NASA's operational approach for the vicarious calibration of on-orbit ocean color satellites (using Gordon and Wang 1994)

Bryan Franz, Sean Bailey, the OBPG, and Jeremy Werdell

MODIS Science Team Meeting, 1 Nov 2006

The vicarious calibration …

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

$L_t = counts * K_{rad} * K_{time} * K_{x,y,z} \ldots * g$

(minimize difference between satellite L_w and ground-truth L_w)

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… was updated for SeaWiFS Reprocessing 4 (July 2002)

$$L_t = L_{r,g,wc,\ldots} + L_a + t_d L_w$$

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pre-Reprocessing 4 (launch – July 2002)

gain calculated using L_w

$g = L_w^{target} / L_w$

assign g and iterate until mean radiance ratio reaches unity

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<u>pre-Reprocessing 4 (launch – July 2002)</u>

gain calculated using L_w

$g = L_w^{target} / L_w$

assign g and iterate until mean radiance ratio reaches unity

<u>post-Reprocessing 4 (July 2002 – present)</u>

gain calculated at L_t

$g = L_t^{target} / L_t$

satellite atmospheric parameters used to propagate L_w^{target} to TOA

* no iteration (less computationally expensive)

* permits exploration of gain offset

* requires disabling correction for non-negligible L_w(NIR)

methods agree to within 0.04%

$$L_t = L_{r,g,wc,\ldots} + L_a + t_d L_w$$

$$L_t^{target} = L_{r,g,wc,\ldots} + \underline{L_a} + t_d L_w^{target}$$

all terms are computed for the full relative spectral response of each sensor band

post-Reprocessing 4 (July 2002 – present)

gain calculated at L_t

$g = L_t^{target} / L_t$

satellite atmospheric parameters used to propagate L_w^{target} to TOA

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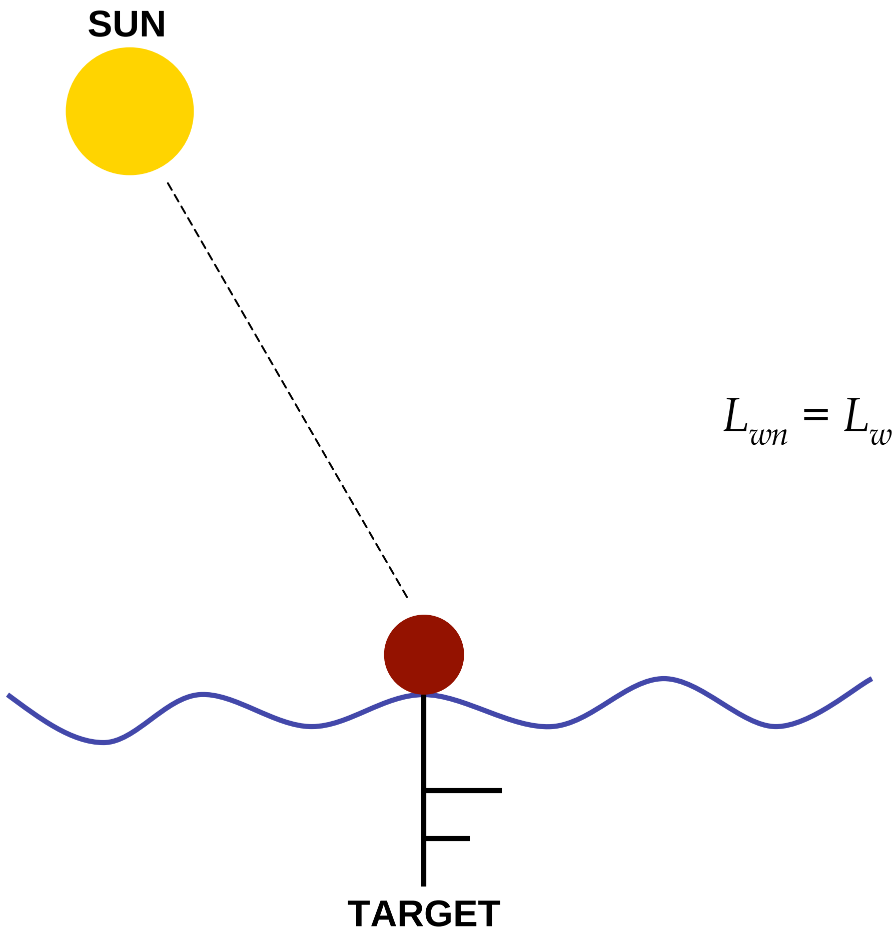
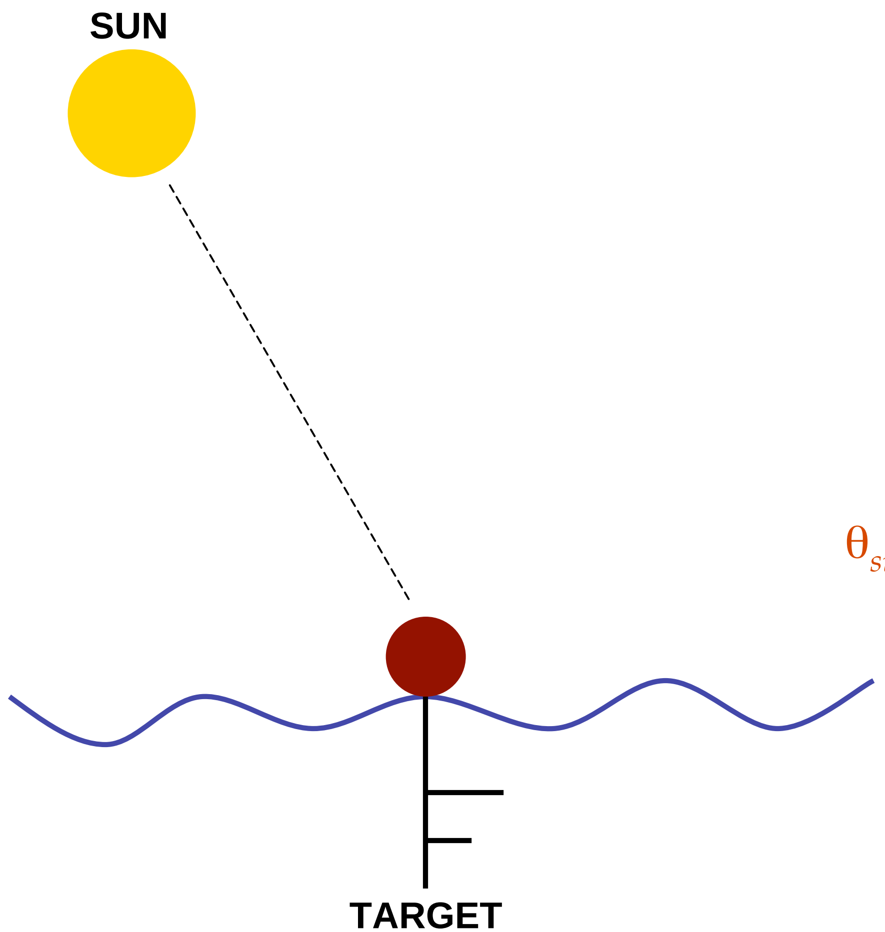


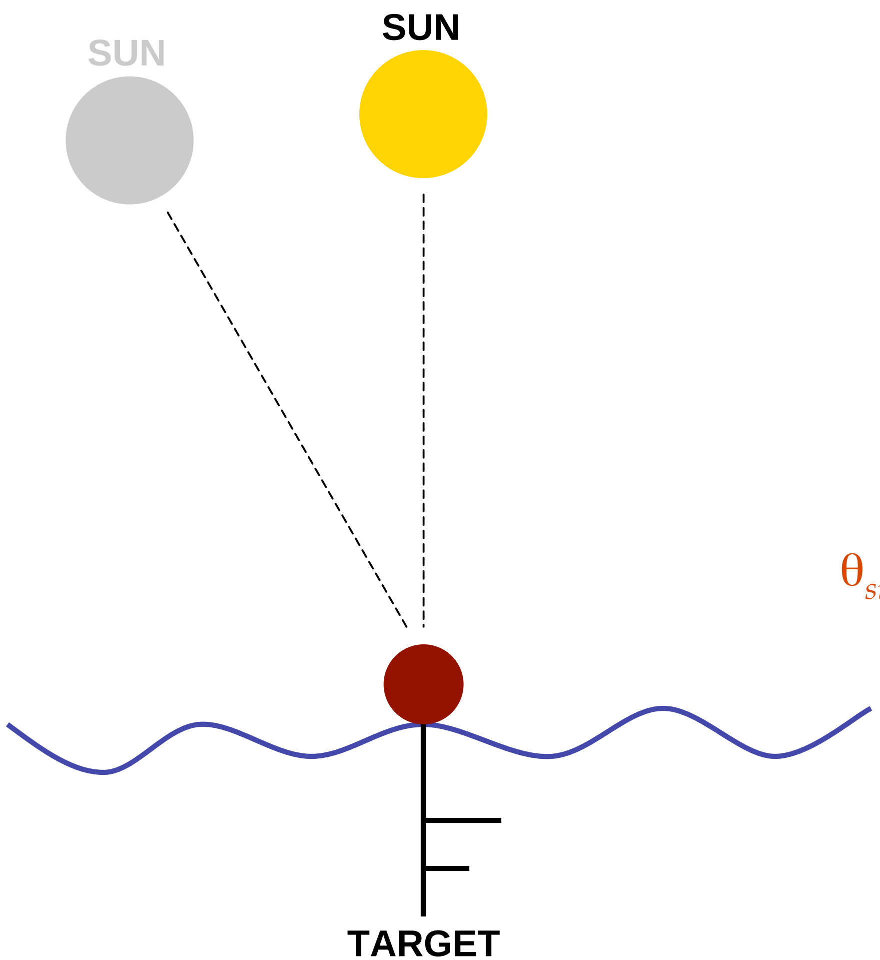
$$L_{wn} = L_w \,/\, (\cos(\theta_{sun})\, t_d\, F_{dist})$$



$\theta_{sun} \neq 0$, $\theta_{sens} = 0$, $\phi_{rel} = 0$

L_{wn}

f/Q from Morel et al. 2002

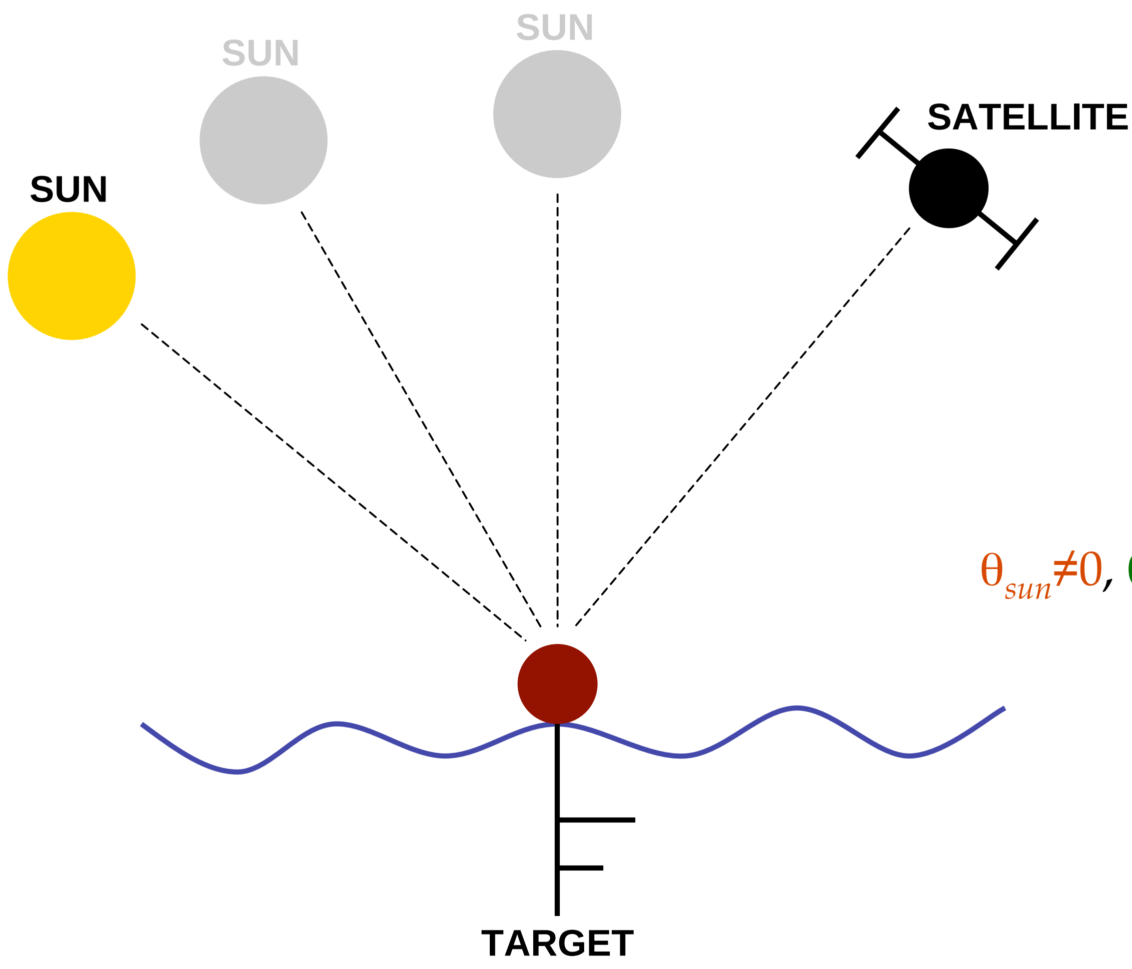


θ_{sun}=0, θ_{sens}=0, ϕ_{rel}=0

L_{wn}

L_{wn}^{ex}

f/Q from Morel et al. 2002



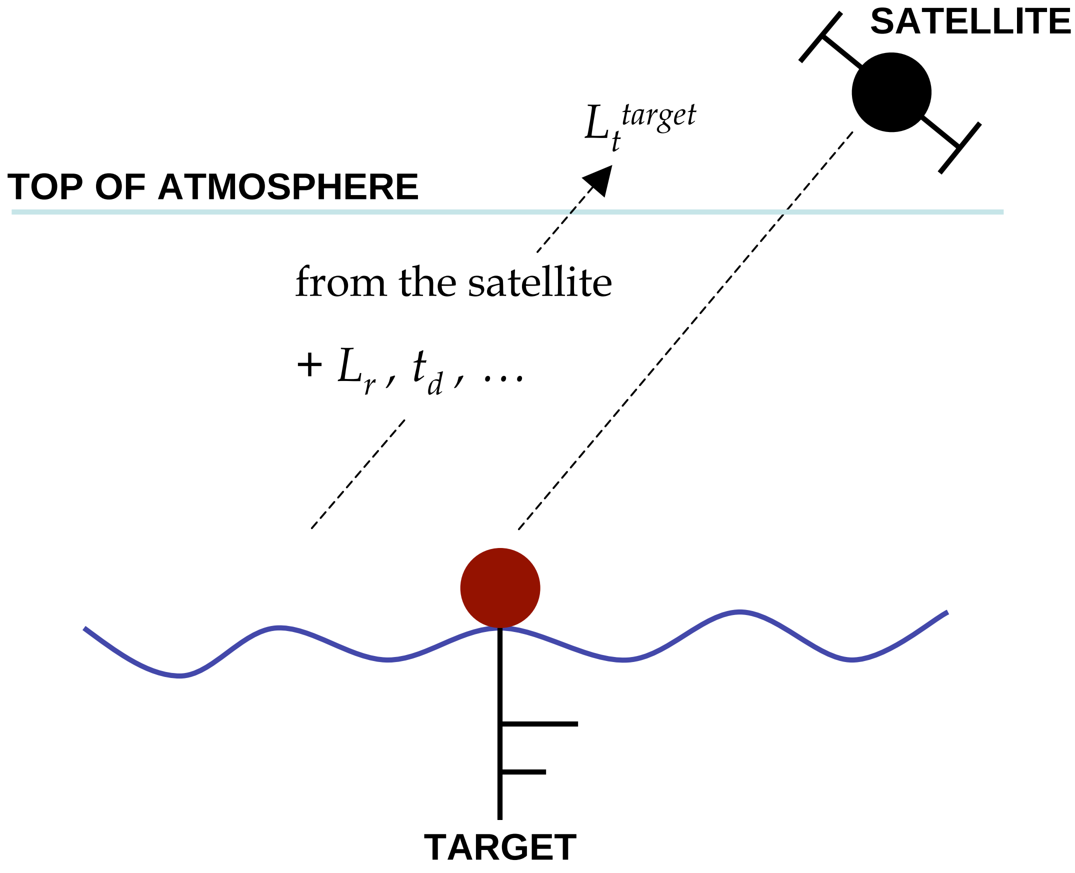
$\theta_{sun} \neq 0$, $\theta_{sens} \neq 0$, $\phi_{rel} \neq 0$

L_{wn}

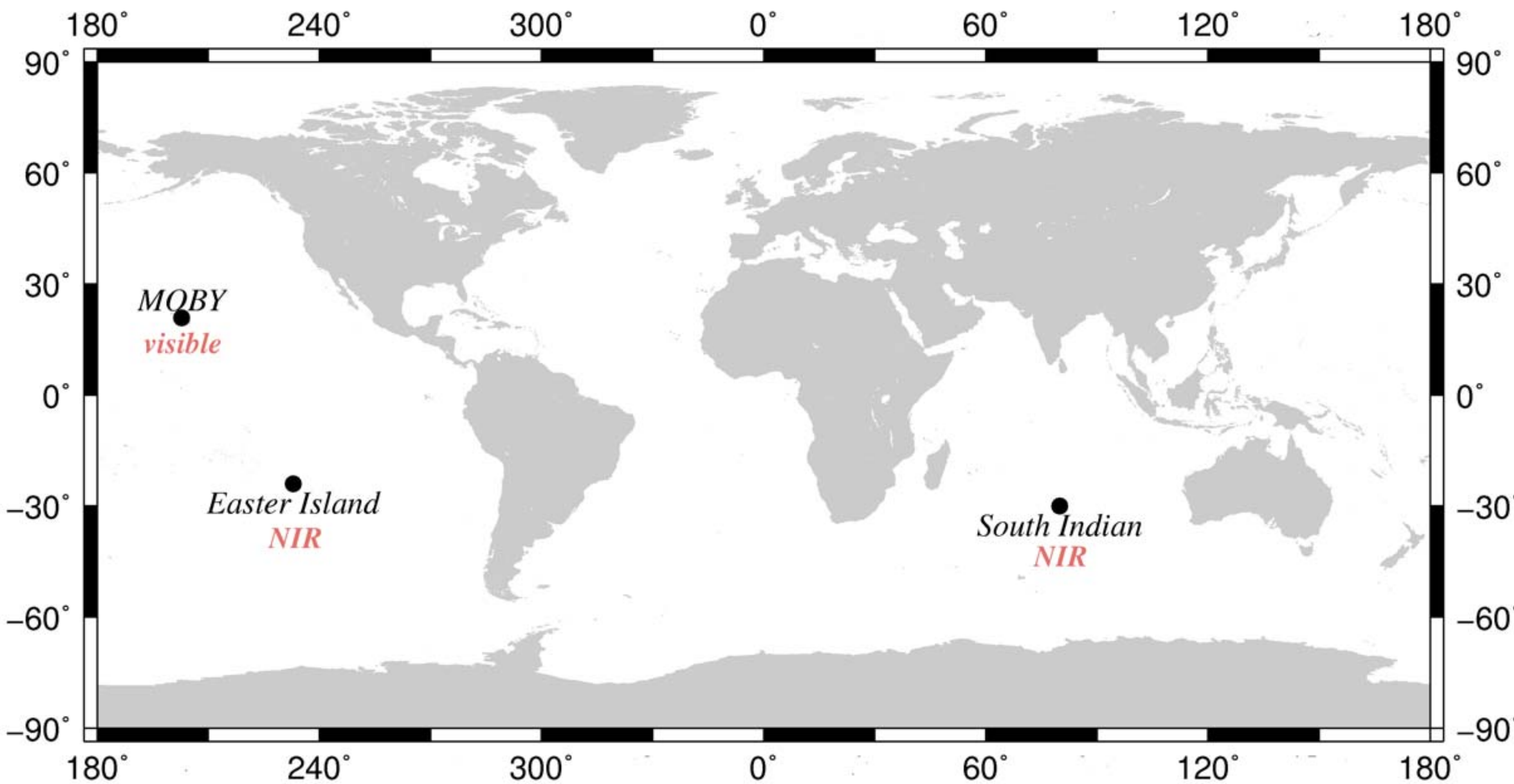
$L_{wn}{}^{ex}$

L_{wn}

f/Q from Morel et al. 2002

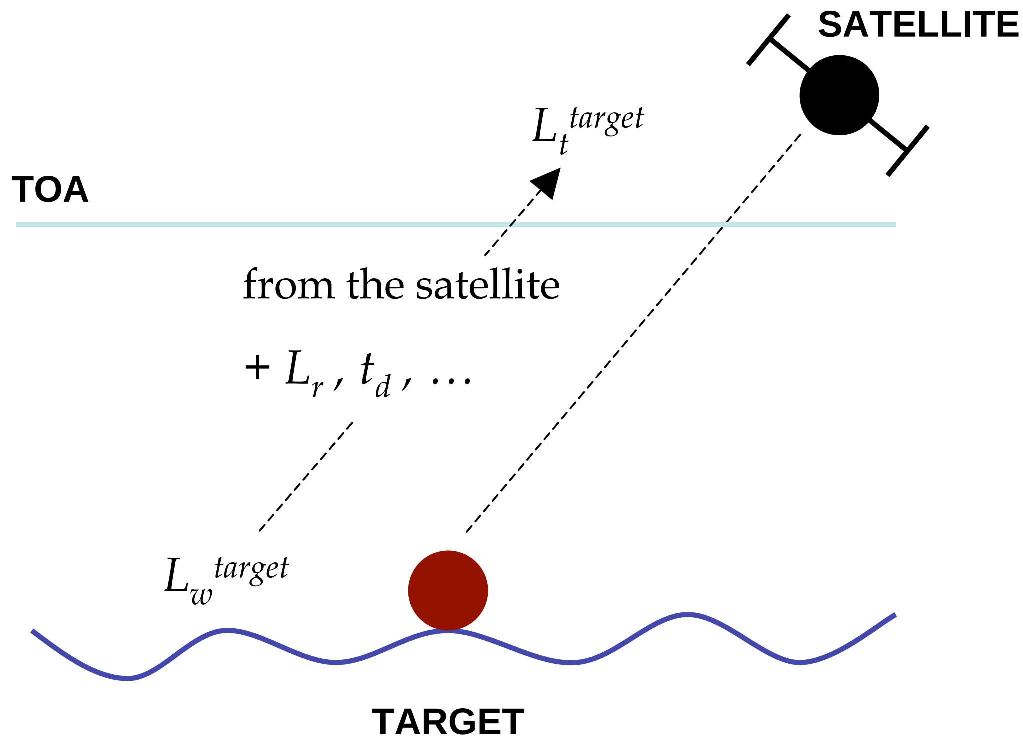

SATELLITE
L_t^{target}
TOP OF ATMOSPHERE
from the satellite
$+ L_r , t_d , \ldots$
TARGET

our operational targets …



$$L_t(\mathrm{NIR}) = L_{r,g,wc,\ldots}(\mathrm{NIR}) + L_a(\mathrm{NIR}) + t_d\, L_w(\mathrm{NIR})$$

<u>assumptions</u>:



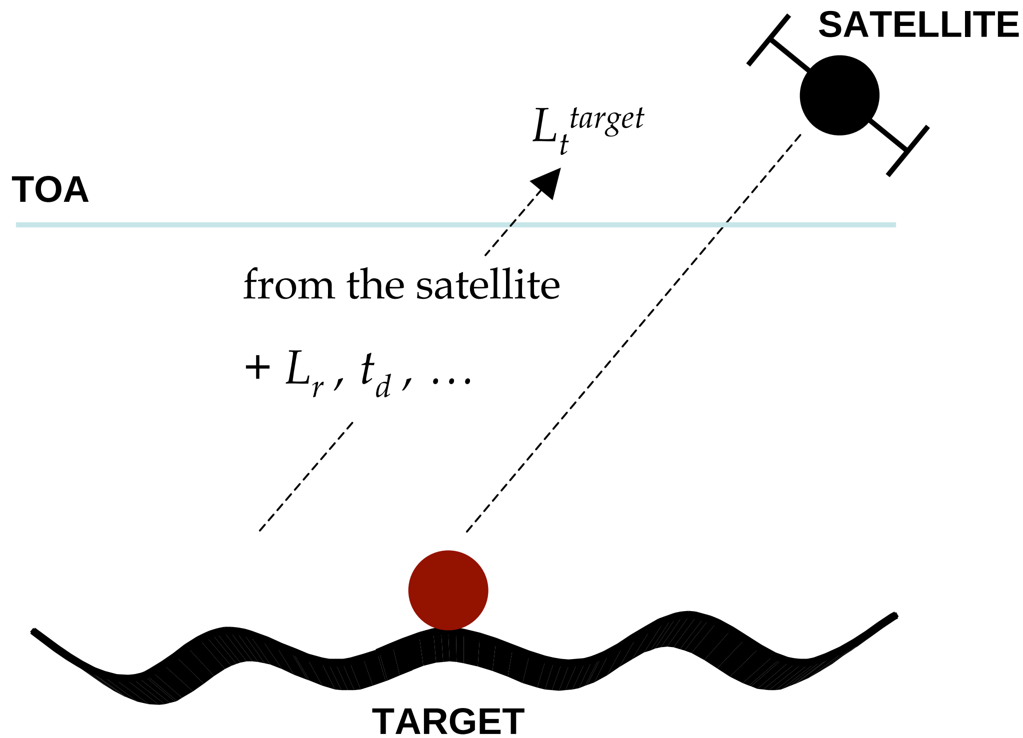
$$L_t(\mathrm{NIR}) = L_{r,g,wc,\ldots}(\mathrm{NIR}) + L_a(\mathrm{NIR}) + t_d\, L_w(\mathrm{NIR})$$

M90

0

assumptions:

(1) target sites exist where aerosol type is known and L_w(NIR) is negligible



$$L_t(\mathrm{NIR}) = L_{r,g,wc,\ldots}(\mathrm{NIR}) + L_a(\mathrm{NIR}) + t_d\, L_w(\mathrm{NIR})$$

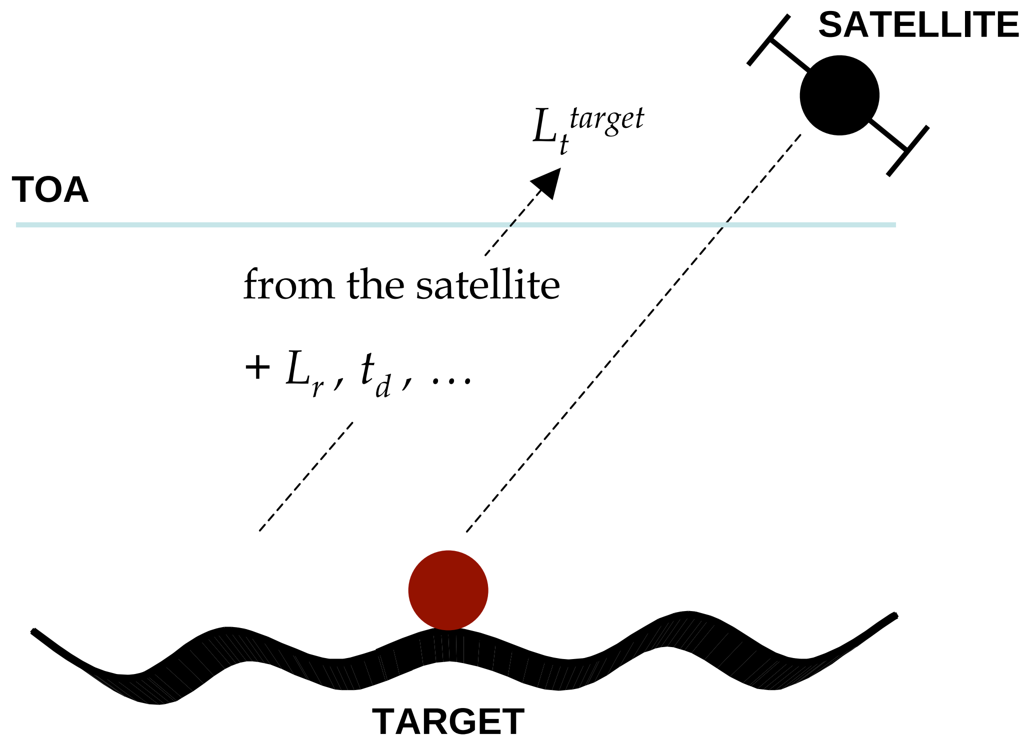
0

M90

<u>assumptions</u>:

(1) target sites exist where aerosol type is known and L_w(NIR) is negligible

(2) 865-nm perfectly calibrated, such that $g(865) = 1.0$



$$L_t(\mathrm{NIR}) = L_{r,g,wc,\ldots}(\mathrm{NIR}) + L_a(\mathrm{NIR}) + t_d\, L_w(\mathrm{NIR})$$

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M90

<u>assumptions</u>:

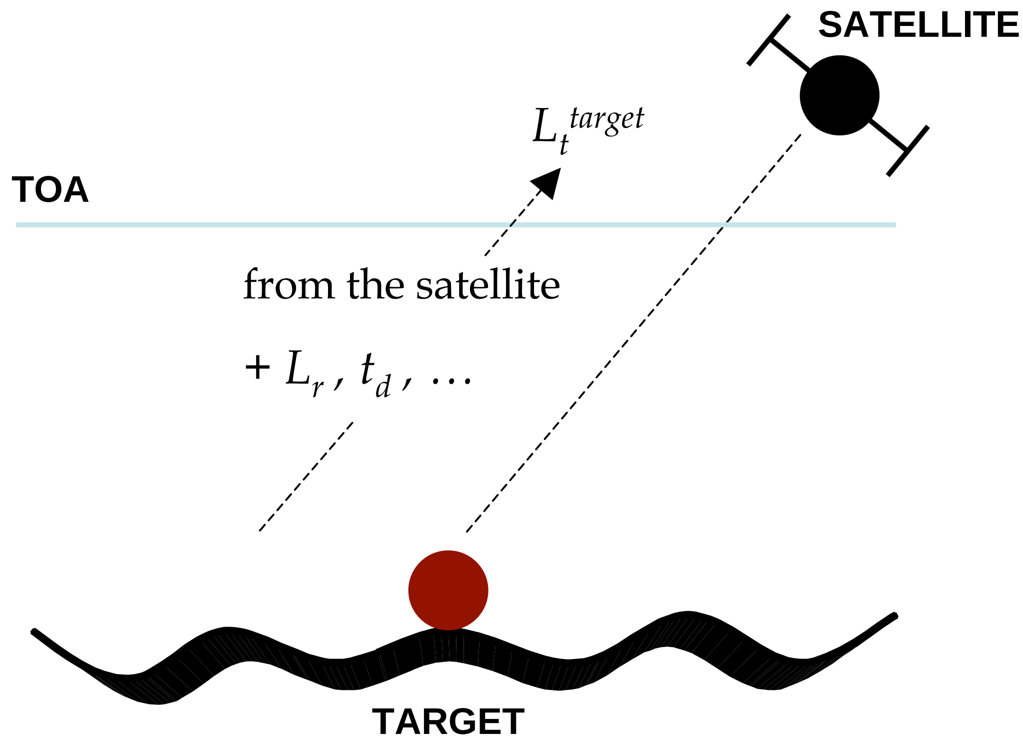
(1) target sites exist where aerosol type is known and L_w(NIR) is negligible

(2) 865-nm perfectly calibrated, such that $g(865) = 1.0$

<u>implementation</u>:

knowledge of the aerosol type and $L_a(865)$ permits the estimation of $L_a(765)$

once $L_a(765)^{target}$ known, calculate $L_t(765)^{target}$



the NIR calibration is completed prior to the VIS calibration … the g(NIR) are now fixed

the OBPG use data from the Marine Optical Buoy (MOBY) for the VIS calibration

MOBY provides hyperspectral L_{wn}(VIS) measured during the satellite overpass

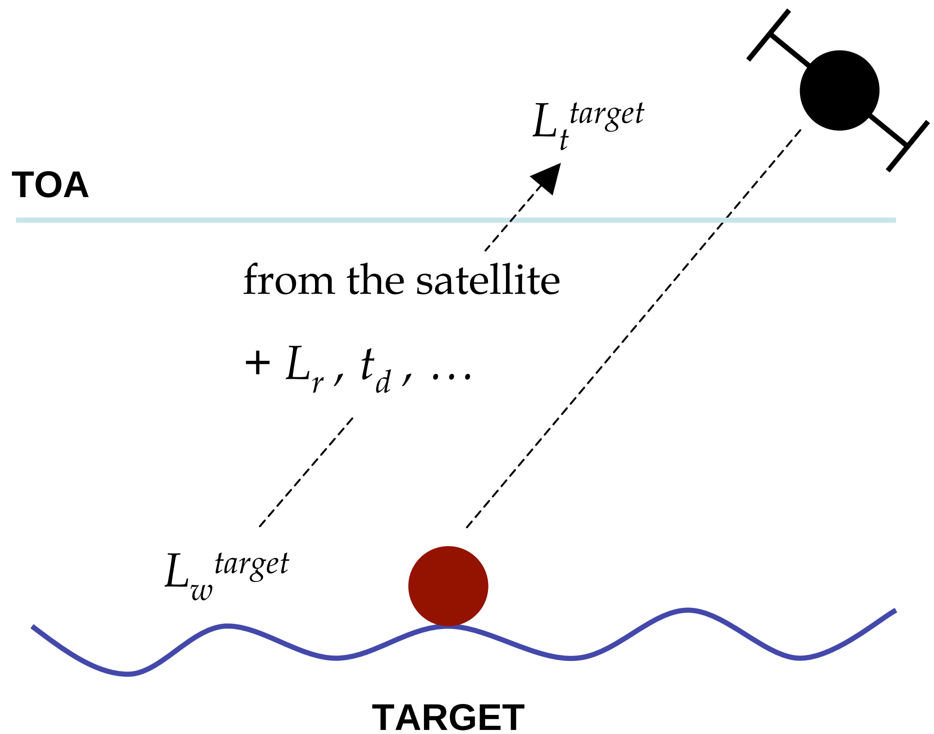
$$L_t(\text{VIS}) = L_{r,g,wc,\ldots}(\text{VIS}) + L_a(\text{VIS}) + t_d\, L_w(\text{VIS})$$

<u>implementation</u>:

calibrated NIR bands used to determine

local aerosol type and concentration,

which provides $L_a(\text{VIS})^{target}$

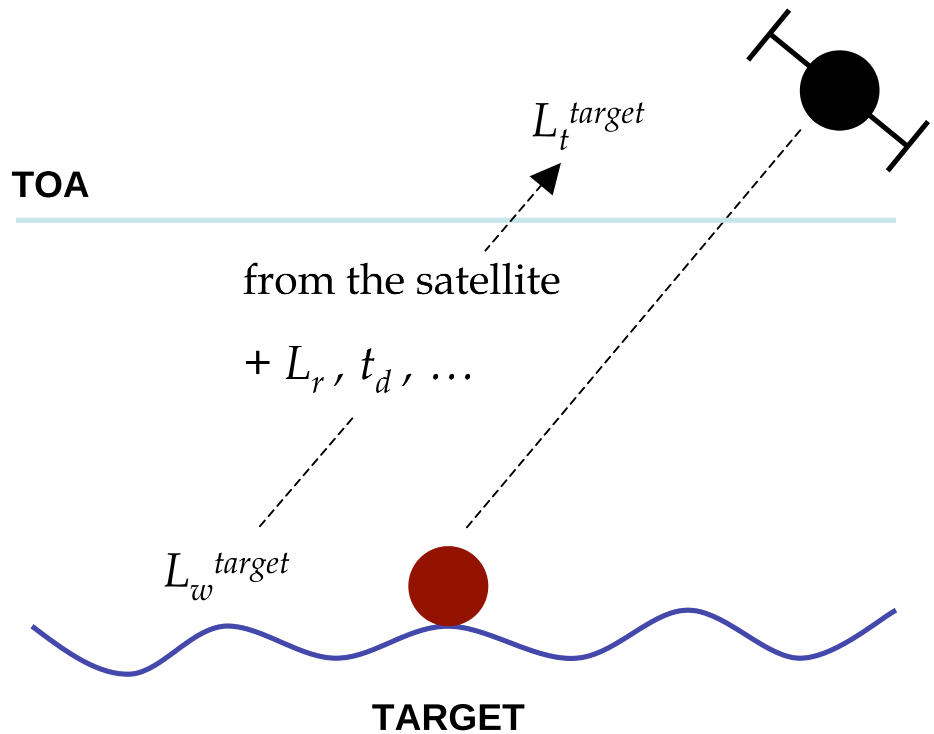


$$L_t(\mathrm{VIS}) = L_{r,g,wc,\ldots}(\mathrm{VIS}) + L_a(\mathrm{VIS}) + t_d\, L_w(\mathrm{VIS})$$

implementation:

calibrated NIR bands used to determine local aerosol type and concentration, which provides $L_a(\mathrm{VIS})^{target}$

calculate $L_t(\mathrm{VIS})^{target}$ using $L_a(\mathrm{VIS})^{target}$, $L_w(\mathrm{VIS})^{target}$, and satellite t_d , …



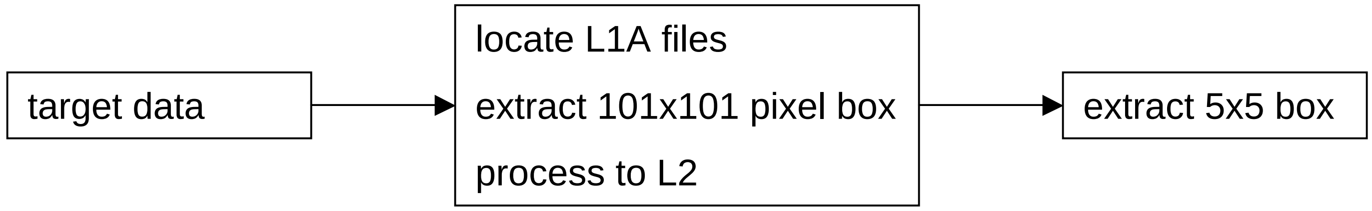
various complications:

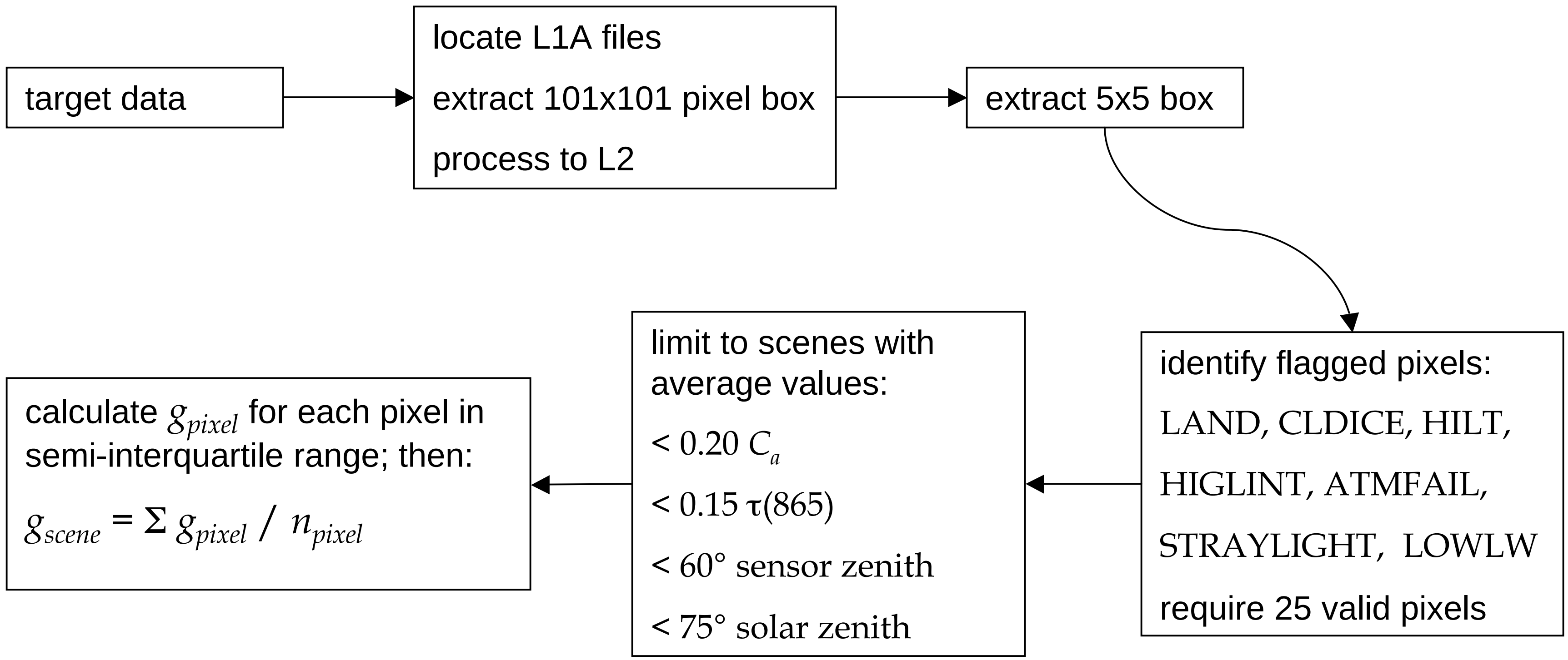
(1) f/Q requires an estimation of C_a

(2) non-hyperspectral targets (conceptually) require adjustment to the satellite spectral bandpass

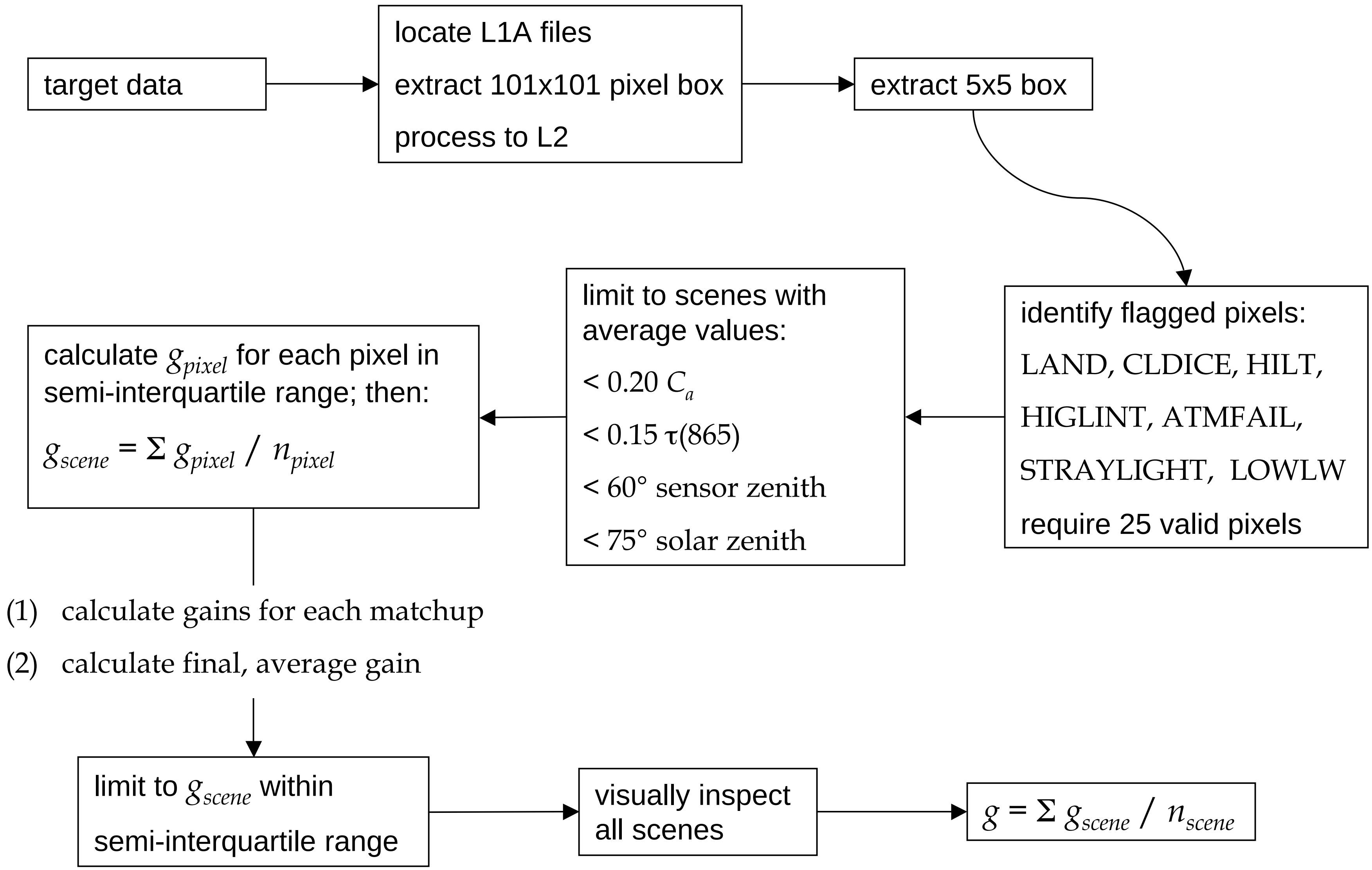
(3) non-clear water targets require an estimation of L_w(NIR)

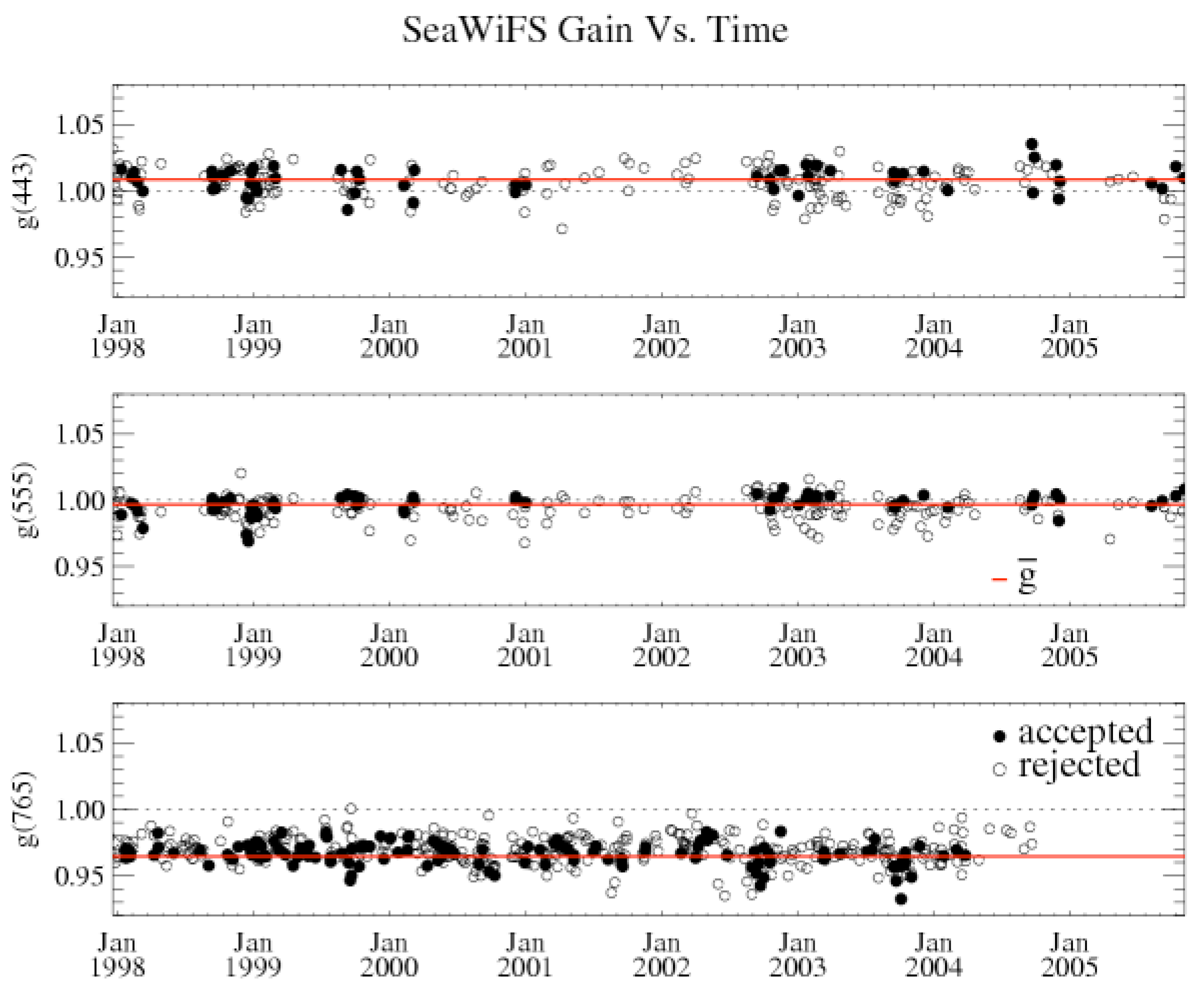
(4) polarization can be problematic as the correction depends on the observed radiances


target data
locate L1A files
extract 101x101 pixel box
process to L2
extract 5x5 box

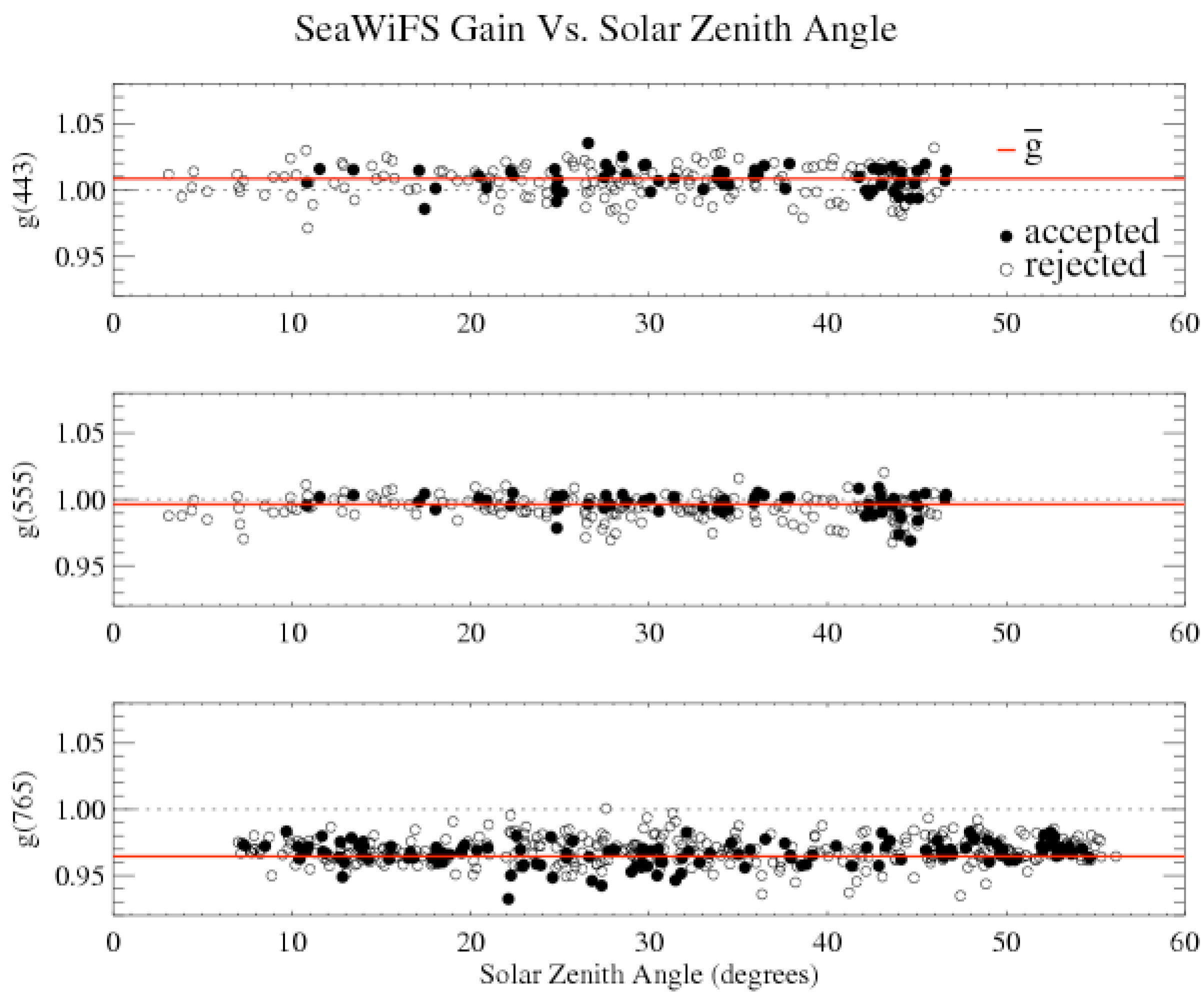


(1) calculate gains for each matchup

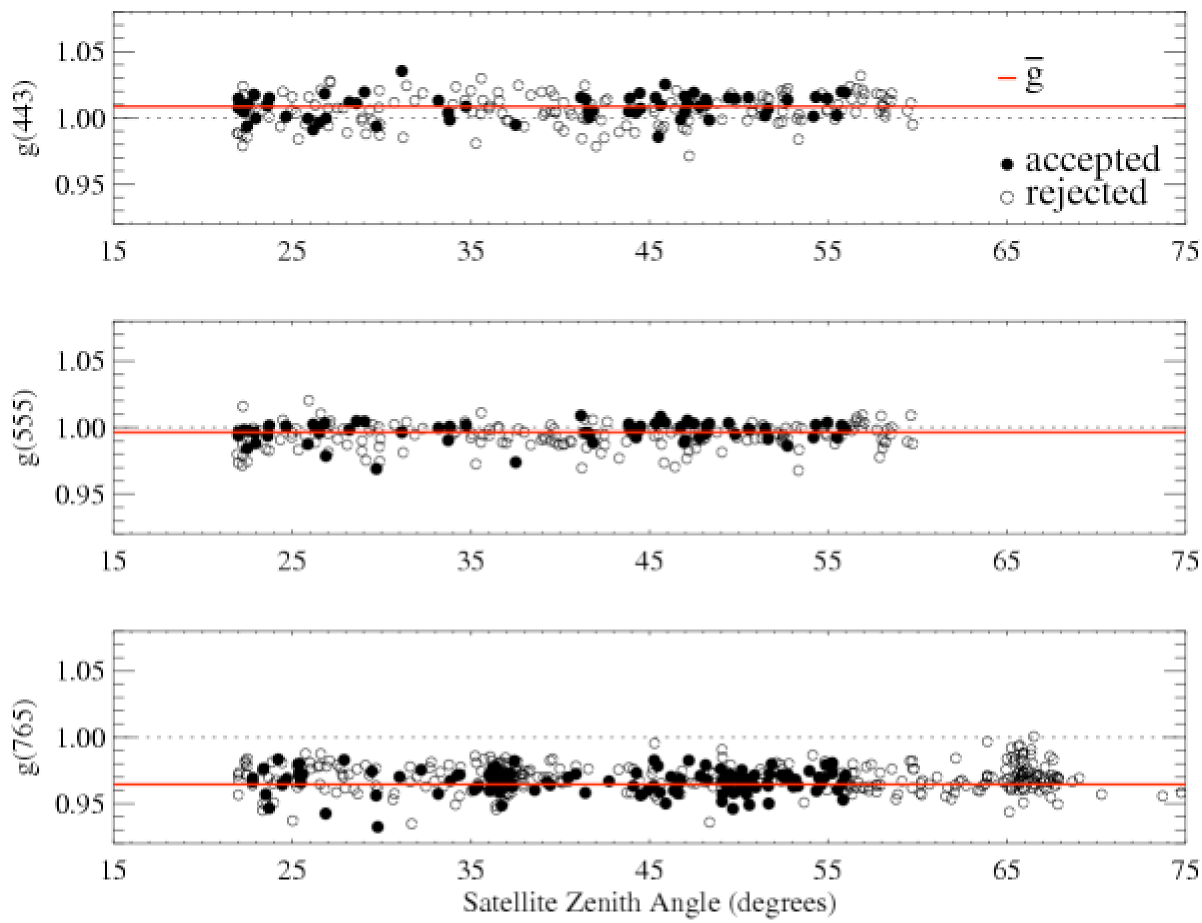

target data
locate L1A files
extract 101x101 pixel box
process to L2
extract 5x5 box
identify flagged pixels:
LAND, CLDICE, HILT,
HIGLINT, ATMFAIL,
STRAYLIGHT, LOWLW
require 25 valid pixels
limit to scenes with average values:
< 0.20 C_a
< 0.15 τ(865)
< 60° sensor zenith
< 75° solar zenith
calculate g_{pixel} for each pixel in semi-interquartile range; then:
$g_{scene} = \Sigma\, g_{pixel} / n_{pixel}$
(1) calculate gains for each matchup
(2) calculate final, average gain
limit to g_{scene} within semi-interquartile range
visually inspect all scenes
$g = \Sigma\, g_{scene} / n_{scene}$



SeaWiFS Gain Vs. Time
g(443)
g(555)
g(765)
1.05
1.00
0.95
Jan 1998
Jan 1999
Jan 2000
Jan 2001
Jan 2002
Jan 2003
Jan 2004
Jan 2005
accepted
rejected


SeaWiFS Gain Vs. Solar Zenith Angle
g(443)
g(555)
g(765)
1.05
1.00
0.95
0
10
20
30
40
50
60
ḡ
accepted
rejected
Solar Zenith Angle (degrees)

SeaWiFS Gain Vs. Satellite Zenith Angle



g remains stable as a function of time, both long-term and seasonally

* verifies temporal calibration

* suggests consistency in MOBY deployments

* scatter (5%) underscores need for independent temporal calibration
  (SeaWiFS 443-nm has degraded 2% since launch)

g consistent with both solar and sensor zenith angles

variations with geometry might suggest problems with

* the atmospheric correction

* the *f/Q* correction

* the *in situ* determination of L_w under certain sky conditions

input the calibration scenes into validation system …

Regression Statistics for SeaWiFS "Validation" Using MOBY Calibration Targets

	412	443	490	510	555	670
N	60	60	60	60	60	60
r^2	0.96	0.91	0.73	0.50	0.41	0.36
RMS	0.053	0.052	0.038	0.035	0.024	0.009
bias	0.02	0.02	0.01	0.01	0.00	0.00
MPD	2.1	1.9	2.2	3.1	5.4	37.2
ratio	1.008	1.011	1.009	1.010	1.003	1.081

satellite-to-*in situ* biases and mean ratios approach zero and unity, respectively input the calibration scenes into validation system …

Regression Statistics for SeaWiFS "Validation" Using MOBY Calibration Targets

	412	443	490	510	555	670
N	60	60	60	60	60	60
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RMS	0.053	0.052	0.038	0.035	0.024	0.009
bias	0.02	0.02	0.01	0.01	0.00	0.00
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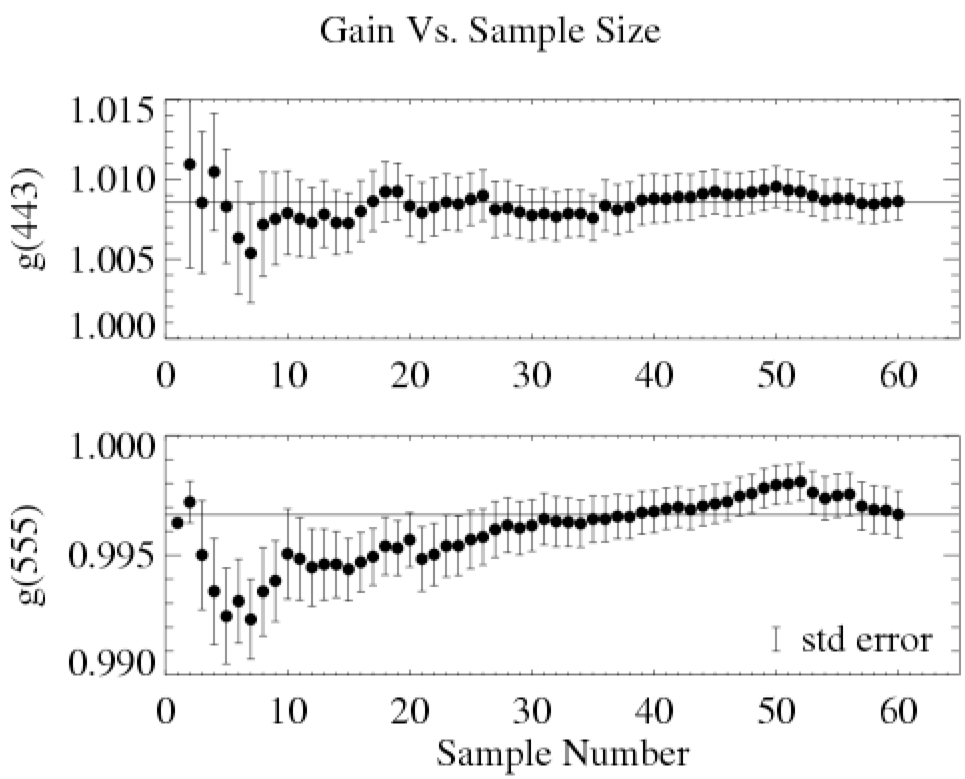
ratio	1.008	1.011	1.009	1.010	1.003	1.081

satellite-to-*in situ* biases and mean ratios approach zero and unity, respectively

RMSs and absolute MPDs not entirely negligible

compare with MPD of 13% for deep water validation set at 443-nm changes in *g* with increasing sample size …



standard error of *g* decreases to 0.1%

overall variability (min vs. max *g*) approaches 0.5%

provides insight into temporal calibration future ruminations …

… statistical and visual exclusion criteria influence g only slightly, yet they reduce the standard deviations … can uncertainties be quantified for the assigned thresholds?

… how do the uncertainties of the embedded models (e.g., f/Q, the NIR-correction, etc.) propagate into the calibration?

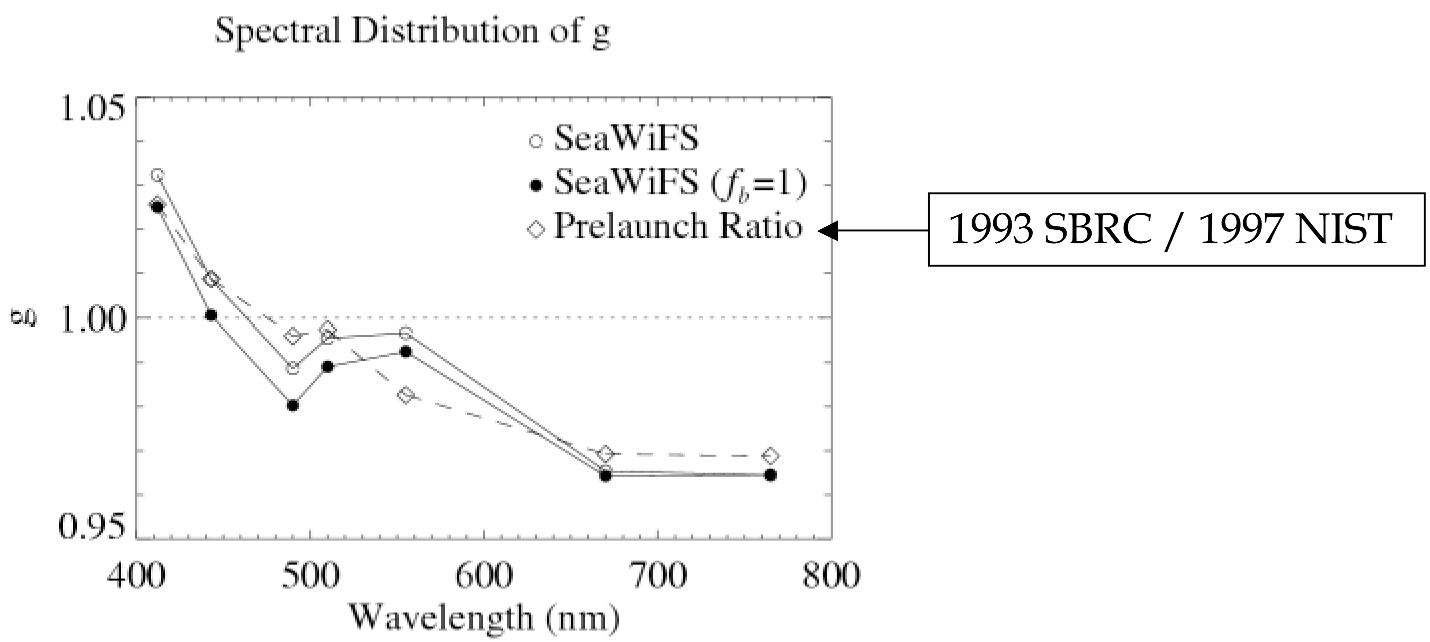
… what are the uncertainties associated with L_w^{target}?

SeaWiFS Preliminary Vicarious Gains and Standard Deviations for Reprocessing 6 (Spring 2007)

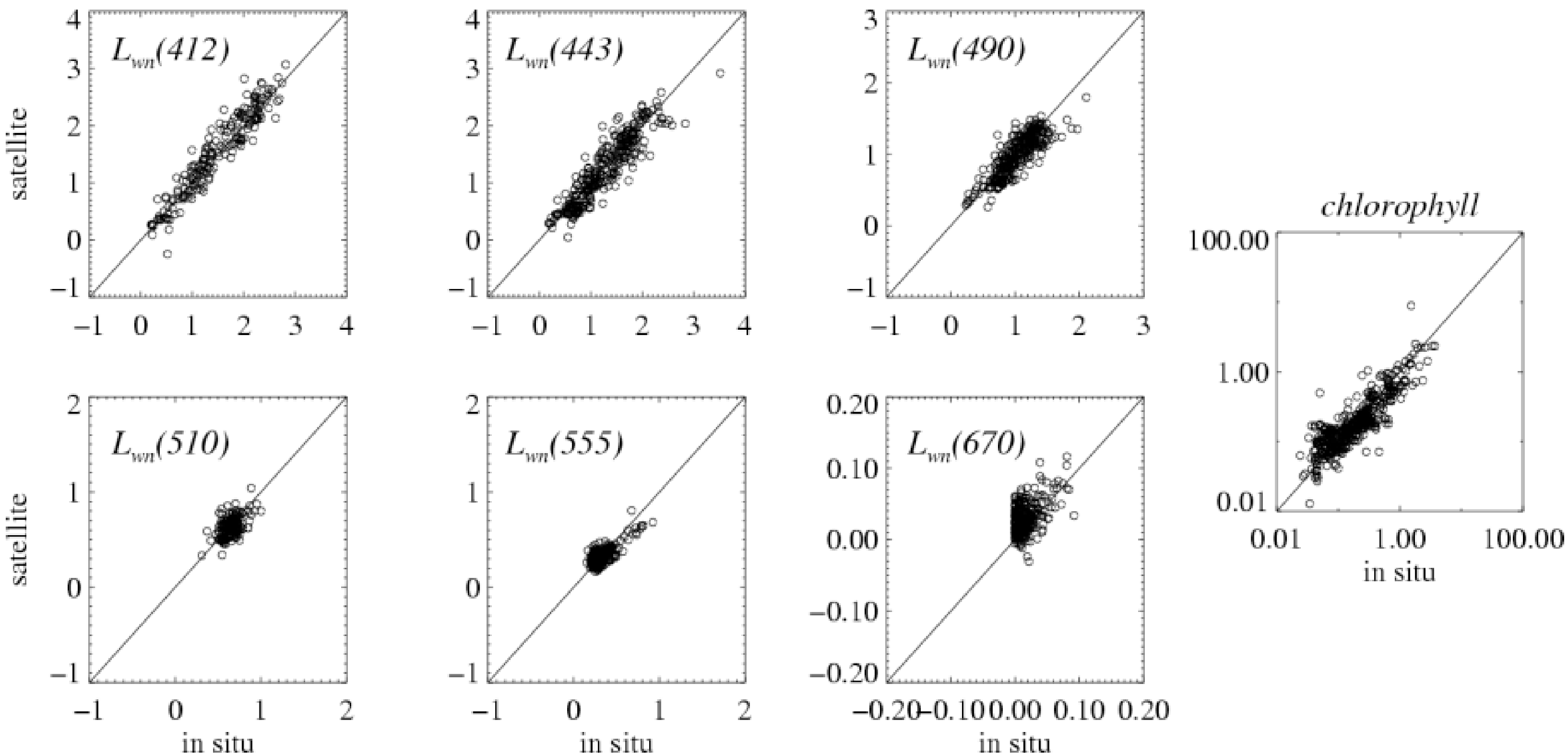
	412	443	490	510	555	670	765	865
$\bar{g}$	1.0324	1.0086	0.9887	0.9955	0.9967	0.9654	0.9645	1
s	0.010	0.009	0.007	0.007	0.008	0.005	0.004	0

SeaWiFS Vicarious Gains, as Above, with the BRDF Correction Disabled ($f_b = 1$)

	412	443	490	510	555	670	765	865
$\bar{g}$	1.0251	1.0006	0.9803	0.9891	0.9925	0.9643	0.9645	1
s	0.007	0.008	0.007	0.007	0.007	0.005	0.004	
%	-1.05	-1.19	-1.08	-0.65	-0.14	0.17		


Spectral Distribution of g
1.05
1.00
0.95
g
400
500
600
700
800
Wavelength (nm)
SeaWiFS
SeaWiFS (f_b=1)
Prelaunch Ratio
1993 SBRC / 1997 NIST

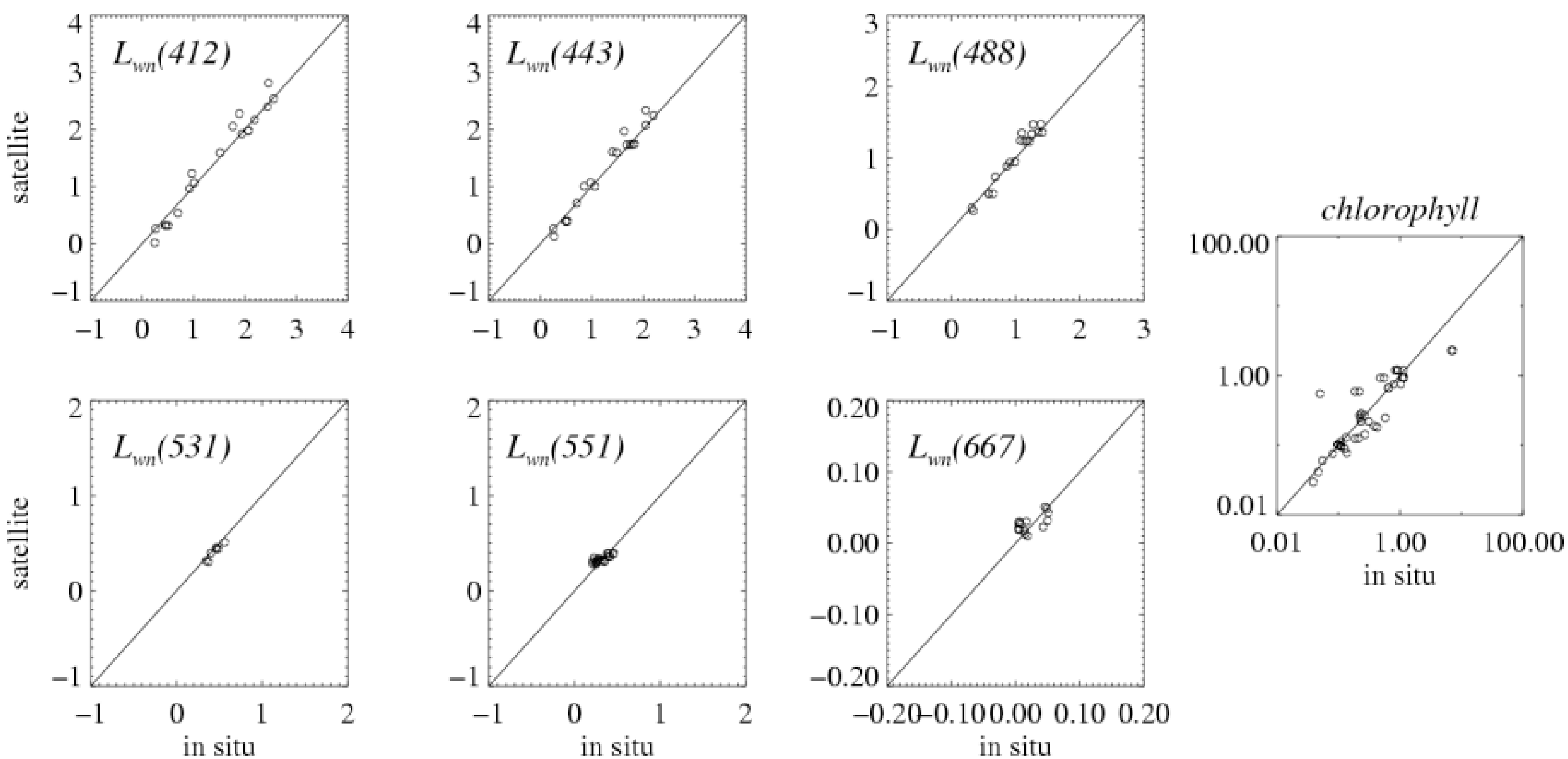
SeaWiFS validation for the deep water subset:



MODIS-Aqua Vicarious Gains and Standard Deviations for Reprocessing 1.1 (August 2005)

	412	443	488	531	551	667	678	748	870
$\bar{g}$	0.9710	0.9848	0.9795	0.9870	0.9850	0.9797	0.9776	0.9855	1
s	0.006	0.005	0.005	0.005	0.005	0.003	0.004	0.004	0

MODIS-Aqua validation for the deep water subset:



Backup slides …

$$L_t = \left(L_r + L_a + t_{dv} L_f + t_{dv} L_w\right) t_{gv} t_{gs} f_p \quad (1)$$

$$L_{wn} = L_w \left(\mu_s t_{ds} f_s f_b f_\lambda\right)^{-1} \quad (2)$$

$$L_{wn}^t = L_w^t \left(\mu_s^t t_{ds}^t f_s^t f_b^t f_\lambda^t\right)^{-1} \quad (3)$$

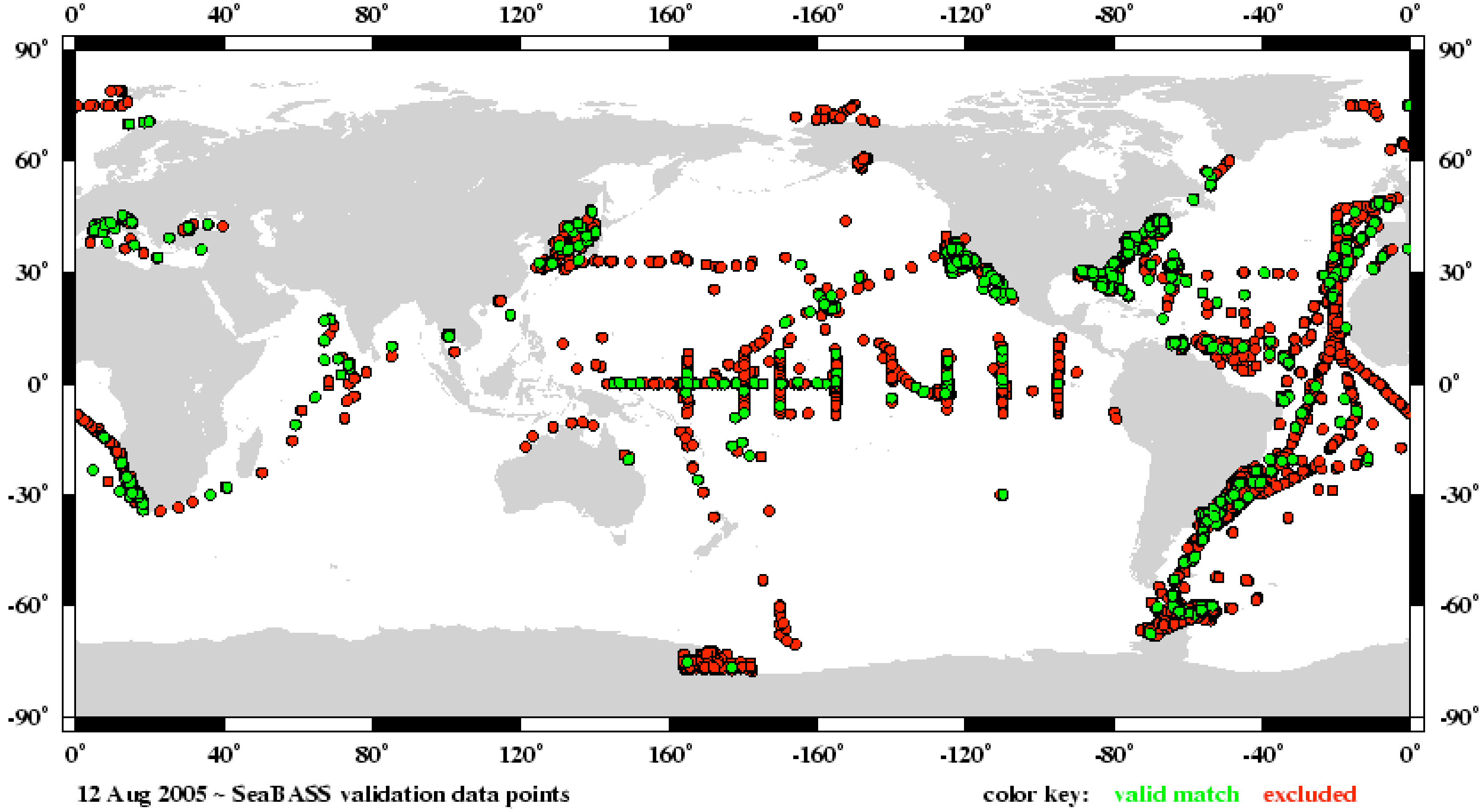
$$L_t^t = \left\{L_r + L_a + t_{dv} L_f + t_{dv} L_{wn}^t \left(\mu_s t_{ds} f_s f_b f_\lambda\right)\right\} t_{gv} t_{gs} f_p \quad (4)$$

$$g = L_t^t L_t^{-1} \quad (5)$$

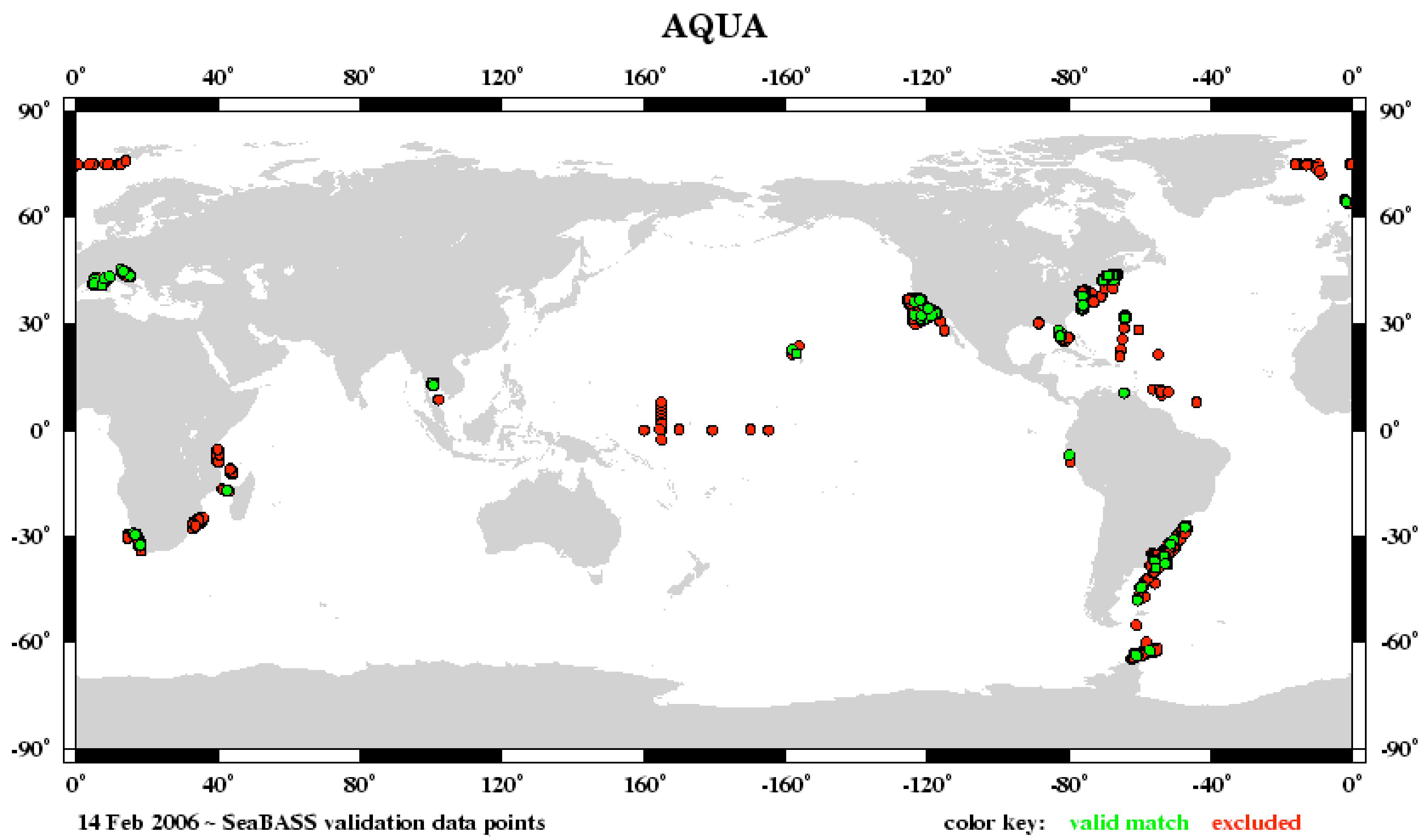
$$L_t = \left(L_r + L_a + t_{dv} L_f\right) t_{gv} t_{gs} f_p \quad (6)$$

$$L_t^t = \left(L_r + L_a^t + t_{dv} L_f\right) t_{gv} t_{gs} f_p \quad (7)$$

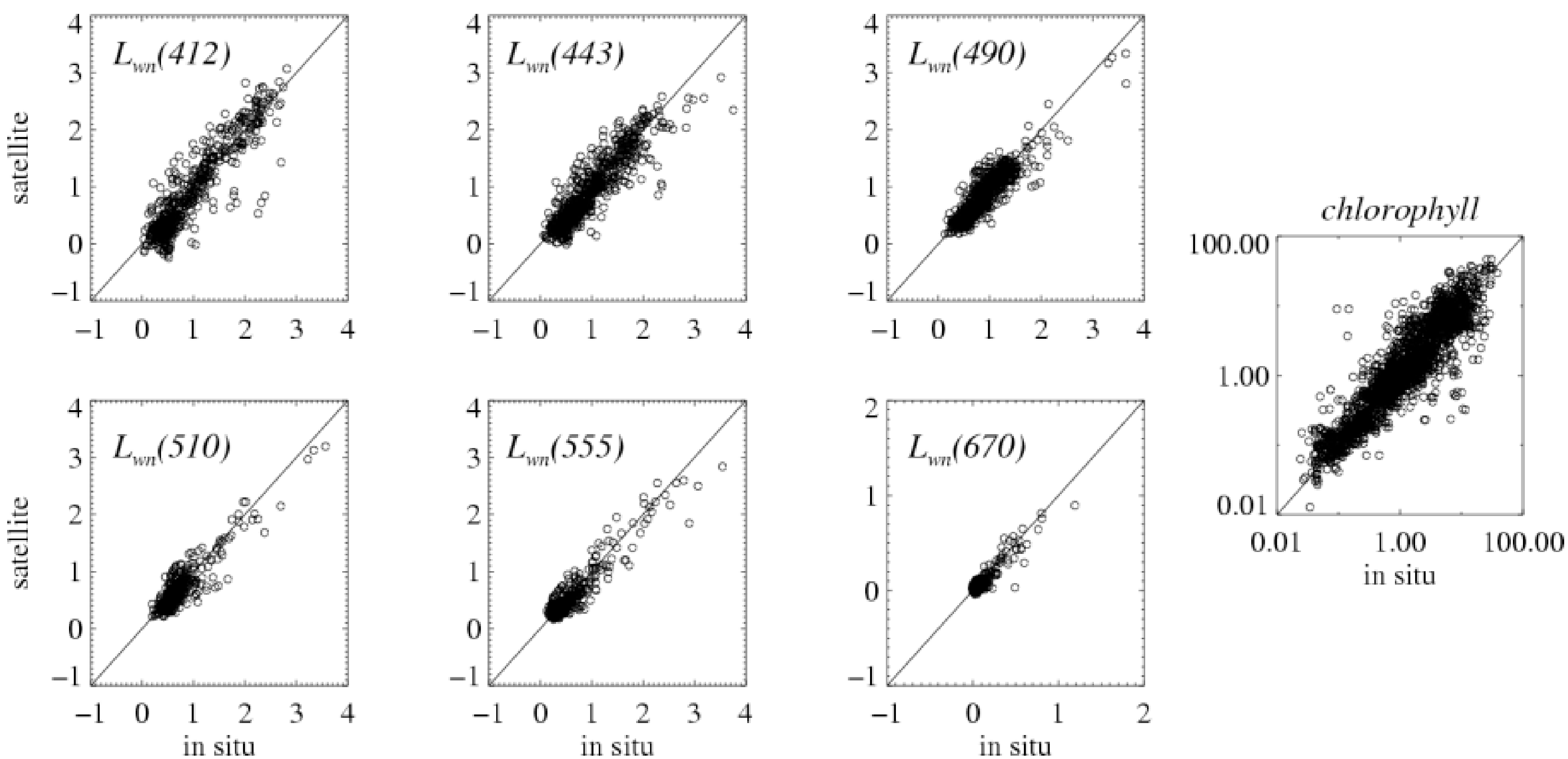
SeaWiFS



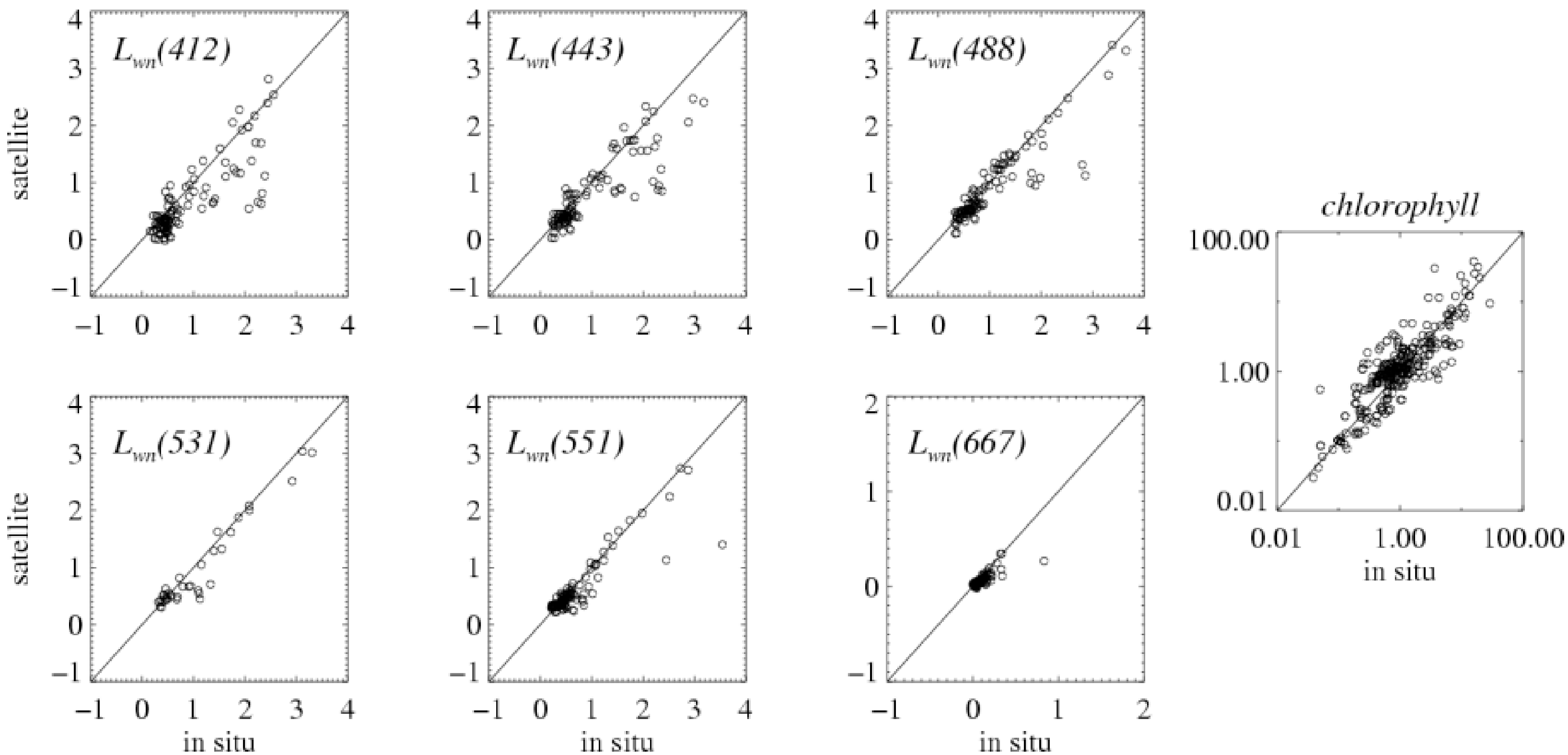
0°
40°
80°
120°
160°
-160°
-120°
-80°
-40°
0°
90°
60°
30°
0°
-30°
-60°
-90°
12 Aug 2005 ~ SeaBASS validation data points
color key: valid match excluded


AQUA
0° 40° 80° 120° 160° -160° -120° -80° -40° 0°
90° 60° 30° 0° -30° -60° -90°
14 Feb 2006 ~ SeaBASS validation data points
color key: valid match excluded

<u>SeaWiFS validation for the global data set</u>:



MODIS-Aqua validation for the global data set:



SeaWiFS validation statistics:

Deep Water Only

Band	N	Median Ratio*	% Difference**	r^2	Bias	rms+	In Situ Range	Satellite Range
lw412	154	1.030	10.783	0.904	0.049	0.232	0.200 - 2.789	-0.246 - 3.069
lw443	242	0.962	13.348	0.845	-0.036	0.232	0.185 - 2.815	0.046 - 2.582
lw490	242	0.956	12.134	0.744	-0.052	0.174	0.232 - 2.076	0.262 - 1.796
lw510	127	0.976	11.084	0.478	-0.011	0.103	0.315 - 0.965	0.333 - 1.042
lw555	242	0.976	16.637	0.676	-0.007	0.077	0.167 - 0.917	0.163 - 0.805
lw670	238	1.618	84.442	0.453	0.013	0.025	0.000 - 0.091	-0.031 - 0.116
chlorophyll	271	0.922	25.966	0.833	-0.083	0.443	0.024 - 3.721	0.030 - 8.882
kd490	149	0.993	13.543	0.897	0.002	0.013	0.014 - 0.278	0.017 - 0.258
aot865	65	1.413	43.136	0.678	0.037	0.064	0.018 - 0.358	0.026 - 0.424

* median of all satellite / in situ ratios
** median absolute percent difference
+ sqrt (∑(satellite - in situ)^2 / n)
chlorophyll data were log transformed prior to calculation of slope, intercept, r2, rms and bias statistics
median ratio and median absolute percent difference were performed on non-transformed data

MODIS-Aqua validation statistics:

Deep Water Only

Band	N	Median Ratio*	% Difference**	r^2	Bias	rms+	In Situ Range	Satellite Range
lw412	13	1.023	5.618	0.966	0.045	0.178	0.240 - 2.586	0.017 - 2.812
lw443	17	0.998	10.858	0.929	-0.044	0.224	0.251 - 2.232	0.124 - 2.337
lw488	17	1.040	5.967	0.844	-0.035	0.180	0.307 - 1.415	0.260 - 1.474
lw531	5	0.930	6.961	0.882	-0.028	0.037	0.338 - 0.480	0.302 - 0.456
lw551	13	1.140	14.020	0.574	0.032	0.058	0.217 - 0.440	0.283 - 0.388
lw667	17	1.813	81.317	0.591	0.011	0.017	0.000 - 0.050	0.010 - 0.049
chlorophyll	28	0.956	28.282	0.740	-0.027	0.709	0.039 - 7.258	0.030 - 2.287
kd488	12	1.149	14.864	0.997	0.015	0.029	0.021 - 0.147	0.022 - 0.224
aot869	14	1.552	55.187	0.646	0.043	0.058	0.018 - 0.171	0.047 - 0.256

* median of all satellite / in situ ratios
** median absolute percent difference
+ sqrt (∑(satellite - in situ)^2 / n)
chlorophyll data were log transformed prior to calculation of slope, intercept, r2, rms and bias statistics
median ratio and median absolute percent difference were performed on non-transformed data

SeaWiFS validation statistics:

Global Results

Band	N	Median Ratio*	% Difference**	r^2	Bias	rms+	In Situ Range	Satellite Range
lw412	480	0.905	24.098	0.827	-0.079	0.332	0.037 - 2.789	-0.246 - 3.069
lw443	629	0.915	17.480	0.830	-0.049	0.262	0.065 - 3.421	-0.010 - 3.019
lw490	587	0.918	15.101	0.821	-0.054	0.207	0.126 - 4.172	0.173 - 3.337
lw510	406	0.918	13.739	0.849	-0.042	0.177	0.195 - 4.174	0.214 - 3.295
lw555	629	0.915	16.878	0.931	-0.040	0.146	0.131 - 4.770	0.163 - 4.255
lw670	603	0.920	45.717	0.876	-0.007	0.045	0.000 - 1.181	-0.037 - 0.996
chlorophyll	1293	0.998	33.086	0.796	-0.006	0.657	0.024 - 32.181	0.030 - 33.621
kd490	247	1.038	15.043	0.743	-0.001	0.052	0.014 - 0.721	0.017 - 0.421
aot865	126	1.422	43.376	0.717	0.030	0.055	0.002 - 0.358	0.017 - 0.424

MODIS-Aqua validation statistics:

Global Results

Band	N	Median Ratio*	% Difference**	r^2	Bias	rms+	In Situ Range	Satellite Range
lw412	120	0.747	30.898	0.742	-0.228	0.420	0.219 - 2.586	-0.014 - 2.812
lw443	133	0.862	18.811	0.815	-0.136	0.317	0.223 - 2.897	0.036 - 2.470
lw488	109	0.923	14.563	0.907	-0.094	0.222	0.307 - 3.540	0.113 - 3.410
lw531	32	0.933	11.178	0.934	-0.117	0.239	0.338 - 3.234	0.302 - 3.037
lw551	120	0.940	12.255	0.943	-0.074	0.164	0.217 - 3.186	0.224 - 3.045
lw667	107	0.682	36.392	0.735	-0.027	0.049	0.000 - 0.349	-0.018 - 0.345
chlorophyll	263	1.084	40.406	0.780	0.084	0.644	0.039 - 29.004	0.030 - 37.837
kd488	32	1.179	19.067	0.795	0.018	0.046	0.021 - 0.394	0.022 - 0.298
aot869	23	1.567	56.686	0.682	0.042	0.057	0.018 - 0.171	0.033 - 0.256