example, surface reflection is strongly dependent on polarization, so that sun glint is partially polarized, depending on the relative sun and viewing directions. In addition, biological and mineral particles have different indices of refraction and different size distributions, and thus scatter light differently, including polarization changes during the scattering.

Some atmospheric RT codes now include polarization (e.g., 6SV; Vermote et al., 2006), and a few researchers have developed proprietary coupled ocean-atmosphere RT codes. Polarization likely will become more important in future ocean color applications.

# Polarization

Ideally,

- Instead of the  $VSF(z, \lambda, \psi)$ , measure the full scattering (Mueller) matrix. The scattering matrix has 16 elements, although not all are independent. and some can be assumed to be zero. The (1,1) element is the VSF.
- Instead of the radiance  $L$ , measure the Stokes Vector (4 elements).

There are no commercial instruments for measurement of the full scattering matrices and Stokes vectors in the ocean, although some individuals are now making underwater Stokes vector measurements (e.g., Tonizzo, et al. 2009)

Doing unpolarized RT calculations leads to errors in radiance of order 10% in particular directions, but usually less than 1% in irradiances

# In Summary

Understand your instruments:

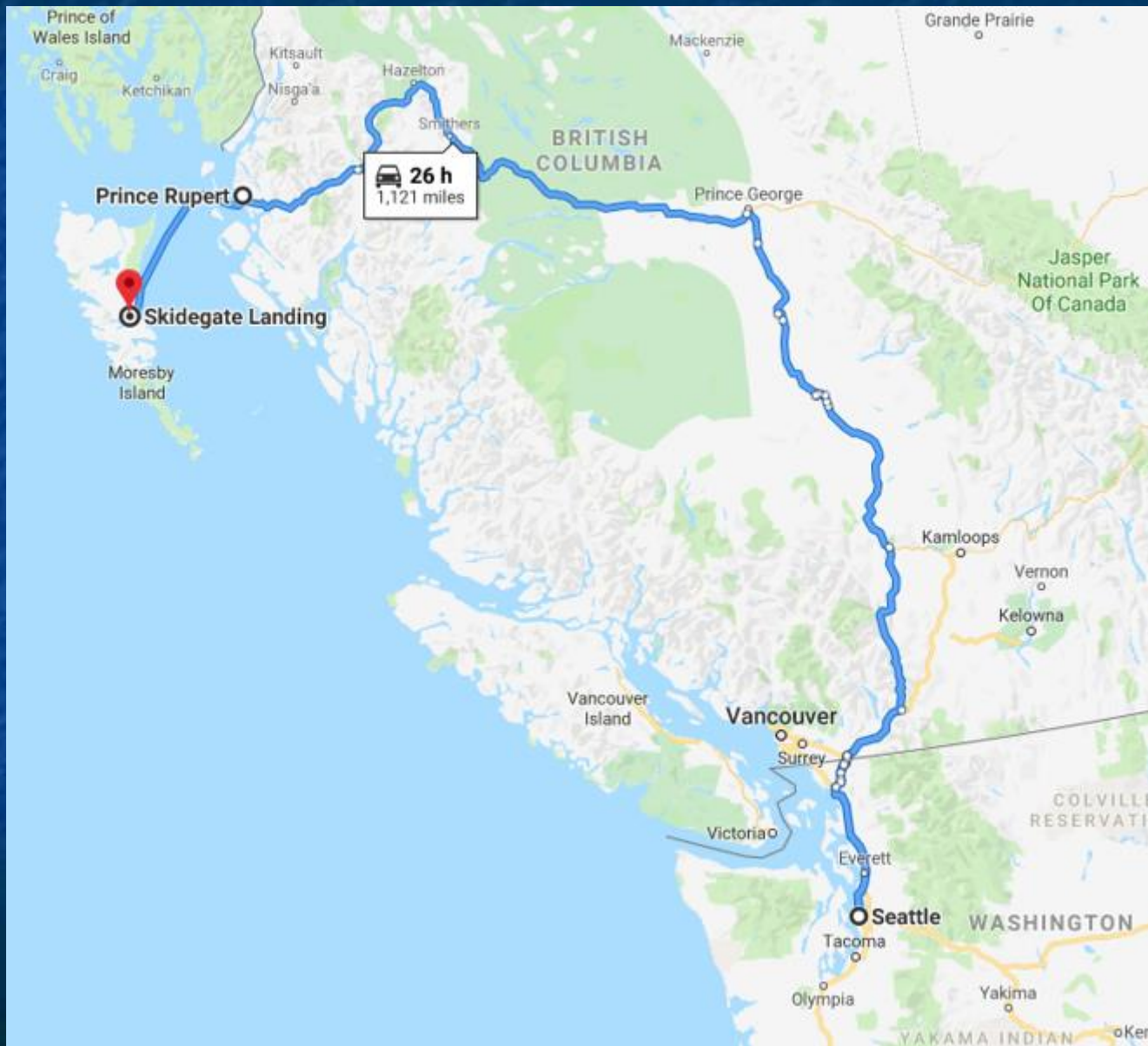
- what do they actually measure?
- how do they convert what they measure to what they output?
- how precise are they?
- how accurate are they?
- what are their systematic errors?
- what are their random errors?

Make as many measurements as you can

Duplicate where ever possible: multiple instruments, multiple methods, multiple models, multiple people for the same quantity



# Haida Gwaii





# Totem Poles at S'Gang Gwaay Llanagaay





# Long House Ruin





# Gale-force Winds and 6 ft Seas





# Calmer Conditions



6 mile crossing to  
Hot Springs Island

