OPTICAL RADIATION MEASUREMENTS

VOLUME 1

Radiometry

Franc Grum
Richard J. Becherer

OPTICAL RADIATION MEASUREMENTS

Volume 1

RADIOMETRY

OPTICAL RADIATION MEASUREMENTS

A Treatise

Edited by FRANC GRUM

Volume 1	**Radiometry** Franc Grum and Richard J. Becherer
Volume 2	**Color Measurement and Evaluation** (in press) *Edited by* Franc Grum

In preparation

Volume 3	**Measurement of Luminescence**
Volume 4	**Visual Measurements**
Volume 5	**Physical Detectors of Radiation**

OPTICAL RADIATION MEASUREMENTS

Volume 1

RADIOMETRY

FRANC GRUM

Research Laboratories
Eastman Kodak Company
Rochester, New York

RICHARD J. BECHERER

Lincoln Laboratory
Massachusetts Institute of Technology
Lexington, Massachusetts

ACADEMIC PRESS
New York San Francisco London 1979
A Subsidiary of Harcourt Brace Jovanovich, Publishers

ACADEMIC PRESS, INC.
111 Fifth Avenue, New York, New York 10003

United Kingdom Edition published by
ACADEMIC PRESS, INC. (LONDON) LTD.
24/28 Oval Road, London NW1 7DX

Library of Congress Cataloging in Publication Data

Main entry under title:

Optical radiation measurements.

CONTENTS: v. 1. Grum, F., Becherer R. J. Radiometry.
1. Radiation--Measurement. 2. Optical measurements. I. Grum, Franc II. Becherer, Richard J., Date
QC475.067 539'.2'028 78-31412
ISBN 0-12-304901-6 (v. 1)

PRINTED IN THE UNITED STATES OF AMERICA

79 80 81 82 9 8 7 6 5 4 3 2 1

Contents

Foreword

Optical radiant energy has always been the connecting link between the human visual system and the external world, and energy from the sun has always been essential to biological growth and development. Yet it is only within recent years that it has become possible to generate, detect, and control optical radiant energy to meet a wide range of needs. A brief list of current areas of application and research that involve radiant energy in a direct way must include astrophysics, clinical medicine, color science, illumination engineering, laser systems, meteorology, military sensors, photography, radiation heat transfer, solar energy, and visual information display. The spectral regions of interest in these areas span the visible, the infrared, and the ultraviolet.

In each of these areas the pace of development has been rapid. New techniques have been introduced and new measurement methods have arisen to meet pressing needs. It is our plan that these volumes, under the title "Optical Radiation Measurements," will provide information on many aspects of these recent developments. Throughout the treatise a basic viewpoint will be taken in the belief that this will prove most useful. Although recent results will be described, it is not intended that these volumes be simply a compendium of data of the type found in handbooks. Each volume will emphasize principles and generally applicable methods.

FRANC GRUM

This page intentionally left blank

Preface

Radiometry embraces a wide range of topics from basic concepts of radiant energy and its tranfer to the calibration of instrumentation. The purpose of this book is to bring together a balanced selection of these topics that will serve as an introduction to the measurement of optical radiant energy and will also be detailed enough to serve as a text for instruction and reference.

The book is divided into three parts: concepts, components, and techniques. Chapters 2–4 describe the basic concepts such as radiation laws, terminology, and the transfer of radiant energy. The emphasis in these early chapters is on fundamentals. Chapters 5–7 survey the major components of radiometric systems. Our intention here has been to introduce increasing amounts of specific performance data, particularly for sources and detectors of radiant energy. The final three chapters, 8–10, describe representative techniques. Radiometry is primarily concerned with measurements and so techniques properly play a central role.

Each chapter is followed by a list of specific references to facilitate further study of a topic of interest. A list of general references is found at the end of Chapter 1. We have included many tables of data and a large number of figures to increase the utility and clarity of the book.

In the matter of units we have adhered to SI (Système Internationale) and SI derived units. The terminology is that now recommended by a number of international standardizing organizations including the CIE (Commision Internationale de l'Éclairage). Throughout the book the symbols used are explicitly defined and units are shown following the related equation.

The reader will realize that in the limited space available in a single book it is not possible, nor is it our intention, to treat all of the applications or techniques of radiometry in detail. As the first volume in the treatise "Optical Radiation Measurements," this book is intended to be introductory in character. Later volumes with chapters by invited authors who are expert in their special areas will complement the present volume in this respect.

Acknowledgments

In preparing this book we have had the benefit of comments and suggestions from a number of our colleagues. We particularly wish to thank Professor F. Billmeyer of Rensselaer Polytechnic Institute; Mr. A. Karoli of Eppley Laboratories; Mr. R. Keyes and Dr. R. Kingston of Lincoln Laboratory, Massachusetts Institute of Technology; and Professor E. Wolf of the University of Rochester for reading and commenting on portions of the manuscript. Their advice has been extremely valuable to us in this undertaking. We are also indebted to Dr. Bruce Steiner of the National Bureau of Standards for a number of helpful discussions over a period of several years regarding the applications of radiometry and radiometric standards. Many of these discussions took place within CORM, the Council for Optical Radiation Measurements.

The cooperation and encouragement of the Eastman Kodak Company and of Lincoln Laboratory, Massachusetts Institute of Technology, are gratefully acknowledged. Early versions and revisions of the manuscript were skillfully typed by Miss Deborah Lionetta, Miss Joyce Craven, and Mrs. Cathy Thayer. Our thanks go to them for their patience. Finally, we wish to express special thanks to our families for their understanding and support in a project that has occupied a considerable amount of personal time over a period of two and one-half years.

This page intentionally left blank

1

Introduction

1.1 RADIOMETRY

Radiometry is the science and technology of the measurement of electromagnetic radiant energy. Measurements of radiant energy are conducted throughout the electromagnetic spectrum, as shown in Fig. 1.1, using methods which are suited to the spectral region of interest. Our objective is to describe the concepts, components, and techniques which are used for radiant energy measurement in the optical region of the electromagnetic spectrum.

Typical configurations of radiometric measurement systems are shown in Fig. 1.2. As shown in the figure, a complete radiometric measurement system will generally involve a number of *components* including a source of radiant energy, a transmission medium through which the radiant energy passes, an object which transmits, reflects, or absorbs radiant energy, an optical system, a detector which converts the radiant energy to another form of energy

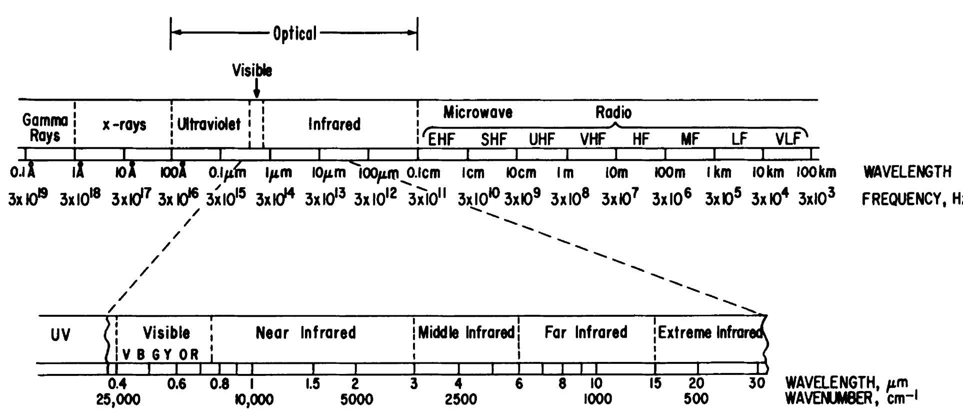

Fig. 1.1 The electromagnetic spectrum.

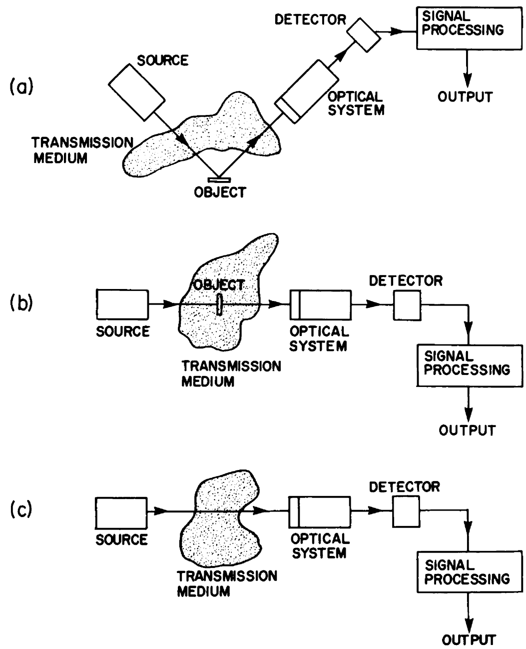

Fig. 1.2 Typical configurations of radiometric measurement systems.

(usually electrical), and a signal processing device. Figure 1.2 shows typical arrangements of these components in three complete radiometric systems. The principal differences among these three configurations is the presence or absence of the object in the path of the radiant energy and the orientation of the optical system to collect the radiant energy which is reflected or transmitted by the object. Although these simplified configurations may not cover all situations, they do represent the arrangements of components used in the majority of all radiometric measurements.

Typical *sources* of radiant energy include the sun, lasers, electrical discharge sources, fluorescent materials, and in general any material body which is heated to a temperature above absolute zero. A theoretically ideal blackbody produces a distribution of radiant power with wavelength which is closely approximated by many practical sources. The characteristics of the radiant energy distribution produced by a blackbody constitute an important starting point for any survey of radiometry.

The *transmission medium* of primary interest is the terrestrial atmosphere. One of the principal characteristics of the terrestrial atmosphere is its variability. Variations in temperature, pressure, water content, and distribution of molecular species cause the optical properties of the atmosphere to vary with time. These variations are in addition to the spatial variations of optical properties which are due to the large-scale gradations which occur in the vertical structure of the atmosphere as a function of altitude above the surface of the earth.

Objects of interest in radiometry are as varied as the applications of radiometry. This variety of objects precludes a comprehensive survey of this component of the radiometric system. However, it is possible to consider the general transmission, reflection, and absorption characteristics of objects which influence the choice among various measurement techniques. This approach is taken in the chapters of this book dealing with techniques.

Optical systems used in radiometric measurement systems will usually consist of lenses, mirrors, apertures, prisms, gratings, filters, interferometers, polarizers, attenuators, diffusers, integrating spheres, fiber optics, or other devices. Much of the effort involved in the development of a radiometric measurement system is directed toward the sophisticated utilization of optical devices.

Detectors play a fundamental role in radiometry. Much of the history of progress in radiometry is associated with progress in the development of detectors. The most important physical detectors of radiant energy are photomultipliers, photographic detectors, pyroelectric detectors, thermocouples, bolometers, photoconductors, and photodiodes. Another very important detection system which plays a preeminent role in many applications is the human visual system. Actually, the human visual system is probably best regarded as a combination of optical system, detectors, and signal processing device. Although a number of psychophysical measurements have been made which permit the characterization of the simpler properties of the human visual system, it is well known that the adaptive capability of our visual system restricts the general applicability of these measurement results. Nevertheless, a knowledge of these simpler properties has proved highly useful in applications of radiometry, such as colorimetry and photometry, which involve the human observer.

Signal processing is also an essential part of a radiometric measurement. Frequently the capability of the signal processing component will dictate the design of the rest of the radiometric system. Signal processing can involve sophisticated mathematical analyses of measurement data performed with the aid of very large digital data processing facilities. It can also be as simple as a direct reading of the electrical signal coming from the detector. Most of the signal processing devices which are used in performing radiometric measurements are not unique to this field. However, the signal processing functions which are performed are usually uniquely associated with the radiometric components or application of interest. For this reason we discuss signal processing requirements in connection with the discussion of related system components or measurement techniques.