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Temperature Sensitivity Characterization of a Silicon Diode Array Spectrometer*

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High spectral resolution remote sensing devices are frequently used to quantify the flux of energy reflected from or transmitted through an optical medium. Their use requires careful calibration against a well-characterized standard. This study was conducted to characterize temperature sensitivity of a typical silicon-detector-based spectroradiometer, demonstrate the potential errors due to temperature effects, and present a methodology to correct for temperature-induced errors. Three Spectron Engineering SE590 units were independently evaluated under varying temperatures at three separate institutions. A procedure for correcting calibration coefficients (radiance/count) as a function of temperature and wavelength was developed and applied. The evaluation showed that at wavelengths between 390 nm and 940 nm the calibration coefficients differed from each other by less than 5% among all ambient temperatures. At 1000 nm, the calibration coefficient decreases about 5% going from 25°C to 35°C and increases about 25% going from 25°C to 0°C. Wavebands below 390 nm responded chaotically to temperature. At any given wavelength above 940 nm the change in calibration coefficient value was a nearly linear function of temperature, an indication that a simple temperature correction can be applied. Calibration coefficients were linearly interpolated for each waveband greater than 940 nm at temperatures between temperature extremes imposed upon the instruments during the experiments. Linearly interpolated calibration coefficients were found to be within 4% of actual values. Users of silicon-detector-based spectroradiometers should be aware of potential errors in data due to temperature effects.

INTRODUCTION

High spectral resolution remote sensing devices are frequently used to quantify the flux of energy reflected from or transmitted through an optical medium. Their use requires that the instruments be calibrated against a well-characterized standard. Generally, instrument calibrations are performed at room temperature (~25°C), from which calibration coefficients are determined relating instrument response to physical units such as irradiance or radiance. The calibration coefficients determined under room temperature conditions are subsequently applied to data collected in field situations where the ambient temperature is not likely to match the calibration room temperature so that the instrument temperature will be different. Also, when these instruments are used in a reflectance measurement mode (i.e., a reference target is periodically viewed in addition to the sample target), instrument temperature may vary between the calibration condition (reference target) and the sample target.

Instrument temperature changes can cause changes in output signal voltages from detectors exposed to the same light intensity (Slater, 1980) such as was found by Jackson and Robinson (1985) for the eight-channel modular multispectral radiometer (MMR). The MMR is a filter-based radiometer that employs three detector types: silicon, lead sulfide, and lithium tantalate. Voltage outputs from the silicon detectors (Channels 1–4) were found to be nearly independent of temperature. The lead sulfide detectors' (Channels 5–7) output voltages were found to vary inversely with internal instrument

*This manuscript has been assigned Journal Series No. 10708, Agricultural Research Division, University of Nebraska.

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Received 22 April 1994; revised 19 November 1994.

REMOTE SENS. ENVIRON. 51:385–389 (1995)
Published 1995 by Elsevier Science Inc.
655 Avenue of the Americas, New York, NY 10010

0034-4257/95/$0.00
SSDI 0034-4257(94)00109-Z

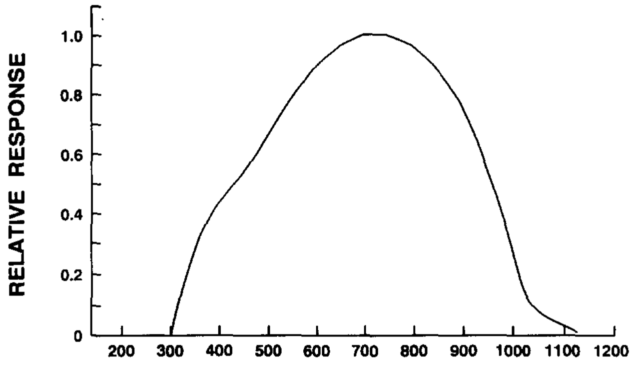

Figure 1. Typical relative response of a silicon detector.

air temperature at a rate of 4–5% °C^{-1}. In an earlier experiment Jackson et al. (1983) found the lithium tantalate (Channel 8) detector's output voltage to be affected by ambient air temperature. Markham et al. (1988) also noted strong temperature sensitivity (3–4% °C^{-1}) in the lead sulfide detectors of these filter radiometers and a small effect due to temperature in the silicon detectors (<0.3% °C^{-1}).

Spectron Engineering's[1] SE590 spectroradiometers (Spectron Engineering, 1987) have been used in many remote sensing studies. The SE590 is typical of portable field remote sensing instruments in that it uses a silicon detector to measure visible and near-infrared electromagnetic radiation that is reflected from a target surface. The SE590 spectroradiometers use series G detector silicon photodiode arrays (PDAs) manufactured by EG&G Optoelectronics (Reticon). Silicon exhibits a broad spectral sensitivity (Fig. 1) with a peak response typically occurring between 700 nm and 800 nm (Baker and Scott, 1975; Slater, 1980).

The SE590 automatically subtracts the signal obtained with the shutter closed from the signal representing remotely sensed data at the time of data acquisition before it is written to a storage medium. The dark signal is a strong function of temperature, approximately doubling for every 7°C increase in the PDA temperature (EG&G, 1992). Most of the PDA's temperature sensitivity is corrected when the dark signal is measured and subtracted during each target scan.

The inherent spectral responsivity of the detector material also varies with temperature and is not accounted for when the dark signal is measured. The temperature sensitivity of the SE590 has been noted by Blad et al. (1990) and Markham et al. (1994), but no attempt was made by these authors to characterize it adequately to allow for its correction. In this article, we characterize the temperature sensitivity of three SE590 spectroradiometers, demonstrate the potential errors due to temperature sensitivity, and present a methodology to correct for temperature-induced errors.

[1] The use of company or trade names is strictly for informational purposes and does not imply endorsement by the United States Department of Agriculture or the University of Nebraska-Lincoln or the National Aeronautics and Space Administration.

INSTRUMENTATION

The SE590 consists of a sensing head (camera) which is electronically coupled by a cable to a controlling unit. As the electromagnetic radiation (EMR) passes through the aperture of the camera it is projected onto a diffraction grating. From the diffraction grating the EMR is focused onto the PDA, where each photodiode element in the PDA measures the energy in a different narrow waveband. Interaction between the energy present in each waveband and a given photodiode element produces a signal which is sent to the controller. Although the PDA contains 256 elements (i.e., 256 wavebands), only 252 are usable for measurement purposes. Channels 0, 1, 254, and 255 contain parity check and parameter information.

When used in the SE590, the PDA, together with its protective glass window, produces a nominal spectral range from about 360 nm to approximately 1130 nm, with a wavelength spacing of about 3 nm between the midpoints of adjacent spectral channels (wavebands) (Starks et al., 1995; Spectron Engineering, no date). The spectral bandwidth of each waveband is on the order of 15 nm full width half-maximum (Markham et al., 1994; Starks et al., 1995).

The controller processes the signal and digitizes it with 12-bit resolution. For each scan, the controller actuates a shutter in the camera, measures and stores a dark signal reading, calculates an optimum scan integration time, acquires the spectral data from the target surface, and automatically subtracts the dark signal from the spectral data.

EXPERIMENTAL PROCEDURES

Three SE590 spectroradiometers were independently evaluated under varying temperatures at their respective institutions: USDA-ARS National Agricultural Water Quality Laboratory (NAWQL), the University of Nebraska-Lincoln (UNL), and the National Aeronautics and Space Administration's Goddard Space Flight Center (GSFC).

NAWQL Study

Temperature stability investigations were conducted in 1993 on the NAWQL SE590 in a temperature-controlled chamber constructed of a 100-W light bulb mounted inside a small commercially available freezer. The freezer and light bulb were connected to temperature controllers so that a constant temperature could be maintained inside the freezer. A J-type fine wire thermocouple was placed inside the SE590 camera case, which allowed monitoring of the internal dead-air space temperature. A K-type thermocouple was mounted on the floor of the freezer and was used as an independent check of temperature controller readouts. Both the J and K thermocouples were monitored using a dual-input thermocouple reader. A small fan was placed on a wire shelf near the top of the freezer to keep the air inside the freezer well mixed. The camera was placed on a wire shelf near the middle of the freezer and covered with a piece of cardboard wrapped in aluminum foil. The foil-covered cardboard was used to prevent the light bulb, when turned on, from heating the camera case and thereby warming the air inside the camera above ambient conditions. Light from a spectrally calibrated irradiance lamp was piped via fiber optic cable to the entrance aperture of the SE590 camera. Nitrogen gas was continually injected into the freezer compartment in order to keep the humidity low, thereby assuring the prevention of condensation on the spectrometer optics and photodiode array. The air temperature inside the freezer was varied from 0°C to 35°C in 5°C increments. After approximately 1 h, the camera came into equilibrium with the freezer ambient atmosphere, and the irradiance source was turned on and allowed to stabilize. Irradiance data were then acquired. Three replications were made at each temperature and averaged to a single value.

UNL Study

The UNL temperature stability data were collected in 1989 using the Kansas State University Evapotranspiration Laboratory's facilities during the First ISLSCP Field Experiment (Sellers et al., 1992). The entire instrument (camera and controller) was placed in an environmental chamber for several hours with the intent of equilibrating the instrument to a predetermined chamber air temperature (16°C, 22°C, 31°C, 35°C, and 44°C, nominal), in a similar manner as given by Markham et al. (1988) for MMR units which are larger in mass than the SE590. Located within the environmental chamber was a 4-lamp, 30-cm integrating sphere. After the SE590 had equilibrated to the ambient temperature, two lamps in the integrating sphere were activated and allowed to stabilize. The SE590 camera was placed near the output aperture of the integrating sphere and the radiance data collected. Fourteen to 20 replications were made at each temperature and averaged to a single value.

GSFC Study

The GSFC SE590 temperature stability data were collected in 1992. The instrument was placed in a temperature-controlled room and allowed to equilibrate for about 2 h in order to achieve equilibrium of the instrument to the temperatures of 13°C, 26°C, and 35°C, nominal, and then used to collect data from a 30-cm integrating sphere. From 20 to 30 replications were made at each temperature and averaged to a single value. For both the UNL and GSFC measurements, the measured temperature was ambient air in the environmental chambers, not within the camera case. The SE590s were assumed, during both the UNL and GSFC experiments, to come into equilibrium with ambient conditions before data were collected from the integrating spheres. The assumption is adequate given that the NAWQL SE590 was found to come into equilibrium with imposed ambient conditions after approximately 1 h.

ANALYSIS

The radiance (L) or irradiance (E) sensed by each waveband (i) of the SE590 is determined via

$$X_i = [DN_i - 1024 / IT][CC_i], \tag{1}$$

where

X_i = spectral radiance ($\mu W\ cm^{-2}\ nm^{-1}\ sr^{-1}$) or spectral irradiance ($\mu W\ cm^{-2}\ nm^{-1}$) in waveband i,
DN_i = signal output recorded as a digital number (counts) in waveband i,
IT = scan integration time (1 / 60 s),
CC_i = calibration coefficient for channel i ($\mu W\ s\ cm^{-2}\ nm^{-1}\ sr^{-1}\ count^{-1}$ or $\mu W\ s\ cm^{-2}\ nm^{-1}\ count^{-1}$).

The "1024" value is an offset introduced during the data collection to allow quantization of negative signals.

The NAWQL experiment was designed to test the stability of the calibration coefficients as a function of temperature, whereas the UNL and GSFC experiments were originally intended to determine the relative response of the SE590s to temperature effects. Calibration coefficients for each waveband of the NAWQL SE590 were readily determined from Eq. (1) at each ambient temperature because the spectral irradiance (E) output from the calibrated lamp was known. The particular light sources used by UNL and GSFC had a constant output of undetermined radiance. Thus the calibration coefficients for the UNL and GSFC SE590s were determined by using the room-temperature spectral radiances (i.e., those collected at ~25°C) as the "known" radiances (L_i) in Eq. (1). The DNs obtained from the radiance sources at the remaining calibration ambient temperatures were then substituted into Eq. (1) to solve for CC_i.

RESULTS

Temperature Sensitivity Characterization

The CC_i for the NAWQL SE590 were found to be within about 5% of each other between 390 nm and 940 nm among all ambient temperature conditions without apparent dependence on temperature. At wavelengths longer than about 940 nm the CC_i's varied inversely

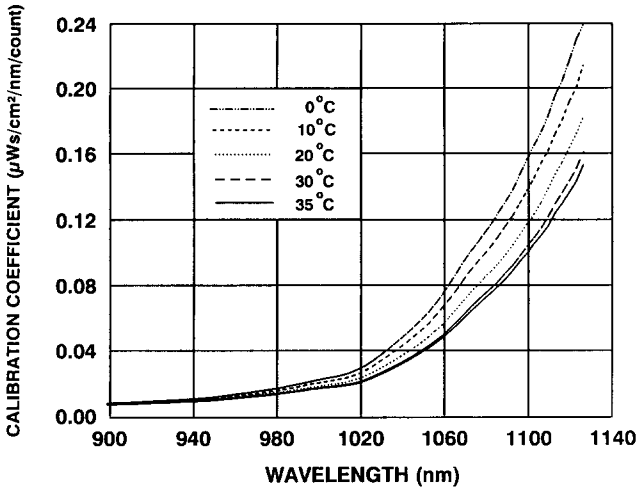

Figure 2. Variation in calibration coefficients as a function of instrument temperature. (NAWQL temperature sensitivity experiment.)

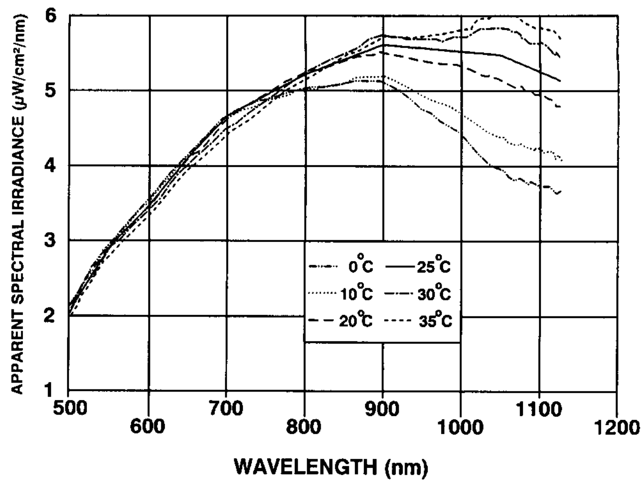

Figure 3. Variation in apparent spectral irradiance from a calibrated lamp as a function of ambient temperature. Apparent spectral irradiance is calculated using DNs from various ambient conditions while CC_i's determined at 25°C were applied in Eq. (1).

with temperature (Fig. 2), and the variation in the CC_i with temperature became more pronounced as wavelength increased. For example, at 1000 nm the CC_i's at 0°C and 35°C were 25% larger and 5% smaller, respectively, than those at 25°C. The UNL and GSFC SE590s behaved in a similar manner. The CC_i responded chaotically to temperature changes at wavelengths less than 390 nm for both the NAWQL and GSFC SE590s, and these data were, therefore, eliminated from further analysis. Calibration coefficients below 400 nm and above 1000 nm were not determined for the UNL SE590 as the data collected at these wavelengths were routinely eliminated from the data files.

Potential Errors

When calibrating at a single temperature the calibration room temperature conditions may differ from field temperature conditions so that incorrect CC_i's may be used in converting DNs to radiance or irradiance terms. To demonstrate the errors in calculating radiance or irradiance from DNs collected under field conditions, where field and calibration temperatures differ, we used the DNs obtained from the calibrated source lamp (NAWQL experiment) at the various ambient temperatures to represent field data and the CC_i's obtained at approximately 25°C to represent calibration coefficients determined at a nominal calibration room temperature. Spectral irradiances were then calculated using Eq. (1). For wavelengths longer than 940 nm the calculated spectral irradiances at ambient temperatures less than 25°C underestimated that determined at 25°C, while spectral irradiances calculated at ambient temperatures greater than 25°C overestimated it (Fig. 3). At a wavelength of 1000 nm irradiance calculated at 0°C was 24% smaller than that calculated at 35°C. The difference in irradiance between the imposed ambient temperatures becomes larger at longer wavelengths.

Spectral radiances calculated from DNs measured at 16°C was 15% smaller than that at 44°C at 1000 nm for the UNL SE590. Similarly for the GSFC SE590, radiance calculated at 13°C was 16% smaller than that calculated at 35°C at 1000 nm. Thus, CC_i's developed at one instrument temperature cannot be satisfactorily applied to data obtained at a different temperature.

Correction Method

The change in CC_i with respect to temperature is nearly linear at given wavelengths longer than about 940 nm. The linearity indicates correction of the CC_i's is possible if the instrument temperature and response at expected temperature extremes are known. Calibration coefficients were linearly interpolated between temperature extremes experienced during the respective experiments for each waveband (≥940 nm) of the SE590s (5°C, 10°C, 15°C, 20°C, 25°C and 30°C for the NAWQL SE590; 22°C, 31°C, 35°C and 39°C for the UNL SE590; and 26°C for the GSFC SE590). Over the wavelength range 940–1126 nm the interpolated CC_i's were compared to and found to be within 4% of the actual values for the NAWQL instrument (Table 1). The UNL (940–1000 nm wavelength range) and GSFC (940–1150 nm wavelength range) estimates of the calibration coefficients were within 1% of actual values (Table 1).

SUMMARY AND CONCLUSIONS

Temperature sensitivity experiments performed on three silicon-detector-based spectroradiometers revealed that output in some wavebands was affected by temperature. Output variations were particularly evident at wavelengths less than 390 nm and at wavelengths longer

Table 1. Average Relative Errors of Linearly Interpolated Calibration Coefficients at Ambient Temperatures between Extremes Encountered during the Respective Temperature Stability Experiments

Institution	*Ambient Temperature (°C)*	*Average Relative Error (%)*
NAWQL (940–1126 nm)	5	0.1
	10	0.3
	15	-3.2
	20	-3.8
	25	-3.4
	30	-2.9
UNL (940–1000 nm)	22	0.3
	31	-0.7
	35	0.1
	39	-0.2
GSFC (940–1155 nm)	26	0.4

than 940 nm. At the 1000 nm wavelength errors in irradiance and radiance calculations approached 30% or more, relative to that determined at 25°C, when temperature effects were not taken into account.

The change in calibration coefficients at any given wavelength was a nearly linear function with respect to temperature. The linearity enables an adequate estimation of calibration coefficients (i.e., within 4% relative error) if the calibration at two temperature extremes expected during the field season are known.

The proposed procedure for temperature compensation of calibration coefficients requires calibration against an irradiance and/or radiance source at two temperature extremes and a means of monitoring the SE590 camera temperature. The determination of the calibration coefficients is straightforward using linear interpolation. In a field setting, a fine-wire thermocouple placed inside the camera case may be used to monitor the internal temperature at the time(s) of data acquisition. The simple assumption that the air inside the camera case is in equilibrium with the ambient conditions experienced in the field is not adequate. On warm sunny days, the camera case is warmed by the sun, thereby heating the air inside the case and, consequently, the PDA, above ambient conditions so that irradiances or radiances calculated using room-temperature calibration coefficients will be overestimated. To demonstrate the effect of solar heating on the internal camera case temperature, we placed an SE590 in full sunlight for 20 min and monitored both the internal camera case temperature and ambient air temperature. The ambient air temperature averaged 26.7°C ($s = 0.4$°C) over the 20-min time period, while the SE590 temperature at the end of the time period was 45.8°, 19°C higher than ambient conditions. Thus a means of monitoring the internal camera temperature is advised.

Although the temperature sensitivity experiment was performed on only one type of silicon-detector-based spectroradiometer, we believe that our findings should alert users of other similar spectroradiometers as to potential errors due to temperature effects.

The authors would like to thank Cindy Hays of the Department of Agricultural Meteorology, University of Nebraska-Lincoln, and John Schafer and Frank Wood of Goddard Space Flight Center for their assistance in collecting and processing the UNL and GSFC data. The UNL experiment was conducted under the NASA Contract NAG5-894.

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