Backscattering (VSF) Protocols: Review and Revision

Jim Sullivan,

M. Twardowski, J. Werdell, W. Slade …

Last revision: 2003

Ocean Optics Protocols For Satellite Ocean Color Sensor Validation, Revision 4, Volume IV

Chapter 5

Volume Scattering Function and Backscattering Coefficients: Instruments, Characterization, Field Measurements and Data Analysis Protocols

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Topics covered in 2003:

1. Introduction: VSF measurement and instrument design

2. Instrument characterization and calibration: beads
   - geometry and weighting functions
   - attenuation/absorption correction
   - calibration methods

3. Instrument characterization and calibration: reflective plaque
   - geometry and weighting functions
   - calibration methods

4. Estimating b_b from single/multiple VSF measurements
   - χ factors, $\beta_p(\theta) = \beta_t(\theta) - \beta_w(\theta)$, $\beta_w(\theta)$ from Morel

Advances/changes since 2003

1. Commercial VSF devices were relatively new

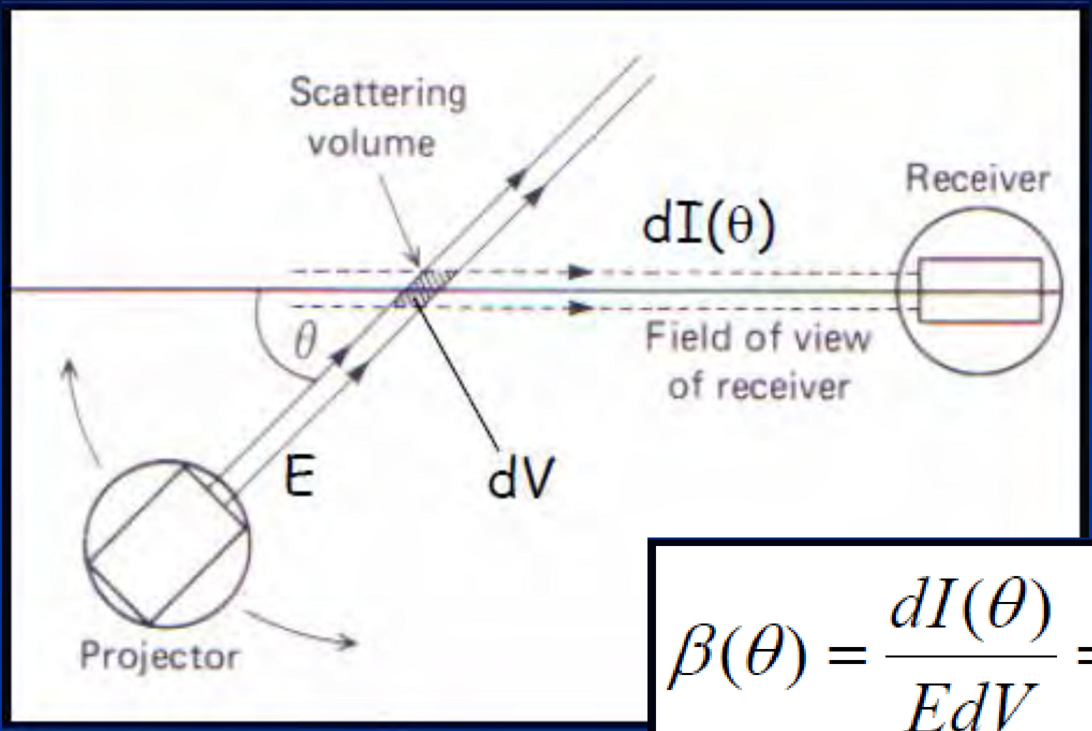
   New product lines have been introduced
   New instrument designs proposed/built

2. Characterization and calibration methods have improved

3. Both natural and methodological measurement uncertainties (χ_p, b_{bw}, etc.) have been better defined

4. Deployment protocols have been refined

Volume Scattering Function (VSF): $\beta(\theta)$



E: incident irradiance

dV: volume

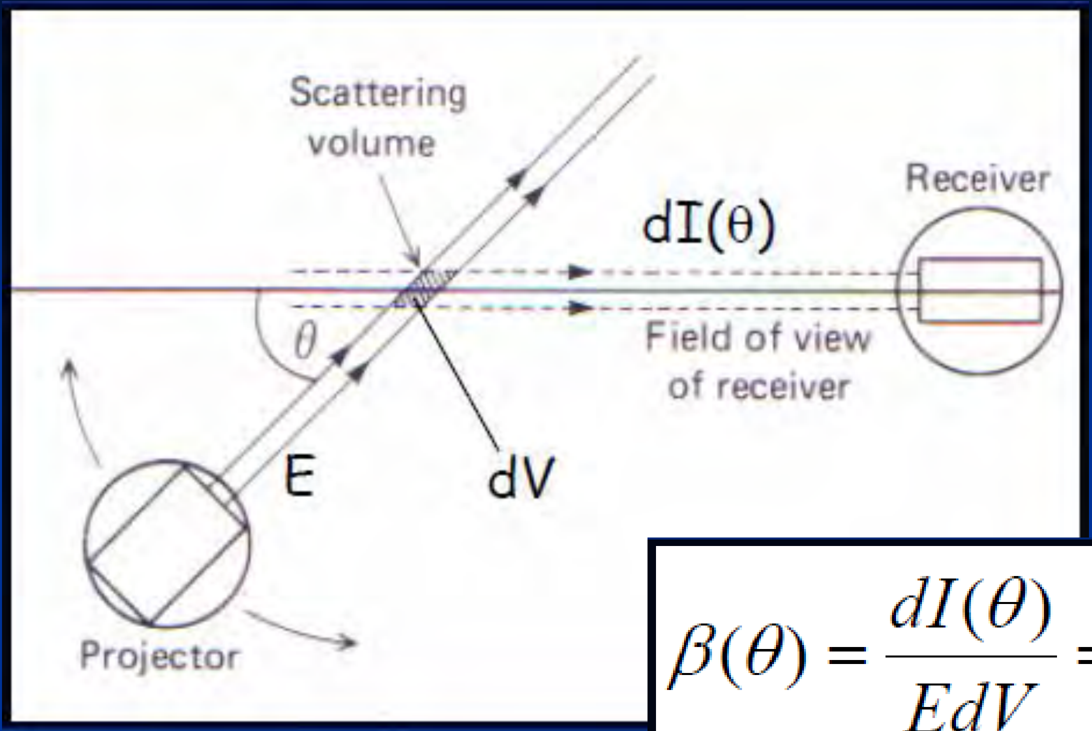
dI(θ): radiant flux in direction θ

$$\beta(\theta) = \frac{dI(\theta)}{EdV} = \frac{W \cdot sr^{-1}}{W \cdot m^{-2} \cdot m^{3}} = m^{-1} \cdot sr^{-1}$$

scattering coefficient (*b*):

$$b = 2\pi \int_{0}^{\pi\ (180^\circ)} \sin(\theta)\, \beta(\theta)\, d\theta$$

Volume Scattering Function (VSF): $\beta(\theta)$



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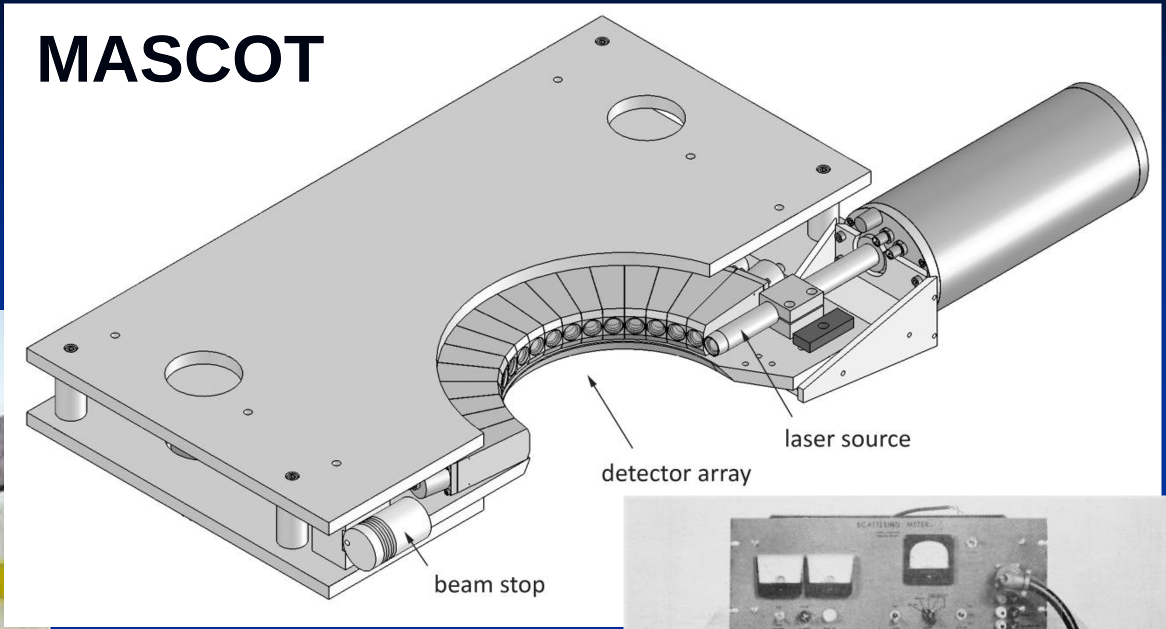
$$\beta(\theta) = \frac{dI(\theta)}{EdV} = \frac{W \cdot sr^{-1}}{W \cdot m^{-2} \cdot m^{3}} = m^{-1} \cdot sr^{-1}$$

backscattering coefficient (b_b):

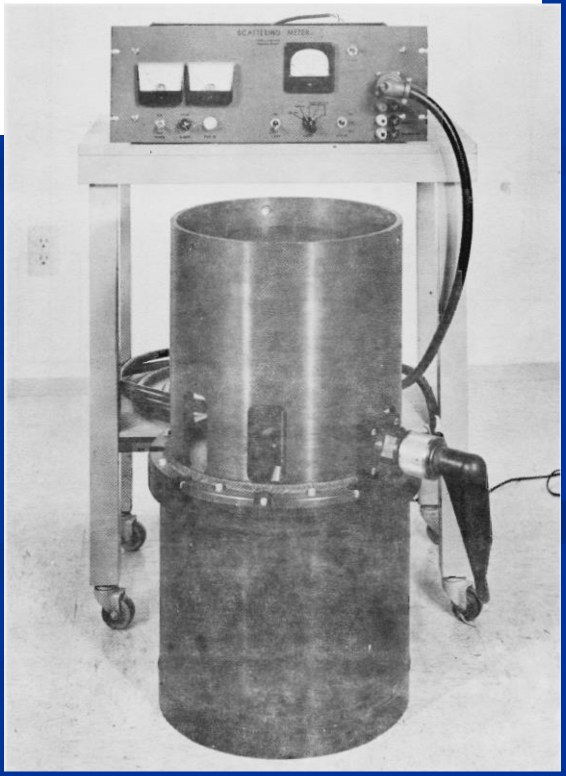
$$b_b = 2\pi \int_{\pi/2\ (90°)}^{\pi\ (180°)} \sin(\theta)\, \beta(\theta)\, d\theta$$

Prototype instruments:

Broad angular range VSF devices:



MVSM



Petzold's GASM

With the full VSF:

$$b_b = 2\pi \int_{\pi/2\ (90^\circ)}^{\pi\ (180^\circ)} \sin(\theta)\, \beta(\theta)\, d\theta$$

However, if we assume a "constant" VSF shape or phase function (Oishi 1990):

$$b_b = 2\pi\ \chi(\theta)\ \beta(\theta)$$

$\uparrow$

single angle VSF measurement

Commercial b_b instruments:

Single and multi-angle VSF devices (single or multi-wavelength):

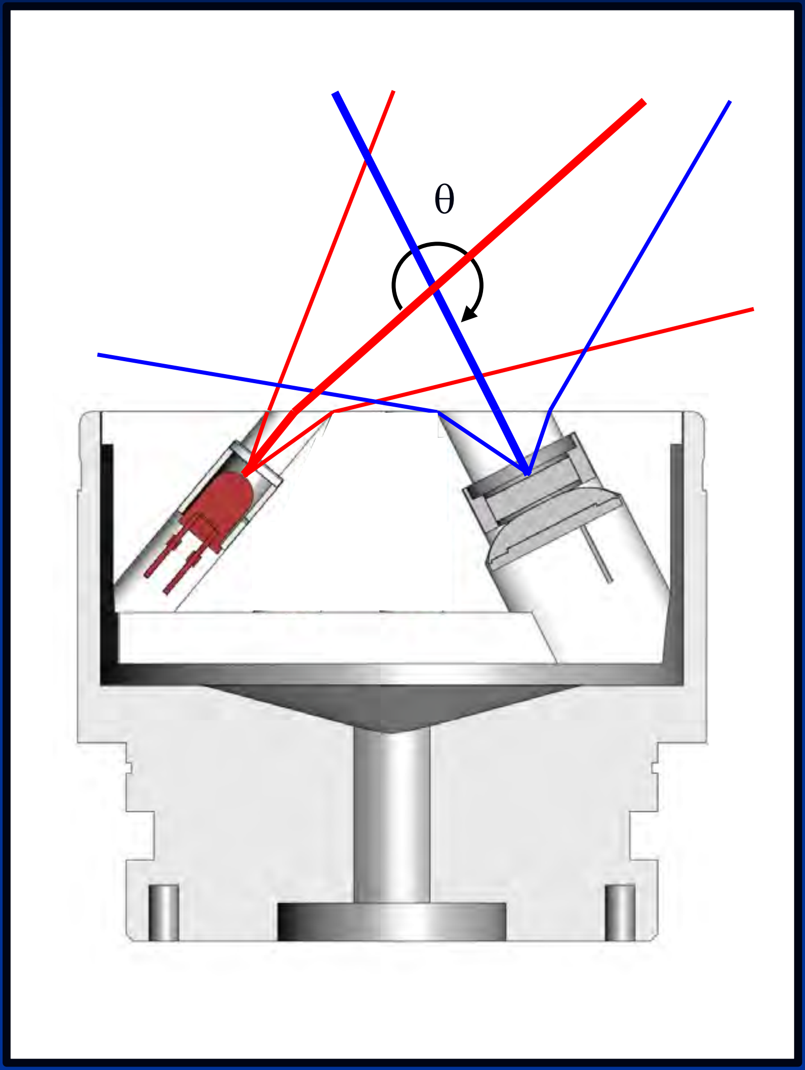
Hydroscat

Eco-BB & Eco-VSF

LISST-VSF

MCOMS

Characterization overview: design and geometry

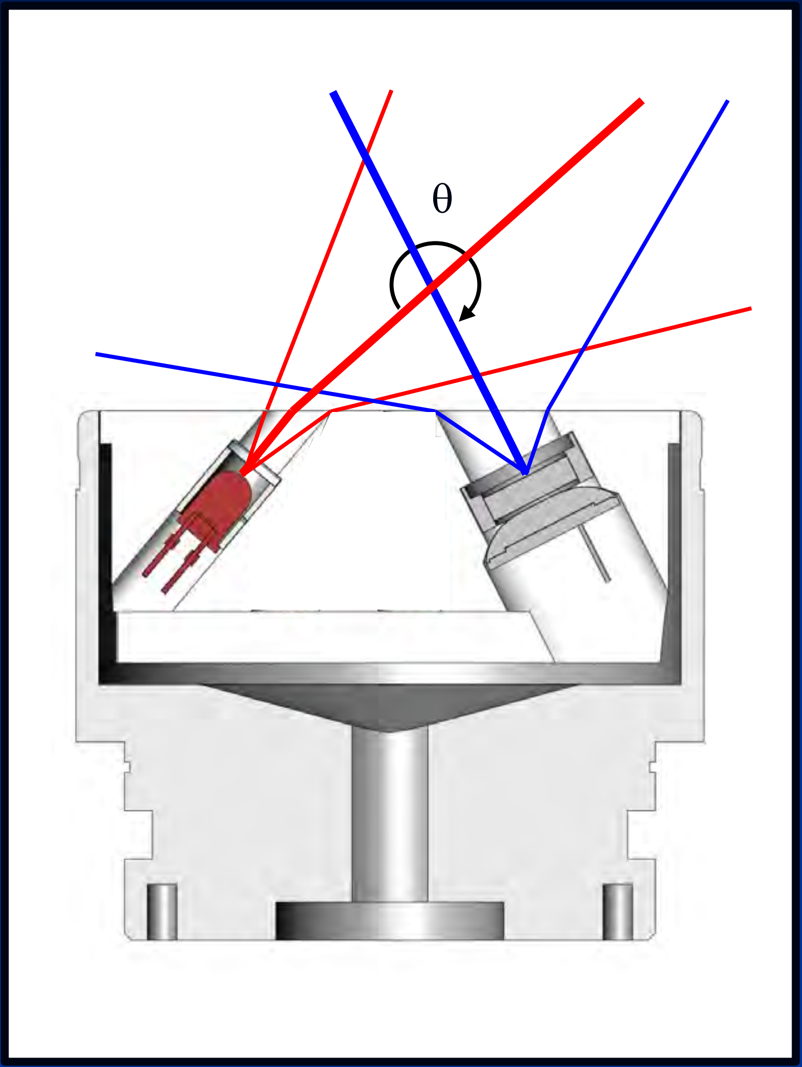


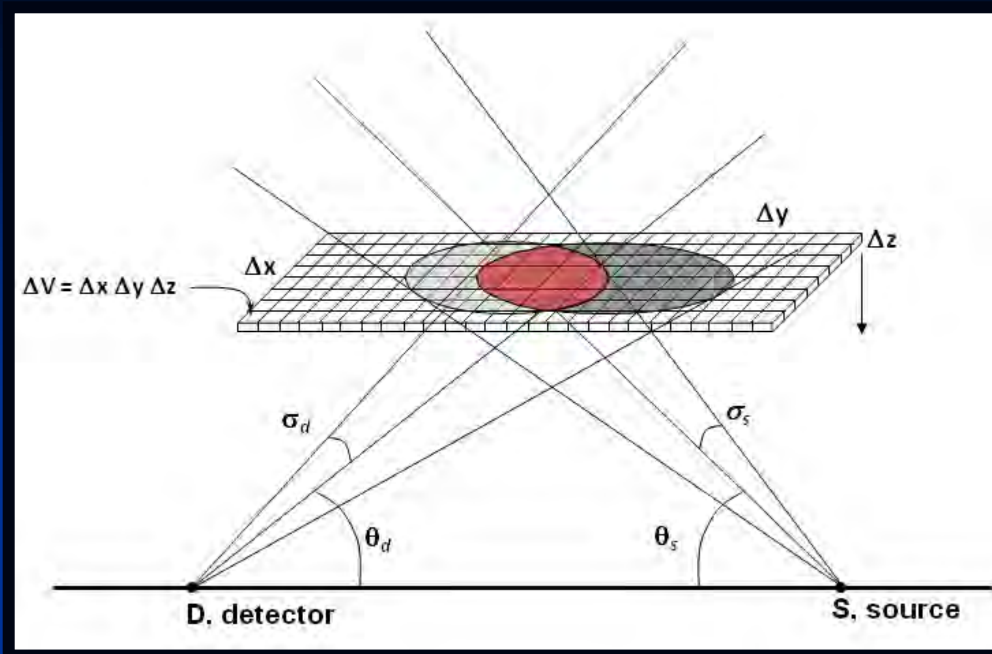
light source and detector pair
(LED & photodiode w/ filter)

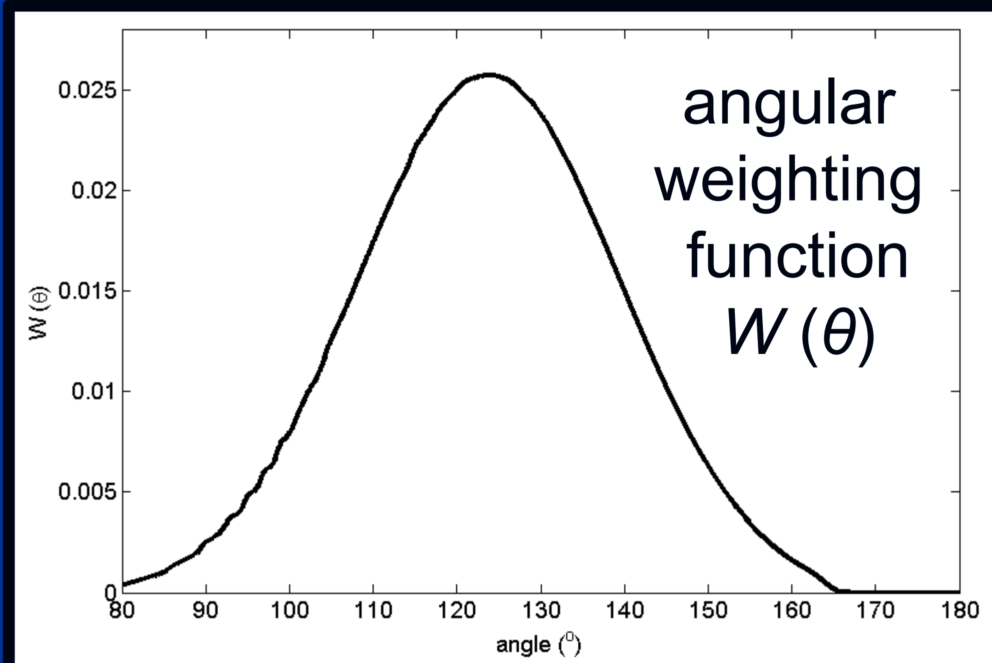
broad angular response

need to determine this response or angular weighting function: $W(\theta)$

Virtual plaque



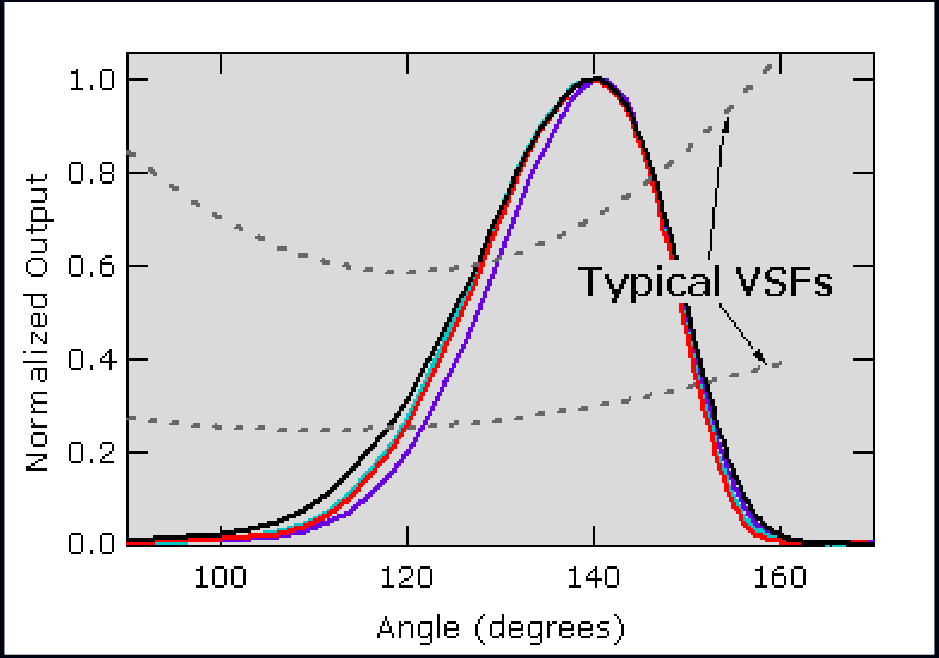




Sullivan et al. 2013

Experimental plaque

angular weighting function $W(\theta)$



Maffione & Dana 1997

Potential uncertainties in $W(\theta)$

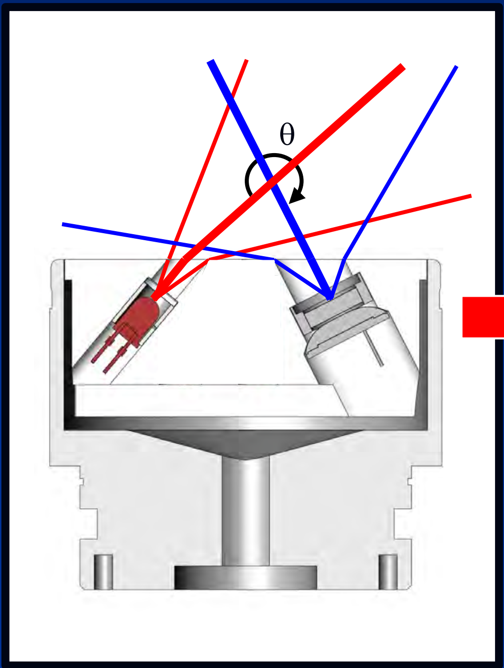
virtual plaque

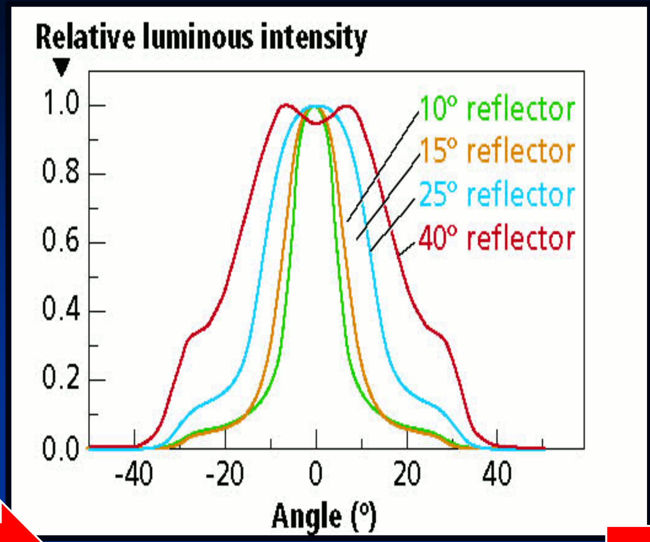
LED spot, detector spatial response, machining and build variation, epoxy/window clarity…

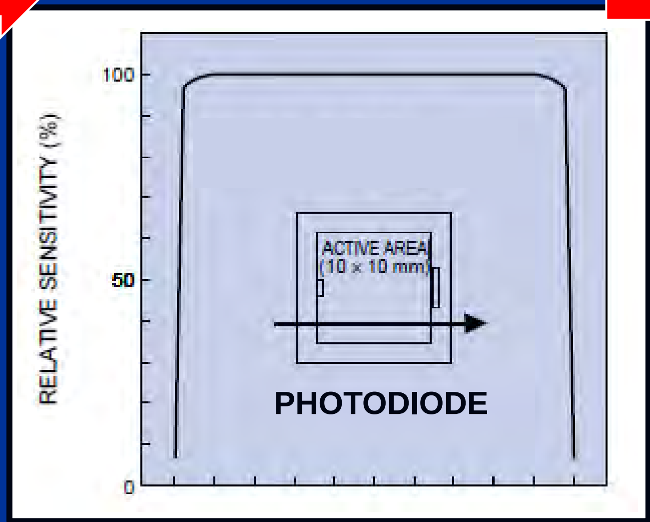
experimental plaque

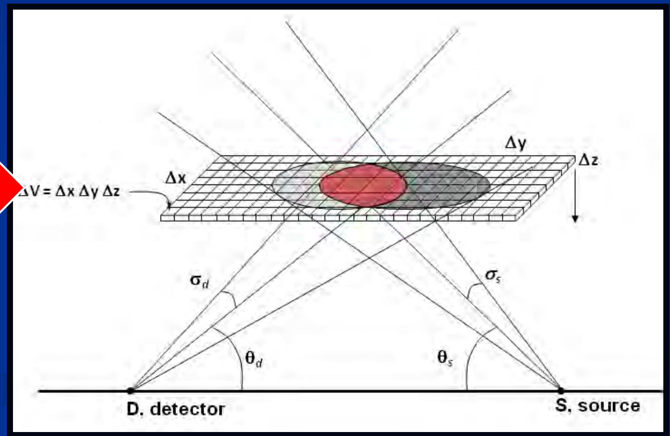
absolute reflectance of plaque, lateral scattering on plaque, gain ratio, K_{bb}, attenuation correction…

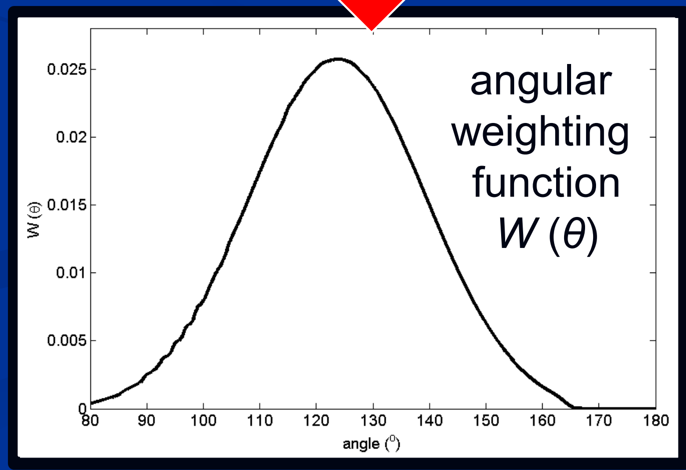




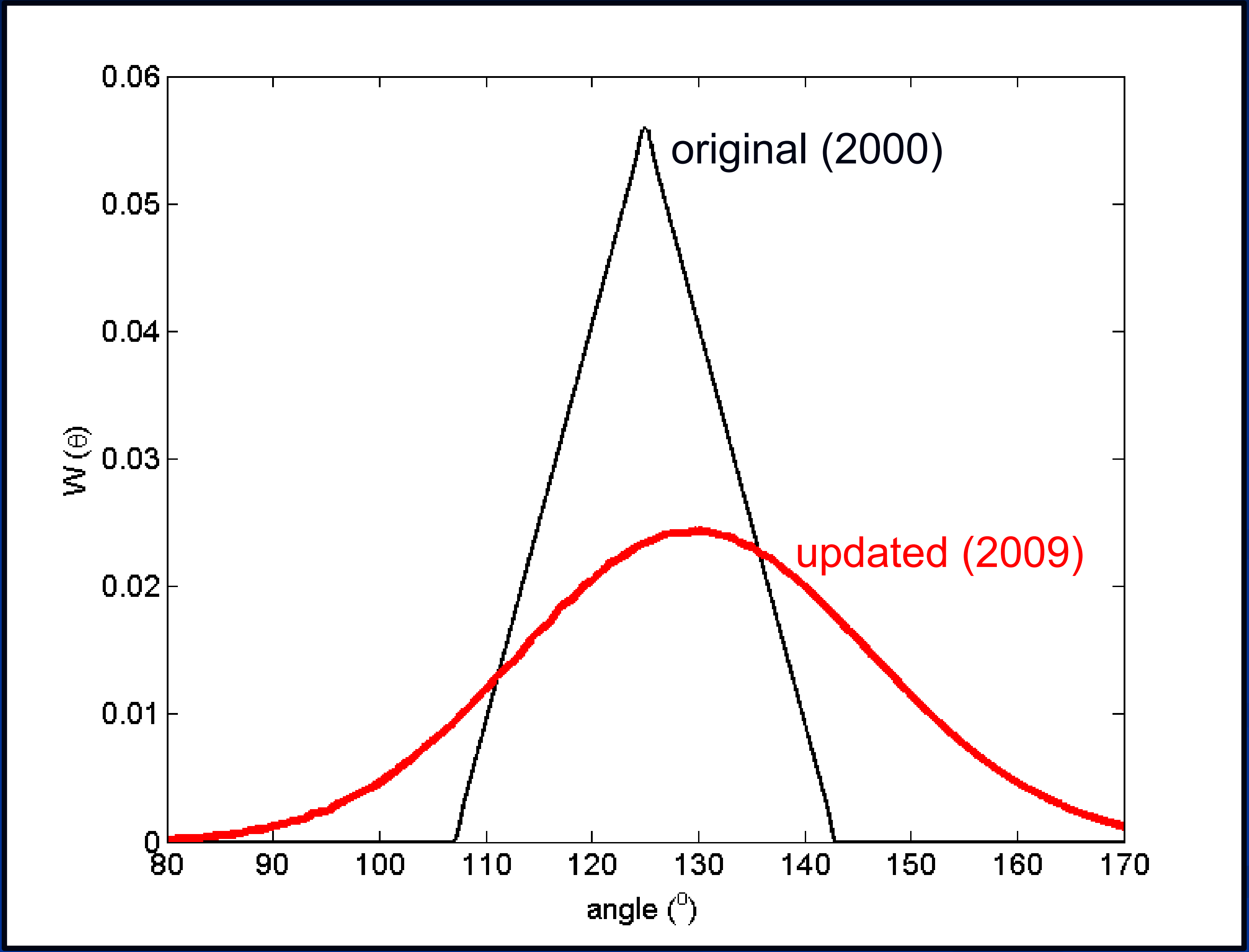






Idealized *W*(θ) for all instruments of this design

Updated $W(\theta)$



Bead calibration overview:

1. Compute $\beta(\theta)/b$ for NIST bead solution and convolve with $W(\theta)$: $\beta(\bar{\theta})/b$

2. Measure sensor counts and b in a bead solution concentration series and obtain slope, $b\,/$counts.

3. Compute scaling factor, SF:

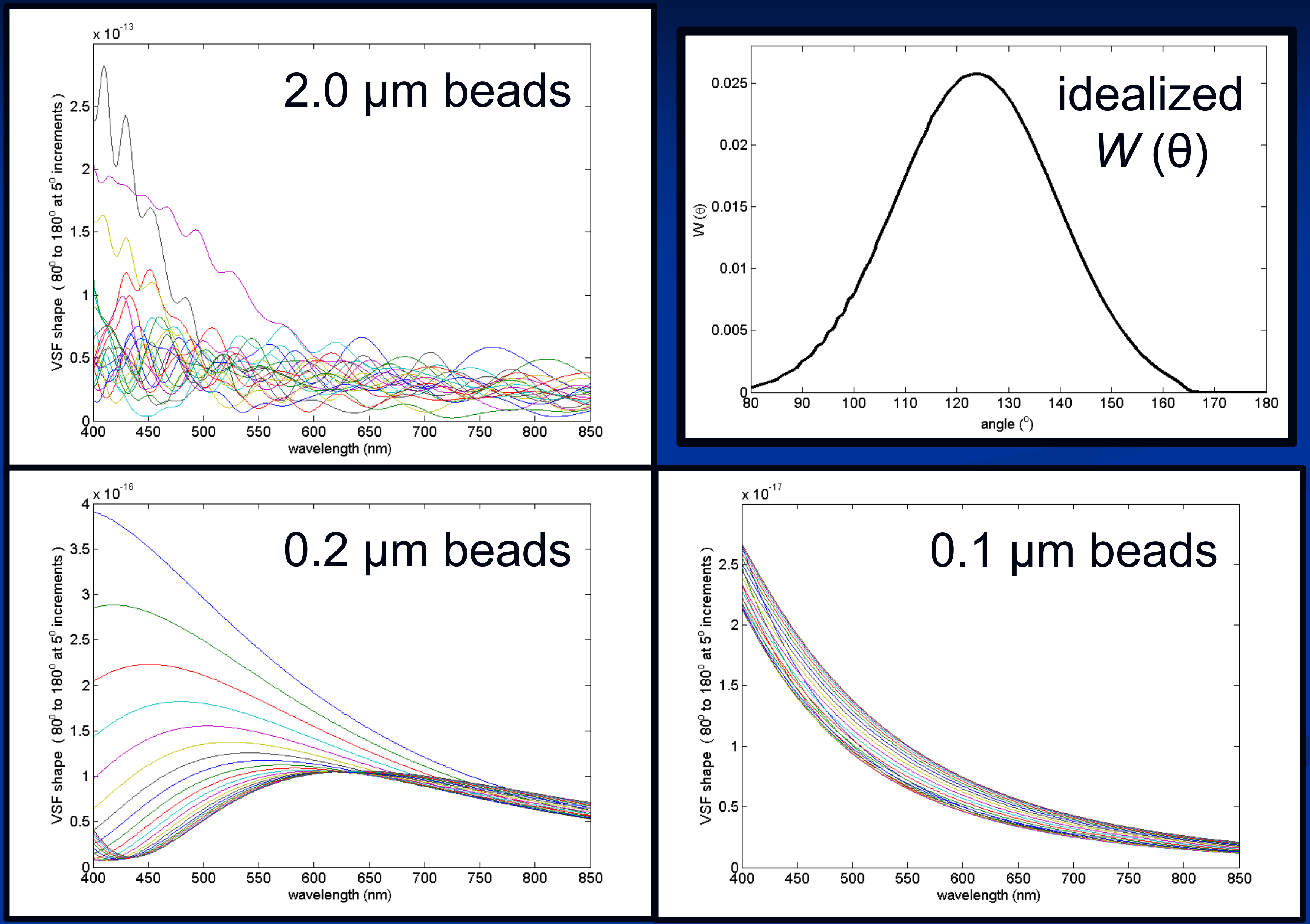
$$SF = \frac{\beta(\bar{\theta})}{b}\frac{b}{counts} = \frac{\beta(\bar{\theta})}{counts}$$

Bead calibration uncertainties

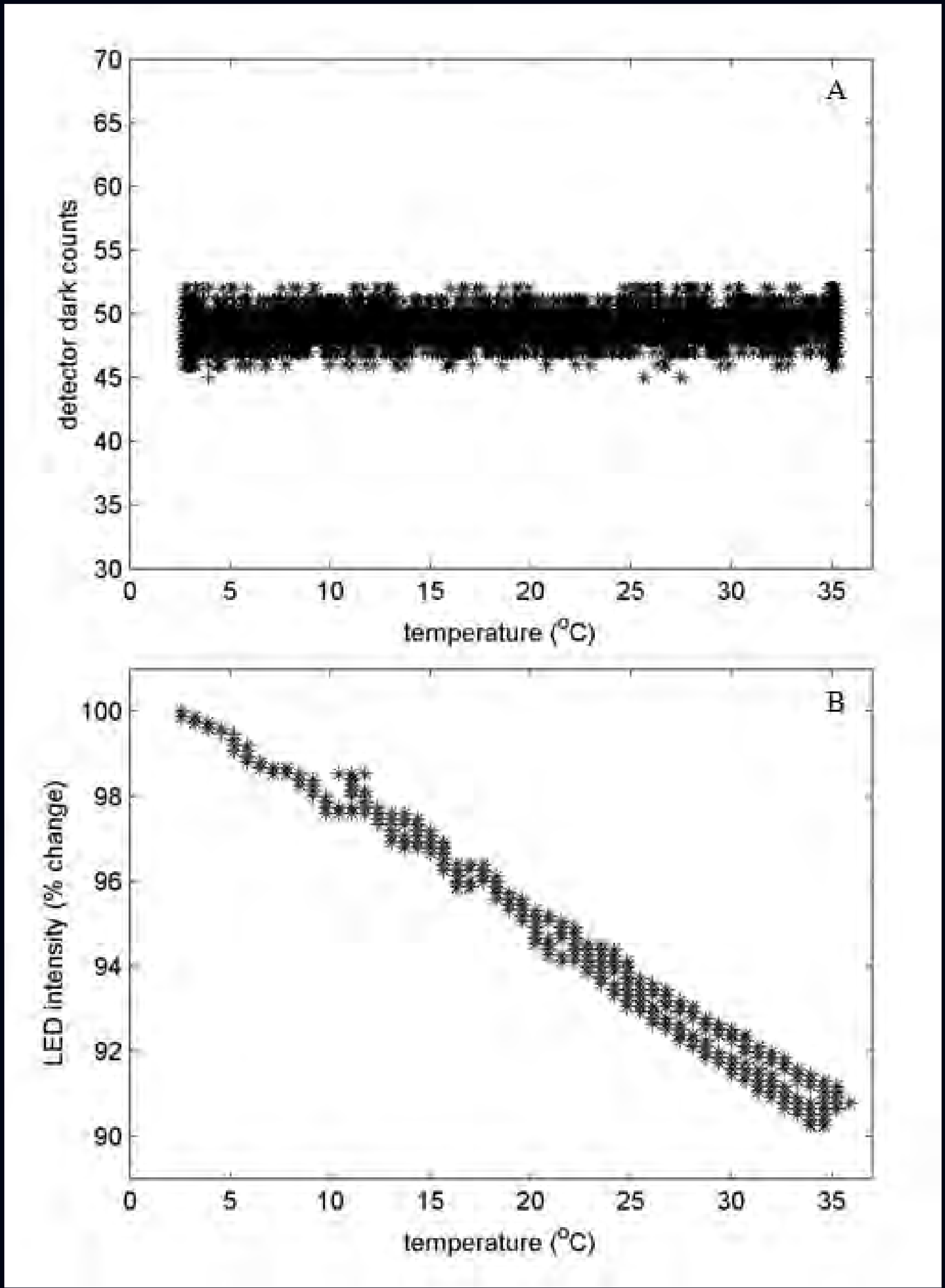
W (θ) & bead size choice (~5 to 10%, should be ~1%)
dark counts (<1%)
temperature (potentially 5%, red LEDs only)
calibration slope uncertainties (should be <1%)
unknown sensor centroid wavelength (~ 0 – 5%)
tank particle contamination during cal (QC check)
bubbles/particles on sensor head optics (large error)

<u>Best case total calibration uncertainty: 2-5%</u>

Spectral -angular VSF shape of NIST beads



ECO temperature dependence

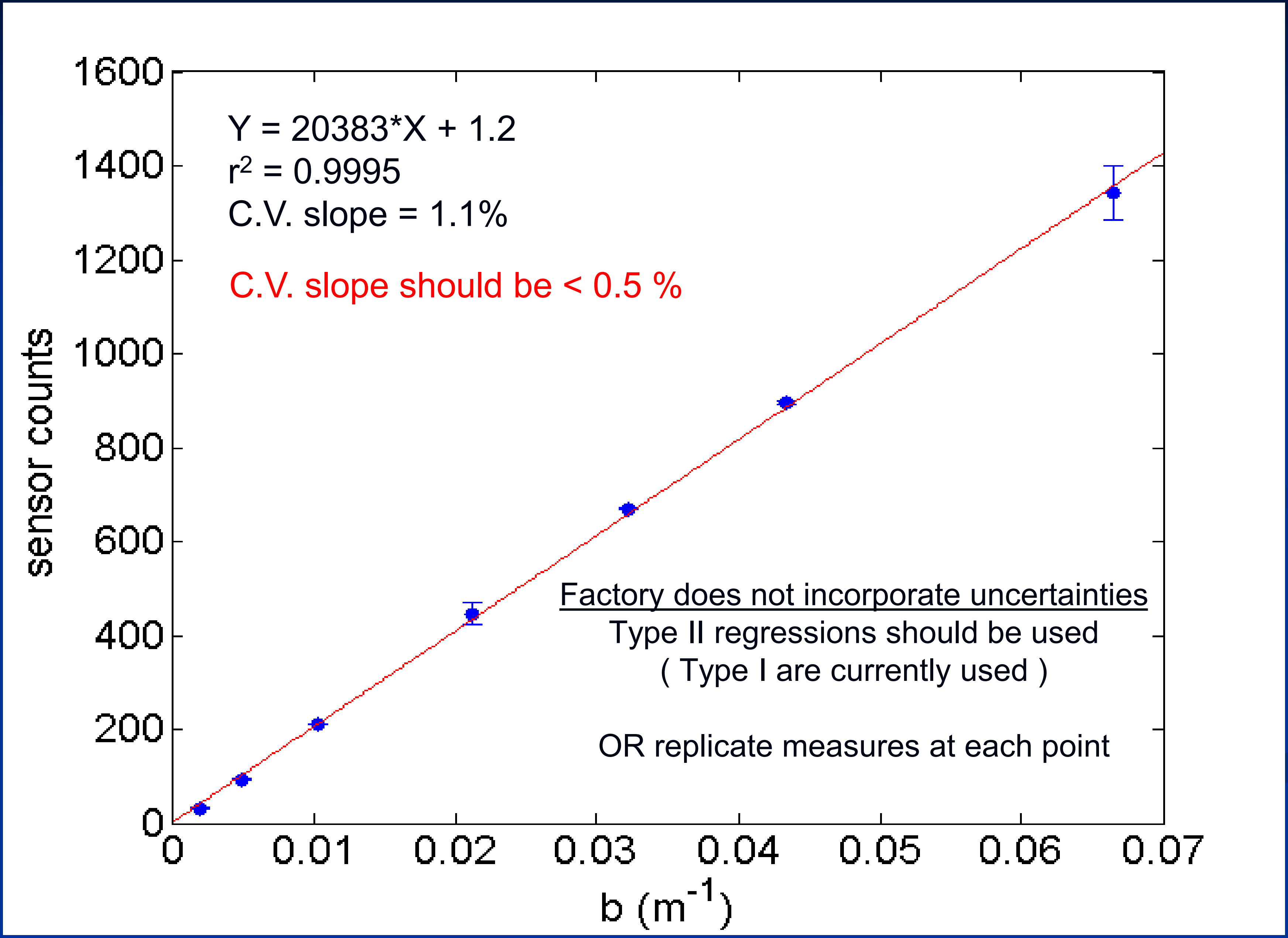


dark counts not affected

~10% variation over full oceanic temperature range (red LEDs)

* tank water during cal

Calibration slope considerations



Sensor centroid wavelength uncertainty

(Factory gives "standard" wavelengths)

factory λ	scaling factor	actual λ	scaling factor	$\Delta\lambda$ (nm)	% diff scaling factor
412	2.428E-05	409	2.500E-05	3	2.9
440	1.572E-05	441	1.557E-05	-1	-1.0
488	2.592E-05	488	2.592E-05	0	0.0
510	1.185E-05	508	1.204E-05	2	1.6
532	1.015E-05	526	1.063E-05	6	4.6
595	6.368E-06	594	6.411E-06	1	0.7
660	5.651E-06	652	5.936E-06	8	4.9
676	4.038E-06	679	3.967E-06	-3	-1.8
715	3.637E-06	717	3.596E-06	-2	-1.1

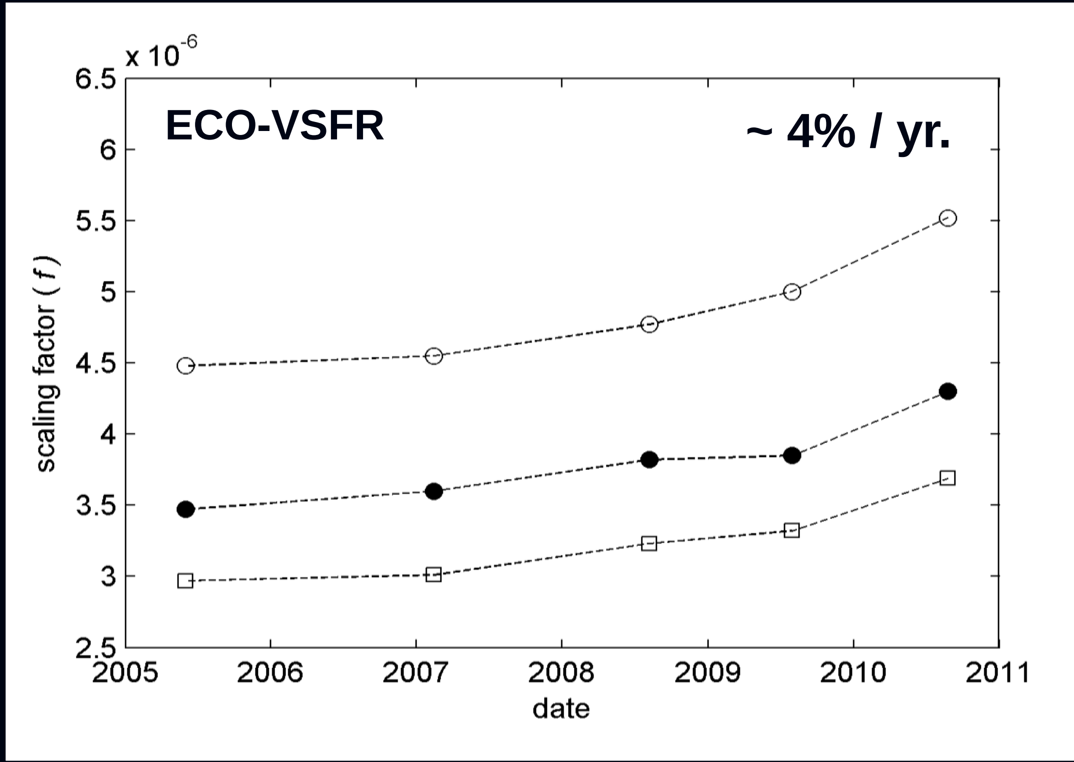
Bead calibration uncertainties

W (θ) & bead size choice (~5 to 10%, should be ~1%)
dark counts (<1%)
temperature (potentially 5%, red LEDs only)
calibration slope uncertainties (should be <1%)
unknown sensor centroid wavelength (~ 0 – 5%)
tank particle contamination during cal (QC check)
bubbles/particles on sensor head optics (large error)

<u>Best case total calibration uncertainty: 2-5%</u>

Calibration drift: ~ 2 to 10% per year (can be >)

Calibration drift:



ECO-BB9

cal date	403	443	487	506	525	594	657	680	720
	wavelength (nm)								
12/12/2013	1.18E-04	1.20E-05	2.36E-05	7.42E-06	7.01E-06	4.30E-06	3.74E-06	3.30E-06	2.75E-06
6/11/2014	1.42E-04	1.20E-05	2.45E-05	7.64E-06	7.04E-06	4.70E-06	3.99E-06	3.34E-06	2.95E-06
9/5/2014	1.50E-04	1.23E-05	2.47E-05	7.77E-06	7.18E-06	5.04E-06	4.14E-06	3.43E-06	3.02E-06
% change	23.9	2.4	4.6	4.6	2.5	16.0	10.2	3.7	9.1

blue λ channels typically have the largest drift (epoxy?)

Data processing

$\beta_t(\theta)$ = SF * (measured counts – dark counts) * e^{La}

calibration scaling factor

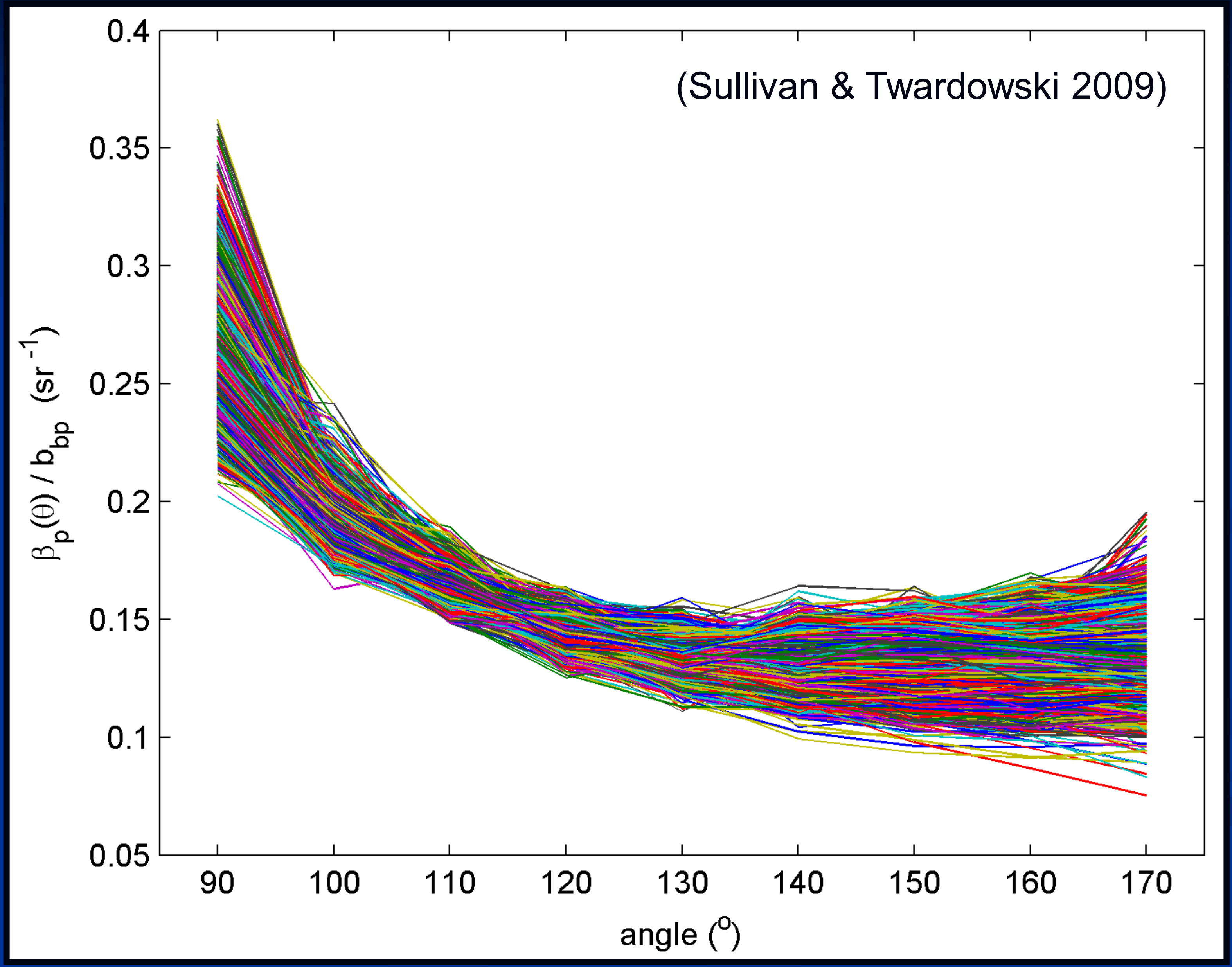
attenuation correction
(L = path length, a = total absorption)

$\beta_p(\theta) = \beta_t(\theta) - \beta_w(\theta)$ (Boss & Pegau 2001; Zhang et al. 2009)

$b_{bp} = 2\pi * \chi_p(\theta) * \beta_p(\theta)$

total $b_b = b_{bp} + b_{bw}$

How constant are particulate phase functions?



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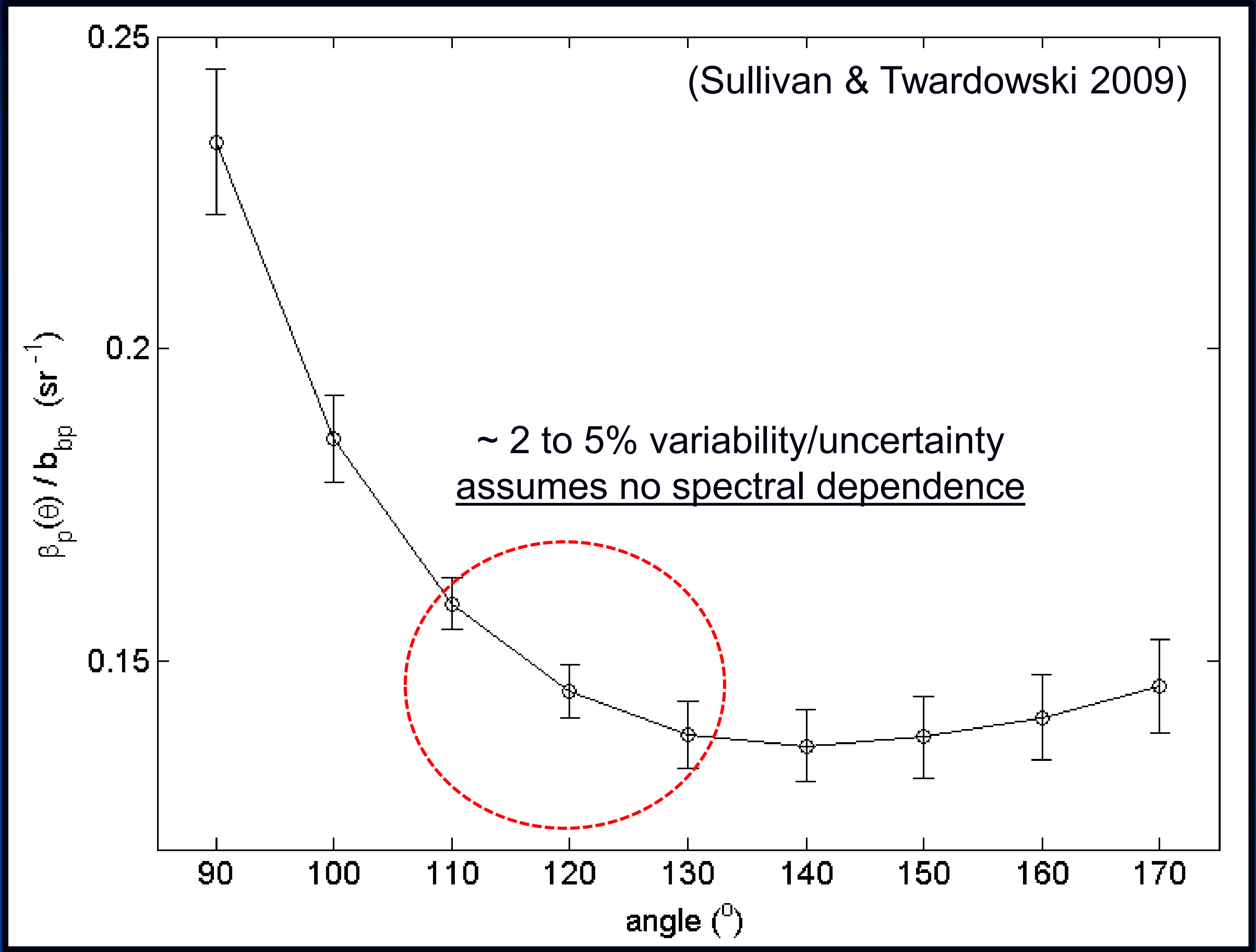
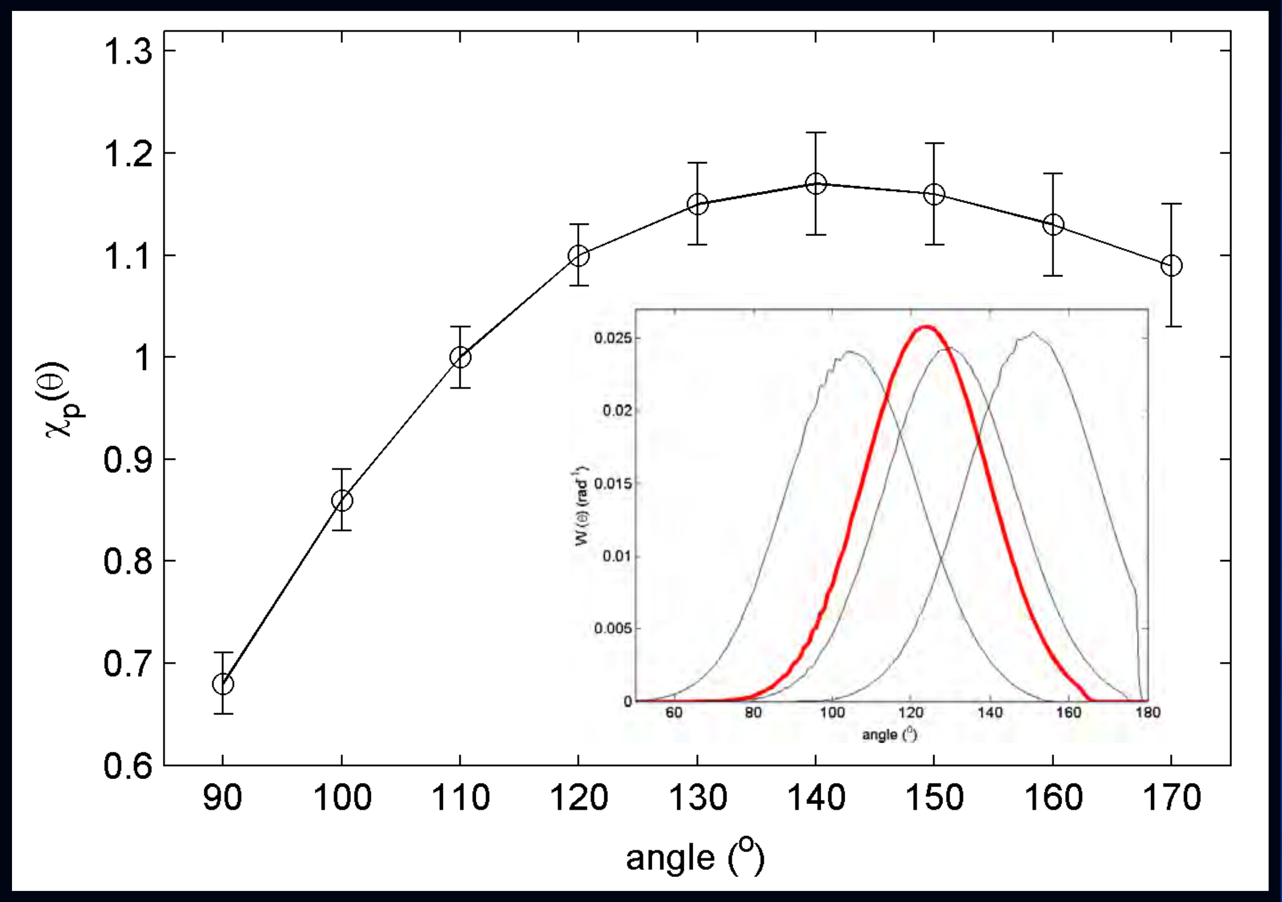


Oishi 1990, Maffione & Dana 1997, Boss & Pegau 2001

χ_p factors ($\chi_p(\theta) = b_{bp} / \beta_p(\theta) * 2\pi$)



ECO centroid angle $\bar{\theta}$ (°)	104	124	130	151
$\chi_p(\bar{\theta})$	0.89	1.076	1.104	1.138

Sullivan et al. 2013

Basic deployment protocols

Recalibration (1-2 times per year, 0.1 μm NIST beads)

In-situ dark counts (each deployment, if possible)

- **EMI/power issue check**

Mounting (no reflections or obstructions in large FOV)

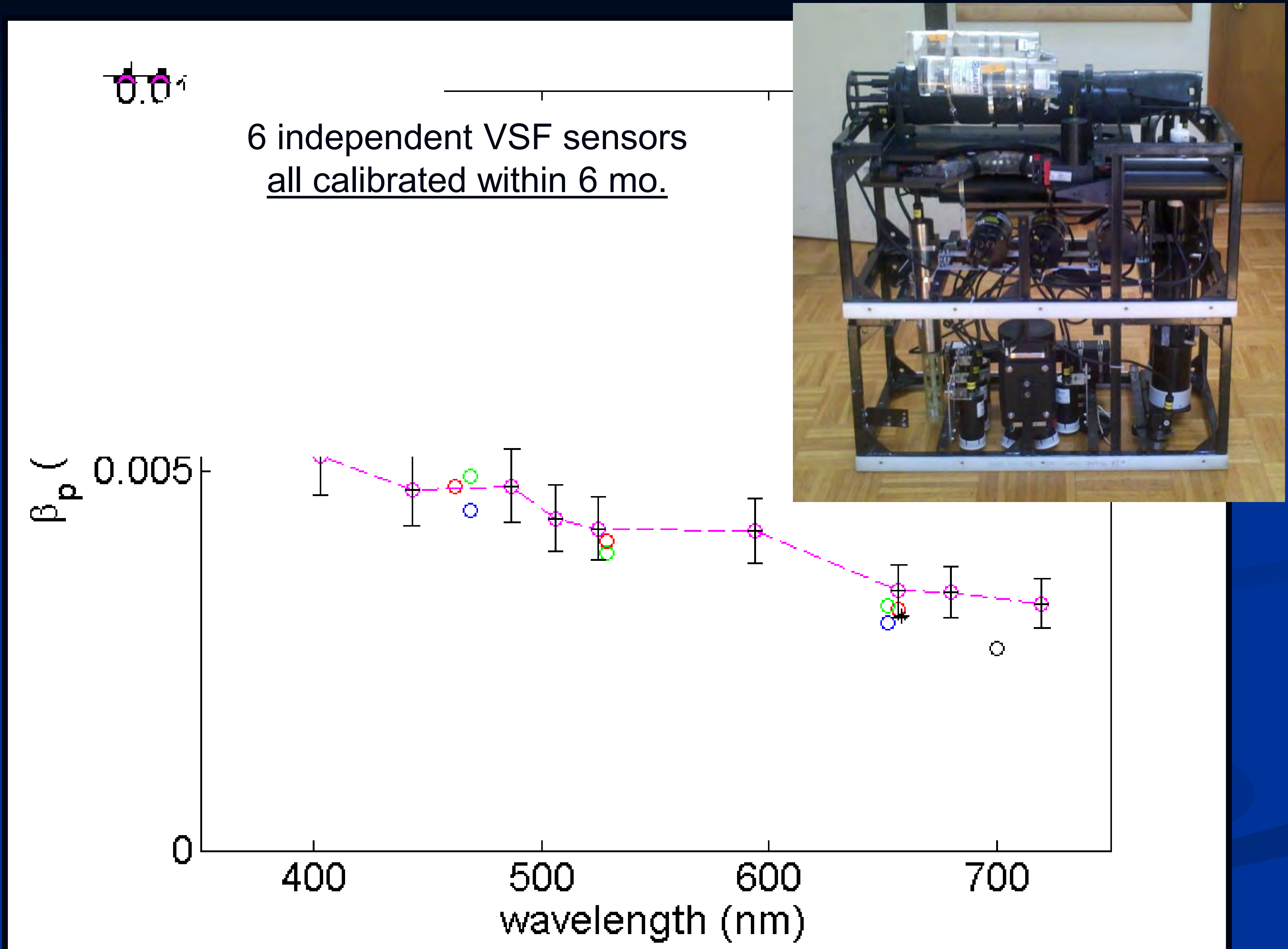
Clean optical faces (each deployment, if possible)

Recognize temperature effects (red LEDs)

- **cold water calibration**

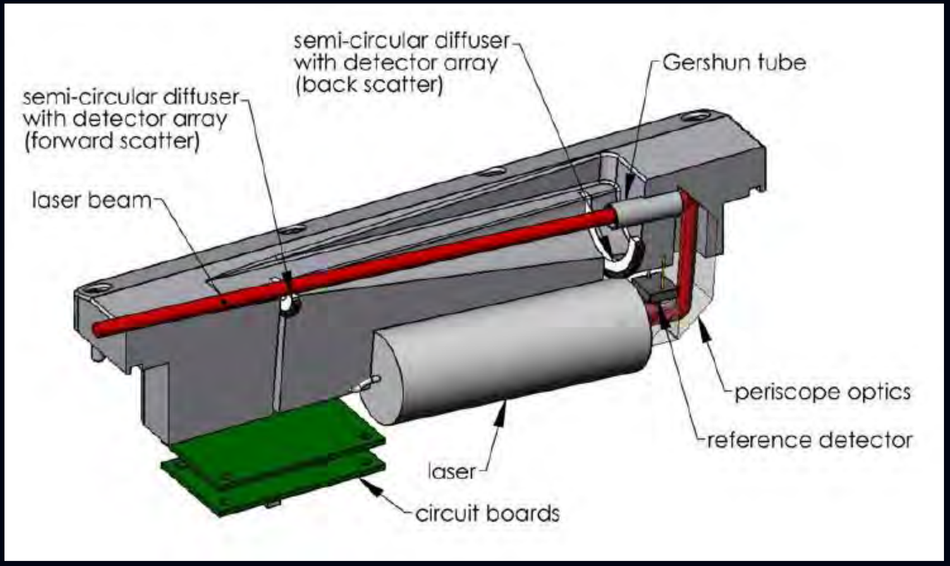
Data averaging /spikes

- **each channel is independent**



< 5% uncertainty achievable

New instrument designs and future needs



Integrated total b and b_b meter (Ed Fry)

LISST-VSF

Hyperspectral b_b, VSF/b_b of polarized elements, high/low gain switching, reference correction, improved optics…

Revision straw man:

1. Introduction: VSF measurement and instruments
   - update current instruments, future designs and needs
2. Instrument characterization and calibration: beads.
   - update geometry and weighting functions
   - update calibration methods
   - update calibration uncertainties
3. Instrument characterization and calibration: reflective plaque.
   - update as needed?
4. Estimating b_b from single/multiple VSF measurements.
   - update χ factors, pure seawater b_{bw} …
5. <u>Measurement uncertainties</u>
   - summarize known
   - discuss unknowns? (spectral χ, depolarization ratio for b_{bw})
6. <u>Deployment protocols (in-situ dark counts, mounting, etc.)</u>

COMMENTS?