Field-based nonimaging spectroradiometers are often used in vicarious calibration experiments for airborne or spaceborne imaging spectrometers. The calibration uncertainties associated with these ground measurements are responsible for the overall modeling error in radiance- or reflectance-based vicarious calibration experiments. Because of limitations in the radiometric stability of compact field spectroradiometers, vicarious calibration experiments are based primarily on reflectance measurements rather than on radiance measurements. To characterize the overall uncertainty of radiance-based approaches and assess the sources of uncertainty, we carried out a full laboratory calibration. This laboratory calibration of a nonimaging spectroradiometer is based on a measurement plan targeted at achieving a ≲10% uncertainty calibration. The individual calibration steps include characterization of the signal-to-noise ratio, the noise equivalent signal, the dark current, the wavelength calibration, the spectral sampling interval, the nonlinearity, directional and positional effects, the spectral scattering, the field of view, the polarization, the size-of-source effects, and the temperature dependence of a particular instrument. The traceability of the radiance calibration is established to a secondary National Institute of Standards and Technology calibration standard by use of a 95% confidence interval and results in an uncertainty of less than ±7.1% for all spectroradiometer bands. © 2000 Optical Society of America

1. Introduction
Field-based reference sampling with a nonimaging spectroradiometer has become popular because of the growing number of airborne and spaceborne imaging spectrometers available for remote sensing. Techniques such as spectral unmixing, use of a spectral angle mapper, and vicarious calibration efforts rely on spectral libraries that are collected by field spectroradiometers and laboratory spectrometers. The uncertainties associated with these measurements are dependent not only on the sampling strategy (e.g., sampling scheme and sample size) but also on the uncertainties associated with the spectroradiometric measurements. To date these libraries are compiled purely in the form of spectral reflectance data, but upcoming technologies will permit the construction of field spectroradiometers that will support radiance-based vicarious calibration approaches as well.

Efforts at calibration of imaging spectrometers have reached a high level of quality. However, we have seen little discussion of solid radiance calibration of nonimaging spectrometers used in remote sensing, except for manufacturer-provided calibrations. The spectroradiometer used in this calibration is a GER3700 (SN 3700-1002) manufactured by Geo Physical and Environmental Research Corporation (for specifications see Table 1). It is a single field-of-view (FOV) spectroradiometer operating in the visible, near-infrared, and shortwave-infrared regions of the spectrum. The wavelength range covered is 400–2500 nm. The radiance is measured with three detectors. The first detector is a silicon (Si) line array with 512 elements. The other two detectors are lead sulfide (PbS) line arrays with 128 and 64 elements, respectively. The PbS detectors are operated in an uncooled environment; therefore ambient- (or room-) temperature operation types of detectors were chosen. The cutoff wavelength for the Si detector can be programmed with software to be 980–1030 nm; the transition between detectors PbS1 and PbS2 is fixed near 1900 nm. The resultant setup has 512 bands covering the 400–1000-nm range, 128 bands...
covering the 1000–1900-nm range, and 64 bands covering the 1900–2500-nm range. In total, 704 spectral bands are recorded simultaneously. The characterization and calibration equipment used in the laboratory includes a tunable dye laser (serving as a spectral reference), an integrating sphere calibration standard (serving as a radiometric reference) calibrated by the National Institute of Standards and Technology (NIST), and a Spectralon panel (serving as a diffuse reflectance standard), which is also calibrated by the NIST.

2. Measurement Plan

A generalized measurement plan to characterize and calibrate irradiance measurement instrumentation was developed by Kostkowski for UV solar irradiance calibration and is adapted here for a spectroradiometer used for radiance measurements in the 400–2500-nm wavelength range. The measurement plan is detailed in Table 2, where the expected errors for a ±10% calibration uncertainty are also listed.

3. Measurement Setup and Characterization

A. Measurement Setup

In general, three different measurement setups are used throughout the characterization process. In the first measurement setup the spectroradiometer is coupled to an integrating sphere (Type 1; see Fig. 1), in the second the spectroradiometer is mounted onto the optical table of the tunable dye laser (Type 2), and in the third setup the spectroradiometer is used on a tripod for reflectance measurements (Types 3a and 3b). In the following sections we discuss the methodology and measurement setup used to assess the error sources as outlined in the general measurement plan in Table 2. Subsections 3.B–3.L discuss the characterization of the spectroradiometer that results in a proper description of the instrument’s measurement behavior. In Section 5 we establish the relation between measured digital numbers and physical units (the actual calibration of the instrument).

B. Signal-to-Noise Ratio

The first characterization step is the determination of the signal-to-noise ratio (SNR) from the following equation:

\[ \text{SNR} = \frac{S}{N} = \frac{R_{\text{DN, total}} - R_{\text{DN, dark}}}{\sigma^2(R_{\text{DN, total}}) + \sigma^2(R_{\text{DN, dark}})^{1/2}}, \]  \hspace{1cm} (1)

where \( R_{\text{DN}} \) is the measured signal (either the dark current or the total signal), DN means a digital number, and \( \sigma \) is the standard deviation. All measurements are performed with the integrating sphere calibration standard. The radiance levels of the integrating sphere are optimized to span the ambient light that is usually present in naturally illuminated scenes (given by a minimum and a maximum radiance; see Fig. 2 and Fig. 8 below). The characterization is performed within these boundaries.

The determination of the corresponding noise present at minimum and maximum radiance is calculated with the inverse SNR NSR (where NSR is the noise-to-signal ratio). The initially estimated NSR was <1%, but the measured NSR is worse than this estimate (Table 3).

C. Noise-Equivalent Signal and Noise-Equivalent Radiance

We derive the noise-equivalent signal (NES), using a special case of Eq. (1), by setting \( \text{SNR} = 1 \). The NES is then given as

\[ \text{NES} = [\sigma^2(R_{\text{DN, total}}) + \sigma^2(R_{\text{DN, dark}})]^{1/2}, \]

\[ \text{NER} = \text{NES} \times C_{\text{gain}}, \]

\( C_{\text{gain}} \) is the calibration gain. The NES has an average value of 5 DN (Fig. 3), which differs by 3.5 DN from that of the dark current.

D. Dark Current

The dark current is defined from

\[ R_{\text{dark}} = \frac{1}{n} \sum_{i=1}^{n} R_0 = R_0, \]

where \( R_0 \) is the measured signal with no flux incident upon the instrument (shutter closed) and \( n \) is the number of measurements. With an average of 1.48 DN in the visible and near infrared and 0.53 DN in the short-wavelength infrared, the dark current is below 0.01% of the total dynamic range of 32,000 DN (Fig. 4).

E. Wavelength Calibration and Spectral Sampling Interval

In an experiment to calibrate wavelength and the spectral sampling interval the center wavelength is determined by use of an emission line of the tunable

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral range</td>
<td>400–2500 nm</td>
</tr>
<tr>
<td>Number of Bands</td>
<td>704</td>
</tr>
<tr>
<td>Linear arrays</td>
<td>1 Si (512 bands) and 2 PbS (128 and 64 bands)</td>
</tr>
<tr>
<td>Bandwidth (nm)</td>
<td>1.5 (400–1050 nm)</td>
</tr>
<tr>
<td></td>
<td>6.2 (1050–1840 nm)</td>
</tr>
<tr>
<td></td>
<td>8.6 (1950–2500 nm)</td>
</tr>
<tr>
<td>Scan time</td>
<td>≥50 ms</td>
</tr>
<tr>
<td>FOV</td>
<td>Dependent on fore optic (2° or 8°)</td>
</tr>
<tr>
<td>Head size</td>
<td>286 mm × 305 mm × 114 mm</td>
</tr>
<tr>
<td>Weight</td>
<td>6.4 kg</td>
</tr>
<tr>
<td>Battery life/voltage</td>
<td>4 h/12 V</td>
</tr>
<tr>
<td>Digitization</td>
<td>16 Bits</td>
</tr>
<tr>
<td>Wavelength accuracy/repeatability</td>
<td>±1 nm/±0.1 nm</td>
</tr>
<tr>
<td>Spectrum averaging</td>
<td>Yes</td>
</tr>
<tr>
<td>Dark-current correction</td>
<td>Automatic</td>
</tr>
<tr>
<td>Operating environment</td>
<td>10–90% Humidity/~10 to 50 °C</td>
</tr>
<tr>
<td>Steps in General Plan</td>
<td>Property or Procedure</td>
</tr>
<tr>
<td>-----------------------</td>
<td>------------------------</td>
</tr>
<tr>
<td>Detailed description of the quantity to be measured including the accuracy desired</td>
<td>Quantity to be measured</td>
</tr>
<tr>
<td>Wavelengths to be measured</td>
<td>400–2500 nm</td>
</tr>
<tr>
<td>Measurement accuracy desired</td>
<td>≤10%</td>
</tr>
<tr>
<td>Geometry of quantity</td>
<td>Nadir-looking measurement of radiances</td>
</tr>
<tr>
<td>Relative spectral distribution</td>
<td>400–2500 nm</td>
</tr>
<tr>
<td>Approximate magnitude</td>
<td>&lt;700 W/(m² sr⁻¹ μm⁻¹)</td>
</tr>
<tr>
<td>Stability</td>
<td>≤5%</td>
</tr>
<tr>
<td>Polarization</td>
<td>≤2%</td>
</tr>
<tr>
<td>Noise-to-signal ratio</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>Identification of potential error sources and their estimation of their magnitude (can also be according to specifications or literature search)</td>
<td>Nonlinearity</td>
</tr>
<tr>
<td>Directional effects</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>Spectral scattering</td>
<td>&lt;0.75%</td>
</tr>
<tr>
<td>Spectral distortion</td>
<td>&lt;0.8%</td>
</tr>
<tr>
<td>Polarization effects</td>
<td>≤2%</td>
</tr>
<tr>
<td>Size-of-source effect</td>
<td>&lt;0.5%</td>
</tr>
<tr>
<td>Wavelength instability</td>
<td>&lt;0.6%</td>
</tr>
<tr>
<td>Detector instability</td>
<td>0.7%</td>
</tr>
<tr>
<td>Uncertainty of the standard</td>
<td>±3 to ±6%</td>
</tr>
<tr>
<td>Instability of the standard</td>
<td>±2%</td>
</tr>
<tr>
<td>Instability of the quantity being measured</td>
<td>Noise in the measurement data</td>
</tr>
<tr>
<td>Selection of the radiance standard</td>
<td>Source standard</td>
</tr>
<tr>
<td>Selection of the spectroradiometer</td>
<td>Selecting the fore optics</td>
</tr>
<tr>
<td>Selection of the system setup</td>
<td>See Subsection 3.C</td>
</tr>
<tr>
<td>Selection of the wavelength standard</td>
<td>Line irradiance or radiance</td>
</tr>
<tr>
<td>Separation from neighboring lines</td>
<td>0.1 nm/1 MHz</td>
</tr>
<tr>
<td>Number and distribution of lines</td>
<td>300, evenly spaced</td>
</tr>
<tr>
<td>Instrument assembly and preliminary checks</td>
<td>Establishing the optical axis</td>
</tr>
<tr>
<td>Setting up the fore optics</td>
<td></td>
</tr>
<tr>
<td>Checking the output signal</td>
<td></td>
</tr>
<tr>
<td>Checking the wavelength readout</td>
<td></td>
</tr>
<tr>
<td>Characterizing the spectroradiometer for all potential errors</td>
<td>Signal-to-noise ratio, noise-equivalent radiance, and dark current</td>
</tr>
<tr>
<td>Wavelength characterization</td>
<td></td>
</tr>
<tr>
<td>Nonlinearity characterization</td>
<td></td>
</tr>
<tr>
<td>Directional and positional characterization</td>
<td></td>
</tr>
<tr>
<td>Spectral scattering characterization</td>
<td></td>
</tr>
<tr>
<td>FOV</td>
<td></td>
</tr>
<tr>
<td>Polarization characterization</td>
<td></td>
</tr>
<tr>
<td>Size of source characterization</td>
<td></td>
</tr>
<tr>
<td>Temperature characterization</td>
<td></td>
</tr>
<tr>
<td>Selection and characterizing the measurement setup</td>
<td>Selection characterization</td>
</tr>
<tr>
<td>Selection of the measurement design</td>
<td>Design</td>
</tr>
<tr>
<td>Data acquisition and calculation of the quantity desired</td>
<td>Carrying out the measurements</td>
</tr>
<tr>
<td>Preparation of the uncertainty report</td>
<td>All sources of uncertainty</td>
</tr>
<tr>
<td>Error: Type A or Type B</td>
<td></td>
</tr>
<tr>
<td>Degrees of freedom</td>
<td></td>
</tr>
<tr>
<td>Combined uncertainty</td>
<td></td>
</tr>
<tr>
<td>Expanded uncertainty</td>
<td></td>
</tr>
<tr>
<td>Unidentified sources of uncertainty</td>
<td></td>
</tr>
</tbody>
</table>
The dye laser (Fig. 5). The refractive index of air is used, and the spectral sampling interval of the laser is set to 1 nm.

The dye laser used produces a directional and high-intensity (~100 times higher than that of the Sun) beam that has a narrow wavelength range. It is pumped by an argon-ion laser and provides a single-mode laser beam with a linewidth of ~1 MHz. The tunable wavelength range is 450–750 nm. The minimum data point increment is 1 MHz. The experimental setup is displayed in Fig. 1 (Type 2 setup). A preliminary analysis showed too much radiant power (e.g., 1 W) on the radiometer, so a power-reduction method that uses a polarizer–half-wave plate–polarizer combination had to be introduced (labeled Optical Elements in Fig. 1). In addition, the laser beam is split; one beam is focused onto a photomultiplier to read out intensity variations over time. The integration times of the radiometer and the photomultiplier are synchronized and used to normalize the intensity variations over time. Based on the center wavelength measurements, the calibration file of the spectroradiometer is updated by use of the new reference center wavelengths.

The initially estimated uncertainty of the center wavelength is <0.06%. The determination of the exact position is better than 0.05% and is used for the final uncertainty calculation. Because these measurements were performed only twice within a total period of 3 days, no information on the instability or drift of the wavelength calibration can be given over time. It must be noted that such a drift could significantly increase the uncertainty.

The spectral response function is measured with the same approach as described above. The only difference is that the responses of adjacent bands of the spectroradiometer are plotted against the laser emission line. The peak of the Gaussian function is determined by the new center wavelength:

$$R_{DN} = k_0 + k_1 \exp \left( -\frac{(\lambda_{GER} - \lambda_{laser})^2}{k_3} \right),$$  \hspace{1cm} (4)

where $R_{DN}$ is the normalized response of the spectroradiometer to the laser line $\lambda_{laser}$ (Fig. 6). We finally determine the FWHM by solving for $R_{DN} = 0.5$. The FWHM is then assigned for each spectral band (Fig. 7). The significant decrease in the FWHM in the two PbS detectors is possibly due to a slight tilting of the detectors against the gratings.

### Table 3. Corresponding NSR of SNR Measurements

<table>
<thead>
<tr>
<th>NSR versus Detector</th>
<th>Si Detector (%)</th>
<th>Detector PbS1 (%)</th>
<th>Detector PbS2 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average NSR at 2200 fl ($n = 38$)</td>
<td>±0.03</td>
<td>0.21</td>
<td>0.27</td>
</tr>
<tr>
<td>Average NSR at 200 fl ($n = 64$)</td>
<td>0.46</td>
<td>1.08</td>
<td>1.69</td>
</tr>
</tbody>
</table>

Fig. 1. Three types of measurement setup for the characterization process. The place holder is a black anodized aluminum holder that mechanically and optically fits the spectroradiometer tightly to the sphere’s exit port. Type 2 measurements were performed on the optical table of the tunable dye laser. Type 3 measurements were performed to measure the FOV. The illuminating source is the Sun (Type 3b) or tungsten halogen lamps (Type 3a).

Fig. 2. SNR determination with a 2200-fluminance setting corresponding to the upper radiances values expected in field measurements (e.g., Spectralon reflectance level as depicted in Fig. 8 below) and the measured standard deviation [see Eq. (1)].
Accurate determination of the center wavelength and the spectral resolution is an important task for a quantitative spectroradiometric analysis. Small deviations (within a few percent) of the center wavelength and the FWHM will significantly influence the overall calibration uncertainty.

F. Nonlinearity
Nonlinearities in spectroradiometers appear as systematic deviations from an expected linear response. To quantify this nonlinearity of an instrument it is necessary to verify that the calibration is performed at the same radiant power that is usually present in field measurements. Furthermore, it is desirable that the radiometer saturate only at radiance levels that are not to be expected in reflectance measurements. At low radiance levels what often appears to be a nonlinearity may only be the result of failure to apply the correct dark signal or offset correction. Here it is advantageous to design the instrument such that systematic and random noise remains below the lowest reflectance to be measured.

Inasmuch as most field instruments make use of a reflectance standard, 100% reflectance must be taken into account in calibration, even though typical reflectances will rarely exceed 60% reflectance. As a consequence, in the present design of field spectroradiometers much of the dynamic range of the instrument is seldom used (60–100% reflective targets; Fig. 8).

There are a number of measurement techniques available for determining the nonlinearity of a spectroradiometer. A powerful method for doing so is the use of a nonlinearity measurement by the superposition-of-sources method, with an integrating sphere as proposed by Sanders. In this method it is assumed that the radiometric system is linear and that the arithmetic sum of the individual signals measured at different radiance levels is equal to the radiance that would be found if all signals irradiated the radiometer at the same time. A linear system would follow the following equation:

$$K_{ab} = \frac{i_{a+b}}{i_a + i_b},$$

where $K_{ab}$ is the nonlinearity correction factor, $i_a$ and $i_b$ are the individual sources, and $i_{a+b}$ are the combined sources. Subsequently, the responsivity and the radiant power are given by

$$i_a = RL_a,$$
and for measurements at different radiances

\[ i_{(a+b)} = K_{ab}RL_{(a+b)}, \]

This process is repeated until the full dynamic range of the radiometer is covered.

Following the superposition-of-sources method, the expected radiance levels of the field measurements were estimated and plotted against integrating sphere radiance values. Based on these calculations, the dynamic range of the calibration can be established. The Spectralon typical radiance is modeled with the radiative transfer code MODTRAN, which provides with a horizontal visibility of 50 km at 2 m above the ground. The original radiance levels (luminance, >12,000 fl) provided by the NIST saturate the instrument in all bands. Therefore the NIST radience level in the integrating sphere is reduced to 2200 fl (maximum) and 200 fl (minimum). This reduction is based on the expected radience levels in field conditions (Fig. 8).

The linearity measurement is performed with the integrating sphere calibration standard, in which each sensitivity level is measured starting from zero in increments up to the saturation level and then back the same way down to zero.

In a next step, the nonlinearity correction factor \( K_{ab} \) is calculated, including the sensitivity correction. The baseline for calculating \( K_{ab} \) is based on the average of all measurements at a certain luminance (Fig. 9).

The major uncertainty in the superposition-of-sources method is introduced by the different sensitivity levels of the radiometer. A comparison of isolated sensitivity levels demonstrates much better linearity within the levels than does a summation of the individual levels. Nevertheless, the total linearity in the observed interval 200–2200 fl is <0.5%, but extrapolation to lower or higher values is not advisable because the nonlinearity cannot be measured without the risk of reaching the noise or saturation level of the spectroradiometer. The estimated uncertainty for the nonlinearity is ±0.5%, meaning that, if the nonlinearity exceeds 0.5%, the measurement equation must be modified for nonlinear behavior of the instrument. The calculated nonlinearity for the three detectors of the spectroradiometer is the result of 52 superpositions for each of the 704 bands. The resultant average nonlinearity is 0.20% for the Si detector, 0.39% for detector PbS1, and 0.44% for detector PbS2. Based on these nonlinearity values, the spectroradiometer is considered to be a linear measurement device.

G. Directional and Positional Effects

When an integrating sphere is used for characterization of the spectroradiometer, directional and positional effects can be neglected and are not measured here. Because of the spectroradiometer’s integrating capabilities, its responsivity correctly coupled to the sphere is invariant with direction and position, and therefore the contribution of these effects to its responsivity is estimated to be less than 0.5% (this corresponds to the estimated error given in Table 2 and therefore assumes a worst-case situation).

H. Spectral Scattering

The effects of spectral scattering occur if a measurement is taken at a specific wavelength \( \lambda \) with a band-pass of \( \lambda_{\text{FWHM}} \). Then some flux from outside \( \lambda_{\text{FWHM}} \) is scattered onto the slit and contributes to the total signal. Spectral scattering effects are significant only if there is a larger flux outside \( \lambda_{\text{FWHM}} \) relative to the one within \( \lambda_{\text{FWHM}} \). The estimation of scattered flux requires the use of filters. These filters must be designed to have a transmittance close to 0 at \( \lambda_{\text{FWHM}} \) and a high transmittance at the wavelengths of the scattered flux. Using a spectroradiometer with 704 bands would therefore require 704 specifically designed bandpass filters.

The spectral scattering sensitivity of the radiometer is not measured separately but is included in the determination of the FWHM by use of the tunable dye laser. The uncertainty introduced by the contribution of spectral scattering is initially estimated to be less than 0.5%. In most cases no tunable laser is available to cover the whole wavelength range of the spectroradiometer because of the limited tuning intervals of dye lasers. In this case complex double monochromators and deconvolution techniques must be used to assess spectral scattering.

I. Field of View

The FOV is determined by the position of the entrance aperture stop relative to the detector area that serves as the field stop. The FOV experiment is carried out in the laboratory with the GER3700 spectroradiometer mounted upon a tripod. Two 650-W quartz-tungsten halogen lamps are used to illuminate a Spectralon target. Assuming that the FOV of the instrument is perfectly round, eight point-symmetrical positions on the ground with the Spectralon panel on a black background are measured for three different altitudes. Using a continuously measuring mode (i.e., a real-time update of the instrument readout), we determined the line on the ground where the signal increases and the FOV of the instrument partially covers the Spectralon panel. The restrictions that apply for this experiment include the assumption that no adjacency effects exist and that...
no diffuse radiation (except the one from the panel) reaches the lens of the spectroradiometer. To measure different contrast types to verify the reproducibility, we carry out the same experiment but use red-and-yellow paper instead of the black-and-white setup. The total field of view is determined from

\[ \theta_f = 2\alpha = 2 \arctan \left( \frac{h - k_0}{hk_1} \right), \]  

where \( h \) is the measurement height (field stop to ground), \( k_0 \) are the fitting constants, and \( \theta_f \) is the FOV.

The uncertainty associated with the experimental determination of the total FOV is \( \pm 5\% \), owing to the Lambertian reflectance properties of the material used. But because in most experiments the integrating sphere calibration standard is used for the measurements, the error associated with the FOV is estimated to be smaller than 0.1%. The sphere illuminates the FOV homogeneously, and the error associated with the FOV is due to possible misalignments and not to the exact determination of the solid angle covered by the FOV.

J. Polarization

The total process of polarization in remote sensing is difficult to quantify because depolarization effects do not allow for a deterministic description of the polarization source. The characterization of the spectral radiance relative to its polarization state is made with Stokes vector \( \mathbf{S} \) and Mueller matrix \( \mathbf{M} \) to describe the polarization-altering characteristics of the sample. Solving the transformed Stokes vector for an unpolarized source passing through an ideal polarizer results in

\[
\mathbf{S}' = \frac{1}{2} \begin{bmatrix} s_0 \\ s_0 \cos 2\phi \\ s_0 \sin 2\phi \\ 0 \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 \\ \cos 2\phi \\ \sin 2\phi \\ 0 \end{bmatrix},
\]

where \( \phi \) is the angle between the polarization axis of the polarizer and the horizontal direction. Based on Mueller matrix \( \mathbf{M} \), the polarization sensitivity \( D(M) \) can be derived, as well as the polarization dependent loss \( \text{PDL}(M) \):

\[
D(M) = \frac{(m_{01}^2 + m_{02}^2)^{1/2}}{m_{00}},
\]

\[
\text{PDL}(M) = 10 \log \frac{m_{00} + (m_{01}^2 + m_{02}^2 + m_{03}^2)^{1/2}}{m_{00} - (m_{01}^2 + m_{02}^2 + m_{03}^2)^{1/2}}.
\]

The polarization measurement setup includes the assumption of an ideal linear polarizer that is linked between the unpolarized spectral radiance source and the unknown polarization-sensitive spectroradiometer. This source is an integrating sphere that completely depolarizes the incident flux, and the sphere’s transmittance is independent of the incident radiation. In most cases it is sufficient to perform a calibration on three rotational positions of the instrument or its polarization-sensitive components. Because in the experiment the radiant source is assumed to be of complete uniformity, it is sufficient to measure some rotation states of the polarizer (i.e. 0°, 45°, and 90°) and not necessary to rotate either the source or the detector. In total, we included 72 measurements at rotations intermediate between the two orthogonal measurements to test whether the maximum and minimum polarization sensitivities had been sampled.

Measuring the three rotational positions of the polarizer yields the following two equations with which \( s_1 \) and \( s_2 \) of the Stokes vector can be determined:

\[
R = 1/2 L_0 (1 + s_1 \cos 2\phi + s_2 \sin 2\phi) R \Delta \lambda \Delta \Theta, \quad (12)
\]

\[
R_{45}s_1 - R_{50}s_2 = R_0 - R_{45},
\]

\[
R_{45}s_1 + R_{50}s_2 = R_{45} - R_{90}, \quad (13)
\]

where \( \Delta \Theta \) is the throughput and \( R \) is the resultant output signal at rotational positions. The experimental determination of \( s_3 \) relies on the use of a quarter-wave plate. Methodically following the presented procedure to derive \( s_1 \) and \( s_2 \) yields

\[
S' = 1/2 L_0 [1 + s_1 \cos 2\phi + s_3 \sin 2\phi], \quad (14)
\]

and the final equation for \( s_3 \) can be given as

\[
s_3 = \frac{R_0 - R_{45}}{R_0 + R_{45}}. \quad (15)
\]

After the successful determination of the Stokes values, Mueller matrix elements \( m_i \) can be defined. The following Mueller matrix for the spectroradiometer is used:

\[
m = \begin{bmatrix} 1 & m_{01} & m_{02} & m_{03} \\ \vdots & \vdots & \vdots & \vdots \\ m_{01} & m_{02} & m_{03} & \vdots \\ \vdots & \vdots & \vdots & \vdots \end{bmatrix}, \quad (16)
\]

where the output signal is

\[
R = 1/2 L_0 (1 + m_{01} \cos 2\phi + m_{02} \sin 2\phi) R \Delta \lambda \Delta \Theta \quad (17)
\]

and therefore

\[
\frac{R_0}{R_{45}} = \frac{1 + m_{01}}{1 + m_{02}}, \quad (18)
\]

\[
\frac{R_{45}}{R_{90}} = \frac{1 + m_{02}}{1 - m_{01}}, \quad (19)
\]

\[
m_{03} = \frac{R_{45} - R_0}{R_0 + R_{45}}. \quad (20)
\]
The final estimation of the polarization effect that is present in spectral measurements is given by the following formula:

\[
P_{\text{corr}} = \frac{1 + s_1^s m_{01} + s_2^s m_{02} + s_3^s m_{03}}{1 + s_1 m_{01} + s_2 m_{02} + s_3 m_{03}},
\]

where \(P_{\text{corr}}\) is the wavelength-dependent polarization correction, \(s_i^s\) is the Stokes vector of the standard, \(s_i\) is the Stokes vector of the polarizer, and \(m_{ij}\) is the Mueller matrix of the radiometer. In the optimal case, three different measurement procedures are required for complete determination of the polarization sensitivity of the radiometer. The instruments needed for the measurements are a stabilized radiometer and an integrating sphere. The experimental measurement setup places the polarizer after the integrating sphere, the setup is designed to determine the Stokes vector of the polarizer (\(s_1, s_2\)). With the polarizer placed after the integrating sphere, the setup is suited for determining the elements \((n_{01}, m_{01})\) of the Mueller matrix of the radiometer. In addition, by use of a quarter-wave plate, the determination of all the elements of the Mueller matrix \((m_{ij})\) is possible. The parameters \(D(M)\) and PDL(\(M\)) can be plotted in the wavelength range 400–900 nm. (The transmittance of the polarizer is nearly 100% above 900 nm; Fig. 10). The correction factor PDL(\(M\)) is not applied to every measurement but is included as a systematic error. The estimated polarization sensitivity is \(\pm 2\%\). The resultant polarization-dependent loss of the spectroradiometric signal is \(< 0.4\%\).

K. Size-of-Source Effect

The size-of-source effect is not determined here because the measured source is never much smaller in size than the imaged area. The errors from this effect are normally in the range of \((0.005–0.5\%)\), and this error arises mostly in field measurements for which spatial inhomogeneity at a sub-FOV level can be expected.

L. Temperature

The special requirements for a field-portable spectroradiometer often do not permit the integration of a cooling system because of space and power-consumption constraints. Because of a lack of information on athermalization efforts inside the spectroradiometer, it is assumed that the thermal effects within the housing of the radiometer are homogenous. Additionally, it is assumed that the changes in defocusing are negligible compared with the effects on changing detectivity of the detector (\(D^*\)). The established temperature model assumes an exponential change of the input signal with any change of environment temperature:

\[
R_{\text{DN},T_{\text{PbS}}} = k_0 + k_1 \exp(-k_2 k_3),
\]

where \(R_{\text{DN},T_{\text{PbS}}}\) is the temperature-dependent detector signal and \(k_n\) are the fit parameters, where \(k_3 = T_{\text{PbS}}\) is the temperature of the spectroradiometer and \(k_3 = T_{\text{PbS}}\) is the temperature of the PbS detector range. The expected interval in this experiment ranges from approximately 22 to 55 °C. An assumption is that there is no heat dissipation from the sphere to the radiometer because a thermal decoupler has been added between sphere and radiometer. The temperature-stabilized environment (at 22 °C) of the calibration chamber is used as a reference. To ensure that all instruments will have the same temperature initially we store the measurement equipment in the chamber for 24 h before the measurements are made. Absolute radiance measurements in the PbS1 and PbS2 detectors range must be calibrated for temperature drifts. The temperature-related effect affects all wavelengths from 987 to 2500 nm (Fig. 11). As a consequence, for field reflectance measurements it is important to minimize the time between reference and target measurement. Otherwise the temperature-induced effects will dominate possible changes in the target.

![Fig. 10. Polarization sensitivity \(D(M)\) scaled on the left axis from 1.5% to 6.5% in the observed region. The polarization-dependent loss (scaled on the right axis) does not exceed 0.5% for this measurement setup.](image1)

![Fig. 11. Three temperature-dependent models of detector PbS1.](image2)
reflectivity. The temperature uncertainty introduced by the different detectors is calculated with the temperature-fitting model for each spectroradiometer band. Because the Si detector is not temperature sensitive, the resultant Si temperature sensitivity is measured to be below <0.1%. The PbS detectors in the temperature range of laboratory measurements exhibit an uncertainty of <1%.

4. Calibration Uncertainty Estimation

Each measurement performed in this calibration was finally assigned a measure for uncertainty that expresses the significance of the measurement. Type A evaluation of the standard uncertainty was applied to the observations by standard statistical methods. Type B evaluation of the standard uncertainty was applied to measurements by non-statistical analyses (e.g., experience, specifications, data from calibration reports).18,19

The combined standard uncertainty of a measurement result \( u_c \) represents the standard deviation of the result. With root sum squares, we can express \( u_c \) as the standard uncertainty of measurement result \( y \):

\[
u_c^2(y) = \sum_{i=1}^{N} \left( \frac{\partial f}{\partial x_i} \right)^2 u_i^2 + 2 \sum_{i=1}^{N} \sum_{j=i+1}^{N} \frac{\partial f}{\partial x_i} \frac{\partial f}{\partial x_j} u_i u_j (x_i, x_j),
\]

(23)

where \( u_i^2(y) \) represents the combined variance, \( u_i(y) \) is the estimated variance, \( \partial f/\partial x_i \) are partial derivatives (sensitivity coefficients), and \( u(x_i, x_j) \) is the estimated covariance. Then the expanded uncertainty \( U \) is defined as

\[
U = k u_c(y),
\]

(24)

with \( y - U \leq Y \leq y + U \), so

\[
Y = y \pm U,
\]

(25)

where \( k \) is the coverage factor, \( y \) is the measurement result, and \( Y \) is the measurand. The coverage factor is in general chosen on the basis of the desired level of confidence. Typically it is in the range \( 2 \pm 0.3 \) (normal distribution; level of confidence, ~95%) for spectroradiometric measurements. Nonstatistical behaviors of some quantities are modeled by use of a rectangular probability distribution:

\[
u_c(y) = \frac{y_{\text{max}} - y_{\text{min}}}{2\sqrt{3}},
\]

(26)

where \( y_{\text{max}} \) and \( y_{\text{min}} \) are the upper and lower limits, respectively, of the measurement. The degrees of freedom from Type A evaluation in this calibration are estimated from

\[
v_i = n - m,
\]

(27)

where \( v_i \) is the degree of freedom from \( u_i(y) \) (component of the combined standard uncertainty generated by the standard uncertainty), \( n \) are the data points measured, and \( m \) are the parameters estimated by fitting a curve to \( n \) points. The evaluation for Type

Table 5. Expanded Uncertainty of the GER3700 Spectroradiometer Laboratory Calibration

<table>
<thead>
<tr>
<th>Detector</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>( Y = y \pm 5.93 )</td>
</tr>
<tr>
<td>PbS1</td>
<td>( Y = y \pm 6.58 )</td>
</tr>
<tr>
<td>PbS2</td>
<td>( Y = y \pm 7.09 )</td>
</tr>
</tbody>
</table>
sources \((Y = y \pm 7.63\%\)) the calibrated expanded uncertainty is better for all spectroradiometer bands than that in the calibration design \((\pm 10\%\)) or in the assumptions made in the measurement plan.

6. Calibration of Absolute Radiance

In the final step, DN’s are converted into radiances by use of an inverse calibration to express the calibration coefficients:

\[
L_{\lambda} = C_{\text{gain}} \cdot R_{\text{DN}} + C_{\text{offset}} \lambda,
\]

where \(L_{\lambda}\) is the calibrated at-sensor radiance, \(C_{\text{gain}}\) is the calibration gain, \(R_{\text{DN}}\) is the measured value, and \(C_{\text{offset}}\) is the calibration offset \((C_{\text{offset}} = R_{\text{dark}} C_{\text{gain}})\). The calibration can also be applied to reflectance data, which will result in the same types of uncertainty being applied to measurement points (Fig. 13).

7. Discussion and Conclusions

A radiance-based laboratory calibration with the final goal of measuring absolute radiance values with an associated uncertainty of \(\pm 10\%\) has been demonstrated. The measurement plan presented covers more experimental details than are actually relevant in a laboratory environment (e.g., the calibration procedures discussed in Subsections 3.G and 3.H are not used in a laboratory environment), but they are included to render the plan usable also for reflectance-based calibration of a similar instrument.

It is inappropriate to define a set of calibration parameters only once in the lifetime of a spectroradiometer. As a consequence, the contributions of scientists will likely always be required for calibration of these kinds of instrument. The discussion of calibration effort relative to calibration accuracy can be resolved satisfactorily only if the figures of merit for a calibration are normalized such that they permit a transparent comparison with other instruments. In addition, determining the extent of the calibration effort requires predictable accuracies. The required calibration accuracy helps in estimating the calibration effort needed and can also be helpful in defining the required recalibration frequency. Any spectroradiometric measurement device tends to drift (or degrade) over time. These drifts generally introduce a higher uncertainty over time, and therefore the overall calibration accuracy might suffer from inappropriate recalibration intervals. A calibration procedure aiming for a \(\pm 10\%\) radiance calibration uncertainty is much more expensive and requires the use of laboratory standards whose overall instrumentation costs in many cases are too great to be supported and maintained. The required calibration accuracy also has an additional effect on the recalibration frequency. Permanent monitoring of possible drifts of calibration parameters is necessary to permit their extrapolation from the laboratory to the operating environment. Many requirements can be relaxed if one aims at a \(\pm 10\%\) radiance calibration accuracy rather than at a \(\pm 1\%\) calibration target. Given the example of the temperature dependency of the PbS detectors, we have not investigated whether the temperature difference also causes a shift of the center wavelengths inside the instrument, which thereby would require simultaneous calibration of the temperature dependence of the signal and center wavelengths. Such a complex characterization procedure is definitely required if the calibration accuracy must be of the order of 1% or less. It also never suffices to calibrate an instrument in the laboratory for the laboratory’s environment temperature and to operate the instrument at different pressure and temperature, hoping to extrapolate the calibration parameters accordingly. It is therefore a promising approach to define the associated uncertainties and pass these measurements on to the next modeling step with a defined level of confidence. But before more-elaborate laboratory setups for the proper measurement of all related factors are discussed, the largest sources of uncertainty, the traceability and reliability of the radiometric calibration standard, must be addressed first. Unfortunately, the importance of solid calibration procedures for ground spectroradiometric equipment has been underestimated in remote-sensing applications so far.

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Fig. 12. Calibration gain and calibration offset for all 704 GER3700 spectroradiometer bands.

Fig. 13. Reflectance-calibrated data displaying the uncertainty change at 2200 nm of the NIST-calibrated reflectance spectrum.
References