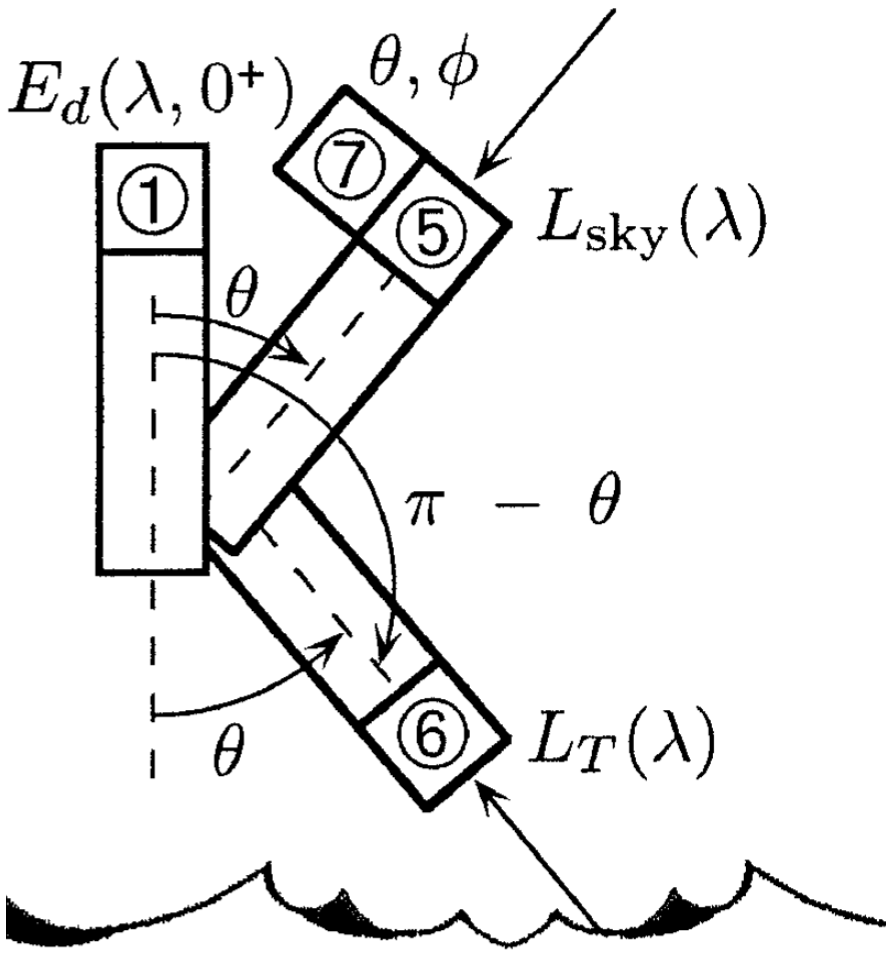
Remove of surface reflected light

Zhongping Lee, Yu-Hwan Ahn, Curtis Mobley, Robert Arnone



(Hooker et al 2003)

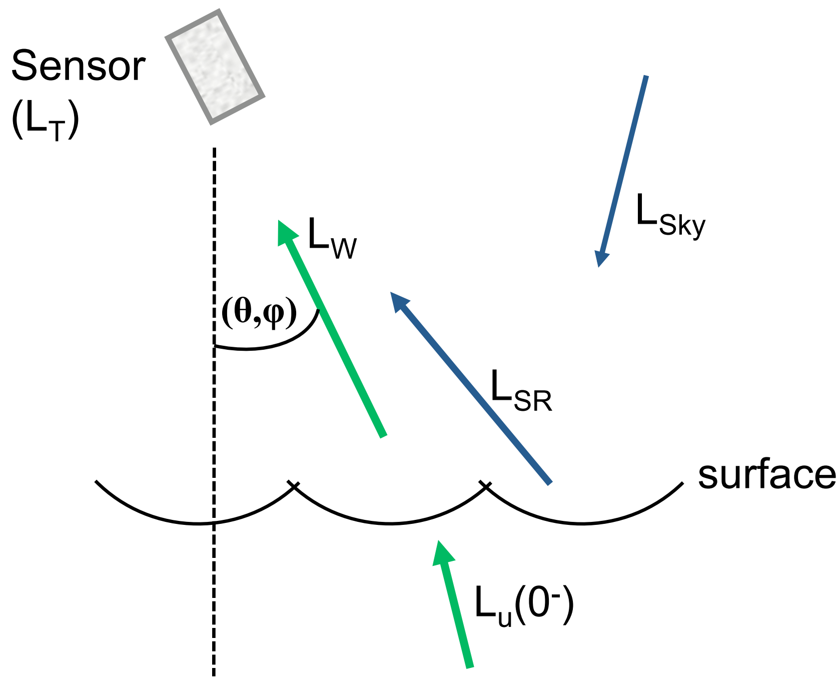
$$R_{rs} = L_w/E_d$$

$$L_t = L_w + \rho\, L_{sky}$$

$$R_{\text{rs}} = (L_t - \rho L_s) \Big/ \left(\frac{\pi}{R_g} L_g \right).$$

$$\rho \approx 0.028$$

(Mobley 1999)



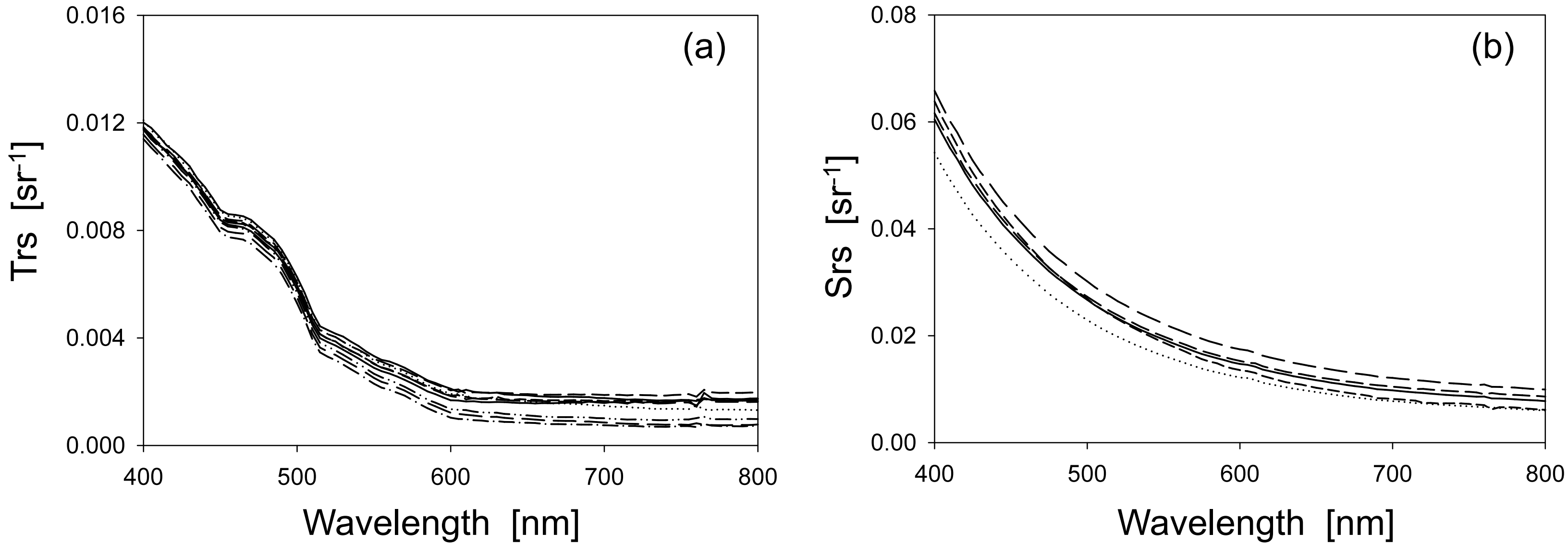
$$L_T(\lambda,\theta,\varphi) = L_W(\lambda,\theta,\varphi) + \sum_i w_i \; F(\theta_i',\varphi_i',\theta,\varphi)\; L_{Sky}(\lambda,\theta_i',\varphi_i').$$

$$L_T(\lambda,\theta,\varphi) = L_W(\lambda,\theta,\varphi) + \rho(\theta,\varphi)\, L_{Sky}(\lambda,\theta',\varphi).$$

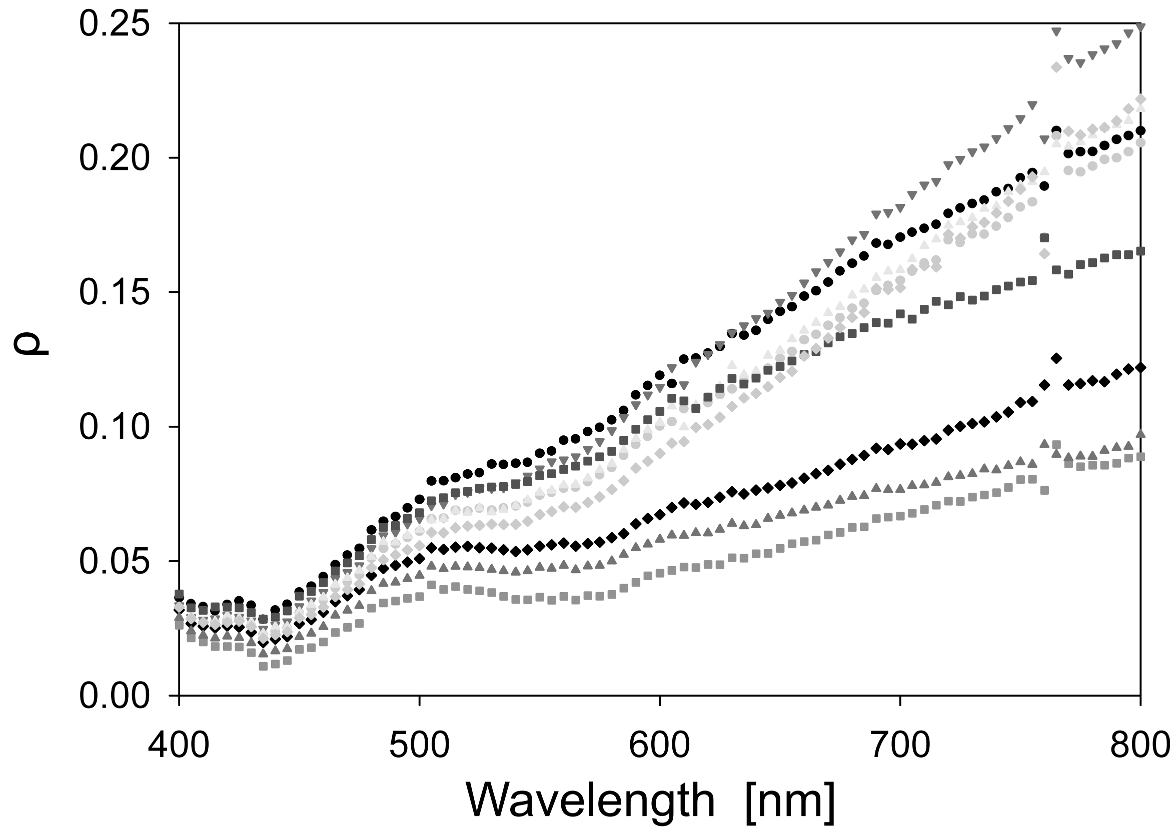
$$\rho(\theta,\varphi) = \frac{L_T(\lambda,\theta,\varphi) - L_w(\lambda,\theta,\varphi)}{L_{Sky}(\lambda,\theta',\varphi)}.$$

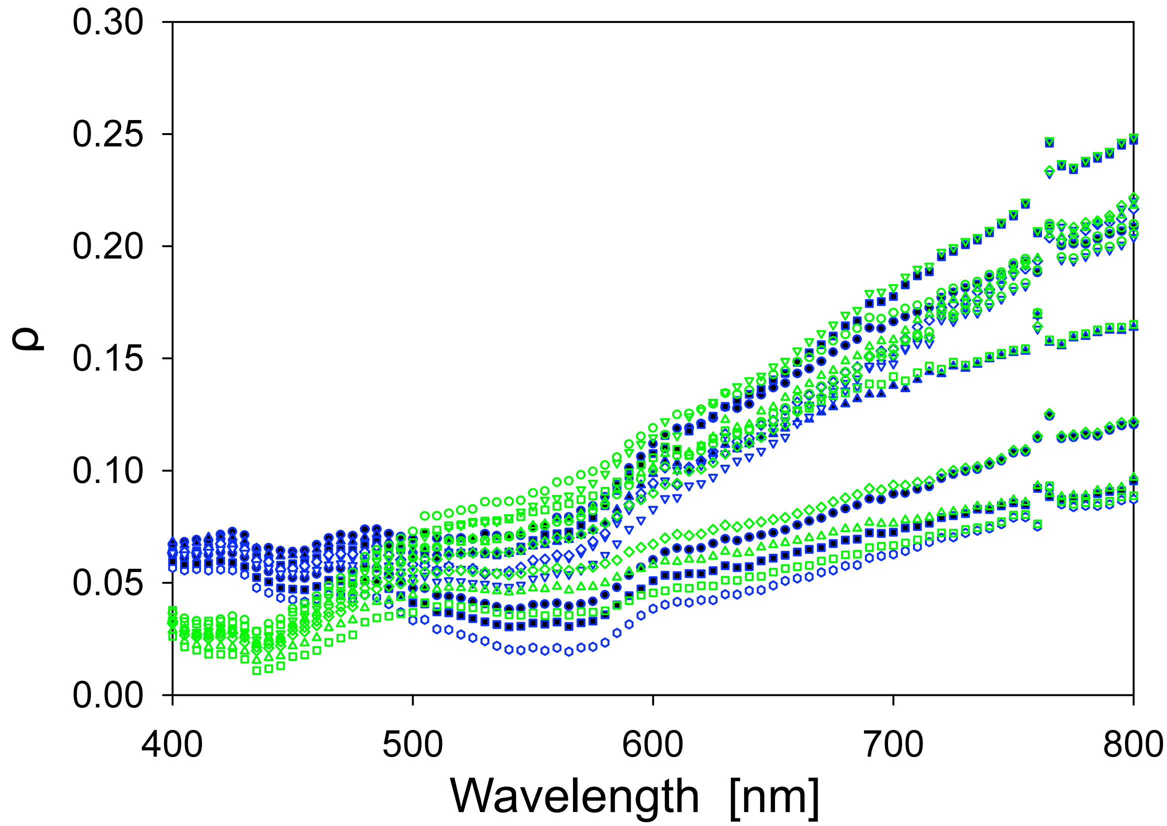
$$\boldsymbol{T_{rs} = L_t/E_d;} \qquad \boldsymbol{S_{rs} = L_{sky}/E_d}$$

$$\rho(\theta,\varphi) = \frac{T_{rs}(\lambda,\theta,\varphi) - R_{rs}(\lambda,\theta,\varphi)}{S_{rs}(\lambda,\theta',\varphi)}.$$



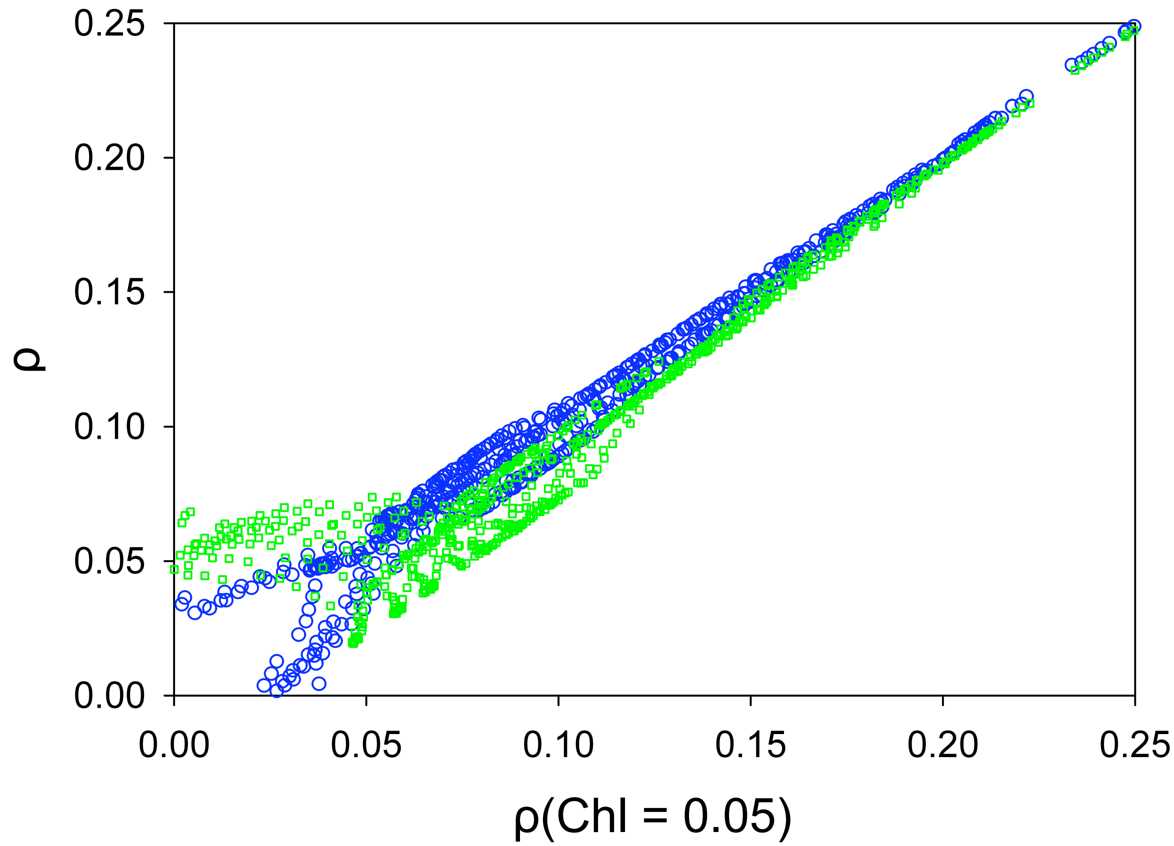
(a)
Trs [sr^{-1}]
0.016
0.012
0.008
0.004
0.000
400
500
600
700
800
Wavelength [nm]
(b)
Srs [sr^{-1}]
0.08
0.06
0.04
0.02
0.00
400
500
600
700
800
Wavelength [nm]


0.25
0.20
0.15
0.10
0.05
0.00
ρ
400
500
600
700
800
Wavelength [nm]

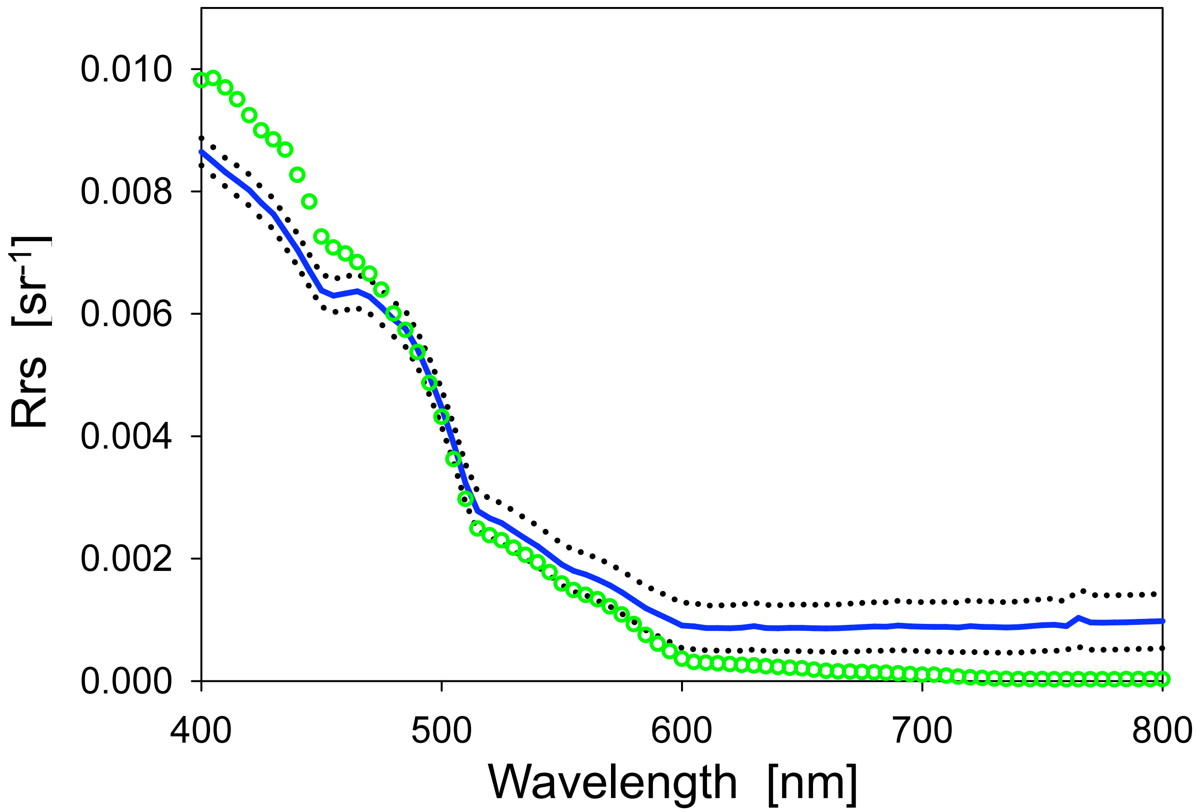


with two different Chl values:

Blue: Chl = 0.1 mg/m^3; **green**, Chl = 0.05 mg/m^3.



Blue: between ρ(Chl = 0.05) and ρ(Chl = 0.025)
Green: between ρ(Chl = 0.05) and ρ(Chl = 0.1)



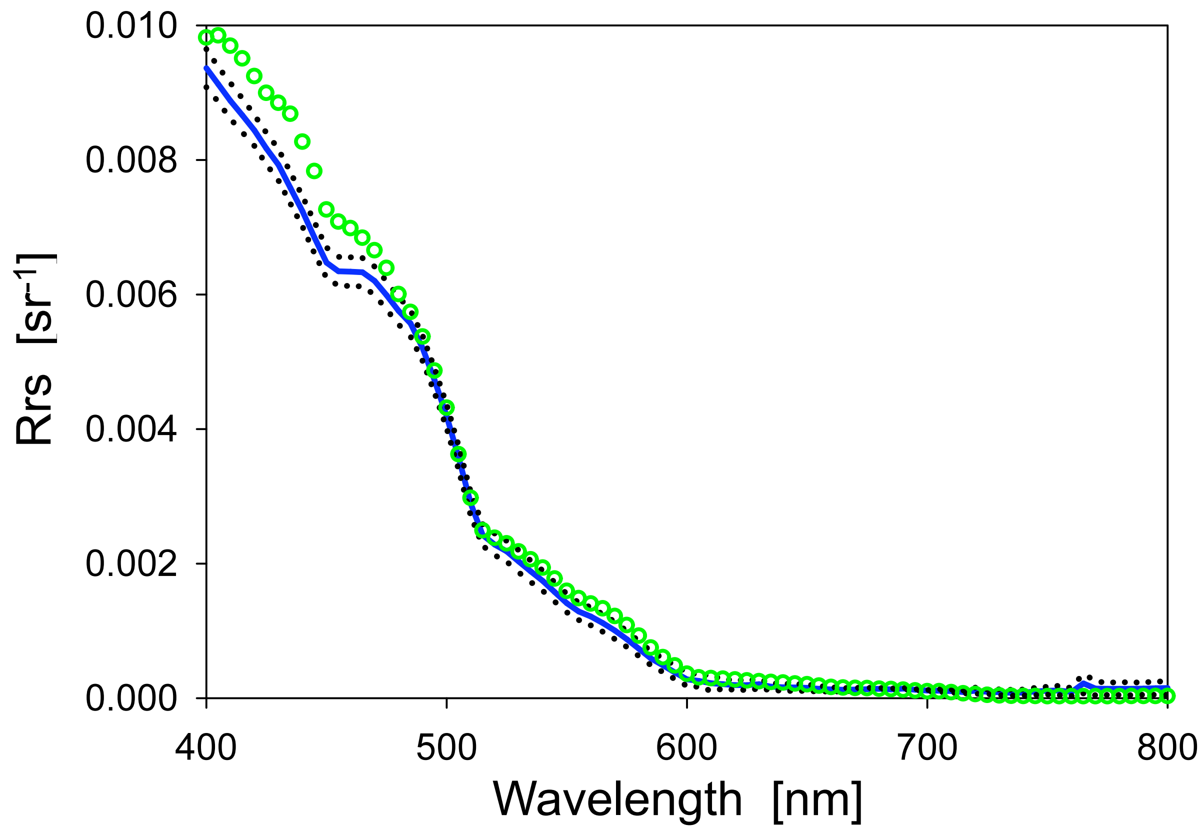
Green: modeled Rrs with Chl = 0.05 mg/m^3 using Morel-Maritorena Case-1 model.

$$L_T(\lambda,\theta,\varphi) = L_W(\lambda,\theta,\varphi) + w_0\, F(\theta,\varphi)\, L_{Sky}(\lambda,\theta',\varphi) + \sum_{i-1} w_i F(\theta_i',\varphi_i',\theta,\varphi)\, L_{Sky}(\lambda,\theta_i',\varphi_i').$$

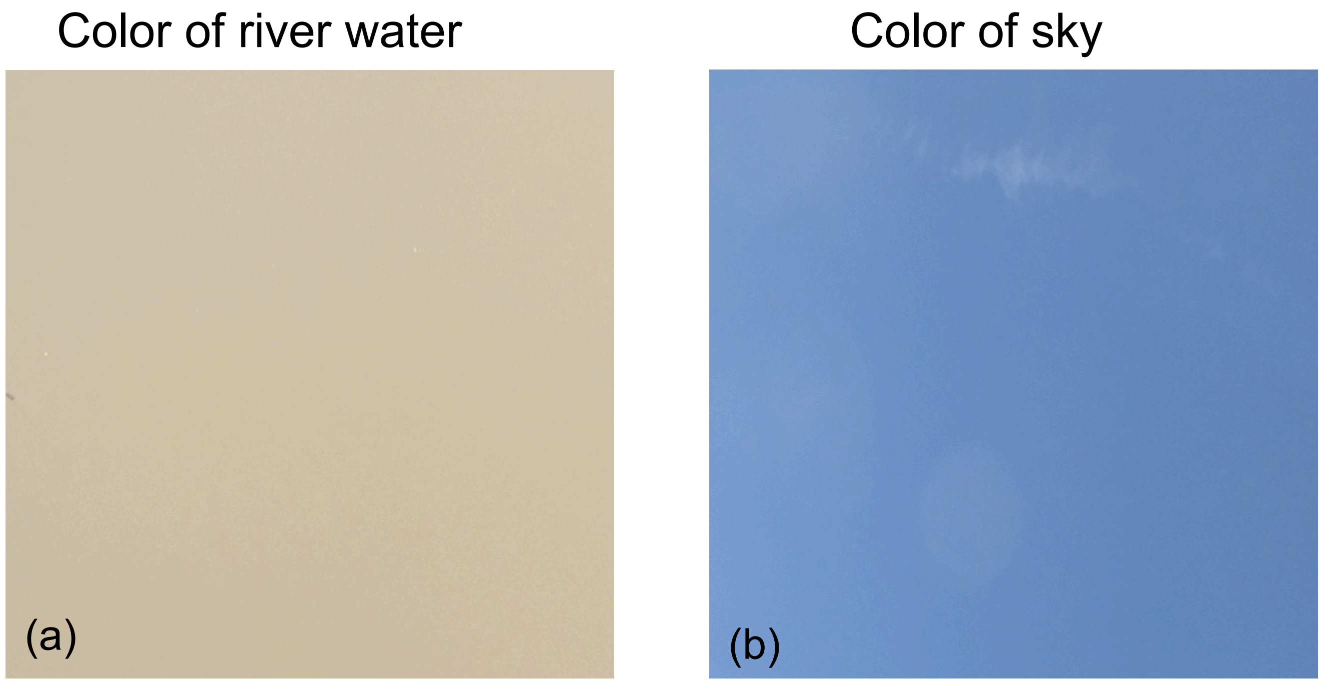
$$T_{rs}(\lambda,\theta,\varphi) \approx R_{rs}(\lambda,\theta,\varphi) + F(\theta,\varphi)\, S_{rs}(\lambda,\theta',\varphi) + \sum_{i-1} w_i F(\theta_i',\varphi_i',\theta,\varphi)\, S_{rs}(\lambda,\theta_i',\varphi_i').$$

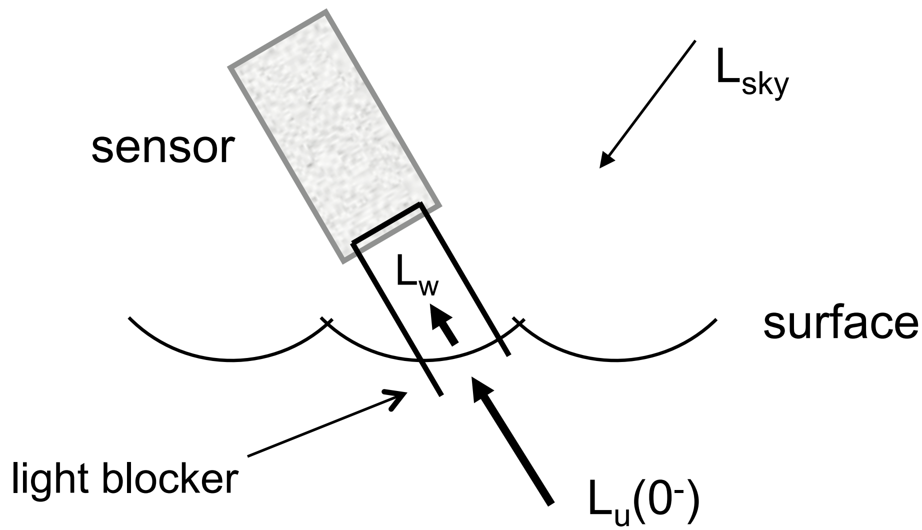
$$T_{rs}(\lambda,\theta,\varphi) \approx R_{rs}(\lambda,\theta,\varphi) + F(\theta,\varphi)\, S_{rs}(\lambda,\theta',\varphi) + \Delta(\theta,\varphi),$$

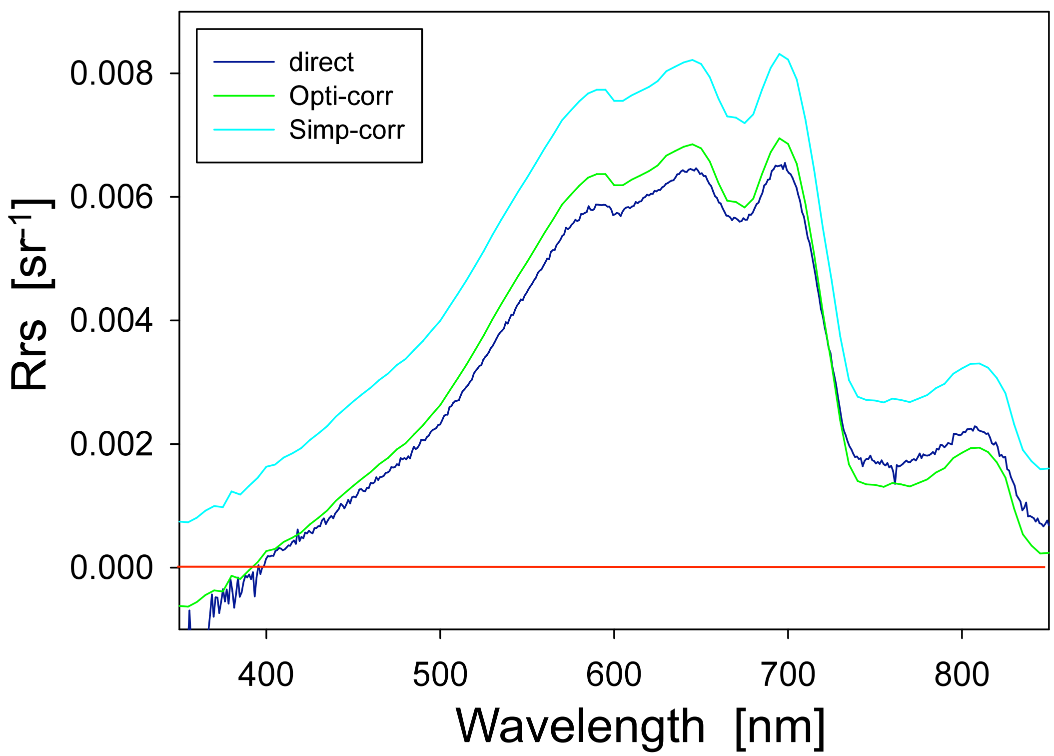
$$R_{rs}(\lambda,\theta,\varphi) \approx T_{rs}(\lambda,\theta,\varphi) - F(\theta,\varphi)\, S_{rs}(\lambda,\theta',\varphi) - \Delta(\theta,\varphi).$$



Blue line: Rrs calculated with a spectral optimization scheme.


Color of river water
Color of sky
(a)
(b)


sensor
L_{sky}
L_w
surface
light blocker
$L_u(0^-)$



direct
Opti-corr
Simp-corr
0.008
0.006
0.004
0.002
0.000
Rrs [sr-1]
400
500
600
700
800
Wavelength [nm]

Conclusion:

1. ρ in general varies with wavelength.

2. Surface-reflected light can be better removed using either “software” or “hardware”.

Correct Angular Variation of Remote Sensing Reflectance based on IOPs

ZhongPing Lee, Keping Du, Kenneth J. Voss, Giuseppe Zibordi, Bertrand Lubac, Robert Arnone, Alan Weidemann

Outline:

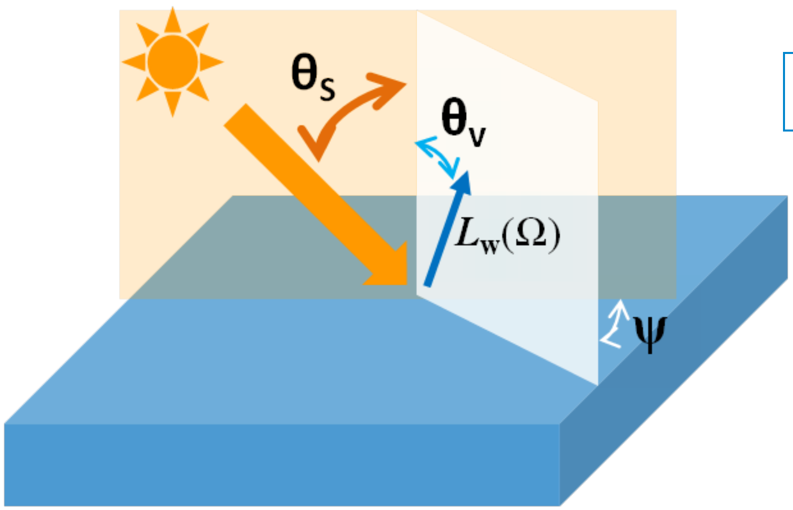
1. Background
2. Rrs model
3. IOP retrieval and BRDF correction
4. Summary

1. Background

Why BRDF Correction?

⇩

Bidirectional Reflectance Distribution Function



θ_s θ_v ψ

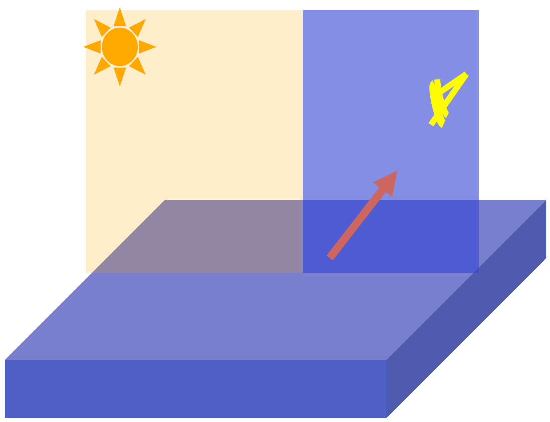
$\Omega(10, 20, \underline{30})$

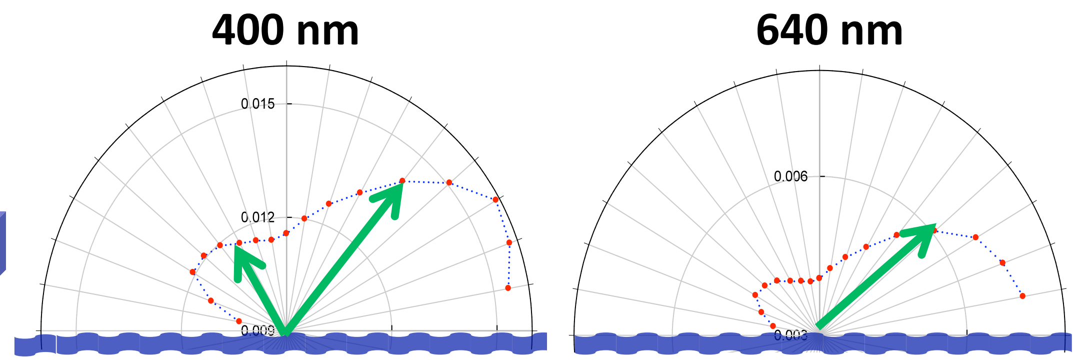
measured photons going further away from Sun (~forward scatter)

$\Omega(10, 20, \underline{150})$

measured photons going closer to Sun (~backscatter)

1. Background (cont.)





Water-leaving radiance in the Sun plane, **zenith** dependence (arrow length indicates radiance value)

Bottom line: **Water-leaving radiance, Lw, is a function of angles.**

BRDF correction: Correct this angular dependence

1. Background (cont.)

$$R_{rs}(\Omega) = \frac{L_w(\Omega)}{E_d(0^+)}$$

Rrs is a function of angles, too.

Define subsurface remote-sensing reflectance as

$$r_{rs}(\Omega) = \frac{L_u(\Omega, 0^-)}{E_d(0^-)}$$

$$R_{rs}(\Omega) = \Re(\Omega)\ r_{rs}(\Omega)$$

Cross-surface parameter

1. Background (cont.)

further

$$\Rightarrow \quad r_{rs}(\Omega) = \frac{f}{Q}(\Omega)\frac{b_b}{a+b_b} = g(\Omega)\frac{b_b}{a+b_b}$$

From radiative transfer equation (Zaneveld 1995)

$$r_{rs} \equiv \frac{D_d}{c+k_L - f_L b_f} \frac{\int_0^{2\pi} \int_0^{\frac{\pi}{2}} \beta(\pi-\theta')\, L(\theta',\varphi')\, \sin(\theta')\, d\theta'\, d\varphi'}{E_{od}}$$

Phase function **shape** is a key property!

1. Background (cont.)

Only two ideal condidtions can we “precisely” correct BRDF effects:

1. Completely diffused distribution (Lambertian).

2. The phase function shape and IOPs are known exactly.

Remote sensing is not in ideal conditions:
BRDF correction is an approximation!

The “Case 1” strategy

All other components co-vary with [Chl]

$$a = F_1([Chl])$$

$$b_b = F_2([Chl])$$

$$R_{rs} = F\left(\frac{b_b}{a + b_b}\right)$$

$$R_{rs} = F([Chl])$$

(*Morel* 1988, *Morel and Maritorena*, 2001)

Case$_1$ approach to correct angular variation (BRDF):

$$R_{rs} = \Re \frac{f}{Q}\{[Chl]\}; \quad \frac{f}{Q} = F\{\theta_{Sun}, \theta, \varphi, \lambda, [Chl]\}\left\{\frac{a_{CDOM}}{[Chl]}, \frac{b_{bp}}{[Chl]}, \tilde{\beta}\right\}$$

BRDF correction data flow:

$$R_{rs}(\Omega) \Rightarrow [Chl] \rightarrow \left\{\frac{f}{Q};\ \Re\right\} \Rightarrow R_{rs}(\Omega_0)$$

Ω: $\{\theta_{Sun}, \theta_v, \phi\}$

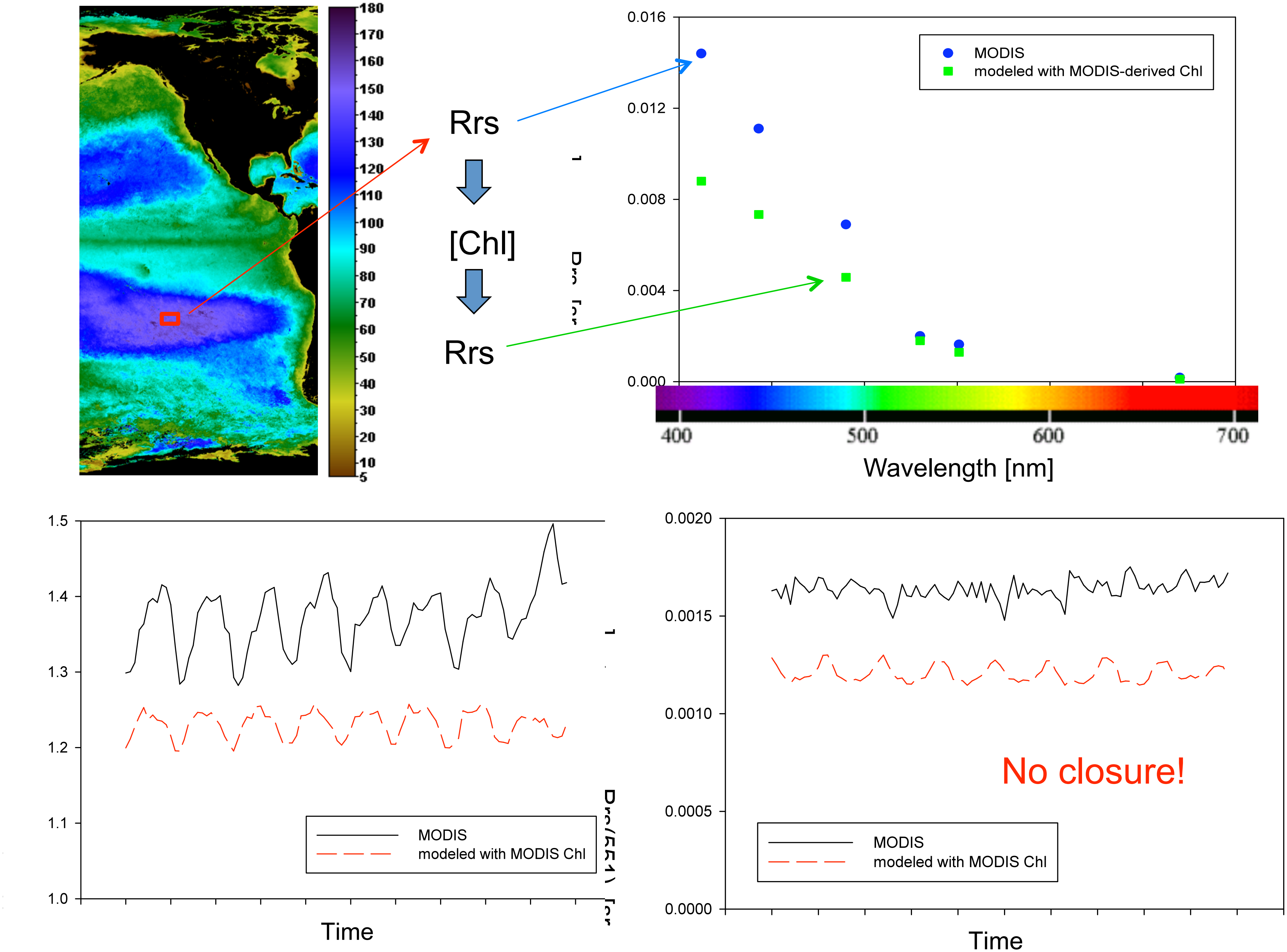
Advantage:

[Chl] is the only in-water property required.

Caveats:

Require waters to follow the Case$_1$ bio-optical relationships, e.g. fixed CDOM:Chl and b_p:Chl dependences.

Remotely it is difficult to know if a pixel belongs to Case-1 or not.



180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
5
Rrs
[Chl]
Rrs
0.016
0.012
0.008
0.004
0.000
MODIS
modeled with MODIS-derived Chl
400
500
600
700
Wavelength [nm]
1.5
1.4
1.3
1.2
1.1
1.0
MODIS
modeled with MODIS Chl
Time
0.0020
0.0015
0.0010
0.0005
0.0000
No closure!
MODIS
modeled with MODIS Chl
Time

1. Background (cont.)

Objectives of IOP-based BRDF Correction:

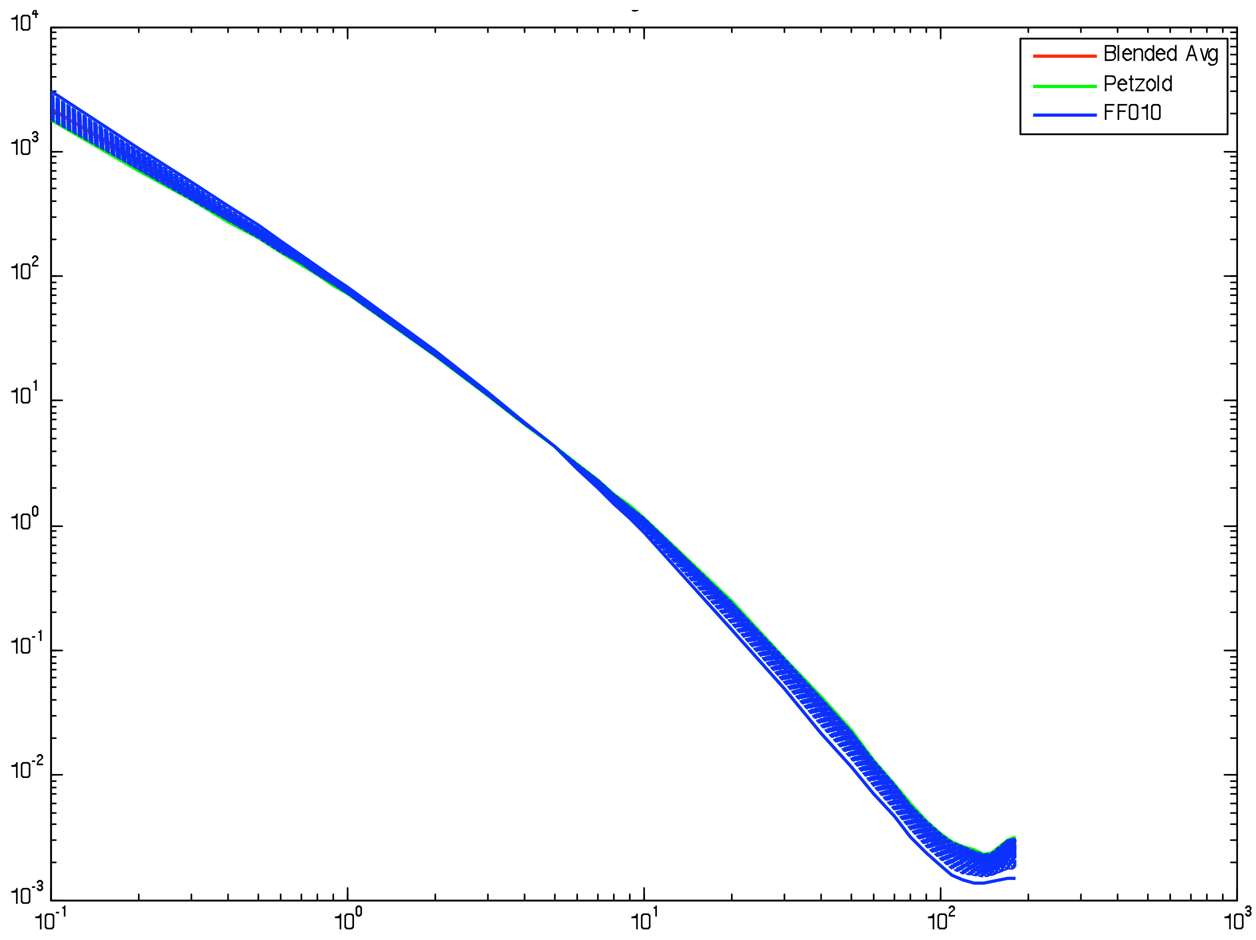
1. reduce or minimize the dependency on empirical bio-optical relationships.

2. avoid the Case-1 assumption.

3. Model coefficients vary with angular geometry only.

2. Rrs model

a. Particle phase function shape



2. Rrs model (cont.)

b. Hydrolight simulations:

θ_s: 0, 15, 30, 45, 60, 75

θ_v: 0, 10, 20, 30, 40, 50, 60, 70

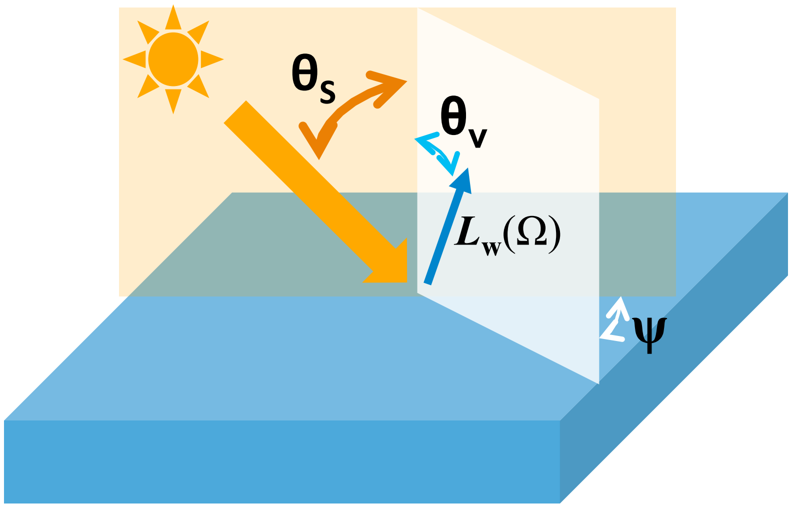
ψ: 0 – 180° with a 15° step

λ: 400 – 760 nm

$b_b/(a+b_b)$: 0 – 0.5

With the blended phase function ***shape***

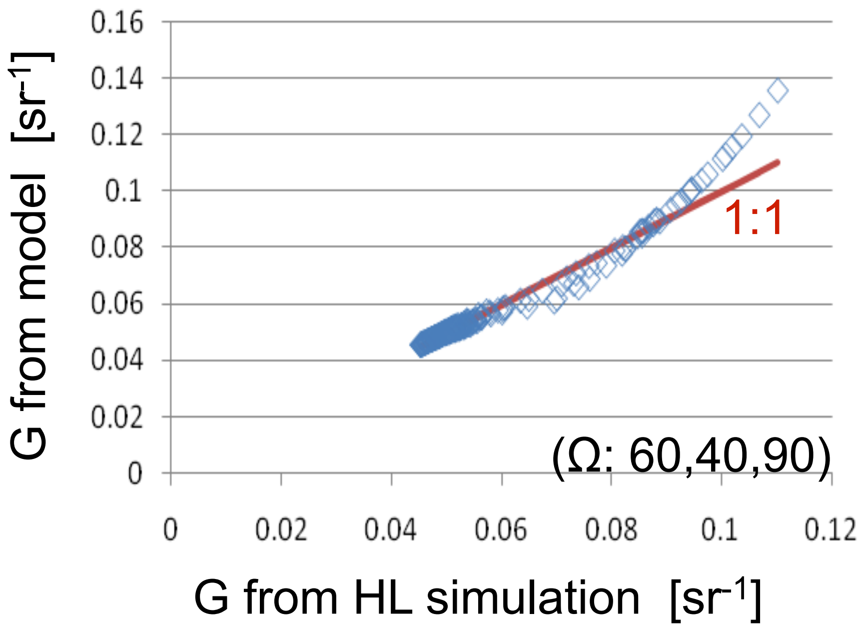
$$G(\Omega) = R_{rs}(\Omega) \Big/ \frac{b_b}{a+b_b}$$



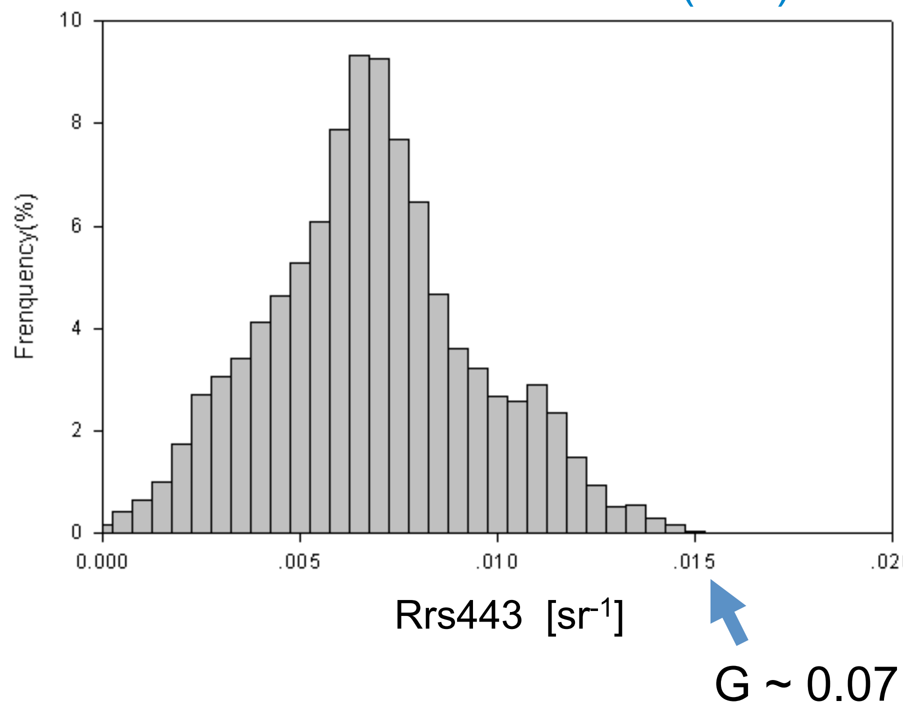
2. Rrs model (cont.)

A ***practical*** choice for algebraic inversion

$$R_{rs}(\Omega) = \left(G_0^w(\Omega) + G_1^w(\Omega)\frac{b_{bw}}{a+b_b} \right)\frac{b_{bw}}{a+b_b} + \left(G_0^p(\Omega) + G_1^p(\Omega)\frac{b_{bp}}{a+b_b} \right)\frac{b_{bp}}{a+b_b}$$



Global distribution of Rrs(443)



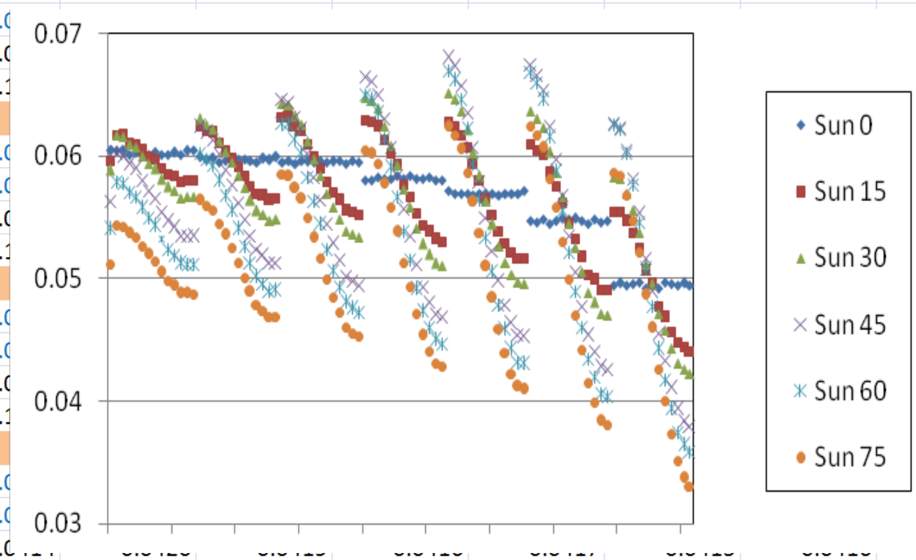
2. Rrs model (cont.)

(with 5 m/s wind)

Table ((7x13+1)x4x6) array, 2208 elements) of {G(Ω)}

(if based on Chl, it is 6x13x7 = 546 elements **per band per Chl**)

	view azimuth angle =>	0	0	15	30	45	60	75	90
	view nadir angle =>	0	10	10	10	10	10	10	10
Sun zenith angle									
0	gw0 =>	0.0604	0.0604	0.0604	0.0601	0.0603	0.0601	0.0601	0.0603
	gw1 =>	0.0							0.0432
	gp0 =>	0.0							0.0403
	gp1 =>	0.1							0.1337
15	gw0 =>	0.0							0.0597
	gw1 =>	0.0							0.0482
	gp0 =>	0.0							0.0401
	gp1 =>	0.1							0.1387
30	gw0 =>	0.0							0.0589
	gw1 =>	0.0							0.0526
	gp0 =>	0.0							0.0403
	gp1 =>	0.1							0.1423
45	gw0 =>	0.0							0.0565
	gw1 =>	0.0							0.0632
	gp0 =>	0.0							0.0419
	gp1 =>	0.1449	0.1398	0.1400	0.1401	0.1420	0.1431	0.1450	0.1471



Angular-dependent model coefficients for Rrs(Ω) are now available.

3. **IOP retrieval and BRDF correction**

IOP approach

Rrs(Ω) → $\{a \& b_b\}$ → G[0] → Rrs[0]

G[Ω] ↑

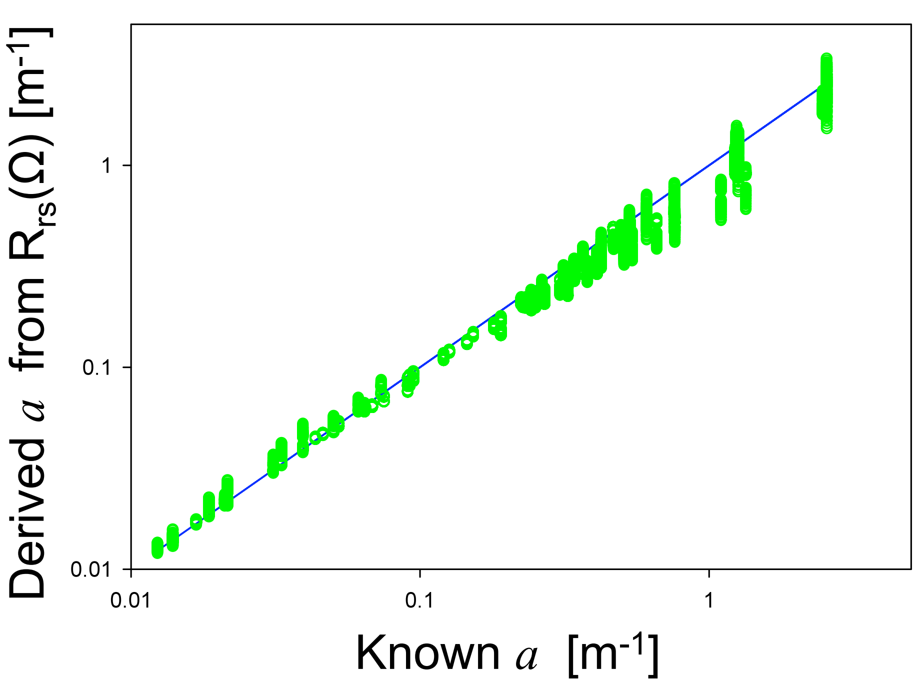
QAA, optimization, linear matrix, etc.

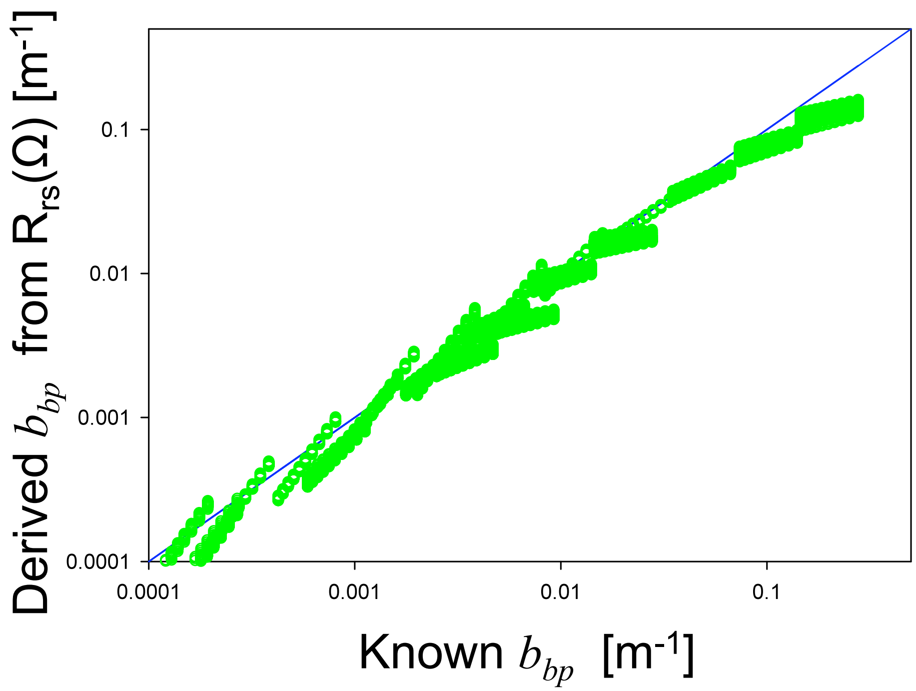
3. **IOP retrieval and BRDF correction** (cont.)

Retrieval and correction examples

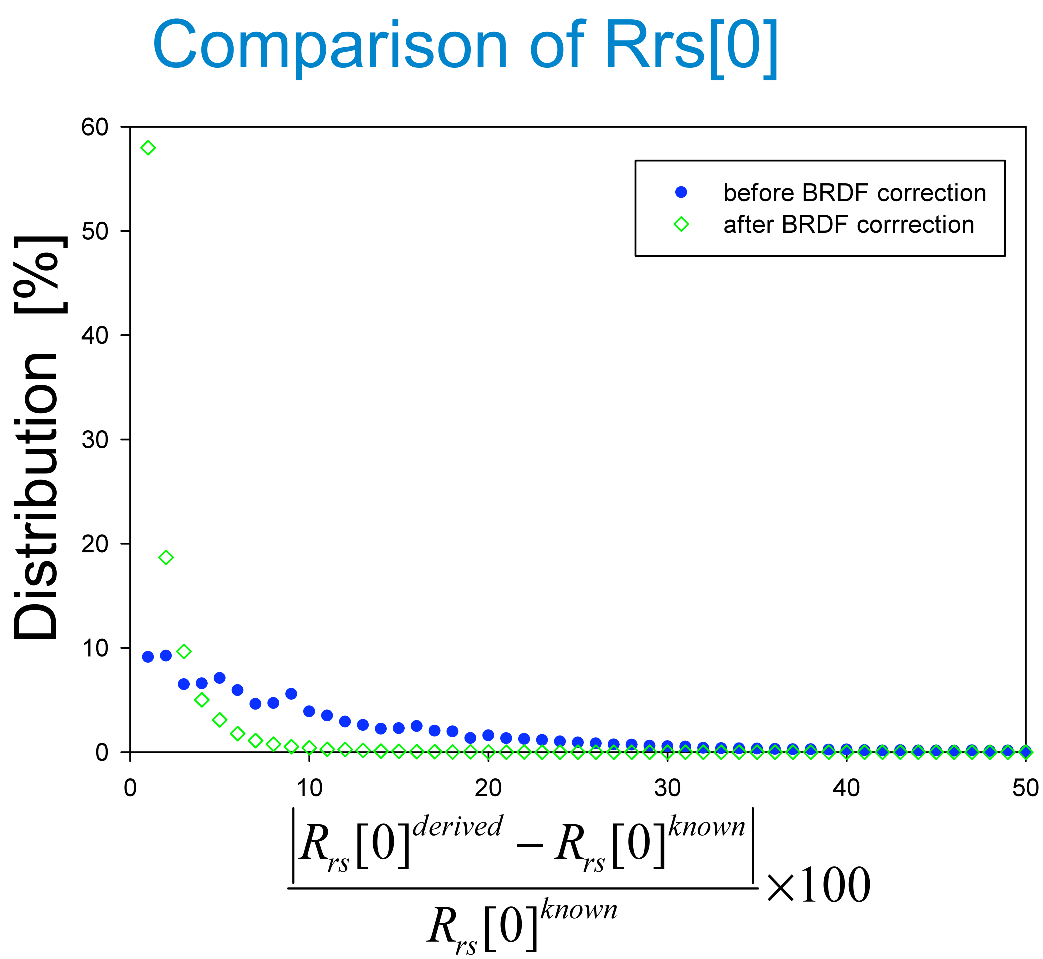
<u>HL simulated data</u>: Sun at 60º, 10-70º view angles and 0-180º azimuth
Wavelength: 400 – 760 nm

Comparison of IOPs (via QAA)





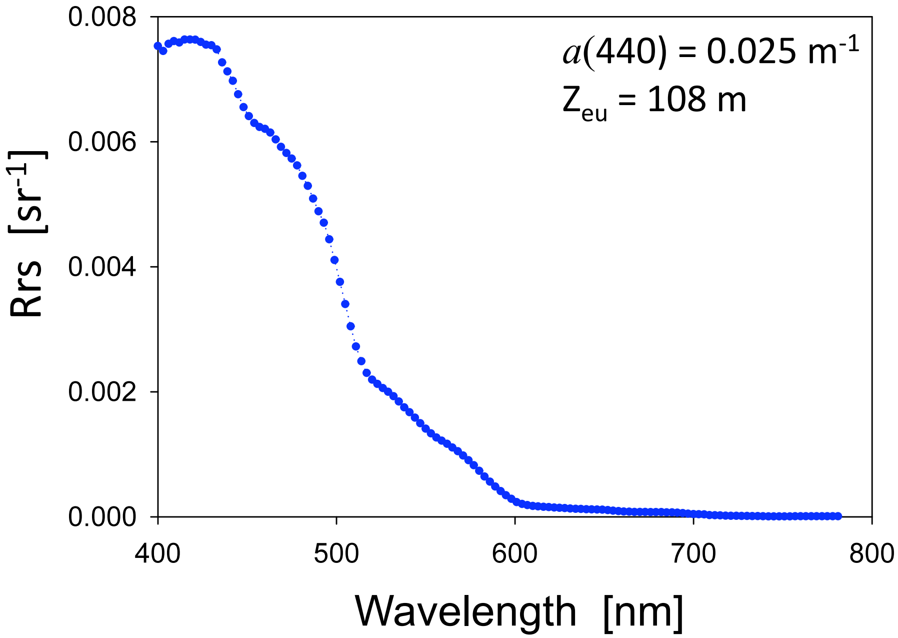
3. **IOP retrieval and BRDF correction** (cont.)



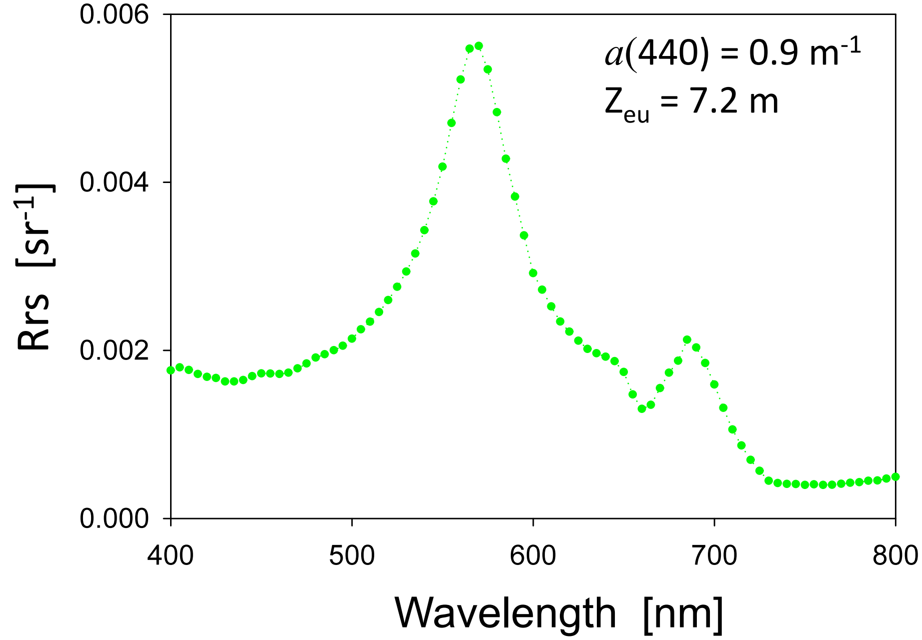
Before correction: 63% & 38% are within 10% and 5%, respectively.
After correction: 99% & 95% are within 10% and 5%, respectively

3. **IOP retrieval and BRDF correction** (cont.)

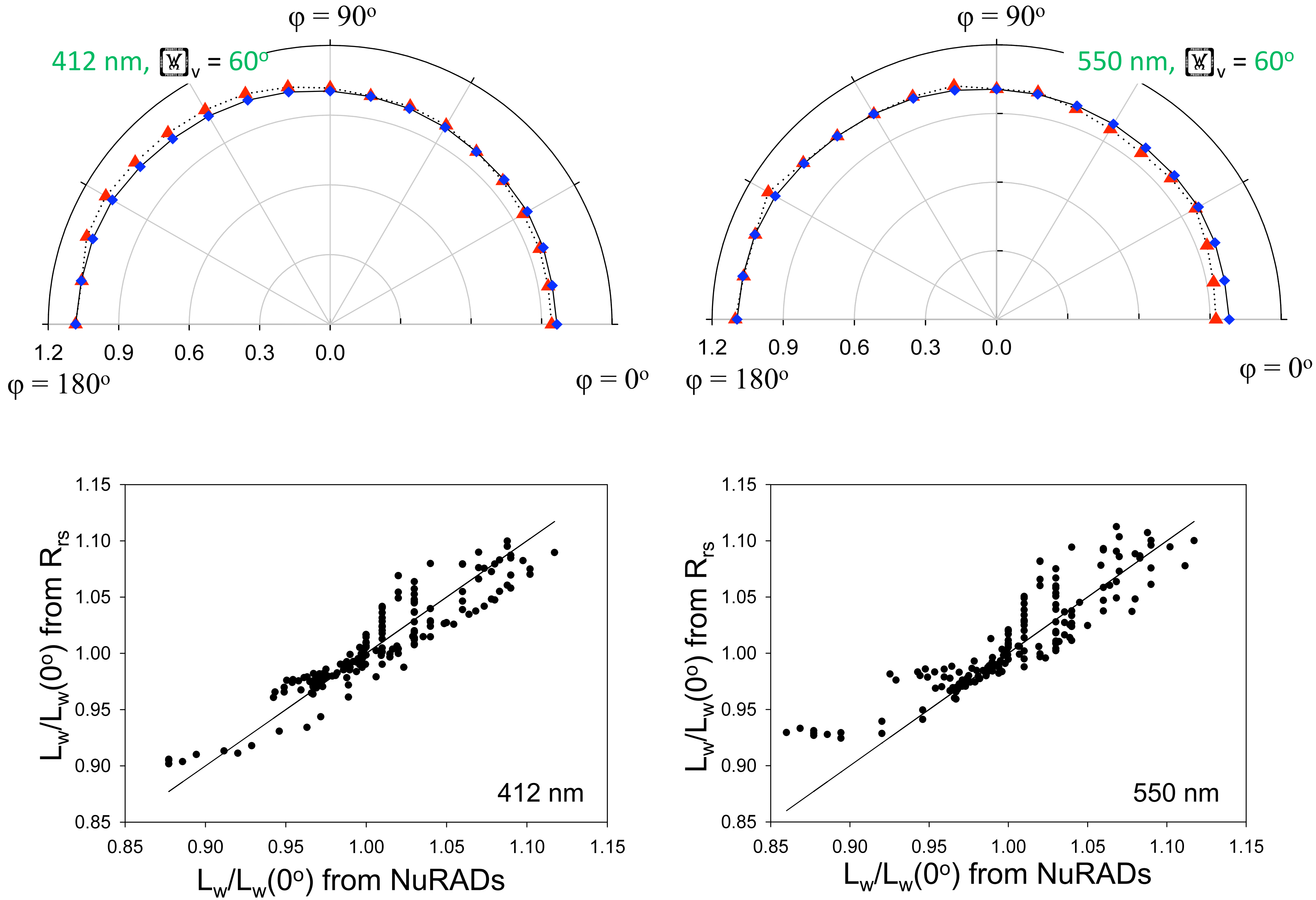
Field measured data



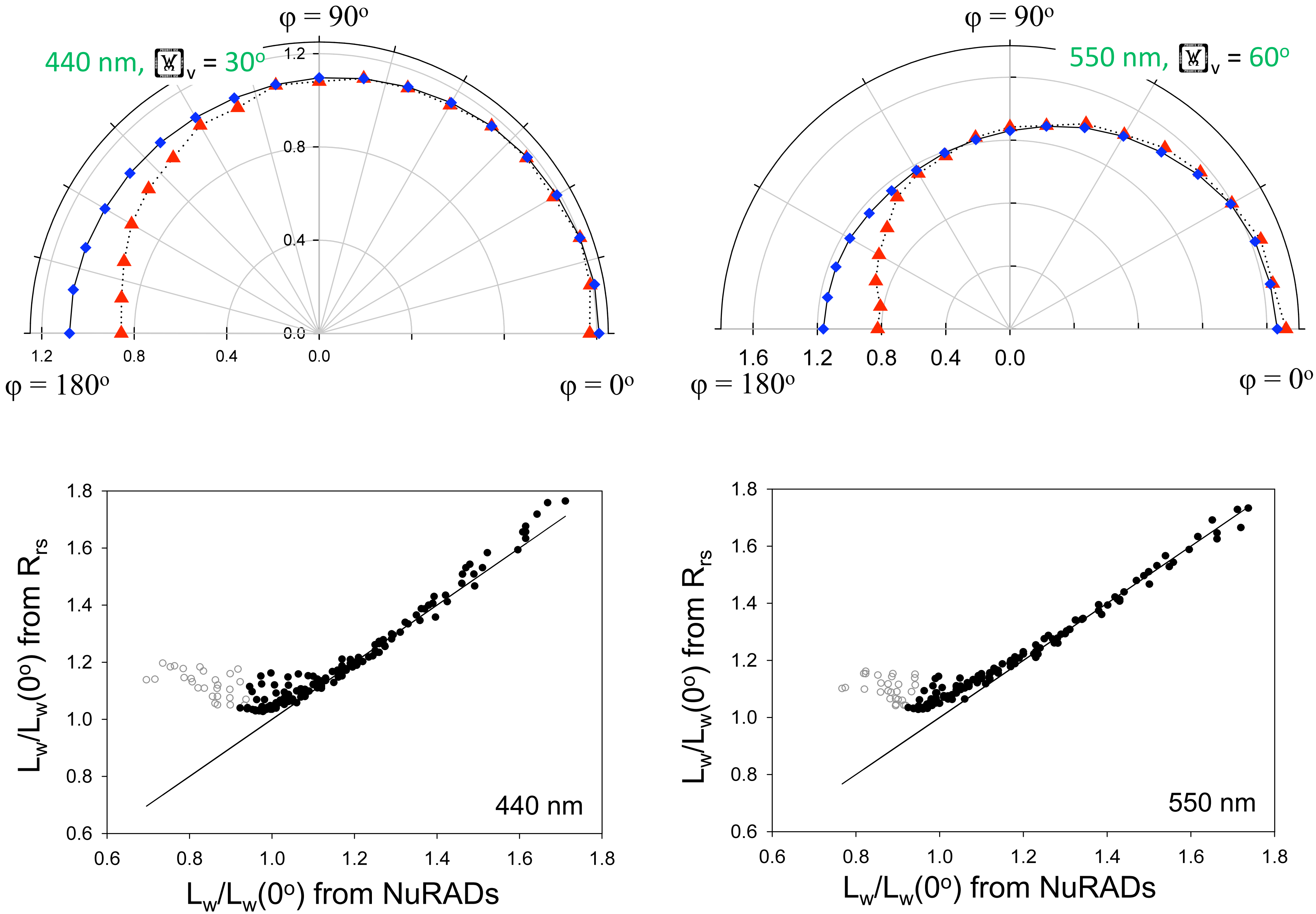
Mediterian Sea, 20040807;
Sun at 30°



Mont. Bay 20060915;
Sun at 60°



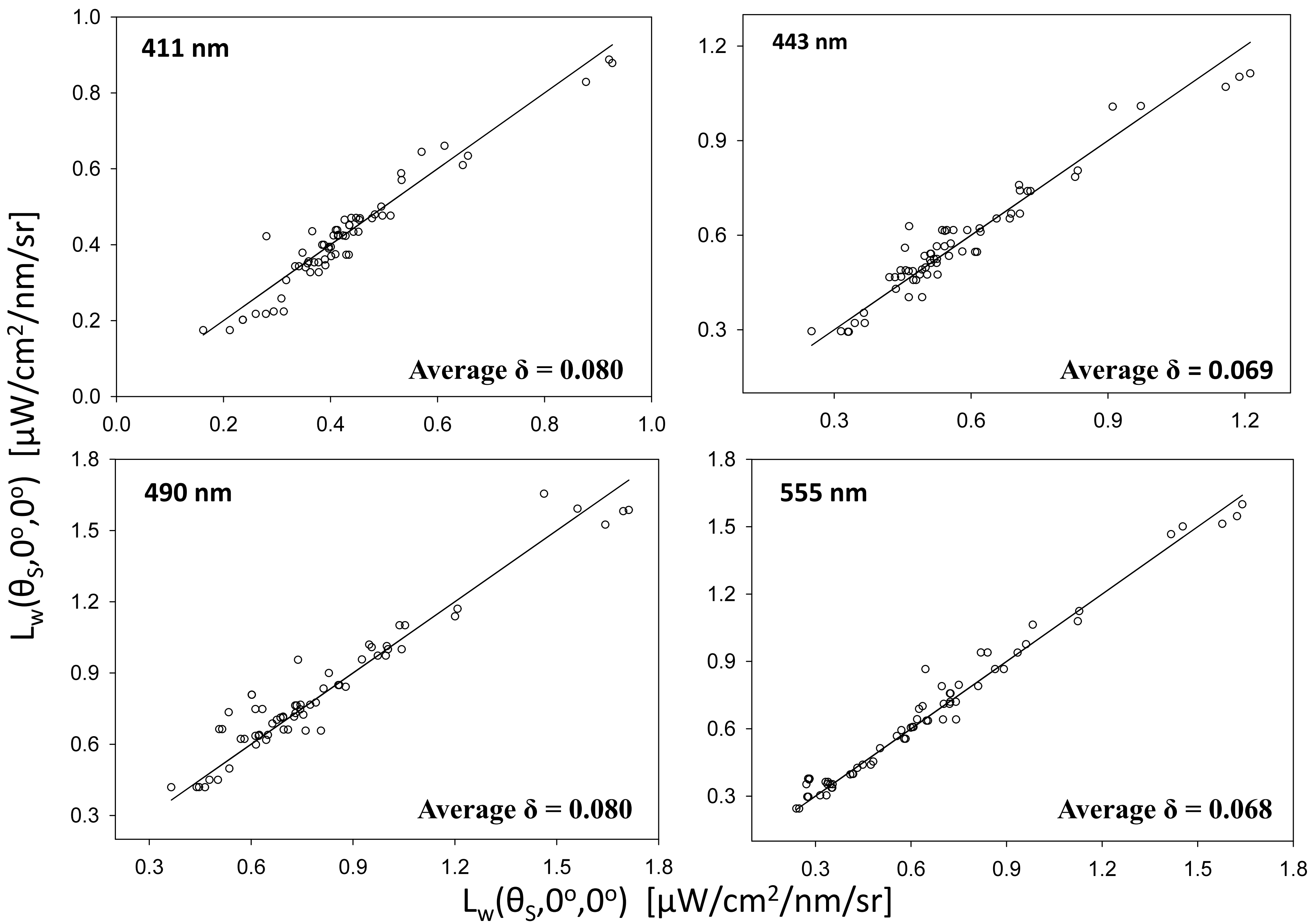
φ = 90o
412 nm, v = 60o
1.2
0.9
0.6
0.3
0.0
φ = 180o
φ = 0o
φ = 90o
550 nm, v = 60o
1.2
0.9
0.6
0.3
0.0
φ = 180o
φ = 0o
Lw/Lw(0o) from Rrs
1.15
1.10
1.05
1.00
0.95
0.90
0.85
0.85
0.90
0.95
1.00
1.05
1.10
1.15
412 nm
Lw/Lw(0o) from NuRADs
Lw/Lw(0o) from Rrs
1.15
1.10
1.05
1.00
0.95
0.90
0.85
0.85
0.90
0.95
1.00
1.05
1.10
1.15
550 nm
Lw/Lw(0o) from NuRADs



φ = 90°
440 nm, v = 30°
φ = 180°
φ = 0°
φ = 90°
550 nm, v = 60°
φ = 180°
φ = 0°
L_w/L_w(0°) from R_rs
L_w/L_w(0°) from NuRADs
440 nm
L_w/L_w(0°) from R_rs
L_w/L_w(0°) from NuRADs
550 nm

(between SeaPrism and in-water spectrometer)

nLw comparison (X-axis: Lw(WIS); Y-axis: nLw from Lw(40,90))



4. Summary

A. Without known PPFS precisely, BRDF correction is an approximation.

B. The model parameter for Rrs is **not** a monotonic function of $b_b/(a+b_b)$. Separating the angular effects of molecule and particle scatterings are important for deriving particle scattering coefficient in oceanic waters.

C. Models and procedures to derive IOPs from angular Rrs, and then to correct the angular dependence, are now developed. This approach can be applied to both multi-band and hyperspectral data, and **no** need to assume waters be Case-1.

D. Excellent results (99% are within 10% error after BRDF correction) are achieved with HL simulated data.

E. Robust results are achieved with field measured data, but more tests/evaluation are necessary.

Thank you!