Cosine Correction Factors for Brewer Solar Irradiance –
Clouds not known except overcast from R

(1) Purpose – Global or total spectral solar irradiance is measured by the Brewer spectrophotometers for the spectral range 290 – 363 nm. The quantity is typically measured with diffusers or integrating spheres. A light beam incident at zenith angle θ ideally follows the cosine of the incident angle, but more often follows a weighting function C(θ,ϕ,λ) which is a function of the zenith angle θ, azimuth angle ϕ, and wavelength. The purpose here is to correct the global/total spectral solar irradiance for this angular response error.

(2) Basic Methodology - The basic method of correction is given in equation 1, where 1/fg is the correction. Basically the correction is separated into two parts, a correction for the direct beam and for the diffuse beam. The method uses UV-MFRSR data where available for the direct to global solar irradiance ratio, R. If UV-MFRSR data is not available and the sky is clear or partly cloudy, the correction uses modeled R values; and if the sky is overcast, R is assumed to be zero, the sky is assumed to be isotropic, and the isotropic correction is used.

(3) Terminology

C(θ,ϕ,λ) = measured angular response in laboratory of Brewer sss*
Cos(θ) = ideal angular response independent of λ and ϕ
f_g = global cosine error to solar irradiance measurements
f_r = direct cosine error to solar irradiance measurements = C(θ,ϕ,λ)/Cos(θ)
f_d = diffuse cosine error to solar irradiance measurements
$1/f_g$ = global cosine correction to solar irradiance measurements
$1/f_r$ = direct cosine correction to solar irradiance measurements
$1/f_d$ = diffuse cosine correction to solar irradiance measurements
$R(\lambda,\theta_o, \ldots.)$ = direct solar irradiance/global solar irradiance from model or measurements
E_{brewer} = uncorrected Brewer solar irradiance measurements
E_{corr} = corrected Brewer solar irradiance measurements
θ_o = solar zenith angle of direct beam
θ = zenith angle
ϕ = azimuth angle
Ω = total ozone
τ_{aer} = aerosol optical depth
RTM = Radiative Transfer Model

*File for each Brewer serial number, e.g. BrssscosineAverage.txt and Brsss_cosineDirect.txt, where sss=serial number, i.e. 134, 140, 144, 146, 147, 154, (141, 135). See appendix II.

(4) Model input parameters

a. Total ozone: The default total ozone is 300 DU, which is a typical value for the northern hemisphere where the sites are located. See http://www.esrl.noaa.gov/gmd.
b. Aerosol properties: The default aerosol optical depth is 0.01-0.04 and is taken from Augustine et al., 2008. Aerosol asymmetry parameter is 0.61, and single scattering albedo is 0.98. Surface albedo is 0.01.

(5) Derivation of cosine correction factors

$$\mathbf{E_{corr}(\theta_o,\lambda) = E_{brewer}(\theta_o,\lambda)/\,fg(\lambda,\theta_o)} \qquad [1]$$

$fg(\lambda,\theta_o) = fd(\lambda,\theta_o)\,[1- R(\lambda,\theta_o)] + fr(\lambda,\theta_o)\,[R(\lambda,\theta_o)]$
$fr(\lambda,\theta_o) = C(\theta_o,\phi,\lambda)/Cos(\theta_o)$
$fd(\lambda,\theta_o)$ = RTM calculated or isotropic

Assumption (a) …

For the direct cosine error fr, ϕ is along Brewer solar tracking transect and θ goes from 0 to 90. Measurements show that C is independent of λ. Therefore, $C(\theta,\phi,\lambda) = C(\theta_o)$

$$\mathbf{E_{corr}(\theta_o,\lambda) = E_{brewer}(\theta_o,\lambda)/fg(\lambda,\theta_o)}$$

$fg(\lambda,\theta_o) = fd(\theta_o)[1- R(\lambda,\theta_o)] + fr(\theta_o)[R(\lambda,\theta_o)]$
$fr(\theta_o) = C(\theta_o)/Cos(\theta_o)$ where θ_o is from 0 to 90 along solar tracking transect*
$fd(\lambda,\theta_o)$ = RTM calculated or isotropic, see below in part 5.

*Filename = Brsss_cosineDirect.txt, where θ is first column, $\cos(\theta)$ is second column, $C(\theta)$ is third column, and $fr(\theta)$ is fourth column. The Brewer spectrophotometer tracks the sun, which makes the direct beam correction easier. The transect from NS from -90 to 0 degrees is used for the correction.

Assumption (b)

For the diffuse beam correction fd, the dependence of $C(\theta_o,\phi,\lambda)= C(\theta_o,\lambda)/$ is assumed to be azimuthally independent. For the Brewer spectrophotometers this is not quite accurate. See appendix II.

Because the instrument tracks the sun, the measurement along this transect is used for the direct beam correction and has no azimuthal dependence and therefore the assumption of $C(\theta_o,\phi,\lambda)= C(\theta_o,\lambda)$ is valid for f_r. For f_r use Brsss_cosineDirect.txt for $C(\theta_o,\lambda)$. For the diffuse correction calculations, Brsss_cosineAverage.txt is used in the RTM calculations.

(6) Sky conditions, clear-sky, partly cloudy, or overcast.

a. Use TSI information but not implemented.
b. Use R value. If R value is less than X then assume overcast, else assume clear-sky.

(7) Solar irradiance ratio R of direct to global solar irradiance

a. Use measurements of direct and global solar irradiance from UV-MFRSR measurements. Use formulation for wavelength dependence described below in section 6.
   i. Case i: Clear to partly cloudy. $R(\lambda,\theta_o) = F[R_{uvmfrsr}(\lambda=368),\lambda_i)]$ where i = 290 to 400 nm, where function F is from a tabulated set of equations as a function of θ and λ in file = Rempirical_uvmfrsr.txt. $R_{uvmfrsr}(\lambda=368)$ is from files XX02yyyymmdd.cal.dat.
   ii. Case ii: Overcast, then R = 0, and fg = fd where fd is isotropic , i.e. use section 6, case c. Use this when R <= determined value.
b. Default if UVMRSR measurements are not available, use modeled values of $R_{model}(\lambda,\theta_o)$ or modeled total angular correction fg(model).
   i. Case i: Clear sky or partly cloudy or unknown, i.e. R != 0.
      1. No ancillary measurements of total ozone or τ_{aer}. Assume total ozone is 300 DU, τ_{aer} = 0.05, etc (i.e. file = Rmodel_clearsky_300DU.txt, where $R(\lambda,\theta_o)$ is function of θ_o and λ. Choose R with closest θ and λ.
      2. Total ozone and/or τ_{aer} are known. Search in R file for closest total ozone and taer (i.e. file = Rmodel_clearsky_function.txt, where function = o3col or tauaer). Then, choose R with closest θ_o and λ.
   ii. Case ii. Overcast, then R = 0, and fg = fd where fd is isotropic, i.e. use section 6, case c.
   iii. Case iii. Sky cloud condition not known, use case i.
   iv. Note: R modeled can be combined with fr and fd to provide fg files. The total angular correction, 1/fg, are given in the files totalCorrection_Brewersss_clearsky_o3col.txt. See appendix I.

(8) **Cases for f_d – Diffuse angular error (diffuse correction = 1/f_d)**

a. Case a. Clear sky or partly cloudy (i.e. R != 0), or unknown clouds.
   i. Unknown ancillary information, e.g. total ozone or τ_{aer}. Lookup table of f_d from RTM calculations as function of θ_o, λ, Ω = 300DU, and τ_{aer}=0.05. Find closest θ_o and λ in file = diffuseCorrection_Brewersss_300DU.txt.
   ii. Known total ozone or τ_{aer}. Lookup table of fd from RTM calculations as function of θ_o , λ, Ω, and τ_{aer}. Find closest θ_o , λ,

Ω, and τ_{aer} in file = diffuseCorrection_Brewersss_clearsky_function.txt, where function = o3col or tauaer. See appendix I.

b. Case c. Overcast, then R = 0, fg = fd, where fd = isotropic. Separate file for each Brewer with 1/fd given in header of file = BrssscosineAverage.txt. Grep for “isotropic_correction”. This is a single constant number for wavelength and solar zenith angle.

$$f_d = 2\pi \int_0^{\pi/2} C(\theta) \sin\theta d\theta$$

$$f_d = 2\pi \sum_0^{\pi/2} C(\theta) \sin\theta \Delta\theta$$

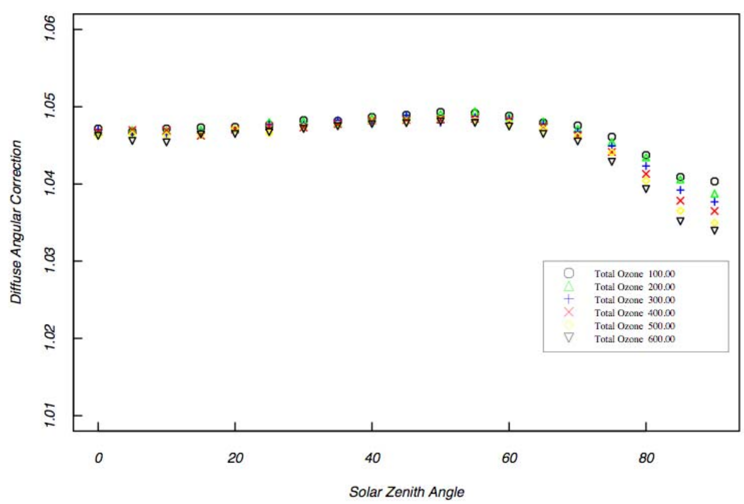
c. Case d. Sky cloud condition not known. Follow case a.

(9) Files: Files can be found at ftp://ftp.srrb.noaa.gov/pub/users/lantz/neubrew/angularresponse

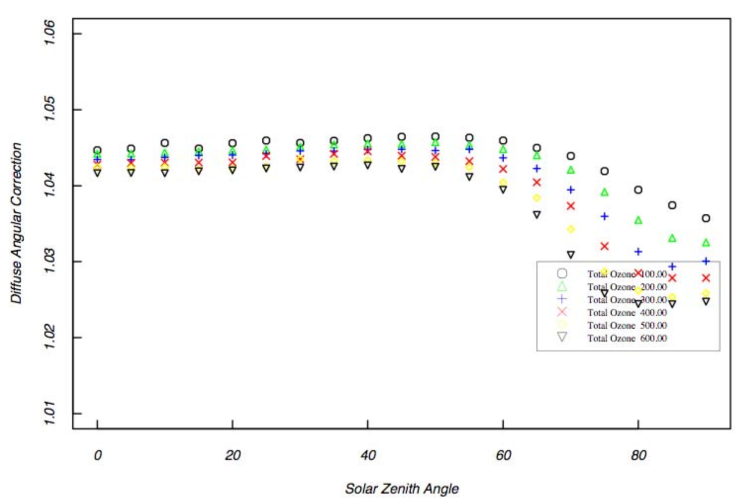
Appendix I: Plots of corrections of the angular response error for Brewer 134.

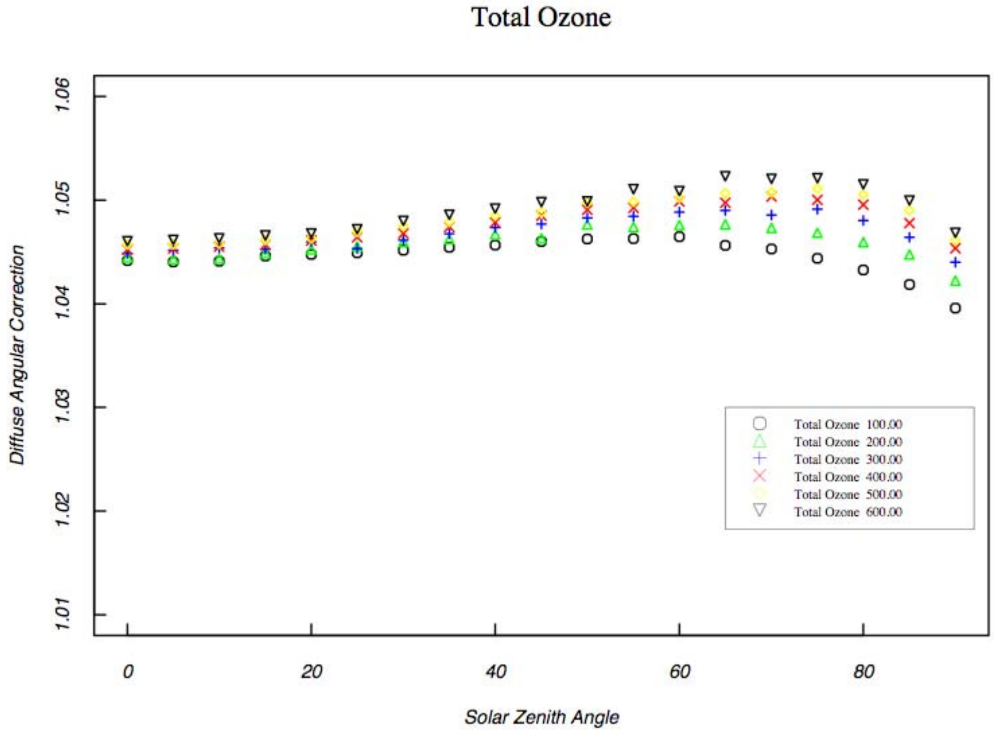
The first 5 plots are of the diffuse angular correction for Brewer 134. The first two plots are the diffuse angular correction when changing total ozone for two different wavelengths (305 and 315 nm). The next 3 plots are the diffuse angular correction for erythemally weighted solar irradiance as a function of solar zenith angle for various total ozones, total aerosol optical depths, and cloud optical depths.

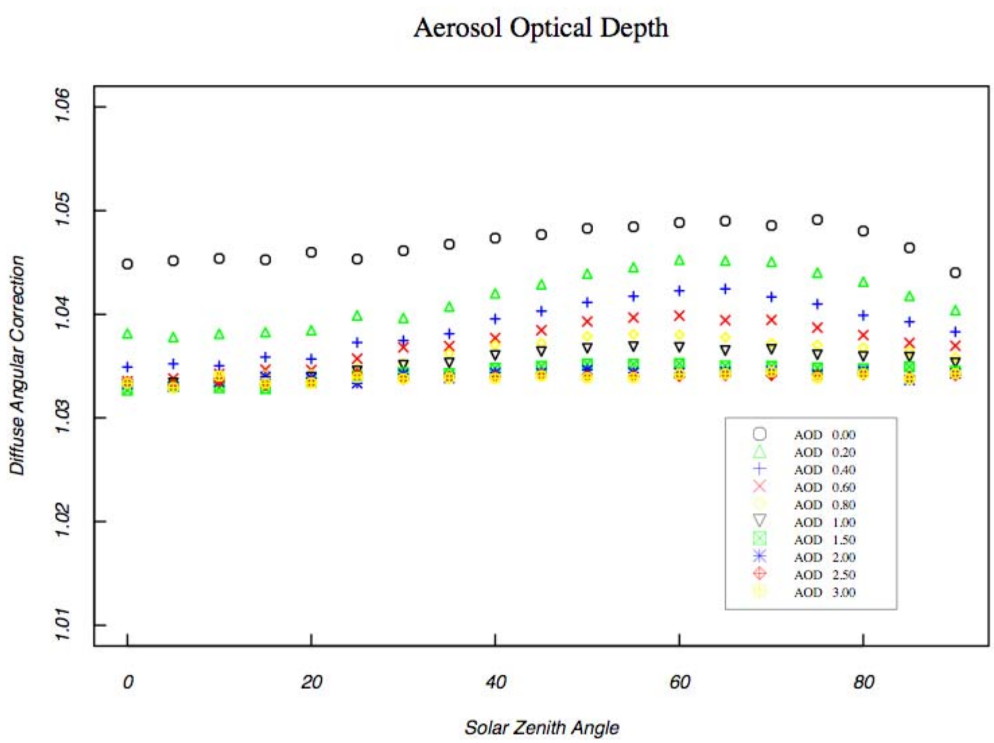
Solar irradiance 315 [nm]: Total Ozone

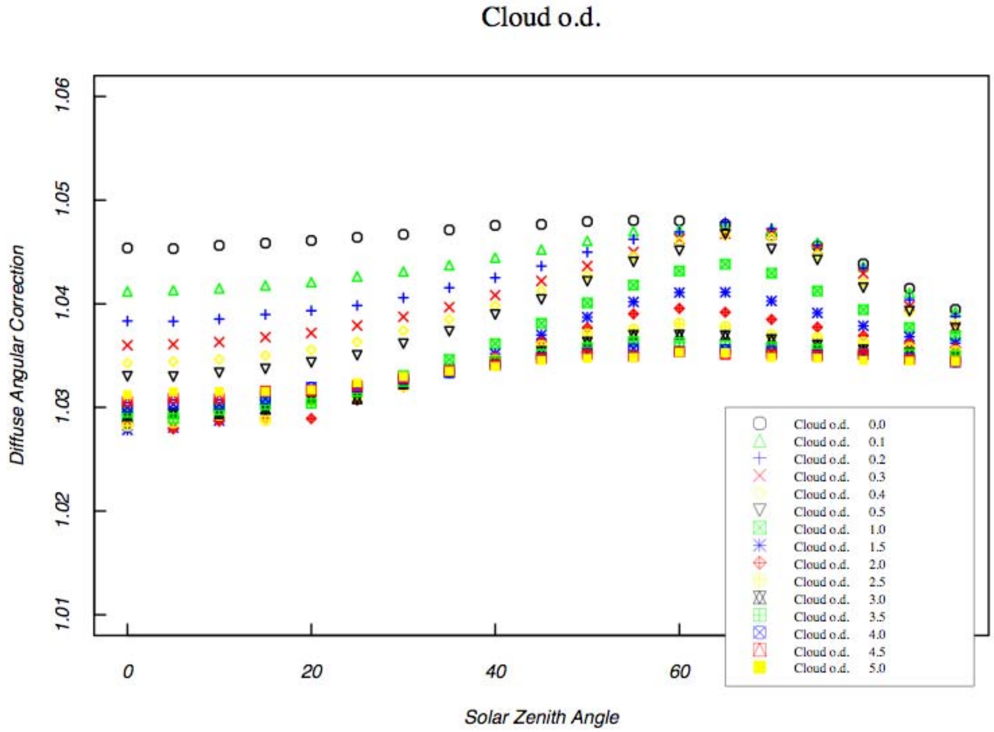


Solar irradiance 305 [nm]: Total Ozone

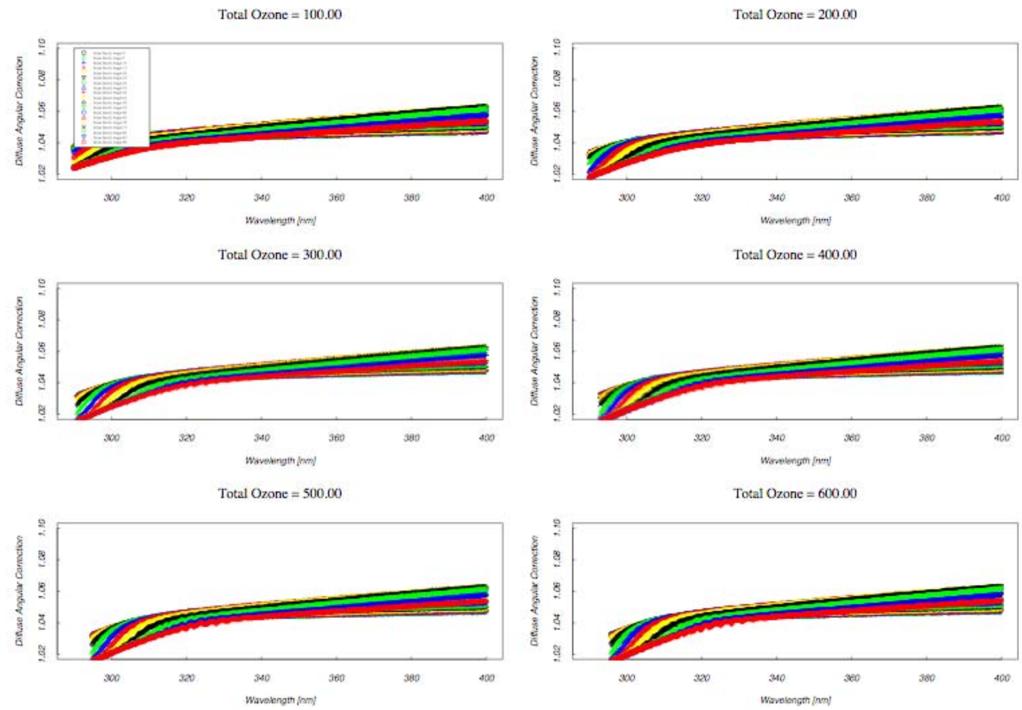



Total Ozone
Diffuse Angular Correction
Solar Zenith Angle
Total Ozone 100.00
Total Ozone 200.00
Total Ozone 300.00
Total Ozone 400.00
Total Ozone 500.00
Total Ozone 600.00

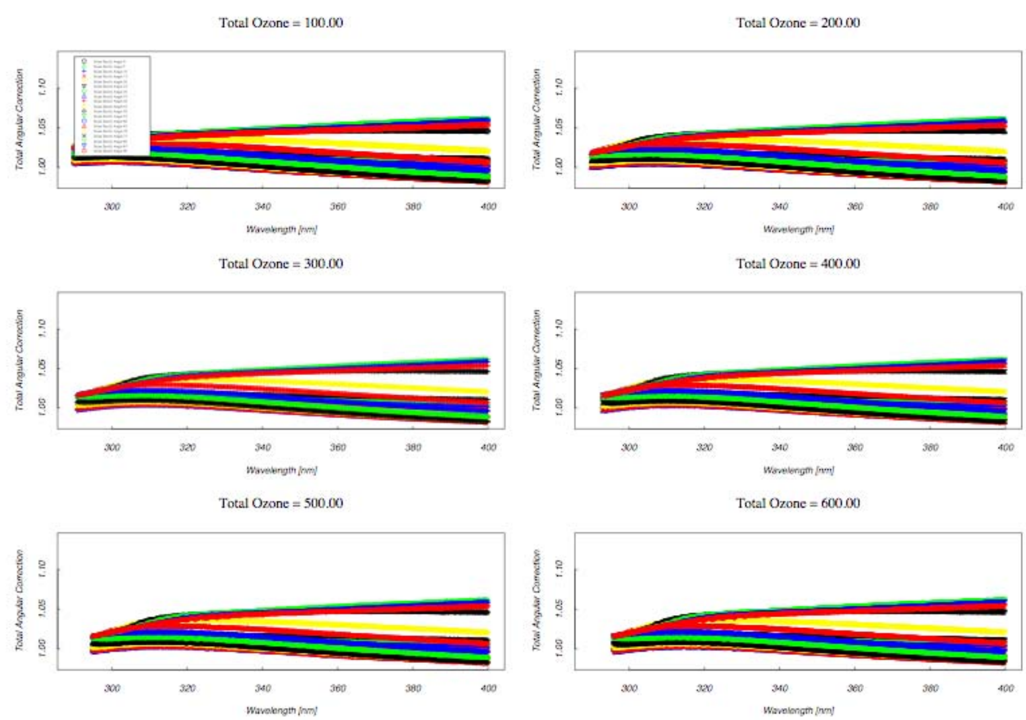

Aerosol Optical Depth
Diffuse Angular Correction
Solar Zenith Angle
AOD 0.00
AOD 0.20
AOD 0.40
AOD 0.60
AOD 0.80
AOD 1.00
AOD 1.50
AOD 2.00
AOD 2.50
AOD 3.00


Cloud o.d.
Diffuse Angular Correction
1.01
1.02
1.03
1.04
1.05
1.06
0
20
40
60
Solar Zenith Angle
Cloud o.d. 0.0
Cloud o.d. 0.1
Cloud o.d. 0.2
Cloud o.d. 0.3
Cloud o.d. 0.4
Cloud o.d. 0.5
Cloud o.d. 1.0
Cloud o.d. 1.5
Cloud o.d. 2.0
Cloud o.d. 2.5
Cloud o.d. 3.0
Cloud o.d. 3.5
Cloud o.d. 4.0
Cloud o.d. 4.5
Cloud o.d. 5.0

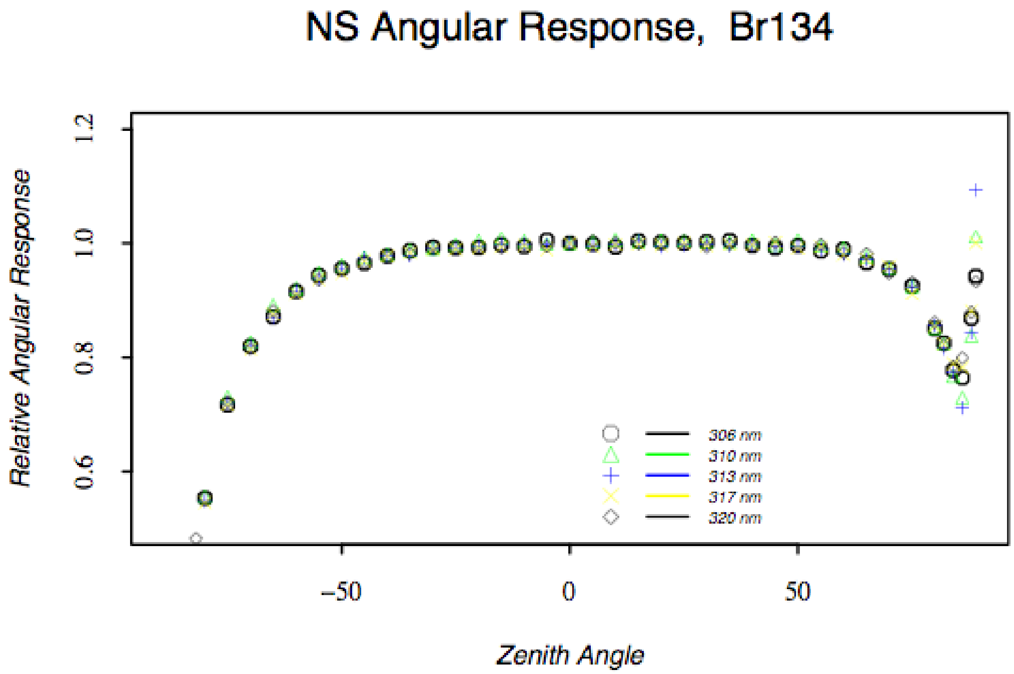
Spectral Diffuse Angular Correction

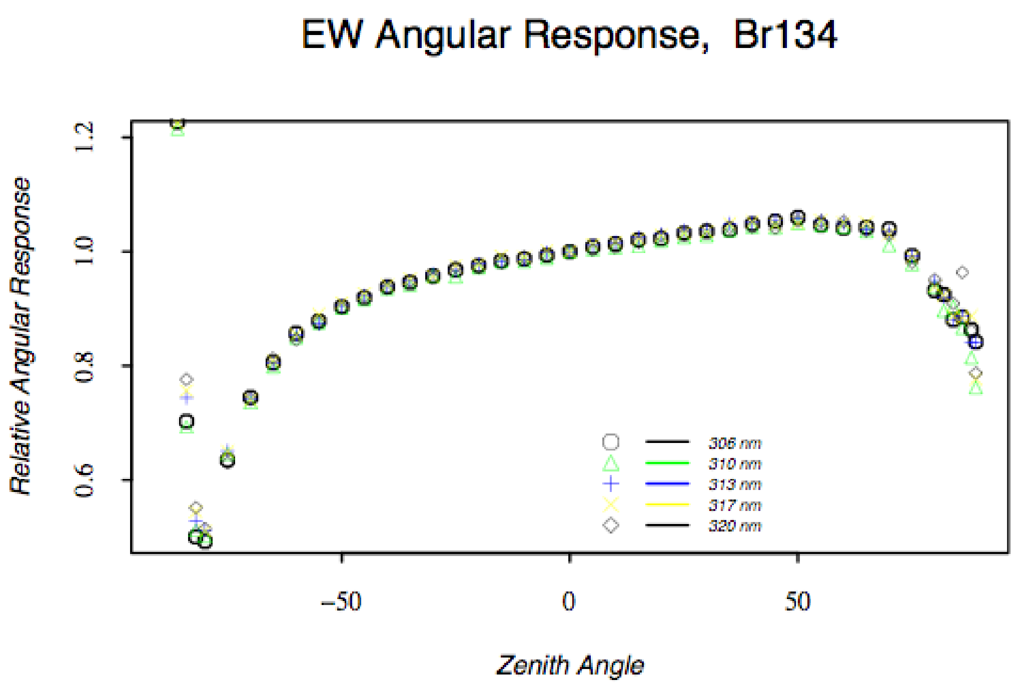


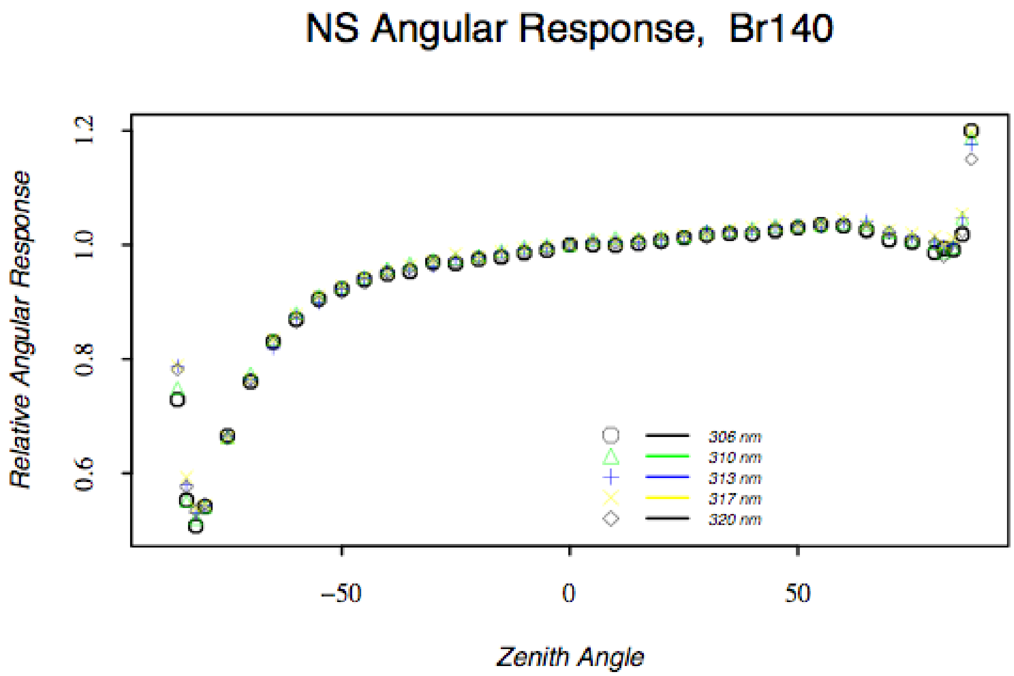
Spectral Total Angular Correction

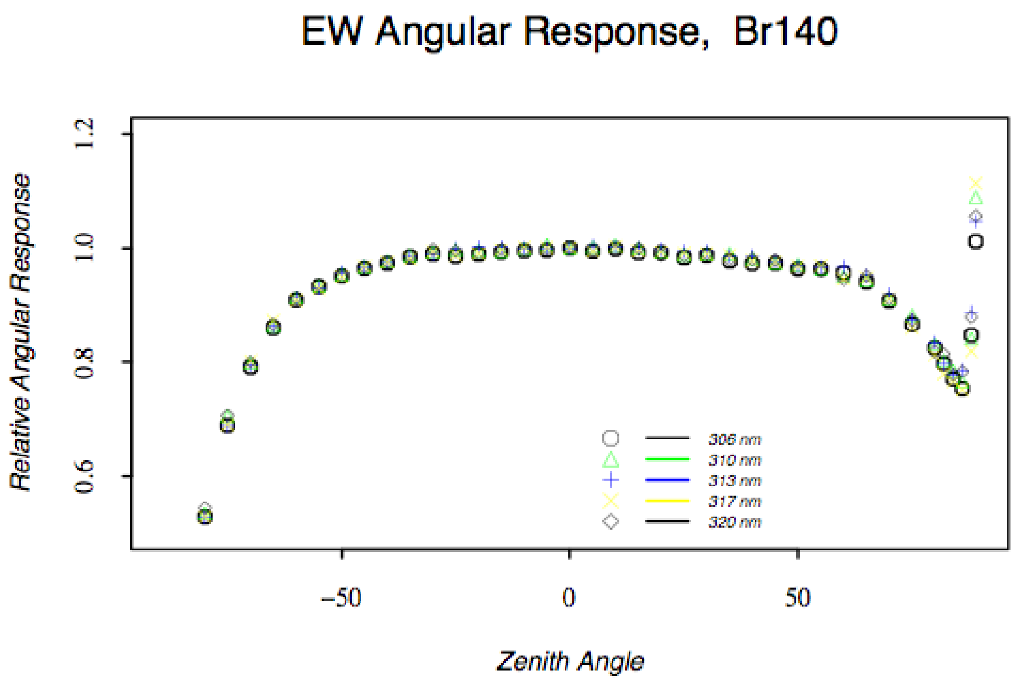


Appendix II. Plots of EW and NS planes of angular dependence of the diffuser. The measurements are normalized to unity at 0 degrees and are relative to the cos(theta).

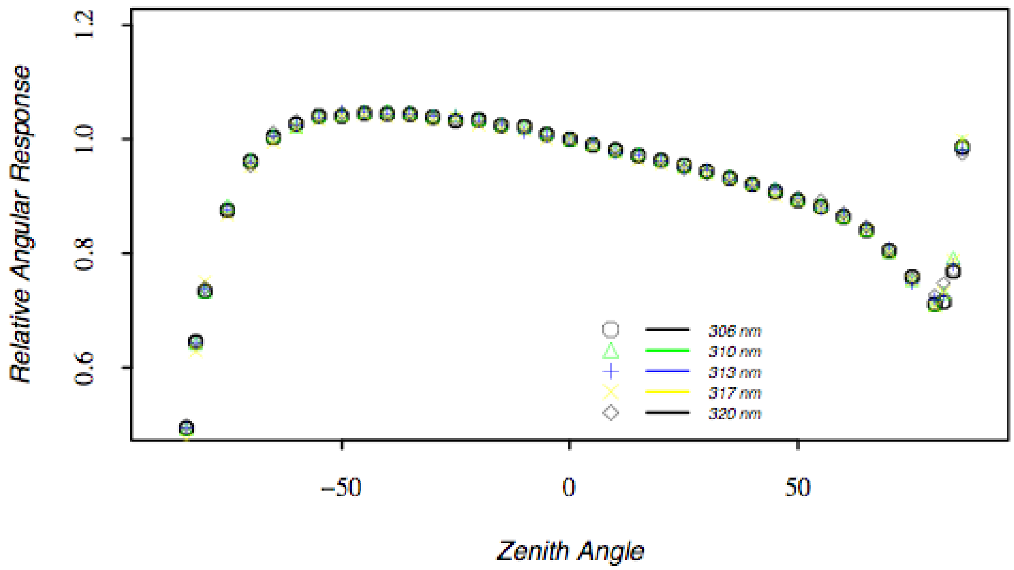




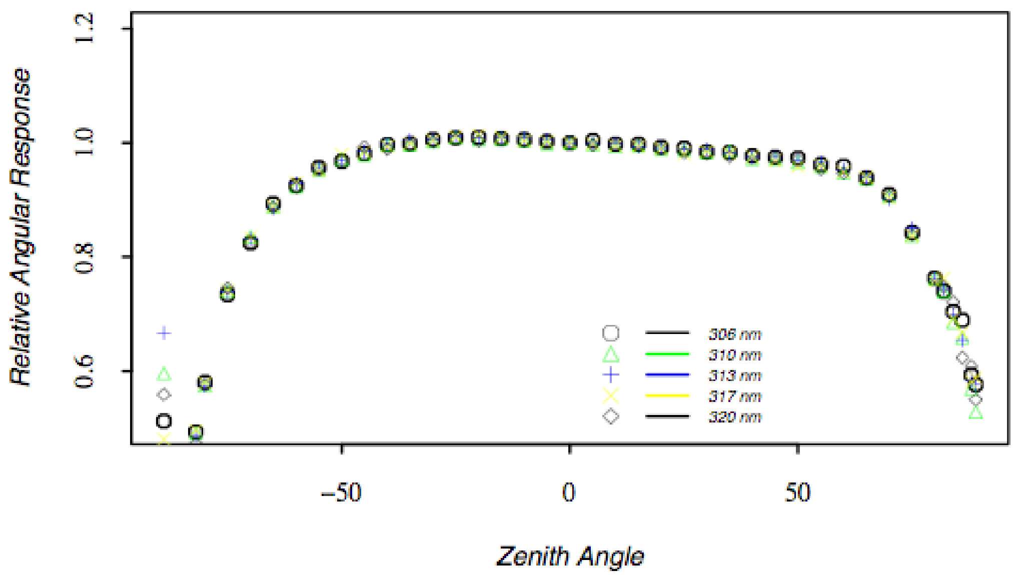

NS Angular Response, Br140
Relative Angular Response
0.6
0.8
1.0
1.2
−50
0
50
Zenith Angle
306 nm
310 nm
313 nm
317 nm
320 nm

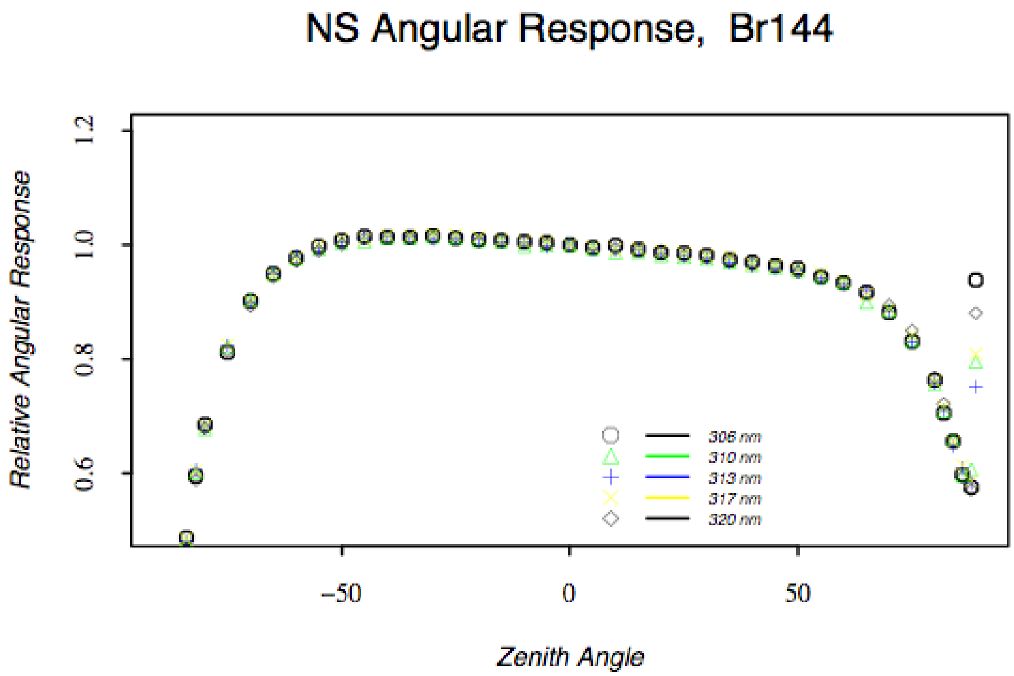

EW Angular Response, Br140
Relative Angular Response
0.6
0.8
1.0
1.2
−50
0
50
Zenith Angle
306 nm
310 nm
313 nm
317 nm
320 nm

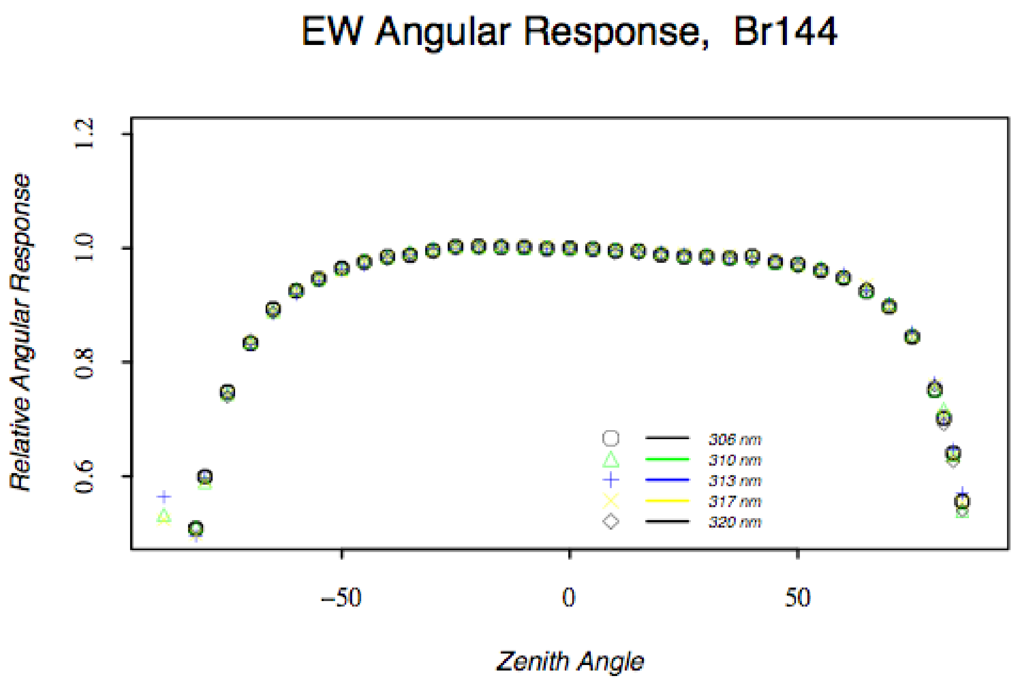
NS Angular Response, Br141

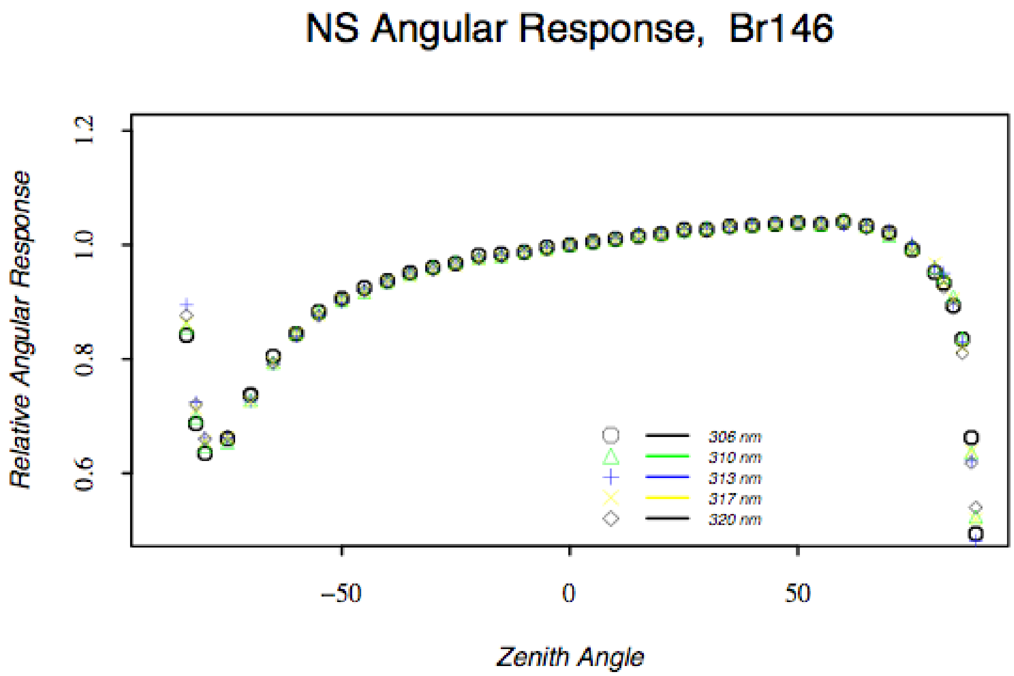


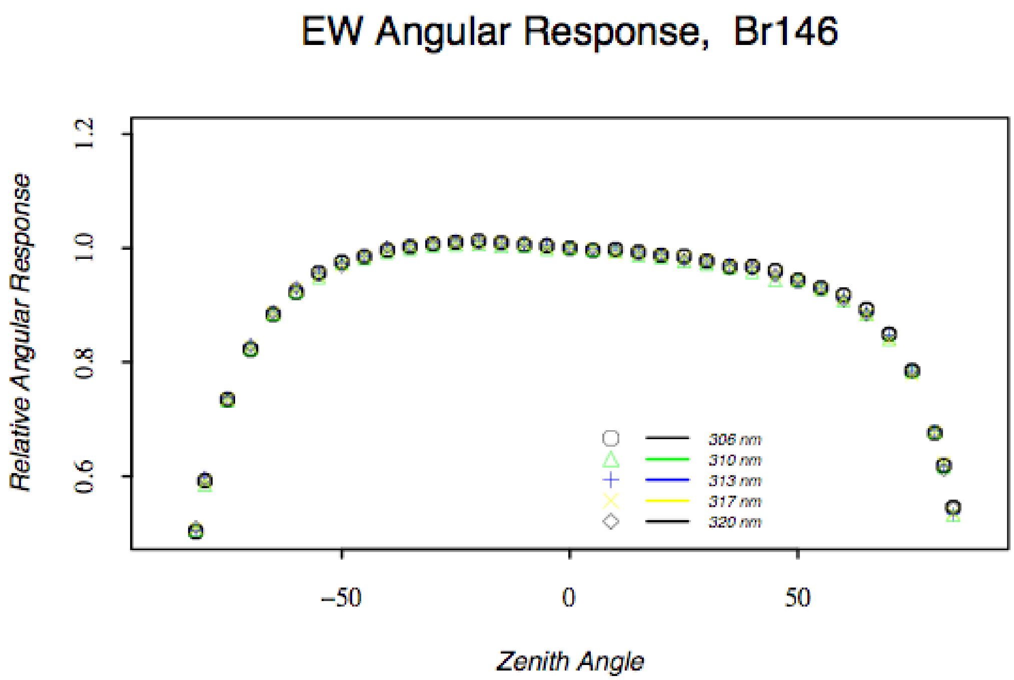
EW Angular Response, Br141

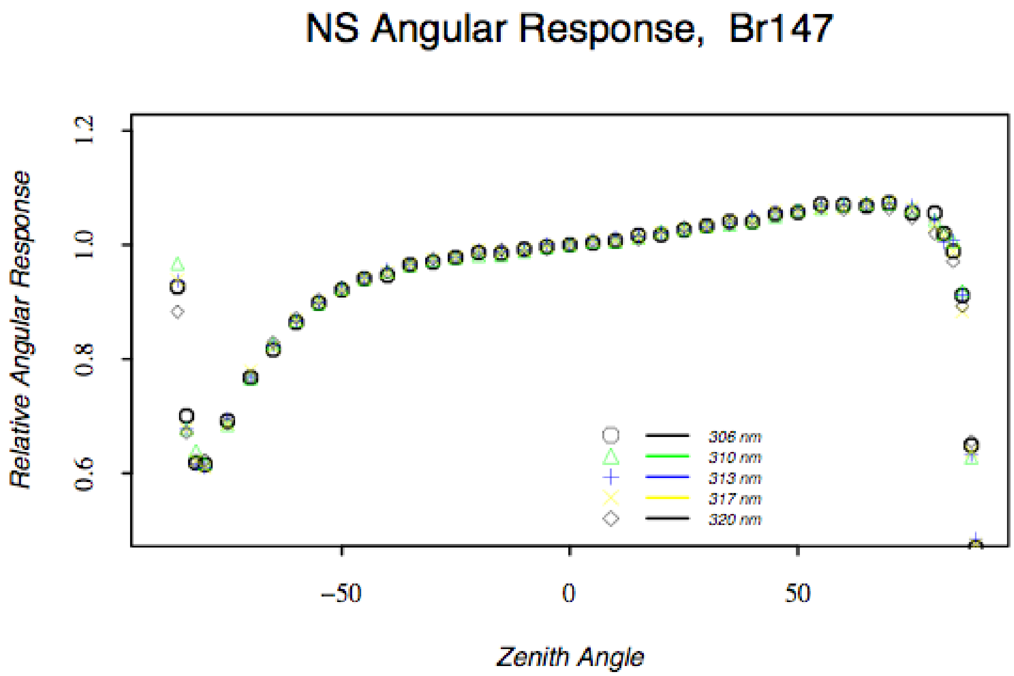


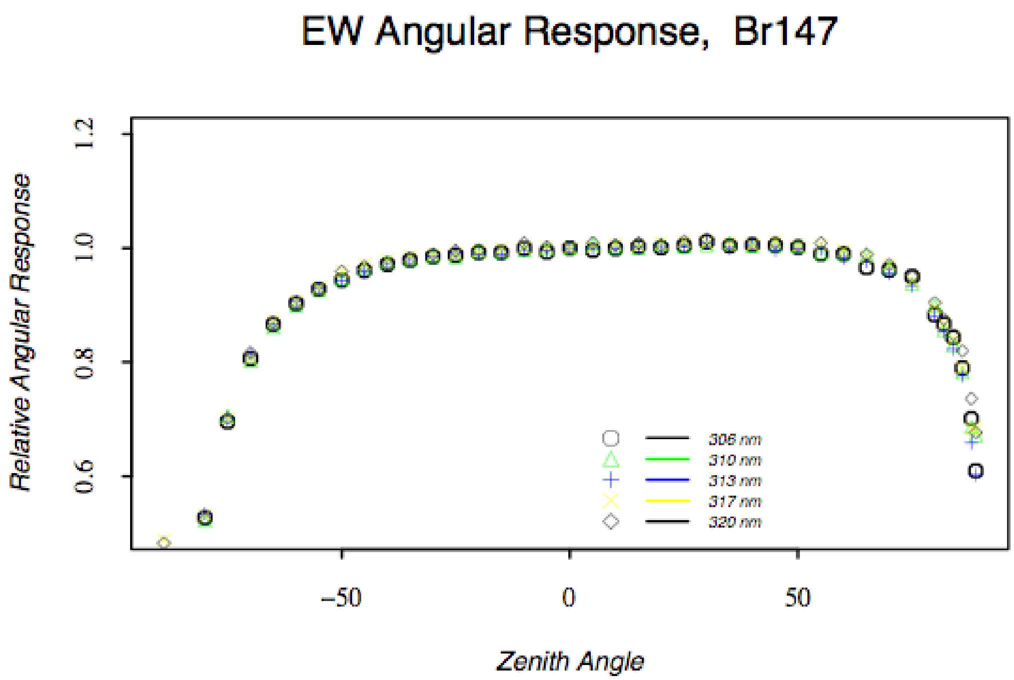

NS Angular Response, Br144
Relative Angular Response
1.2
1.0
0.8
0.6
306 nm
310 nm
313 nm
317 nm
320 nm
−50
0
50
Zenith Angle


EW Angular Response, Br144
Relative Angular Response
1.2
1.0
0.8
0.6
306 nm
310 nm
313 nm
317 nm
320 nm
−50
0
50
Zenith Angle

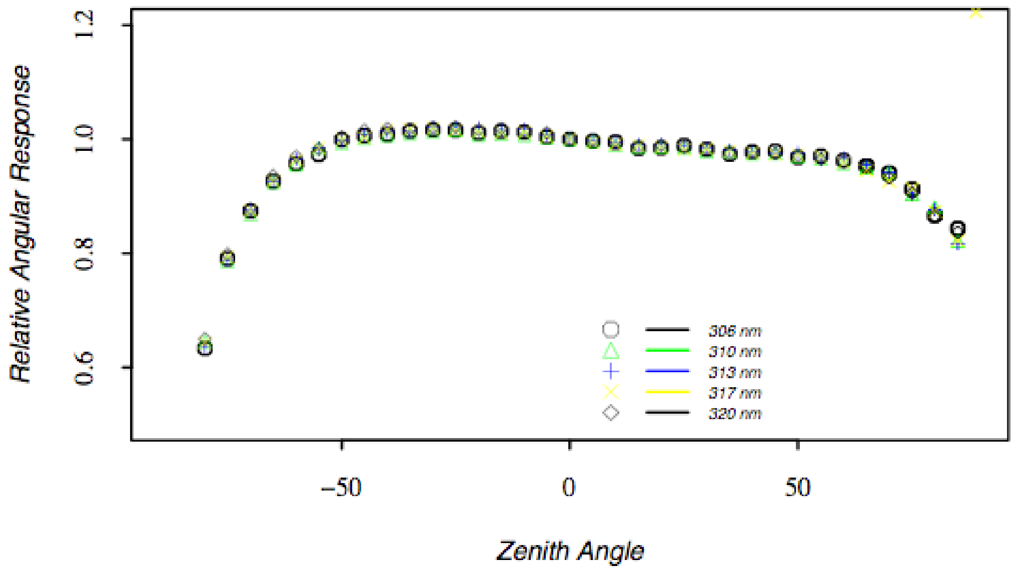

NS Angular Response, Br146
Relative Angular Response
1.2
1.0
0.8
0.6
−50
0
50
Zenith Angle
306 nm
310 nm
313 nm
317 nm
320 nm


EW Angular Response, Br146
Relative Angular Response
1.2
1.0
0.8
0.6
−50
0
50
Zenith Angle
306 nm
310 nm
313 nm
317 nm
320 nm


NS Angular Response, Br147
Relative Angular Response
Zenith Angle
0.6
0.8
1.0
1.2
−50
0
50
306 nm
310 nm
313 nm
317 nm
320 nm


EW Angular Response, Br147
Relative Angular Response
Zenith Angle
0.6
0.8
1.0
1.2
−50
0
50
306 nm
310 nm
313 nm
317 nm
320 nm

NS Angular Response, Br154



EW Angular Response, Br154