

# Establishing the stability of multifilter UV rotating shadow-band radiometers

David S. Bigelow and James R. Slusser

Natural Resource Ecology Laboratory, Colorado State University, Fort Collins

**Abstract.** A modified Langley technique is used in a preliminary evaluation of the stability of ion-assisted deposition interference filters. The technique uses lamp-calibrated direct-normal irradiance measurements to return estimates of the extraterrestrial solar irradiance over the passband of the filter. Results from prototype and production UV-multifilter rotating shadow-band radiometers deployed in the U.S. Department of Agriculture UV Radiation Monitoring program indicate a 1%/yr drift in filter measurements. Measurements are reported to be within 8% of the SUSIM Atlas-3 extraterrestrial solar irradiance.

## 1. Introduction

The U.S. Department of Agriculture (USDA) UV-B Radiation Monitoring Network [Bigelow *et al.*, 1998] began operations in 1994 with the goal of establishing a geographical and temporal UV climatology of the United States. By establishing and monitoring this climatology the USDA hopes to determine whether food and fiber production in the United States will be impacted by changing levels of UV irradiance associated with stratospheric ozone depletion.

The ultraviolet multifilter rotating shadow-band radiometer (UV-MFRSR) is a new instrument that extends the utility of the visible radiation MFRSR developed by Harrison *et al.* [1994] into the UV. The instrument utilizes 2 nm nominal FWHM bandwidth ion-assisted-deposition (IAD) filters to obtain total-horizontal, direct-normal and diffuse-horizontal irradiances at 300, 305, 311, 317, 326, 332, and 368 nominal center wavelengths. Because of its capacity to return direct-normal measurements the instrument is also ideally suited for determining optical depths. Optical depths retrieved using the Harrison and Michalsky [1994] objective algorithm are quite robust against filter instability since day-to-day changes in filter throughput result in proportional changes in the technique's interpolated  $V_0$  intercepts. This is further illustrated in the basic Langley equation given below, where  $V_\lambda$  is the measured instrument response at a particular channel,  $\ln V_{0,\lambda}$  is the instrument response at the top of the atmosphere,  $m_i$  is the air mass, and  $\tau_i$  is the optical depth. The  $i$  represents the  $i$ th absorber and  $\lambda$  the wavelength at which the measurement is made.

$$\ln V_\lambda - \ln V_{0,\lambda} = \sum m_i \tau_i$$

The technique further assumes that the atmosphere remains stable throughout the Langley event. This is usually achieved indirectly through the limiting of the air mass range and therefore time over which the technique is applied. For a detailed discussion of Langley error analysis the reader is referred to Shaw [1976].

Unlike the determination of optical depth, the instrument, when used as a radiation detector, is very sensitive to conditions which change filter throughput, and reports of filter instability [Basher and Matthews, 1977; Schmid and Wehrli, 1995; Schmid *et al.*, 1998;

Bigelow *et al.*, 1998] and problems in calibrating filter instruments [Shaw, 1976, 1983; Booth *et al.*, 1994] are cause for serious concern for any agency operating a network of filter radiometers.

The USDA UV-B Radiation Monitoring Program has 83 multifilter rotating shadow-band radiometers deployed in its climate network. Half of these contain IAD ultraviolet filters (UV-MFRSR), and half contain traditional dielectric filters that are sensitive at visible wavelengths (VIS-MFRSR). Because of the large number of shadow-band instruments used by the network and its standard practice of rotating instruments throughout the network to achieve regular recalibration, the network must be able to establish the stability of each instrument during its tenure at a network site.

The network's preliminary experience with UV-MFRSR instrument stability, evaluated by Langley analysis, repeated spectral response functions and lamp calibrations, is summarized using both prototype and production models. Additional information and data from the USDA UV-B Radiation Monitoring Program can be found at the network's World Wide Web site, URL: <http://uvb.nrel.colostate.edu>.

## 2. Stability Evaluation Methods

### 2.1. Langley Analysis

Langley analysis, using software based upon the objective algorithms established by Harrison and Michalsky [1994], is the primary method used by the USDA UV-B Radiation Monitoring Program to track instrument stability.  $V_0$  values returned by the Langley analysis (the zero air mass intercept of the natural log of the cosine-corrected direct beam signal voltages versus air mass) are grouped by unit and time to produce a time series for each instrument. Each  $V_0$  in turn can be used to determine an independent estimate of the calibration factor of that filter using the spectral response function (SRF) of the filter and the extraterrestrial solar irradiance [Bigelow *et al.*, 1998; Shaw, 1976; WMO, 1978].

Only minimal modification to the Harrison and Michalsky [1994] algorithm is required to apply the algorithm to UV wavelengths. The range of air masses suitable for Langley regressions is governed by the product of air mass  $m$  and optical depth  $\tau$ . The strong absorption due to ozone and the increased Rayleigh scattering, proportional to  $\lambda^{-4}$  at the shorter UV wavelengths, causes the attenuation of the direct beam to be much greater in the UV than in the visible for the same air mass. Since the current state-of-the-art solid-state detectors are limited to not more than four decades of dynamic range, air mass ranges need to be

more restricted to stay within this range. For our UV wavelengths (300–368 nm) an air mass range between 1.5 and 3.0 is used in place of the 2.0 to 6.0 limits used in the visible. The only other modification to the algorithm is the relaxation of the 0.006 limit on the allowable residual standard deviation of the variance around the final regression to 0.009.

Plate 1 displays a time series of  $V_0$  values using an instrument that made measurements in Texas (latitude 29.13°N; longitude 103.5°W; elevation 670 m) between October 1997 and August 1998. In the plate, each color represents a separate wavelength and each point a separate Langley event at that wavelength. Dates are given as a decimal within each year.  $V_0$  values from the 300 nm and 305 nm channel have additionally been divided by 7 to allow this wavelength to be plotted on the same scale as the other wavelengths.

A more complicated time series results when a site has a history with more than one unit. In such instances the  $V_0$  values are influenced by any repairs or adjustments that may take place between the unit's field deployments. This includes gain settings that are unique to the head and data logger boards at each site.

Plate 2a displays  $V_0$  values from a more typical time series. In this case the unit was first sent to Utah and then to Arizona. After leaving Utah, the instrument had its Spectralon diffuser replaced with one made from Teflon, had a quartz window inserted at the exit end of its new diffuser, and had its head and board gains adjusted. The resulting step change in  $V_0$  values is readily apparent and not surprising in this extreme example. In long-term measurement programs, however, it is not unusual to have instrumentation wear out, fail, or require adjustment. When this occurs calibration relationships change. Since the network tracks these instrument modifications and recalibrations, it is more efficient to incorporate the knowledge of these changes into the stability check and not have these confound the network's estimates of instrument stability. This is accomplished by tracking  $I_0$  values, obtained from the intercept of the natural log of the lamp-calibrated, cosine-corrected direct-beam irradiance versus air mass regression, rather than  $V_0$  values. The  $I_0$  values are computed identically to the  $V_0$  values except calibrated data are used in place of the only cosine-corrected voltages in the more typical Langley analysis. Plate 2b displays the same stability check when  $I_0$  values are used in place of  $V_0$  values.

In addition to simplifying the tracking of instrument stability, the  $I_0$  check is a powerful tool for identifying erroneous calibrations. In Plate 2b for instance, there is a small sustained step increase in the 326 nm channel during the period the unit was in Arizona. Because of the nature of the increase, a step versus a more gradual change, it is likely a consequence of a questionable lamp calibration rather than filter or diffuser degradation. Likewise, the missing 317 nm channel (yellow) Utah data are the result of the  $I_0$  being estimated in excess of 3.2 W/m<sup>2</sup>/nm (off scale). Further investigation revealed that this channel was saturated (gains set too high) and was clearly producing erroneous Langley intercepts during this time period.

Because the estimated  $I_0$  values are in effect repeated estimates of the extraterrestrial solar irradiance over each filter's passband it is possible to use them in more traditional types of statistical analysis. Plate 3 presents the network's longest continuous UV-MFRSR measurement time series, a 2 1/2 year record comprised of four UV-MFRSRs that had been deployed at a Colorado site. In Table 1 the mean and variance of  $I_0$  for each unit's tenure at the site has been computed and compared to the SUSIM Atlas-3 extra terrestrial solar irradiance (D. Prinz, unpublished data, 1998). Ideally, the mean  $I_0$  of each instrument at each channel will coincide with the SUSIM Atlas-3 solar irradiance (no bias), and the standard deviation will approach the uncertainty of the SUSIM Atlas-3 solar irradiance measurement. The extraterrestrial solar irradiance, estimated from the repeated  $I_0$  values for each of the four UV-MFRSRs, is identified as UVRSR in the table. The mean is

computed as the average of all morning and afternoon Langley intercepts recorded during each unit's tenure at the site. This is compared to the extraterrestrial solar irradiance (labeled SUSIM) computed by the integral multiplication of the SRF of each unit with the SUSIM Atlas-3 extraterrestrial solar irradiance. Measured wavelengths and passbands as well as the standard deviation of the estimated means are also given. Because of an overflow problem in our computer code, no standard deviations are available for the 305 nm wavelengths, and only two Langley events were observed for the 300 nm channel.

The ratio of the estimated UVRSR mean to the SUSIM flux indicates that the UV-MFRSR estimates are within 8% of the solar flux. Although no detailed error analysis of the SUSIM Atlas-3 mission is available at this time, it is assumed that uncertainties in the irradiances at our passbands are no worse than those reported by Woods *et al.* [1996] in their detailed description of the uncertainties of the SUSIM Atlas-1 and Atlas-2 missions. Herman *et al.* [1999] have taken a similar approach to the error budget of the SUSIM Atlas-3 data in their presentation of TOMS UV radiation climatology. Because our study used the 0.15 nm resolution spectra of the SUSIM Atlas-3 mission we would expect an agreement of 5–6% to be quite good. Three quarters of the comparisons listed in Table 1 are at or better than 5% across all passbands above 305 nm. It is apparent that there are only small differences in comparison results between different units at identical wavelengths or between different wavelengths within a single unit. Earlier units, however, are distinctly different than the later units. We attribute this to bias and imprecision in our lamp calibrations.

These comparison results differ from those of Schmid *et al.* [1998] in that the Harrison and Michalsky [1994] objective Langley algorithm was successfully applied to passbands below 320 nm, and reasonable agreement between an extraterrestrial spectra and the Langley technique was obtained at our less than pristine site. At the 368 nm passband our ratios of 0.96, 1.01, 0.92, and 0.95 compare favorably with the 1.6% and 2.3% differences reported by Schmid *et al.* [1998] for their SUSIM/SOLSTICE Atlas-1 and Atlas-2 comparisons even though they are derived using a different Langley algorithm and a different solar spectra. An important difference in the two Langley methods is the lack of a bandwidth correction in our Langley method which Schmid *et al.* [1998] have estimated to be significant for 2 nm passbands below 320 nm. Preliminary work by the authors at Mauna Loa, a much more pristine location, suggests this might introduce an approximate 3% error at 300 nm. Another difference is that our Langley technique does not include a separate ozone air mass term [Tomasi *et al.*, 1998], which at 300 nm will introduce an error of as much as 5%. Significant improvements in wavelength accuracy are also noted to have been implemented in the SUSIM instrument after the Atlas-2 mission. There was a factor of 10 improvement in the wavelength accuracy and factor of 2 improvement in the signal-to-noise ratio of the SUSIM Atlas-3 instrument over that of the SUSIM-Atlas-2 instrument.

The coefficient of variation (CV) of the UV-MFRSR  $I_0$  estimates is between 2% and 16% with a median CV of 8%. Although these values are not as good as those reported by Schmid *et al.* [1998], we consider them acceptable, considering that the site is not located at high elevation or in a pristine environment. It is also encouraging that these results in the UV are generally only slightly worse than those reported by Harrison and Michalsky [1994] for a VIS-MFRSR operated at Boulder, Colorado. Further work in tuning our objective Langley analysis technique to specific latitudes, wavelength specific air mass ranges, implementing bandpass corrections, and limiting our Langley events to mornings only holds promise for improving both the precision and the bias in our  $I_0$  estimates.

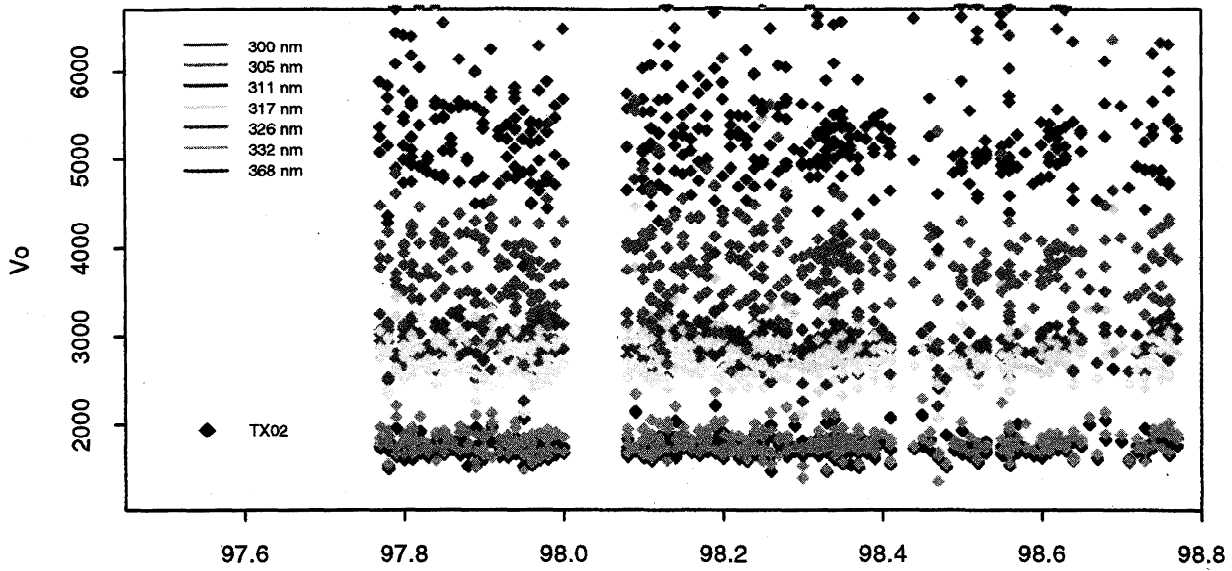


Plate 1.  $V_o$  time series for unit #308.

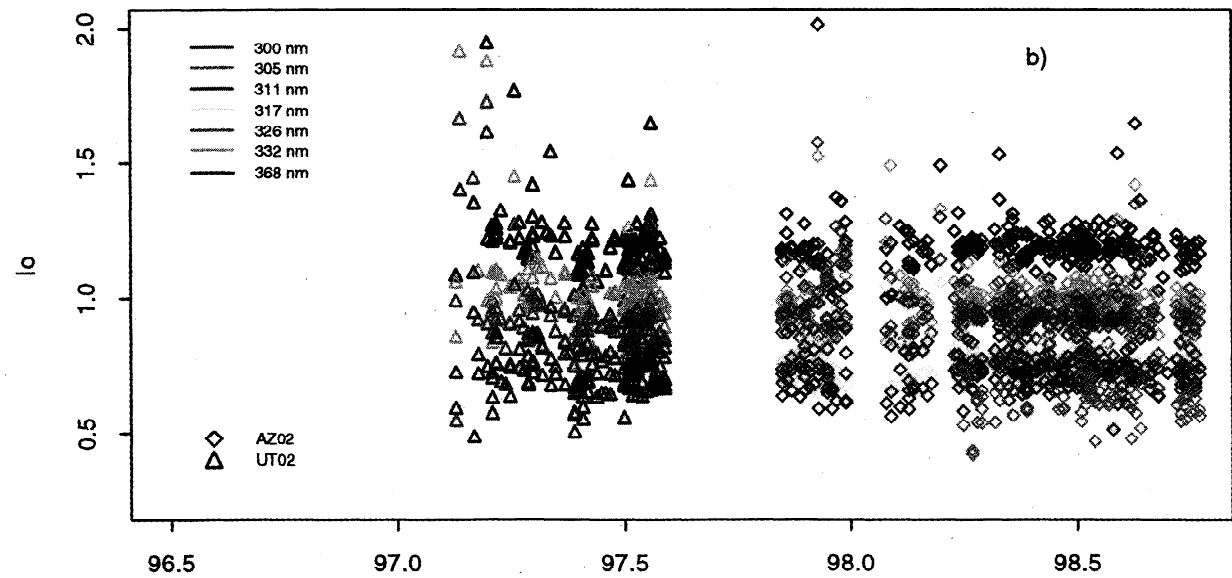
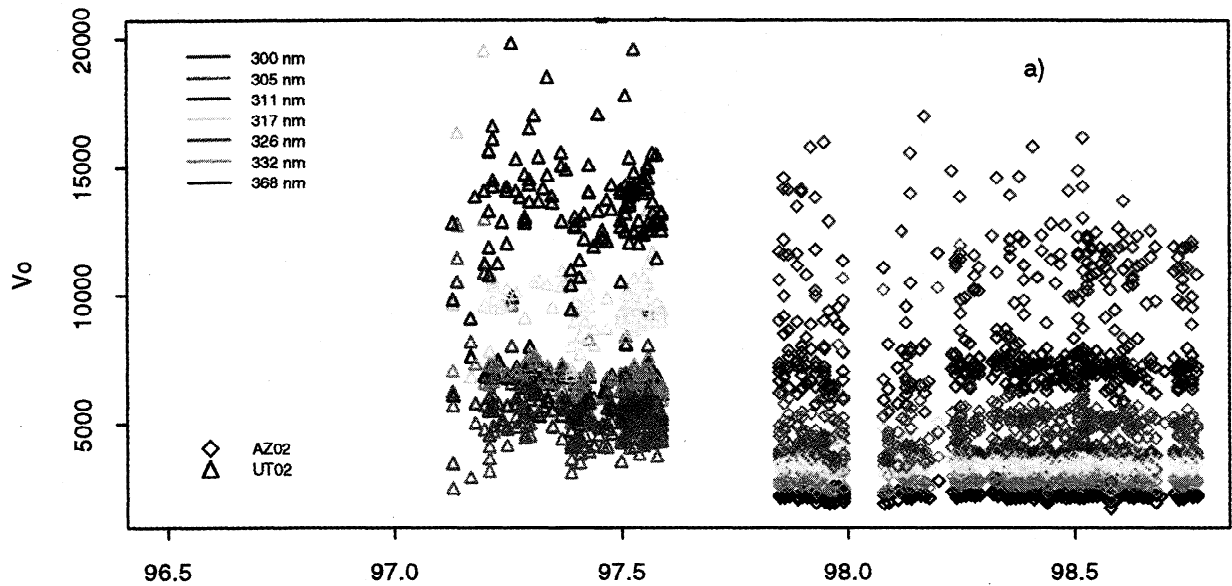


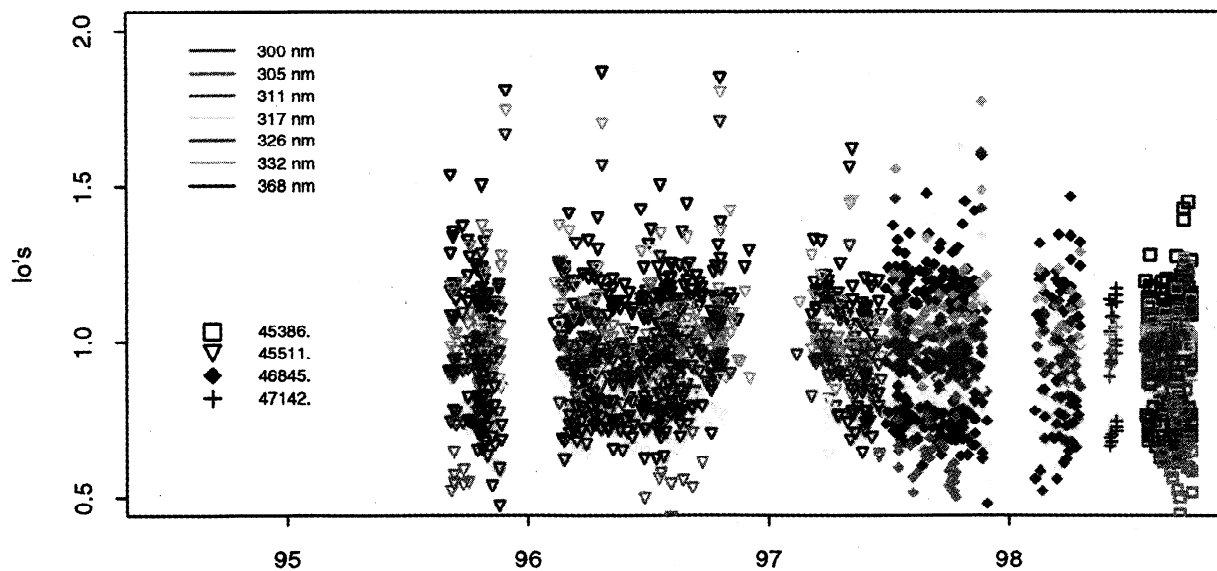
Plate 2.  $V_o$  versus  $I_o$  for unit #286.

**Table 1.** Average of  $I_0$  Values From Four Units at the Central Plains Experimental Range, October 1995 Through September 1998

Unit	Wavelength and (Passband), nm	Extraterrestrial Solar Flux, W/m <sup>2</sup> /nm		n	Ratio UVRSR/SUSIM	UVRSR Standard Deviation
		SUSIM	UVRSR			
231	300.4 (2.9)	0.4801	0.406	1	0.85	na
295	300.3 (2.3)	0.4843	na	0	na	na
294	300.4 (2.3)	0.4844	0.4510	1	0.93	na
395	300.3 (2.1)	0.4821	na	0	na	na
231	305.7 (2.8)	0.6288	0.570	175	0.91	...
295	305.8 (2.3)	0.6142	0.622	116	1.01	...
294	305.8 (2.3)	0.6142	0.630	5	1.03	...
395	306.0 (2.2)	0.6126	0.616	37	1.01	...
231	312.0 (2.9)	0.7141	0.773	147	1.08	0.099
295	311.9 (2.2)	0.7230	0.754	150	1.04	0.124
294	311.8 (2.1)	0.7255	0.693	9	0.96	0.046
395	311.7 (2.4)	0.7262	0.736	56	1.01	0.105
231	318.1 (2.7)	0.7382	0.771	219	1.04	0.067
295	318.1 (2.1)	0.7469	0.786	154	1.05	0.084
294	318.3 (2.3)	0.7448	0.719	7	0.97	0.013
395	318.3 (2.2)	0.7462	0.726	51	0.97	0.054
231	325.9 (2.4)	0.9983	0.933	256	0.93	0.076
295	326.0 (1.8)	0.9621	0.946	170	0.98	0.073
294	326.0 (1.8)	0.9702	0.928	9	0.96	0.048
395	326.0 (1.9)	0.9751	0.910	52	0.93	0.068
231	332.9 (2.7)	0.9709	1.032	311	1.06	0.080
295	332.8 (2.1)	0.9787	1.045	179	1.07	0.085
294	332.8 (2.0)	0.9810	0.972	9	0.99	0.056
395	332.8 (2.0)	0.9696	0.961	52	0.99	0.066
231	367.4 (2.4)	1.1992	1.153	333	0.96	0.109
295	368.5 (1.8)	1.1866	1.199	191	1.01	0.143
294	368.5 (1.8)	1.1855	1.091	9	0.92	0.051
395	368.6 (1.6)	1.1859	1.128	56	0.95	0.107

A simple linear regression of  $I_0$  values versus time indicates that the 311 nm through 368 nm channels have declined approximately 1%/yr at this site. Regressions using the  $I_0$  values of individual units, however, exhibit greater variation. The original unit at the

Colorado site, unit 231 (Plate 3), exhibited declines of 2.1 to 2.7%/yr for the 311, 332, and 368 channels. The decline was 1% for the 317 channel, but there was no change noted in the 326 nm channel. The second unit in the time series (unit 295) exhibited



**Plate 3.** Time series of  $I_0$  for a Colorado site.

increases in  $I_0$  values of 18, 6.6, 2.3 and 5.4% for the 311, 317, 332, and 368 nm channels but a 1.8% decrease in the 326 nm channel. Units with the shortest time series were even more variable confirming that a longer  $V_0$  or  $I_0$  time series is necessary to achieve a robust estimate of trends [Harrison and Michalsky, 1994; J. Michalsky, personal communication, 1998].

Presently, our trend estimates suffer from the use of a linear model to characterize the noisy data and the necessity of chaining together short time series. J. Michalsky (personal communication, 1998) has successfully used the interquartile range of the ratios of the most recent 20  $V_0$  values from pairs of wavelengths to improve the accuracy of  $V_0$  estimates in VIS-MFRSRs. It is likely that this or other nonparametric techniques of estimating trend will improve the quality of our estimates. It is also possible that our results are influenced by the newness of our instruments, each of which was deployed for the first time. Basher and Matthews [1977] commented on studies by Title [1974] and Title *et al.* [1974] which note that new filters may suffer from irradiance-induced aging and benefit from a "baking out" process of several months. Although it is known that the manufacturer of the UV-MFRSR does indeed "bake out" the filters as a part of the manufacturing process, it is unclear if this has improved the stability of the SRF. On the basis of these observations it follows that new instruments may be more likely to exhibit larger changes in filter response than units that have a longer in-service history. To date, the network's history is only with new instruments.

Because of calibration facility throughput limitations and the lack of a traveling irradiance standard for the UV-MFRSR class of instrumentation, the network is compelled to rotate its instruments throughout the network to maintain continuous measurement records at each site and regular calibration of its instrumentation. Thus Langley  $I_0$  stability checks are of paramount importance to the USDA UV Radiation Monitoring Program because of its importance in correctly estimating trends at sites.

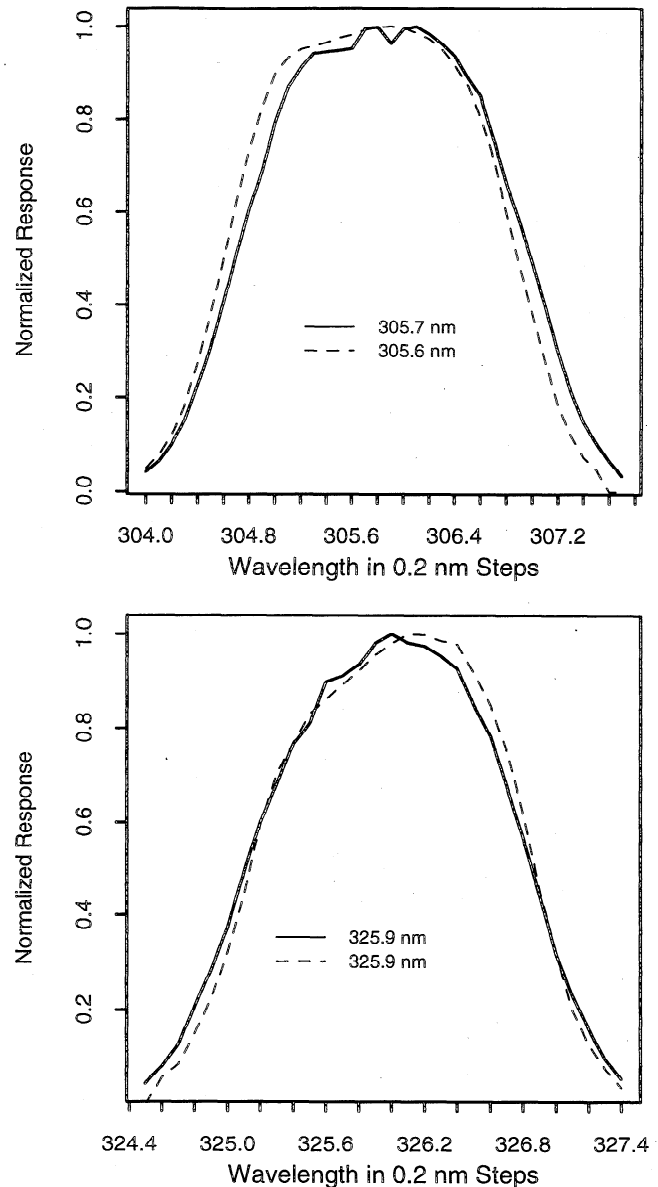
## 2.2. Repeated Spectral Response Measurements

The network also evaluates stability of its UV-MFRSRs by comparing the reproducibility of each unit's spectral response function (SRF) to its previous SRF each time an instrument is returned for calibration. Signs of instability include shifted center wavelengths, broadened or narrower passbands at full width at half maximum (FWHM) of peak response, and the appearance of tails on the wings of the SRF. Since Network SRF are measured through the diffuser, signs of instability may also reflect degradation or other changes in the diffuser.

Figure 1 contrasts the remeasured SRF of unit 286 to its original SRF at the 305 nm and 326 nm channels. The original SRF was measured, while the instrument was configured with a Spectralon diffuser, no quartz exit window beneath the diffuser, lower head gains, and the original electrical components. The second SRF took place after the instrument had been in the field for 239 days and modified, the same modifications outlined for the example illustrated in Plate 2. Within each plot is the old and new center wavelength determined as the wavelength that corresponds to one half of the integrated area under the curve. The original Spectralon SRF is the solid line in each plot, and the Teflon SRF is the dashed line.

Two features of the plots are apparent. First the original SRF appears noisier, especially around the wavelength peak. Second, wavelengths are shifted, although at the 305 nm channel the shift is toward the shorter wavelengths, while at the 326 nm channel, the shift is in the opposite direction. These differences are not the expected results from changes in diffuser materials.

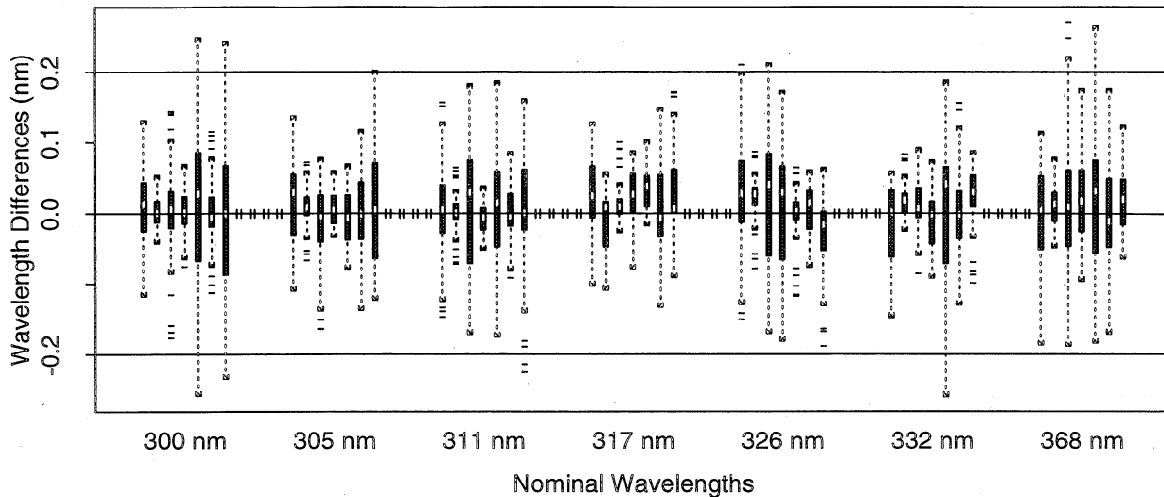
An examination of seven pairs of UV-MFRSR SRFs, the only ones available at this writing, suggests that calibration facility



**Figure 1.** Remeasured spectral response functions for the 305 and 326 nm channels.

performance has improved, and there has not probably been any actual changes in center wavelengths or passbands. All of the original measurements are noisier than their remeasured SRF. Approximately one third of the filters shows a shift in wavelength to the visible. One third shows a shift in the opposite direction, and one third shows no shifts. In the case of all but two filters the shifts in center wavelengths were less than 0.1 nm. The two remaining filters shifted to the longer wavelengths by 0.2 nm. On a per instrument basis, three instruments exhibit a general shift toward longer wavelengths, one instrument to shorter wavelengths, and four displayed no shift. A visual examination of plots of differences in SRF by wavelength (not shown) further revealed that differences near the center of the passbands were much less than at the wings and that noise on the order of  $\pm 0.5\%$  was not uncommon across all wavelengths.

In Figure 2 box plots of the difference between remeasured SRFs of each instrument at each 0.1 nm wavelength step throughout each passband indicate that about one half of the changes in SRF are within 0.1 nm, and all but about 12% are within 0.2 nm of their



**Figure 2.** Distribution of differences between original and remeasured spectral response functions by channel of seven UV-MFRSRs.

original values. With such a limited number of repeated SRF measurements it cannot be determined if the changes are real or an artifact of the measurement system. Presently, it is suspected to be an artifact of the measurement system since the wavelength repeatability stated by the manufacturer is only 0.2 nm [Yankee Environmental Systems, 1994].

Although the comparison of sequentially measured SRFs would appear to be a straightforward test of filter stability, it is dependent on the frequency as well as the precision and accuracy of the measurements. In the case of the USDA UV Radiation Monitoring Program this frequency is only once per year, and the current calibration facility does not have a long-term history that establishes a tight tolerance and stable characterization system. Gross changes in filter center wavelengths might be detected after a few years, but these changes would be apparent through the tracking of  $I_0$  values long before they could be detected by only examining the spectral response characterizations.

### 2.3. Repeated Lamp Calibrations

The third method of evaluating the stability of the UV-MFRSR filters available to the USDA UV Radiation Monitoring Program is based on repeated lamp calibrations of the filters. As is the case of the repeated SRFs, the usefulness of repeated lamp calibrations is tied to the frequency and quality of the measurement. As pointed out previously (section 2.1), many factors common to network

operations can affect lamp calibration results. It is important then when making lamp calibration comparisons to ensure that the unit being evaluated has not had any modifications made to it between calibrations. Ideally, this would dictate a beginning and ending calibration for each unit prior to any necessary adjustments being performed. Only one unit (unit 270) in the USDA UV Radiation Monitoring Program currently has met this criterion. Interestingly, this instrument had also been evaluated by two different calibration facilities on two occasions each.

Table 2 summarizes a 558 day calibration history for the prototype unit 270. The instrument was first calibrated by the manufacturer [YES, 1994], June 13, 1996, and then again on June 22 during the 1996 North American Spectroradiometer Interagency Intercomparison [Early et al., 1998a] by the U.S. Global Change Radiation Program's Central UV Calibration Facility (CUCF) located in Boulder, Colorado. A third calibration by the CUCF on September 20, 1997, was followed some three months later by a final calibration by the manufacturer. Calibration factors are given in volts/watt/m<sup>2</sup> per nanometer.

The methods used for the original and final manufacturer's calibration are described in Yankee Environmental System's Optical Calibration Facilities manual [YES, 1994]. The facility uses a National Institute of Standards and Technology (NIST) traceable 1000 W Optronics FEL lamp. The lamp is mounted 50 cm from the detector in a black-walled, light tight enclosure and is maintained at a constant 8 A current during the calibration event through the use

**Table 2.** Calibration History for Prototype Unit 270

Nominal Center Wavelength, nm	Calibration Date, Laboratory, and Lamp Number			
	June 13, 1996 YES (Optronics F340)	June 22, 1996 CUCF (NIST PS03)	Sept. 20, 1997 CUCF (NIST 96598)	Dec. 22, 1997 YES (Optronics F-437)
300	-76.3895	-89.97585	-90.18234	-91.16275
305	-6.7906	-7.52500	-8.63287	-8.81671
311	-1.67185	-1.94120	-2.55553	-2.37663
317	-1.89951	-1.98671	-2.10333	-2.19811
326	-0.775453	-1.09170	-0.99704	-1.0661
332	-1.1376	-1.00166	-1.20856	-1.25781
368	-0.308765	-0.3104	-0.32129	-0.32904
Cumulative Days in Service	0	+10	+465	+558

of a feedback loop which holds the current to within 0.001%. The June 22, 1996, CUCF calibration was performed with a portable calibrator described by *Early, et al.* [1998b]. The calibrator employs an adaptor plate specific to the UV-MFRSR which positions a 1000 W FEL NIST secondary standard lamp 50 cm from the top of the UV-MFRSR diffuser in a blackout environment. The lamps are produced by the CUCF using a dedicated system that measures absolute irradiance based on the average of three NIST-calibrated traveling primary standards. The same system was employed for the 1997 CUCF calibration, except the measurement was made in a laboratory setting rather than in the field.

The September 20, 1997, calibration is considered to be the more reliable of the four calibrations because greater care was taken to maintain temperature stabilization of the head during the calibrations and the calibration used a NIST-certified lamp. The June 22, 1996, calibration also used a NIST lamp, but the head temperature was not so carefully monitored. Because of the faith placed in the NIST lamps, the closeness of the original calibration to the June 22, 1996, calibration (10 days) and the fact that the unit was not in operation during those initial 10 days, it follows that the original June 13, 1996, calibration must be in error. This is confirmed through an examination of the  $I_0$  time series produced with the June 13, 1996, lamp calibrations. Beginning then with the June 22, 1995, lamp calibration, the table indicates that calibrations have changed by approximately 1% (300 nm) to 17% (332 nm) depending on the wavelength. The median change was 7%.

Unfortunately, there is no way to determine if the differences between NIST lamps and YES lamps (Optronics) are the cause of the calibration differences. Recent work by *Kiedron et al.*, [1999] suggests that although a single lamp may return results consistent to 0.5%, dissimilar lamps, even NIST lamps and their derivatives, may be different by as much as 4-6% of their stated tolerances. In our limited data set (one instrument) there appears to be a general upward trend in all of our wavelength calibrations, suggesting that there is probably some drift in the calibration factor of our instrument. The significance and magnitude of the drift as determined by the lamp calibrations, however, cannot be quantified at this time. Neither the manufacturer nor the CUCF have made detailed error budgets for their calibration facilities, other than those already cited, as of this submission.

### 3. Discussion

Each of the three methods for determining stability has its problems. All are heavily dependent on the quality of the calibration facility characterizing the instrumentation. The  $I_0$  tracking method, however, has the advantage of frequent and abundant stability checks, and large inaccuracies in either lamp calibrations or filter functions readily show up as step changes coincident with instrument recalibration or as bias when compared to the extraterrestrial solar irradiance. The method is amenable to statistical control charting or other time series analysis, but the variance of the  $I_0$  estimates needs to be reduced before corrections to data sets can be made with any great confidence. Even when these discontinuities are mitigated, there will remain small differences (step changes) in  $I_0$  when tracking stability of various units at one site due to slight differences in the SRF (center wavelength and passband) of the various instruments that reside at a site. Presently, these differences are thought to be small. An example of these expected differences can be seen by examining the variance of the convolved SUSIM extraterrestrial solar irradiance in Table 1. Coefficients of variation (CV) of the mean of each set of filters at a given nominal wavelength is approximately 5%. These are probably worst cases since they involve a prototype instrument

with wider passbands (unit 231) and a unit (unit 294) with only a small number of  $I_0$  measurements.

The tracking of SRFs and lamp calibrations are an important component of the network quality assurance efforts. The infrequent nature of the measurements and sensitivity to both calibration laboratory performance (long-term stability of precision and bias) and long-term stability of a calibration laboratory's absolute reference lamps, however, render them less useful than the Langley method for assessing long-term instrument stability. This is especially true during start-up operations in any network or measurement campaign, a critical time in a program's development. The USDA UV Radiation Monitoring Program has obtained spectral response characterization and lamp calibration for its instruments through both the manufacturer (YES) and through a new federal calibration facility (CUCF). Both facilities are in the process of establishing and improving their quality assurance programs. Unfortunately, neither has a long-term history upon which the network can infer calibration quality. Until these facilities have demonstrated a stable, longer-term record of measurement quality, the network needs to be cautious about the interpretation of its instrument characterizations.

### 4. Conclusions

Evaluating the stability of filter instruments is an essential task for any measurement program. The task is often confounded, however, by the infrequency of SRF measurements and lamp calibrations as well as uncertainties associated with calibration laboratory measurement programs. This can be especially problematic during the start-up phases of a measurement program. The Langley analysis technique is also affected by poor quality SRF measurements and lamp calibrations, but because of frequent, automated stability checks, they are much easier to identify, especially in the early phases of a program. The  $I_0$  Langley method is also amenable to traditional time series analysis and therefore has the potential for providing the basis for adjusting measurement data for instrument drift.

The USDA UV Radiation Monitoring Program has begun to apply the  $I_0$  Langley method to evaluate the stability of its deployed instruments. On the basis of a preliminary evaluation of a few prototype and production instruments it appears that there is an approximate 1%/yr decline in its instruments'  $I_0$  values due to filter instability. It is unclear as to whether the decline is a result of wavelength shifts or loss of instrument sensitivity, but in either case, the general stability of the  $I_0$  time series indicates that the IAD filters employed in the UV-MFRSR are much more stable than the filters in VIS-MFRSRs deployed by the network [*Bigelow et al.*, 1998]. The UV-MFRSR returns values that are within 8% of the SUSIM Altas-3 extraterrestrial solar irradiance. The precision of the measurements is estimated to be approximately 8% based on the CV of the estimated extraterrestrial solar irradiance.

It is anticipated that future improvements in the Langley analysis technique will reduce the uncertainties in the  $I_0$  measurements. Further limiting or changing air mass ranges, limiting Langley events to morning hours, and using nonparametric methods to further select valid Langley events are all under study at this time.

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D.S. Bigelow and J.R. Slusser, Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, CO 80523. (daveb@nrel.colostate.edu)

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