Backscattering (VSF) Protocols: Review and revision with emphasis on WET Labs sensors

Jim Sullivan, Mike Twardowski, Wayne Slade, Jeremy Werdell and everyone else in this room…

Last revision: Vol. IV - 2003

Chapter 5

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

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Additionally in Chapter 1 (IOPs) - scattering by pure seawater and particles, scattering measurement concepts (VSF and b_b)

Topics covered in Chapter V:

1. Introduction: VSF measurement and instrument design

2. Instrument characterization and calibration: beads
   - geometry and weighting functions
   - path-length attenuation correction
   - calibration methods (not current)

3. Instrument characterization and calibration: reflective plaque
   - geometry and weighting functions (very brief)
   - calibration methods (referenced off)

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

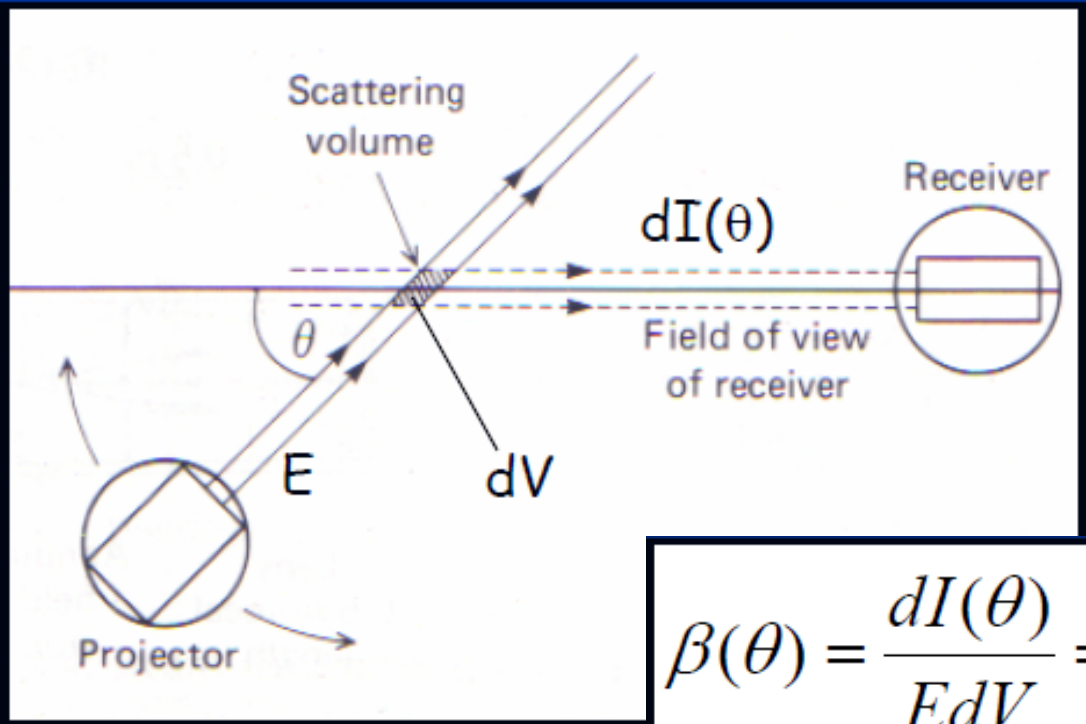
    New product lines have been introduced
    New instrument designs proposed/built

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

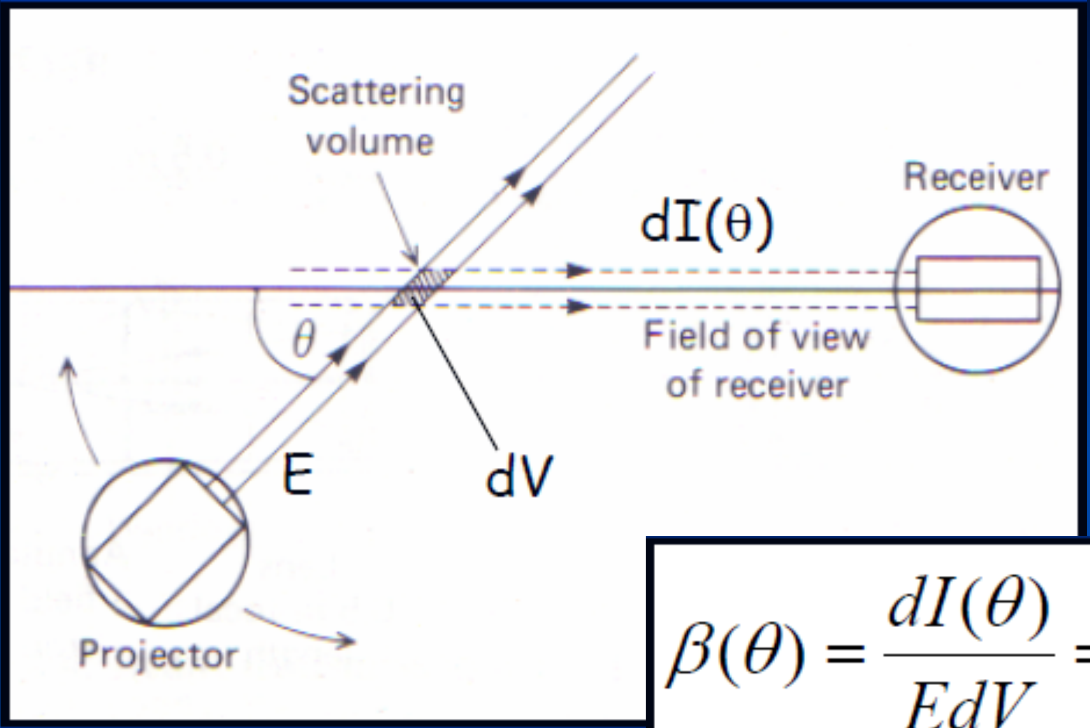
dI(θ): radiant flux in direction θ

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

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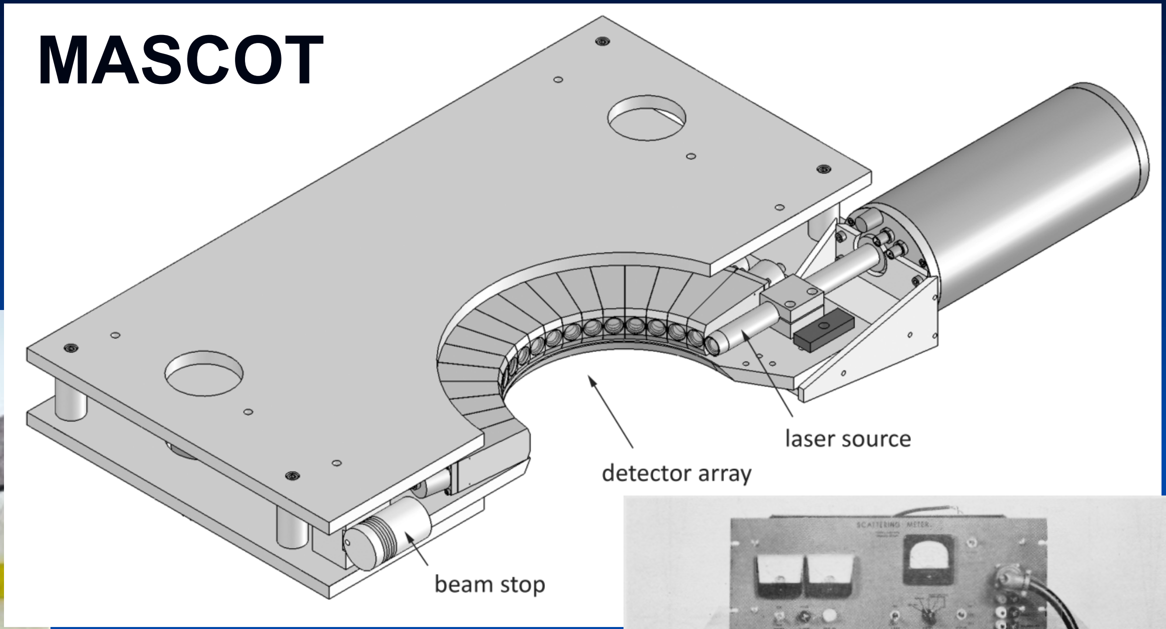
$$\beta(\theta) = \frac{dI(\theta)}{EdV} = \frac{W \cdot sr^{-1}}{W \cdot m^{-2} \cdot m^{3}} = m^{-1} \cdot sr^{-1}$$

backscattering coefficient (b_b):

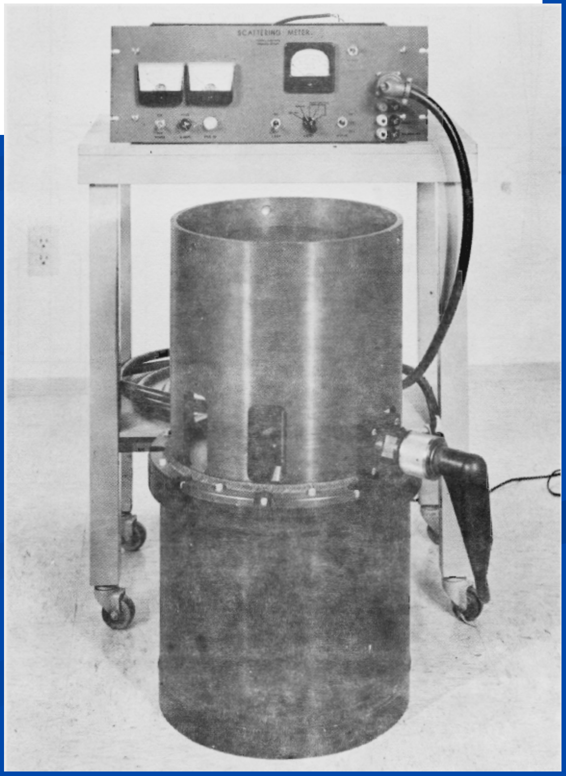
$$b_b = 2\pi \int_{\pi/2\ (90°)}^{\pi\ (180°)} \sin(\theta)\, \beta(\theta)\, d\theta$$

Prototype instruments:

Broad angular range VSF devices:



MVSM



Petzold's GASM

With the full VSF:

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

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):

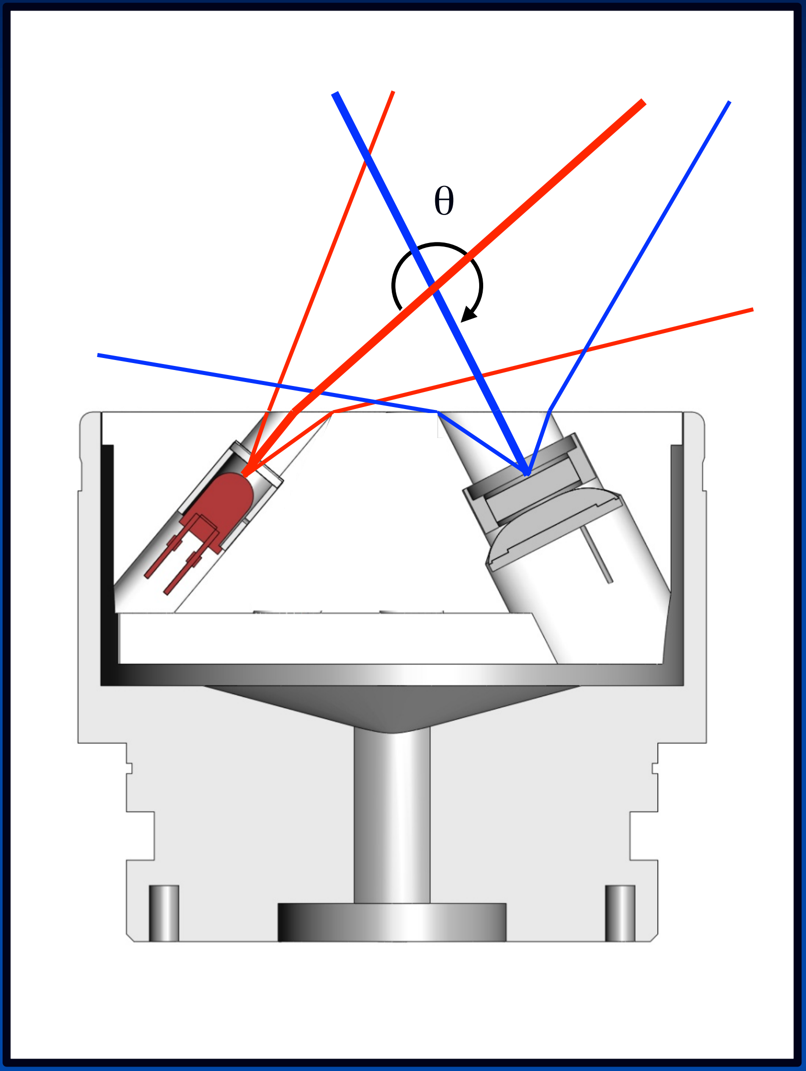
Hydroscat

Eco-BB & Eco-VSF

LISST-VSF

MCOMS

Characterization overview: design and geometry



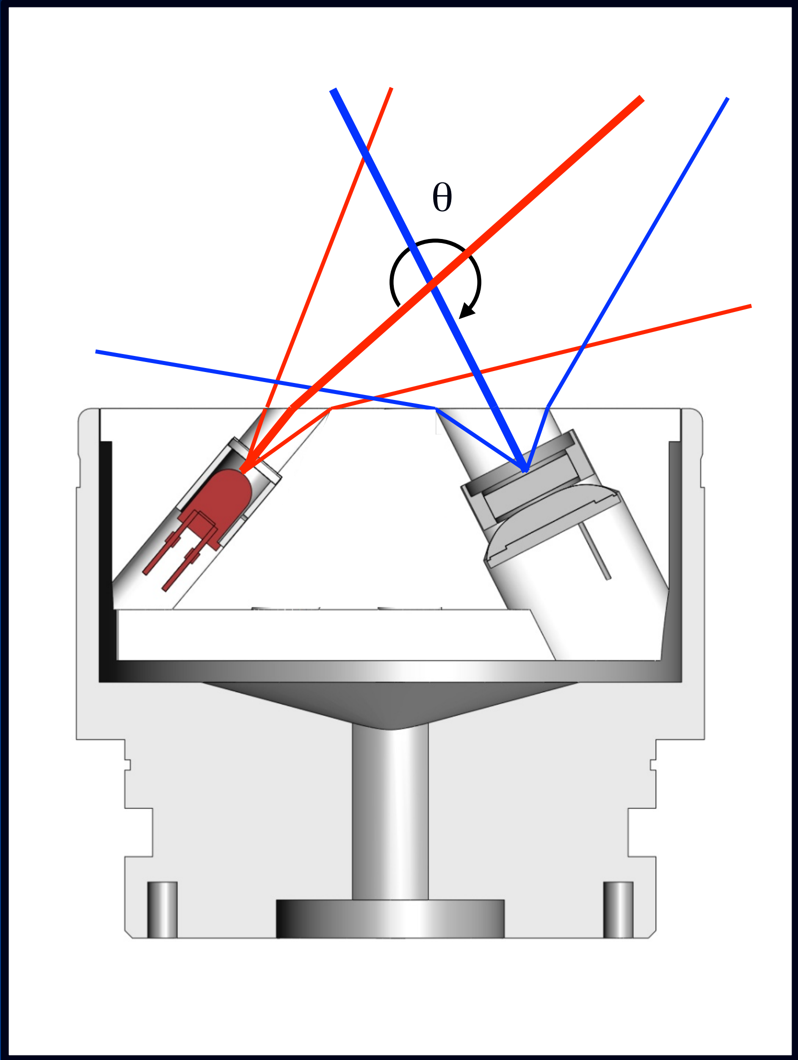
light source and detector pair
(LED & photodiode w/ filter)

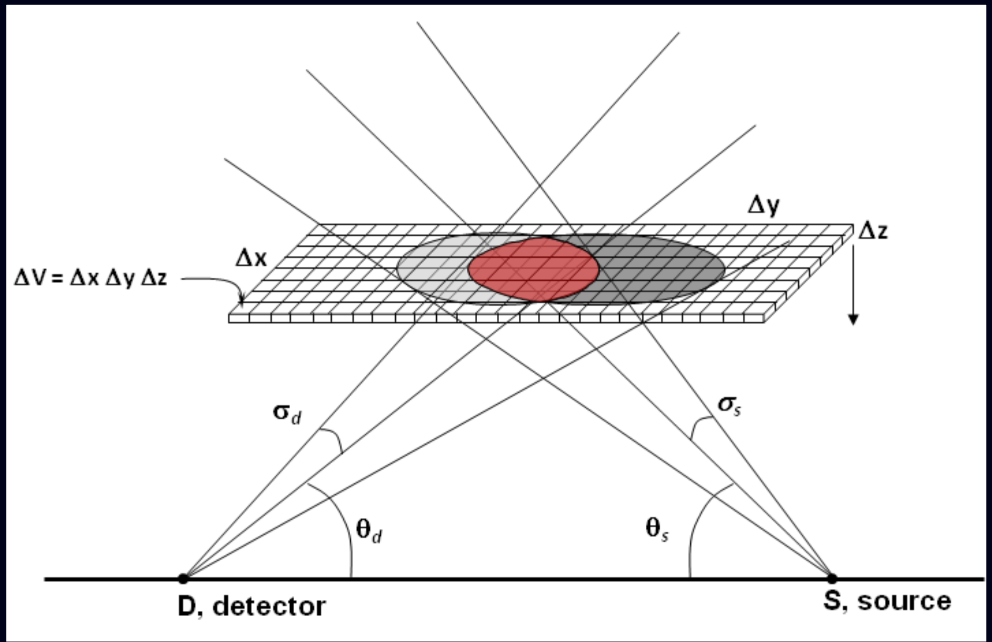
<u>broad angular response</u>

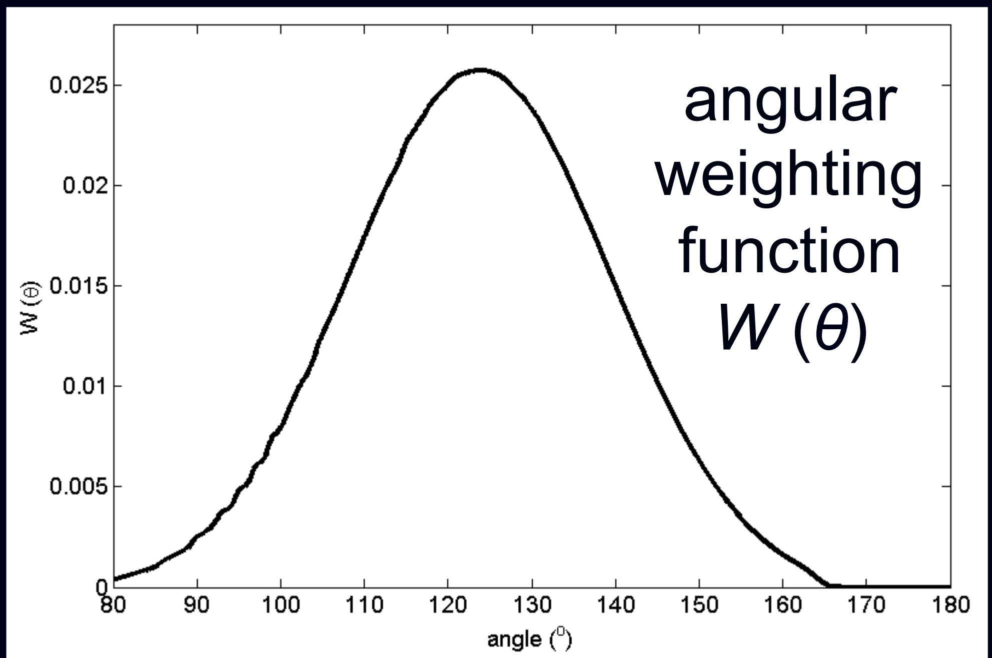
need to determine this response or angular weighting function: $W(\theta)$

"$W(\theta)$ accounts for instrument specific factors including the divergence and uniformity of the source beam and detector angular response function, the working volume geometry, variations in attenuation of flux scattered to the detector from different volume elements, and optical reflection and absorption losses in the system."

Virtual plaque (explicit)



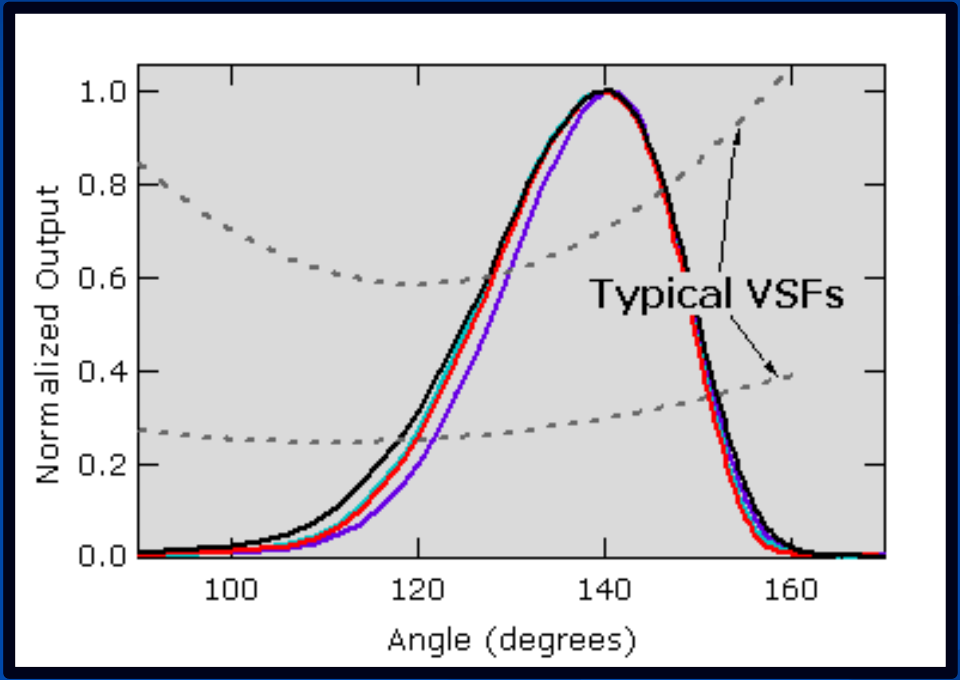




Sullivan et al. 2013

Experimental plaque (implicit)

angular weighting function $W(\theta)$

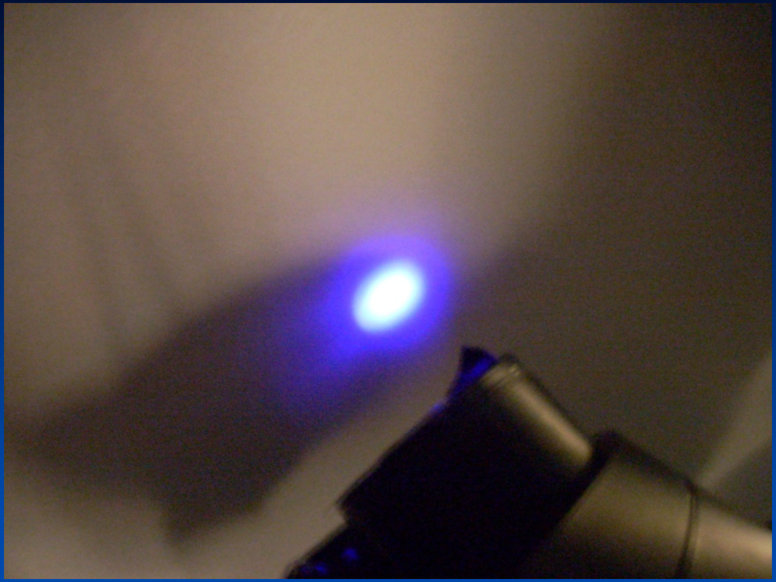


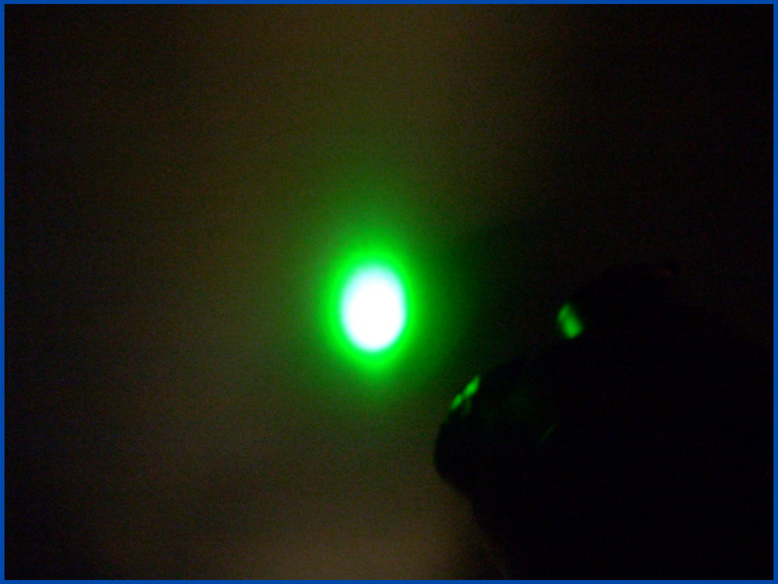
Maffione & Dana 1997

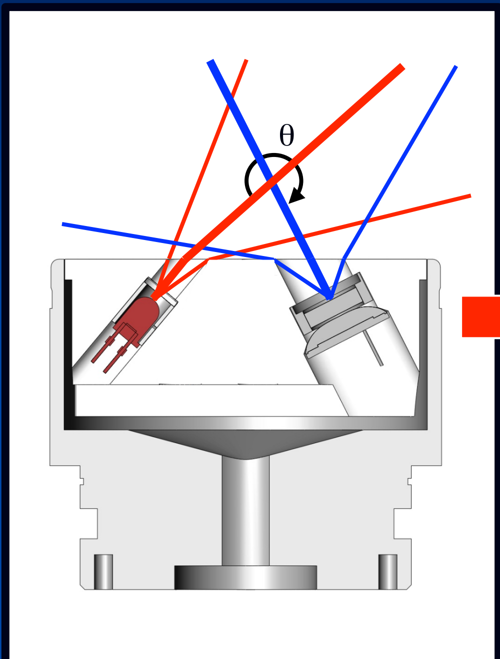
Potential uncertainties in $W(\theta)$

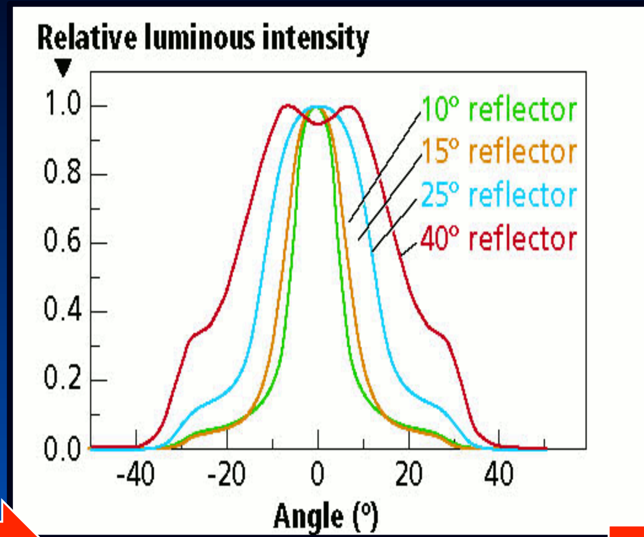
virtual plaque

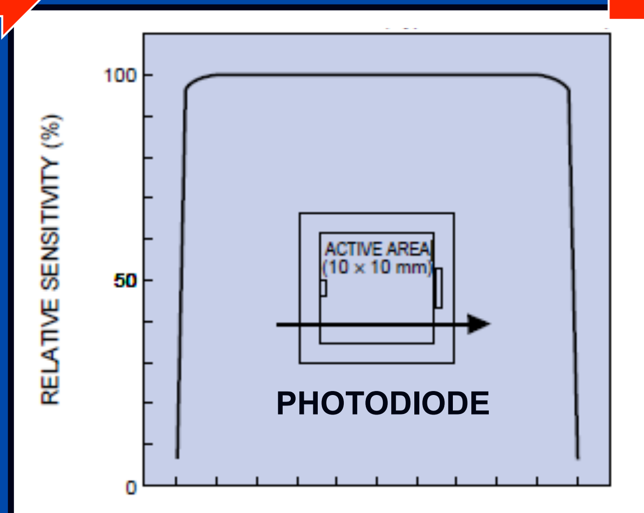
LED spot/intensity, detector spatial response, machining and build variation, epoxy/window clarity…

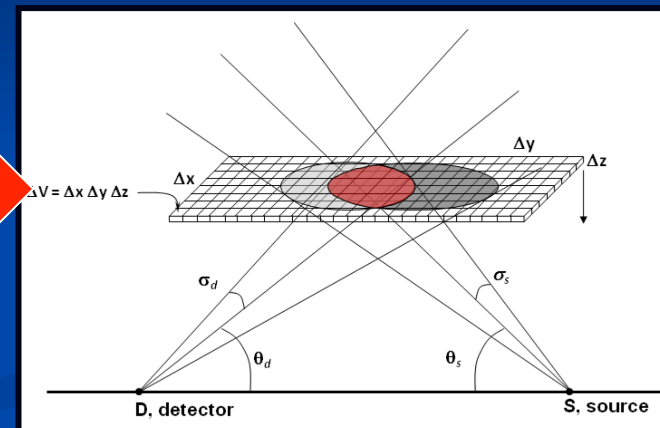


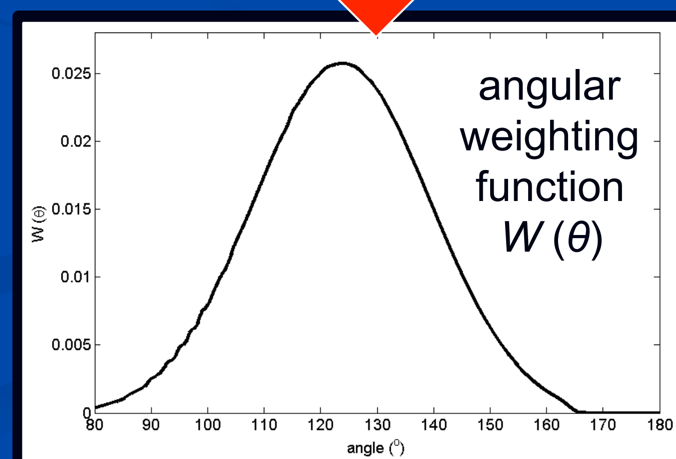




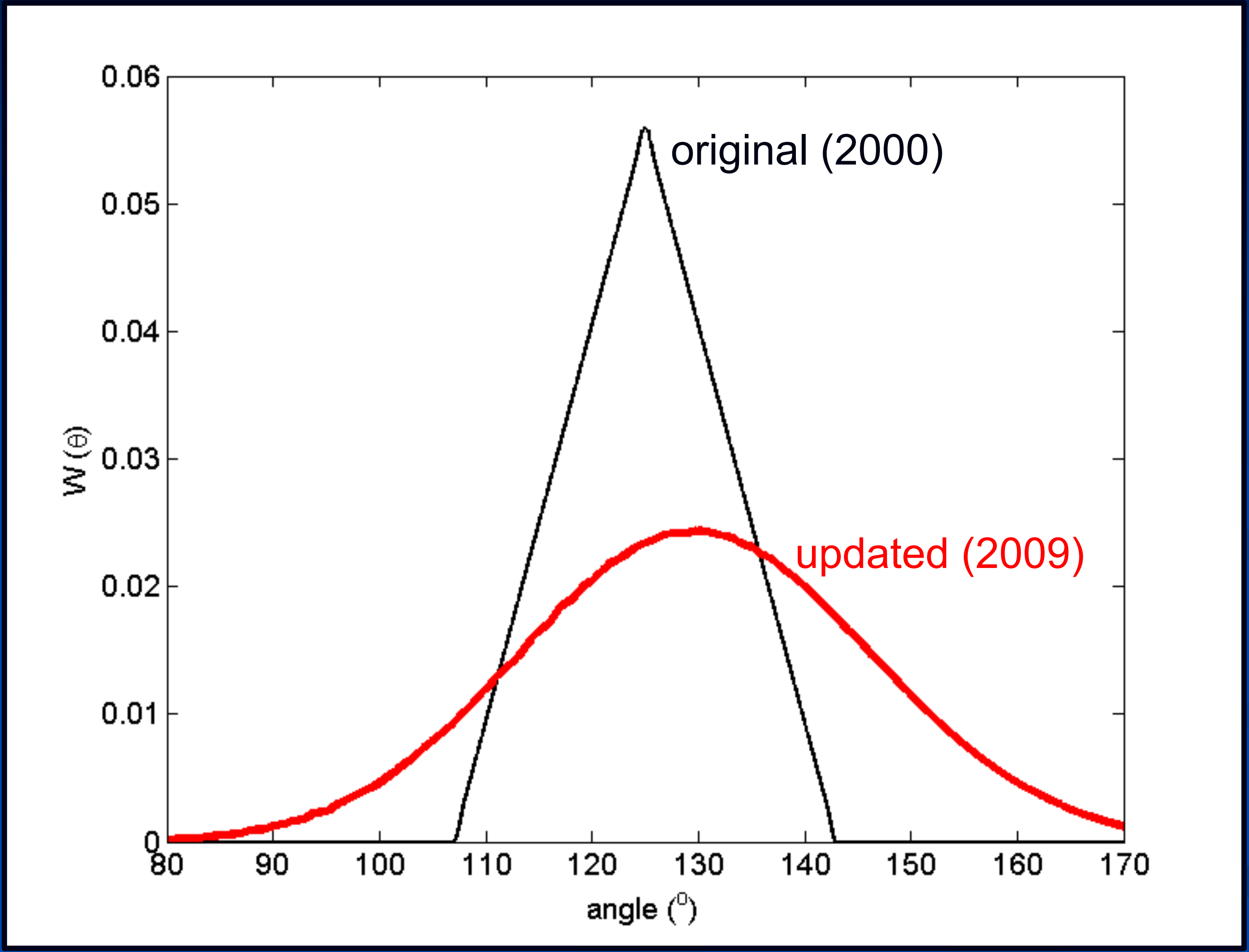






Idealized $W(\theta)$ for all instruments of this design

Updated $W(\theta)$



Potential uncertainties in $W(\theta)$

virtual plaque

LED spot/intensity, 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, LED intensity…

David Dana can elaborate

Bead calibration overview:

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

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

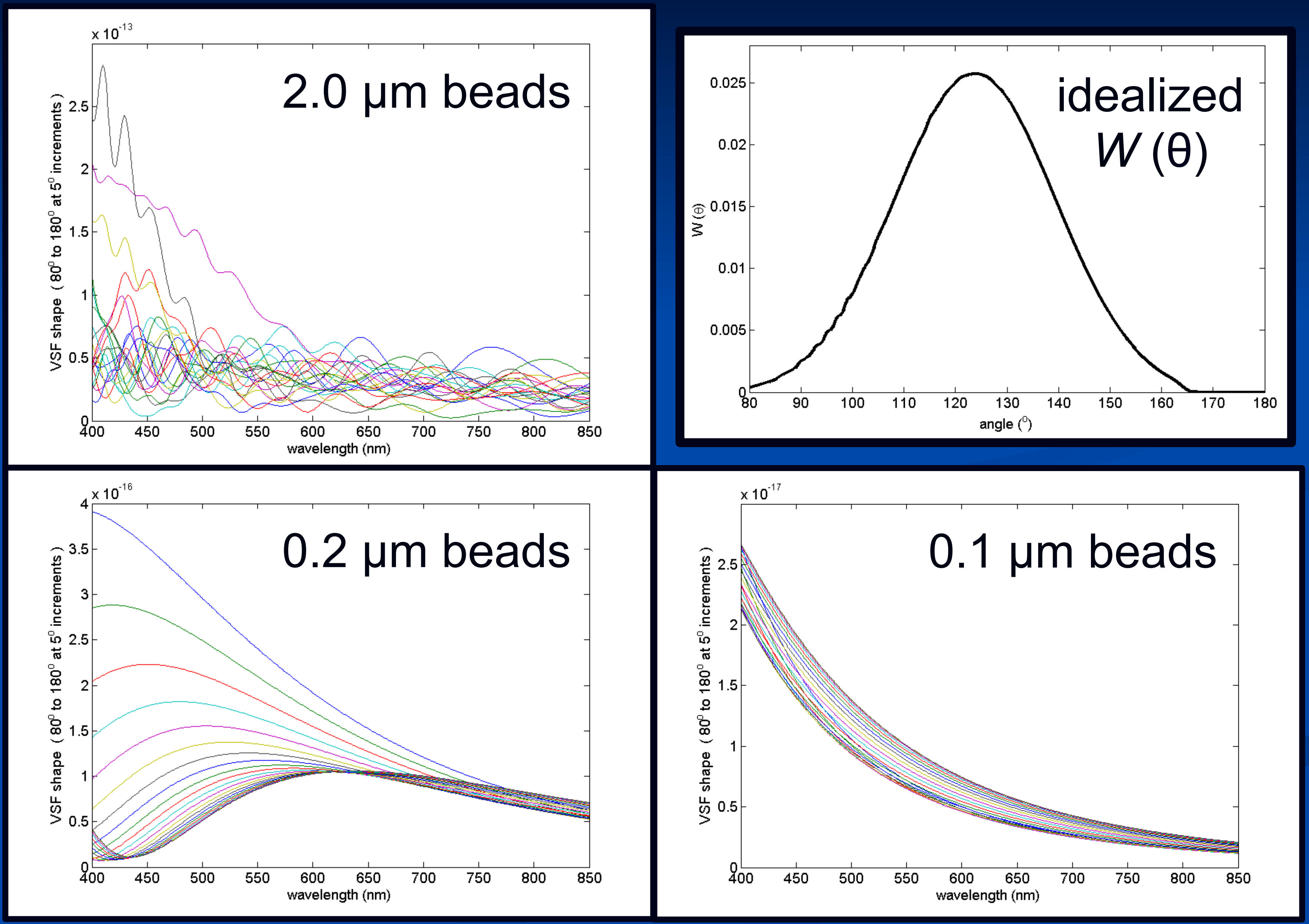
3. Compute scaling factor, SF:

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

Bead calibration uncertainties

$W(\theta)$ & bead size choice (~5 to 10%, should be ~1%)

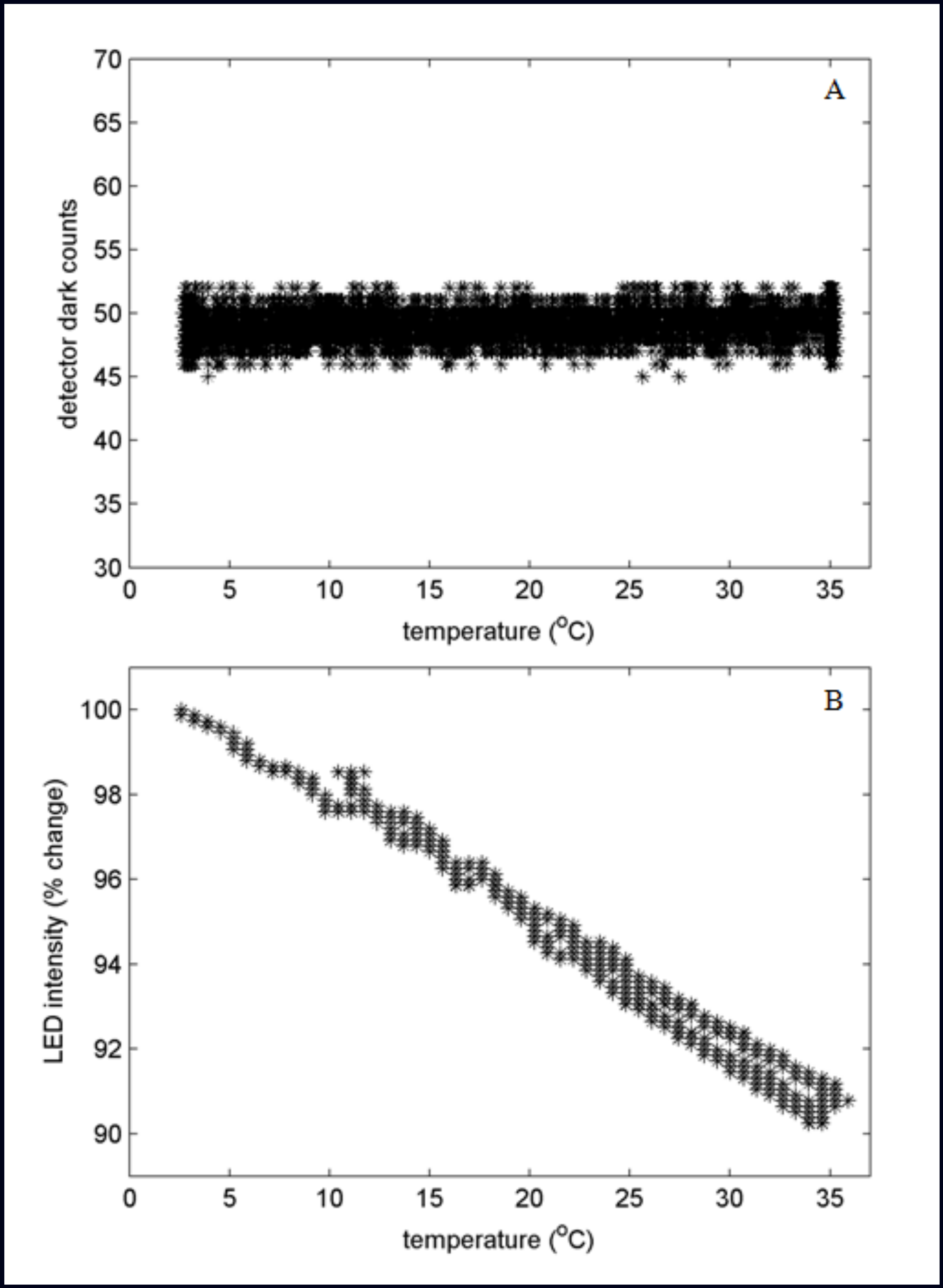
Spectral -angular VSF shape of NIST beads



Bead calibration uncertainties

$W(\theta)$ & bead size choice (~5 to 10%, should be ~1%)
dark counts (<1%)
temperature (potentially 5%, red LEDs only)

ECO temperature dependence



dark counts not affected

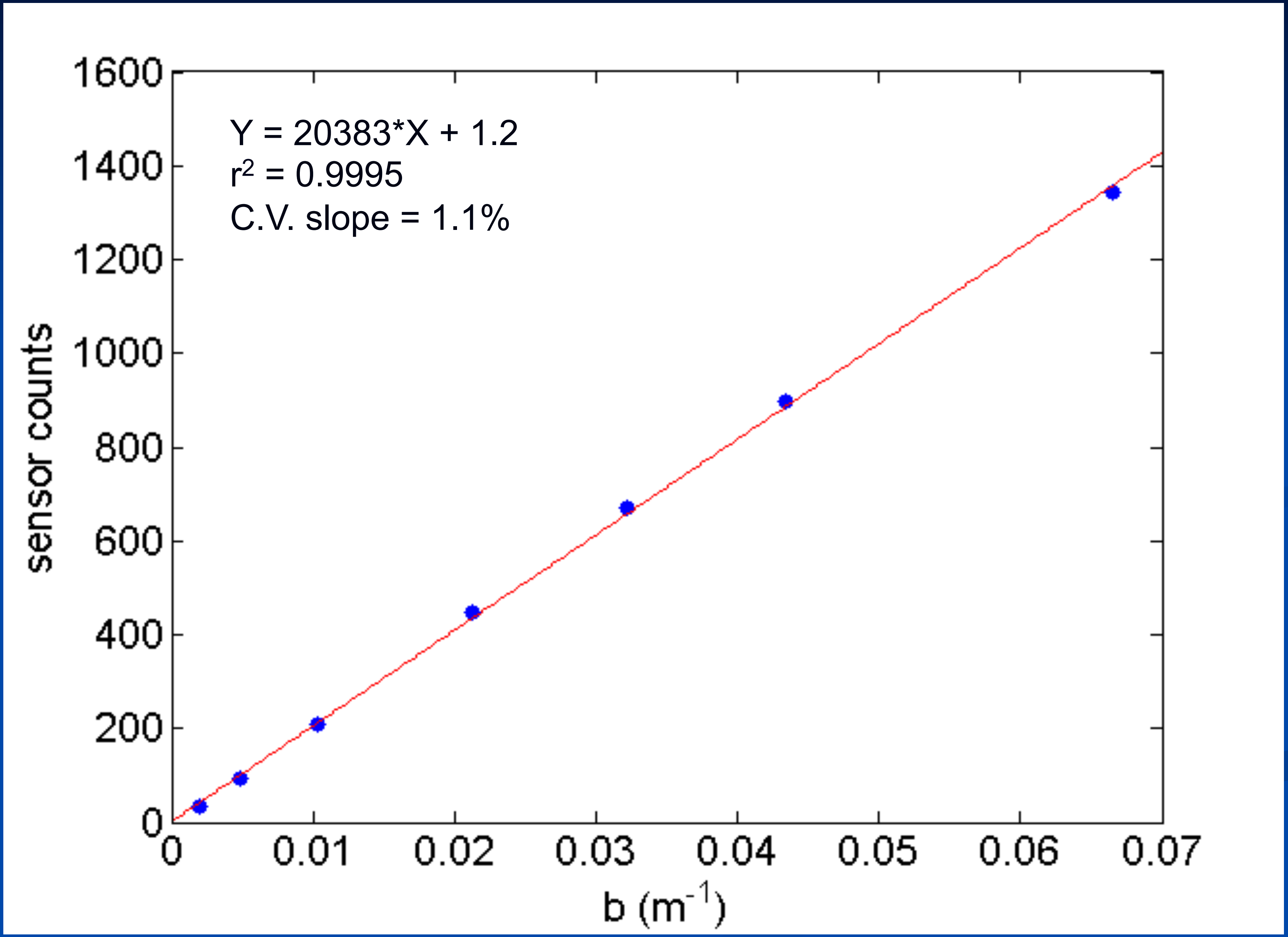
~10% variation over full oceanic temperature range (red LEDs)

* tank water during cal

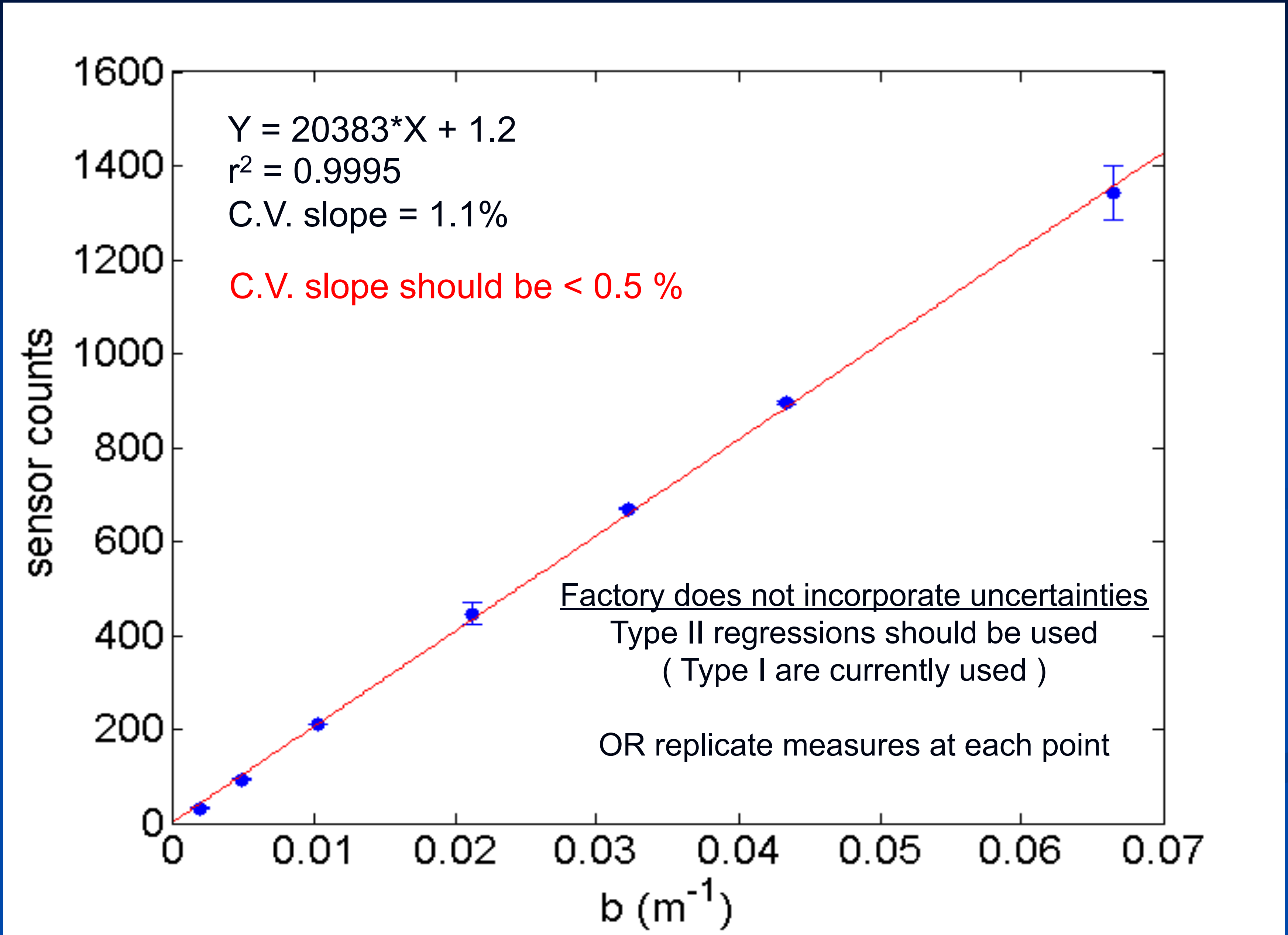
Bead calibration uncertainties

$W(\theta)$ & bead size choice (~5 to 10%, should be ~1%)
dark counts (<1%)
temperature (potentially 5%, red LEDs only)
calibration slope uncertainties (should be <1%)

Calibration slope considerations



Calibration slope considerations



Bead calibration uncertainties

$W(\theta)$ & 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%)

Sensor centroid wavelength uncertainty
(Factory gives "standard" wavelengths)

factory λ	scaling factor	actual λ	scaling factor	Δλ (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

$W(\theta)$ & 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>

Bead calibration uncertainties

$W(\theta)$ & bead size choice (~5 to 10%, should be ~1%)
dark counts (<1%)
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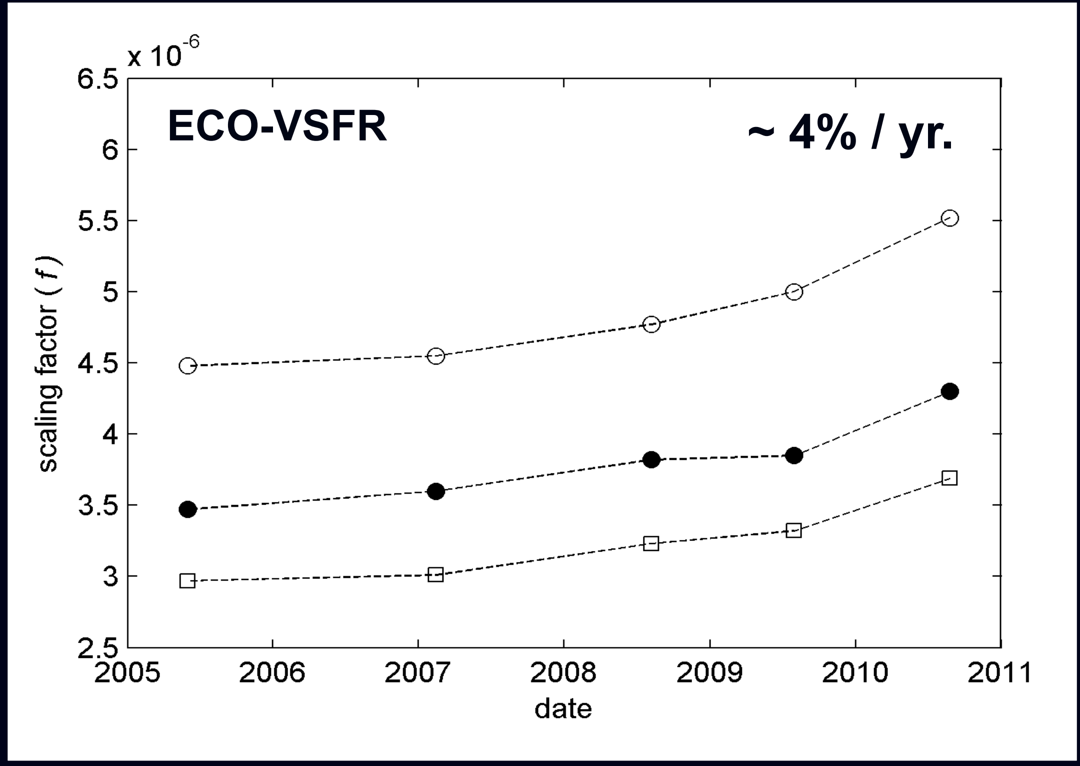
<u>Best case total calibration uncertainty: 2-5%</u>

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

Calibration drift:

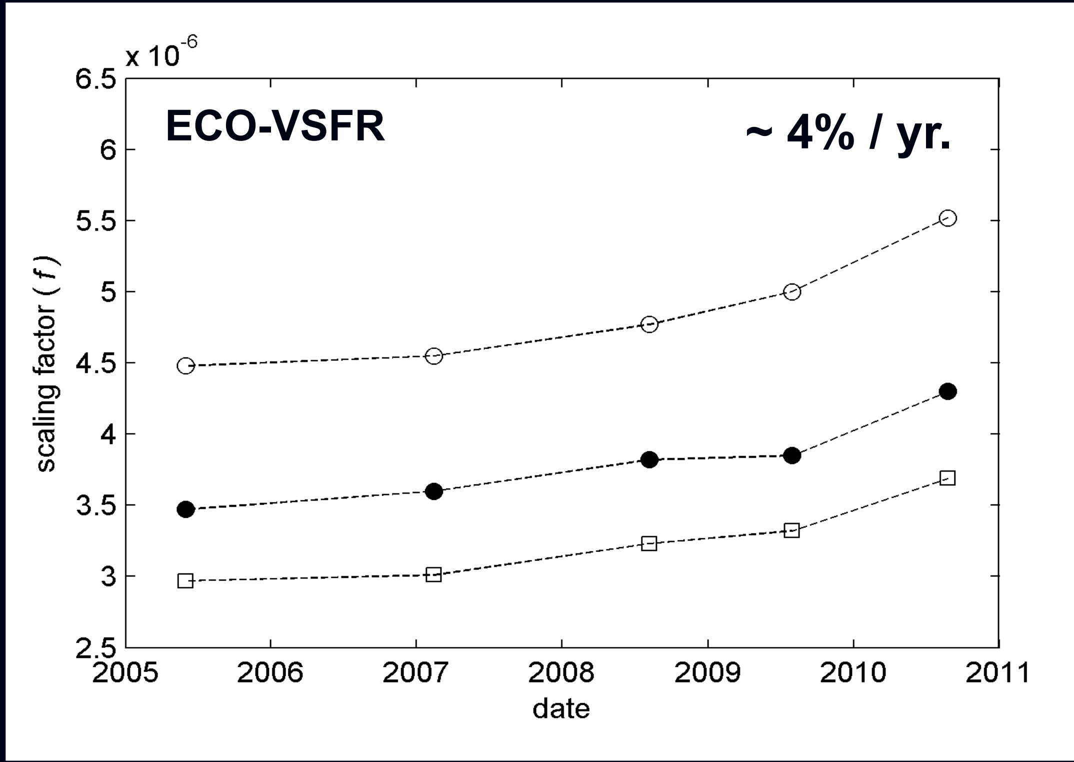


ECO-BB9

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?)

Calibration drift:



ECO-BB9

	wavelength								
cal date	412	440	488	510	532	595	650	676	715
7/10/2013	1.37E-05	1.37E-05	1.06E-05	8.19E-06	7.39E-06	4.85E-06	4.16E-06	3.57E-06	3.27E-06
2/11/2015	1.62E-05	1.32E-05	1.07E-05	8.20E-06	6.78E-06	3.66E-06	2.93E-06	3.20E-06	2.71E-06
% change	17	-4	1	0	-9	-28	-35	-11	-19

avoid factory "re-tuning" during standard service

Data processing

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

calibration scaling factor

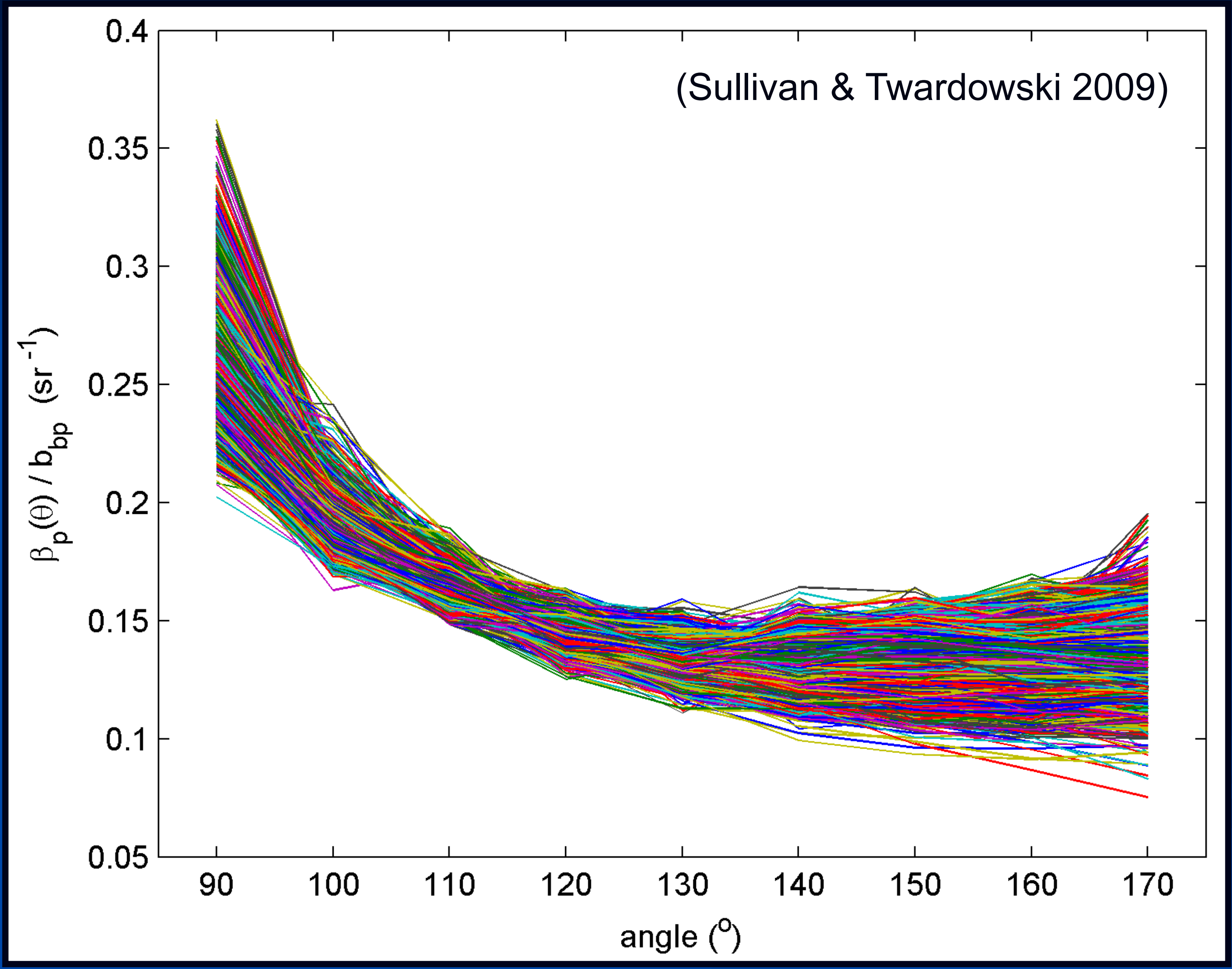
attenuation correction
(L = path length, a = total absorption)

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

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

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

How constant are particulate phase functions?



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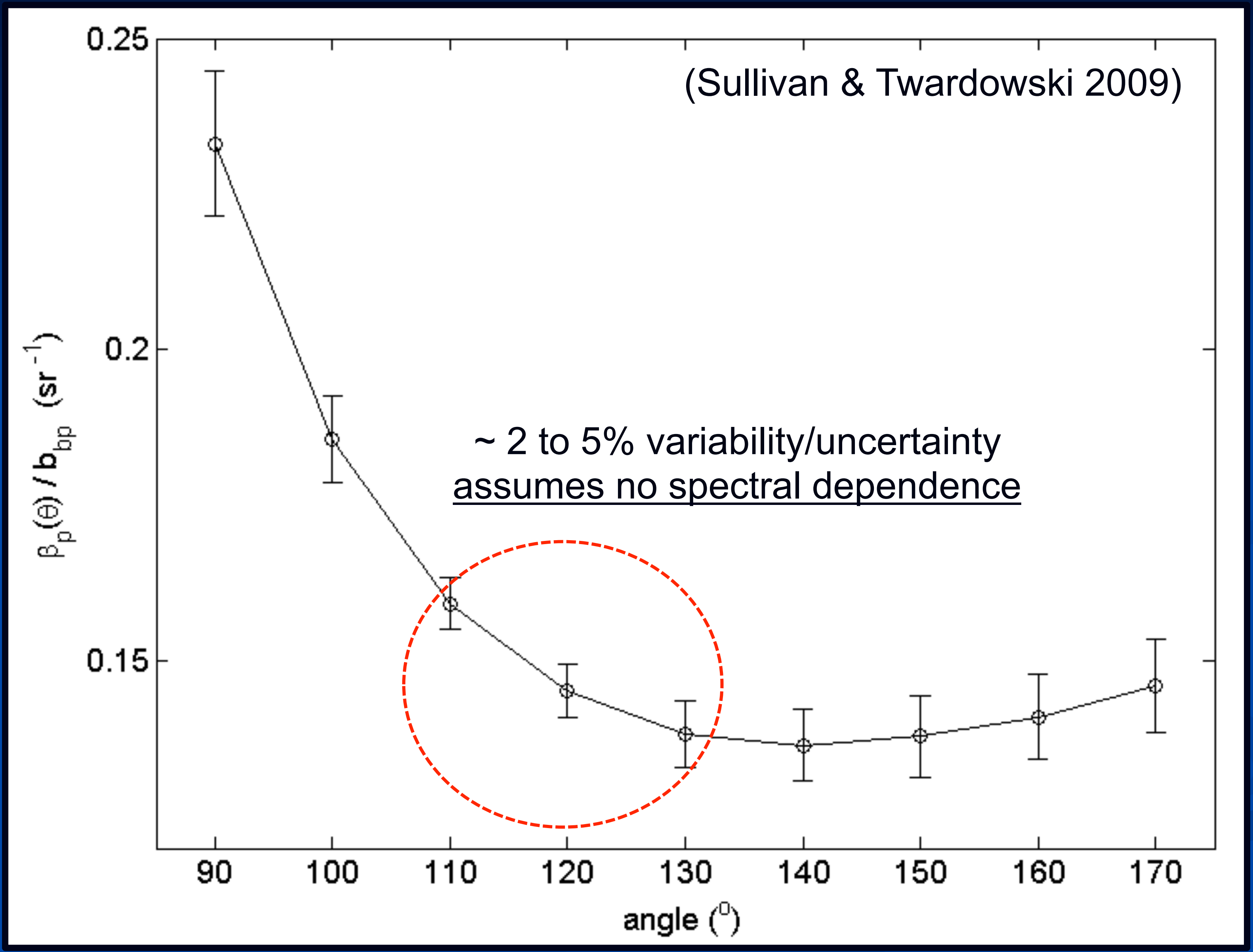
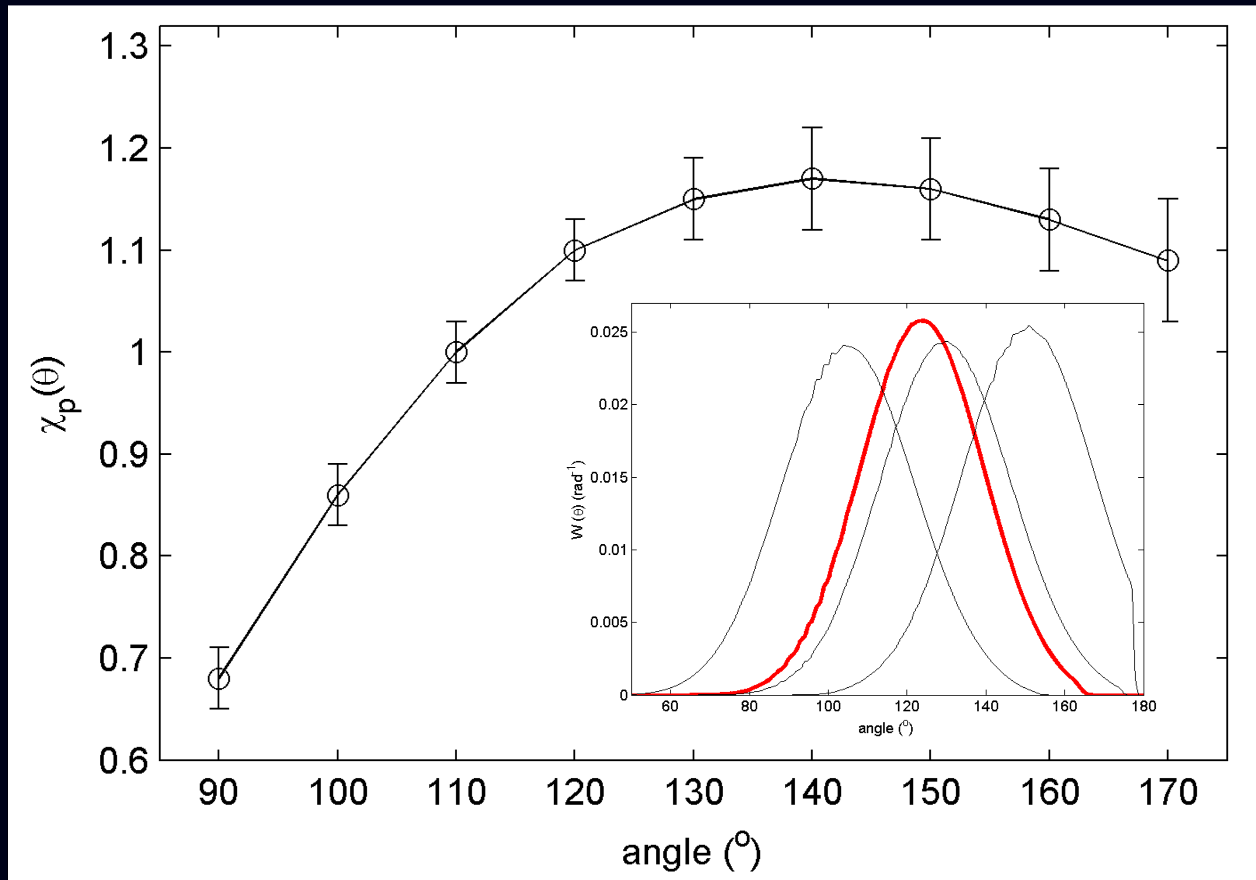


Oishi 1990, Maffione & Dana 1997, Boss & Pegau 2001

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)

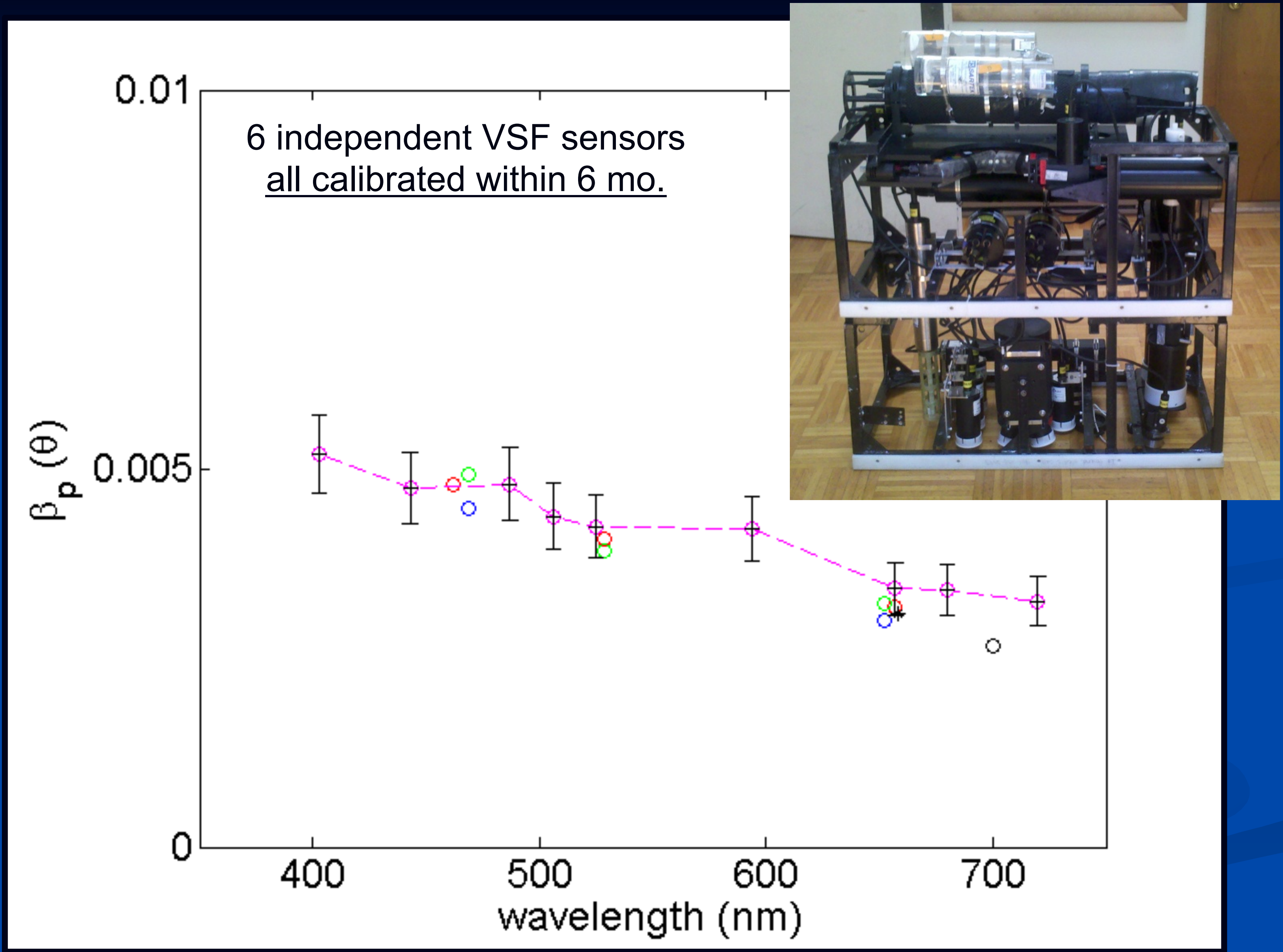
Clean optical faces (each deployment, if possible)

Recognize temperature effects (red LEDs)

cold water calibration

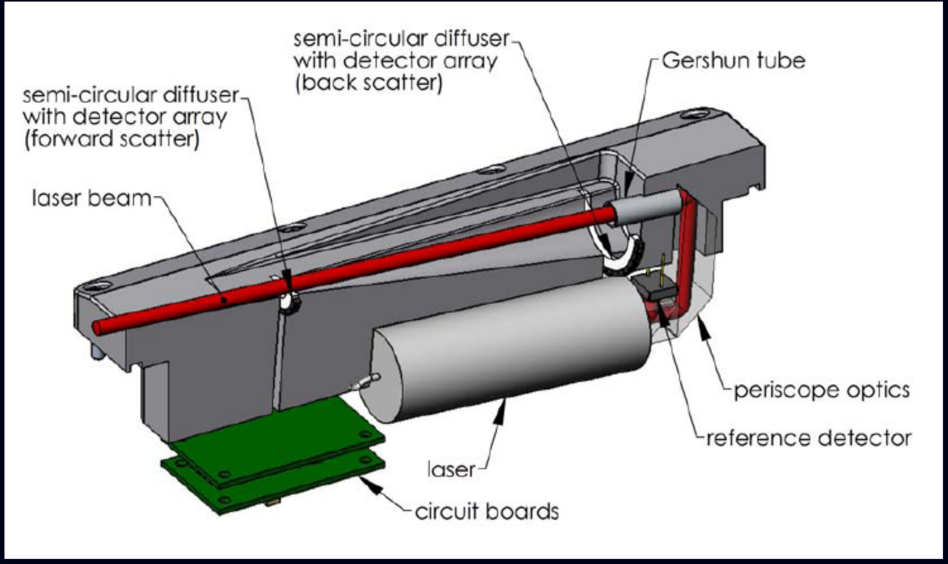
Data averaging /spikes

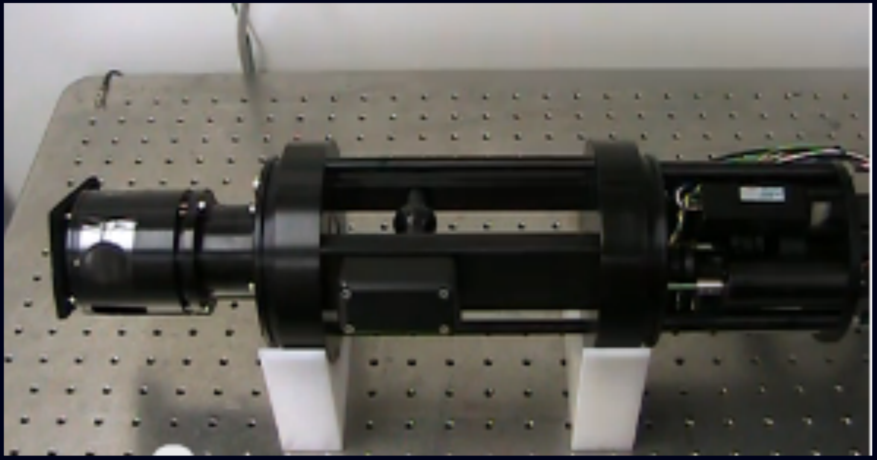
each channel is independent, volume is small



< 5% uncertainty achievable

New instrument designs and future needs





LISST-VSF

Integrated total b and b_b meter (Ed Fry)

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. Measurement uncertainties

    summarize known
    discuss unknowns? (spectral χ, depolarization ratio for b_{bw})

6. Deployment protocols (in-situ dark counts, mounting, etc.)

COMMENTS?