Field calibration unit for ultraviolet spectroradiometers

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Horizontal standard lamps calibrate the spectral irradiance responsivity of spectroradiometers that measure solar ultraviolet irradiance. A field calibration unit and power supply developed to meet the requirements for using these standards in the field are described and their operation and associated uncertainties are detailed. Results from assessments obtained at two field instrument intercomparisons indicate that the horizontal standard, field calibration unit, and power supply operate within the design tolerances, making them suitable for performing routine calibrations in the field on most ultraviolet spectroradiometers. © 1998 Optical Society of America

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1. Introduction

Interest in measuring climatic change over large geographical regions and long time scales has prompted the deployment of numerous instruments in a variety of networks for monitoring environmental quantities. One specific quantity is solar ultraviolet (UV) irradiance at the surface of the Earth. Depletion of stratospheric ozone could lead to increased UV irradiance, especially in the more biologically harmful UV-*B* wavelength region (280–315 nm). Thus several U.S. government agencies have established networks of instruments, some deployed nationally and others globally, that are capable of spectral measurements of UV irradiance.[1]

To detect changes in UV irradiance, the instruments must be calibrated for absolute spectral irradiance responsivity. Determining the responsivity of an instrument requires measuring the signal as a function of wavelength $S(\lambda)$ obtained when a source of known spectral irradiance $E(\lambda)$ is incident upon the collection optic of the instrument, usually a diffuser. For the simplest form of the measurement equation,

the spectral irradiance responsivity $R(\lambda)$, hereafter termed the responsivity, is given by

$$R(\lambda) = S(\lambda)/E(\lambda).$$

When an unknown source is measured, such as the sky and Sun, the spectral irradiance of that source is calculated from $R(\lambda)$ and the measured signal $S(\lambda)$.

2. Motivation

The most common and convenient standards for spectral irradiance are 1000-W modified FEL-type quartz–tungsten–halogen lamps. These lamps are calibrated by the Facility for Automated Spectroradiometric Calibrations (FASCAL) at the National Institute of Standards and Technology (NIST) in the vertical position, i.e., the long axis of the lamp is vertical so that the optical axis from the lamp to the sensor is horizontal.[2] However, because the diffuser of solar UV monitoring instruments is horizontal to collect radiation from the entire hemisphere of the sky, the optical axis of the diffuser is vertical. Because these instruments are usually too cumbersome and delicate to be turned on their sides to view a calibrated standard lamp for responsivity calibrations, they require a lamp operating in the horizontal position. Techniques were developed for calibrating 1000-W modified FEL-type lamps in the horizontal position, which showed that the spectral irradiance of these lamps in this position is 6–10% lower at UV wavelengths than their spectral irradiance in the vertical position, probably because of different convective cooling efficiencies.[3]

The responsivity calibration of monitoring instru-

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ments should be performed at the field location where they are operating. There is no guarantee that the responsivity will remain unchanged upon transporting an instrument from the laboratory, where it is calibrated, to a field location. Therefore the laboratory technique for calibrating lamps in the horizontal position was replicated on two occasions in 1994 to calibrate instruments in the field. The lamp mount was attached, with translation and rotation stages, to a vertical pole on a large tripod. An alignment laser was attached to the same pole above the lamp. The tripod and laser were adjusted to center the beam on and retroreflect it from the diffuser, thus defining the optic axis. A lamp alignment jig was then inserted into the mount and adjusted so that it was centered on and perpendicular to this optic axis and 50 cm above the diffuser. Substitution of the lamp for the alignment jig allowed it to be operated horizontally in proper alignment with the diffuser.

This technique was first used in June 1994 at the Environmental Protection Agency monitoring site in Research Triangle Park, North Carolina. The instruments to be calibrated were located on a concrete pad in the middle of a field. Because light only from the standard lamp should be incident upon the diffuser, alignment and operation were performed at night. A major disadvantage of this technique was that 1000-W lamps are excellent insect attractors. Therefore a swarm of insects gathered around the lamp when it was operating, and many of their remains were deposited on the lamp envelope and the instruments. In addition, working around all these insects was unpleasant.

The technique was used again at the North American Interagency Intercomparison of Ultraviolet Monitoring Spectroradiometers in September 1994 at Table Mountain outside Boulder, Colorado. Six different instruments designed to measure solar UV irradiance were present at this intercomparison and all were calibrated for responsivity once in the laboratory and twice outdoors.[4] Fortunately, the air temperature was cold enough at night that insects did not fly toward the lamp. However, the lamp still had to be operated at night and had to be tediously aligned with each instrument. The result was that these calibrations lasted into the early morning hours. In addition, calibrations in the site laboratory and in the field conclusively showed that the instruments' responsivities could change significantly upon movement from the laboratory to the pads, but were reasonably stable when the instruments were not moved.

The experiences detailed above suggested three important requirements for using horizontal standard lamps to perform responsivity calibrations of spectroradiometers. First, the calibrations must be performed *in situ* at any time of the day and at the location where the instrument operates routinely. Second, the standard lamp must align easily, rapidly, and properly with respect to the diffuser for a variety of instruments and must be optically isolated from the surroundings. Third, the combined uncertainty
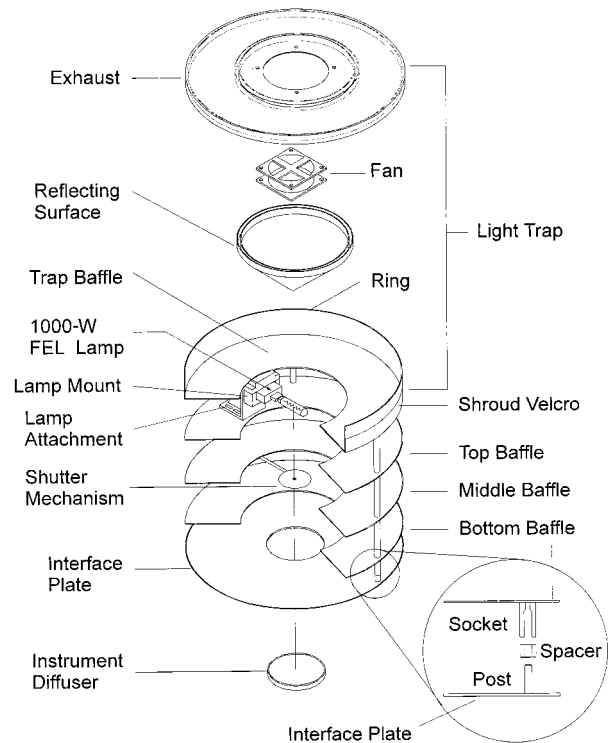

Fig. 1. Cut-away exploded diagram of the field calibration unit.

of the spectral irradiance of the standard and the responsivity of the spectroradiometer must be less than 2% so that expected changes in solar irradiance of 10% per decade are detectable and statistically significant. To meet these requirements, a field calibration unit was developed for performing the responsivity calibrations. This unit was operated successfully at subsequent intercomparisons in 1995 and 1996, is used for routine calibrations at the NIST monitoring site, and serves as the prototype for similar units to be operated by the National Oceanic and Atmospheric Administration's Central Ultraviolet Calibration Facility (CUCF) in Boulder, Colorado.

3. Description

A. Field Calibration Unit

The field calibration unit was designed to satisfy two operational criteria. First, the lamp must be mounted horizontally in a shielded enclosure that is large enough that the unit does not overheat and that the spectral irradiance of the lamp does not change from its calibrated values. Second, the unit must easily, reliably, and properly mount on a variety of instruments.

A cut-away exploded drawing of the field calibration unit is shown in Fig. 1 with the major components indicated. All the machined parts are aluminum and were black anodized. The central portion consists of three circular baffles, 45 cm in diameter and separated by 15 cm, with an attachment for a horizontal lamp on the top baffle. The attachment consists of a slotted bracket, a mount for

a modified FEL-type lamp, and a plate between the bracket and mount. There are sufficient translational and rotational degrees of freedom so that the lamp can be properly aligned as described below. There is also a plate on the top baffle containing connectors for the power and sensor cables. The middle baffle has a shutter mechanism for blocking the direct beam from the lamp to the instrument diffuser. The holes in the baffles are sized so that there is no direct path from the lamp mount to the diffuser. This is to recreate the baffling conditions under which FEL-type lamps are calibrated.[2]

A light trap above the lamp serves both to prevent scattered light from reaching the diffuser, either from outside the field calibration unit or from the lamp, and to maintain a flow of air through the unit to prevent overheating. The trap baffle attaches to the central portion of the unit and supports a ring. This ring, in turn, supports the reflecting surface, fan, and exhaust. The reflecting surface is above the lamp and is sloped so that there are no reflections from it back down onto the diffuser. The fan pulls air over the lamp and out the exhaust, which is made light-tight by a series of interlocking baffles. The top of the exhaust is not shown in Fig. 1. A cloth shroud attaches to the ring with Velcro and fits around the central portion to assure that no light reaches the diffuser except that from the lamp. Both the central portion and the light trap are disassembled for shipping and easily reassembled at their destination.

The key to the unit is an interface plate, which is unique to each type of instrument. The interface plate fits on top of the instrument, and the central portion of the unit attaches to posts on the interface plate. Spacers on the posts set the correct height of the lamp from the diffuser. A detail of the attachment of the central unit to the interface plate is shown in Fig. 1. Spacers with the correct heights were made for each type of instrument, as well as a set of spacers with a range of height adjustment in case the other spacers were incorrect.

The lamp is aligned by use of an alignment tool consisting of an aluminum cup that fits over the diffuser and an aluminum rod that attaches to the cup. The height of the cup is machined so that the top of the rod is 50 cm above the diffuser. A lamp alignment jig is placed in the lamp mount, and the mount is translated and rotated until the bottom of the jig is flush with and centered on the rod. The lamp attachment is then fixed in position. At the intercomparisons, the lamp jig was aligned on one instrument, and the alignment was checked on the other instruments. In every case the lamp was properly aligned with the diffuser, indicating that the interface plates had been properly designed for each instrument. The distance was also tested with the distance indicator used in the laboratory and was correct for each instrument.

B. Power Supply

A power supply is used with the field calibration unit to provide a constant dc current to the lamp and to apply power to the exhaust fan and the shutter mechanism. The power supply used in the laboratory was packaged in a transportable container and used at all the intercomparisons. This power supply, described in more detail in Ref. 5 and referred to hereafter as the laboratory power supply, consists of a Hewlett-Packard 6030A 1000-W linear constant current supply, a Leeds and Northrup 0.1-Ω calibrated shunt resistor, a Hewlett-Packard 3457A 6.5-digit voltmeter, a Burr–Brown PCI-2006M 16-bit digital-to-analog board, and a laptop computer.[6] The shunt resistor is in series with the lamp. The current through the lamp from the power supply is measured by the voltage across this shunt resistor. The computer acquires these voltage readings from the voltmeter by way of the general purpose interface bus and controls the current output of the supply using the voltage from the digital-to-analog board. This current is adjusted by the computer to remain within 0.08 mA of the set current, either 7.9 or 8.2 A depending on the lamp. The voltage across the lamp is also monitored by the voltmeter.

Although the laboratory power supply was adequate for the intercomparisons, it was too large and heavy for easy transport. Therefore another power supply was assembled in a transportable container that could be moved about by only one person and is referred to as the field power supply. This power supply has a modified Xantrex XHR 150-7 1000-W switching constant current supply, an Isotek RUG-Z-R100 0.1-Ω calibrated shunt resistor (considerably smaller than that used in the laboratory current supply), a Keithley 2000 6.5-digit voltmeter, and a laptop computer. The current through the lamp is again measured by the voltage across the shunt resistor, while the voltage across the lamp and the temperature of the shunt resistor are monitored. The major difference between the power supplies, in addition to the type of current supply, is the use of the RS-232 interface instead of the general purpose interface bus. This interface is used to acquire the voltage readings from the voltmeter and to control the output current of the current supply with 14-bit resolution. Therefore the current can be controlled to within only 0.35 mA, but the decrease in current resolution is more than compensated for by the improved transportability. A schematic diagram of the electrical connections of the field power supply and calibration unit is shown in Fig. 2.

C. Operation

Operation of the field calibration unit is relatively simple. The appropriate interface plate is placed on the instrument, then the central portion of the unit, with light trap, is attached to the plate. The lamp mount does not usually have to be adjusted, although its alignment can be checked with the alignment tool and lamp jig. The major advantage of the unit is that the position of the lamp does not need to be adjusted on each instrument. It can be set once and then used on many different instruments. The lamp is placed in the lamp mount, the power and sensor
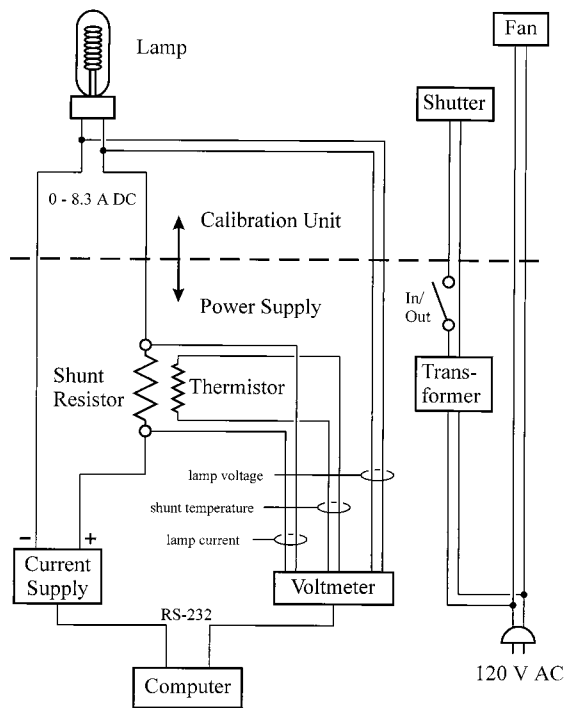
Fig. 2. Schematic diagram of the electrical connections of the field power supply and calibration unit.

Table 1. Relative Standard Uncertainties (%) in the Spectral Irradiance of the Lamps used to Propagate the Scale from the Laboratory to the Field

Lamp	Effect[a]	280	300	320	340	360	380	400
					Wavelength (nm)			
FASCAL	R	0.21	0.17	0.12	0.09	0.06	0.04	0.03
	S	0.60	0.55	0.50	0.46	0.42	0.40	0.38
rss total		0.64	0.58	0.51	0.47	0.42	0.40	0.38
Secondary	R	0.56	0.44	0.45	0.26	0.29	0.29	0.32
	S	0.71	0.66	0.61	0.57	0.53	0.51	0.50
rss total		0.90	0.79	0.76	0.63	0.60	0.59	0.59
Horizontal	R	1.32	0.62	0.54	0.53	0.37	0.43	0.59
	S	0.83	0.78	0.74	0.71	0.68	0.67	0.66
rss total		1.56	1.00	0.92	0.89	0.77	0.80	0.89

[a]R, random; S, systematic; rss, root-sum-square.

cables are attached to the connectors, and the shroud is placed around the central unit. The computer program increases the lamp current slowly to its set current, and the shutter is moved into position to block the direct beam from the lamp to the diffuser. A spectral scan is performed by the instrument during the 10-min warm-up of the lamp to measure the signal from the diffuse light incident on the diffuser. The shutter is then moved out of the direct beam, and another spectral scan, or scans, is performed by the instrument to measure the signal from the total light incident on the diffuser. The direct signal is then the difference between the signals measured with the total and diffuse light. After the lamp is turned off, by slowly decreasing the current, the field unit can be removed from the instrument after approximately 10 min of cooling down.

D. Uncertainties

The uncertainties associated with the responsivity calibration are important because they determine the best accuracy to which the solar UV irradiance can be measured. The uncertainties are determined using the approach described in Appendix D of Ref. 7 and so will not be discussed in detail here. The uncertainty in the calibration begins with the uncertainty in the spectral irradiance of the horizontal standard lamp. The relative standard uncertainties in spectral irradiance of the lamps used to propagate the spectral irradiance scale from NIST to the field calibration unit are given in Table 1 at selected wavelengths. The uncertainties are divided by the effect of the source of the uncertainty, either random or systematic, and are also

totaled by use of the root-sum-square (rss) for each lamp. The sources of uncertainty are generally the same as those encountered in calibrating the responsivity of an instrument, which are discussed in more detail below in describing that calibration.

All the lamps used to propagate the spectral irradiance scale are 1000-W modified FEL-type quartz–tungsten–halogen lamps. The lamps were seasoned at NIST at 8.5 A for 12 h and at 8.2 A for 48 h, then screened for stability (less than 2% variation in irradiance at 250 nm over another 24 h of operating at 8.2 A) and for the absence of absorption lines from aluminum. A set of three lamps operating vertically and calibrated by the FASCAL facility at NIST[2] form the basis for the spectral irradiance scale. The uncertainty in the spectral irradiance of a FASCAL lamp is given in Table 1 and is dominated by sources arising from systematic effects. With a spectroradiometer, these lamps are used to calibrate a set of three secondary lamps, again operating vertically. This set of three lamps is used for routine calibrations of other lamps, thereby reducing the amount of time the FASCAL lamps are operated. The uncertainties resulting from this calibration for a secondary lamp are given in Table 1. These uncertainties include those from the FASCAL lamps as well as those from the measurement. Finally, the secondary lamps are used to calibrate the lamps operating horizontally that are used in the field calibration unit. The total uncertainties resulting from this calibration, given in Table 1 for a horizontal lamp, are generally close to 1%. Note that the uncertainties arising from random effects are comparable with those arising from systematic effects for the horizontal lamps.

The components of uncertainty associated with the calibration of the responsivity are conveniently divided according to their source between the lamp, alignment of the lamp, and the instrument. The relative standard uncertainties in responsivity that arise from the different components are given in Table 2 at selected wavelengths. These uncertainties were calculated for a Brewer spectroradiometer

Table 2. Relative Standard Uncertainties (%) in the Spectral Irradiance Responsivity of a Typical Brewer Spectroradiometer

Component of Uncertainty	Effect[a]	Wavelength (nm)				
		290	307.5	325	342.5	360
Lamp irradiance	R	0.91	0.60	0.55	0.51	0.37
Lamp irradiance	S	0.80	0.76	0.73	0.71	0.68
Lamp current	R	0.06	0.05	0.05	0.05	0.05
Lamp current	S	0.11	0.10	0.10	0.09	0.09
Alignment	S	0.39	0.39	0.39	0.39	0.39
Diffuser size	S	0.47	0.47	0.47	0.47	0.47
Wavelength	S	0.23	0.02	0.04	0	0.10
Signal	R	0.60	0.33	0.43	0.38	0.30
rss total		1.51	1.19	1.19	1.14	1.04

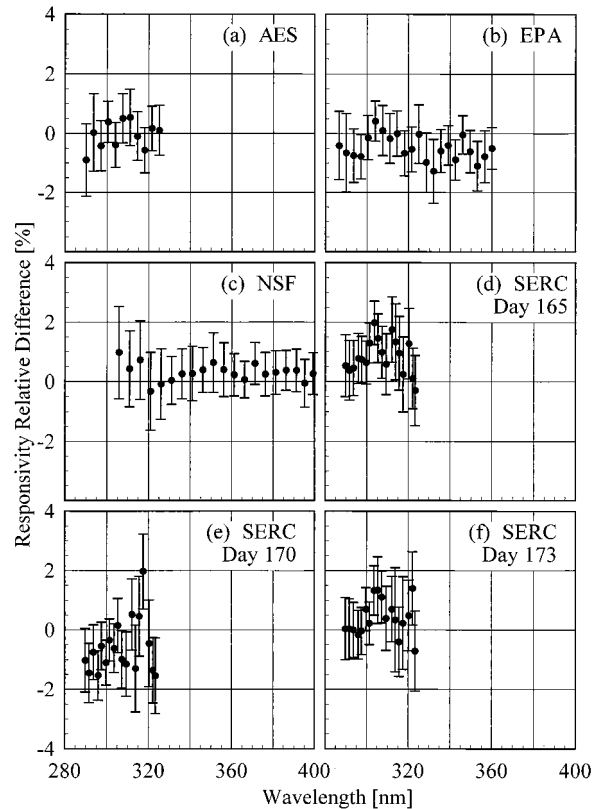[a]R, random; S, systematic; rss, root-sum-square.

Fig. 3. Responsivity relative difference as a function of wavelength determined from standard lamps operating from a tripod and in the field calibration unit, demonstrating that the field calibration unit has no effect on the lamp irradiance. The instruments are indicated in the panels, and the vertical lines are the standard uncertainties of the differences.

and the field power supply, both operating outdoors. This spectroradiometer is among the most common instrument used for measuring solar UV irradiance.

The uncertainty in the lamp irradiance is repeated from Table 1, after fitting with a natural cubic spline to the appropriate wavelengths. The uncertainties in lamp current arising from random effects are the resolution to which the current is set and the temperature of the shunt resistor. The uncertainties arising from systematic effects are the accuracy of the voltmeter and the resistance of the shunt. The standard uncertainties in the current are 0.42 and 0.81 mA from the random and systematic effects, respectively.

The lamp in the field calibration unit is aligned parallel to the diffuser of the instrument with a standard uncertainty of 0.5° and centered on the diffuser with a standard uncertainty of 0.16 cm. The standard uncertainty in the distance from the lamp to the diffuser is 0.1 cm. These uncertainties all arise from systematic effects in aligning the lamp jig.

The diffuser of the instrument is larger than the 1-cm^2 entrance aperture used to calibrate the horizontal lamps. Therefore there are uncertainties arising from systematic effects that are due to decreased irradiance toward the edges of the diffuser and to the goniometric distribution of irradiance from the lamp. There is also an uncertainty in the wavelength of the instrument that translates into an uncertainty in the responsivity, again from a systematic effect. Finally, noise in the signal of the instrument contributes an uncertainty arising from a random effect.

The total relative standard uncertainty in the responsivity of the instrument is given in Table 2. This total uncertainty is only slightly greater than the total uncertainty for the horizontal lamp given in Table 1. Therefore use of the field calibration unit does not add an appreciable component to the uncertainty of the calibration. Note that the total uncertainties given in Table 2 are the minimum uncertainties that are possible when measuring solar UV irradiance. Some additional sources of uncertainty in the solar measurement are the signal, the wavelength (due to the spectral shape of the solar irradiance), and the stability of the responsivity of the instrument. These can contribute significantly to the final uncertainty in the solar UV irradiance.

4. Performance

The performance of the field calibration unit was determined at the intercomparisons held in 1995 and 1996. At the 1995 intercomparison, the effect of the field calibration unit on the irradiance of the horizontal lamp was measured. Two horizontal standard lamps, both calibrated at the same time in the laboratory at NIST, were used indoors to calibrate the responsivity of all the instruments. One lamp was mounted on the tripod and determined the responsivity of an instrument; then the field calibration unit was placed on the instrument and used with the other lamp to determine the responsivity. The same laboratory power supply was used for both lamps. The relative difference in responsivity determined by use of the two lamps is shown in Fig. 3 as a function of wavelength. The instruments are indicated in the panels by the agency responsible for the monitoring network: AES is the Atmospheric Environment Service of Canada, EPA is the Environmental Protection Agency, NSF is the National Science Foundation, and SERC is the Smithsonian Environmental
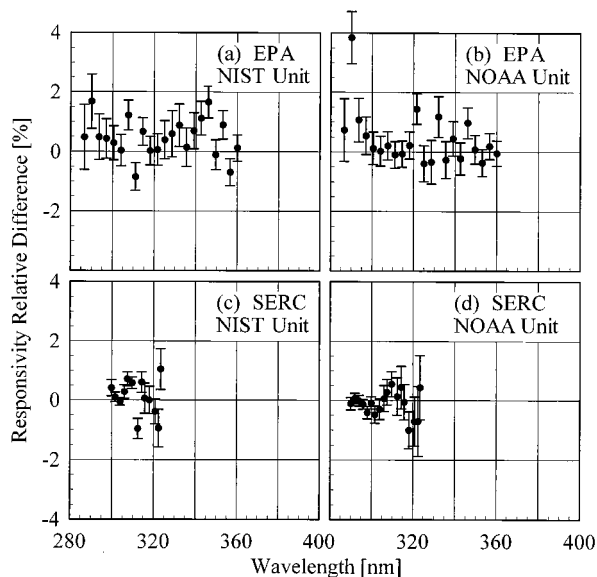
Fig. 4. Responsivity relative difference as a function of wavelength determined from the laboratory and field power supplies, demonstrating that there is no discernible difference in performance between the two. The instruments and field calibration units are indicated in the panels, and the vertical lines are the standard uncertainties of the differences. NOAA, National Oceanic and Atmospheric Administration.
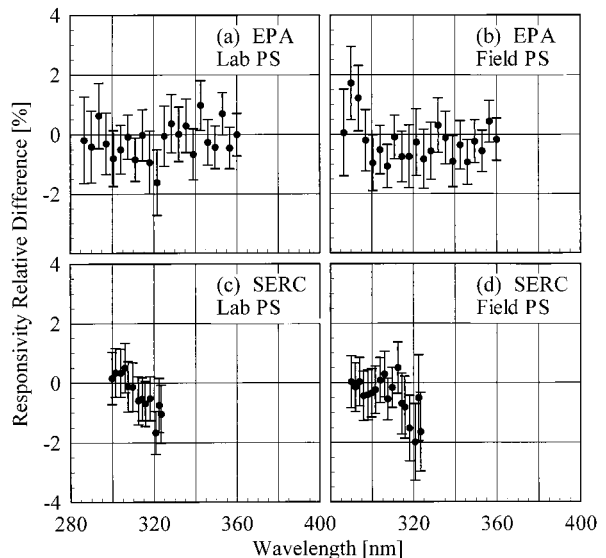

Fig. 5. Responsivity relative difference as a function of wavelength determined from the NIST and the National Oceanic and Atmospheric Administration field calibration units, demonstrating that there is no discernible difference in performance between the two. The instruments and power supplies are indicated in the panels, and the vertical lines are the standard uncertainties of the differences.

Research Center. The responsivity of the SERC instrument was determined in this manner on three different days. The standard uncertainties of the differences are shown as vertical lines in Fig. 3 and are due to the lamp irradiances and currents arising from random effects, lamp alignments, and the signals. In nearly all cases the relative differences are zero within the uncertainties. Therefore the field calibration unit has no appreciable effect on the spectral irradiance of the horizontal lamp operated within it.

Both the laboratory and the field power supplies were present at the 1996 intercomparison, as well as another field calibration unit of the same design built by the CUCF. Therefore the field calibration units and power supplies were compared indoors on selected instruments prior to being deployed outside. All combinations of field calibration unit and power supply were used to determine the responsivity of the EPA and SERC instruments. The relative difference in responsivity determined with the laboratory and field power supplies is shown in Fig. 4 as a function of wavelength. The instruments and field calibration units are indicated in the panels, and the standard uncertainties of the differences are shown as vertical lines. These uncertainties are due to the lamp currents and the signals. In nearly all cases the relative differences are zero within the uncertainties. Therefore there is no discernible difference in performance between the two power supply systems.

The relative difference in responsivity determined with the two field calibration units is shown in Fig. 5 as a function of wavelength. The instruments and power supplies are indicated in the panels, and the standard uncertainties of the differences are shown as vertical lines. These uncertainties are due to the lamp irradiances and currents arising from random effects, lamp alignment, and the signals. Again, in nearly all cases the relative differences are zero within the uncertainties. Therefore there is no discernible difference in performance between the two field calibration units. Because the different power supplies are equivalent, as well as the different field calibration units, they were used interchangeably to determine the responsivity of the instruments outdoors at the intercomparison.

The NIST field calibration unit has been used for over 2 years for routine responsivity calibrations of the instruments deployed at the NIST UV monitoring site. Similar field calibration units, with field power supplies, are expected to be used by the CUCF for calibrating instruments in a variety of monitoring networks. The NIST unit was also used successfully at the Fifth SeaWiFS Intercalibration and Round-Robin Experiment[8] to determine the responsivity of instruments designed to measure downwelling spectral irradiance at visible and near-infrared wavelengths. The field unit was attached to an interface plate supported by three legs. The instruments, cylindrically shaped with diameters of approximately 10 cm, were mounted onto the interface plate from the bottom.

5. Conclusions

A field calibration unit was developed to be easily and reliably mounted on a variety of instruments to determine their spectral irradiance responsivity under

field conditions. A standard lamp is mounted horizontally in an enclosure that attaches to an interface plate unique to each type of instrument. A transportable, computer-controlled power supply is used to operate the lamp at a constant dc current. This field calibration unit was used at two intercomparisons of UV spectroradiometers and successfully overcame the disadvantages of using the laboratory technique for responsivity calibrations outdoors. In addition, results obtained at the intercomparisons demonstrate that the field calibration unit does not affect the spectral irradiance of the standard lamp and that there is no performance difference between different power supplies and field calibration units. Therefore this field calibration unit is expected to find wide application in solar UV irradiance monitoring networks and in other applications in which calibrations of spectral irradiance responsivity are required under field conditions.

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