WAVELENGTH CALIBRATION METHOD FOR SPECTRORADIOMETERS WITH PICOMETER UNCERTAINTIES

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Abstract

Accurate wavelength calibration of array spectroradiometers is critical to many applications. We developed a new method for calibration of array spectroradiometers' wavelength scales using a wavelength-tunable kilohertz-pulsed optical parametric oscillator (OPO) laser and achieved a wavelength uncertainty on the level of picometers; a reduction of approximately two orders of magnitude compared to those using traditional methods. This high-accuracy wavelength calibration method can also be used to determine a spectroradiometer's pixel-to-pixel wavelength interval with an uncertainty of a few picometers, which is the key to achieving small uncertainties when a detector-based method is used for spectral calibration of array spectroradiometers using tunable lasers. Using this calibration method can also significantly reduce the overall measurement uncertainties in various applications.

Keywords: Wavelength Calibration, Pixel-to-Pixel Wavelength Interval, Spectroradiometer, Spectrometer, Spectrophotometer.

1 Introduction

Accurate wavelength calibration of array spectroradiometers is critical to many applications. For example, when measuring optical radiation of a light source using a spectroradiometer, a small wavelength error can result in a large spectral measurement error in the spectral region where the spectrum of the light source (e.g. a colour LED source) rises or falls sharply, or where the spectral responsivity of the spectroradiometer changes rapidly. An array spectroradiometer is typically calibrated for its wavelength scale by measuring a limited number (e.g. 10) of narrow spectral emission lines with known wavelengths and then determining the wavelengths for the corresponding pixels near the calibrated wavelengths. The wavelengths of the rest of the pixels, a majority, are obtained through interpolations, extrapolations, or curve-fitting based on the calibrated pixels. Using this conventional calibration approach, the wavelength uncertainty across the entire spectral range is limited from less than a nanometer (for metrology-grade spectroradiometers) to a few nanometers (for low cost spectroradiometers). In order to reduce the wavelength uncertainty, a much larger number of spectral lines is required for the wavelength calibration. Therefore, Fabry–Perot etalons and Lyot filters were proposed to be used for wavelength calibrations [Blattner et al. 2014] [Perret et al. 2010], both of which produce multiple transmission maxima over the spectroradiometer's spectral range. However, such devices are not readily available. Also, their transmission maxima are typically broad, which limits the wavelength calibration uncertainty.

2 New method for wavelength calibration

In this paper, we describe a new approach for calibration of spectroradiometers' wavelength scales that uses a fully-automated, kilohertz-pulsed optical parametric oscillator (OPO) laser. The OPO laser is tunable for wavelength from 210 nm to 2400 nm with a narrow bandwidth (*e.g.*, 0.08 nm at 350 nm, 0.14 nm at 600 nm, and 0.48 nm at 1100 nm), and it has been used at NIST for correction of stray light of spectroradiometers [Zong et al. 2006], and the calibration of detectors and spectroradiometers [Zong et al. 2012] [Zong et al. 2014]. The setup for the wavelength calibration is shown in Figure 1. A metrology-grade 1024-pixel CCD-array spectroradiometer with a fiber optic irradiance probe was calibrated for its wavelength scale using the OPO laser system. The spectral range of the spectroradiometer is from 300 nm to 1100 nm with a bandpass of approximately 2.5 nm. The OPO laser was tuned across the entire spectral range of the spectroradiometer with a wavelength step of 5 nm. The wavelength of the OPO laser was measured by both the spectroradiometer (with specified wavelength accuracy of ±0.3 nm) and a high-accuracy laser spectrum analyzer (with specified wavelength accuracy of 3 pm at 350 nm wavelength, 7 pm at 600 nm, and 24 pm at 1100 nm). The spectral resolution ($\lambda/\Delta\lambda$) of the laser spectrum analyzer is 2×10^4, corresponding to a bandpass of 0.0175 nm at 350 nm, 0.03 nm at 600 nm, or 0.055 nm at 1100 nm which is much narrower than the bandwidth of the OPO laser. The software provided by the spectroradiometer's manufacturer and that provided by the laser spectrum analyzer's manufacturer were used for this calibration. The measured values from both instruments were peak wavelengths. The total number of measured laser lines was approximately 160. Because the wavelength calibration was fully automated, the total measurement time was less than one hour.

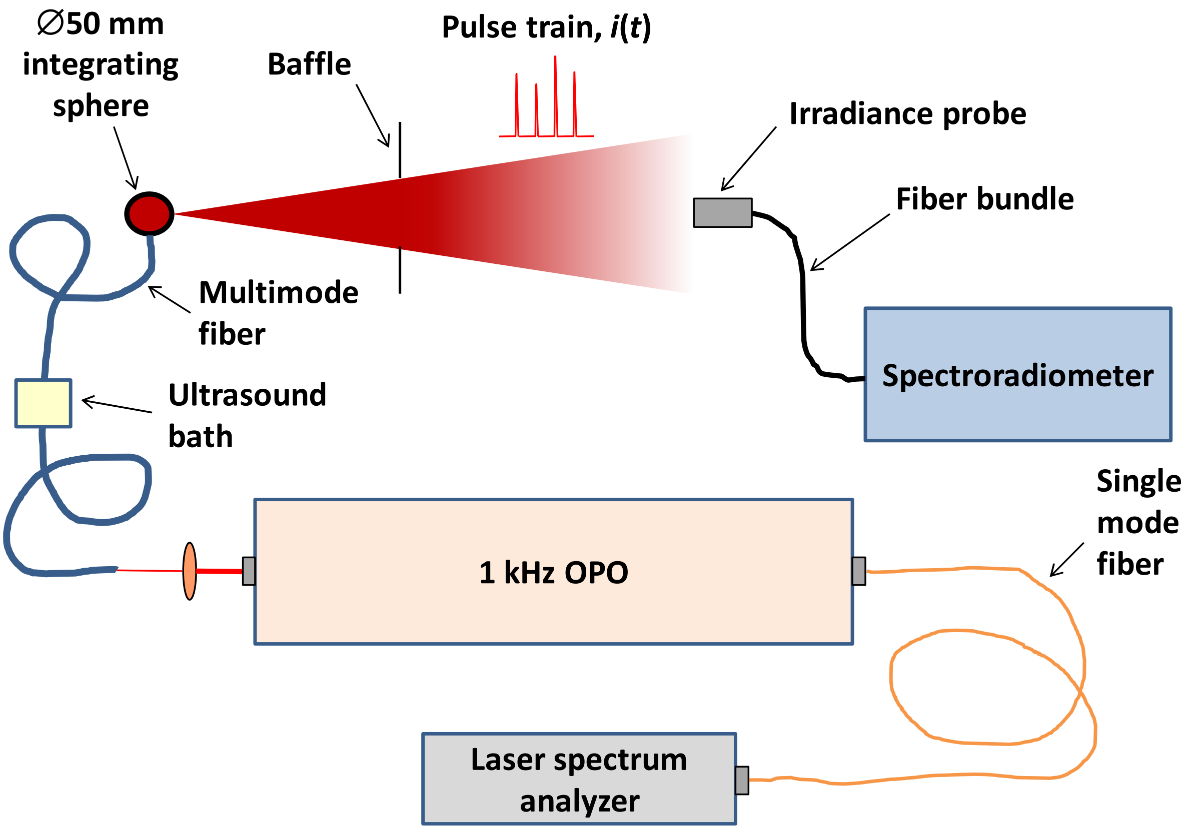

Figure 1 – Schematic for the wavelength calibration

3 Results of the wavelength calibration

The wavelength of the OPO laser measured by the spectroradiometer and that measured by the laser spectrum analyzer were compared. Using the laser spectrum analyzer as the reference standard, the wavelength error of the metrology-grade spectroradiometer at each measured wavelength was obtained. Figure 2 shows the wavelength errors of the spectroradiometer across its entire spectral range with the wavelength interval of 5 nm. The wavelength error varies from approximately -0.2 nm to 1 nm across the spectral range and changes rapidly in some spectral regions, indicating a fine-step wavelength calibration is required. The significantly larger than specified wavelength errors may be due to the replacement of the original fiber optic irradiance probe with a new one of the same type for this calibration. Using the determined wavelength errors at every 5 nm interval and the wavelength values of all pixels provided by the manufacturer based on the factory's wavelength calibration, the wavelength error of each pixel was obtained by interpolation between measured wavelengths, and a correction for the wavelength error was applied to each pixel. As a result, the wavelength uncertainty of the spectroradiometer is significantly reduced. Note the wavelength calibration results may change slightly when a mathematic method other than the peak wavelength method (such as centroid wavelength method or center wavelength method) is used because of spectroradiometer's asymmetric bandpass functions and possible asymmetric spectra of the kilohertz-pulsed OPO laser.

By knowing the accurate wavelength of each pixel, the pixel-to-pixel wavelength interval can be obtained. Figure 3 shows the gradual change of the pixel-to-pixel wavelength interval of the array detector of the spectroradiometer, which is approximately a linear function of pixel index number of the array detector. The uncertainty of the pixel-to-pixel wavelength interval can further be reduced to a level of a few picometers by curve-fitting the measured values which effectively eliminates the random measurement noises. Note the obtained pixel-to-pixel wavelength intervals do not depend on the mathematic method used for the wavelength measurements because the measurement errors associated with the mathematic method cancel at the two adjacent measured wavelengths.

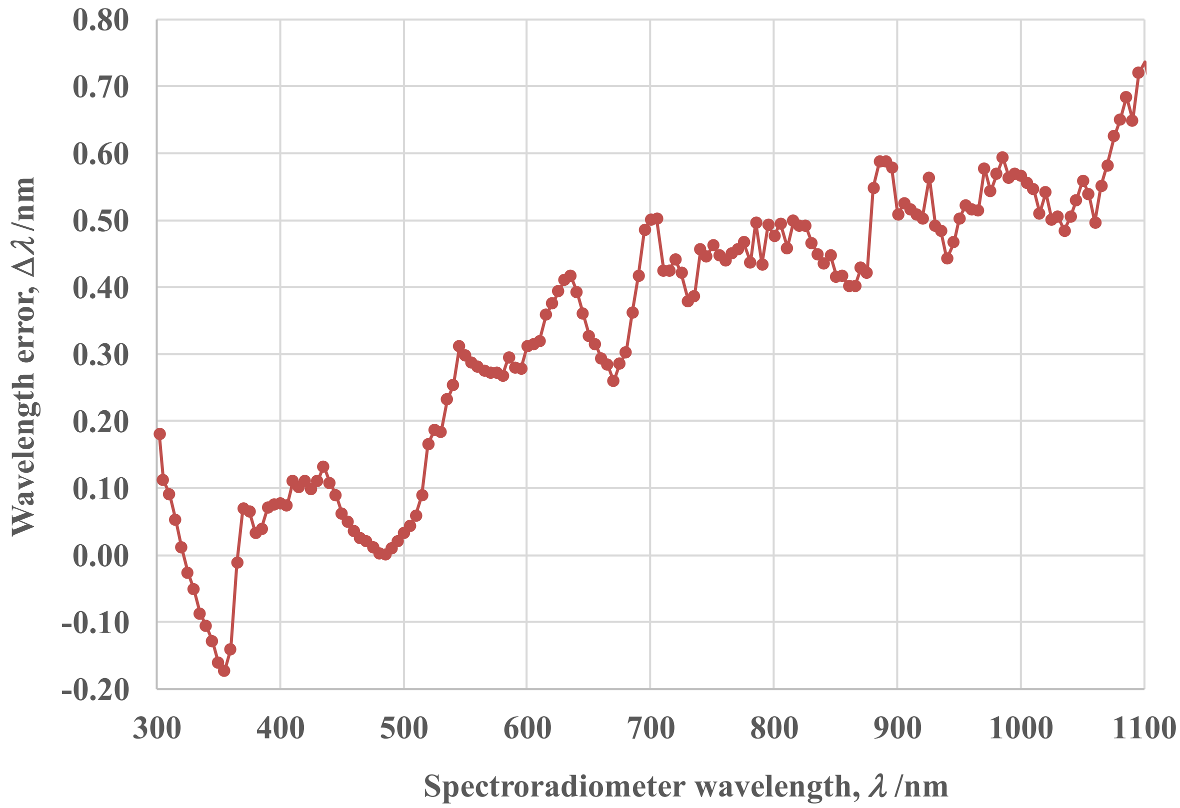

Figure 2 – Plot of the wavelength errors of a metrology-grade spectroradiometer

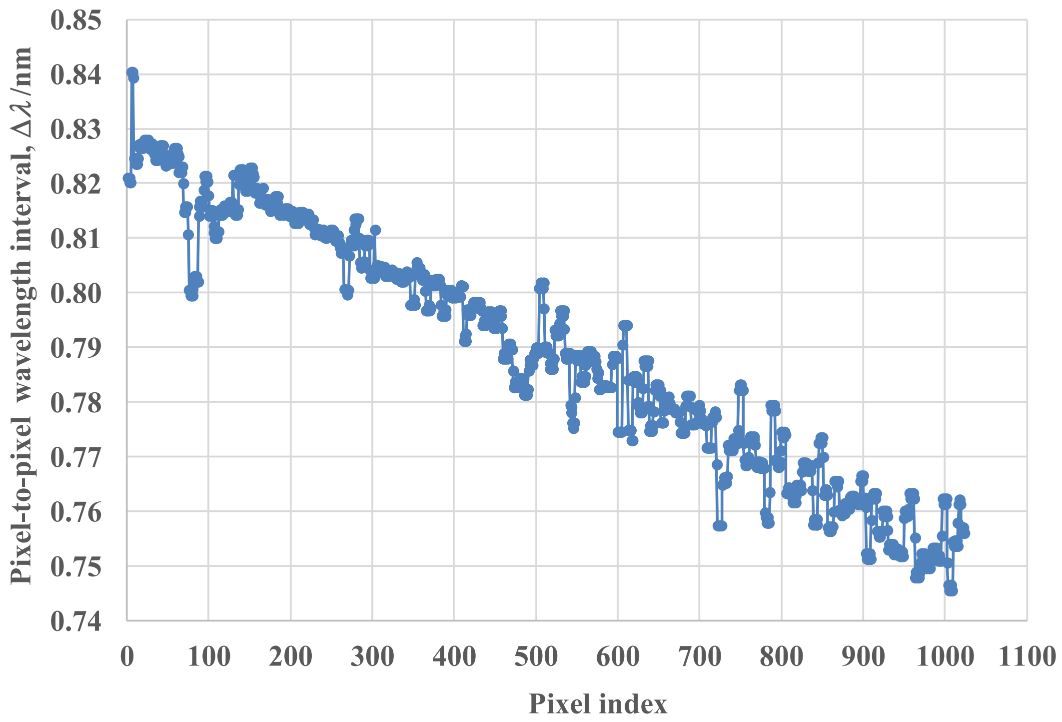

Figure 3 – Plot of pixel-to-pixel wavelength interval of the spectroradiometer

4 Summary

A new method for calibration of array spectroradiometers' wavelength scales was demonstrated using a fully-automated, kilohertz-pulsed, wavelength-tunable OPO laser. A calibration uncertainty of wavelength scale on the level of picometers can be achieved across the entire spectral range of the spectroradiometer; a reduction of approximately two orders of magnitude compared to the conventional approaches. This method can also be used to determine a spectroradiometer's pixel-to-pixel wavelength interval with an uncertainty of a few picometers, which is the key to achieving small uncertainties when the detector-based method is used for spectral calibration using the OPO laser [Zong et al. 2014]. High accuracy wavelength calibration of array spectroradiometers can also significantly reduce overall measurement uncertainties in many applications.

References

BLATTNER, P., FOALENG, S. M., VAN DEN BERG, S., GAWHARY, O. E., BLUMTHALER, M., GROBNER, J., and EGLI, L. 2014. Devices for characterizing the wavelength scale of UV spectrometers. Proceedings of NEWRAD 2014, S. Park, P. Karha, and E. Ikonen, eds., 201-202.

PERRET, E., BALMER, T., and HEUBERGER, M. 2010. Self-consistent algorithm for calibrating spectrometers to picometer accuracy over the entire wavelength range. Appl. Spectrosc., 64 (10), 1134-1144.

ZONG, Y., BROWN, S. W., JOHNSON, B. C., LYKKE, K. R., and OHNO, Y. 2006. Simple spectral stray light correction method for array spectroradiometers. Appl. Opt., 45 (6), 1111-1119.

ZONG, Y., BROWN, S. W., EPPELDAUER, G. P., LYKKE, K. R., and OHNO, Y. 2012. A new method for spectral irradiance and radiance responsivity calibrations using kilohertz pulsed tunable optical parametric oscillators. Metrologia, 49, S124-S129.

ZONG, Y., and SHAW P. 2014. Applications of pulsed OPO laser systems for optical radiometry. Proceedings of NEWRAD 2014, S. Park, P. Karha, and E. Ikonen, eds., 12-13.