

Sensitivity of Spectroradiometric Calibrations in the Near Infrared to Variations in Atmospheric Water Vapor

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SENSITIVITY OF SPECTRORADIOMETRIC CALIBRATIONS IN THE NEAR INFRARED TO VARIATIONS IN ATMOSPHERIC WATER VAPOR

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ABSTRACT

Spectra of natural sunlight and artificial sources are important in photovoltaic research. Calibration of the spectroradiometers used for these measurements is derived from the response to spectral irradiance standards from the National Institute of Standards and Technology (NIST). Some photovoltaic devices respond in the near infrared, or NIR, so spectral measurements and calibrations are needed in this region. Over the course of several calibrations, we identified variations $> 5\%$ in spectroradiometer NIR calibration data for a certain spectroradiometer. Reviewing calibration procedures and historical data, we noted that the variations were seen in water vapor absorption bands. We used spectral transmission models to compute changes in atmospheric transmission (as a function of water vapor content) over path lengths occurring during calibration. The results indicate that the observed variations result from varying water vapor content. A correction algorithm for adjusting measured data was developed based on our analysis.

1.0 INTRODUCTION

1.1 Devices and Sources in the Near Infrared

The spectral response of PV devices continues to migrate into the near-infrared (NIR) region of wavelengths > 1000 nm (1). Figure 1 shows representative spectral response functions for some PV technologies. Figure 2 shows natural (thin black line) and simulated (large area continuous Solar Simulator- (thick gray line) spectral distributions.

The absorption bands between 1300 nm and 1500 nm and 1800 nm to 1900 nm in the natural sunlight spectrum are due to absorption by water vapor in the atmosphere. The depths of these features vary only slightly with the

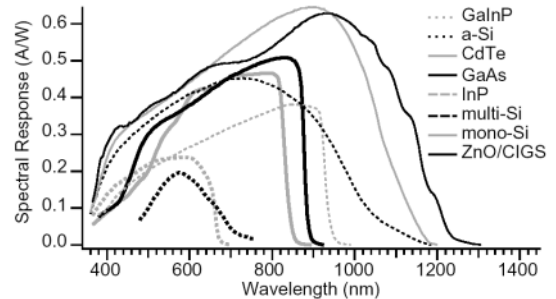


Fig. 1: Representative spectral response functions for eight PV technologies, three of which respond at wavelengths > 1000 nm.

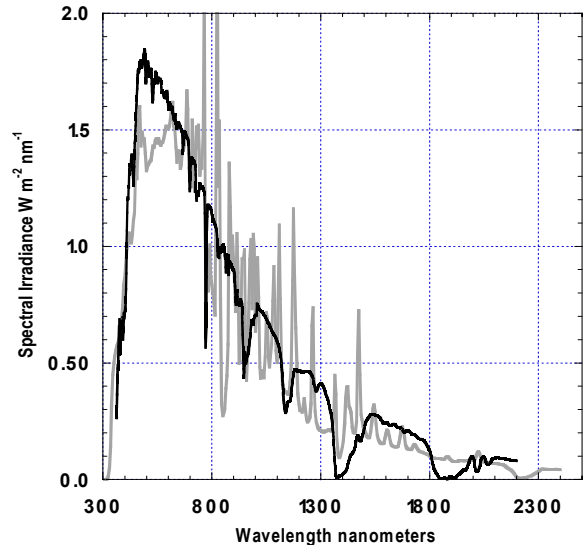


Fig. 2: Natural sunlight (thin black line) and Solar Simulator (thick gray line) spectral distributions.

amount of water vapor. This means the bands always absorb strongly. The depth of the 820 nm absorption band increases as the water vapor content of the atmosphere increases, and the depth of this band can be used to estimate the water vapor content of the atmosphere. The natural sunlight spectrum is representative of absorption over the entire path length from the top of the atmosphere to the ground. Our investigations address the issue of absorption over shorter path lengths in the calibration laboratory.

2.0 SPECTRAL STANDARDS AND CALIBRATIONS

Calibrations of spectroradiometers are the response of the system (input optic, monochromator, detector) to a known spectral distribution of a calibrated source (2). Spectral irradiance lamp standards are available from national standardizing laboratories, or from third parties transferring calibrations from reference to production lamps. There is additional uncertainty in third party lamps, due to uncertainties in the transfer process. Figure 3 shows a typical spectroradiometer calibration setup.

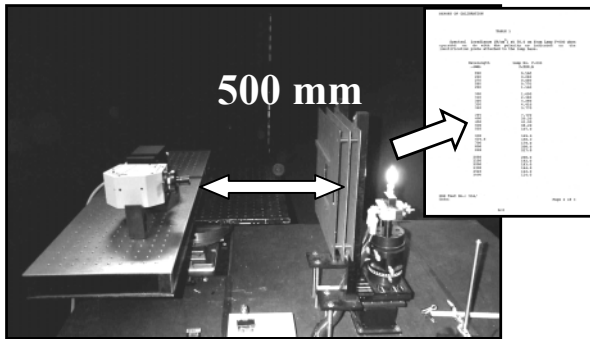


Fig. 3: Spectroradiometer (left) with NIST Spectral Irradiance Standard Lamp (right) and NIST tabulated spectral irradiance at 35 wavelengths (inset). Note the specified calibration distance is 500 mm.

For each standard lamp, NIST gives 35 data points that "skip over" the water vapor bands at 720, 820, 940, 1120, 1300 to 1500, and 1800 to 1950 nm as in figure 4.

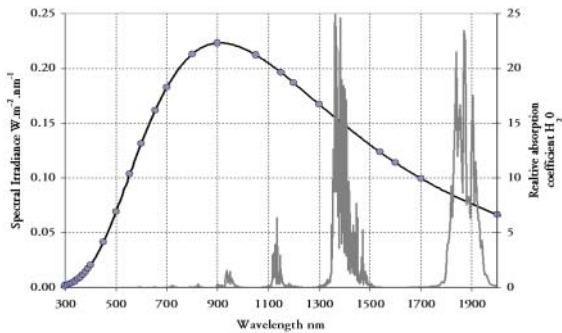


Fig. 4: NIST standard lamp data (points), interpolated data (black line), and (spiked gray line) spectral absorption coefficient of water vapor.

The result of a spectroradiometer calibration is the detector response $R(\lambda)$ as a function of wavelength, λ . The response is defined as the ratio of a known radiant flux (from the standard lamp) $E(\lambda)$ to the detector signal $S(\lambda)$ at each wavelength; or $R(\lambda) = E(\lambda)/S(\lambda)$. When a measurement is made, the unknown irradiance, $I(\lambda)$, is the product of the signal from the unknown source, $U(\lambda)$, multiplied by the response function: $I(\lambda) = U(\lambda) * R(\lambda)$. Figure 5 is a plot of the response functions for three calibrations each of two NREL spectroradiometers in the region from 1000 to 2000 nm where water vapor absorption is strong, along with the water vapor absorption bands of interest.

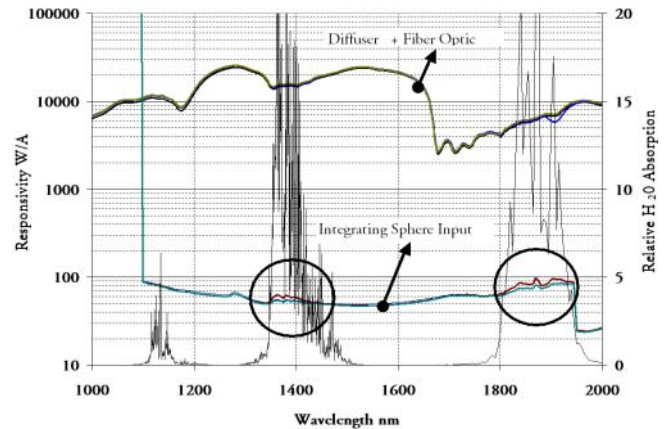


Fig. 5: Three response functions for a diffuser + fiber optic receiver system (top curves) and three response functions for integrating sphere receiver (lower curves) with water vapor spectral absorption curve (spiked light gray line).

3.0 WATER VAPOR AND RESPONSE FUNCTIONS

In figure 5, the upper curves are for a spectroradiometer system with a diffuser and fiber optic input system. The lower curves are for a system with an integrating sphere input optic. Relative humidity in the laboratory where each of the responsivity functions were generated was 22%, 23%, and 44%, for the Diffuser system, and 22%, 26%, and 41% for the sphere system.

Changes in the response function for the integrating sphere receiver system, (circled), are more apparent than in the diffuser-fiber optic system.

All calibration files depicted above pertain to the same NIST lamp, power supply, and monitoring equipment, over a period of 18 months. It is apparent that the changes seen are inherent in the spectroradiometer system with the integrating sphere input.

Possible explanations for the variable response seen in the integrating sphere system are: a) the sphere coating absorbs water vapor; b) the path length from the lamp to the input slit of the monochromator for the sphere system is much greater, due to multiple reflections from the sphere walls before photons reach the sphere exit (monochromator entrance) port, or (c) some other component of the monochromator system is hygroscopic.

Option (c) is rejected since replacing the sphere input optic with the diffuser/fiber optic input, variations in the response function in the water vapor absorption region are nearly negligible. Option (a) is not viable since the sphere coating is spectrolon, an inert compound (polytetrafluorethylene) that is not hygroscopic. Thus, option (b) is the only remaining alternative.

This led us to investigate the observed variations due to water vapor absorption over path lengths expected in the laboratory. If the variations seen in the calibration files are the result of variations in the water vapor content of the atmosphere in the laboratory, there will be errors in measurements made under different atmospheric conditions. We explored the relationship between water vapor absorption and path length using complex and simple atmospheric spectral transmission models.

4.0 SPECTRAL MODELING

A "moderate resolution transmission" code, MODTRAN, developed by Air Force Geophysical Laboratory (AFGL) is a complex, rigorous radiative transfer model written in FORTRAN (3-5). AFGL has licensed MODTRAN through the Ontar Corporation (<http://www.ontar.com>). MODTRAN (ver. 4) code evolved over 30 years, and consists of about 52,000 lines of source code. The model uses a "band model" implementation of the HITRAN absorption line database (6-8).

HITRAN contains over 1 million spectral absorption lines for 38 gaseous constituents of the earth's atmosphere, along with 27 additional molecules for which only absorption cross sections are given. HITRAN is considered an international standard database for atmospheric molecular spectroscopy. HITRAN contains 23,406 water vapor absorption lines between 1000 nm and 2000 nm, as seen in figures 4 and 5.

The MODTRAN band models are computationally efficient "transmission function" approximations that produce an "equivalent absorption" over the radiative transfer passband. The highest effective resolution in MODTRAN is quoted as 2.0 cm^{-1} . This is a resolution of approximately 0.2 nm and 0.8 nm, at 1000 nm and 2000 nm, respectively. We used MODTRAN 4.0 to look at the relative changes in calibration lamp spectral intensity by

changing water vapor content by a factor of two over a path length of 1.0 meter.

The area of an integrating sphere of radius 8 cm is 804 cm^2 . For an exit port area of 4.9 cm^2 , we estimate the number of reflections before a ray exits the port to be 164, the ratio of the total area to the exit port area. Using the radius of the sphere as the average path length of a reflection, the equivalent path length is 1.312 m. Ray tracing software would be a way to verify this estimate. An example of ray tracing software results in figure 6 shows how 19 rays propagate "through" a sphere. With these assumptions, we set 1.0 meter as the path length in our MODTRAN model runs. Coincidentally, 1 m (0.001 km) is the minimum path length MODTRAN accepts.

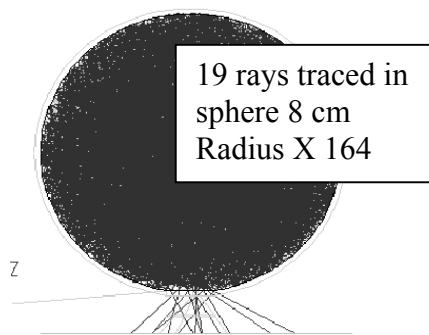


Fig. 6: Ray tracing software example for 19 rays (entering from bottom) propagating in a sphere.

4.1 MODTRAN Model

Input parameters for our MODTRAN model runs were for a horizontal path of 1.0 m at the altitude of 1800 m (1.8 km) above sea level (ASL). We used the 1976 United States Standard Atmosphere (USSA) with 330 ppm (parts per million) carbon dioxide loading (9). All other transmission parameters were automatically computed for the selected profile. The only parameter changed from run to run was the water vapor content. MODTRAN requires and input of equivalent atm-cm of water vapor. We used values of 1.5 atm-cm and 3.0 atm-cm of water vapor to study the effect of doubling water vapor content.

At the 1.8 km altitude of our laboratory, these values are approximately the equivalent to relative humidity of 30% and 60%, respectively (10). MODTRAN runs were executed to produce the water vapor transmission data for 800 nm to 2000 nm for each of the two water vapor conditions over the 1-meter path length.

The resulting water vapor transmissions were then multiplied by the NIST spectral irradiance standard lamp curve, and the difference between the two resulting lamp spectra was computed. Figure 7 is a plot of the absolute

difference, in $\text{Watt m}^{-2} \text{ nm}^{-1}$ between the 30% and 60% relative humidity cases. Note that the noise level of the spectrometer, when a dark scan is performed, is $2\text{-microwatt m}^{-2} \text{ nm}^{-1}$.

These MODTRAN results show that, indeed, a doubling of the water vapor content in the laboratory can produce differences in absolute spectral irradiance that are two orders of magnitude above the noise equivalent power for the spectroradiometer system.

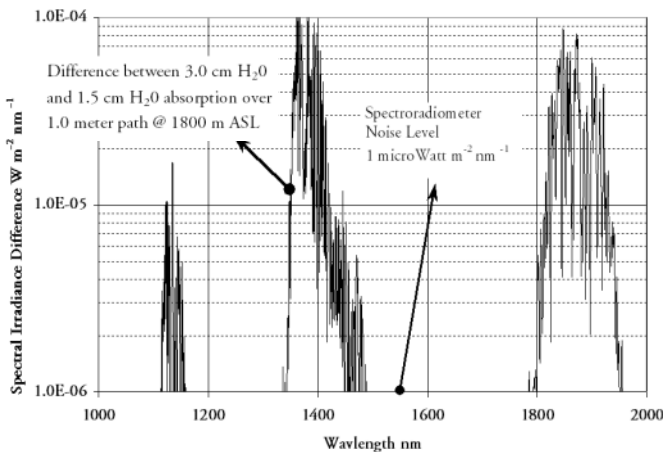


Fig. 7: Absolute difference in spectral irradiance for NIST lamp with a factor of two change in water vapor content over a path length of 1.0 m at 1.8 km ASL.

4. 2 SMARTS Spectral Model

SMARTS, (Spectral Model for Atmospheric Transmission of Sunshine) is based on parameterizations of the different extinction processes in the atmosphere (11). The effective spectral resolution at each computed point is 5 nm in the NIR water vapor bands of interest. SMARTS incorporates ten widely used “reference” atmospheric profiles, including the 1976 USSA. The model accounts for Rayleigh, ozone, nitrogen dioxide, uniformly mixed gases, water vapor, and aerosol extinction properties, using individual parameterizations of MODTRAN components, or derived from analysis of multiple MODTRAN model results. Thus, SMARTS2 may be viewed as a “simplified” or “parameterized” MODTRAN model.

We wished to see if SMARTS was accurate enough to reproduce the MODTRAN results presented above. While SMARTS can produce water vapor transmission directly as an output (among 24 other spectral parameters) for each model run, the only way to examine the variation in transmission with path length is to perform two model runs at different altitudes and compute the effective transmittance as the ratio of the two irradiance files.

We computed the SMARTS direct normal spectral irradiance at our laboratory altitude of 1.800 km and at 1.801 km, using water vapor of 1.5 atm-cm and 3.0 atm-cm, the USSA atmosphere, and an air mass of 1.0. All other atmospheric parameters unchanged between runs. The ratio of the irradiance at the lower altitude to the irradiance at the (1 meter) higher altitude should be the effective transmittance of the 1 meter path length with water vapor concentration equivalent to 30% and 60% RH, respectively. Figure 8 is a plot of the SMARTS water vapor transmission (black line) over 1.0 m at 60% RH compared with the MODTRAN direct computation of water vapor transmission over the 1.0 meter path (gray line). Similar results were obtained for the 1.5 atm-cm (30% RH) case.

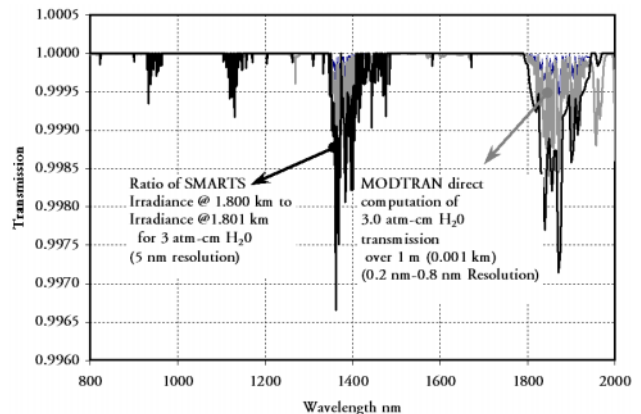


Fig. 8: Comparison of SMARTS (black line) and MODTRAN (gray line) derived water vapor transmission for 1.0 meter path length at 60% RH.

Differences between the SMARTS and MODTRAN results are primarily due to the difference in spectral resolution of the two models. The SMARTS model indicates the same relative sensitivity to changing water vapor as the MODTRAN results above.

5.0 CORRECTING SPECTRAL DATA

Multiple MODTRAN or SMARTS model runs at water vapor concentrations of 0.5, 1.0, 2.0, and 3.0 atm-cm of water, roughly equivalent to relative humidity levels of 10%, 20%, 40% and 60% at the NREL laboratory altitude of 1.8 km provide data to show transmittance of the water vapor as a function of relative humidity at several wavelengths. Figure 9 shows the relationship between transmission and water vapor derived in this way for wavelengths of 1361, 1382, and 1829 nm.

The correlation with water vapor content varies considerably from wavelength to wavelength and, therefore, across absorption bands. However, inspection of figure 7 shows that between about 1350 nm and 1380

nm, adding a "linear" correction to measured data would reduce the error in data measured at 60% RH, when calibration was performed at 30% RH. Similarly, in the region from 1800 nm to 1950 nm, a "parabolic" correction function would appear to reduce the error in spectral data measured at 60% RH for calibrations at 30% RH.

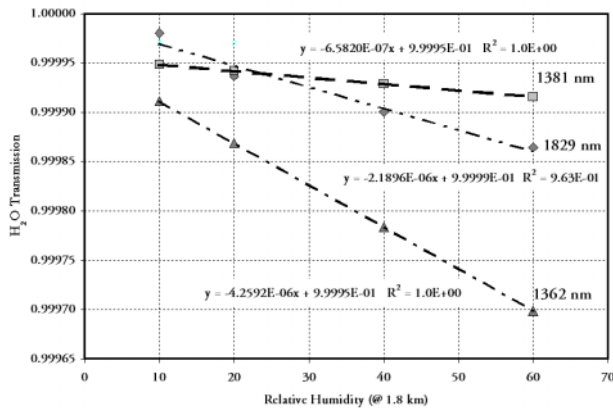


Fig. 9: Relationship between water vapor absorption at 3 wavelengths with respect to varying relative humidity.

We derived linear and parabolic fits to the coefficients for the correlations of water vapor transmittance shown in figure 9. Resulting correction functions, $T_i(\lambda)$, become:

For $1360 \text{ nm} < \lambda < 1380 \text{ nm}$;

$$M_1(\lambda) = 2.00056 \cdot 10^{-07} \cdot \lambda - 2.76735 \cdot 10^{-04}$$

$$\text{and } T_1(\lambda) = M_1(\lambda) \cdot \text{RH} + 1.0.$$

For $1800 \text{ nm} < \lambda < 1900 \text{ nm}$;

$$M_2(\lambda) = 8.7584 \cdot 10^{-10} \cdot \lambda^2 - 3.24061 \cdot 10^{-6} \cdot \lambda + 2.9954 \cdot 10^{-03}$$

$$\text{and } T_2(\lambda) = M_2(\lambda) \cdot \text{RH} + 1.0.$$

Measured irradiance $E(\lambda)$ can be modified to a corrected irradiance, $E_c(\lambda)$, by computing

$$E_c(\lambda) = E(\lambda) + (1 - T_i(\lambda)) \cdot E(\lambda).$$

Applying these corrections to a calibration file to correct to "zero" RH (or water vapor), the user would use the same algorithms to correct measured data taken at an arbitrary water vapor content (RH) to the equivalent with "no" water vapor. For outdoor measurements of natural solar radiation with an "RH=0" corrected calibration file, the measured irradiance in the water vapor bands will be more representative of the true irradiance.

6.0 SUMMARY

We quantitatively correlated the variation in calibration response functions for spectroradiometer systems with

integrating sphere input optics with the differences in the water vapor content of the atmosphere. MODTRAN and SMARTS spectral radiative transfer models are in reasonable agreement on the relative changes in atmospheric transmission over path lengths as short as 1 meter. These models can be used to produce data for developing correction functions to reduce errors in measurements under varying water vapor concentrations.

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