Calibration of WETLabs' Eco-type VSF meters

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Materials: WETLabs Eco-series backscattering sensor.
Mie code.
Weighting function of instrument response with respect to angle (*$W_1(\theta)$*) and wavelength (*$W_2(\theta)$*).
Calibration beads of known size distribution and optical properties.

Methods:
Measure the dark current of the instrument by placing the instrument in water with a black tape masking the detector.
Measure the signal in DIW in a black bucket.
Add beads in a logarithmic series (e.g. 2-4-8-16-32-64 etc') and in each case record the counts from the VSF meter as well as beam attenuation and absorption with the ac-9/ac-s.

Using the Mie code generate the VSF, $\beta(\lambda,\theta,D)$ as function of wavelength (λ), diameter (D) and angle (θ), and the associated efficiency factor $Q_b(\lambda,D)$ for the wavelength(s) of the sensor. The following integral provides the weighted (by angle, wavelength and size) angular distribution function:

$$\hat{\beta}(\lambda_0,\theta_0)=\frac{\int_{\lambda_{\min}}^{\lambda_{\max}}\int_0^{2\pi}\int_{r_{\min}}^{r_{\max}}W_2(\theta)W_1(\lambda)N(D)\beta(\theta,\lambda,D)dD\sin\theta d\theta d\lambda}{\frac{1}{4}\int_0^{2\pi}W_2(\theta)\sin\theta d\theta\int_{\lambda_{\min}}^{\lambda_{\max}}W_1(\lambda)\int_{r_{\min}}^{r_{\max}}N(D)\pi D^2Q_b(\lambda,D)dDd\lambda} \quad (1)$$

Where *$W_1(\lambda)$* is the wavelength weighting function (e.g. A Gaussian with a known FWHM), *$W_2(\theta)$* the angular weighting function of the sensor, and *$N(r)$* the particulate size distribution of the beads. Given that these three function appear in both nominator and denominator, their absolute magnitude is not needed, only their shape. The shape of *$W_1(\lambda)$* is given based on the source output spectra, the spectrum of the filter on the receiver side and the photodector's sensitivity. The shape of *$W_2(\theta)$* from WETlabs. *$N(r)$* is given from the beads manufacturer. We obtain the needed phase function by normalizing $\hat{\beta}(\lambda_0,\theta_0)$ (e.g. see below).

Rather then solve (1) directly we perform it in a series of steps:
1. Compute a size and wavelength weighted angular scattering distribution function:

$$\dot{\beta}(\lambda_0,\theta)=\sum_{k=1}^{K}\sum_{j=1}^{J}W_1(\lambda_j)N(D_k)\beta_{jk}(\lambda_j,D_k,\theta). \qquad (2)$$

We discretized the wavelength weighting function, $W_1(\lambda)$, to a 100 wavelenth values (J=100) spanning in equal intervals three standard deviations on each side of the wavelength of maximal value for the empirical curve describing $W_1(\lambda)$ (see appendix). Similarly we discretized the calibration beads size distribution function to a 100 wavelenth values (K=100) spanning in equal intervals three standard deviations on each side of the modal size for the curve describing *N(r)* (see appendix).

2. Compute the associated phase function by requiring that its spatial integral be 1:

$$\tilde{\beta}(\lambda_0,\theta)=\frac{\dot{\beta}(\lambda_0,\theta)}{2\pi\int_{\phi_0}^{\pi}\dot{\beta}(\lambda_0,\theta)\sin\theta d\theta} \qquad (3)$$

The limit of the integral in the denominator, ϕ_0, accounts for the fact that when we compute scattering we do it with an instrument of a finite acceptance angle (0.7 degree for the ac-9 or ac-S used here).

3. Convolve the phase function with the angular responsivity function to obtain the angle averaged phase function at θ_0:

$$\tilde{\beta}_{theory}(\lambda_0,\theta_0)=\frac{2\pi\int_{\theta_0}^{\pi}W_2(\theta)\tilde{\beta}(\lambda_0,\theta)\sin\theta d\theta}{2\pi\int_{\theta_0}^{\pi}W_2(\theta)\sin\theta d\theta} \qquad (4)$$

For a given set of calibration beads and a given instrument (assuming no changes in spectral output or filters) $\tilde{\beta}_{theory}(\lambda_0,\theta_0)$ is constant. We proceed with the calibration procedure by performing a series of measurements of beads of known properties with both the VSF meter and an ac-9. For non-absorbing beads, c_p can substitute for b_p (e.g. a single band beam transmissometer can be used for the calibration).

The signal measured for k dilution experiments relates to the ac-9 measurements as follows:

$$signal_k = dark\_signal + A\{\tilde{\beta}_{theory}(\lambda_0,\theta_0)b_{p,k}\}\exp(-c_k r) \qquad (2)$$

Where $b_{p,k}$ is the particulate scattering coefficient for dilution k, c_k the associated total beam attenuation (this attenuation correction is most often negligible and account for attenuation along the path).

Regression analysis using the dilution series yields A, the factor needed to obtain the VSF in future measurements:

$$\beta(\lambda_0, \theta_0) = \frac{(signal - dark\_signal)\exp(cr)}{A}$$

Why should wavelength be important?

The solution of scattering of light by a spherical particle was solved by Mie (1905). It can be showed that the solution depends on the index of refraction and on a size parameter, x=πn/λ, where D is the particle diameter, n the index of refraction of the medium and λ the wavelength relative to the same medium the index of refraction is referenced to.

Similar changes in x will yield similar changes in the output of the solution thus:

$$\frac{dx}{x} = \sqrt{\left(\frac{d\lambda}{\lambda}\right)^2 + \left(\frac{dD}{D}\right)^2 + \left(\frac{dn}{n}\right)^2}$$

Typically, for the sensors we analyzed here, dn/n<1% in the range of wavelength response. For the instruments analyzed here and the beads used by WETLabs (D=2μm dtdev= 0.08μm), dn/n~1%, dD/D=0.08/2=4%, and dλ/λ~20/500=4%. These result I changes in x (compared to accounting for only size changes, as currently performed by WETLabs) that can result in significant changes in $\tilde{\beta}_{theory}(\lambda_0, \theta_0)$, as shown below.

Results

I compared the values of $\tilde{\beta}_{theory}(\lambda_0, \theta_0)$ with those generated by WETLabs for beads with median size of 2μm and standared deviation of 0.08μm (Table 1) for the bb-9 specs I measured or obtained from WETLabs (see appendix, source output curves measured using Satlantic HyperPro).

Discrepencies with values up to 7% are found between the values currently used by WETLabs and those calculated here. When I compute $\tilde{\beta}_{theory}(\lambda_0, \theta_0)$ for a hypothetical instrument with a 1nm FWHM around the nominal wavelength the discrepancies with WETLabs values drop to less than 1.6%. highlighting the importance of wavelength averaging.

λ	λ_{max}	FWHM	Factors WETLABS	Factors MISC	Factors mono	relative difference MISC-WETLabs	Relative difference Mono-WETLabs
412	406.5	14.5	0.009937765	0.0099462	0.0100334	0.000848053	-0.009577298
440	439.5	13	0.010592302	0.0108131	0.0106535	0.020419491	-0.00576095
488	485.5	16.5	0.008712004	0.0090828	0.0086855	0.04082403	0.003046816
510	510	21	0.007381331	0.0074913	0.0073629	0.014679615	0.002500042
532	525.5	16	0.006256404	0.0067074	0.0062431	0.067238647	0.002128645
595	592.5	14	0.004166	0.0042296	0.0041128	0.015036883	0.012852104
650	651.5	14.5	0.003197367	0.0032285	0.003179	0.009643116	0.005761023
676	679	27	0.002929816	0.0029209	0.0029142	-0.003052518	0.005344304
715	720.5	18	0.00260853	0.0025842	0.0025657	-0.009414829	0.016555044

Table 1. Published nominal wavelength, wavelength of maximal response, FWHM of wavelength responsivity function $W_1(\lambda)$, $\tilde{\beta}_{theory}(\lambda_0,\theta_0)$ currently used by WETLabs, $\tilde{\beta}_{theory}(\lambda_0,\theta_0)$ determined using the approach presented here, $\tilde{\beta}_{theory}(\lambda_0,\theta_0)$ determined using the approach presented here assuming the , $W_1(\lambda)$as FWHM=1nm around the nominal wavelengths, the relative differences between the approaches.

For the Eco-VSF sensor the results are also different when wavelength characteristics are taken into account. In particular, for the 532 and 660nm nominal wavelengths, the differences (a bias!) seem to increase with the angle to a maximum of 5%.

λ	Centroid angle	Factors WETLABS	Factors MISC	relative difference MISC-WETLabs
660	100	0.00316691	0.0032835	0.035506533
660	125	0.0029804	0.0031074	0.040870052
660	150	0.00202236	0.00211	0.041537299
528	100	0.005728	0.0059232	0.032912902
528	125	0.006448	0.0066665	0.032834936
528	150	0.004504	0.0047325	0.048207142
440	100	0.007680	0.007754	0.009531364
440	125	0.011368	0.0114483	0.006985317
440	150	0.009426	0.0094099	-0.001728467

WETLabs, $\tilde{\beta}_{theory}(\lambda_0,\theta_0)$ determined using the approach presented here, and the relative difference between the approaches.

Summary

It seems obvious from the results presented here that WETLabs needs to take into account the wavelengths characteristics of its sensors. At least a few in every series should have their source output and receiver responsivity be fully characterized (including effects due to epoxy and windows (if present). Similarly, the angular response of the sensors needs to be evaluated as well (e.g. Fig. A3) to establish the uncertainties of the calibration coefficient contributed by the uncertainties in $\tilde{\beta}_{theory}(\lambda_0,\theta_0)$.

Appendix

The different weighting functions needed to evaluate equ. 1. We are interested in their 'shape' not in their magnitude (as we normalize by it).

I. *$W_1(\lambda)$*- this weighting function depends on the light source and receiver (filters are inserted before the receiver electronics). Three weighting functions contribute to *$W_1(\lambda)$*: The output of the LED (we measured it with a calibrated radiometer and found some notable differences with those provided by WETLabs, Fig. A1), the spectral characteristics of the filter in front of the detector (obtained from the manufacturer) and the detector (photodetector) responsivity itself (obtained from the http://beammeasurement.mellesgriot.com/tut_photo_det.asp). *$W_1(\lambda)$* is the product of these three functions (Fig. A2).

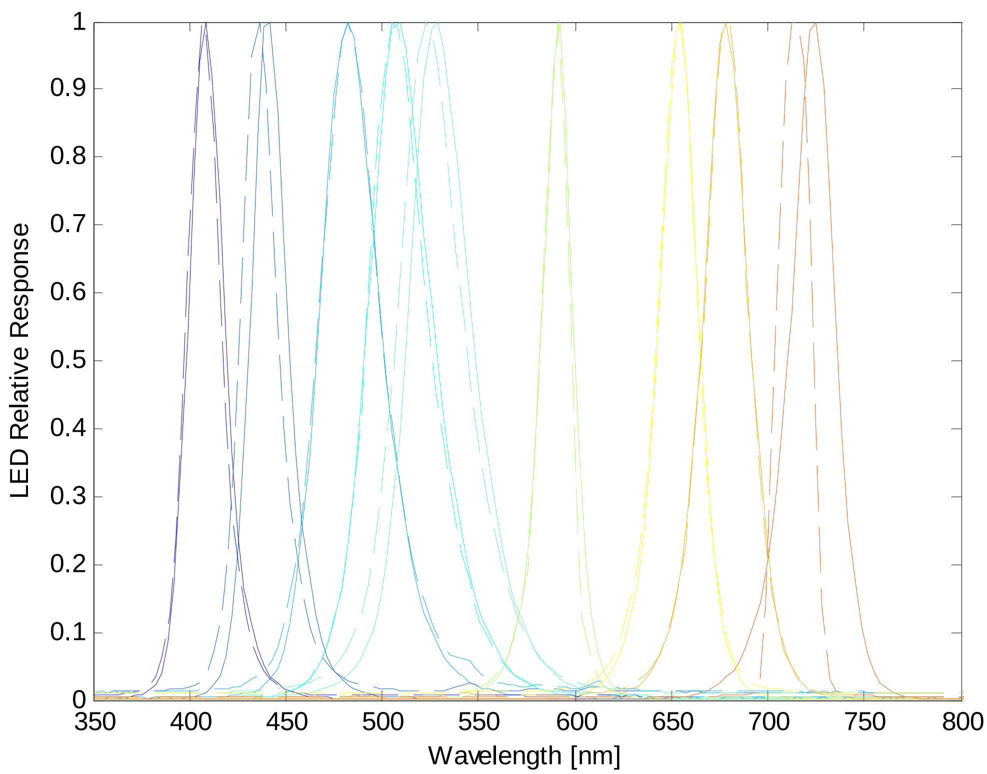

Figure A1. Normalized source output for MISC's bb9 (solid line) vs. that provided by WETLabs (dashed line).

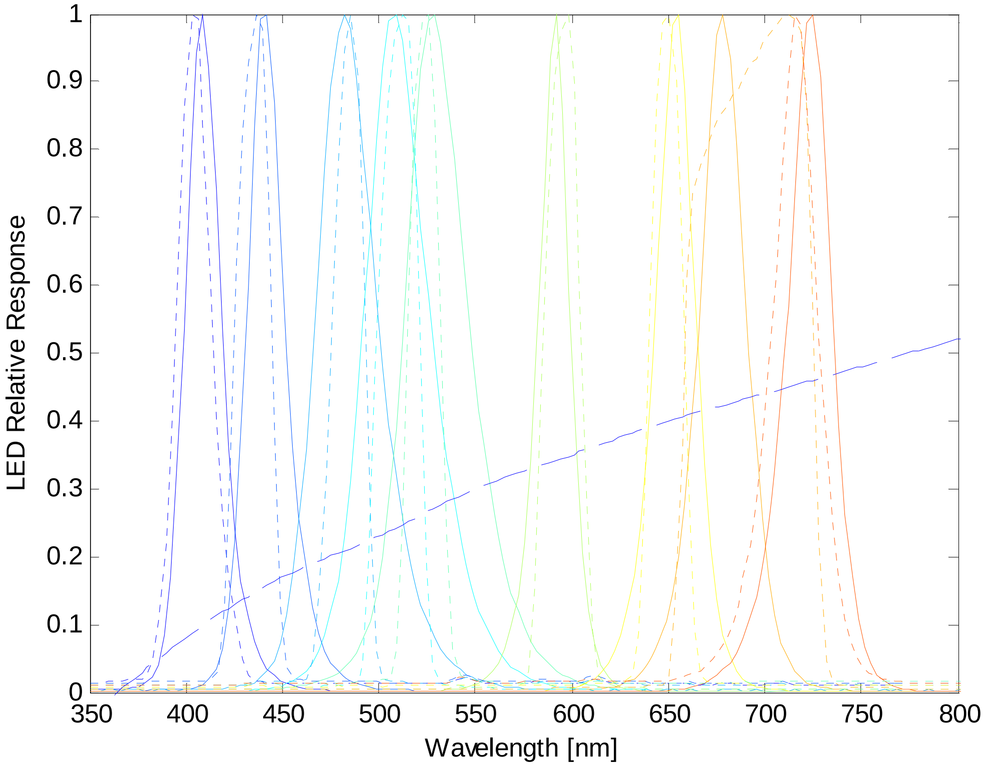

Figure A2. Normalized source output (solid line, measured at MISC), detector filter sensitivity (dotted line, provided by WETLabs), and photodiode responsiivity (dashed line, found on WWW). The shape of $W_1(\lambda)$ for each sensor is the product of these three curves.

II. $W_2(\theta)$- this weighting function depends on the geometry of the light source and receiver. It is the product of the angular response function, of the source and receiver, i.e. the likelihood that a photon will be emitted by the detector will make it into the receiver with scattering angle θ, assuming it had backscattered. We obtain it from the manufacturer (Fig. A3).

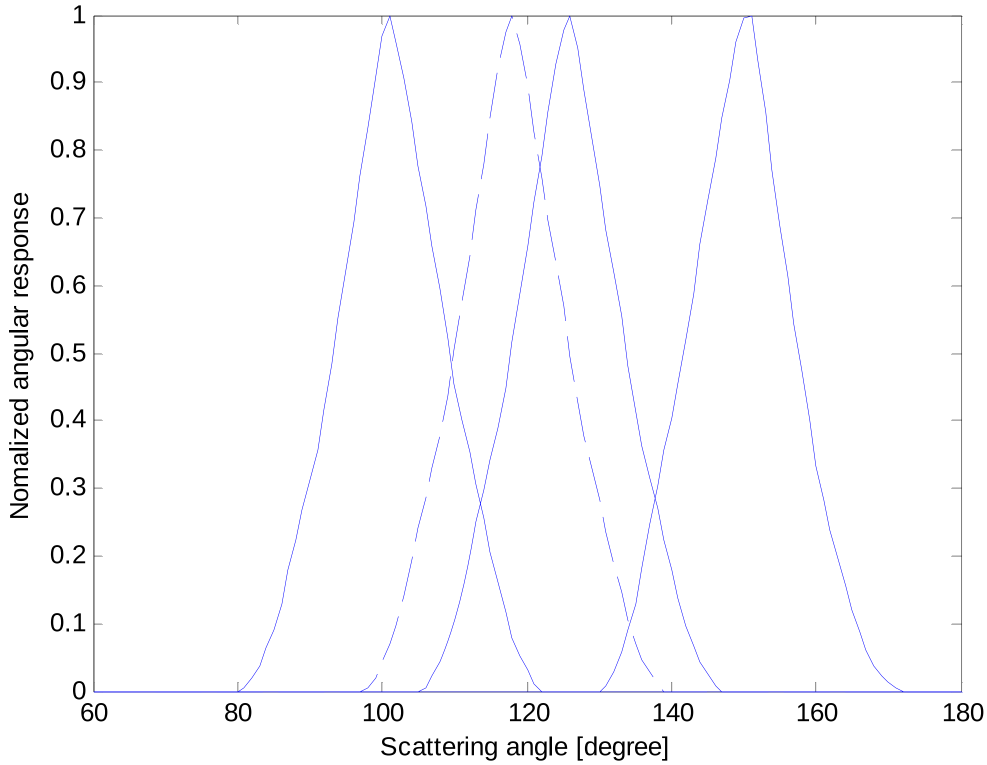

Figure A3. Normalized angular response. The shape of $W_2(\theta)$ was provided by WETLabs.