- 1. P. N. Slater, *Remote Sensing: Optics and Optical Systems*, p 119, Addison-Wesley, Reading, MA, 1980.
- F. Grum and R. J. Becherer, *Radiometry*, Vol. 1 in Optical Radiation Measurements series, F. Grum, Ed., p 115, Academic Press, New York (1979).
- Comptes Rendus de la 16<sup>e</sup> CGPM (16<sup>th</sup> Conférence Générale des Poids et Mesures), Resolution 3, 1979. http://www.bipm.org/en/CGPM/db/16/3/.
- F. E. Nicodemus, Ed., Self Study Manual on Optical Radiation Measurements, Part I—Concepts, NBS Technical Note 910-1, pp 99–100, US National Bureau of Standards, Washington, DC, 1976.

Boyd, R. W., Radiometry and the Detection of Optical Radiation, John Wiley and Sons, New York (1983).

Budde, W., *Physical Detectors of Optical Radiation*, Optical Radiation Measurements, v. 4, Grum, F. and Bartleson, C. J., Eds., Academic Press, New York (1983).

Dereniak, E. L. and Crowe, D. G., *Optical Radiation Detectors*, John Wiley & Sons, New York (1984).

Dereniak, E. L. and Dereniak, T. D., *Geometrical and Trigonometric Optics*, Cambridge University Press, Cambridge, UK (2008).

Greivenkamp, J. E., *Field Guide to Geometrical Optics*, SPIE Press, Bellingham, WA (2004) [doi:10.1117/3.547461].

Holst, G. C., Common Sense Approach to Thermal Imaging, JCD Publishing, Winter Park, FL, and SPIE Press, Bellingham, WA (2000).

Howell, J. R., A Catalog of Radiation Heat Transfer Configuration Factors. http://www.engr.uky.edu/rtl/Catalog/intro.html.

NIST Physical Measurement Laboratory, CODATA Internationally Recommended Values of the Fundamental Physical Constants, 2006.

http://physics.nist.gov/cuu/Constants/index.html.

Palmer, J. M. and Grant, B. G., *The Art of Radiometry*, SPIE Press, Bellingham, WA (2009) [doi:10.1117/3.798237].

Refractive Index.Info. http://refractiveindex.info/.

Robertson, A., "R2-35 Uncertainties in Distribution Temperature Determination," *Report to CIE Division 2*, Ottawa, Canada, 2005.

Vincent, J. D., Fundamentals of Infrared Detector Operation and Testing, John Wiley & Sons, New York (1990). Wolfe, W. L. and Zissis, G. J., Eds., *The Infrared Handbook*, US Government, Washington, DC (1978), and SPIE Press, Bellingham, WA (1985).

Wyatt, C. L., *Electro-optical System Design for Information Processing*, McGraw Hill, New York (1991).

Wyatt, C. L., Radiometric Calibration: Theory and Methods, Academic, New York (1978).

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