



# Incandescent lamp-based facility for measuring the long-term radiometric stability of spectrographs

PING-SHINE SHAW,\* JOHN T. WOODWARD, B. CAROL JOHNSON,  STEVEN W. BROWN, AND HOWARD W. YOON 

Sensor Science Division, Physical Measurement Laboratory, National Institute of Standards and Technology, 100 Bureau Drive, Gaithersburg, Maryland 20899, USA

\*Corresponding author: shaw@nist.gov

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The long-term temporal stability of a spectrograph is one of the most important characteristics affecting the spectrograph's radiometric performance. For many applications, from monitoring ocean color and lunar irradiance to laboratory irradiance measurement standards, the stability of a spectrograph is a primary factor in the overall measurement uncertainty and therefore is the major criterion for the suitability of the spectrograph as an optical-scale transfer standard. Here we report a facility built for testing the long-term radiometric stability of commercial, fiber-coupled spectrographs. The facility uses tungsten quartz-halogen irradiance standard lamps, type "FEL," of the National Institute of Standards and Technology (NIST) as light sources. To ensure the highest stability of these lamps during spectrograph tests, parameters such as lamp current, lamp voltage, and signals from an independent filter radiometer were continuously recorded to monitor any possible instability caused by such effects as lamp aging. Using this facility, we report the stability study of four spectrographs with spectral coverage from the UV to short-wave infrared over an interval of two months during which the lamp irradiance was stable to better than 0.02%. The tested spectrographs show good stability in general, ranging from 0.02% to 0.1% in the visible over a span of 11 days. For a longer two-month test, the variation in spectrograph responses increases by less than 0.1% with no discernable long-term drifts. In addition, we measured the response variation of two of the test spectrographs before and after they were sent to remote field locations and subjected to adverse environmental conditions. In this case, a larger response variation of up to 1.0% dependence on the wavelength was observed. We discuss the performance of the facility and the implications for using these spectrographs for several of NIST's remote sensing projects as radiometric transfer standards based on these stability measurements.

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## 1. INTRODUCTION

Spectrographs have long been the alternatives to traditional scanning monochromators for measuring the spectral intensity distribution of broadband sources. They provide fast and efficient measurements without complex mechanical movement of gratings. The development of spectrographs accelerated over the last few decades because of the advent and refinement of innovative technologies such as the solid-state photodiode array detector (PDA), charge-coupled device (CCD) imager, fiber optics, and grating design. Benefiting from these improvements, current commercial state-of-the-art spectrographs have high sensitivity, low stray light, and a portable compact design. Many of these spectrographs also come with optical fiber bundles for coupling of incident light, active temperature control for reducing response instability due to temperature fluctuation, and fast electronics for data processing and communication.

With that, it is of interest to see whether these spectrographs can be used for a range of radiometric applications where reliable and accurate measurements are required. However, like all radiometric detectors, an essential property of the spectrographs that affects their applicability is their long-term and short-term response stability which can be a dominant component in the overall measurement uncertainty. In the past, systematic studies on the stability of spectrographs have been scarce [1,2]. A previous report [1] investigated the stability of some spectrographs available at that time a decade ago and concluded that there were large variations in stability among different models. For more recent state-of-the-art spectrographs and even future spectrographs, it is necessary to investigate their stability performance. A spectrograph with good stability can potentially be used, for example, as a transfer standard for calibrating light sources both in laboratories and in field locations for remote sensing. This has the benefit of shortening the calibration chain by eliminating

several spectral irradiance or radiance scale transfer steps using working-standard light sources such as the commonly used FEL lamps [3].

In recent years, several remote sensing projects at the National Institute of Standards and Technology (NIST) have used spectrographs for measuring spectral irradiance and radiance, where the long-term stability of the radiometric responsivity is critical. These include the NIST Stars program [4], the Lunar Spectral Irradiance Instrument (LUSI) project [5], and the more recent airborne LUSI project [6]. These programs aim to determine the top-of-the-atmosphere, SI-traceable, absolute spectral irradiance of the moon or bright stars. Additionally, in collaboration with NIST, the Marine Optical Buoy (MOBY) project [7–9] uses commercial spectrographs to monitor the stability of onsite calibration sources. The typical goal of these projects is to achieve about 1% (coverage factor  $k = 2$ ) in measurement uncertainty. Furthermore, NIST is actively pursuing detector-based absolute calibration of spectrographs using a tunable laser [10] which aims at using spectrographs as transfer standards for NIST's internal photometry and radiometry program to shorten the calibration chain in disseminating scales from NIST's primary standards. In this case, the uncertainty requirement is a fraction of a percent. To achieve these targeted uncertainties with spectrographs, it is desirable to be able to measure and assess the stability of candidate spectrographs.

We recently constructed a facility dedicated to monitoring the stability of spectrographs using FEL standard irradiance lamps. Our goal is to be able to document any fluctuation and drift from the source irradiance with a resolution below 0.1% level when the source is used to irradiate spectrographs over a long interval of several months. For this study, the primary FEL lamp used for illuminating spectrographs was issued and calibrated by NIST's Facility for Automated Spectroradiometric Calibrations 2 (FASCAL 2) [11], where much research was devoted to establishing FEL lamps [11,12] as NIST's transfer standard source from near-UV to IR. While the lamps were previously calibrated for spectral irradiance at FASCAL 2 and are capable of transferring irradiance scales to spectrographs, the work here emphasizes using their stability properties to monitor the relative response changes of spectrographs over a long-time interval. As we learn from this work reported below, the stability of the lamps during months of testing with a total of more than 20 h of operation is much better than the quoted uncertainty associated with the lamps' absolute irradiance calibration. To verify the lamp stability during any measurement interval, we continuously recorded the FEL lamp current and voltage drop at the lamp terminals. An additional filter radiometer, which consisted of a silicon photodiode and a 650 nm bandpass filter, was installed to constantly monitor the lamp output. The measured lamp data were used to identify changes in lamp output such as aging, which can occur during long operation.

To demonstrate the capability of the facility, four commercial spectrographs were studied by performing a series of stability measurements that lasted two months. Monitoring several spectrographs at the same time provided a more statistically meaningful performance indicator of similar spectrographs. Data from all four spectrographs indicate that their instability during the entire measurement time ranges from less than

$\pm 0.02\%$  to  $\pm 0.1\%$  in the wavelength regions with a high signal-to-noise ratio. The fact that we were able to discern variation of the spectrographs to better than  $\pm 0.02\%$  also validates the excellence in lamp stability. We discuss possible mechanisms that contribute to variations in stability within the group of four spectrographs. An additional investigation shows that the spectrographs were subject to larger variation of  $\pm 0.5\%$  after the spectrographs were moved out of the measurement laboratory and deployed in remote sites for field studies. Here a possible cause for such instability is the mechanical stability of coupling between the input fiber and the spectrograph body. Lastly, we discuss the potential benefits of using these spectrographs as radiometric transfer standards based on measured stability from this work.

## 2. EXPERIMENTAL SETUP

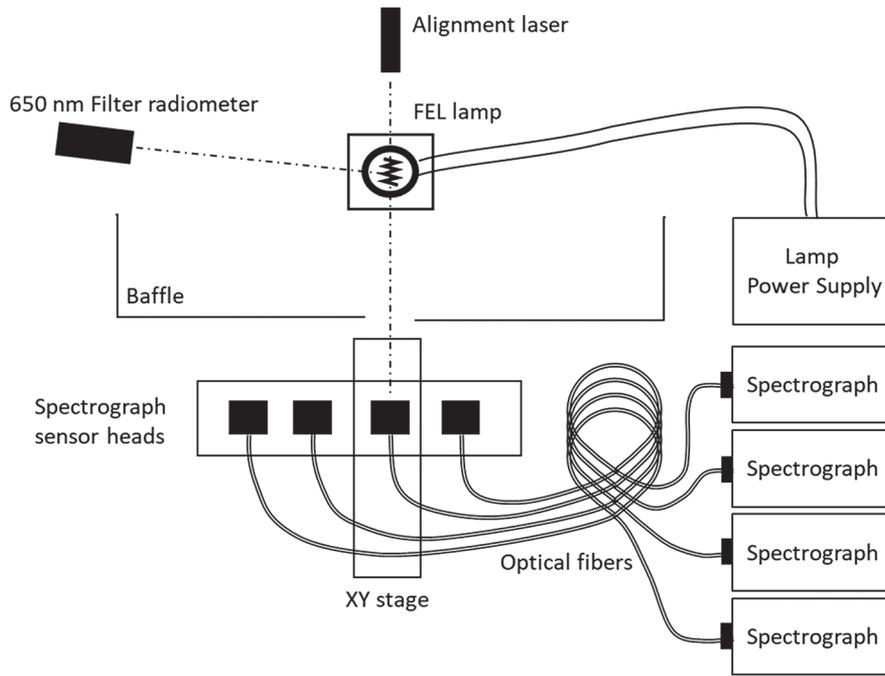
The facility is stationed within a laboratory room with black painted walls to reduce stray light. A schematic of the experimental setup is shown in Fig. 1. The light source used to monitor the stability of the test spectrographs is an FEL lamp. Light from the lamp irradiates the sensor head of a spectrograph and is then guided by an optical fiber bundle to the main unit of the spectrograph where the light is spectrally dispersed and imaged onto an imaging detector of either a PDA or a CCD imager. While measurement was performed with one spectrograph at a time, several spectrograph sensor heads can be mounted on a two-axis computer-controlled motion stage such that each of the spectrograph sensor heads can be brought into the measurement position sequentially. Placed between the lamp and the spectrograph sensor head is a baffle system with a circular aperture 10 cm in diameter that limits the light from the lamp. The baffle reduces the scattered light onto the spectrograph sensor head at the measurement position.

### A. Operation and Monitoring of the Lamp Source

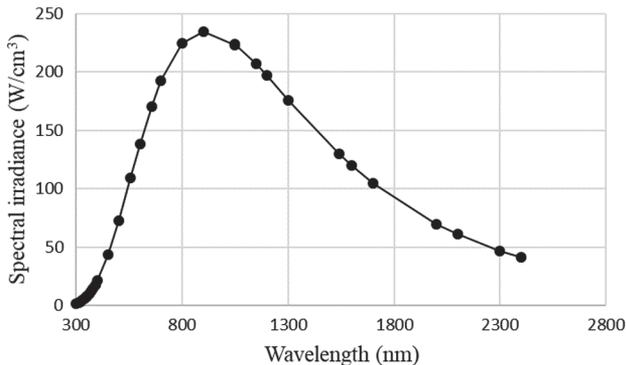
The 1 kW FEL-type quartz–halogen lamp used for this facility, designated as S194, was issued by the FASCAL 2, where the lamp had been burned in and calibrated for spectral irradiance at a distance of 50 cm from the front of the bi-posts of the lamp when operated at a lamp current of 8.2 A. The FASCAL 2 irradiance scale of S194 is derived from a high-temperature blackbody operated near 3000 K. The temperature scale of the blackbody, in turn, is derived from the responsivity scale of filter radiometers which is traceable to a cryogenic radiometer [11]. Shown in Fig. 2 is the spectral irradiance of S194. The expanded uncertainty at  $k = 2$  of the irradiance is more than 1% below 450 nm, between 0.9% and 0.5% in the visible, and less than 0.5% in the NIR and short-wave infrared spectral regions [12].

Previous studies have shown that the spectral irradiance of an FEL lamp is sensitive to the filament temperature which, in turn, depends on the electric current flowing through the filament [13–15]. The relationship between the irradiance and the current can be approximated by a power law. For lamps operated at 8 A, measurements show that a 1 mA change in lamp current results in about 0.06% change in irradiance at 655 nm [13].

For this work, we use a current-regulated power supply for the lamp to reduce uncertainty from current variation. The actual



**Fig. 1.** Schematic diagram of the experimental setup for long-term stability measurement of spectrographs.



**Fig. 2.** Spectral irradiance scale of the FEL lamp, S194, at a distance of 50 cm from the lamp as calibrated at NIST’s FASCAL 2 facility. The circles are actual data points, and the connecting lines are used to guide the eyes.

lamp current is monitored by measuring the voltage, using a digital voltmeter, across a calibrated shunt resistor (0.100037 ohm) that is connected in series with the lamp. The voltmeter also measures the voltage across the lamp terminals through a multiplexer. The lamp current and lamp voltage, along with a time stamp, are continuously recorded and saved in a computer file when the lamp is in operation.

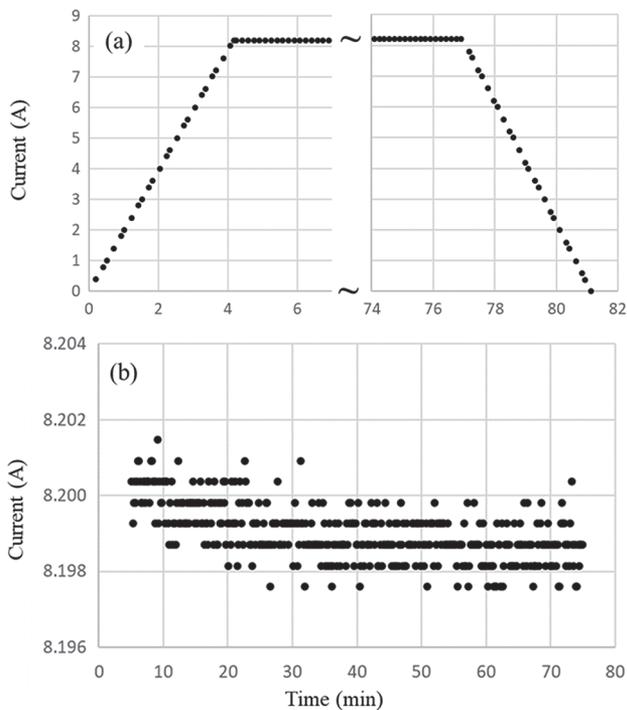
To further validate the irradiance stability of the lamp, an additional filter radiometer with a bandpass filter at 650 nm is utilized to monitor the lamp output. The choice of 650 nm is a compromise between enough monitor signal and sensitivity to lamp output changes since the sensitivity to lamp output increases with shorter wavelengths, but the lamp irradiance decreases with shorter wavelengths as shown in Fig. 2. The filter radiometer is facing the lamp at a direction about 90° from the lamp to test spectrograph axis. A separate amplifier and a

voltmeter measure the filter radiometer response, and the data are continuously acquired and saved in a computer data file.

The lamp S194 was used for the full duration of this study. For each session of lamp operation, the lamp current is ramped up from 0 to 8.2 A linearly in about 4 min through commands sent by a computer to the current power supply. After the lamp current reaches 8.2 A, it is given 20 min for the lamp output to stabilize before measurements of the spectrograph begin. Once the measurements of all the spectrographs are completed, the computer ramps down the lamp current to 0 A and shuts off the lamp. Recorded lamp data during this process are used, together with the spectrograph response data to assess the performance of the lamp during each spectrograph measurement. Figure 3 shows the lamp current derived from the voltage across the shunt resistor as a function of time of a typical session of lamp operation. The time 0 min indicates the start of the lamp current ramp-up process and, after 4 min, the lamp current reaches operating value and is regulated at 8.2 A by the current power supply. Figure 3(b) shows detailed lamp current after ramping up the lamp current. The current measured over an hour of operation is 8.199 A with a standard deviation of 1 mA.

**B. Spectrographs under Test**

All spectrographs used for this study were commercially available fiber-coupled models from two manufacturers. Initially, five spectrographs participated in this study. However, one spectrograph developed mechanical instability problems in the middle of the study, and its measurement results are excluded from this report. The four spectrographs are designated as S1, S2, S3, and S4. Spectrographs S1, S2, and S3 have a 1024-channel readout from a CCD imager which covers wavelength ranges of 380 to 1040 nm (S1), 297 to 1102 nm (S2), and 300



**Fig. 3.** (a) Ramping up and down of the FEL lamp current using a regulated current power supply with an operating current set at 8.2 A. The lamp current was derived from the measured voltage across a calibrated shunt resistor with a resistance of 0.100037 ohm. (b) Detailed lamp current plot after reaching the operational value of 8.2 A. The quantization of lamp current is caused by the resolution of the digital voltmeter.

to 1102 nm (S3). Spectrograph S4 also has a 1024-channel readout, but from three PDAs (Si, InGaAs, and extended InGaAs), which covers a wavelength range from 350 to 2500 nm. All CCDs and PDAs of the four spectrographs are temperature stabilized. These test spectrographs were purchased over several years to reflect more of a general performance of spectrographs rather than spectrographs of a certain model. Each of the spectrographs has a cosine collector sensor head that couples the incident light into an optical fiber bundle which, in turn, guides the light into the spectrograph. Two of the spectrographs, S1 and S2, have cosine collectors made by the spectrograph manufacturer. These cosine collectors have a diffuse transmitting component located in front of the optical fiber bundle. The active area of these cosine collectors is circular with a diameter of 1.7 cm. For the other two spectrographs, S3 and S4, we constructed their cosine collector using an integrating sphere with the optical fiber coupled into one of the ports of the integrating sphere. The entrance port of the integrating sphere is 1 cm in diameter. There is also an aperture outside the integrating-sphere entrance port with which the field-of-view is significantly limited. This contrasts with the full hemispherical field-of-view of the cosine collectors used by S1 and S2.

As illustrated in Fig. 1, all cosine collectors of the test spectrographs are mounted on a two-dimensional motion stage such that each cosine collector can be moved to a position where the cosine collector has a direct line of sight to the FEL lamp. Since all spectrographs are fixed, the movement of cosine collectors is accomplished by flexing their optical fiber bundles. A fixed

alignment laser behind the FEL lamp is used to align each cosine collector. The pointing of the alignment laser is pre-adjusted using a lamp fiducial plate such that the laser is aligned through the center of the FEL lamp. The alignment for each of the instruments begins with moving its cosine collector via the motion stage to a position where the cosine collector is directly facing the FEL lamp. The cosine collector is then adjusted such that the alignment laser beam is centered on the active area of the cosine collector and the laser beam is retroreflected. Once the orientation of the cosine collector is aligned, the distance between the lamp and the front surface of the cosine collector is adjusted to 50 cm by using a tubular inside micrometer. Subsequently, the coordinates of the stage are saved to the computer such that the aligned position can be repeated later by commanding the stage to the saved stage coordinates. This alignment procedure is repeated for each cosine collector.

With motion stage coordinates determined for all spectrographs under test, measurement of FEL lamp's spectral irradiance by each of the test spectrographs can be performed in sequence once the FEL lamp current is ramped up to the operating current and after its warm-up interval as discussed before. Because the higher light throughput of the cosine collectors of S1 and S2 saturated their detector outputs even at the shortest integration times, they are always operated with an internal neutral density filter. Typical data acquisition parameters for test spectrographs are 50 and 70 ms integration time for a single exposure by the CCD and PDA, respectively, and 100 exposures are performed for each measurement. The total acquisition time is therefore 5 and 7 sec to obtain a set of measurement data. Furthermore, the measurement is repeated nine times and the average of the nine sets of data is used for further analysis. After this series of measurements, the same measurement sequence is repeated for background measurement where an occulting disk is placed in the light path so that the cosine collector is not illuminated. The background data are then subtracted from the data to obtain a net signal.

### 3. RESULTS

The stability of all four test spectrographs S1, S2, S3, and S4, were monitored for just over two months. During the entire measurement interval, all test spectrographs remained mounted on the test bench of the laboratory to simplify the environmental conditions to which the test spectrographs were subject. There were two modes of operation, weekly tests over the two-month interval and daily tests over a week within the two-month interval. After the two-month measurements, two spectrographs, S1 and S2, were taken off the stage and shipped across the country for outdoor remote sensing field work. After the deployment of these spectrographs, they were returned to the laboratory, and their responses were again measured and compared to those before the deployment. This test enabled us to gain insight into the effects such as vibration, temperature, and environmental pollution have on the responses of the spectrographs.

#### A. Stability of the FEL Lamp

The stability of the FEL lamp S194 is crucial to assessing the stability of the spectrographs. In terms of lamp stability, we must be

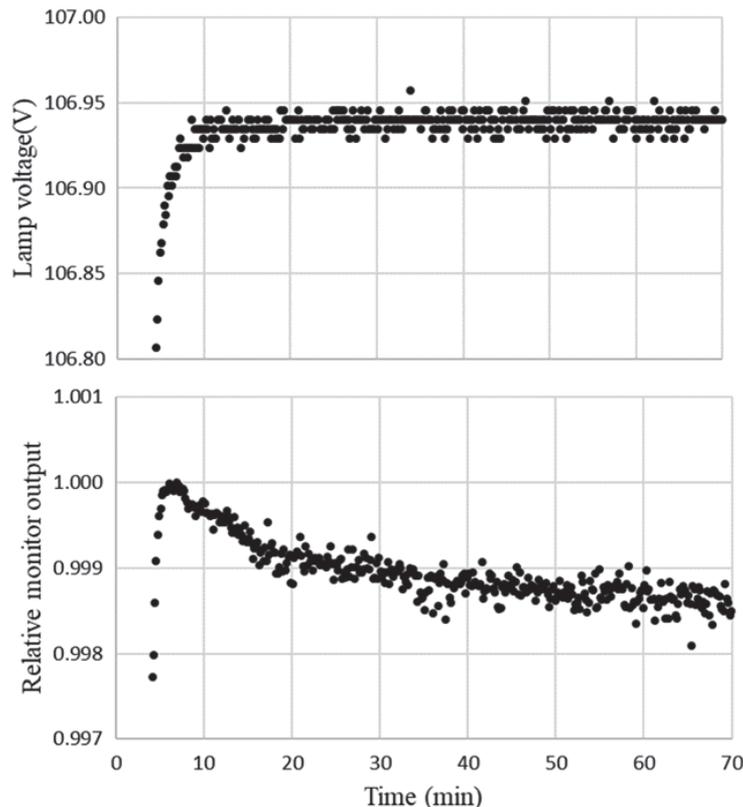
concerned with both the short-term stability and the long-term stability. The short-term stability refers to the temporal behavior of the lamp after it is turned on for one cycle of irradiance measurement. Enough lamp warm-up time must be allowed for the lamp to reach a steady state before any measurement is conducted. On the other hand, long-term stability refers to the repeatability of the spectral irradiance after many separate measurement cycles. The long-term instability, typically manifesting itself as drift over time, is most often caused by the aging of the lamp due to irreversible filament evaporation.

We use two sets of measurements to assess the lamp stability. The first is the data from the fixed 650 nm filter radiometer which are collected whenever the lamp is in operation and including the times when spectrographs were being measured. After many measurement cycles, the collected data provide insight into lamp stability especially the long-term stability after many cycles of operation. We should note that the filter radiometer views a different side of the lamp from the side viewed by the test spectrographs and, given the asymmetric shape of the lamp filament, the filter radiometer data may not perfectly reflect the short-term irradiance variations as measured by the test spectrographs. To validate the short-term stability of the lamp, a separate measurement is conducted where the lamp irradiance is monitored directly by a test spectrograph during the entire measurement cycle, including the ramp-up and warm-up phases of operation.

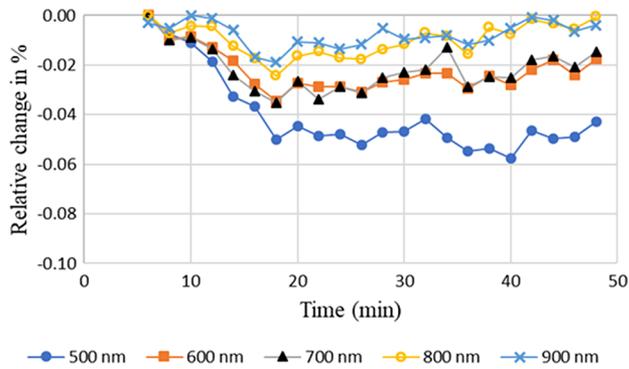
Figure 4 shows the lamp voltage and the 650 nm filter radiometer output as a function of time during a typical light-on process. As with Fig. 3, the time 0 min indicates the start of

the lamp current ramp-up process. The lamp voltage increases drastically near the end of the 4 min lamp current ramping time and continues to rise, even though the lamp current has reached the operating value of 8.2 A. Eventually, it reaches a steady voltage of  $106.94 \pm 0.01$  V after the 15 min mark. The lamp voltage reflects the resistance of the lamp filament with the lamp current at a constant operating value. The resistance of the lamp filament, in turn, depends on the filament temperature, which explains the time lag between the lamp current and lamp voltage. On the other hand, the output of the 650 nm filter radiometer shows an initial spike and reaches a maximum value at the 6 min mark or 2 min after the lamp current reaches the operating value and then undergoes a slow decline with a very long time constant. For the time interval of an hour after the 20 min warm-up time, the change in the output of the 650 nm filter radiometer is less than 0.05%. The slow decline of the output of the filter radiometer can be attributed to the approach to an equilibrium state both in filament temperature and in physical movement of the filament due to thermal expansion.

Figure 5 shows the results of using the spectrograph S1 to directly monitor the lamp irradiance during a lamp light-on cycle as a function of time at wavelengths of 500, 600, 700, 800, and 900 nm. It is evident that the data show a decline from their peak values within the initial 20 min time for all wavelengths. This is similar to the temporal trend manifested by the data of Fig. 4, but with a much smaller magnitude. Furthermore, the initial decline is larger for shorter wavelengths. This is consistent with a slight decrease of filament temperature after the lamp current reaches its operation value. At an equivalent blackbody



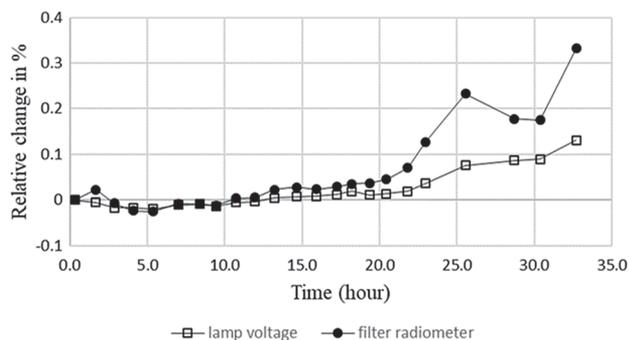
**Fig. 4.** Temporal trend of the voltage measured across FEL lamp S194 and the response of the 650 nm filter radiometer monitoring the lamp luminance during a measurement session using the FEL lamp.



**Fig. 5.** Output change of FEL lamp S194 during a warm-up interval at 500, 600, 700, 800, and 900 nm measured by using the spectrograph S1.

radiant temperature of around 3000 K, a decrease in temperature will cause a larger decrease in spectral radiance at 500 nm than at 900 nm. After the initial 20 min decline and, unlike the filter radiometer data, the spectrograph data remain stable or even increase slightly after the initial decline. Overall, after the 20 min warm-up time, the fluctuation for each wavelength is under 0.02%. It is of interest to note that the fluctuations observed here after warm-up time are less than those observed with the 650 nm filter radiometer. The difference is most likely caused by the fact that the monitor and spectrographs are viewing different parts of the lamp filament.

Finally, it is important to monitor the 650 nm filter radiometer output and that of the lamp voltage during multiple measurement sessions where the lamp is subject to multiple light-on and light-off cycles. These data provide insight into the long-term stability of the lamp and therefore irradiance after many operating hours. Figure 6 shows lamp voltage and 650 nm filter radiometer output data at the end of the warm-up time of each measurement session during the entire stability study. A measurement session typically lasts one to two hours and includes ramping up the lamp current, warm-up interval, spectrograph measurements and, lastly, ramping down the lamp current to shut down the lamp. The data points of Fig. 6 are plotted against the total operating hours of the S194 lamp since the beginning of this work and represent the percent change relative to the very first measurement session of this study.



**Fig. 6.** Steady state of the voltage across the FEL lamp S194 and the output of the 650 nm filter radiometer of each measurement cycle as a function of the total operating hours of the S194 since the commencement of this study. The rise after 20 operating hours, which correspond to two months of use for this work, indicates aging of the lamp.

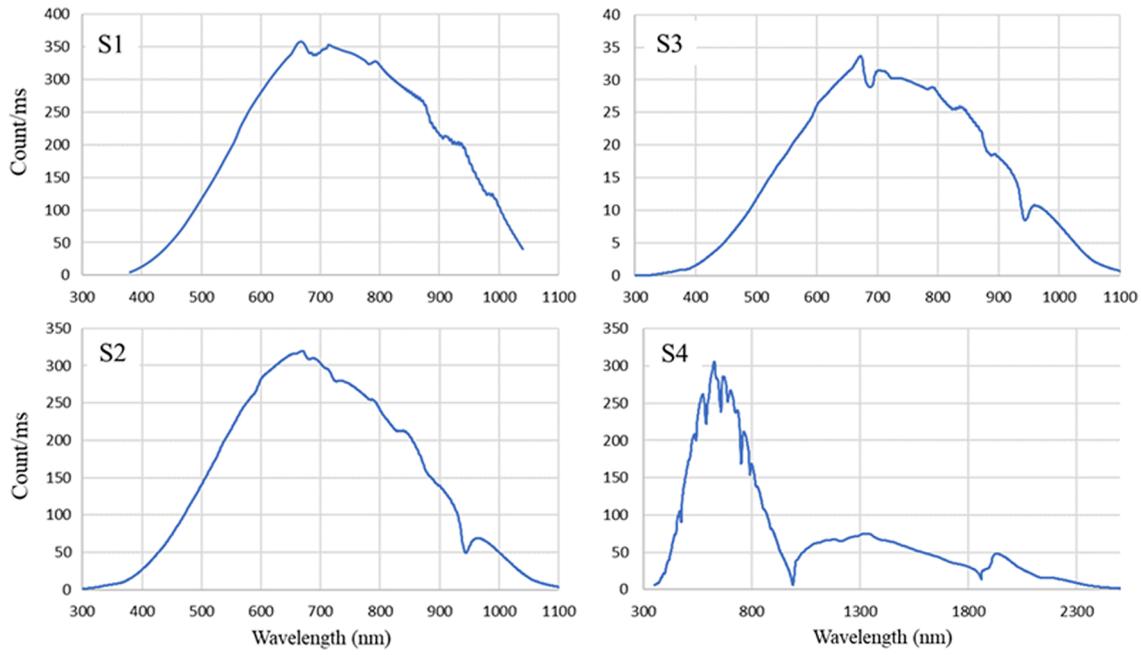
As indicated in Fig. 6, both the irradiance at 650 nm and the lamp voltage are stable in the  $\pm 0.02\%$  level for the first 20 h of lamp operation. After 20 h, both values start to increase to several tenths of a percent. This is consistent with gradual filament evaporation which leads to higher filament resistance, voltage, temperature and, subsequently, higher radiant power emitted by the lamp. Below we report the results of monitoring test spectrographs by lamp S194 measured during the first 20 hours of lamp operation which corresponds to an interval of two months. Fig. 6 indicates that the stability of the lamp S194 during the two months interval is  $\pm 0.02\%$  at 650 nm.

## B. Stability of Static Spectrographs

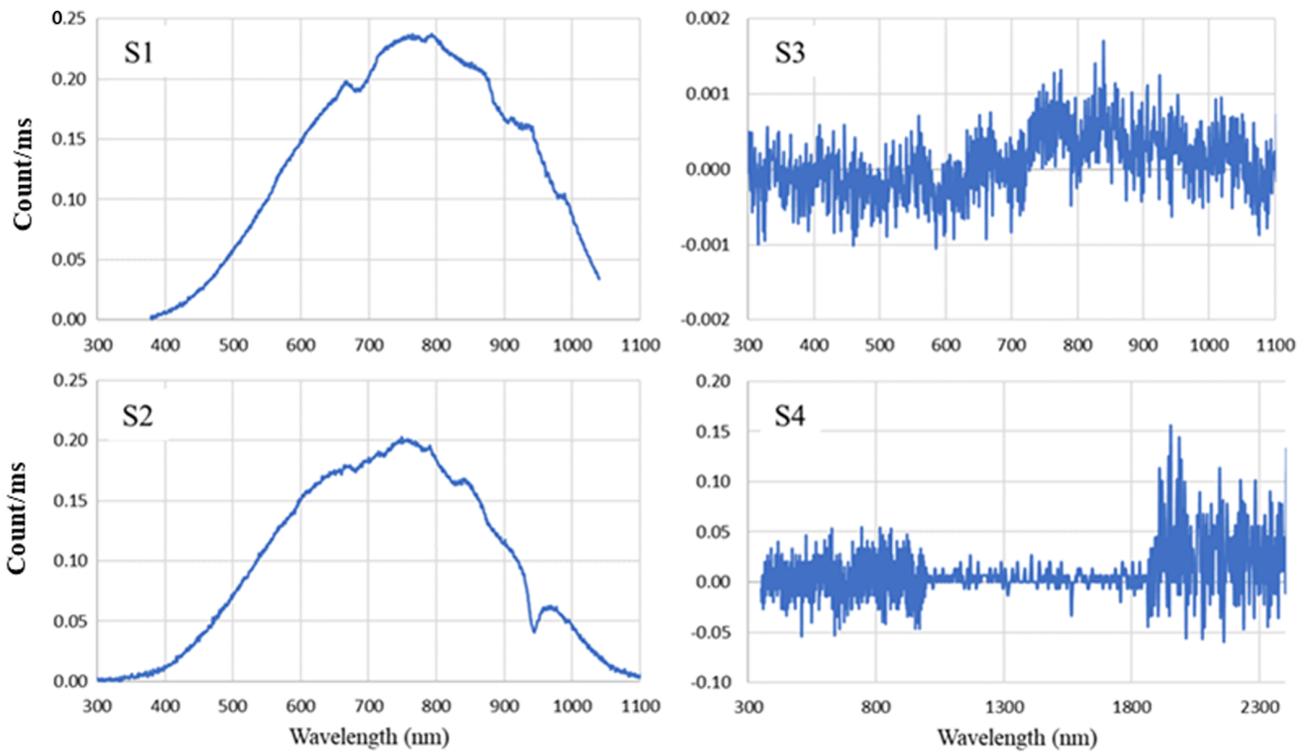
Typical responses, in counts per millisecond, of the four test spectrographs, S1, S2, S3, and S4, are shown in Fig. 7 when irradiated by the light from lamp S194 at 50 cm. These responses were calculated by subtracting data collected with the occulting disk in place from the unblocked, direct measurements. Shown in Fig. 8 are the background data used to derive data of Fig. 7. The background data for S1 and S2 are just under 0.1% of the direct data and the spectral shapes somewhat resemble those of the direct data. This indicates that the source of the background irradiance is scattered light in the laboratory that falls in the field-of-view of the cosine collector, including the light reflecting off the spectrograph side of the occulting disk. On the other hand, in contrast to S1 and S2, S3 and S4 have negligible background down to the noise level of the direct data. This can be clearly attributed to the field-of-view limiting apertures of the cosine collectors of S3 and S4 as opposed to the open field-of-view cosine collectors of S1 and S2. The higher background signal of S1 and S2 from scattered light may well manifest itself as noise and fluctuation in the measurement data of these two spectrographs.

Figure 9 shows the deviation from the mean of the spectra acquired by the four spectrographs on the daily schedule where a total of seven daily measurement sessions were conducted over the span of 11 days. To quantify the variation during these measurements, the standard deviation of each wavelength of each spectrograph of all measurements was calculated and used to derive the relative standard deviation or the coefficient of variation (COV), expressed in percent.

Figure 10 shows the COV of all four spectrographs of seven daily measurement sessions. In general, the COV rises below 400 nm because of the low spectral irradiance output from the lamp in the UV and resulting in a small signal-to-noise ratio. The COV increases for spectrograph S4 at the IR end because of the low responsivity in that spectral region. Additionally, there are wavelength regions corresponding to the water vapor absorption bands that demonstrate an overall increase in COV indicating variation of humidity in the laboratory. Other than these wavelength regions, we observe that the integrating-sphere-coupled spectrograph S3 has the lowest COV of about 0.02%, followed by 0.05% for spectrographs S1 and S2. The IR spectrograph S4 has somewhat higher COV of 0.1% from visible to near-IR and rises steadily into the IR to about 1% at the end of the spectral range close to 2400 nm. We note that the low 0.02% COV obtained by spectrograph S3 is additional evidence supporting that the lamp S194 variation was less than 0.02%



**Fig. 7.** Spectral responses in raw counts of test spectrographs S1, S2, S3, and S4, illuminated by FEL lamp S194.

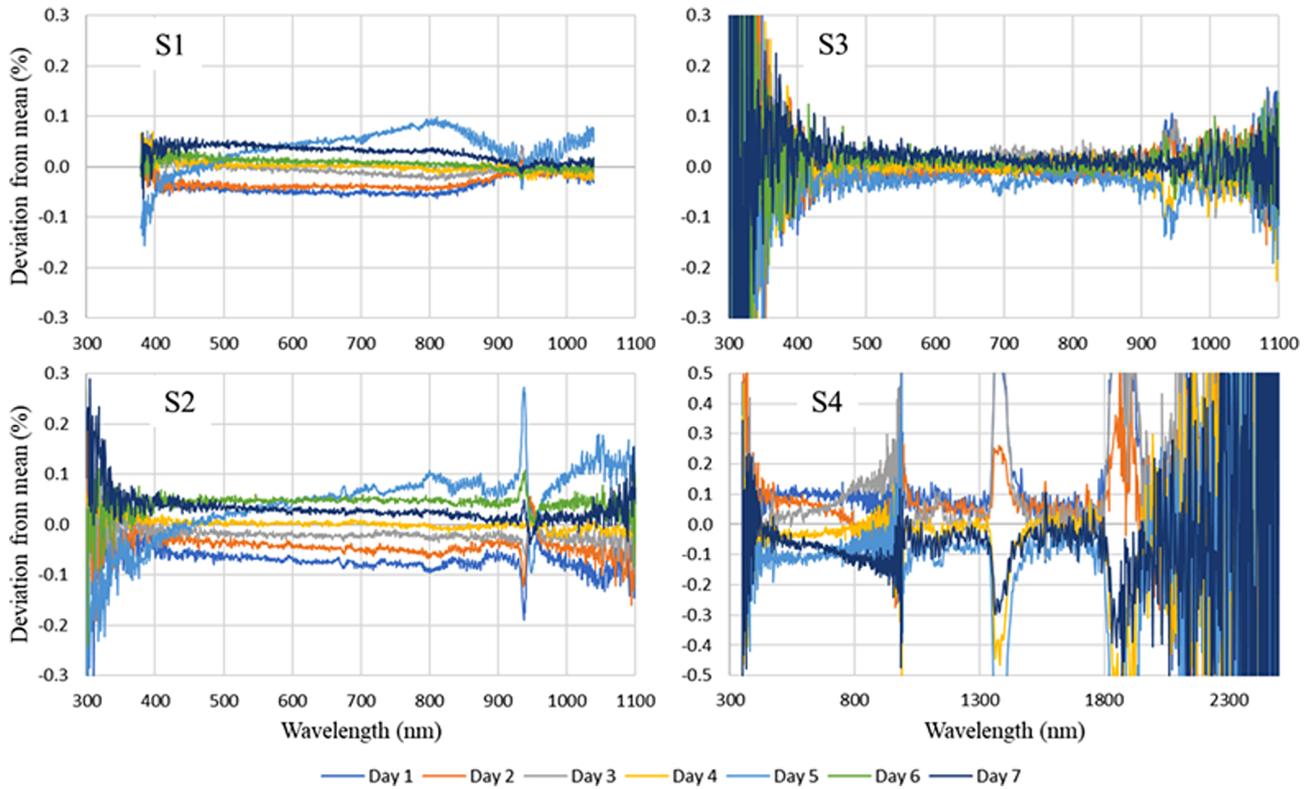


**Fig. 8.** Background counts measured by test spectrographs S1, S2, S3, and S4. The background counts were taken under the same conditions as in Fig. 7, but with a circular disk placed in front of the sensor heads to block direct light from FEL lamp S194.

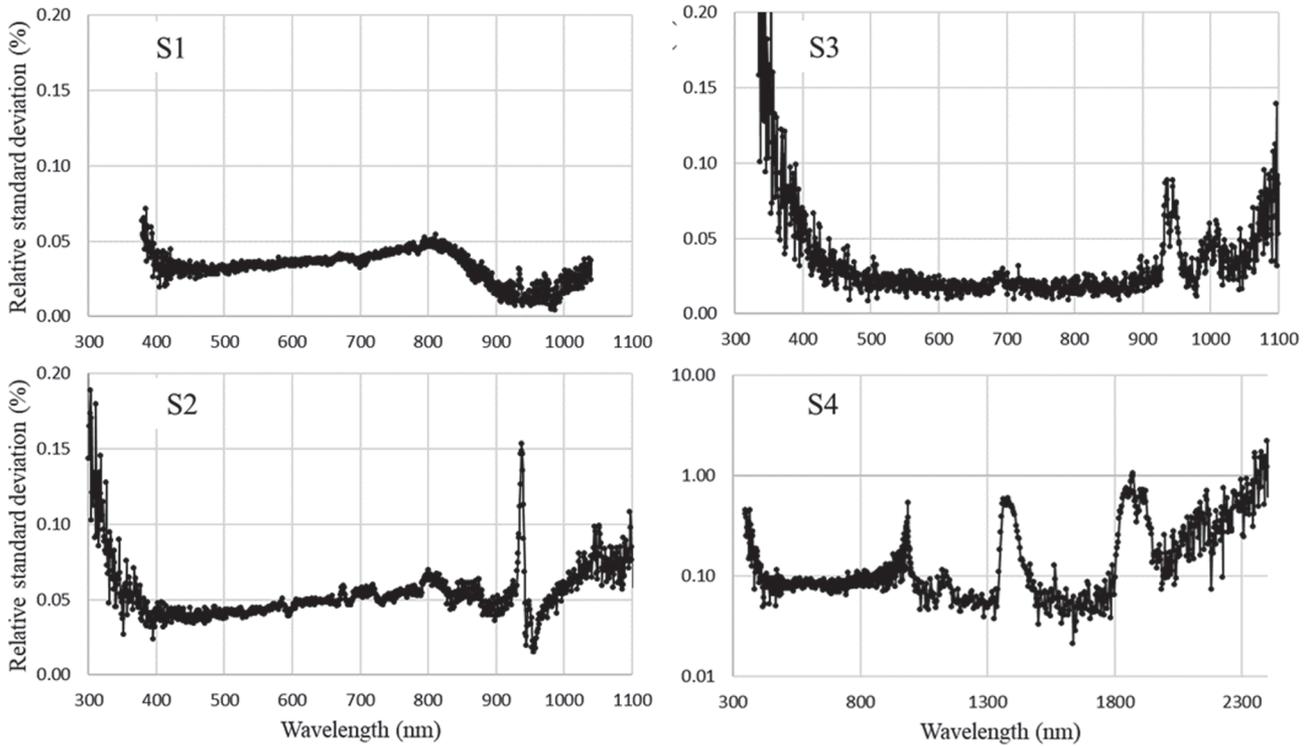
during the entire measurement interval. As discussed above, part of the reason that spectrograph S3 performs so well is due to the fact that we installed a baffle system to limit the field-of-view of the entrance port of the integrating sphere. Cosine collectors of S1 and S2 spectrographs have an unrestricted hemispheric view and are much more influenced by the scattered light from their environment. On the other hand, while S4 has a similar cosine

collector configuration as S3, the larger COV of S4 could arise from more intrinsic detector noise.

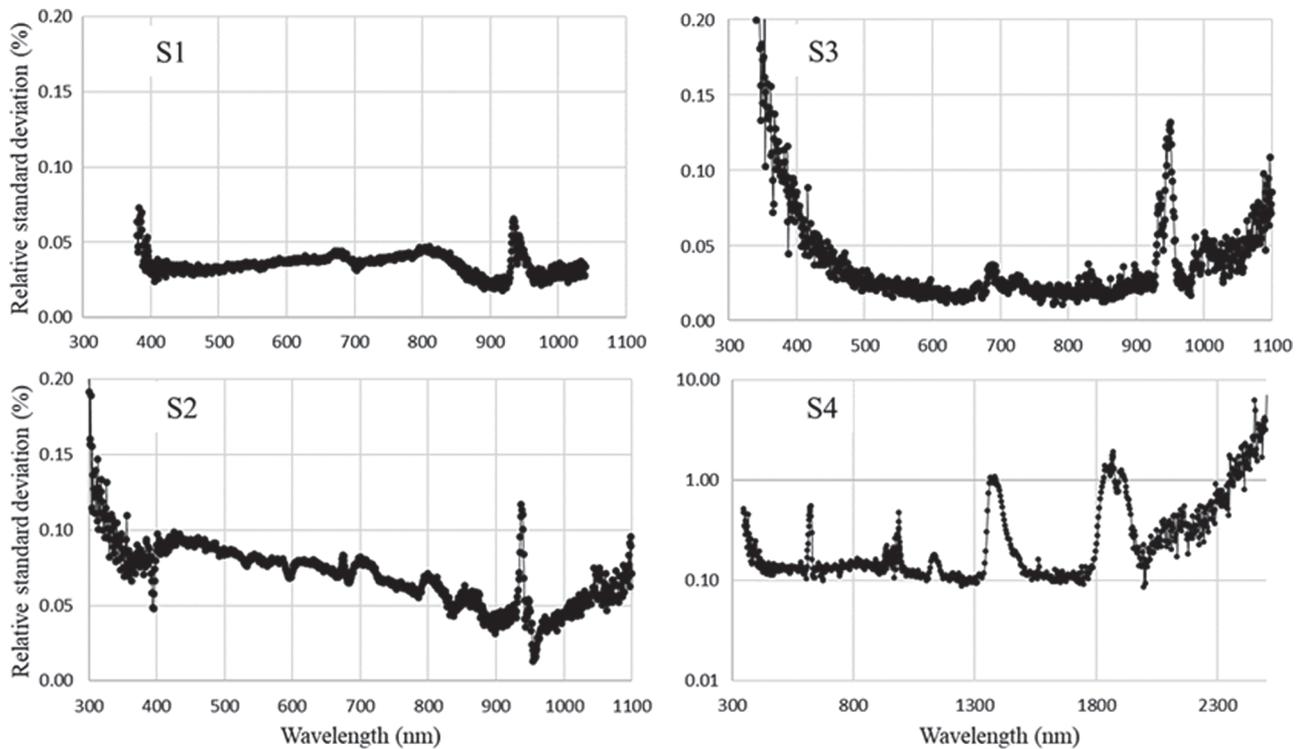
We also performed the same COV calculation for all spectrographs using all the data from the two-month measurement sessions, including the daily tests and weekly tests. The results are shown in Fig. 11. Comparing the longer-term COV of Fig. 11 with the shorter-term COV of Fig. 10, we find that,



**Fig. 9.** Relative spectral responses of test spectrographs S1, S2, S3, and S4, illuminated by FEL lamp S194 measured from seven sessions measured in consecutive days over the span of 11 days. For each spectrograph, the curves have been normalized to the mean of the seven measurements.



**Fig. 10.** Short-term relative standard deviation or coefficient of variation of the spectral responses of test spectrographs S1, S2, S3, and S4, illuminated by FEL lamp S194. The relative standard deviation is derived from data of seven sessions conducted over the span of 11 days.



**Fig. 11.** Long-term relative standard deviation or coefficient of variation of the spectral responses of test spectrographs S1, S2, S3, and S4, illuminated by FEL lamp S194 derived from data of 15 measurement sessions conducted over the span of two months.

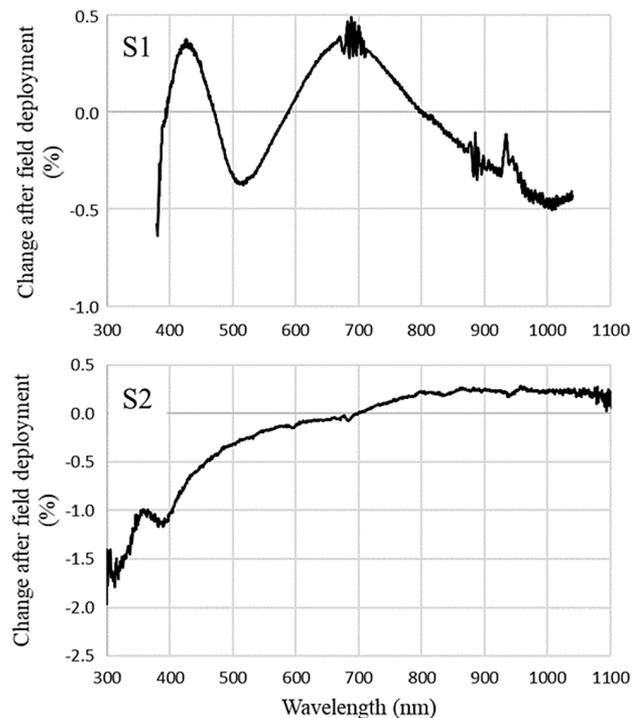
other than the low signal-to-noise ratio and water vapor absorption band wavelength regions, the increase in values of COV is less than 0.02% for spectrographs S1 and S3, less than 0.05% for spectrograph S2, and less than 0.1% for spectrograph S4. There was no statistically significant long-term drift in the responses of these spectrographs over the entire measurement interval.

**C. Stability of Spectrographs from Field Deployment**

Lastly, it is of interest to test the stability of spectrographs subjected to such effects as vibration from shipping and varying environmental conditions. At the end of the two-month laboratory stability test, two spectrographs, S1 and S2, were deployed to Arizona and Hawaii, and their responses before and after deployment were compared. The response change is shown in Fig. 12. For wavelengths longer than 400 nm, spectrograph S1 shows up to  $\pm 0.5\%$  variation, while spectrograph S2 shows an increase of up to 0.25% in response for wavelengths longer than 700 nm and decrease of up to 1.0% in response for wavelengths shorter than 700 nm. Overall, these changes are about an order of magnitude higher than the COV from the two-month laboratory study and show clear impact from transportation and harsh environmental conditions outside the range of the NIST laboratory.

**4. DISCUSSION AND CONCLUSIONS**

We have used an incandescent lamp as a broadband light source for monitoring the stability of spectrographs. The lamp current was regulated to better than 1 mA at a nominal operational current of 8.2 A, thus ensuring good stability. In addition,



**Fig. 12.** Relative response change of test spectrographs S1 and S2 after deployment for week-long field work. The percent change of the spectrograph response is the change in response after deployment as compared to the response before shipment for field work.

the performance of the lamp was constantly monitored both electrically and optically, by measuring the filament voltage

and the irradiance output with the 650 nm filter radiometer, to detect any sign of lamp instability. The lamp used for this study operated for a total of 20 h in a span of two months before aging was detected. Based on the analysis of lamp and spectrograph data, we conclude that the irradiance of the lamp source was stable to within  $\pm 0.02\%$  of the average value during the entire two-month interval.

Using this stable source, the stability of the test spectrographs can be measured and evaluated. We found that the COV in spectrograph response varies from 0.02% to 0.1% in the visible for the four test spectrographs over a week-long interval in general laboratory conditions. There was a slight increase in COV when the test interval was extended to two months. However, we observed no discernable long-term drift after two months for all spectrographs tested. For individual spectrographs, the most stable spectrograph, S3, among the four spectrographs is the one with a cosine collector that includes a field-of-view limiting aperture before its integrating sphere. Note that, over the entire test interval, the stability of the spectrograph S3 was comparable to the lamp stability. It is possible that the stable measurement of the spectrograph was limited in part by the lamp stability.

The stability results for all four spectrographs tested demonstrated that they can serve well as transfer standards for in-laboratory absolute spectral irradiance measurement when the uncertainty requirement is below 0.1% in the visible. While the monitoring of the spectrographs of this work is limited to two months because of the aging of the lamp, we plan to use a better selection of lamps and limit the operation time of lamps used to greatly increase the time of stability monitoring. Furthermore, in combination with our current effort on calibrating spectrographs using tunable lasers [10], we are currently working to develop spectrographs as broadband irradiance transfer standards and to provide an alternative to current incandescent lamp standards. Lamps are difficult to setup and operate and, as we can see from this study, aging of lamps after many hours of operation could mean deviation from original calibrated values and scheduled recalibration is required. On the other hand, spectrographs are more suitable as irradiance transfer standards because they are compact, easy to operate, and highly stable, as demonstrated in this work.

Further stability tests of spectrographs before and after deployment to the field revealed somewhat larger response variation of, dependent on the wavelength, up to 1.0%, resulting from transportation and adverse environmental conditions. While this is worse than the stability of spectrographs confined to laboratory conditions, it is still acceptable for field research [3–6]. Both Ref. [1] and our previous experience with fiber-coupled spectrographs suggest that the mechanical stability of coupling of the spectrograph entrance aperture and the fiber end are critical to the optical stability of some of the spectrographs. This could be one of the major sources which contributed to the instability of the spectrographs after transportation. It is conceivable that vibration by the handling of the spectrographs causes some systematic shift between the fiber end and the entrance aperture of a spectrograph, and this could potentially change the optical throughput and shift the wavelength scale of the spectrograph. In addition, the thermal effect on the wavelength and responsivity of a spectrograph needs to be characterized. All these effects can contribute to the 1% variation

observation in this work. Currently, identifying the source of spectrograph instability is part of an ongoing effort at NIST on improving the stability of spectrographs designated for field deployment.

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**Data Availability.** Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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