Physics

Calibration of O.C. Sensors Definitions and Requirements

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Physics

Outline

- Brief review of radiometric calibration for ideal sensors.
- Some characterization issues regarding non-ideal sensors.
- Calibration requirements for ocean color sensors, i.e., allowable uncertainties given desired accuracy in the derived products.

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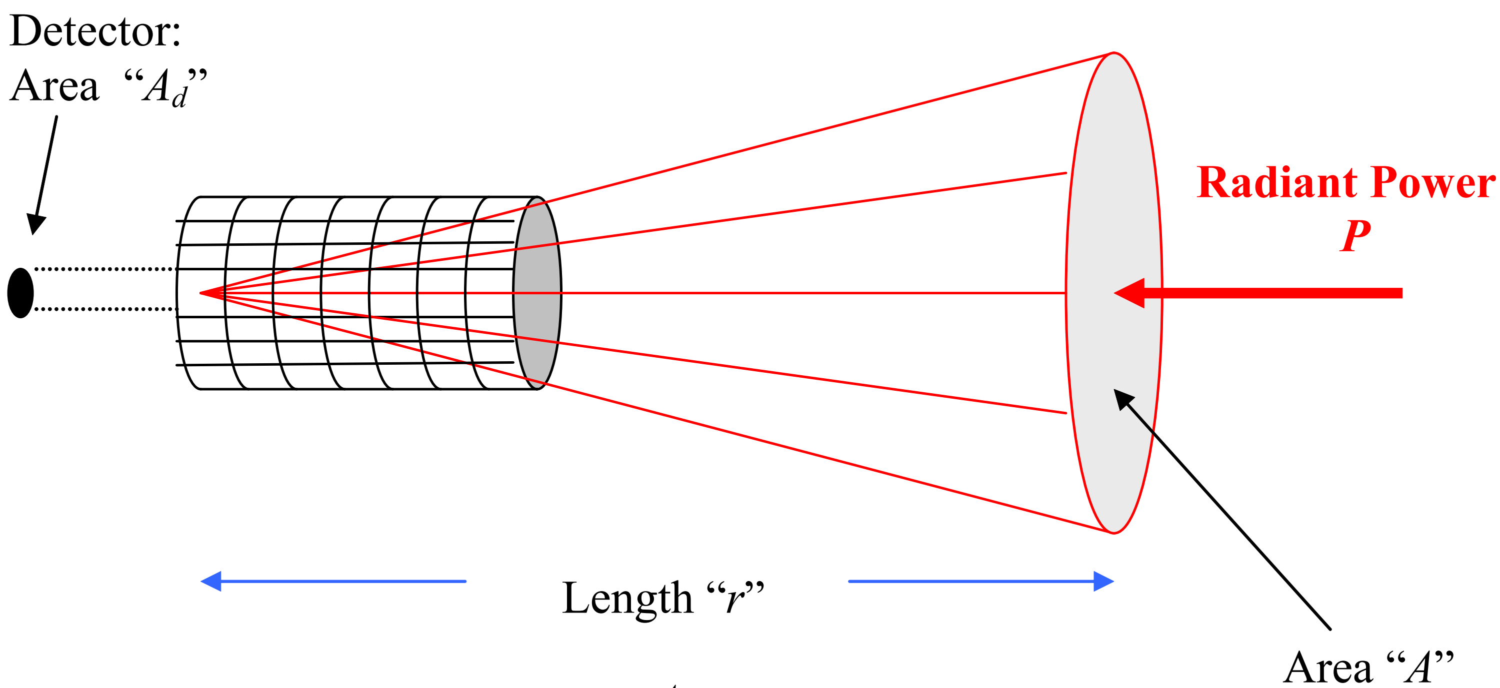
Radiance (L)
Reflectance (ρ)



$$\Omega = \frac{A}{r^2}$$

$$L = \frac{P}{A_d \Omega}$$

$$\rho = \frac{\pi L}{F_0 \cos\theta_0}$$

Calibration Review

Physics

Radiance Based

Consider an ideal sensor (assumed linear) that has responds to radiation in a small band of wavelengths $\lambda \pm \Delta\lambda/2$ around λ. Then viewing a diffuse calibration source of radiance $L_c(\lambda)$, e.g., a calibration sphere, the sensor's response V_c (voltage, current, etc) will be

$$V_c(\lambda) = k_L(\lambda)\, L_c(\lambda)$$

Then viewing a scene of radiance $L(\lambda)$, the sensor's response will be

$$V(\lambda) = k_L(\lambda)\, L(\lambda) = [V_c(\lambda)/\, L_c(\lambda)] \times L(\lambda)$$

A calibration sphere can be added to the sensor to effect calibration monitoring in orbit (MODIS).

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Reflectance Based

Let the same sensor view a lambertian reflectance plaque of reflectance R_p. The plaque is illuminated (normally) by irradiance E_p yielding a radiance $R_p E_p/\pi$ into the sensor which responds:

$$V_P(\lambda) = k_L(\lambda)\, R_p(\lambda) E_p(\lambda)/\pi$$

Now, if it views a scene illuminated normally by an irradiance E, the response will be

$$V(\lambda) = k_L(\lambda)\, \rho(\lambda) E(\lambda)/\pi,$$

so

$$V(\lambda)/V_P(\lambda) = \rho(\lambda)E(\lambda) \,/\, R_p(\lambda)E_p(\lambda)$$

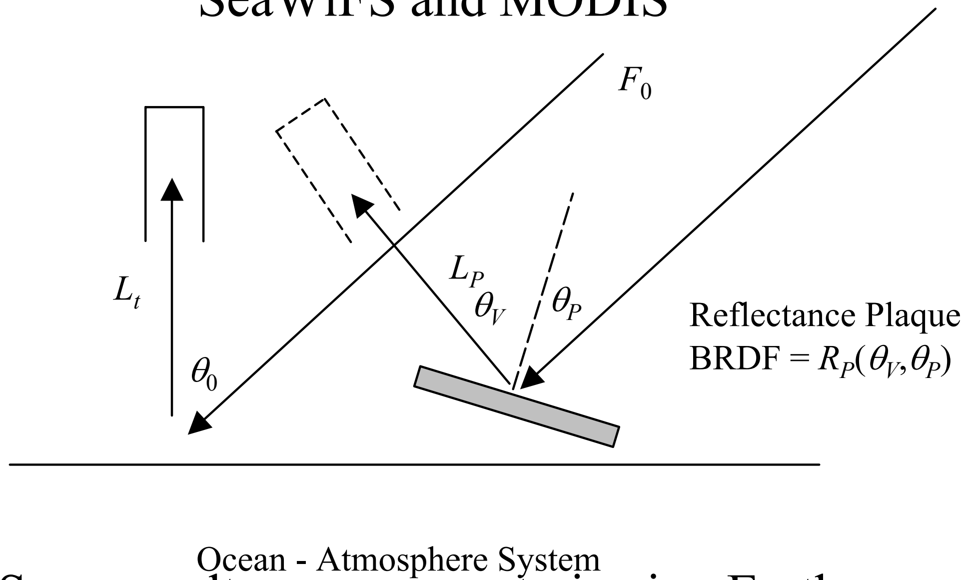
If $E(\lambda)$ and $E_p(\lambda)$ are the same (as with reflectance calibration on orbit), then

$$V(\lambda)/V_P(\lambda) = \rho(\lambda) \,/\, R_p(\lambda)$$

Reflectance plaques can be attached to sensors to monitor calibration in orbit (SeaWiFS and MODIS)

Physics

On-Orbit Reflectance Calibration SeaWiFS and MODIS



Sensor voltage or current viewing Earth:

$$V_t = k_r L_t = k_r F_0\, \rho_t \cos(\theta_0)/(\pi a^2)$$

Sensor voltage or current viewing Plaque:

$$V_p = k_r L_p = k_r F_0\, R_P \cos(\theta_p)/(\pi a^2) \;\; = K_r R_P \cos(\theta_P)$$

(a is the earth-sun distance in A.U.)

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Therefore,

$$\rho_t \cos(\theta_0) = \frac{V_t}{V_P} R_P \cos(\theta_P)$$

or

$$\rho_t \cos(\theta_0) = K_r V_t$$

Note 1: F_0 is not needed to find ρ_t.

Note 2: If R_P degrades (decreases) in orbit, K_r will decrease with time and the estimated ρ_t will be too low. *So stability of* R_P must be monitored (SeaWiFS uses the moon, and MODIS uses an onboard monitoring device)

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Characterization: What about non-ideal sensors?

Assuming the calibration procedures are exact, all sensors have non-ideal performance that must be understood to properly utilize them.

These need to be characterized. Among them are

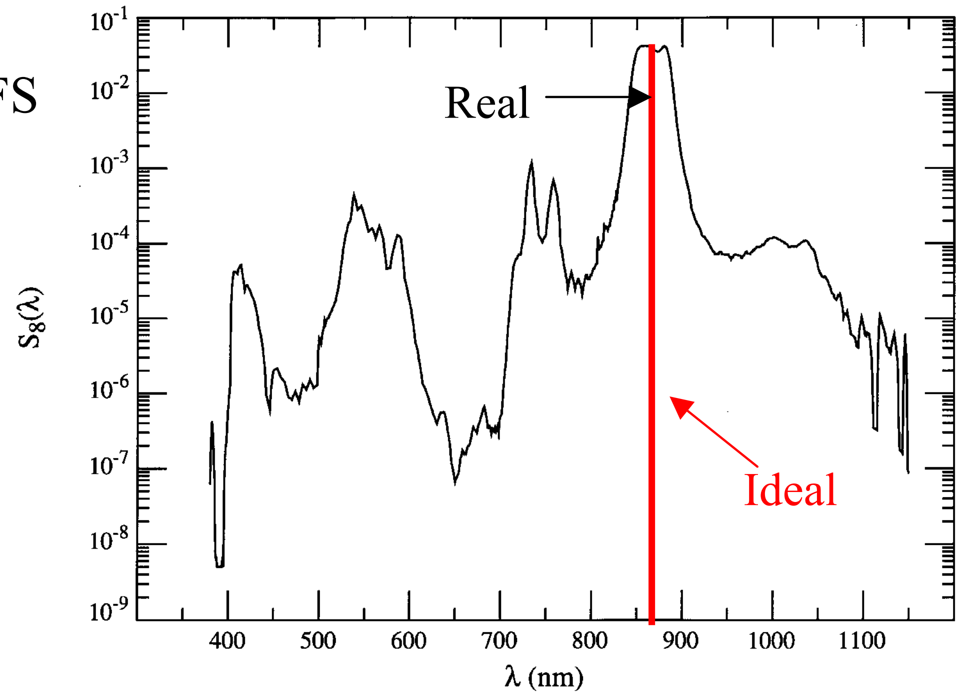
- Out-of-band response
- Polarization sensitivity
- Bright target response
- Non-linearity

⋮

Out-of-Band Response: Sensors with Broad Spectral Bands

Sensors do not view the earth with infinitesimally narrow spectral bands (as we have been assuming, e.g., SeaWiFS Band 8 (865 nm).

$S_8(\lambda)$ is the electrical output of SeaWiFS from nearly monochromatic input of radiance 1 mW/cm^2-µm-Sr at λ.



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For a broad spectral source, e.g., the earth, the output of the sensor is proportional to

$$\langle L(\lambda)\rangle_{S_i} \equiv \frac{\int L(\lambda) S_i(\lambda)\, d\lambda}{\int S_i(\lambda)\, d\lambda}$$

For SeaWiFS 865 band, ~ 9% of the Rayleigh component of the radiance is backscattered from wavelengths below 600 nm! So influence of out-of-band sensitivity can be large. This is important to know, because the Rayleigh component must be calculated to effect atmospheric correction. The calculation requires the Rayleigh cross section which depends on λ.

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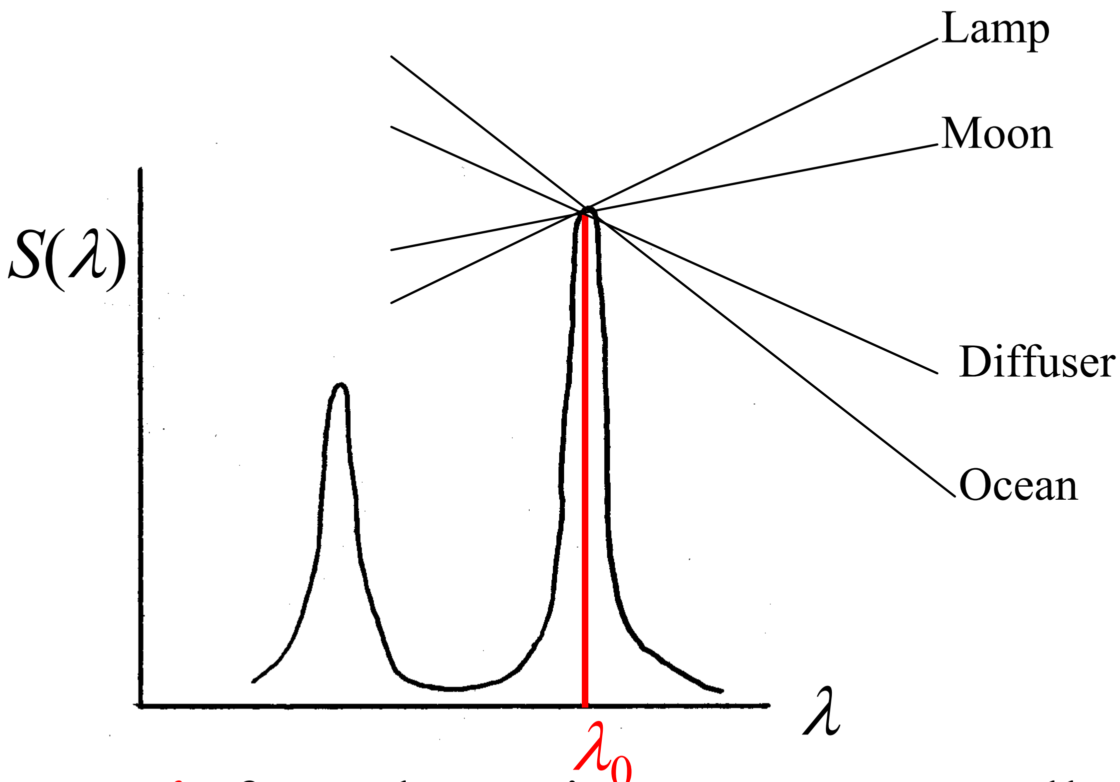
Note that with significant out-of-band, the "measured" radiance is dependent on the spectral distribution of the calibration source, which could be the moon, a calibration lamp, solar diffuser, or the ocean.



Even if the radiances at λ_0 from the various sources are all the same, the "measured" radiances will be different. This suggests vicarious calibration, i.e., looking at the ocean, will be the best, but characterization of the out-of-hand response is still essential.

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Polarization Sensitivity

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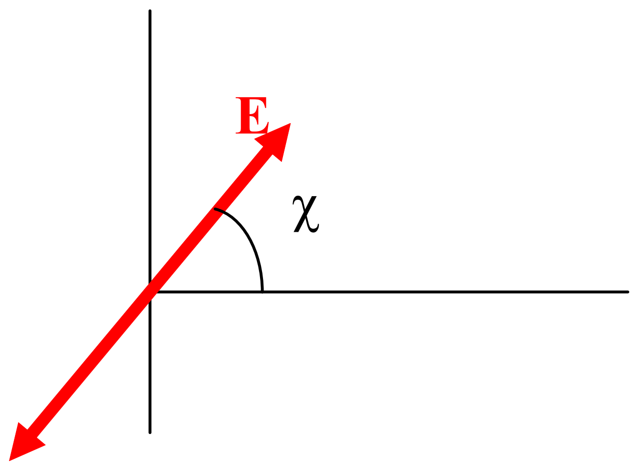
Instrument Polarization Sensitivity

Shine linearly polarized radiance from a source into the instrument.

Let polarization (direction of **E** field) be specified by the angle χ with respect to some direction.



Then

$$L_m(\chi) = M_{11} L_{\text{Source}} \left[1 + a \cos 2(\chi - \delta) \right]$$

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If the incident light is partially polarized, i.e., has a degree of polarization ($0 \le P \le 1$), then

$$L_m(\chi) = M_{11} L_{\text{Source}} \left[1 + aP\cos 2(\chi - \delta)\right]$$

To calibrate the instrument, use an unpolarized source of known radiance, then

$$L_m^{UP}(\chi) = M_{11} L_{\text{Source}}^{UP} \quad \Rightarrow \quad M_{11}$$

Note that this would be the measured radiance for $a = 0$, i.e., an instrument with no polarization sensitivity. Call this L_{true}. Then

$$L_m(\chi) = L_{\text{True}} \left[1 + aP\cos 2\alpha\right],$$

and if the polarization sensitivity is not addressed, the error in the associated radiance could be as much as $\pm aP$.

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Given a, δ and P, χ, we can find L_{True} from L_m.

MODIS
Characterization

Radiance
into MODIS

Physics

Note: We shall see later that a radiance error of 1% at 412 nm results in a water-leaving radiance error of ~ 10%.

How large are *a* and *δ*? How large is *P*?

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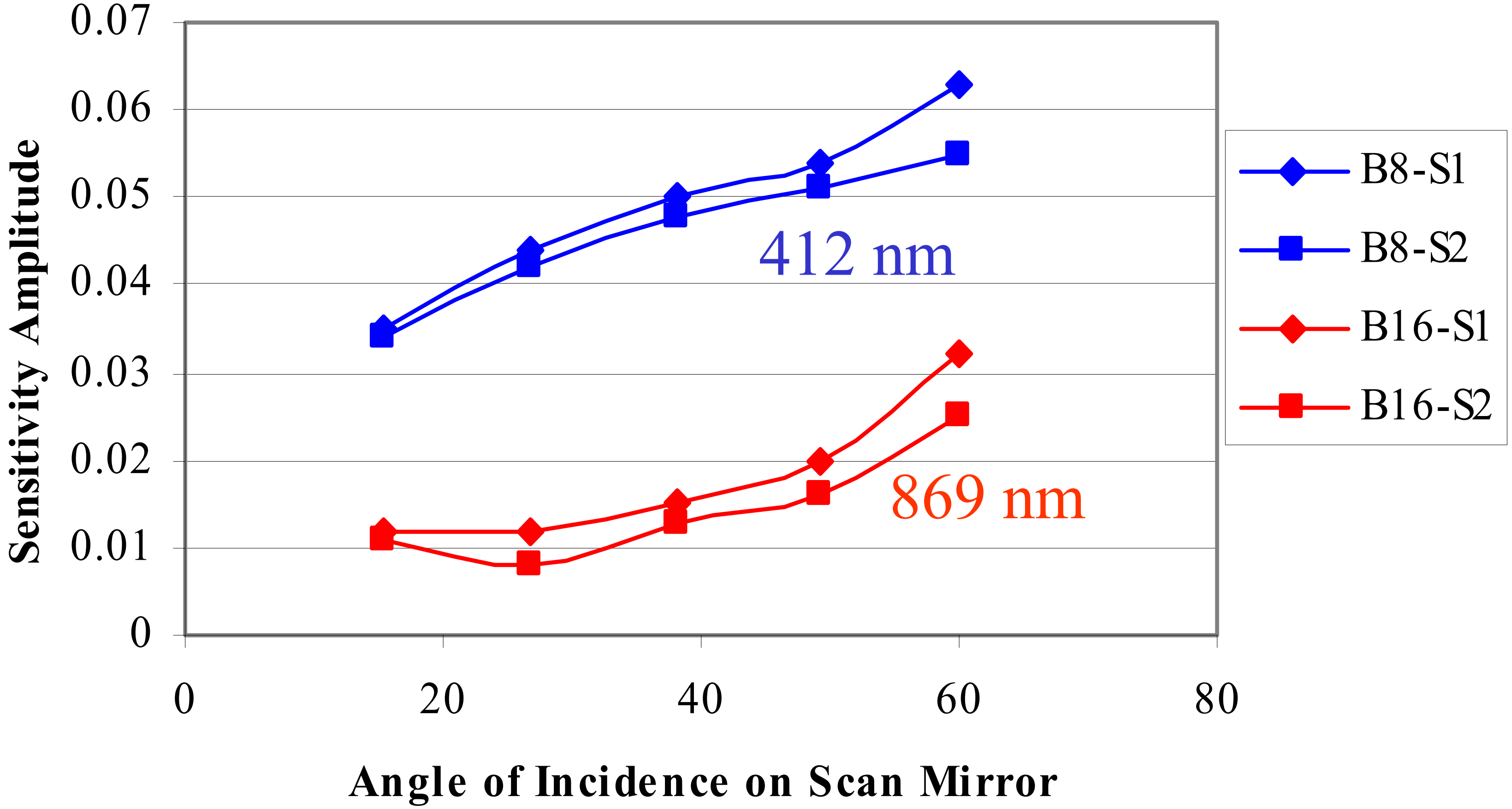
TERRA/MODIS



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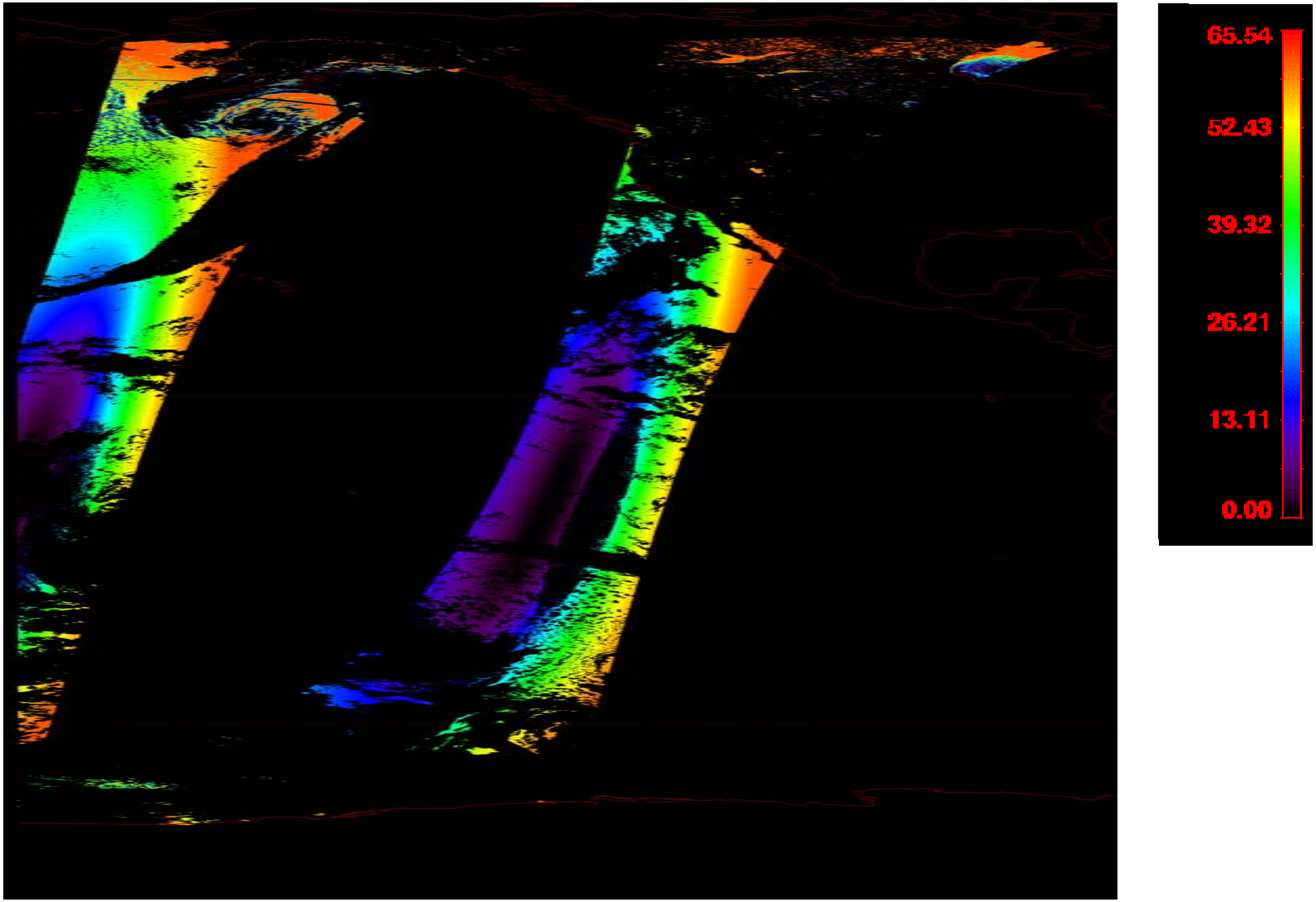
Rayleigh Component Only



Degree of Polarization (December)

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Polarization sensitivity is a significant problem with MODIS, and may be in future sensors. It must be carefully characterized in future sensors!

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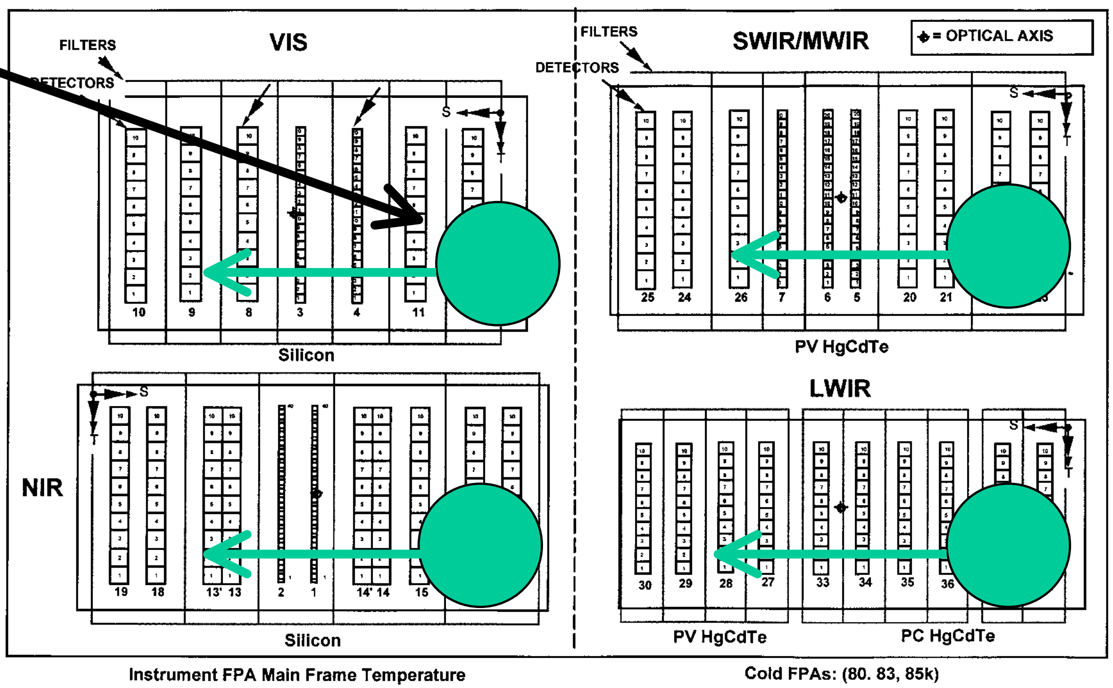
Bright Target / Scattered Light

Modern sensors have large focal planes, a cloud on one part can influence the signal on the whole focal plane!

MODIS Focal Planes

Cloud moving across focal planes



Needs to be characterized!

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Calibration Requirements for Ocean Color Sensors

The Remote Sensing Problem

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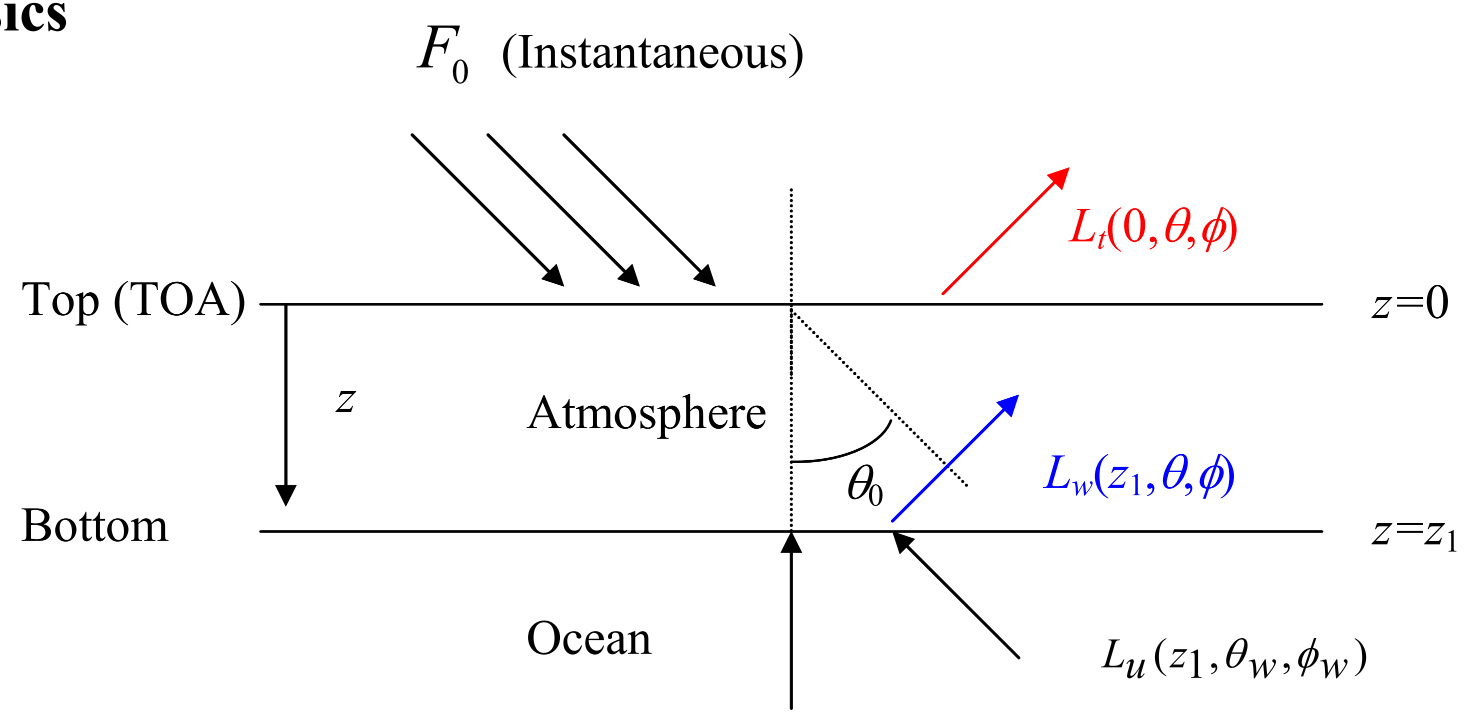

The goal is given L_t find L_w

Actually, we want $[L_w]_N = L_w/t_s\cos(\theta_0)$, where t_s is the transmittance of F_0 from z = 0 to z = z_1.

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We will use reflectance ρ rather than radiance L to describe the processes. They are related by

$$\rho = \pi L / F_0 \cos(\theta_0)$$

The TOA reflectance is $\rho_t(\lambda) = \rho_r(\lambda) + \rho_A(\lambda) + t_v(\lambda) t_s(\lambda) [\rho_w(\lambda)]_N$,

Rayleigh (ρ_r); Diffuse Transmittances (t_v, t_s); Normalized water-leaving Reflectance ($[\rho_w]_N$)

where

$\rho_A(\lambda) = \rho_a(\lambda) + \rho_{ra}(\lambda)$:

$\rho_r(\lambda)$ is the Rayleigh reflectance in the absence of aerosols.

$\rho_a(\lambda)$ is the aerosol reflectance in the absence of Rayleigh Scattering.

$\rho_{ra}(\lambda)$ is the reflectance component for photons that have been both Rayleigh and aerosol scattered.

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Aside: Influence of error in F_0.

ρ_r is provided through look up tables (LUTs), so if radiance is measured,

$$L_t(\lambda) = L_r(\lambda) + L_A(\lambda) + t_v(\lambda)t_s(\lambda)[L_w(\lambda)]_N$$

And we need F_0 to compute L_r. We will see that $L_r/L_t \sim 0.9$ in the blue, so the influence of any error in F_0 is magnified, i.e., 1% error in F_0 leads to a 10% error in $L_t - L_r$, and greatly increases the error in $[L_w]_N$.

If reflectance is measured,

$$\rho_t(\lambda) = \rho_r(\lambda) + \rho_A(\lambda) + t_v(\lambda)t_s(\lambda)[\rho_w(\lambda)]_N$$

and F_0 is needed only to convert $[\rho_w]_N$ to $[L_w]_N$, assuming $[L_w]_N$ is what is desired.

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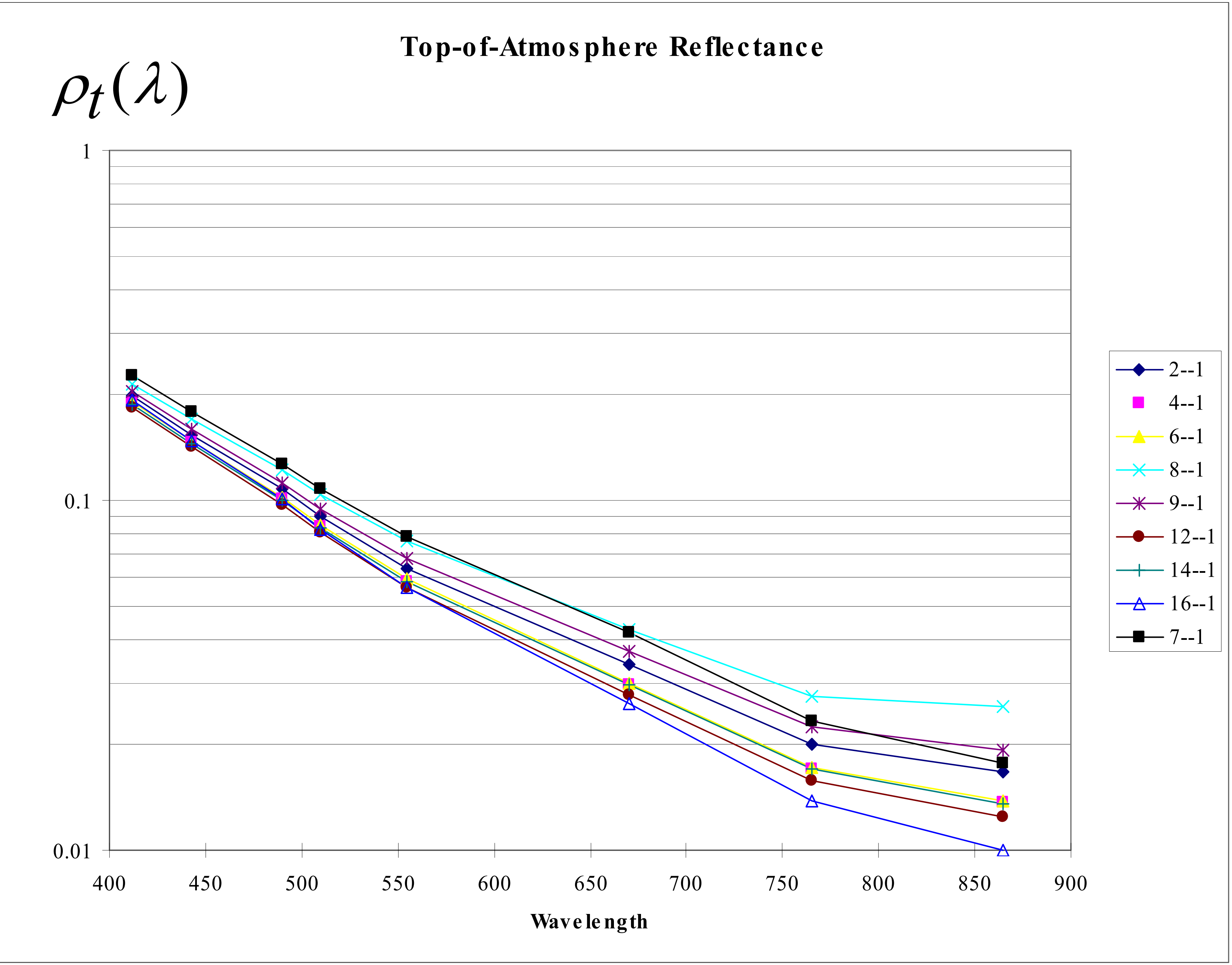
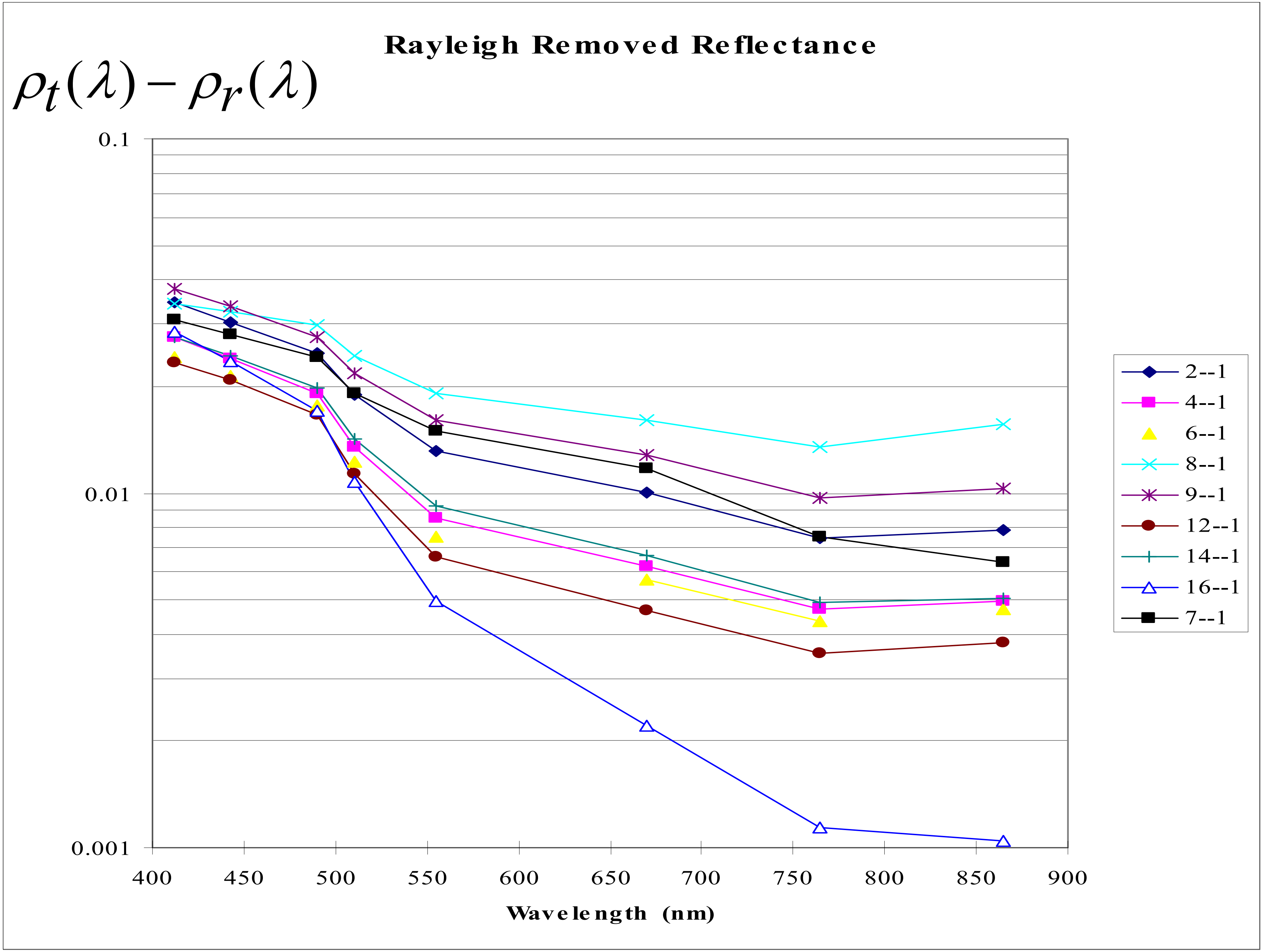
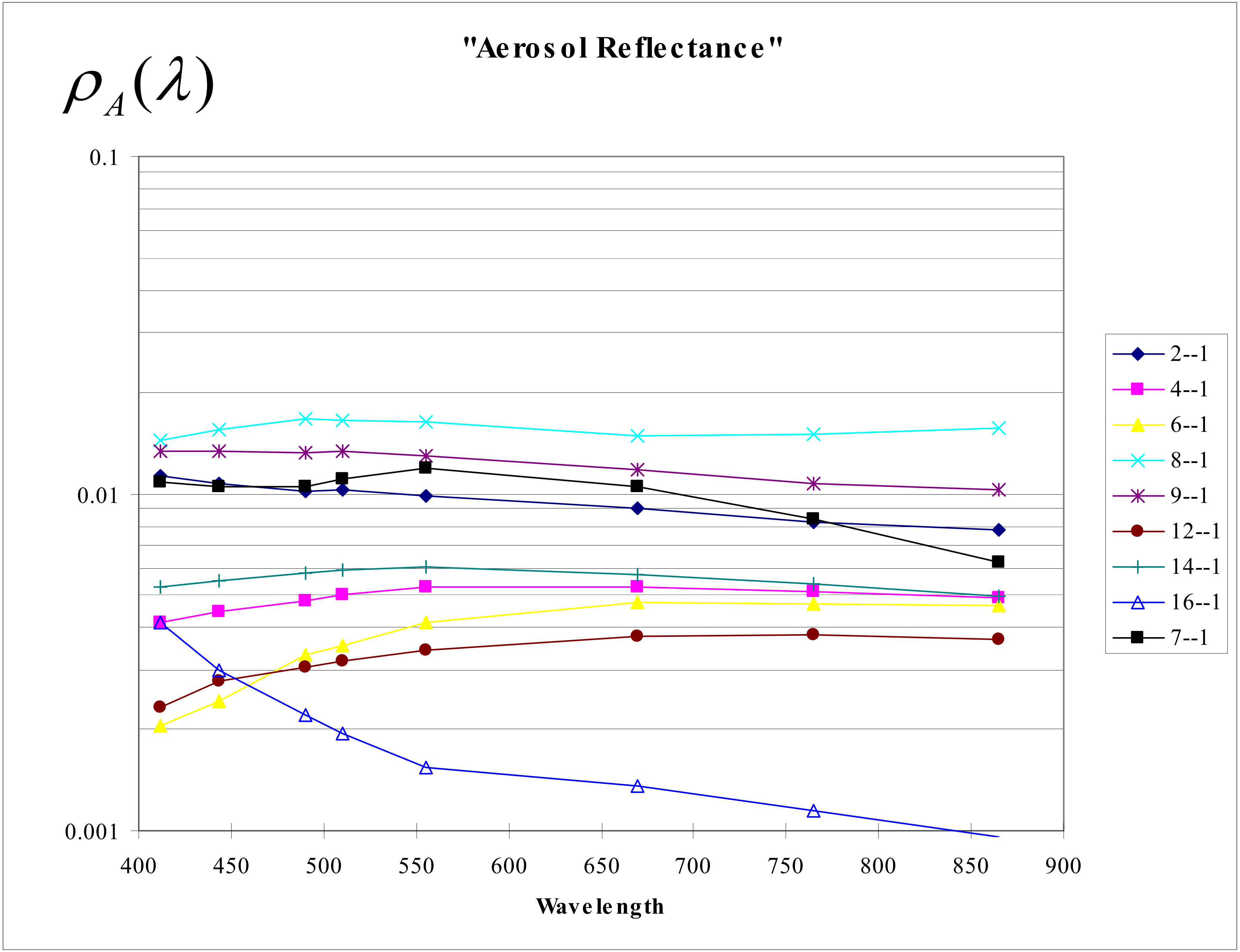
$$\rho_t(\lambda) = \rho_r(\lambda) + \rho_A(\lambda) + t_v(\lambda) t_s(\lambda)[\rho_w(\lambda)]_N$$

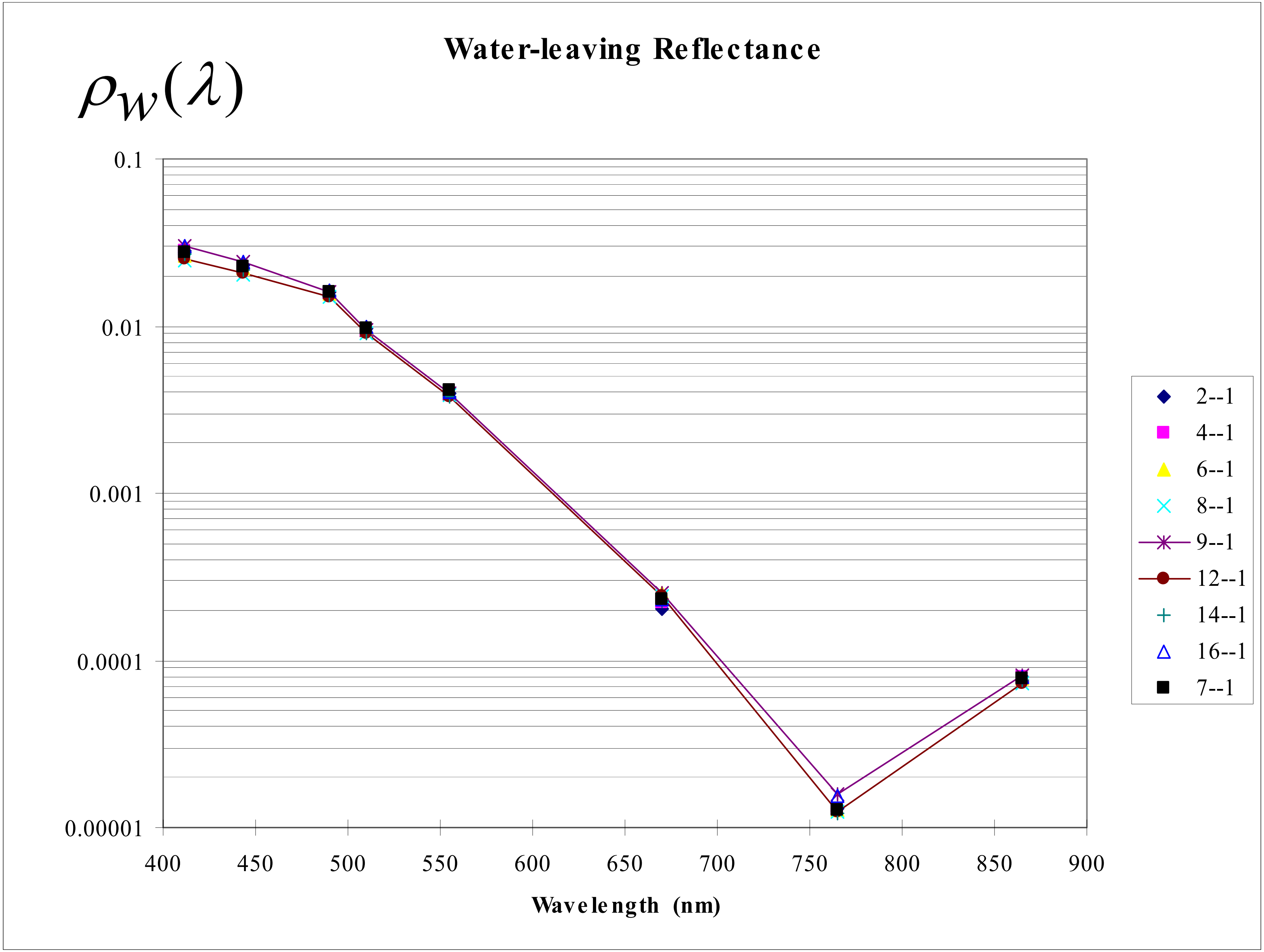
Typical values for these terms in the waters of Hawaii obtained from SeaWiFS are shown in the next four slides. (Courtesy SeaWiFS Project and Dennis Clark)


Top-of-Atmosphere Reflectance
$\rho_t(\lambda)$
1
0.1
0.01
400
450
500
550
600
650
700
750
800
850
900
Wavelength
2--1
4--1
6--1
8--1
9--1
12--1
14--1
16--1
7--1



Rayleigh Removed Reflectance
$\rho_t(\lambda) - \rho_r(\lambda)$
0.1
0.01
0.001
400
450
500
550
600
650
700
750
800
850
900
Wavelength (nm)
2--1
4--1
6--1
8--1
9--1
12--1
14--1
16--1
7--1


"Aerosol Reflectance"
$\rho_A(\lambda)$
0.1
0.01
0.001
400
450
500
550
600
650
700
750
800
850
900
Wavelength
2--1
4--1
6--1
8--1
9--1
12--1
14--1
16--1
7--1



Water-leaving Reflectance
$\rho_W(\lambda)$
0.1
0.01
0.001
0.0001
0.00001
400
450
500
550
600
650
700
750
800
850
900
Wavelength (nm)
2--1
4--1
6--1
8--1
9--1
12--1
14--1
16--1
7--1

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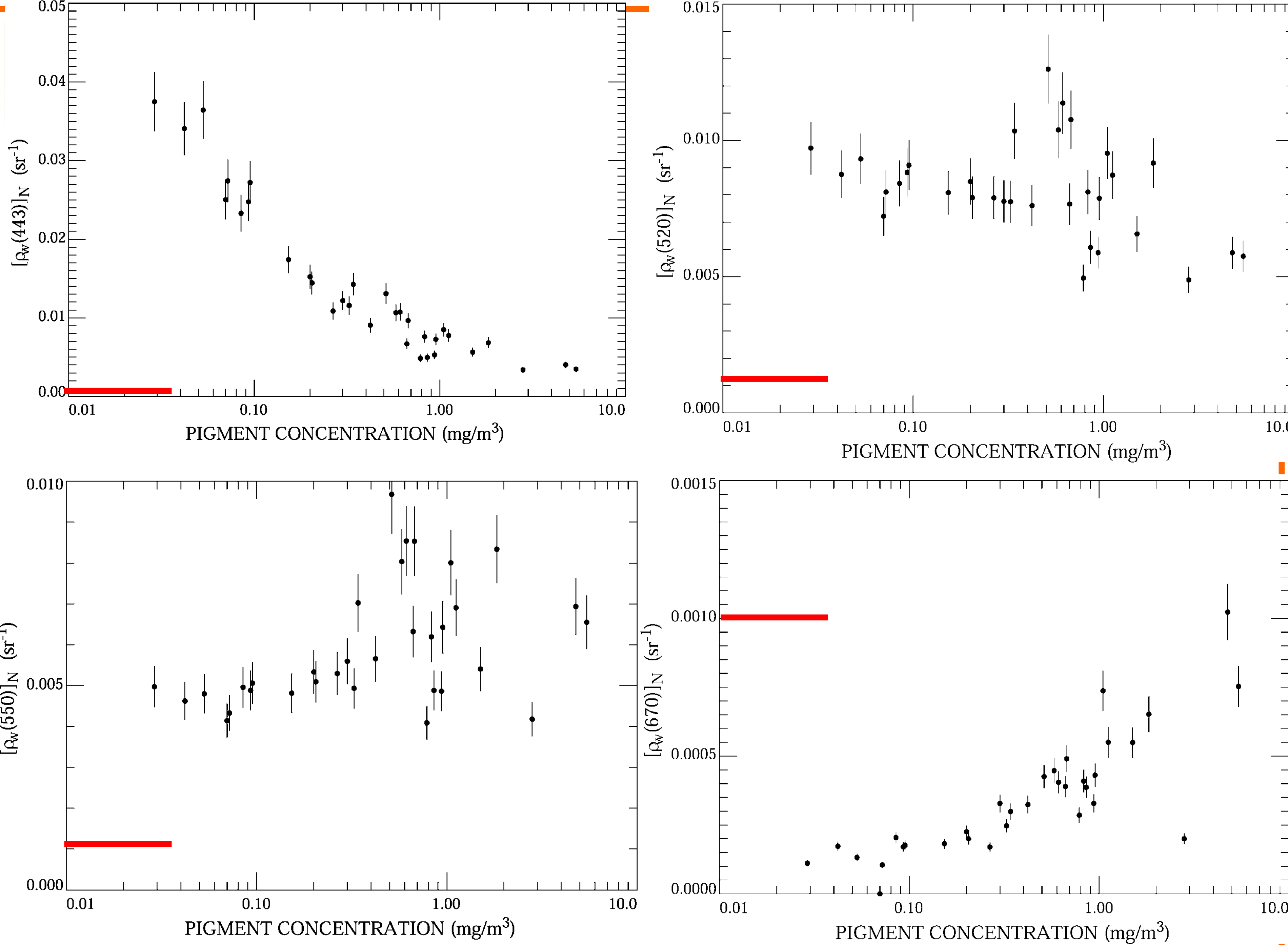
So for these waters, ρ_w/ρ_t ranges from 12% at 412 nm to 5% at 555 nm.

The next slide shows the variation of $[\rho_w(\lambda)]_N$ with Pigment Concentration at four wavelengths (λ = 443, 520, 550, and 670 nm) for Case 1 Waters (Courtesy Dennis Clark). The red line indicates 0.001 in the scale.



0.05
0.04
0.03
0.02
0.01
0.00
[ρW(443)]N (sr-1)
0.01
0.10
1.00
10.0
PIGMENT CONCENTRATION (mg/m3)
0.015
0.010
0.005
0.000
[ρW(520)]N (sr-1)
0.01
0.10
1.00
10.0
PIGMENT CONCENTRATION (mg/m3)
0.010
0.005
0.000
[ρW(550)]N (sr-1)
0.01
0.10
1.00
10.0
PIGMENT CONCENTRATION (mg/m3)
0.0015
0.0010
0.0005
0.0000
[ρW(670)]N (sr-1)
0.01
0.10
1.00
10.0
PIGMENT CONCENTRATION (mg/m3)

Physics

The originally announced goal for ocean color sensors:

The uncertainty in the (normalized) water-leaving radiance retrieved from the sensor in oligotrophic waters at 443 nm should not exceed 5%, and uncertainty in Chlorophyll should be < 30%.

For such waters, $[\rho_w(443)]_N$ is approximately 0.04, meaning that the maximum error allowed is 0.002. The atmospheric correction algorithm was specifically designed to meet this goal.

Physics

If we take the error in atmospheric correction to typically be of the order of 0.001, then meeting this goal would require the sensor have a calibration uncertainty no more than about 0.001/0.20 or ~ 0.5% at 443 nm. This is difficult to meet even prelaunch!

⇒ In-orbit calibration (vicarious) or calibration adjustment is needed.

However, we can try to look at it another way, i.e., using the *Chlorophyll a* requirement of 30% uncertainty.

Consider some spectra of $[\rho_w(\lambda)]_N$

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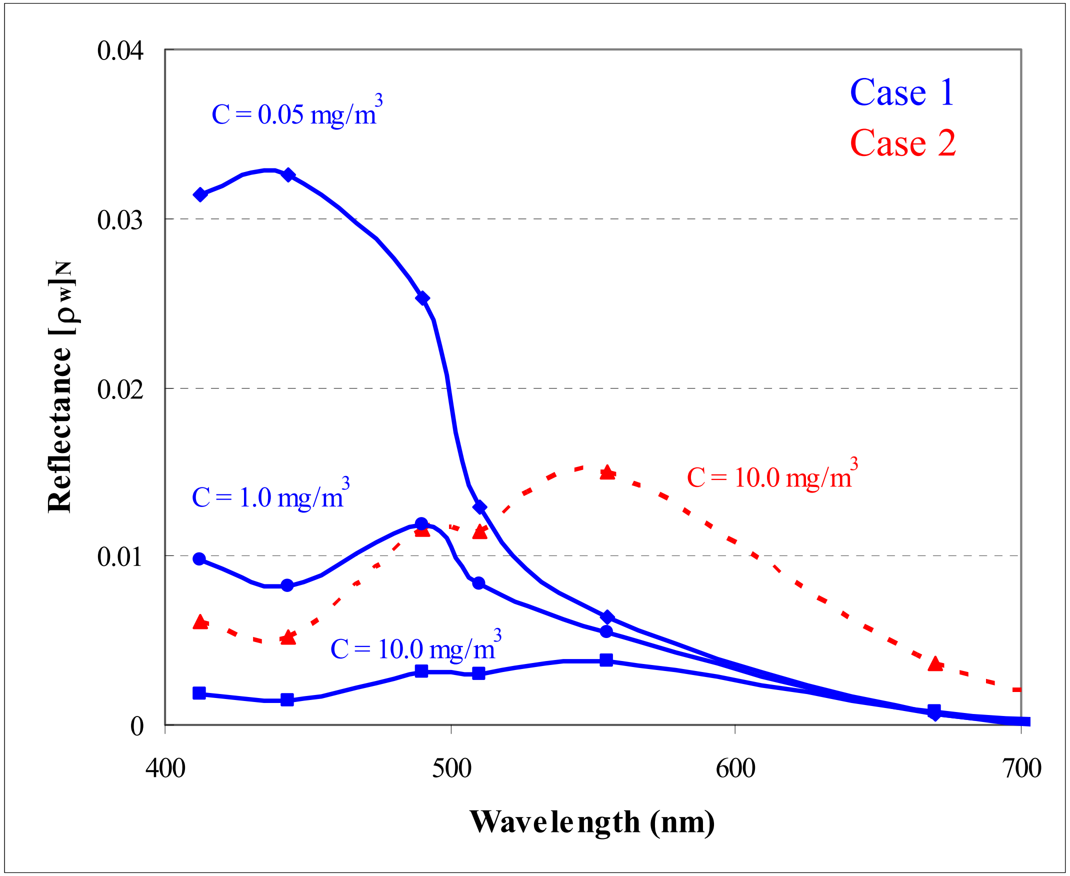
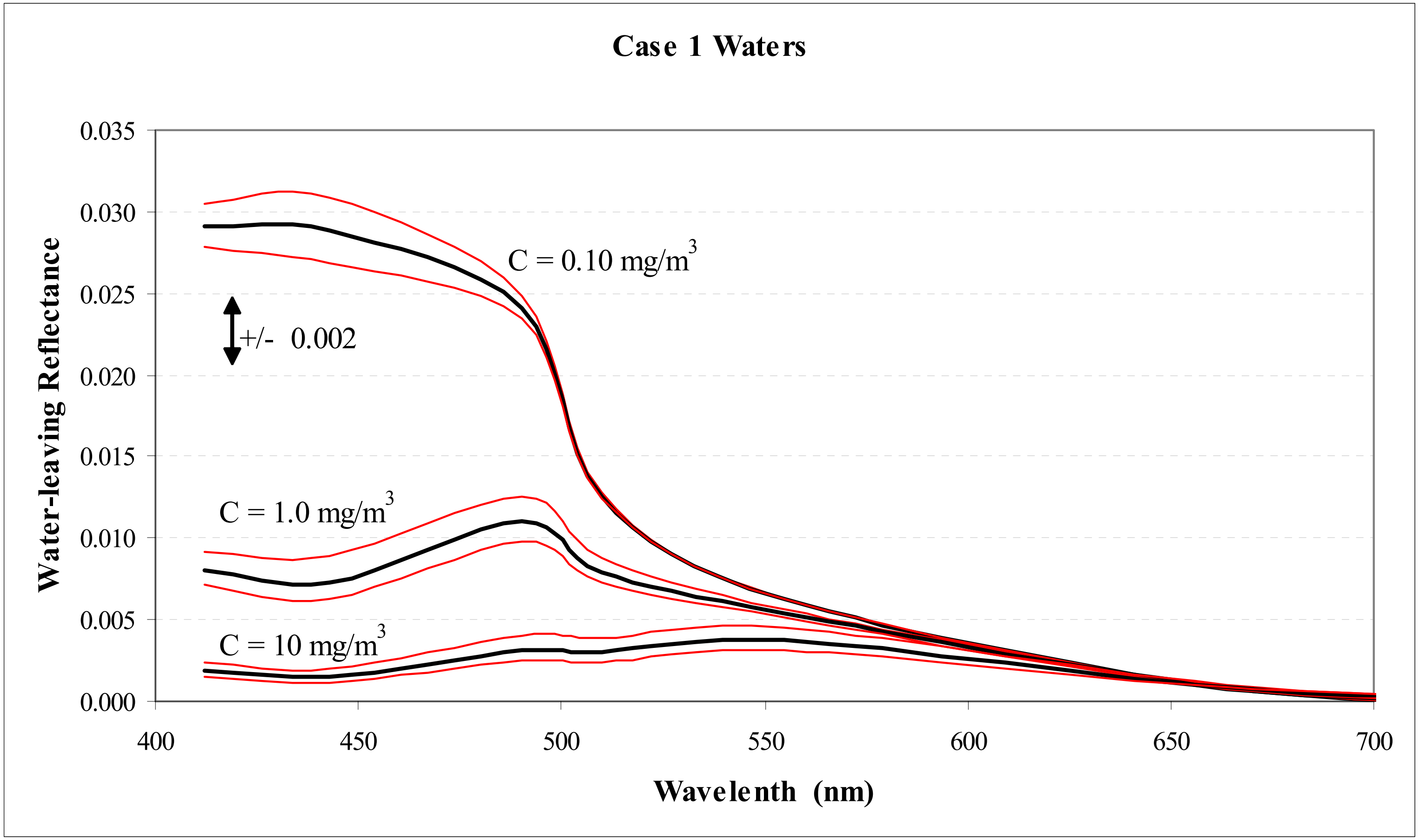


Case 1
Case 2
C = 0.05 mg/m3
C = 1.0 mg/m3
C = 10.0 mg/m3
C = 10.0 mg/m3
Reflectance [ρw]N
Wavelength (nm)
0.04
0.03
0.02
0.01
0
400
500
600
700

Physics

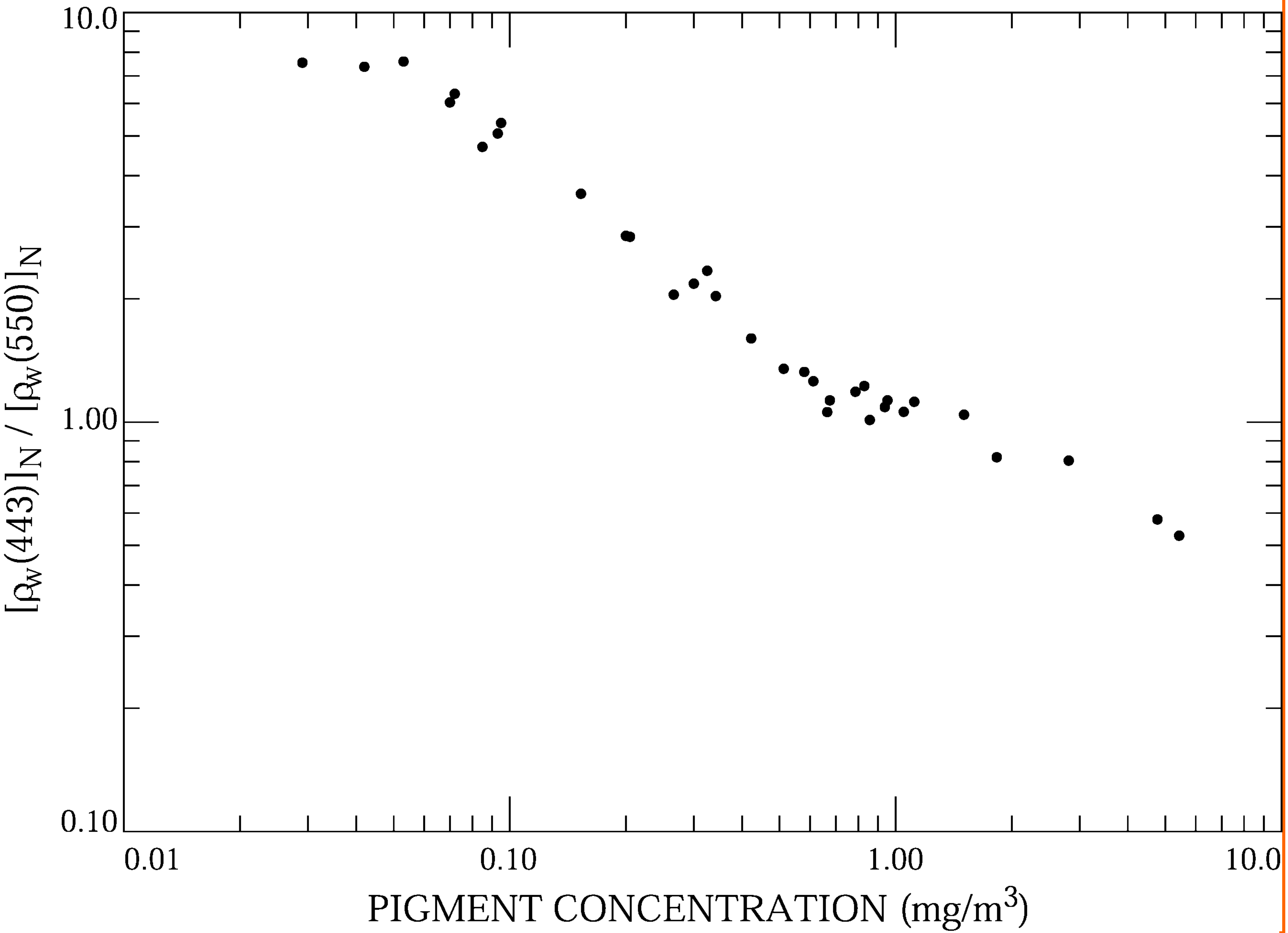


Red lines are +/- 30% error in C

Only in the low to moderate C waters is an accuracy of +/- 0.002 sufficient in the blue.

But it is clear that the shape of the spectra is as, or more, important than the absolute reflectance.

This is manifest in the “ratio algorithms” traditionally used in ocean color.



10.0
1.00
0.10
0.01
0.10
1.00
10.0
$[\rho_W(443)]_N / [\rho_W(550)]_N$
PIGMENT CONCENTRATION (mg/m^3)

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For this data,

$$C \cong \left(\frac{\rho_w(550)}{\rho_w(443)} \right)^{1.7}$$

so

$$\frac{\delta C}{C} \cong 1.7 \times \left(\frac{\delta\rho_w(550)}{\rho_w(550)} - \frac{\delta\rho_w(443)}{\rho_w(443)} \right)$$

and if the $\delta\rho_w$'s are the direct result of calibration errors, we see again that the *impact on C* is minimized if the calibration error in the two bands is of the same sign!

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For High C, Gordon *et al.* (1983) used

$$C \cong A\left(\frac{\rho_w(550)}{\rho_w(520)}\right)^{2.5}$$

so

$$\frac{\delta C}{C} \cong 2.5\times\left(\frac{\delta\rho_w(550)}{\rho_w(550)}-\frac{\delta\rho_w(520)}{\rho_w(520)}\right)$$

In the worst case (520 and 550 errors are in the opposite direction), to retrieve C to within 30% requires the water-leaving reflectances in these bands within ~6% assuming the same relative error in each!

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Worst case:

Relative errors have opposite signs and ~ the same magnitude.

$$\frac{\rho_w(443)}{\rho_t(443)} \sim 0.12 \Rightarrow \delta\rho_t(443) \sim 0.09 \times 0.12 \sim 0.11\text{, or } 1.1\%$$

$$\frac{\rho_w(550)}{\rho_t(550)} \sim 0.05 \Rightarrow \delta\rho_t(443) \sim 0.09 \times 0.05 \sim 0.045\text{, or } 0.45\%$$

However, note that for high C, $\rho_w(443) \sim 0.001$ to 0.002, making $\rho_w(443)/\rho_t(443) \sim 0.006$-0.012 or $\delta\rho_t(443) \sim 0.06$-0.12%.
Calibration to this accuracy is not possible.

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Best case:

Relative errors have same sign and ~ the same magnitude.

Then

$$\frac{\delta C}{C} \cong 1.7 \times \left(\frac{\delta\rho_w(550)}{\rho_w(550)} - \frac{\delta\rho_w(443)}{\rho_w(443)} \right) \sim 0$$

This can likely happen at low C, but for high C, ρ_w's are small in the blue (~ 0.001 to 0.002), $\delta\rho_t$'s must be correspondingly smaller.

Reality is somewhere between the best and worst cases.

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How does calibration influence atmospheric correction?

Let

$$\rho(\lambda)_{Est} = \rho(\lambda)_{True}[1+\alpha(\lambda)]$$

at 443 nm and in the NIR, and compute the error in atmospheric correction at 443 nm.

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$$\rho(\lambda)_{Est} = \rho(\lambda)_{True}[1+\alpha(\lambda)]$$

$t_v(443)\Delta\rho_w(443)$

In NIR, small calibration errors of opposite sign are as important as large errors with the same sign!

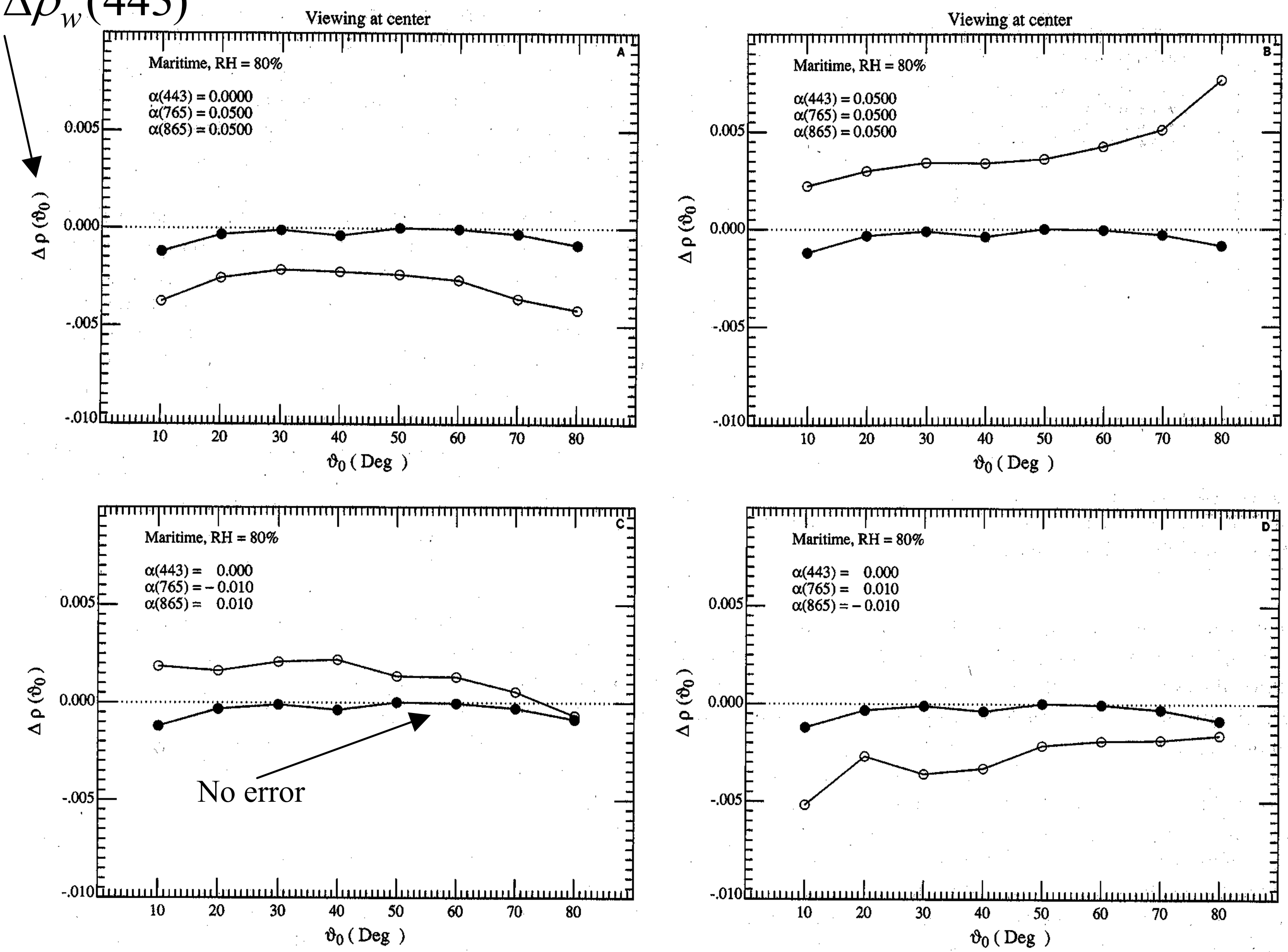

Figure 19. Error in the retrieved $t(443)\rho_w(443)$ for viewing at the center of the scan with a maritime aerosol at RH = 80% as a function of the solar zenith angle with $\tau_a(865) = 0.2$ and calibration errors $\alpha(443)$, $\alpha(765)$, and $\alpha(865)$ in equation (18) (open circles). Solid circles are for $\alpha(\lambda_i) = 0$ for all λ_i.

Again, atmospheric correction favors calibration errors of the same sign in all bands, but of course decreasing toward the blue.

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Conclusions Regarding Acceptable Calibration Error

- The 30% uncertainty in C can be met with this error as long as the error in the other bands all have the same sign, and even then there will be difficulties at high C where $\rho_w(443) \sim 0.001 - 0.002$.
- To meet 5% uncertainty in $\rho_w(443)$ in oligotrophic waters, $\delta\rho_w(443)/\rho_w(443) \sim 0.5\%$.
- Atmospheric correction also favors calibration errors in all bands having the same sign.

It would seem that the calibration requirements of ocean color sensors are too stringent to be met by standard calibration techniques.

However, they can be met to a certain extent by vicarious calibration techniques.

We shall review these now.

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Radiometric Vicarious Calibration

$$\rho_t(\lambda) = \rho_r(\lambda) + \rho_A(\lambda) + t_v(\lambda)t_s(\lambda)[\rho_w(\lambda)]_N$$

Compute using atmospheric Pressure

Estimate using sun shotometer and sky radiance

Determine using in-situ measurements

Estimate ρ_t and adjust calibration to force agreement with the estimated value. Calibration accuracy is limited by the accuracy of the surface measurements.

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System Vicarious Calibration

By "system" I mean calibration of the sensor *and* the atmospheric correction algorithm.

$$\rho_t(\lambda) = \rho_r(\lambda) + \rho_A(\lambda) + t_v(\lambda)t_s(\lambda)[\rho_w(\lambda)]_N$$

Determine using in-situ measurements

1) Assume calibration in longest NIR band is correct (no error).

2) Adjust calibration in second longest NIR band so that the spectral variation of ρ_A is consistent with the aerosol type typical at the calibration site.

3) Apply atmospheric correction algorithm to ρ_t and adjust the calibration to force agreement with the measured values of $[\rho_w(\lambda)]_N$. (Note: ancillary data, etc., measured at cal. site.)

4) Can avoid 1) by applying radiometric vicarious calibration methods to longest NIR band.

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System calibration has several advantages:

1) The residual calibration errors will all be of the same sign.

2) The residual calibration errors will decrease from the NIR to the blue.

3) The NIR error can be reduced/quantified by radiometric vicarious calibration. Reducing this error will concomitantly reduce the residual error in all shorter wave bands.

4) Pragmatically, the sensor is being forced to do the job for which it was designed.