Chapter 1

Introduction to Radiometry

1.1 Definitions

Consider the following definitions a starting point for our study of radiometry:

radio- [<L. *radius*] a combining form meaning ray, raylike

-metry [Gr. -*metria* < *metron*] a terminal combining form meaning the process, art, or science of measuring

radiometer (rä'dë-óm´í-ter) ***n.*** [*radio*- + -*meter*], an instrument for detecting and measuring the intensity of radiant energy, by exposing to sunlight a set of vanes blackened on one side and suspended on an axis in a vacuum and measuring their speed of rotation (i.e., the mechanical energy into which the radiant energy has been converted) (See Fig. 1.1)

radiometry (rä'dë·óm´í·tri), ***n.*** the use of the radiometer: the measurement of radiation[1]

These definitions are taken from Webster's *New World Dictionary*, and may be satisfactory for the general nonscientist. The definitions are not satisfactory, however, for scientists and engineers pursuing the art of radiometry. So let's get technical:

radiometry (rä'dë·óm´í·tri) ***n.*** the measurement of optical radiant energy

The practical electromagnetic spectrum extends from dc to frequencies greater than 10^{20} Hz. The optical portion of the spectrum covers the five-decade frequency range from 3×10^{11} to 3×10^{16} Hz, corresponding to the wavelength range from 10 nm to 1000 µm, as shown in Fig. 1.2. This range includes the ultraviolet, visible, and infrared regions. Shorter wavelengths are called x rays and gamma rays, while longer wavelengths are microwave and millimeter radio waves.

Figure 1.1 Classic vane radiometer, commonly called the Crooke radiometer.[1] [Reprinted by permission from *Webster's Third New International® Dictionary, Unabridged* ©1993 by Merriam-Webster, Incorporated (www.Merriam-Webster.com)].

The optical radiation spectrum will be treated in this text, including the ultraviolet, visible, and infrared regions. The visible portion of the optical spectrum covers a rather narrow band of wavelengths between 380 nm and 760 nm; the radiation between these limits, perceivable by the unaided normal human eye, is termed "light." Measurements within this region may be called "photometric" if the instruments used incorporate the response of the eye. The short wavelength (ultraviolet) limit of radiometric coverage is about 200 nm, approximately the shortest wavelength that our atmosphere will transmit. The longest wavelength (infrared) treated in this book is about 100 µm. This wavelength range includes 99% of the energy (95% of the photons) from a thermal radiator at 0° C (273.16 K).

1.2 Why Measure Light?

But why measure light in the visible, ultraviolet, or even infrared region? What are these measurements good for? Let's look at some historical perspectives:

> *I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of science, whatever the matter may be.*
>
> *Lord Kelvin*

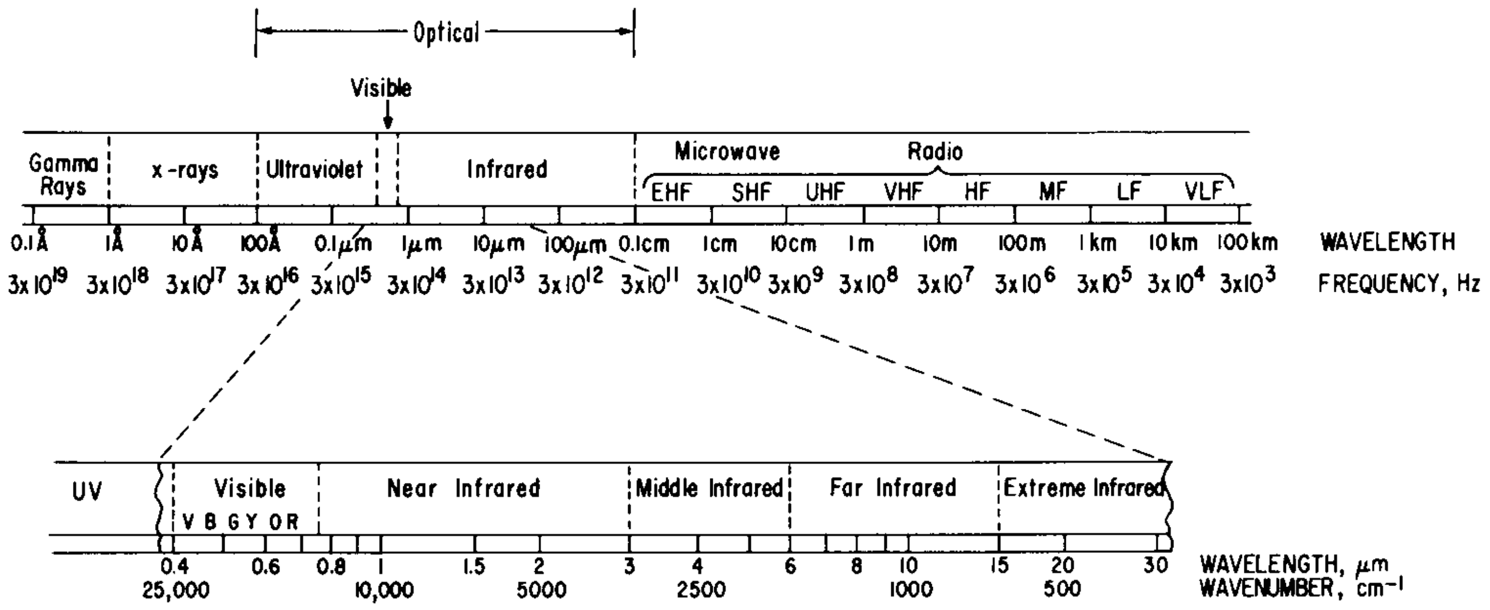

Figure 1.2 The electromagnetic spectrum.[2] [Reprinted by permission of author from *Optical Radiation Measurement* series, Vol. 1, F. Grum and R. J. Becherer, *Radiometry*, p. 1 (1979)].

> *...nobody will object to an ardent experimentalist boasting of his measurements and rather looking down on the "paper and ink" physics of his theoretical friend, who on his own part is proud of his lofty ideas and despises the dirty fingers of the other.*
>
> *Max Born*

> *If you are really doing optics, you get photons under your fingernails.*
>
> *James M. Palmer*

Measurement is the point at which the rubber meets the road. Hypotheses, uncorroborated by measurement, cannot fulfill the same function. And if rubber doesn't meet the road, the car cannot move.

The measurement of light is often critical in transitioning from theory to the development of systems and techniques. Although instrument and system design may be based on theory, performance evaluation and system improvement require that accurate radiometric measurements be applied. When calibrated measurements are needed, that is, when field or laboratory measurements must be correlated with specific values presenting the relationship between measured phenomena and an absolute standard, radiometric measurements take on even greater significance.

1.3 Historical Background

Scientists and engineers have been involved in the measurement of light since the early experiments and instruments described by P. Bouguer in 1729 and by J. H. Lambert in 1760. Exploration into other spectral regions began with the discovery of the infrared region by W. Herschel in 1800 and the ultraviolet region by J. W. Ritter the following year. Table 1.1 shows some of the significant events in the history of radiometry and photometry.

Table 1.1 Some significant events in radiometry.

Year	Event	Principal investigator
?	... and then there was light!	from *Genesis*
1666	Investigation of the visible spectrum	Newton
1729	Inverse square law	Bouguer
1760	Cosine law, exponential absorption	Lambert
1800	Discovery of the infrared region	Herschel
1801	Discovery of the ultraviolet region	Ritter
1830	Radiation thermopile (first practical detector)	Nobile, Melloni
1837	Calorimetric detector	Pouillet
1839	Photoelectric effect	Becquerel
1859	Relation between absorption and emission	Kirchhoff

Table 1.1 (*Continued.*)

Year	Event	Principal investigator
1860	Standard lamp fueld by sperm whale oil	British Metropolitan Gas Act
1879	Incandescent lamp (carbon filament)	Edison
1880	Bolometer	Langley
1892	Integrating sphere (theory)	Sumpner
1893	Absolute thermal detector (pyrheliometer)	Angstrom, Kurlbaum
1900	Blackbody radiation theory	Planck
1900	Integrating sphere (reduction to practice)	Ulbricht
1905	Photoelectric effect	Einstein
1910	Tungsten lamp	Collidge
1931	Adoption of colorimetric standards	International Commission on Illumination (CIE)
1936	Photomultiplier tube (multistage)	Zworykin, Morton & Malter
1938	Pyroelectric detector (theoretical)	Ta
1948	Adoption of platinum blackbody for standard candela	Consultative Committee on Photometry and Radiometry (CCPM)
1954	Silicon photodiode	Chapin, Fuller & Pearson
1955	Pyroelectric detector (reduction to practice)	Chenowyth
1960	Invention of light amplification by stimulated emission of radiation (LASER)	Maiman
1961	Tungsten-halogen lamp	Zubler & Mosby
1970	Laser calorimetry	West
1975	Fourier transform spectrometer	Vanesse
1977	Photometry relegated to subset of radiometry	CCPM
1980	Self-calibrated silicon detector	Zalewski & Geist
1983	Trap detector	Zalewski & Duda
1984	Definitive measurement of the Stefan-Boltzmann constant	Quinn & Martin
1985	Cryogenic absolute radiometer	Martin, Fox, & Key; Foukal

1.4 Radiometric Measurement Process

This book describes the many facets of optical radiation measurement, from radiation sources to detectors and signal processing. To fully understand and appreciate a radiometric measurement, we must understand the processes of generation, transmission, and detection of optical radiation. In addition, we must possess a firm grasp of the underlying mathematics and what is loosely called “measurement science.”

A generic radiometric configuration is shown in Fig. 1.3. A target, or object of measurement interest, can be either active, emitting radiation by virtue of its temperature or some form of atomic excitation, or passive, reflecting radiation from a different active or passive illuminator. Examples of active sources include the sun, tungsten or fluorescent lamps, lasers, and any nontransparent object with a temperature greater than 0 K. Passive sources include the entire range of natural and artificial reflective surfaces that make up our environment. An additional source of optical radiation can be classified as background, the radiation that may be in our instrumental field of view along with the target. Also included is the intervening medium, the atmosphere, which includes both radiation sources and sinks, acting through the mechanisms of absorption, emission, and scattering. The myriad of small arrows in Fig. 1.3 represent scattered, absorbed, emitted, and reflected radiation.

After traversing the atmosphere, the rays from the target (and possibly the background as well) reach our instrument, whose parameters define the ranges over which the spatial, spectral, temporal, and radiometric characteristics of incoming radiation will be accepted. This is accomplished through the use of lenses and mirrors, choppers and apertures, prisms, gratings, filters, attenuators,

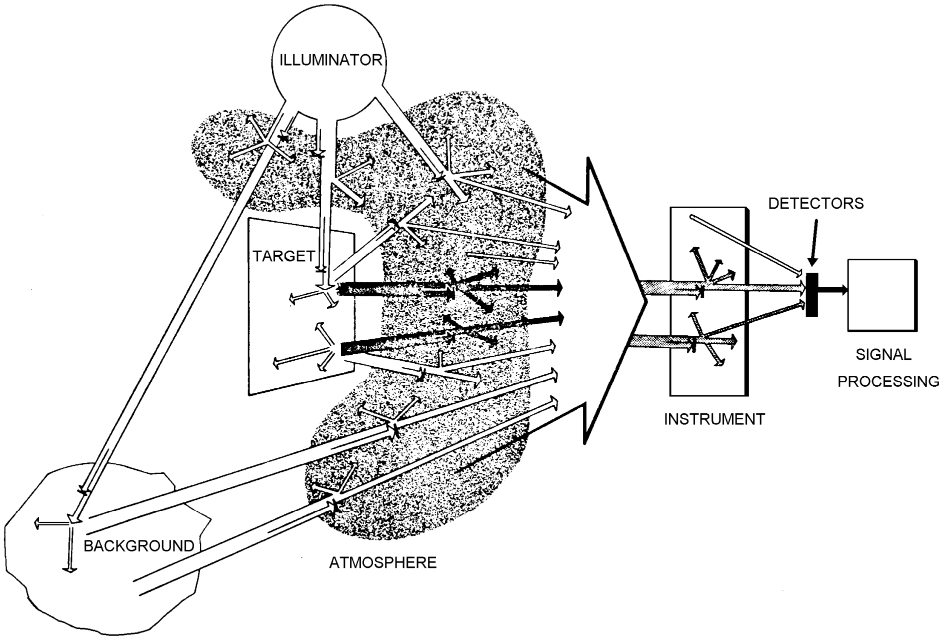

Figure 1.3 Generic radiometric configuration.[2] [Reprinted by permission of author from *Optical Radiation Measurement* series, Vol. 1, F. Grum and R. J. Becherer, *Radiometry*, p. 7 (1979)].

polarizers, optical fibers, etc. The optical radiation transmitted through the instrument is finally incident on one or an array of detectors, transducers which convert the incident optical radiation to a more tractable form of energy. Detectors may be thermal (thermoelectric, bolometric, and pyroelectric) or photon (photoemissive, photoconductive, and photovoltaic) in character; other viable detectors include the human eye and photographic film.

The final block in the diagram involves signal processing. Most of the detectors in common use generate electrical signals. Postdetector processing may include filtering, linearization, and background suppression before the processed result is recorded and displayed. Even the eye and film detectors include processing steps, such as the filtering and interpretation of information by the brain and the photographic development process for film.

1.5 Radiometry Applications

The fields in which radiometric instruments and techniques are used are very diverse. Table 1.2 lists some of the more common applications.

Table 1.2 Common applications of radiometry.

Appearance measurement
Astrophysics
Atmospheric physics
Clinical medicine
Colorimetry
Diagnostic medicine
Remote-sensing satellites
Electro-optics
Illumination engineering
Laser measurements
Materials science
Meteorology
Military systems
Night-vision devices
Optoelectronics
Photobiology
Photochemistry
Photometry
Radiative heat transfer
Solar energy
Television systems
Visual displays
Vision research

Most books on radiometry begin with a vast and often confusing array of terms, definitions, etc. In this work, detailed listing of terminology is relegated to the glossary in Appendix E, and radiometric terms will be introduced as they are needed.

Radiometry and photometry are applied to a variety of phenomena whose output occurs over many orders of magnitude. Tables 1.3 through 1.5 illustrate the ranges of illumination encountered. "Luminance" is power per unit area and unit solid angle weighted by the spectral response of the eye; its units are lumens per square meter per steradian ($lm/m^2/sr$), or candelas per square meter (cd/m^2). "Illuminance" is power per unit area weighted by the same function; its units are lumens per meter squared (lm/m^2).[*]

Table 1.3 Luminances of astronomical sources.

Source	Luminance (cd/m^2)
Night sky, cloudy, no moon	10^{-4}
Darkest sky	4×10^{-4}
Night sky, clear, no moon	10^{-3}
Night sky, full moon	10^{-2}
Clear sky 0.5 hr after sunset	0.1
Clear sky 0.25 hr after sunset	1
Cloudy sky at sunset	10
Gray sky at noon	10^{2}
Cloudy sky at noon	10^{3}
Moon	2.5×10^{3}
Average clear sky	8×10^{3}
Clear sky at noon	10^{4}
Solar disk	1.6×10^{9}
Lightning	8×10^{10}

Table 1.4 Luminances of practical sources.

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[*] For more thorough discussions of photometry, see J. T. Walsh, *Photometry*, Dover, New York (1958); P. Moon, *The Scientific Basis of Illuminating Engineering*, Dover, New York (1961); and R. McCluney, *Introduction to Radiometry and Photometry*, Artech House, Boston (1994).

Source	Luminance (cd/m^2)
Minimum visible level (human)	3×10^{-6}
Scotopic vision valid (human)	< 0.003
Photopic vision valid (human)	> 3
Green electroluminescent	25
T8 cool white fluorescent	10^4
Acetylene burner	10^5
60 W inside frosted lamp	1.2×10^5
Candle	6×10^5
Sodium vapor lamp	7×10^5
High-pressure Hg vapor lamp	1.5×10^6
Tungsten lamp filament	8×10^6
Plain carbon arc crater	1.6×10^8
Cored carbon arc crater	10^9
Atomic fusion bomb	10^{12}

Table 1.5 Illuminances of various sources.

Source	Illuminance (lm/m^2)
Absolute minimum $M_v = 8$	1.6×10^{-9}
Typical minimum $M_v = 6$	10^{-8}
0 M_v star outside atmosphere	2.54×10^{-6}
Venus	1.3×10^{-4}
Full moonlight	1
Street lighting	10
Recommended reading	10^2
Workspace lighting	10^2 to 10^3
Lighting for surgery	10^4

References

1. *Webster's Third New International® Dictionary, Unabridged,* Merriam-Webster, Inc. (1993).
2. F. Grum and R. J. Becherer, *Radiometry*, Vol. 1 in *Optical Radiation Measurements*, F. Grum, Ed., Academic Press, New York (1979).