Vicarious Calibration of Ocean Colour Sensors

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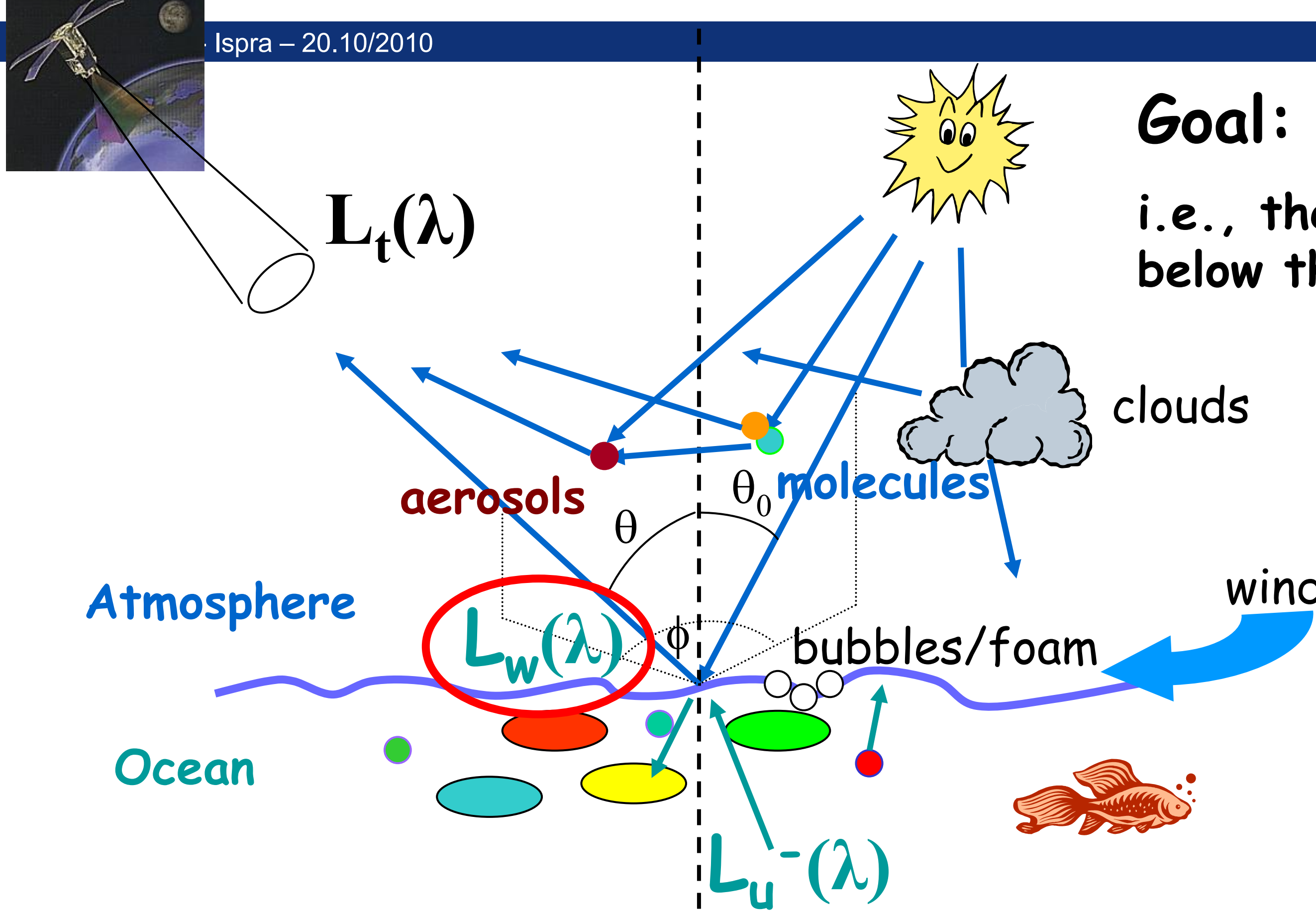
- Ocean Colour Radiometry
- Principles of Vicarious Calibration
- Data Sources for Vicarious Calibration
- Applications

Ocean Colour Radiometry

Goal: retrieve $L_w(\lambda)$ or $R_{rs}(\lambda)$,

i.e., the radiance emerging from below the sea surface

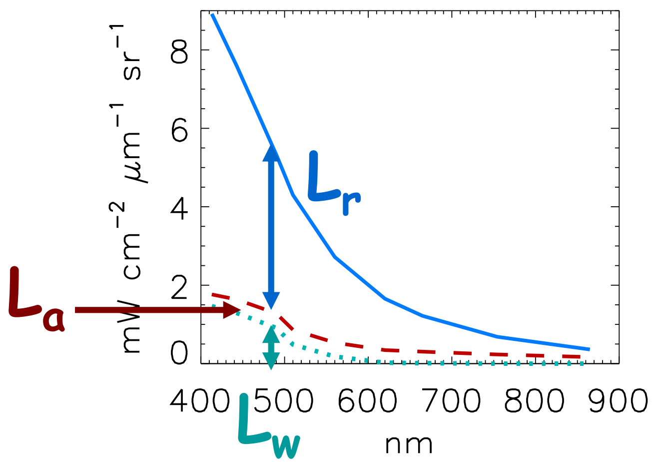


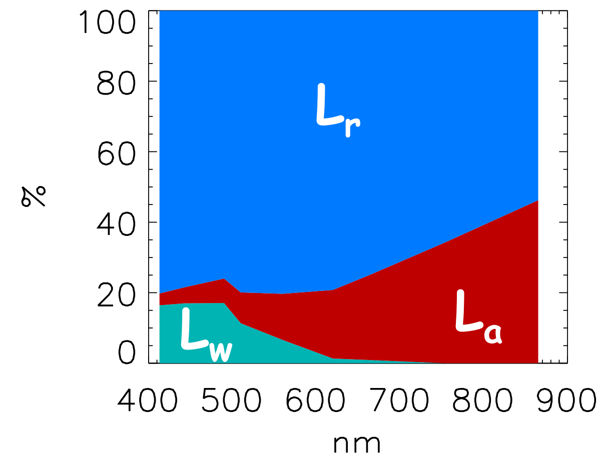
$$L_{toa}(\lambda) = L_{atm}(\lambda) + t_d(\lambda).L_w(\lambda) + t_d(\lambda).L_{wc}(\lambda) + t(\lambda).L_g(\lambda)$$

- $L_{atm}(\lambda)$ → Rayleigh (L_r) + aerosol (L_a)
- $L_w(\lambda)$ → water-leaving radiance
- $L_{wc}(\lambda)$ → modelled
- $L_g(\lambda)$ → masked or corrected

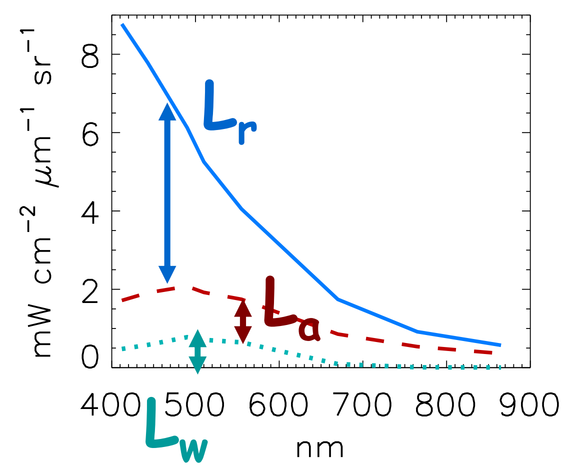
Ocean Colour Radiometry: Radiance Budget

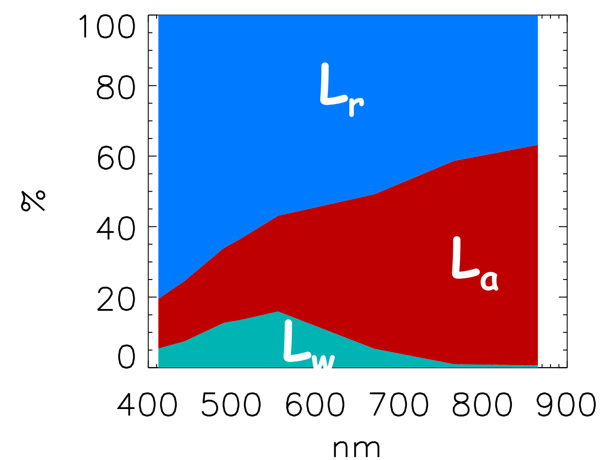
MERIS
MOBy
29/05/2002
Clear water
Clear marine atmosphere





SeaWiFS
AAOT
18/07/2002
Coastal waters
Continental air mass





Rule of thumb: L_w accounts for ~10% of L_t

Ocean Colour Radiometry: Requirements

Typical requirements for L_w retrieval: 5% (abs.)

e.g., McClain et al., 1992

Requirements for L_t uncertainty: 0.5%

To fulfill such stringent requirements:
a comprehensive cal/val strategy for the duration of the mission

- pre-launch calibration
  (that might be affected by transfer-to-orbit)
- on-board devices
- stability tracking (lunar measurements, solar diffusers,…)
- vicarious calibration
- …

Vicarious Calibration: One piece of the puzzle (1)

Vicarious calibration is one, albeit important, aspect to the total instrument calibration process – a process that begins with prelaunch characterization and is continued <u>throughout the life of the mission.</u>

… makes use of a single set of fractional gains, where unity indicates no correction.

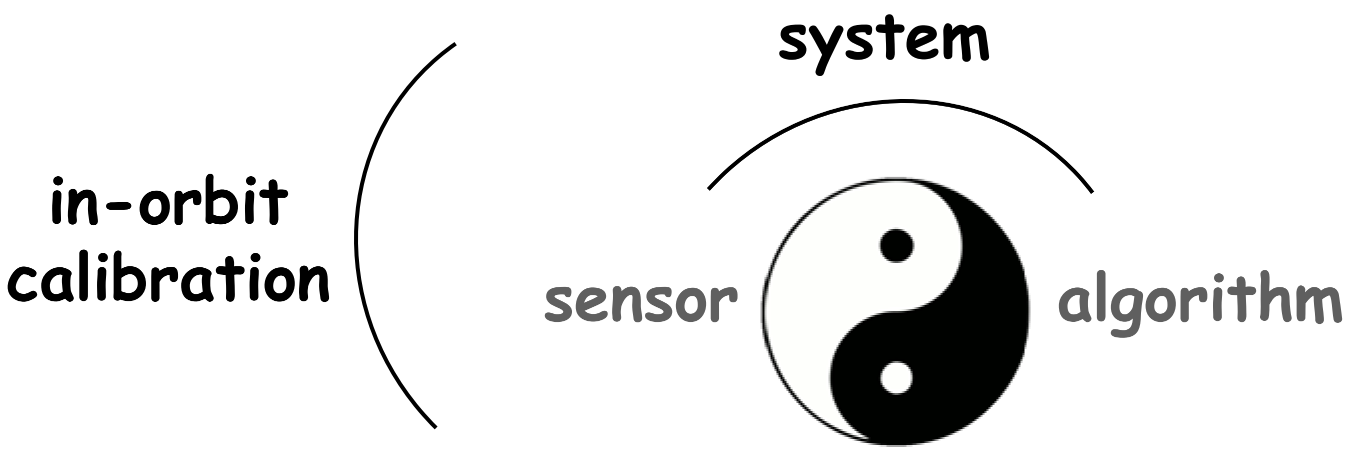
$$L_t(\lambda) = g(\lambda) \,.\, K(\lambda) \,.\, f(t\text{-}t_0,\lambda)\ [DC(\lambda)\text{-}DC_{dark}(\lambda)]$$

- $L_t(\lambda)$: TOA radiance
- $g(\lambda)$: vicarious gain
- $K(\lambda)$: counts-to-radiance conversion
- $f(t\text{-}t_0,\lambda)$: temporal dependence
- $DC(\lambda)$: digital counts
- $DC_{dark}(\lambda)$: dark counts

Vicarious Calibration: One piece of the puzzle (2)

… is derived by minimizing the difference between satellite L_w and ground-truth L_w (for the NIR, L_w is assumed to be zero)

… modifies the integrated instrument-atmospheric correction system. It effectively accounts for undetermined post-launch instrument changes and atmospheric correction biases, assuming that temporal trends are independently removed.



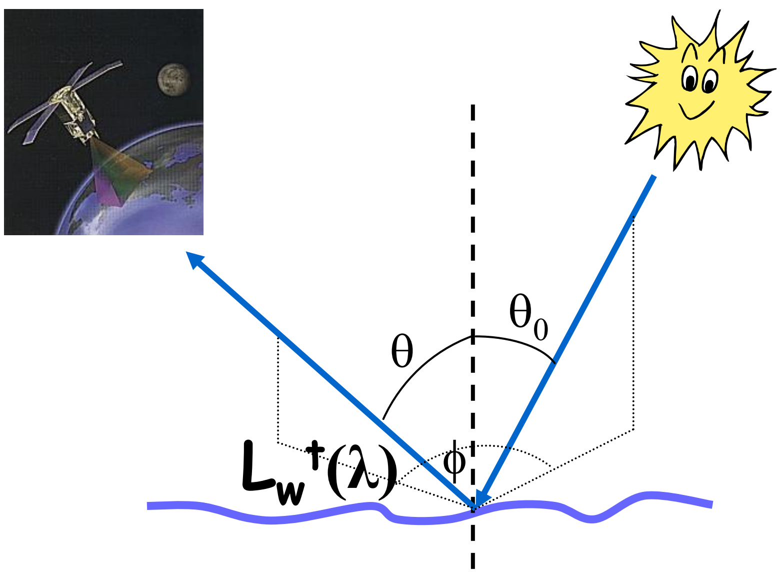
Vicarious Calibration in Practice

$$L_t(\lambda) = L_{atm}(\lambda) + t_d(\lambda)\, L_w(\lambda)$$

Target: $$L_t^t(\lambda) = L_{atm}(\lambda) + t_d(\lambda)\, L_w^t(\lambda)$$

$$g(\lambda) = L_t^t(\lambda) \,/\, L_t(\lambda)$$

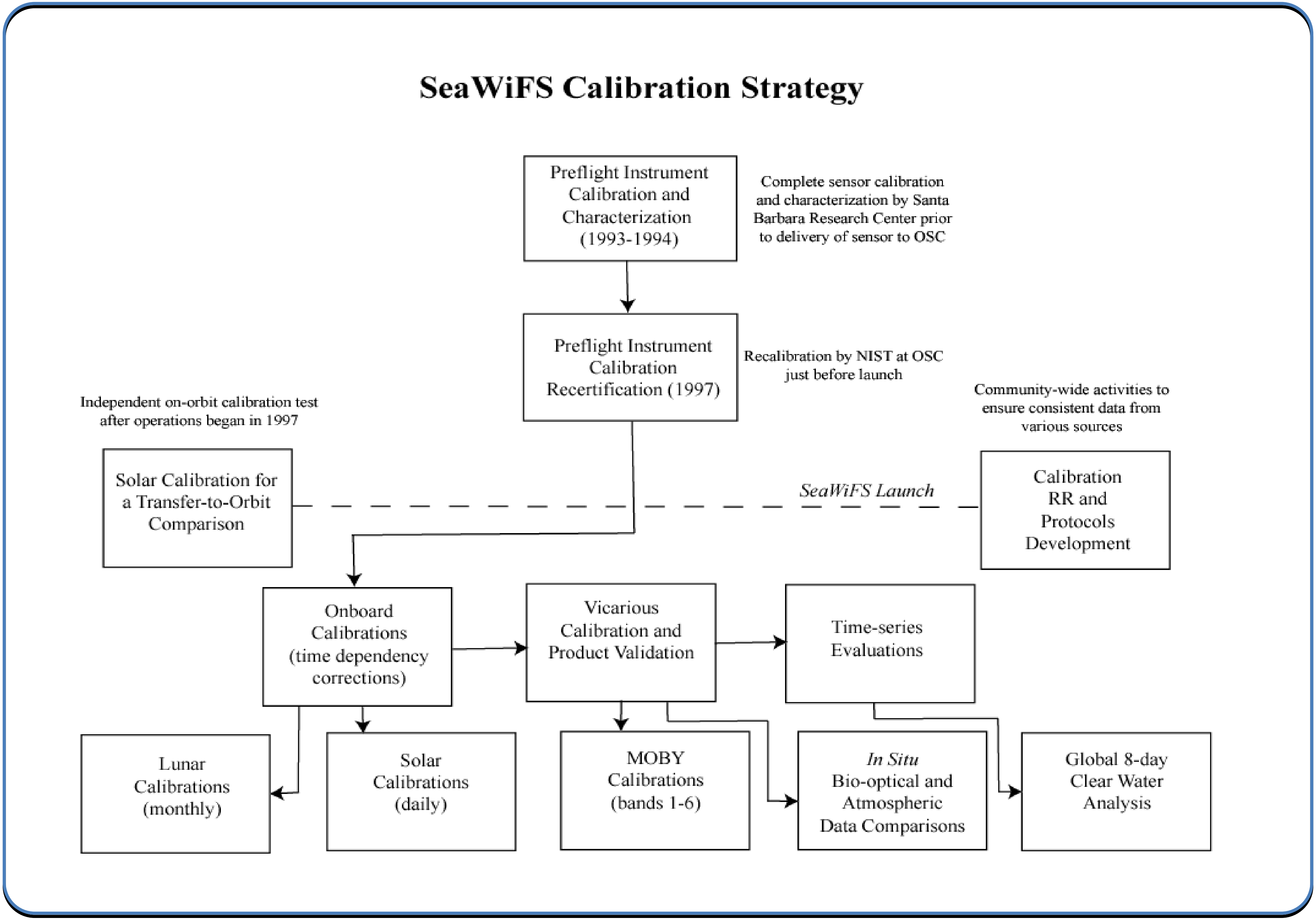
surface measurements



actual field measurements

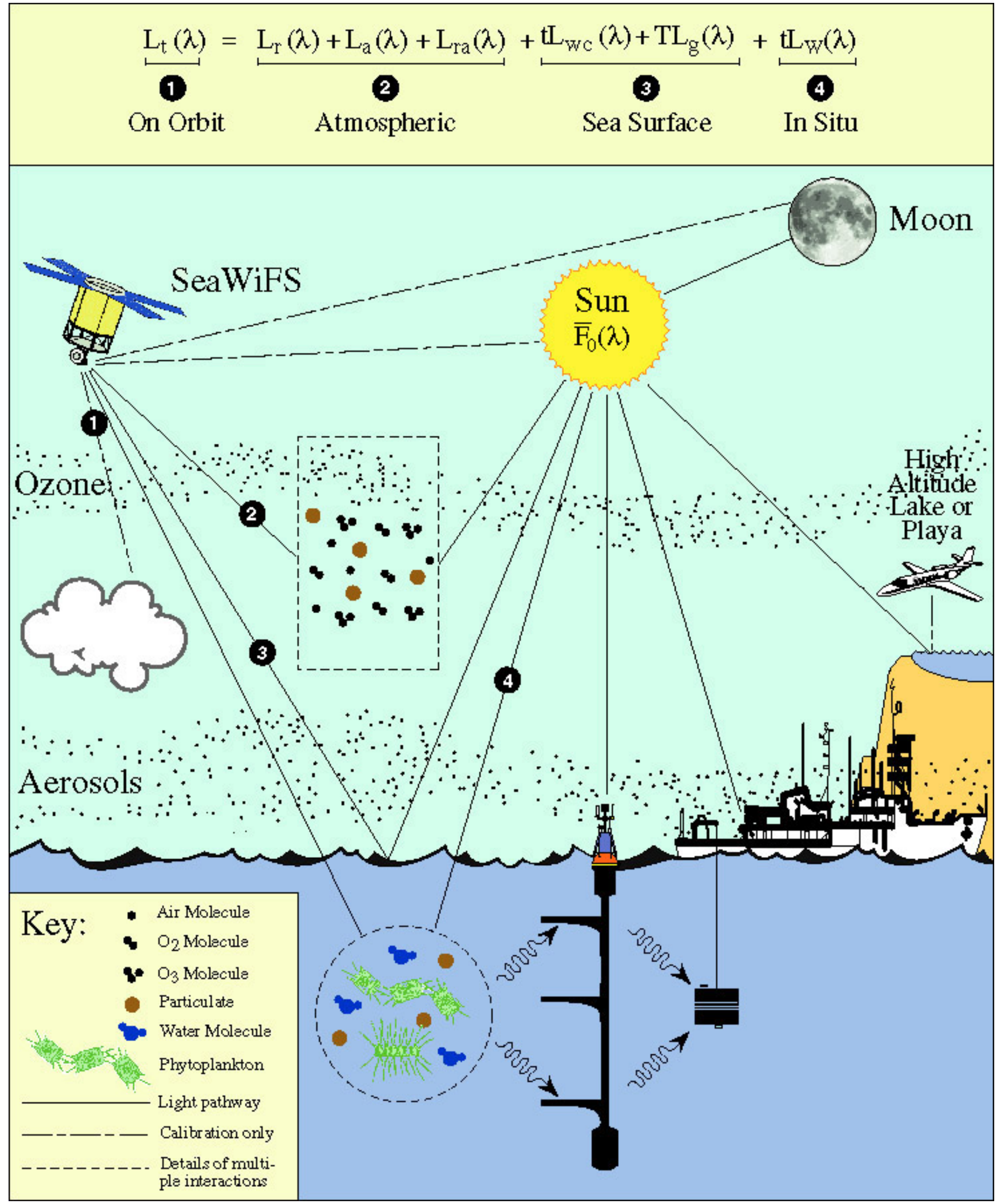
$$L_w^t(\lambda,\theta,\theta_0) \Leftarrow L_w(\lambda',\theta',\theta'_0)$$

accounting for spectral characteristics and bidirectional effects


SeaWiFS Calibration Strategy
Preflight Instrument Calibration and Characterization (1993-1994)
Complete sensor calibration and characterization by Santa Barbara Research Center prior to delivery of sensor to OSC
Preflight Instrument Calibration Recertification (1997)
Recalibration by NIST at OSC just before launch
Independent on-orbit calibration test after operations began in 1997
Community-wide activities to ensure consistent data from various sources
Solar Calibration for a Transfer-to-Orbit Comparison
SeaWiFS Launch
Calibration RR and Protocols Development
Onboard Calibrations (time dependency corrections)
Vicarious Calibration and Product Validation
Time-series Evaluations
Lunar Calibrations (monthly)
Solar Calibrations (daily)
MOBY Calibrations (bands 1-6)
In Situ Bio-optical and Atmospheric Data Comparisons
Global 8-day Clear Water Analysis

Satellite Calibration Elements:

- **Laboratory** - before launch, sensor is calibrated in lab
- **On-orbit** - daily solar and monthly lunar observations are used to track changes in sensor response
- **Vicarious** - comparison of data retrievals to in-water, ship, and airborne sensors is used to adjust instrument gains



Data Sources for Vicarious Calibration

Original (SeaWiFS pre-launch) ideal requirements on sea-truth data for vicarious calibration activities

(1) clear maritime atmosphere
(2) clear-water site
(3) horizontally homogeneous water mass
(4) hyperspectral instrumentation
(5) extraordinary calibration
(6) daily-to-weekly monitoring of derived L_{wn}
(7) avoidance of platform perturbation
(8) cloud-free site
(9) coincident aerosol measurements
(10) atmosphere free of terrestrial influence
(11) free from biofouling

A Virtual Laboratory for Calibration

Table from Bailey et al., *AO*, 2008

This resulted in the Marine Optical Buoy (MOBy) taking a major role in vicarious calibration activities

Alternatives Choices for Data Sources

<u>**Alternatives have provided satisfactory results:**</u>

- data sets derived from commercial, off-the-shelf instrumentation (globally-distributed data, BOUSSOLE) — Bailey et al., *AO*, 2008
- ocean reflectance model — Werdell et al., *AO*, 2007
- coastal sites (above-water radiometry) — Mélin & Zibordi, *AO*, 2010

Match-up Selection Protocol

Whichever site is selected, the match-up selection protocol is more restrictive than for validation purposes.

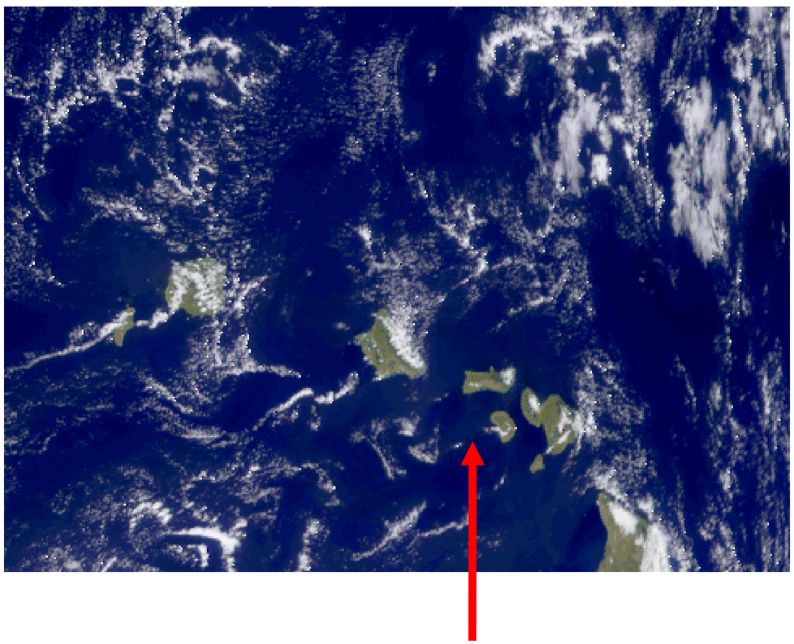
- Square of NxN pixels
- Set of excluding flags (clouds, glint, …)
- Maximum time difference (e.g., 1-h)
- Maximum viewing and solar zenith angles (e.g., 56° and 70°)
- Maximum τ_a
- Maximum Chl*a*
- Maximum wind speed
- Homogeneity of L_w and τ_a

…

Vicarious Calibration: Examples (1)

Ocean Biology Processing Group (OBPG) - NASA

SeaWiFS **MODIS** **OCTS / POLDER**



MOBy
(Hawaii)

Table 1. Derived Vicarious Gain Coefficients for OCTS and POLDER Spectral

Wavelength (nm)	Gain Coefficient $G^{(VC)}(\lambda)$ OCTS	Gain Coefficient $G^{(VC)}(\lambda)$ POLDER
412	1.12426	—
443	1.01539	1.06465
490	0.95084	1.02350
520	1.01784	–
565	1.03255	0.97541
670	1.00859	1.01845
765	0.92093	1.02946
865	1.00000	1.00000

Wang et al., *AO*, 2002

Vicarious Calibration: Examples (2)

Vicarious calibration coefficients

Vicarious calibration for POLDER ocean color bands using spatially-distributed field measurements

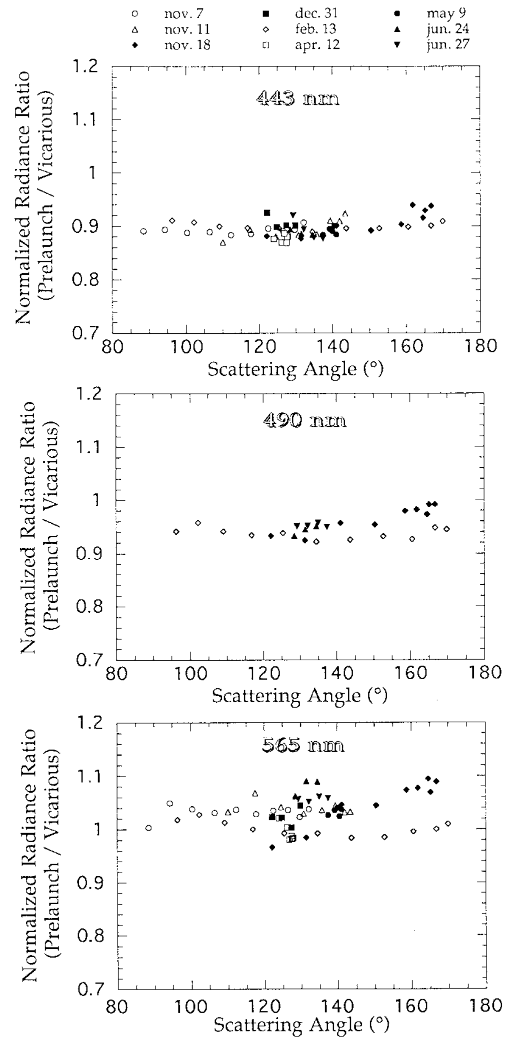


Fig. 5. Ratio of prelaunch- and postlaunch-calibrated (this study) POLDER normalized radiances $A_k(\lambda)$ as a function of scattering angle for the spectral bands centered at 443, 490, and 565 nm, and for the whole matchup data set.

Fougnie et al., *IEEE*, 1999

Vicarious Calibration: Examples (3)

Vicarious calibration
for GLI (ADEOS-2)
using MOBy (7 days)
or land target, or SeaWiFS

Vicarious calibration coefficients

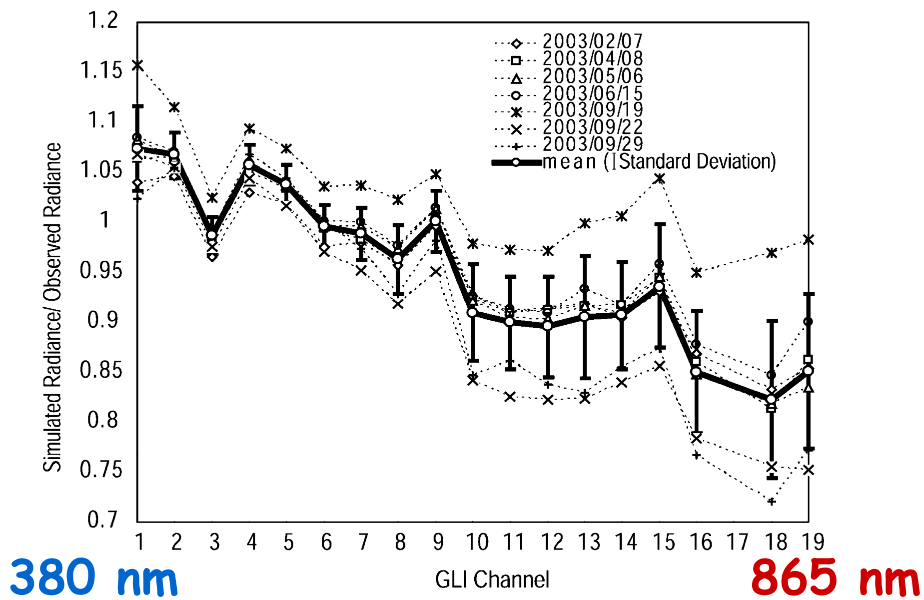


Fig. 2. Vicarious calibration coefficient for each channel except for channel 17. The dotted lines show the coefficients for the seven days in Table II. The solid line shows (open circle) the mean and (error bar) the standard deviation of the seven coefficients.

Yoshida et al., *IEEE*, 2005
Murakami et al., *IEEE*, 2005

Inter-Sensor Calibration

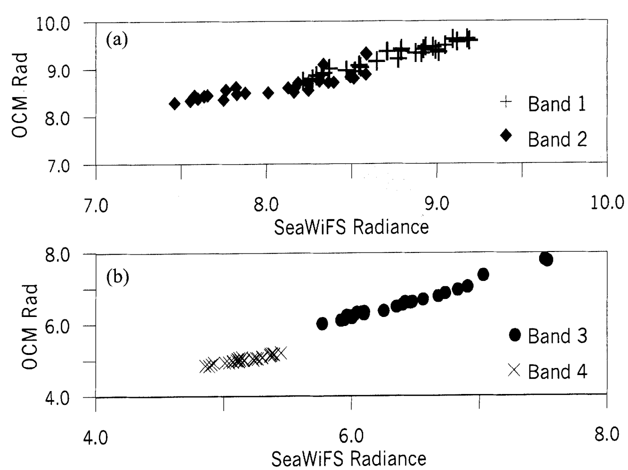
Target: $L_t^t(\lambda) = L_{atm}(\lambda) + t_d(\lambda)\, L_w^t(\lambda)$ ← reference satellite

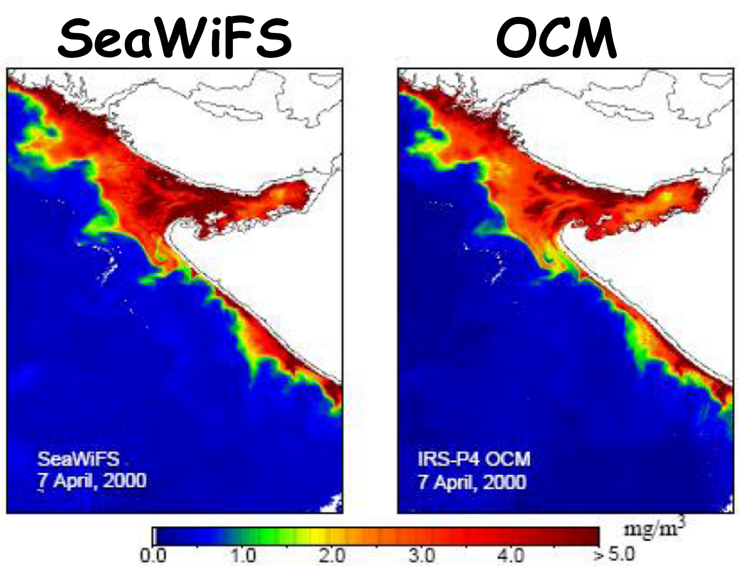
MOS wrt SeaWiFS — Wang & Franz, *AO*, 2000

COCTS (HY-1A) wrt SeaWiFS — Pan et al., *CSB*, 2004

OCM (IRS-P4) wrt SeaWiFS

Chauhan et al., *IEEE*, 2003





Suresh et al., *SPIE*, 2006

Atmospheric Correction

Main principles of 'standard' atmospheric correction"

$$L_t(\lambda_{nir1}) = L_r(\lambda_{nir1}) + L_a(\lambda_{nir1}) + t_d(\lambda_{nir1})\, \cancel{L_w(\lambda_{nir1})}$$

$$L_t(\lambda_{nir2}) = L_r(\lambda_{nir2}) + L_a(\lambda_{nir2}) + t_d(\lambda_{nir2})\, \cancel{L_w(\lambda_{nir2})}$$

black pixel

$$\Rightarrow \frac{L_a(\lambda_{nir1})}{L_a(\lambda_{nir2})}$$

↓ aerosol model

$$L_t(\lambda_{vis}) = L_r(\lambda_{vis}) + L_a(\lambda_{vis}) + t_d(\lambda_{vis})\, L_w(\lambda_{vis})$$

Conditions of non-negligible L_w in the NIR are handled with an iterative process.

NASA-OBPG Vicarious Calibration

Derives adjustment factors, one per sensor band, to minimize mean bias between in situ calibration source and satellite $R_{rs}(\lambda)$ retrievals.

- system calibration
  - compensates for error in both instrument calibration and retrieval algorithm
- two step process:
  - calibrate NIR bands to improve aerosol retrieval
  - calibrate visible using calibrated aerosol retrieval and in situ radiometry
- calibration site considerations
  - prefer clear water location to minimize heterogeneity and R_{rs} (NIR)
  - prefer stable (known) aerosol type

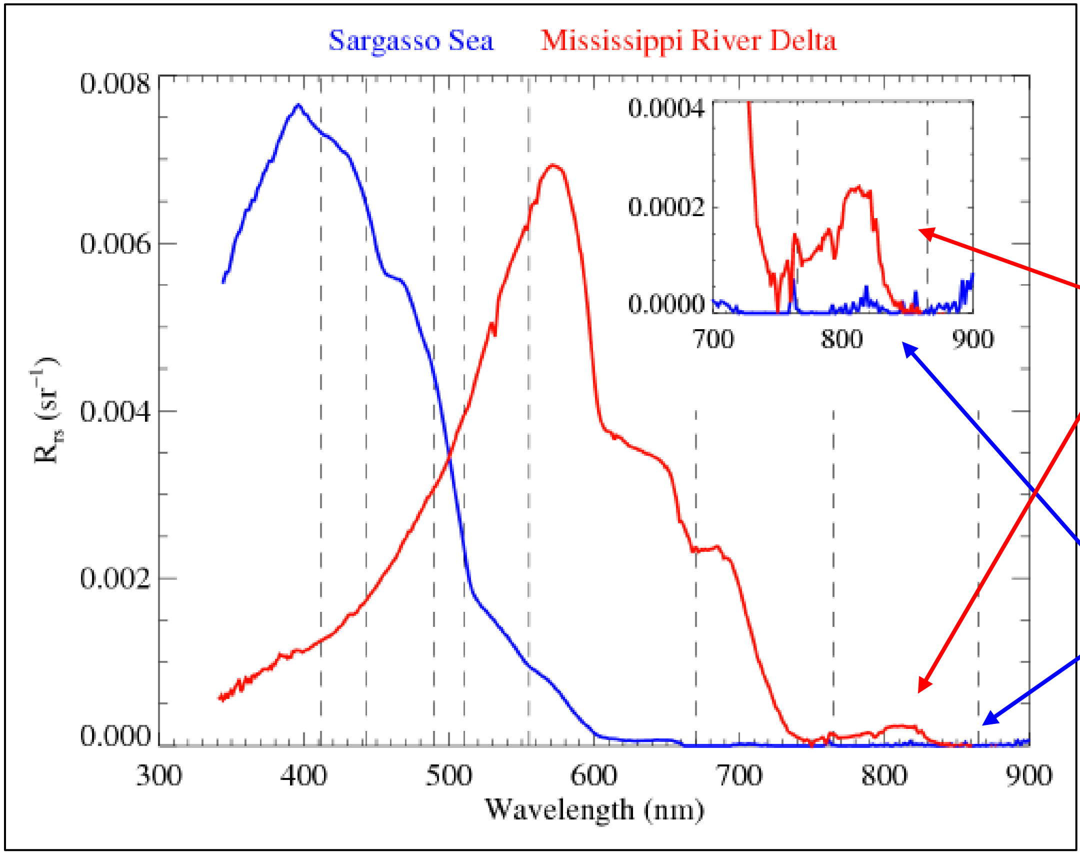
OBPG Vicarious Calibration: NIR Bands (1)

- At 865 nm (SeaWiFS): no vicarious calibration; measurements are used to provide aerosol amounts in the atmospheric correction algorithm based on the assumption that the water-leaving radiance component is negligible and can be ignored in the NIR
- This is a valid assumption in clear, open ocean waters
- The shorter NIR band (765 nm for SeaWiFS) is adjusted relative to the 865-nm band by fixing the aerosol model in the atmospheric correction process
  - This requires the additional assumption that the aerosol type is known
  - A maritime model is chosen based on measurements from the AERONET sunphotometer stationed at Tahiti.

OBPG Vicarious Calibration: NIR Bands (2)

$R_{rs}(\lambda)$ is small in NIR (λ > 700nm)

… but not necessarily insignificant



L_w(NIR) ≠ 0

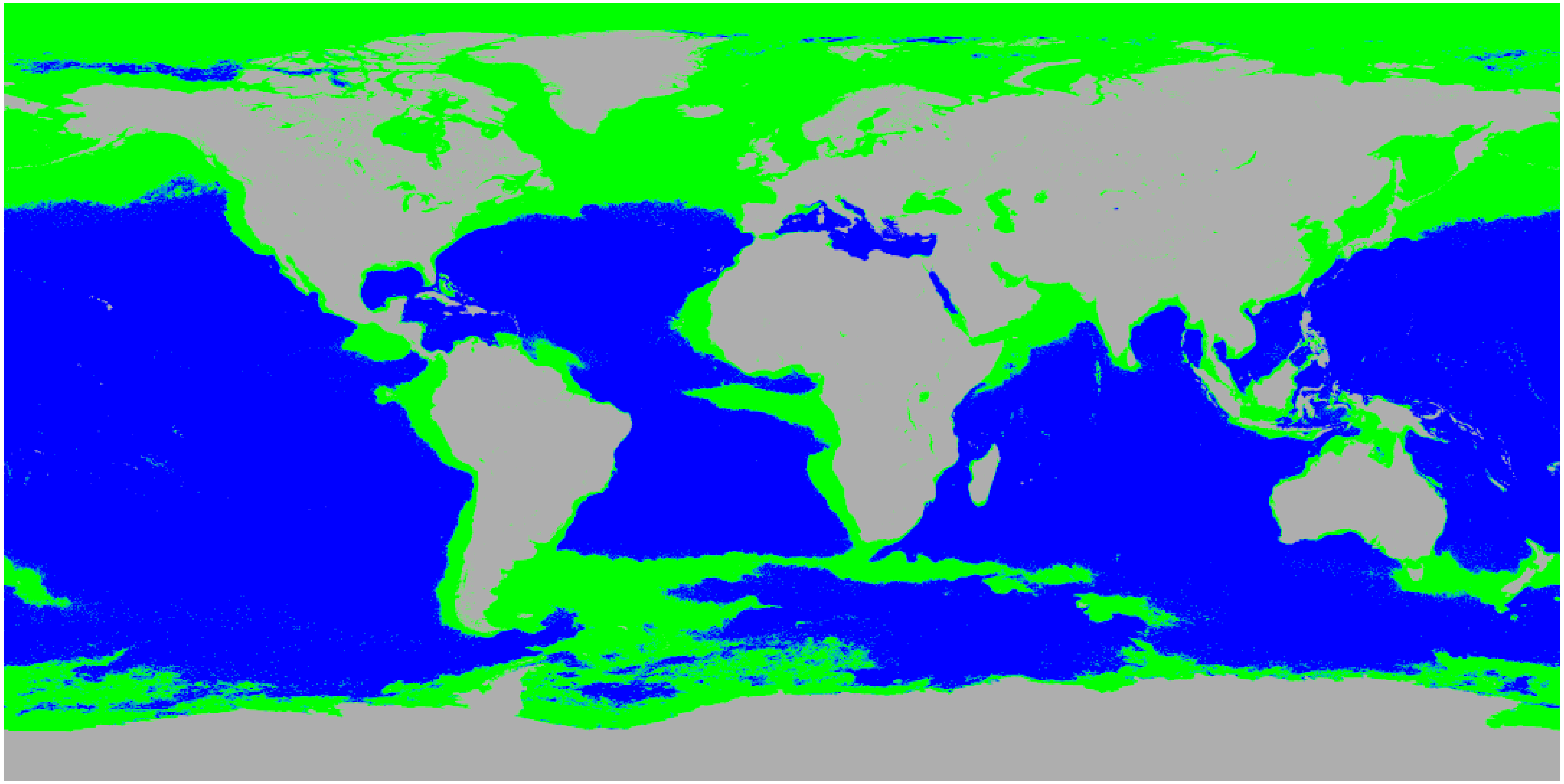
(turbid / highly productive water)

L_w(NIR) = 0 (clear water)

To reduce uncertainties in the aerosol model selection process for vicarious calibration targets, it is best to avoid vicarious calibration in turbid/productive waters

OBPG Vicarious Calibration: NIR Bands (3)

$R_{rs}(\lambda)$ is small in NIR (λ > 700 nm)



Green is where the NIR correction is likely to be applied

(Chl > 0.3 mg m^{-3})

OBPG Vicarious Calibration: Visible Bands

Once the NIR calibration is fixed, the VIS bands are adjusted using a consistent, well calibrated / characterized in situ source

For SeaWiFS and the MODIS instruments this source has been the Marine Optical Buoy (MOBY)

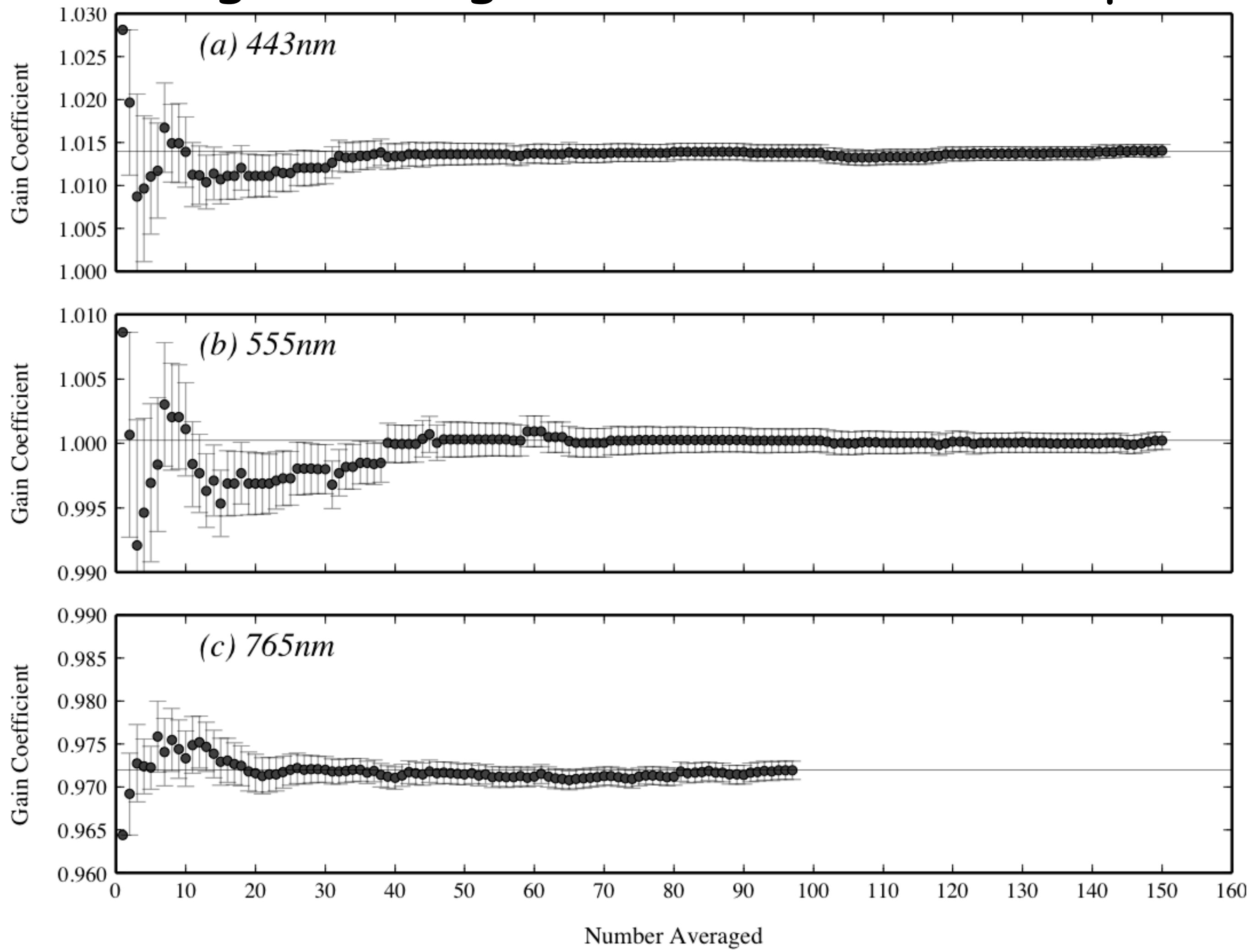
Gain calculation:

$$g_i(\lambda) = \frac{L_t^{predicted}}{L_t^{observed}} \qquad g(\lambda) = \frac{1}{n}\sum_{i=1}^{n} g_i(\lambda)$$

in practice: using robust mean of semi-interquartile

SeaWiFS Vicarious Gains

Convergence of g's calculation with sample size



Franz et al., *AO*, 2007

It takes time to gather a sufficient number of samples to reach a stable vicarious calibration

Vicarious Calibration with ORM (1)

OCEAN SURFACE REFLECTANCE MODEL

$$R(0^-) = f'(C_a)\frac{b_b(C_a)}{a(C_a)+b_b(C_a)}$$

$$L_{wn} = \Re\, F_0 \frac{R(0^-)}{Q(C_a)}$$

b_b, a, f', and Q estimated using C_a

R and F_o are constants

in Case-1 water, plausible estimates of L_{wn} can be derived from C_a using an ocean surface reflectance model

Morel and Maritorena (2001)

Morel, Antoine, and Gentili (2002)

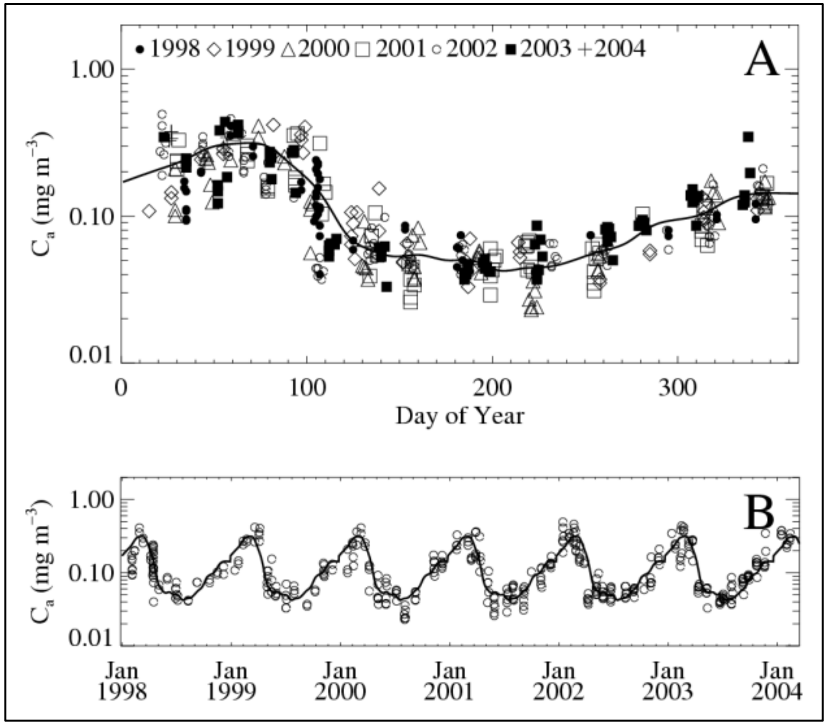
Ciotti, Cullen, and Lewis (1999)

Werdell et al., *AO*, 2007

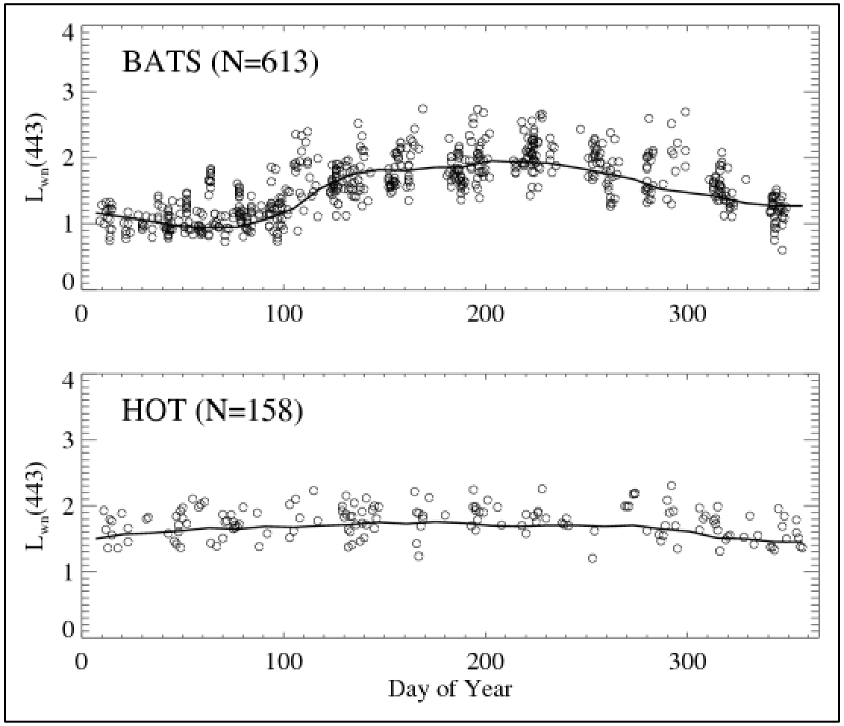
Vicarious Calibration with ORM (2)

general C_a expressions developed for BATS and HOT

here is the expression for BATS fluorometric C_a:



verified the "ORM-C_a model" combination through comparisons with in situ L_{wn}



Werdell et al., *AO*, 2007

Vicarious Calibration with ORM (3)

- using the C_a expressions as input into an ORM, we can estimate L_{wn} for every day of the year at both BATS and HOT
- these L_{wn} are then input into the vicarious calibration system

Vicarious Calibration with ORM (4)

Table 3. Percent differences[a] between the MOBY and ORM $\bar{g}$.

	412	443	490	510	555	670
BATS	-0.31	-1.18	-1.14	-0.52	0.14	-0.07
HOTS	-0.74	-0.53	-0.48	-0.14	0.44	-0.21
BATS + HOTS	-0.52	-0.86	-0.81	-0.33	0.29	-0.13

[a] Calculated via $(\bar{g}_{ORM} - \bar{g}_{MOBY}) * 100\% / \bar{g}_{MOBY}$.

Table 4. Percent differences[a] between the HOT and BATS ORM $\bar{g}$.

412	443	490	510	555	670
-0.44	0.66	0.66	0.38	0.30	-0.13

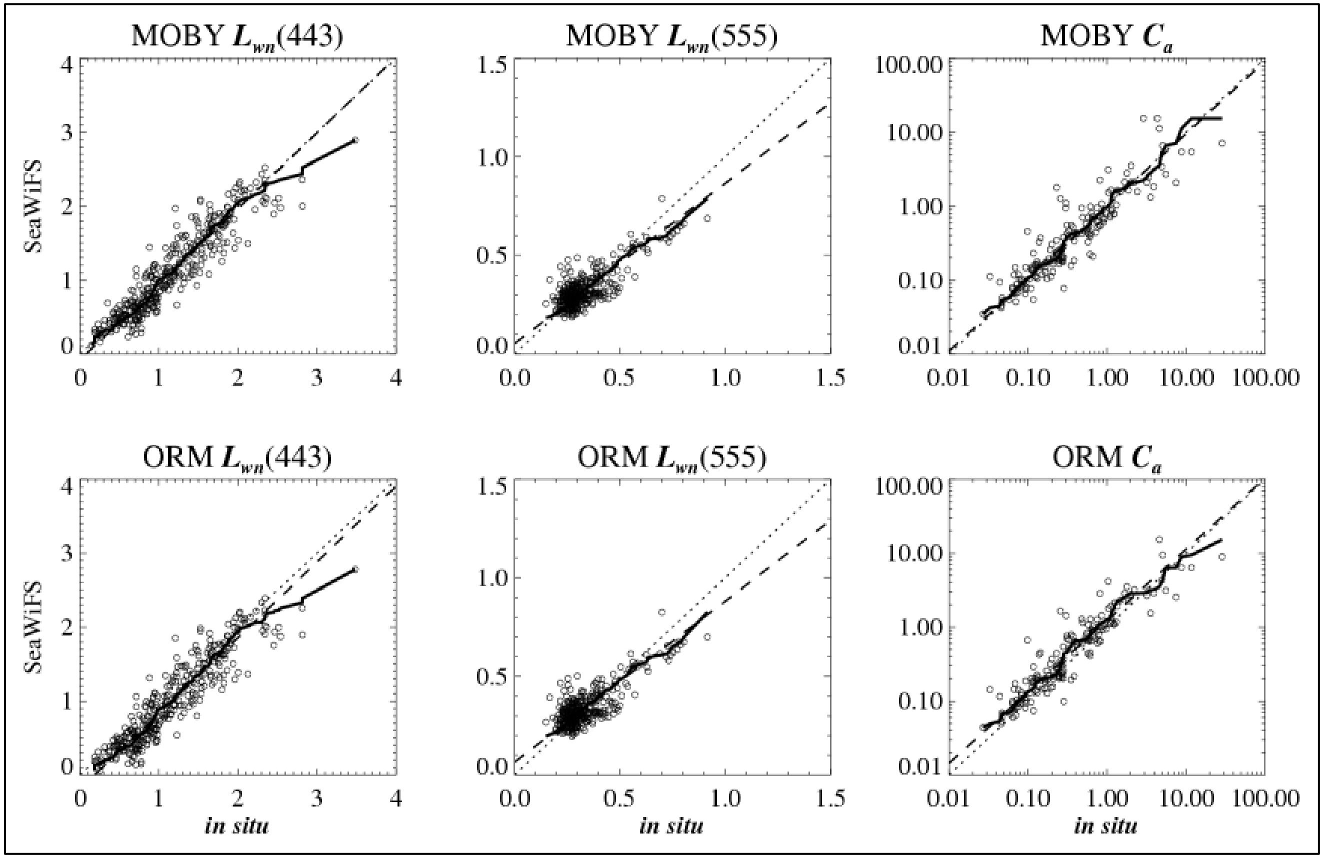
[a] Calculated via $(\bar{g}_{HOT} - \bar{g}_{BATS}) * 100\% / \bar{g}_{BATS}$.

Werdell et al., *AO*, 2007

Vicarious Calibration with ORM (5)

MOBy g's

ORM g's



not obvious in the validation scatter plots, but …

changes in L_{wn}(443) of -7% and L_{wn}(555) of +4% create changes in C_a of +30%

Werdell et al., *AO*, 2007

A Case Study: Regional Vicarious Calibration

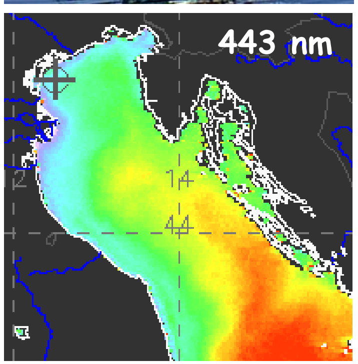
Vicarious calibration corrects for a systematic bias
Remaining bias in some coastal regions

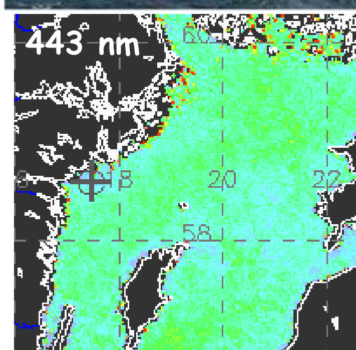
→ **Regionally-specific vicarious calibration** Franz et al., *AO*, 2007

AERONET-OC sites:
Availability of $L_w(\lambda)$,
$\tau_a(\lambda)$, aerosol optical properties

Acqua Alta
Oceanographic Tower

Gustav Dalen
Lighthouse Tower



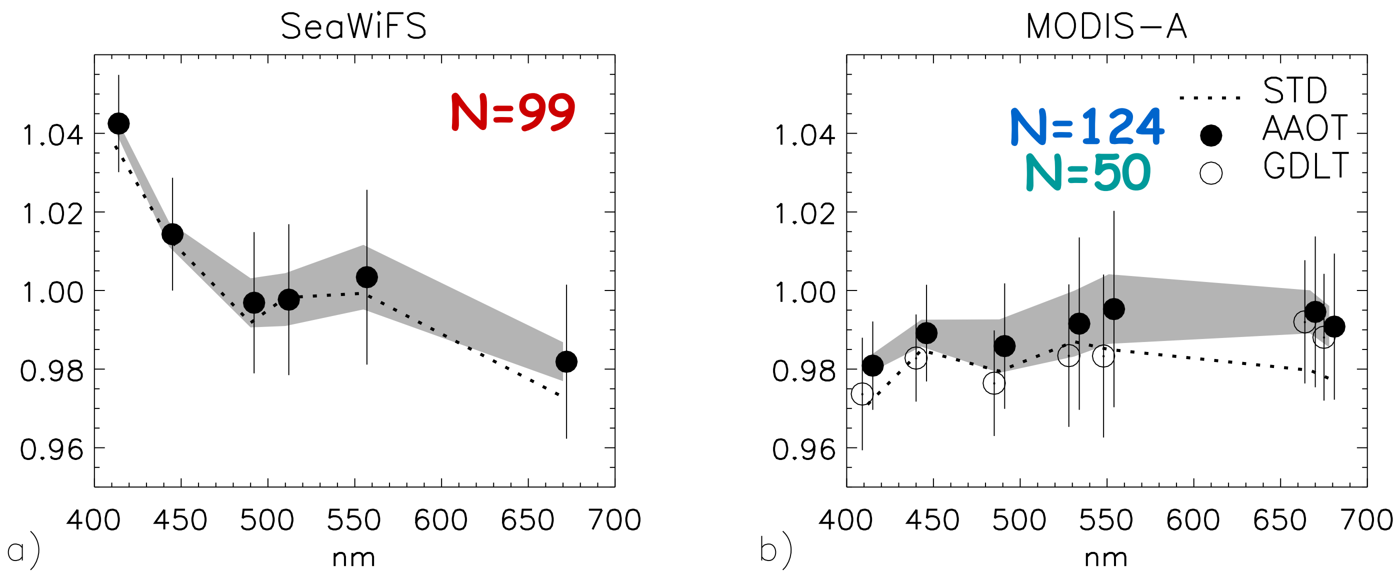


Zibordi et al., *JAOT*, 2009

Regional Vicarious Calibration (1)

Target: $L_w(\lambda)$ in the VIS only, keeping NIR coef. as standard

Vicarious Calibration Coefficients



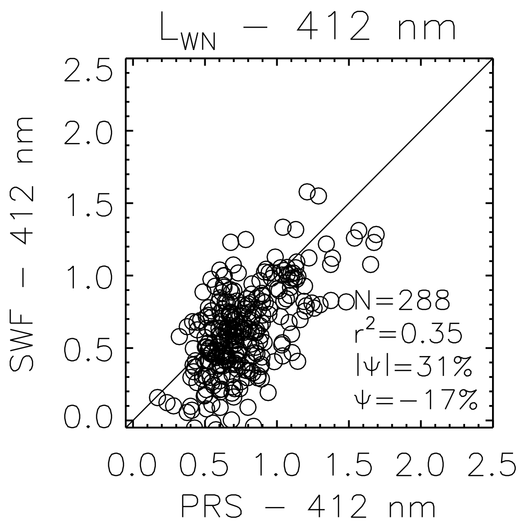
Mélin & Zibordi, *AO*, 2010

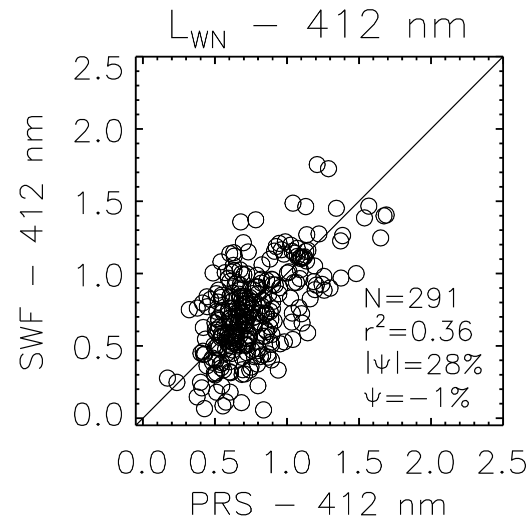
Regional Vicarious Calibration (2)

Validation Statistics

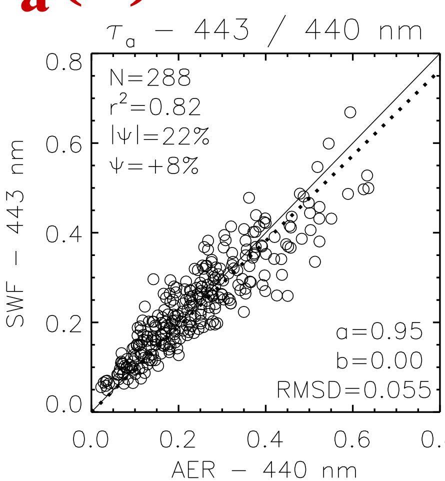
STD → **AAOT-VIS**

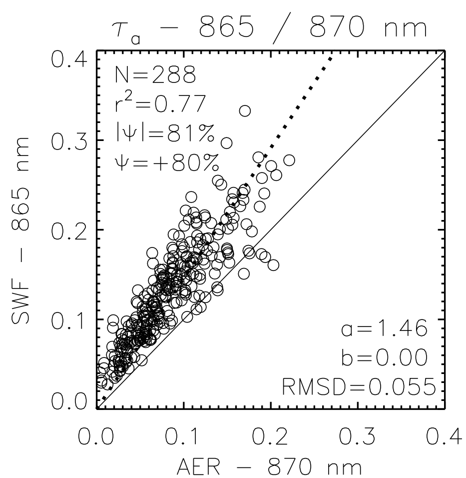
$L_{wn}(\lambda)$

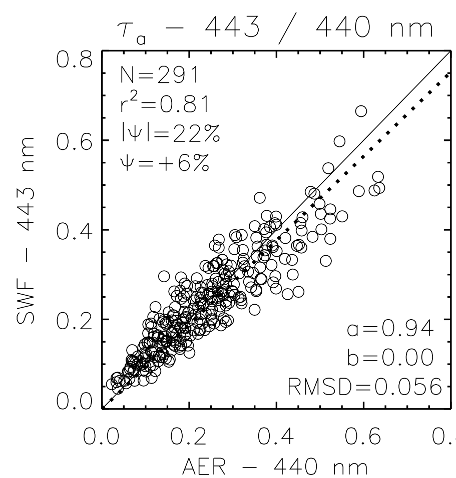


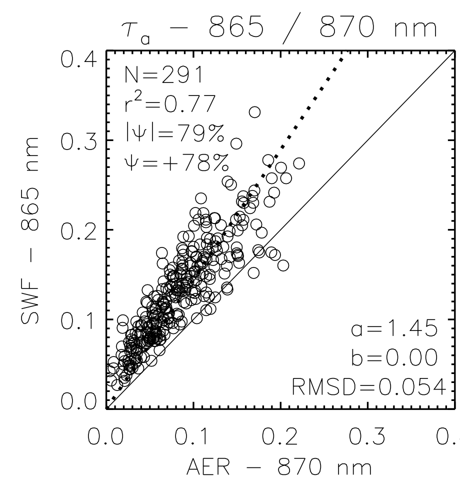


$\tau_a(\lambda)$







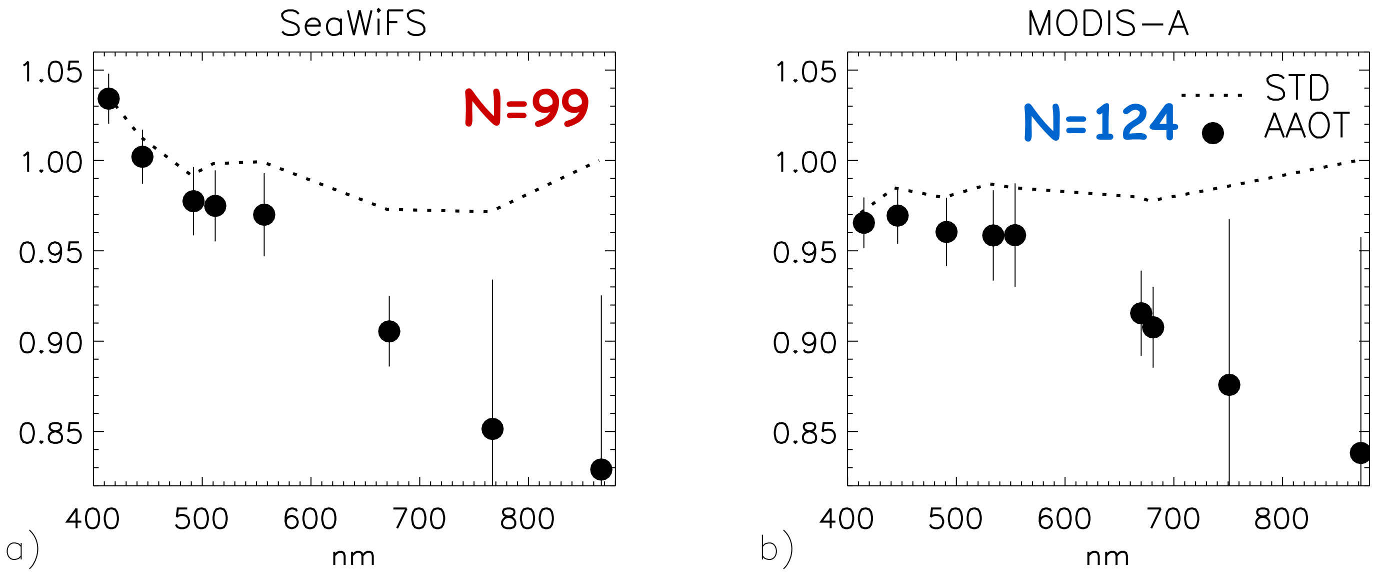


Mélin et al., *RSE*, 2007

Regional Vicarious Calibration (3)

Target: $L_w(\lambda)$ in the <u>VIS</u> & $\tau_a(\lambda)$ in the <u>NIR</u>

Vicarious Calibration Coefficients



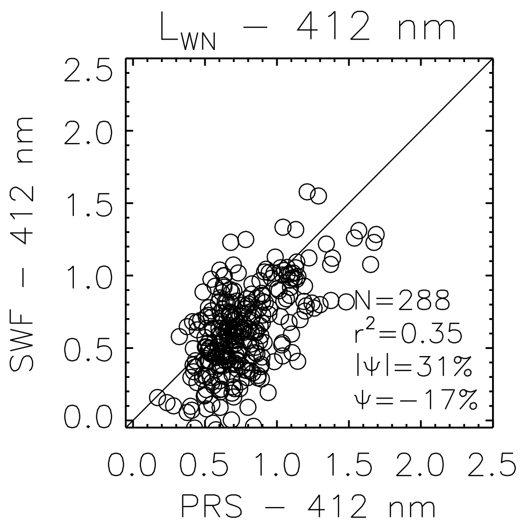
Mélin & Zibordi, *AO*, 2010

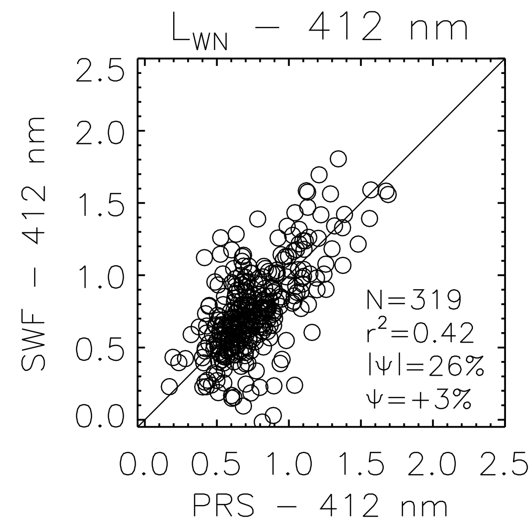
Regional Vicarious Calibration (4)

Validation Statistics

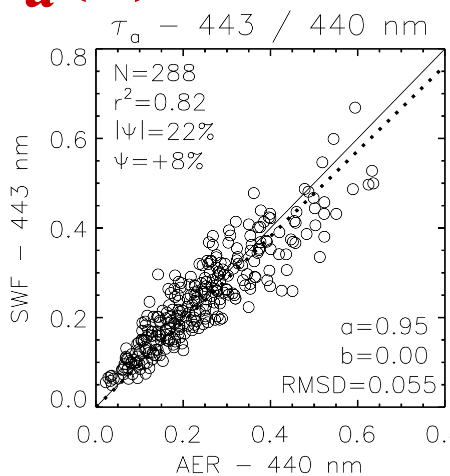
STD → **AAOT-VIS/NIR**

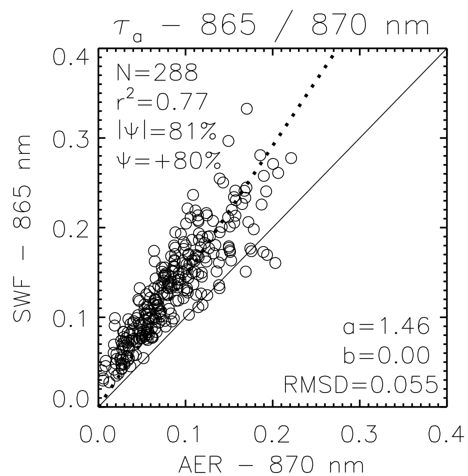
$L_{wn}(\lambda)$

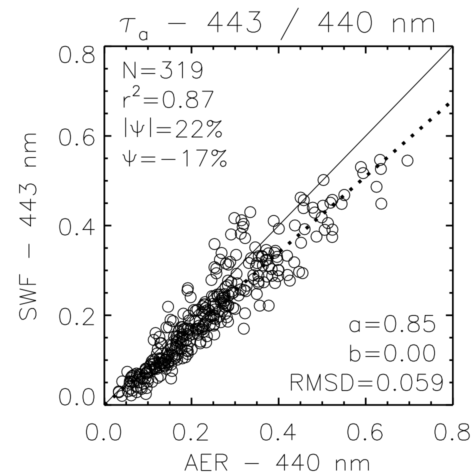


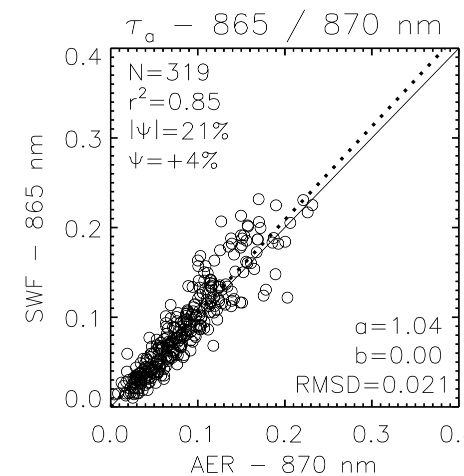


$\tau_a(\lambda)$









Regional Vicarious Calibration (5)

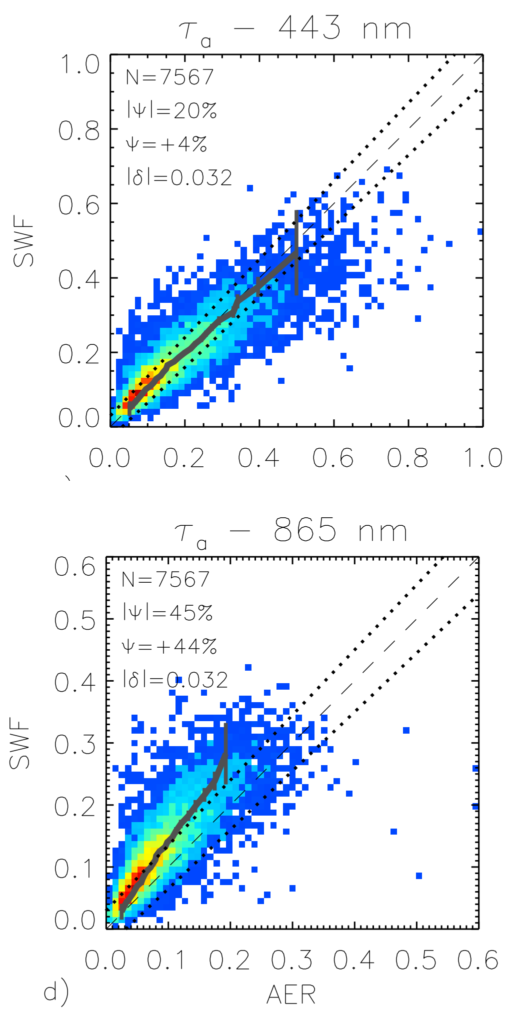
Lessons:

- Derived consistent VC coef. at 2 different coastal sites
- Successfully targeted both $L_w(\lambda)$ and $\tau_a(\lambda)$, but obtaining large VC corrections ([0.85,0.83] in the NIR!)
- Underlined deficiencies in the aerosol models of the atmospheric correction

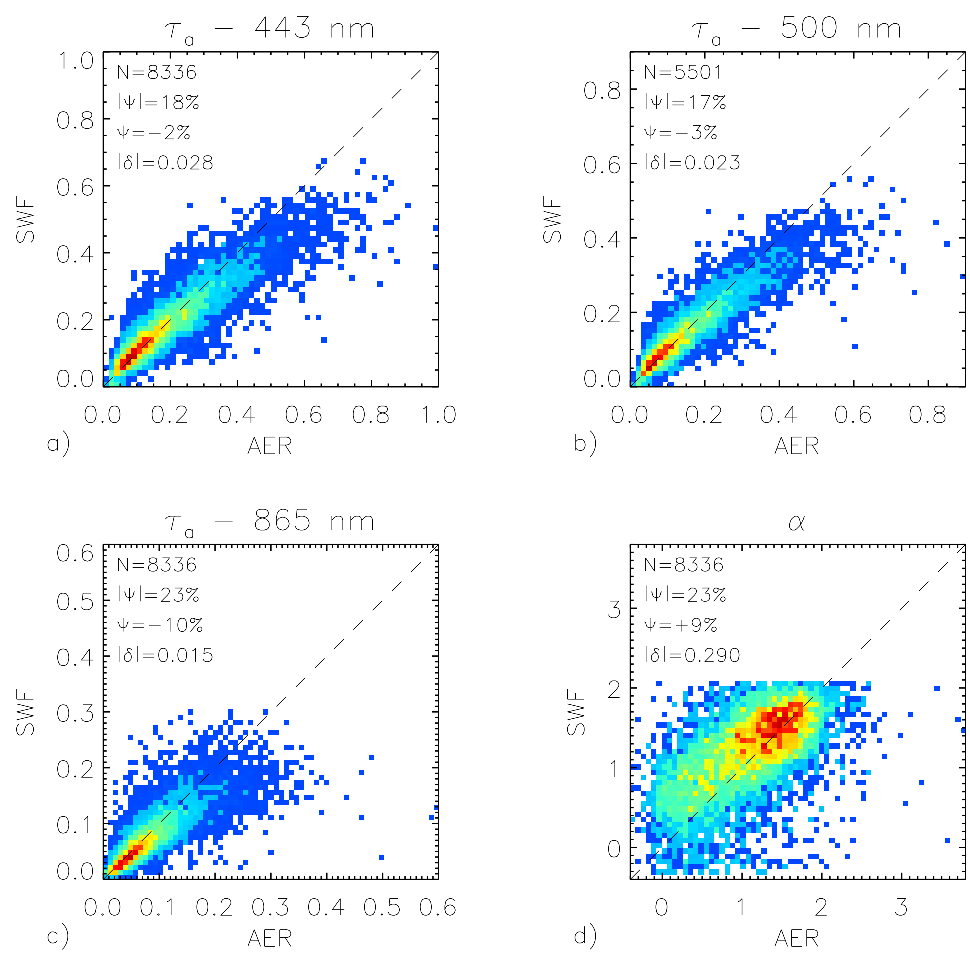
Regional Vicarious Calibration (6)

Recent updates in the atmospheric correction

Ahmad et al., *AO*, 2010, Bailey et al., *OE*, 2010



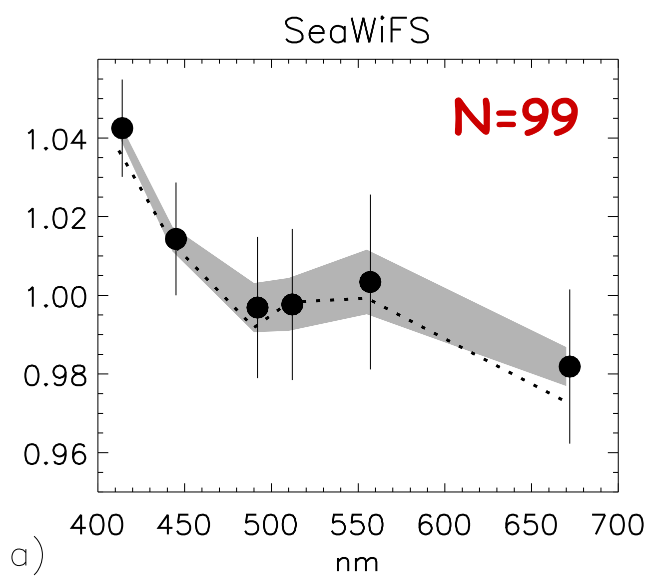
after update

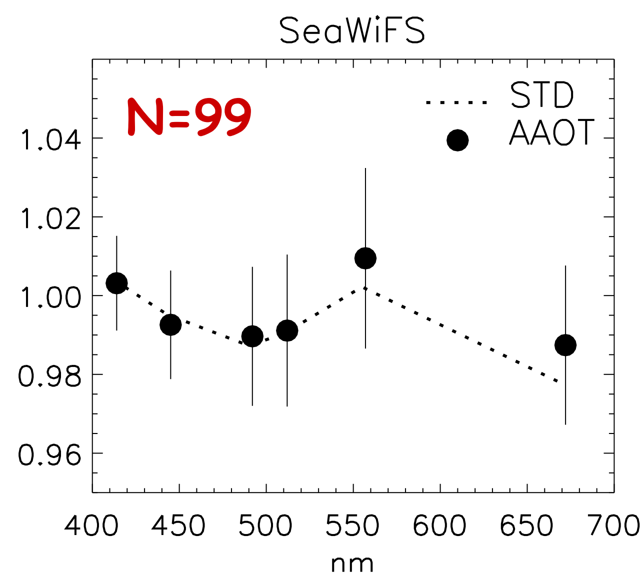


Mélin et al., *RSE*, 2010

Regional Vicarious Calibration (7)

new atmospheric correction





Differences (%) between standard and regional coef.

λ	412	443	490	510	555	670 nm	
	0.548	0.112	0.512	-0.052	0.409	0.919	%
NEW:	-0.096	-0.263	0.239	0.083	0.723	0.990	%

The convergence of g's is a measure of the improvements in the atmospheric correction

CONCLUSIONS

Calibration of the system [sensor+algorithms]

One element in the overall calibration strategy

Effectively removes the bias in L_w (or R_{rs})

Need for high-quality radiometric field measurements

Stringent requirements applied for the choice of the VC site(s)

Alternative approaches are good tests for the atmospheric correction