Inverting In-Water Reflectance

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Inverting In-Water Radiance

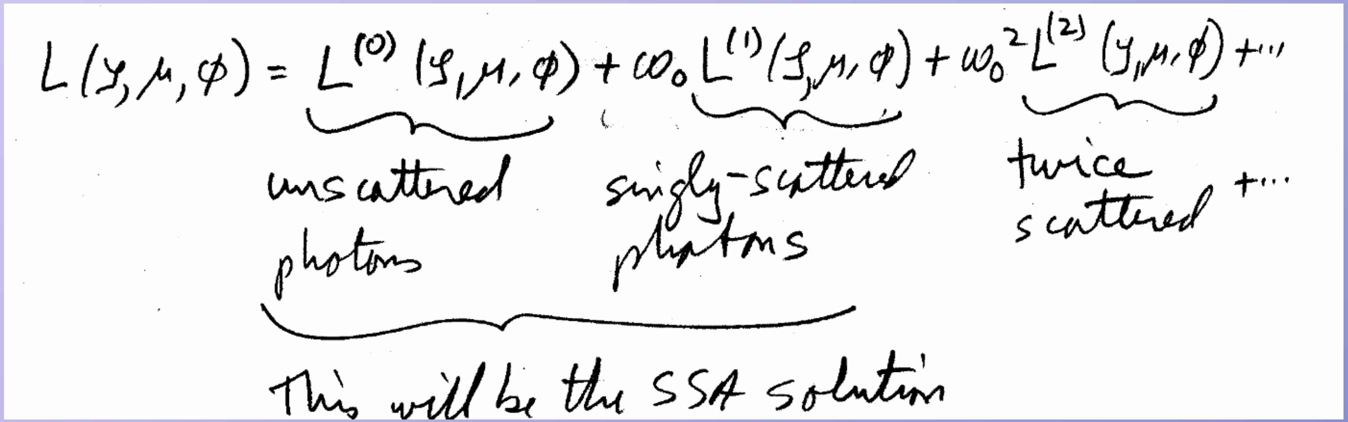
Estimation of the absorption and backscattering coefficients from in-water radiometric measurements

Stramska, Stramski, Mitchell, Mobley

Limnol. Oceanogr. 45(3), 2000, 629-641

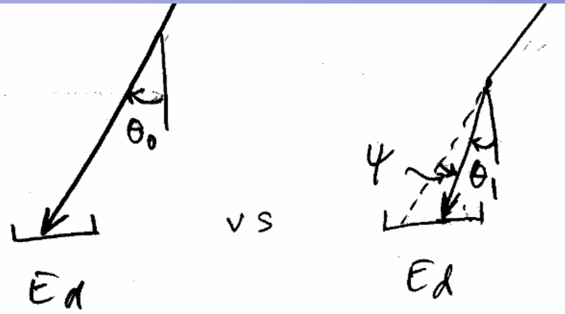
SSA and QSSA don’t work in the water

- SSA assumes single scattering near surface



$$L(\zeta,\mu,\phi) = \underbrace{\underbrace{L^{(0)}(\zeta,\mu,\phi)}_{\text{unscattered photons}} + \omega_0 \underbrace{L^{(1)}(\zeta,\mu,\phi)}_{\text{singly-scattered photons}}}_{\text{This will be the SSA solution}} + \omega_0^2 \underbrace{L^{(2)}(\zeta,\mu,\phi)}_{\text{twice scattered}} + \cdots$$

- QSSA assumes that “Use the forumlas from SSA but treat b_f as no scattering at all.



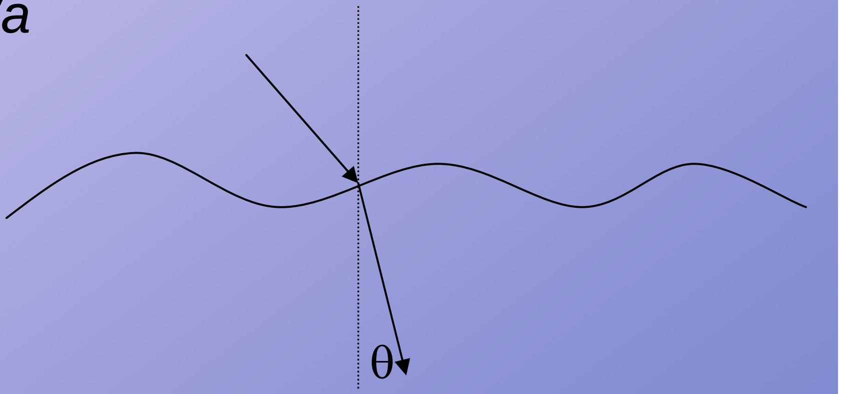
almost the same Ed since $\theta_0 \approx \theta_1$

Stramska, et al. Approach

- Empirical Model for estimating K_E, a, b_b
  - Requires $L_u,(z,\lambda)$ $E_u(z,\lambda)$, *and* $E_d(z,\lambda)$
- Work focuses on blue (400-490nm) and green (500-560 nm)
- Numerous Hydrolight simulations
  - Runs with IOPs that covaried with [Chl]
  - Runs with independent IOPS
  - Raman scattering, no Chl fluorescence
- Field Results from CalCOFI Cruises, 1998

Conceptual Background

- Irradiance Reflectance $R = E_u/E_d$
  - Just beneath water: $R(z=0^-) = f * b_b/a$
  - $f \alpha 1/\mu_0$ where $\mu_0=\cos(\theta)$
  - Also $R \alpha \frac{1}{\bar{\mu}}$ (Timofeeva 1979)



- Radiance Reflectance $R_L=L_u/E_d$
  - Just beneath the water
    - $R_L(z=0^-) = (f/Q)(bb/a)$, *where* $Q=(E_u/L_u)$
  - f and Q covary ➔ *f/Q* less sensitive to angular distribution of light

Conceptual Background

- Assume
  - $R(z) = E_u/E_d \alpha\, b_b(z)/a(z)\ \alpha \frac{1}{\overline{\mu}}$
  - $R_L(z) = L_u/E_d\ \alpha\, b_b(z)/a(z)$,
    not sensitive to directional
    structure of light field
  - ∴R_L/R *can be used to estimate* $\overline{\mu}$
  - *Many Hydrolight runs to build in-water empirical model*
- K_E *can be computed from* E_d, E_u
- *Gershuns Law* $a=K_E*\overline{\mu}$
- *Again, many Hydrolight runs to build in-water empirical model of* $b_b(z) \sim a(z)*R_L(z)$

Algorithm I

1. **Profile $E_d(z)$, $E_u(z)$, $L_u(z)$**
2. **Estimate $K_E(z)$**
   1. $K_E(z) = –d\ ln(E_d(z) –E_u(z)]/dz$
3. **Derive $\mu(z)$**
   1. $\mu(Z) \sim R_L(z) /R(z) = L_u(z)/E_u(z)$
      1. $\mu_{est}(\lambda_b)=0.1993+(-37.8266*R_L(\lambda_b).\text{^}2+2.3338*R_L(\lambda_b)+0.00056)./R_b;$
      2. $\mu_{est}(\lambda_g)=0.080558+(-28.88966*R_L(\lambda_g).\text{^}2+3.248438*R_L(\lambda_g)-0.001400)./R_g$
4. **Inversion 1:** Apply Gershun's Law
   1. $a(z)=K_E(z)*\mu(z)$
5. **Inversion 2:**
   - $b_b \sim a(z)*R_L(z)$

   $b_{b,est}(\lambda_b)=11.3334*R_L(\lambda_b).*a(\lambda_b)-0.0002;$

   $b_{b,est}(\lambda_g)=10.8764*R_L(\lambda_g).*a(\lambda_g)-0.0003;$

Curt's Method 2
from LI-COR Lab!

A lovely result of the
Divergence Law for
Irradiance

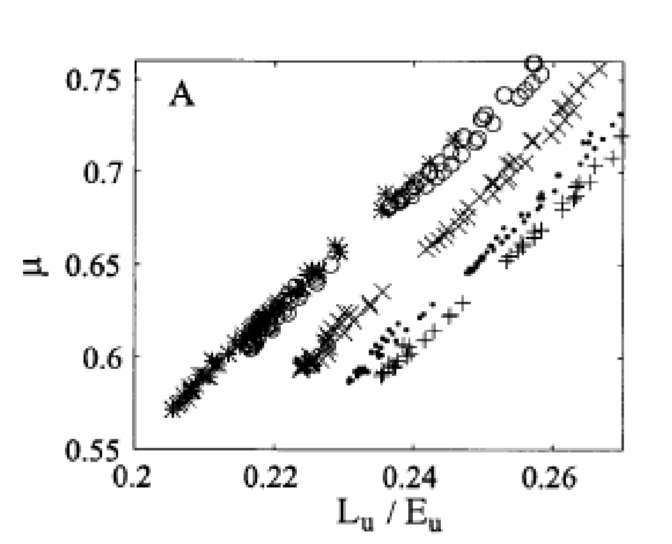
Algorithm II

- Requires knowledge of attenuation coefficient *c*
- Regress simulated μ vs L_u/E_u for variety of b_b/b and $\omega_0 = b/c$
- $b_{est}=0.5*(b_1+b_2)$

  $b_1=c - a_{est}$ (underestimate)

  $b_2=b_w + (b_{b,est}-.5*b_w)/0.01811$ (overestimate)
- Compute $\omega_0 = b_{est}/c$
- Retrieve based on b_b/b:

  $$\mu_{2,est} = m_i(\omega_0)*(Lu/Eu) + b_i(\omega_0)$$
- As before
  - Use $\mu_{2,est}$ to retrieve *a*
  - Use R_L and *a* to retrieve b_b



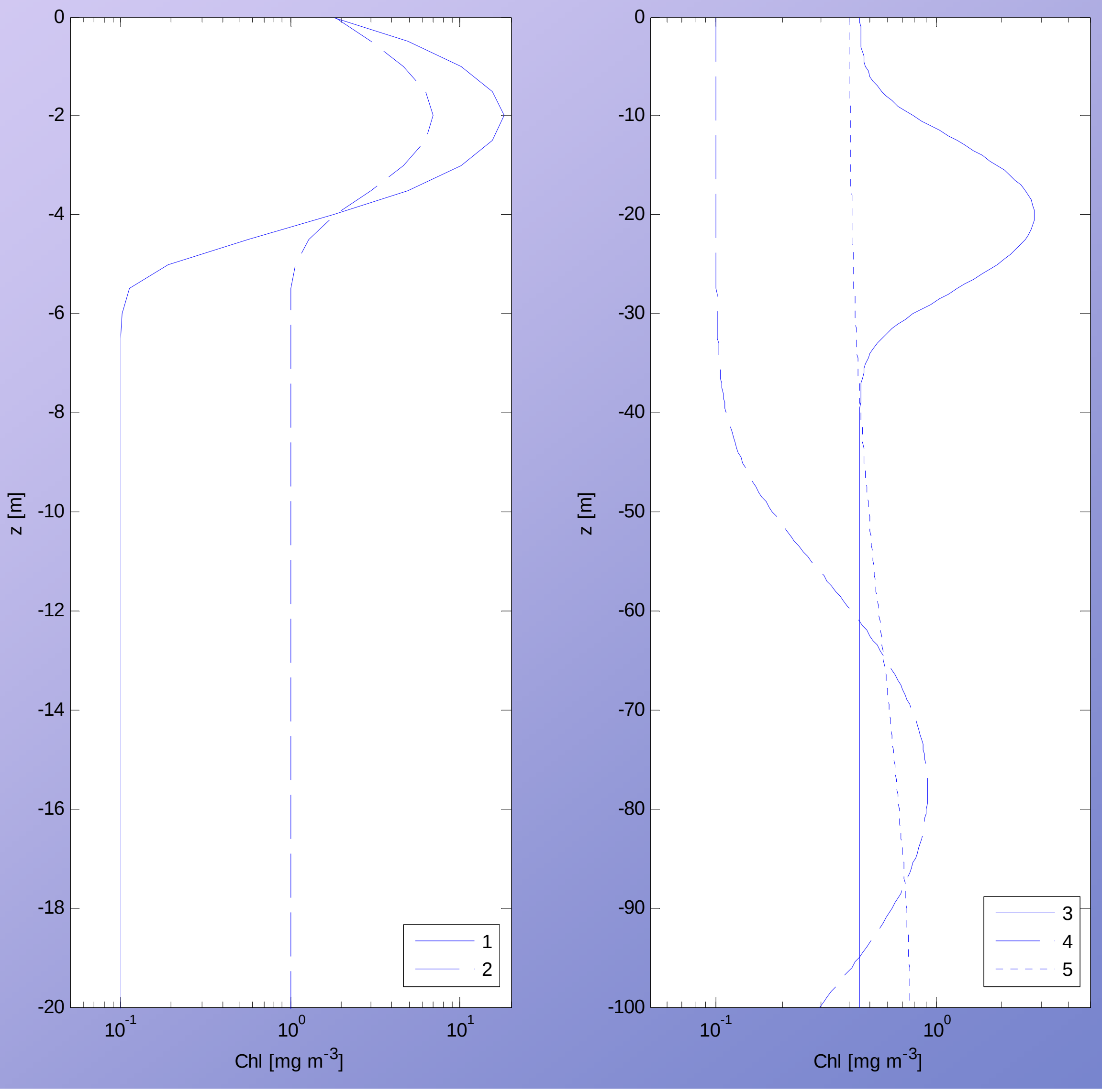
Model Caveats

- Assumes inelastic scattering and internal light sources negligible
  - Expect errors in b_b to increase with depth and decreasing Chl.
  - Limit model to top 15 m of water column
- Blue (400-490 nm) & Green (500-560 nm)
- Used Petzold phase function for simulations
  - Acknowledge that further work was needed here

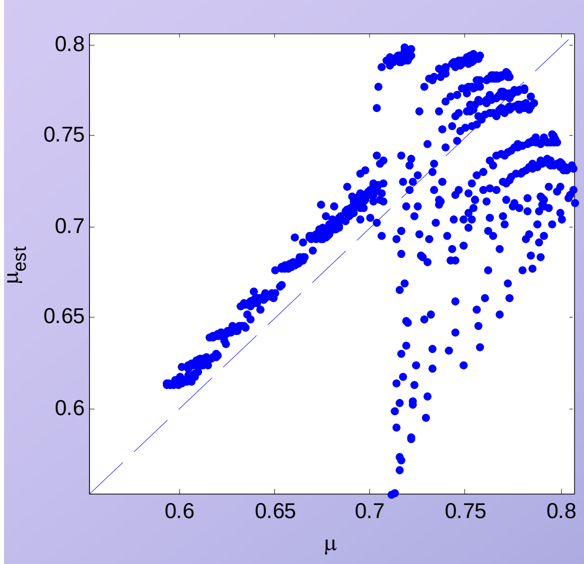
My Model #1

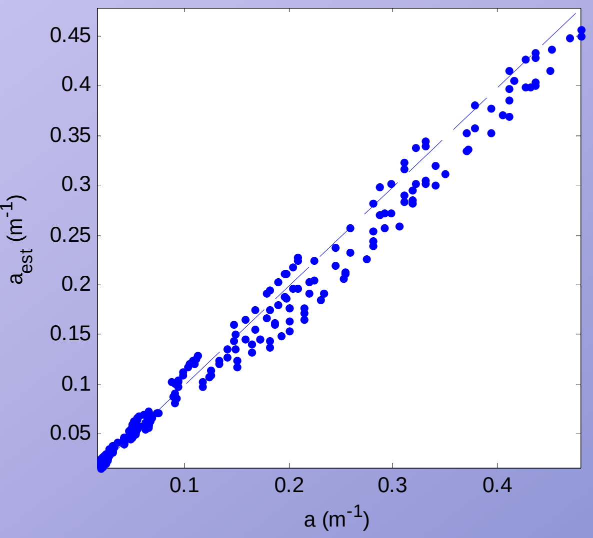
- Hydrolight Case 1
  - Raman scattering only
  - Chlorophyll profile with 20 mg/L max at 2 m
  - Co-varying IOPs
  - 30 degree sun, 5 m/s wind, b_b/b=.01

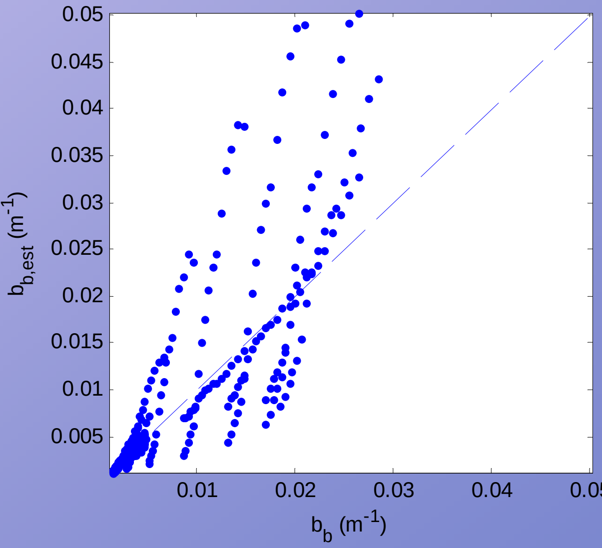
Chlorphyll Profile #1



AOP/IOP Retrieval Results

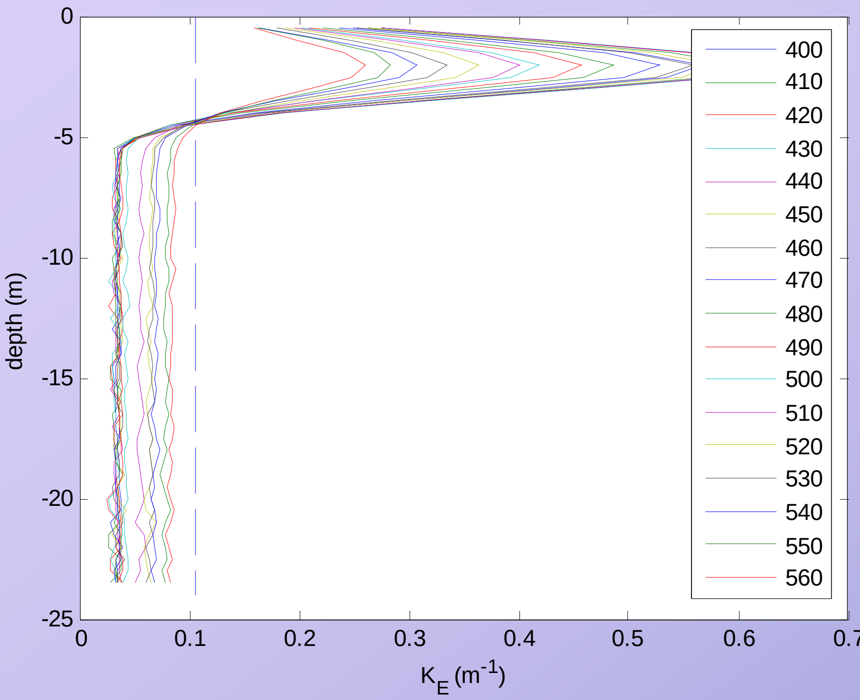


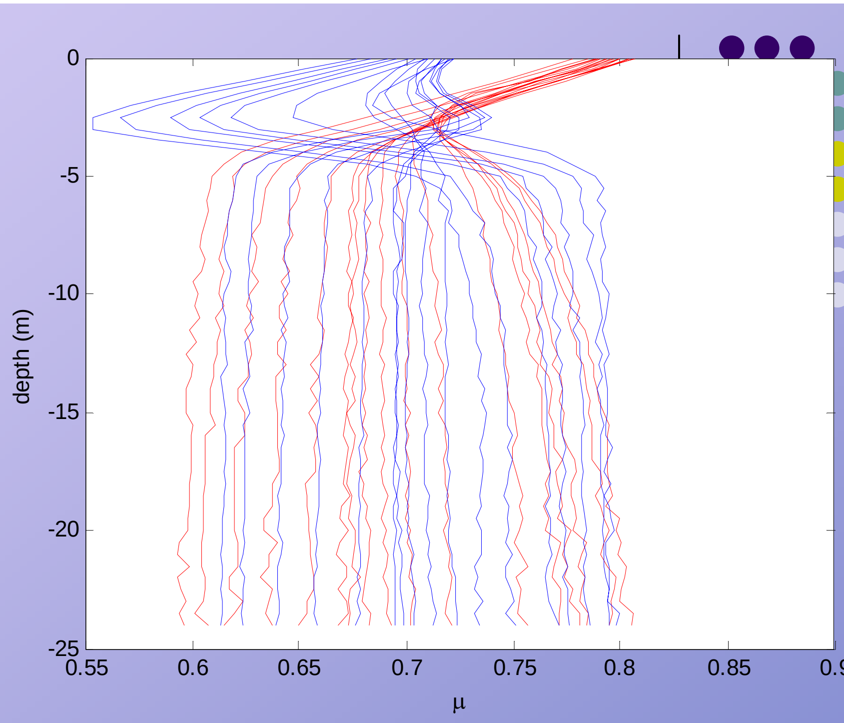


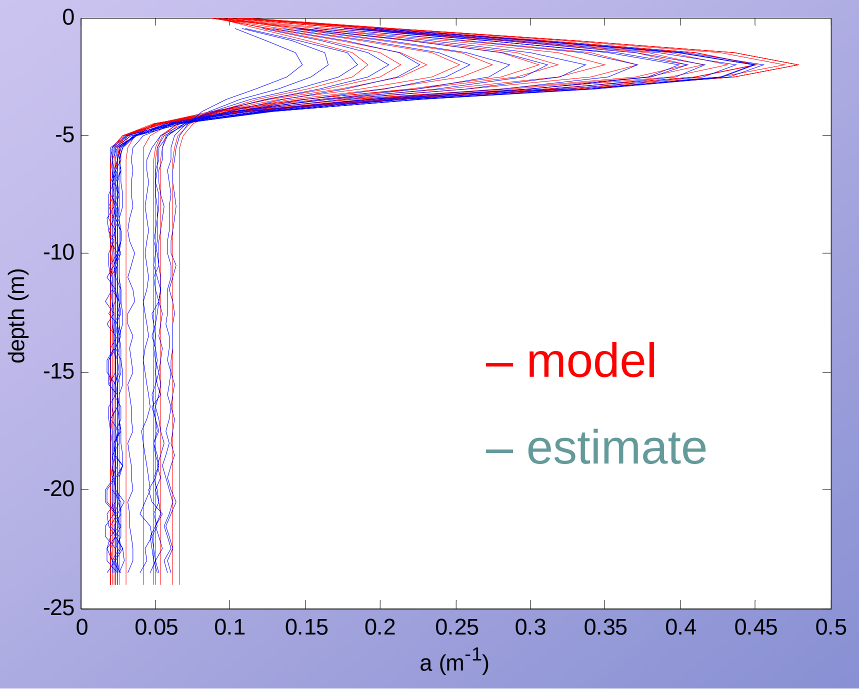


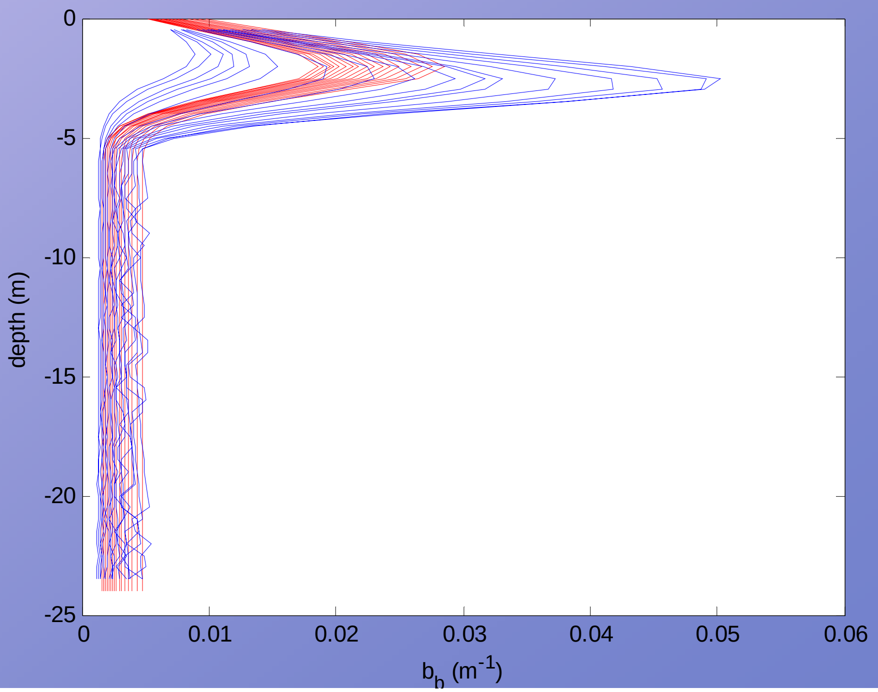
Relative Error for Retrieval

AOP/IOP	Stramska	Me	Comments
$\mu(z)$	< 12%	<22.3%	Max errors in blue = 2X max in green
$a(z)$	< 12 %	< 25 %	No dependence on l Underestimates a by 25% in large Chl max. Otherwise noisy overestimate
$b_b(z)$	< 30%	<28% <169%	< 1 m, > 5.5 m 2-5m (Chl max)

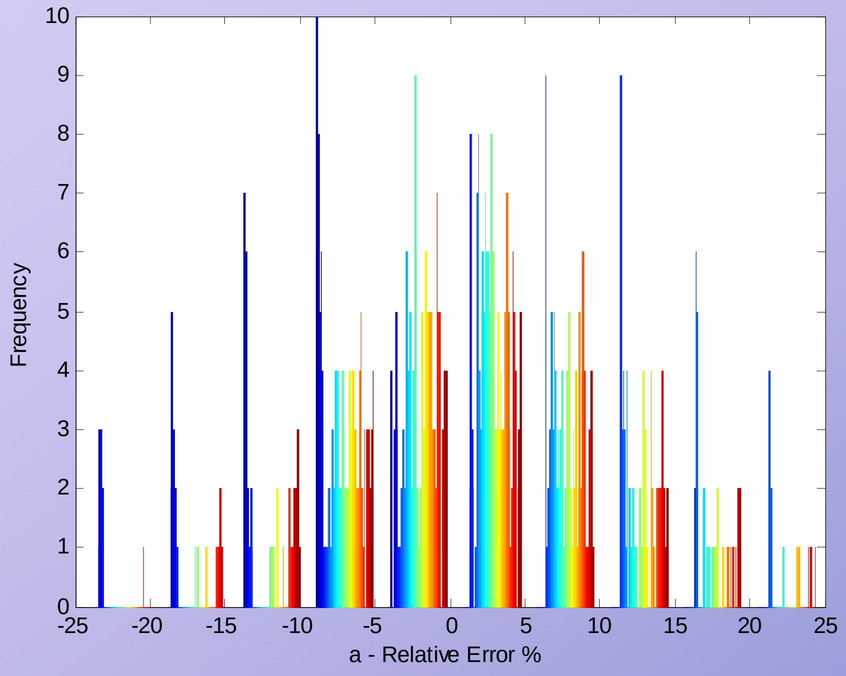

0
-5
-10
-15
-20
-25
depth (m)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
K_E (m^{-1})
400
410
420
430
440
450
460
470
480
490
500
510
520
530
540
550
560

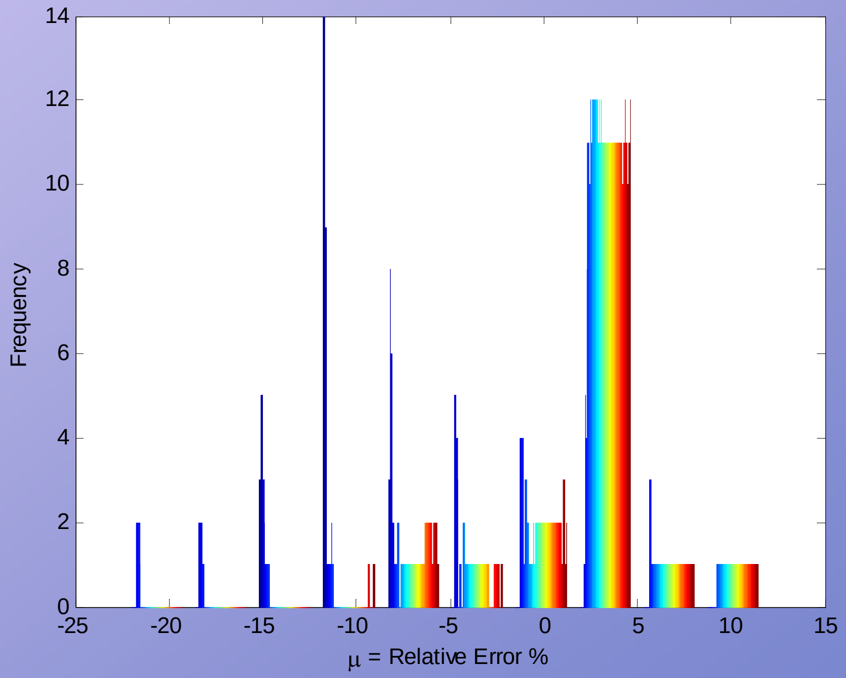

0
-5
-10
-15
-20
-25
depth (m)
0.55
0.6
0.65
0.7
0.75
0.8
0.85
0.9
μ


0
-5
-10
-15
-20
-25
depth (m)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
a (m^{-1})
– model
– estimate

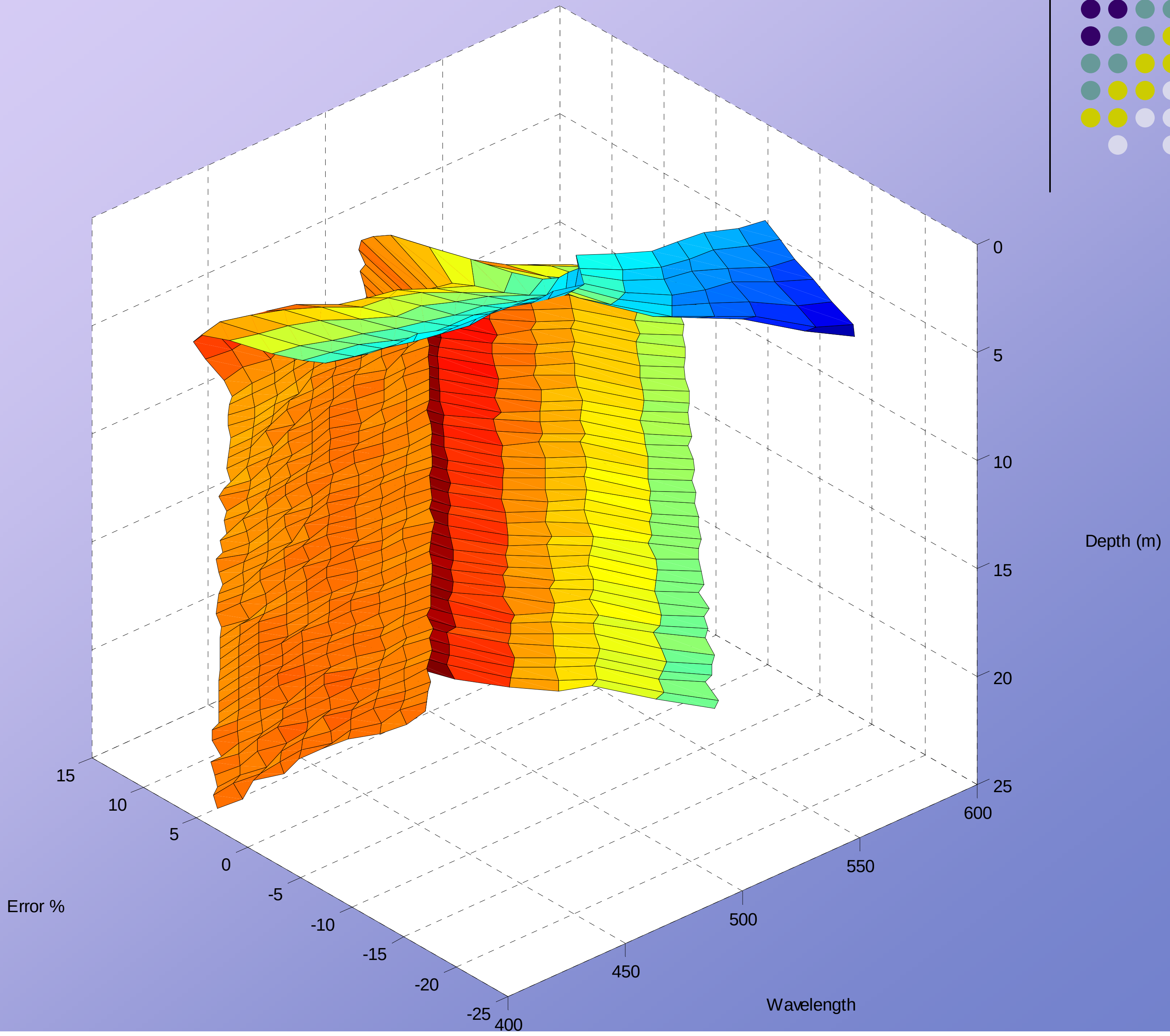

0
-5
-10
-15
-20
-25
depth (m)
0
0.01
0.02
0.03
0.04
0.05
0.06
b_b (m^{-1})

Relative Error Distribution

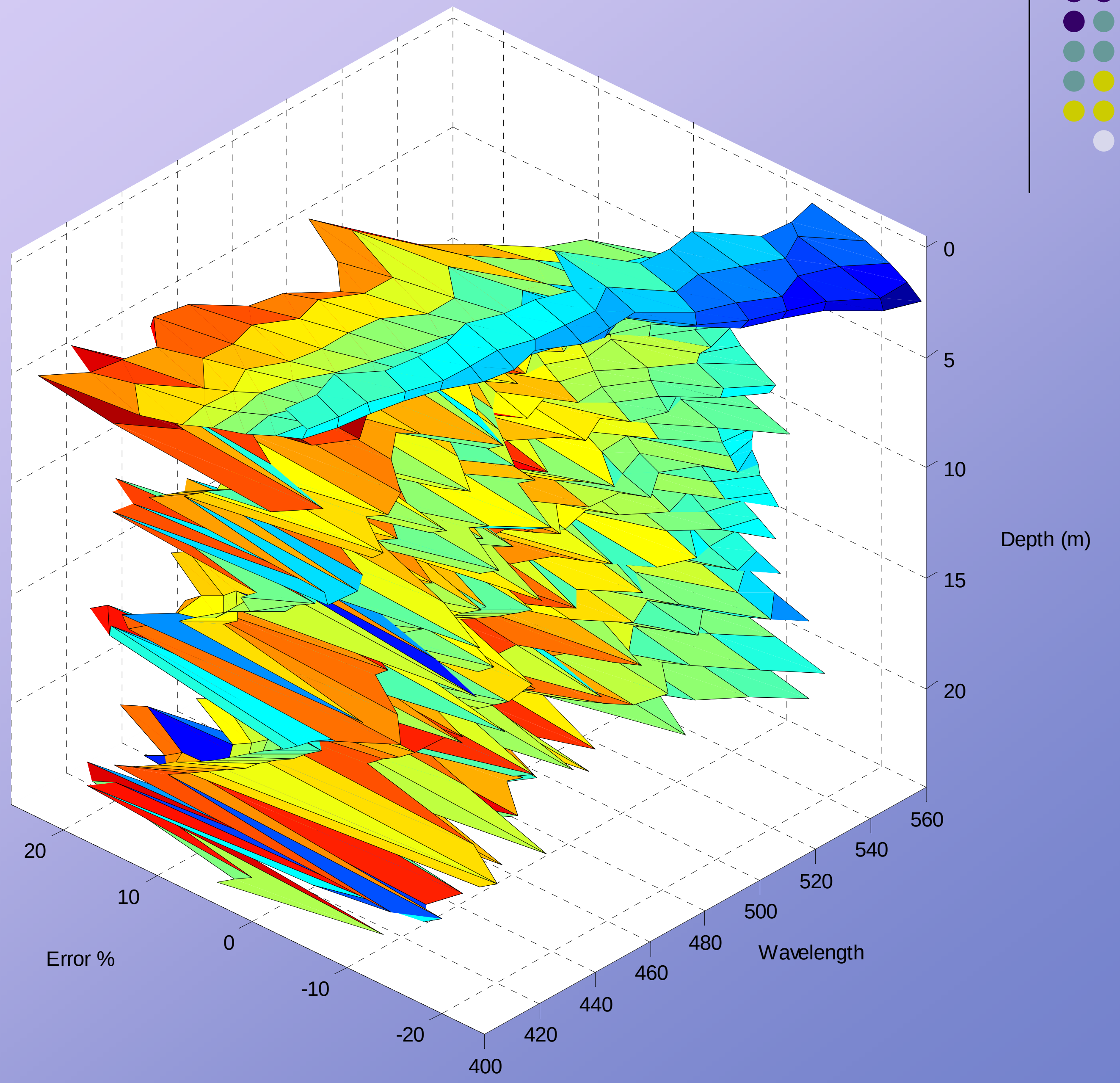




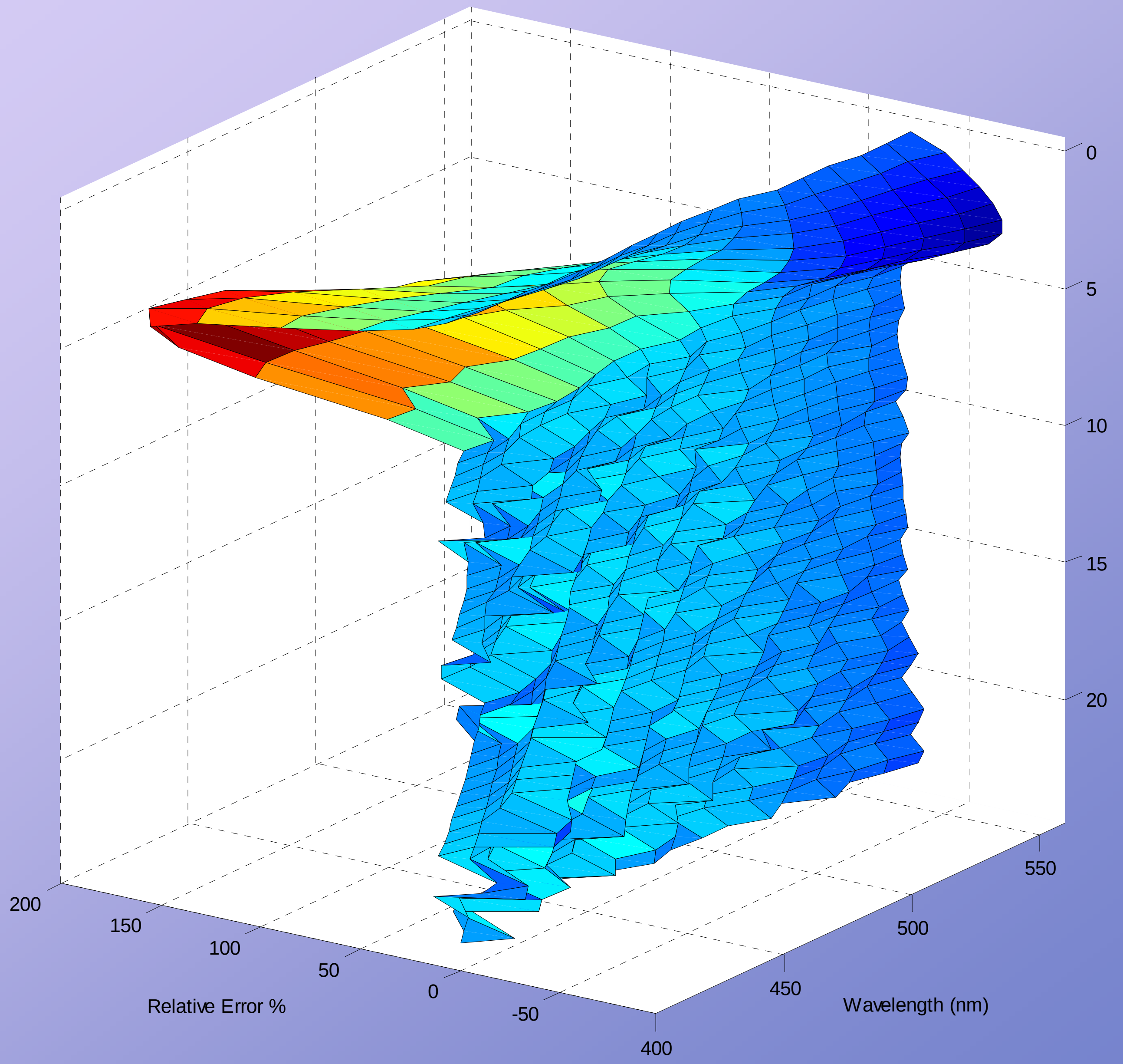
Relative Error μ_{est} vs. $\mu_{Hydrolight}$ (%)



Error Estimating a

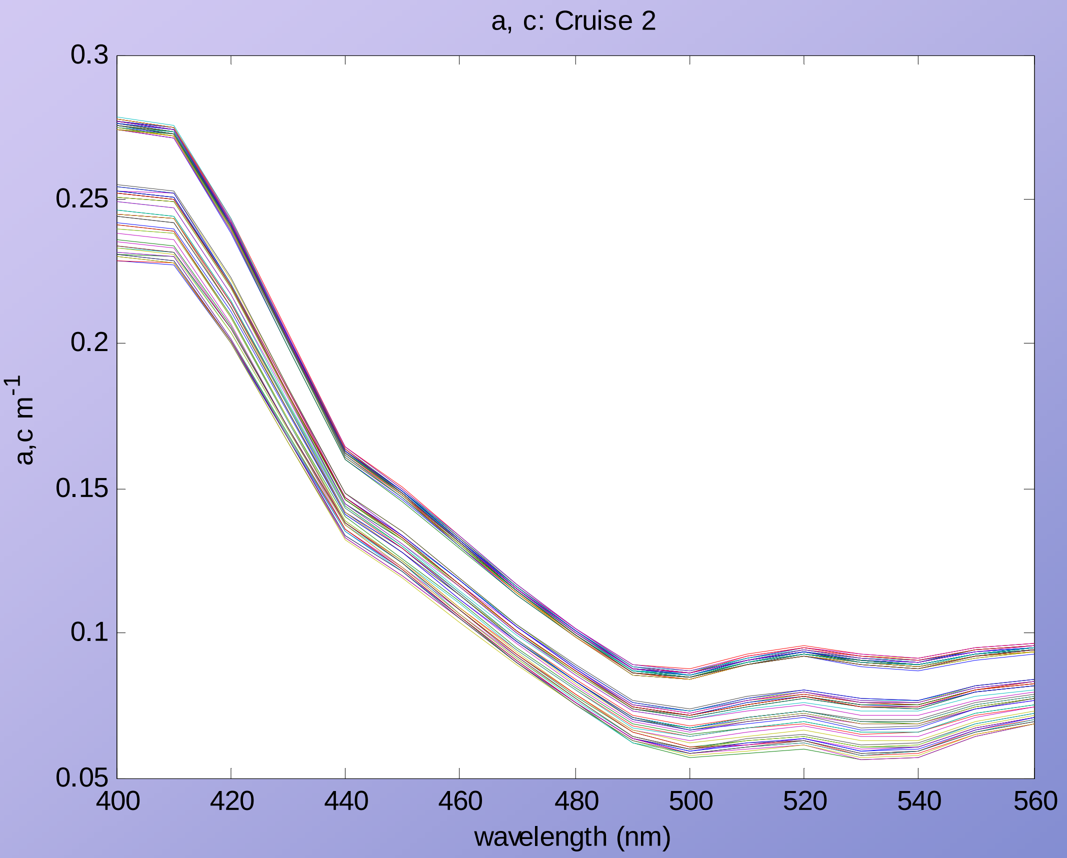


Error Estimating b_b

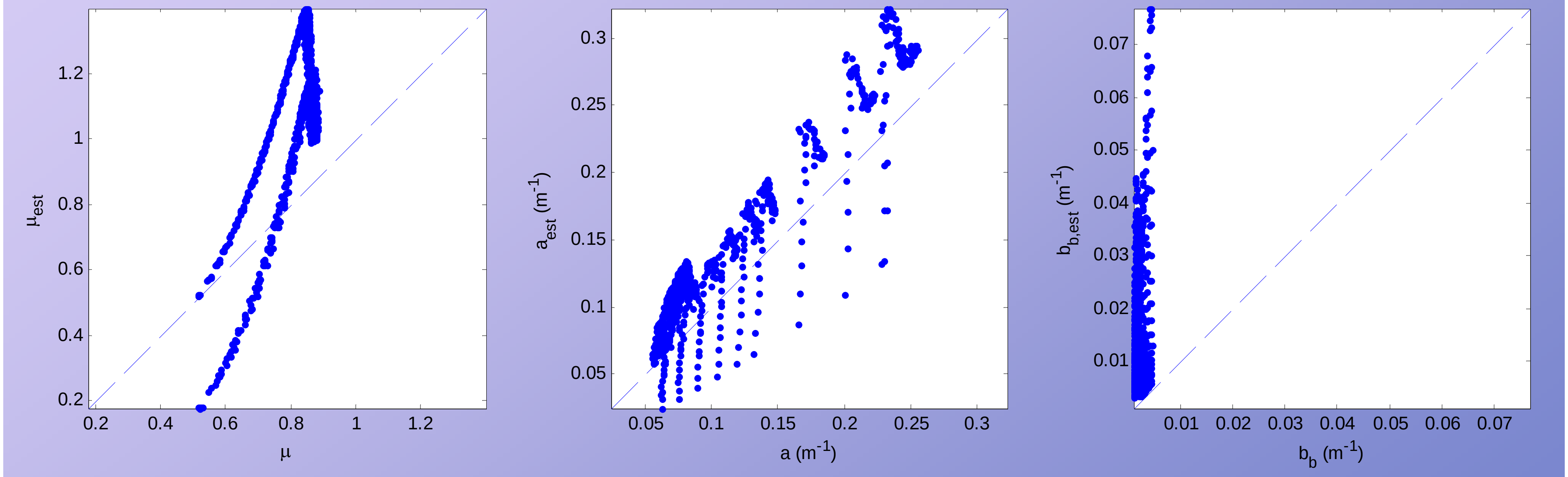


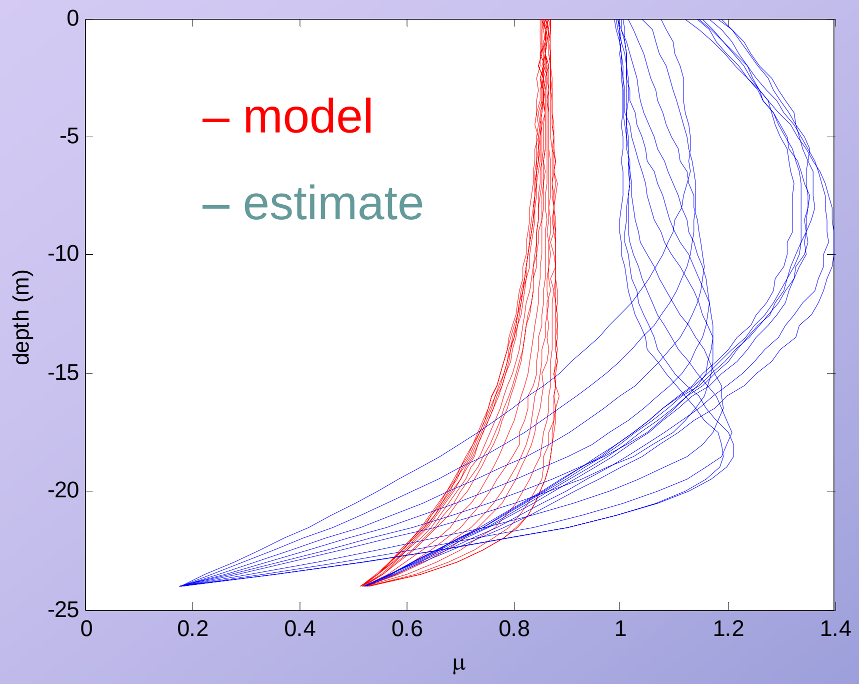
My Model #2

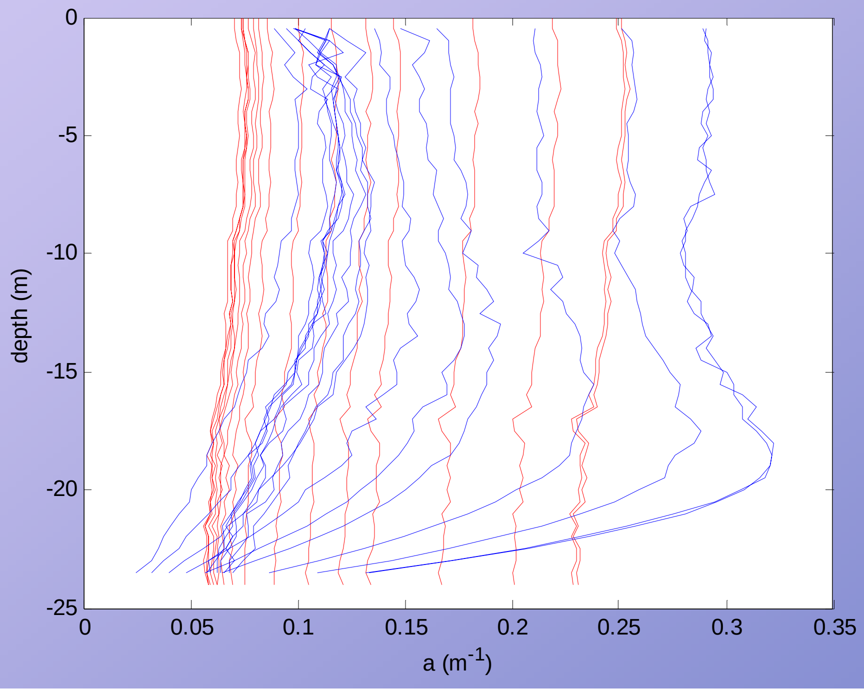
- Hydrolight Case 2
  - IOPs
    - AC-9 from 9 July 2004 Ocean Optics cruise
    - Cruise 2, Profile 063, ~27 m bottom
    - $b_b/b = 0.019$ (b_b from Wetlabs ECOVSF)
  - Raman scattering only
  - Well mixed water, [Chl] ~3.5 ug/L
  - 50% cloud cover

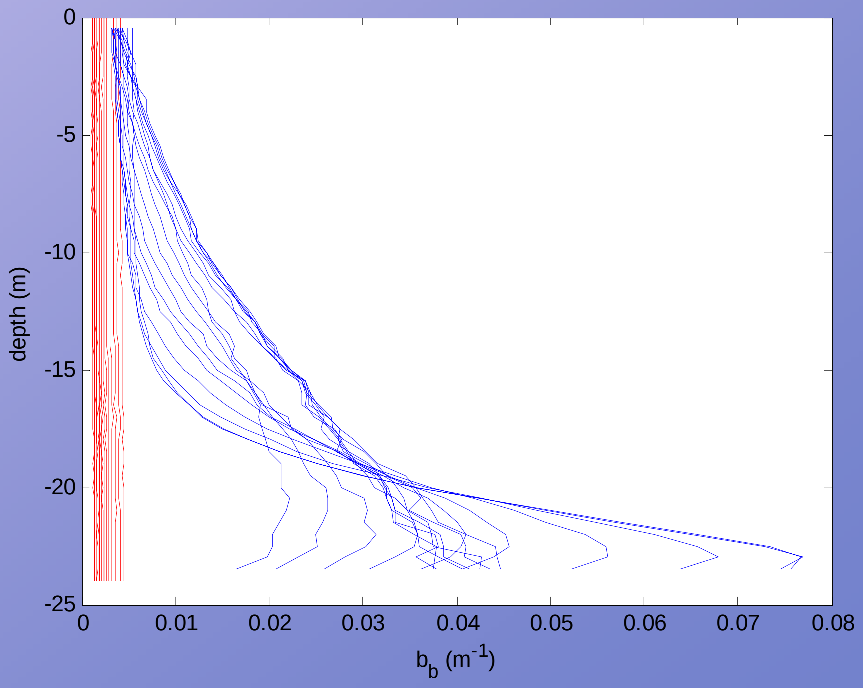

a, c: Cruise 2
0.3
0.25
0.2
0.15
0.1
0.05
a,c m^{-1}
400
420
440
460
480
500
520
540
560
wavelength (nm)

AOP/IOP Retrieval Results

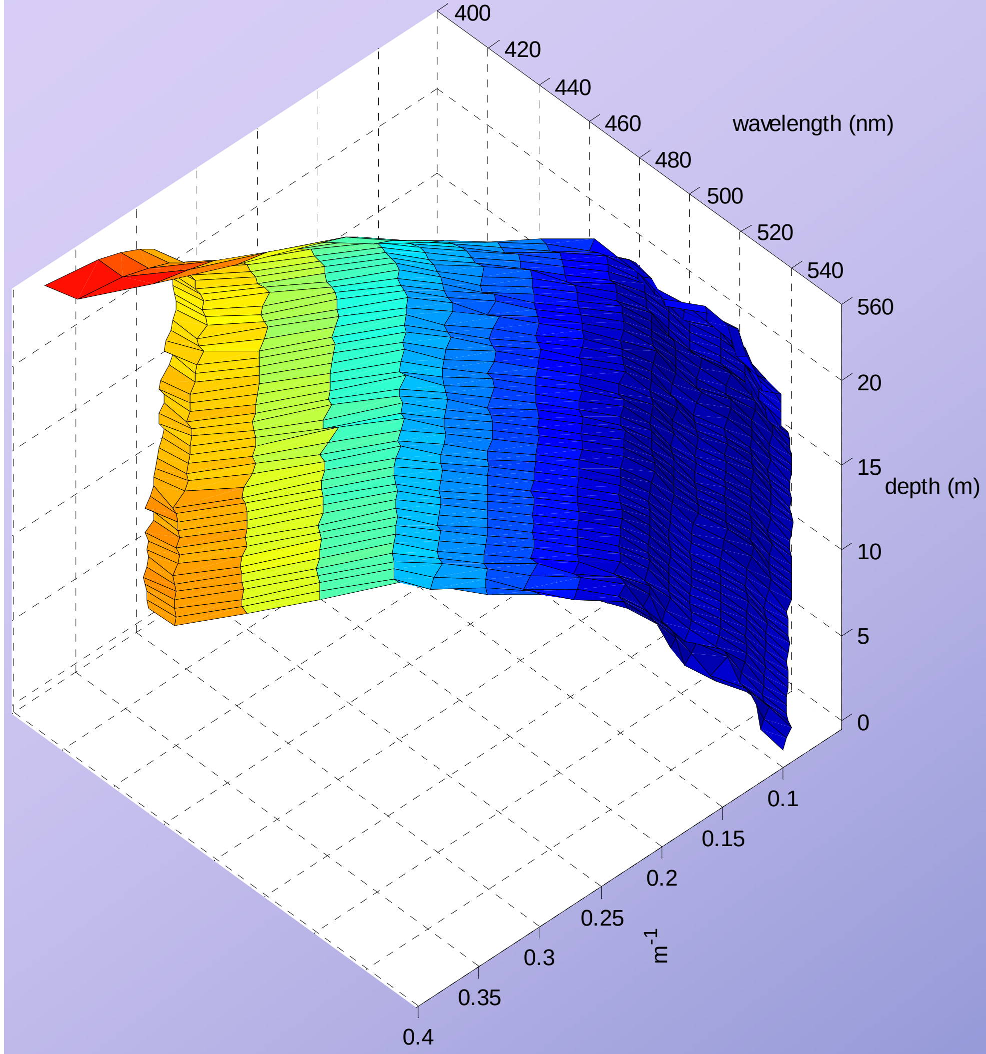



– model
– estimate
depth (m)
0
-5
-10
-15
-20
-25
0
0.2
0.4
0.6
0.8
1
1.2
1.4
μ

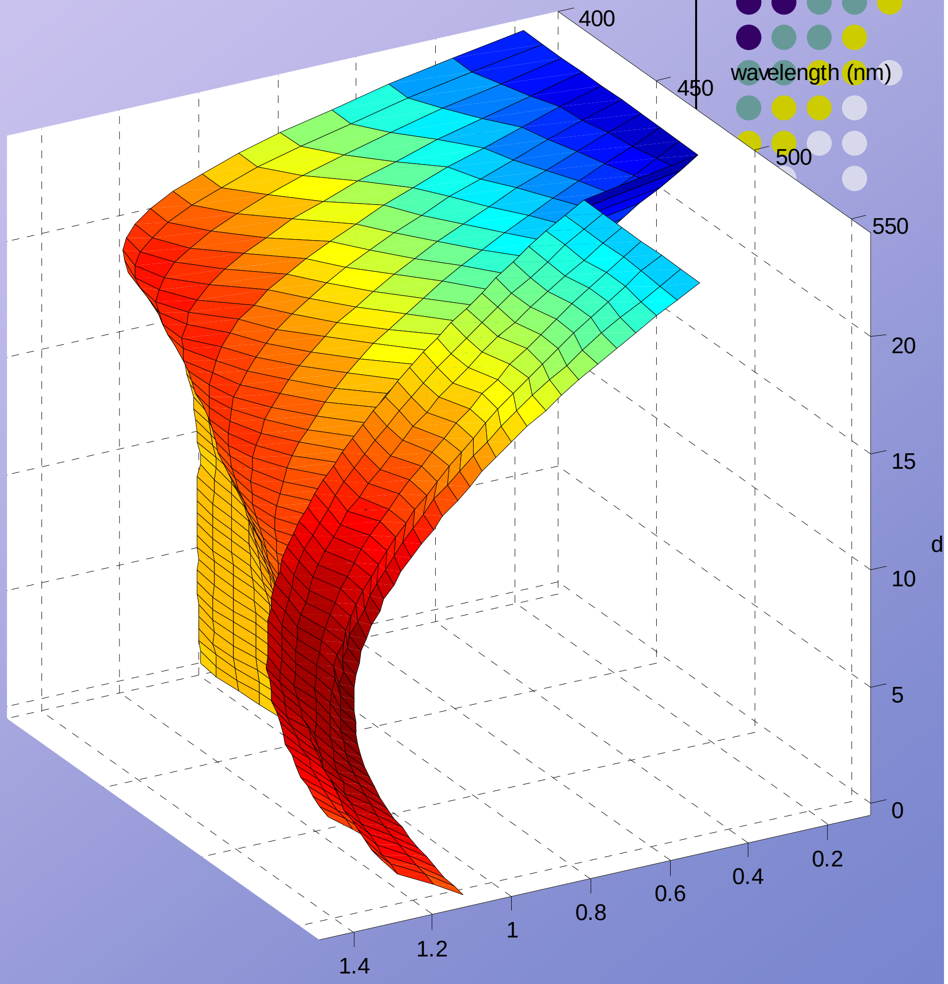

depth (m)
0
-5
-10
-15
-20
-25
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
a (m^{-1})

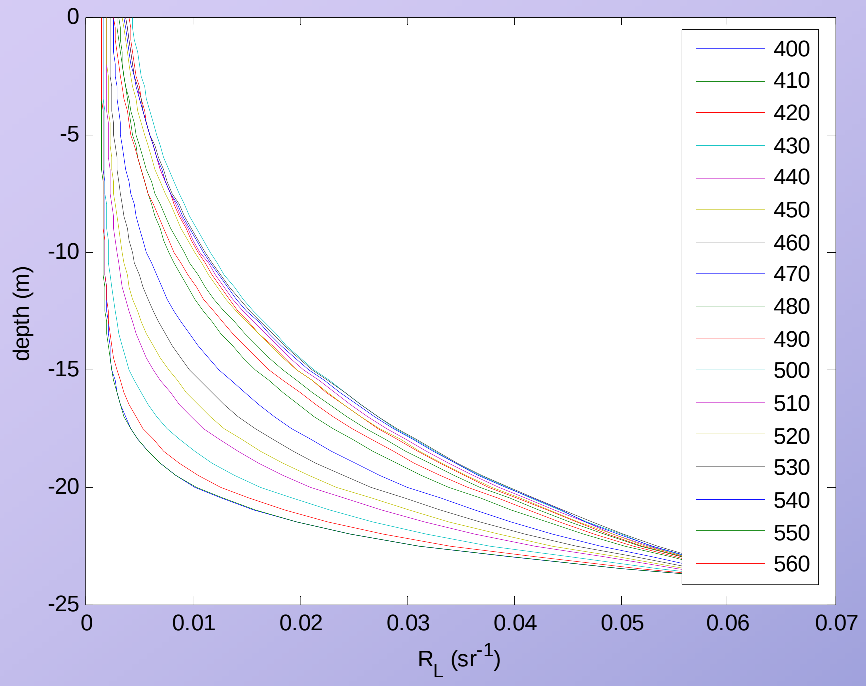

depth (m)
0
-5
-10
-15
-20
-25
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
b_b (m^{-1})

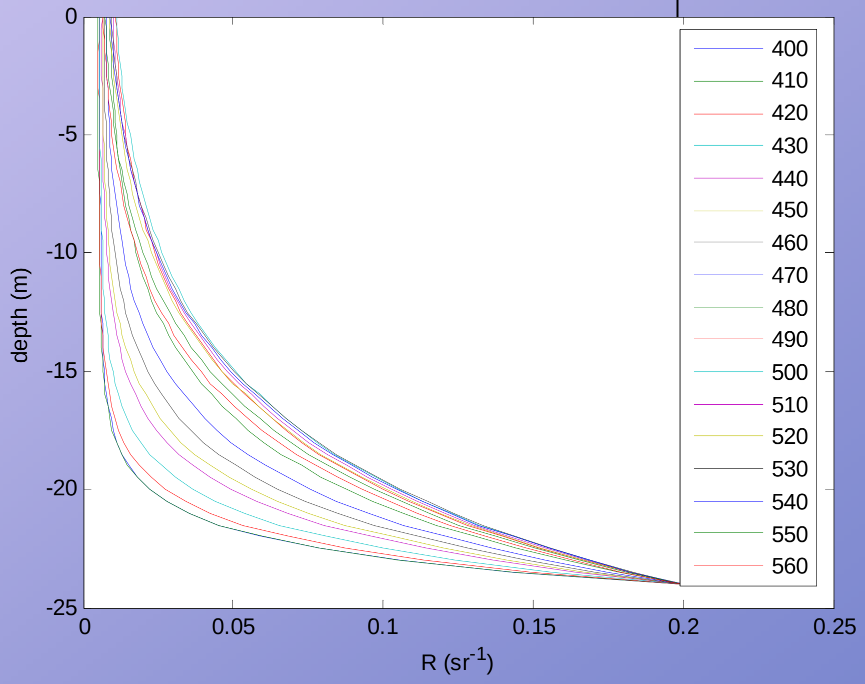
KE - Cruise 2



μ_{est} - Cruise 2




depth (m)
0
-5
-10
-15
-20
-25
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
R_L (sr^{-1})
400
410
420
430
440
450
460
470
480
490
500
510
520
530
540
550
560


depth (m)
0
-5
-10
-15
-20
-25
0
0.05
0.1
0.15
0.2
0.25
R (sr^{-1})
400
410
420
430
440
450
460
470
480
490
500
510
520
530
540
550
560

Conclusions

- *Stramska, et al.* model is highly tuned to local waters
  - CalCOFI Cruise
  - Petzold Phase Function
  - 15 m limitation is apparent
- Requires 3 expensive sensors
- Absorption is most robust measurement retrieved by this approach
- 3-D graphics are useful for visualization of multi-spectral profile data and error analysis
- Lots of work to do to theoretical and practical to advance IOP retrieval from in-water E and L.