Validation of Cosine Error Determination and Cosine Error Correction

Parameterization of Cosine Error

Since appropriate laboratory data are not available, we calculated the cosine error of the SUV-100 spectroradiometer from measurements with a test apparatus and by comparing measured and modeled spectral irradiance at 600 nm. The procedure is described in detail by *Bernhard et al.* [2004] using data of the SUV-100 instrument at the South Pole. Here we present a comparison of results of the test apparatus and the model-based parameterization for the instrument at Barrow. The measurements with the test apparatus were performed in March 2004 with the "upgraded" cosine collector, which was installed in December 2000. This upgrade mostly eliminated the dependence of the instrument's cosine error on azimuth angle and wavelength.

Figure 1 shows the cosine error of the instrument derived from the model-based parameterization and measurements with the test apparatus, averaged over all available azimuth angles. The data set marked with black dots was calculated from the comparison of measured and modeled spectral irradiance at 600 nm. The data set indicated by open circles was derived from measurements of the test apparatus and the solid line indicates the final parameterization of the cosine error. Difference between the parameterization and the measurements with the test apparatus are within the combined uncertainties of the two methods.

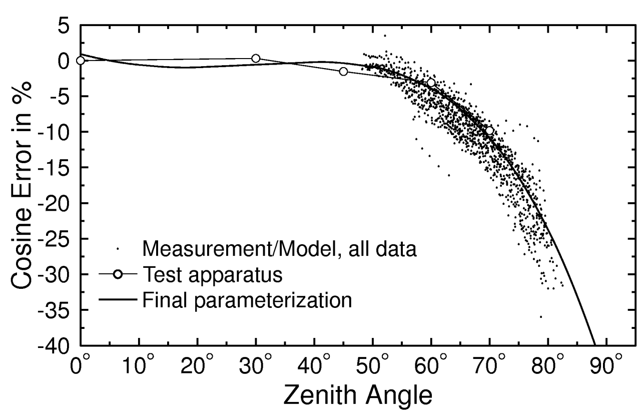

Figure 1. Cosine error of the SUV-100 spectroradiometer at Barrow determined from a comparison of measured and modeled spectral irradiance at 600 nm and measurements with the test apparatus. Data is from Volume 14, covering the years 2004-2005. The cosine error of other volumes may be different.

Comparison of SUV-100 and GUV-511 Measurements

To further validate the parameterization of the cosine error and the results of cosine error correction, we compared SUV-100 measurements from the Volume 14 period with measurements of a collocated GUV-511 multi-filter radiometer.

The GUV-511 instruments provide measurements at four approximately 10 nm wide UV bands centered at 305, 320, 340, and 380 nm. A fifth channel measures photosynthetic photon flux density (PPFD) or Photosynthetically Active Radiation (PAR), defined as number of photons in the 400-700 nm wavelength interval incident per unit time on a unit surface. More information about the instrument can be found at http://www.biospherical.com/nsf/instruments.asp#GUV. The calibration of the GUV-511 radiometer is described in Section 4.3 of the Volume 12 Network Operations Report.

The contribution of direct solar irradiance to global (= direct + diffuse) irradiance is larger in the visible than in the UV. Measurements in the visible are therefore more affected by the cosine error than measurements at shorter wavelengths and are more suitable for validating the cosine error correction procedure. For this reason, the GUV's PAR measurements were used for comparison with the SUV-100.

The SUV-100 measures only up to 600 nm and PAR therefore cannot be calculated directly from its data. Fortunately PAR can be derived with an accuracy of ±1% from spectral irradiance at 400, 500, and 600 nm using the parameterization:

$$PAR_{\text{estimated}} = c_1 E(400\text{nm}) \ + \ c_2 E(500\text{nm}) \ + \ c_3 E(600\text{nm}),$$

where E(400nm), E(500nm), and E(600nm) are spectral irradiance measured by the SUV-100 at 400, 500, and 600 nm. The coefficients c_1, c_2, and c_3 are:

$c_1 = -0.000221461$ (µE nm)/(µW s)
$c_2 = +0.0014567$ (µE nm)/(µW s)
$c_3 = -0.0000170416$ (µE nm)/(µW s).

Note that PAR is reported in units of $\mu E/(cm^2\ s)$. "E" stands for Einstein. 1 E equals 1 mol of photons or 6.022×10^{23} photons.

In Figure 2, the cosine error of the SUV-100 spectroradiometer of the Volume 14 period is compared with the cosine error of the GUV's PAR channel. The cosine error of the GUV is smaller than ±2% for zenith angles less than 66°. For zenith angles between 66° to 78°, the GUV overestimates radiation by 2.0 - 5.5%. For zenith angles larger than 87°, radiation is underestimated by more than 5%. Isotropic radiation is underestimated by 0.7%. Cosine errors of the GUV-511 are smaller than those of the SUV-100 for zenith angles larger than 60°. The SUV-100 underestimates isotropic radiation by 4%.

Figure 3 shows the ratio of PAR measurements of the SUV-100 spectroradiometer and the GUV-511 radiometer at Barrow. Ratios are based on data from the Volume 14 (2004-2005) period. GUV-511 data have not been corrected for the instrument's cosine error. The left panel of Figure 3 is based on Version 0 SUV-100 measurements, which also have not been corrected for the cosine error. The right panel of Figure 3 is based on cosine error corrected Version 2 SUV-100 measurements. Clear-sky data are indicated in blue color in both panels. We note that clear-sky flagging is conservative; not all clear-sky situations are labeled as such.

Figure 3 supports the following conclusions:

- Version 2 SUV-100 data generally agree better than Version 0 SUV-100 with GUV-511 measurements. The standard deviation of the ratios of SUV / GUV is 6.4% for Version 0 and 5.3% for Version 2.
- The average ratio of SUV / GUV for the Version 2 data set differs by less than ±1% from 1 up to solar zenith angles smaller than 83° (green line in right panel of Figure 3).
- The distribution of the Version 0 data set is bimodal. Ratios of SUV / GUV for clear skies are at the low end of the distribution and decrease with increasing solar zenith angles. Ratios for overcast situations show little dependence on the solar zenith angles and tend to be below the one-line by a few percent.
- The bimodal pattern can be expected from the different cosine-errors of the two instruments and the different contribution of the Sun's direct beam for clear sky and overcast situations: during clear sky periods, when visible radiation mostly originates from photons of the direct beam, the larger negative cosine error of the SUV-100 leads to systematic underestimation of PAR measurements. During overcast periods, PAR is underestimated by the cosine error for isotropic radiation, which is approximately independent from the solar zenith angle. Since the isotropic error of the SUV-100 is larger than that of the GUV-511 (–4% versus –0.7%), the ratio of SUV / GUV tends to be low.
- For the Version 2 data set, ratios of SUV / GUV show little dependence on sky condition.
- Beyond 85°, ratios of SUV / GUV tend to be larger than one. This is a consequence of the sharp drop-off the GUV's cosine error at very large zenith angles and the fact that both the parameterization of the SUV-100's cosine error and the cosine error correction become uncertain at solar zenith angles beyond 80°. Absolute radiation levels are small at large zenith angles and the increasing relative error is of little practical consequence.

In conclusions, differences between GUV and SUV measurements of the two versions can be explained with the different cosine errors of the two instruments. The better agreement for the Version 2 data set and the absence of a bimodal distribution validates the Version 2 cosine correction method.

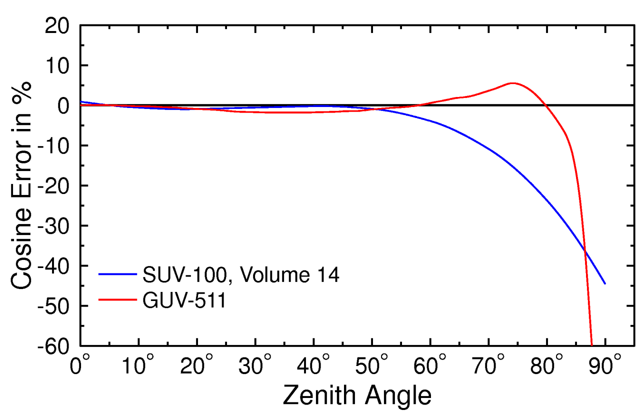

Figure 2. Cosine errors of the SUV-100 spectroradiometer and the GUV-511 radiometer. SUV-100 data are identical to the curve labeled "Final Parameterization" in Figure 1.

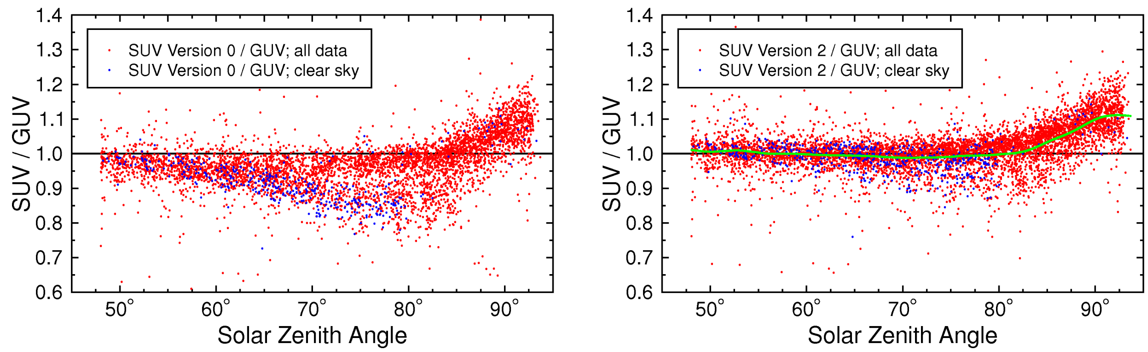

Figure 3. Ratio of PAR measurements of the SUV-100 spectroradiometer and GUV-511 radiometer at Barrow, based on data from the Volume 14 (2004-2005) period. GUV-511 data are not corrected for the instrument's cosine error. Left panel: Ratio of Version 0 SUV-100 and GUV-511 PAR measurements. SUV-100 data are not corrected for the cosine error. Right panel: Ratio of Version 2 SUV-100 and GUV-511 PAR measurements. SUV-100 data are cosine error corrected. Clear-sky data are indicated in blue color in both panels. The green line in the right panel was calculated by convolving all data with a triangular function of 3° full width at half maximum.

References

Bernhard, G., C.R. Booth, and J.C. Ehramjian (2004), Version 2 data of the National Science Foundation's Ultraviolet Radiation Monitoring Network: South Pole, *J. Geophys. Res.*, *109*, D21207, doi:10.1029/2004JD004937.