Fundamentals of Infrared Technology

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FOREWORD

The infrared region of the electromagnetic spectrum is proving to be of ever-increasing usefulness in both laboratory and field applications. In the laboratory, infrared spectroscopy is a technique which is familiar to physicists and chemists as a tool with which to explore molecular structure. Since World War II there have been vigorous developments in spectrophotometers, especially the double-beam recording type with which the infrared "finger print" absorption spectra of substances can be run off in seconds or minutes. Thus infrared spectrophotometry can now be regarded as a standard analytical technique, and further startling improvements are not expected in the excellent instruments that are commercially available. Also, the technical literature is fairly complete on this subject, as to both principles of operation of the equipment and the theories involved in their application. Infrared methods have hence proved their worth in academic surroundings and also in broad scale industrial applications, and are considered to be indispensable to the organic chemist and to many others who are interested in the microconstitution of matter.

Field uses of the infrared part of the spectrum have come into prominence more recently, and only since World War II has infrared been accepted as a proven technique. It is, of course, of major interest to the military, for "seeing in the dark" and for the detection and tracking of objects whose surface temperature is so low that they cannot be seen by the human eye. The most recent years have witnessed a rapid growth in the application of infrared techniques to *non*-military operations in the out-of-doors. I do not refer here to infrared photography, which again is an established technique but is sensitive only at wavelengths shorter than about 1.3 microns. The type of infrared discussed in this book deals chiefly with wavelengths considerably longer than 1 micron and hence with radiant energy to which infrared film and photocells are not sensitive.

The September 1959 issue of the *Proceedings of the Institute of Radio Engineers* was notable in that it contained articles describing, for perhaps the first time in the general literature and on such a broad scale, both the physical principles and the applications of infrared technology. The present book covers much of this ground, and includes additional engineering aspects of infrared applications. It represents one of the very few publications which treats this considerable body of knowledge in a unified fashion suitable for classroom use or self-instruction.

The infrared developments since about the time of World War I were surveyed in an article by Arnquist[1] in the journal issue just mentioned. A historical survey of the even earlier developments, starting with the discovery of the infrared spectral region by Herschel in the year 1800, has been given Barr.[2] The reader is referred to these two articles as providing an excellent background in the field of infrared radiation.

Any complete infrared system, be it for laboratory or for field use, consists of five basic and rather separate parts, elements, or subsystems. The first is the source of radiation, called the "target" in military parlance. The target is almost always seen against its radiant background, and this fact must be taken into account when evaluating target radiation. In a field instrument this radiation reaches the infrared equipment only after traversing the atmosphere for a certain distance; this path may be short—just a few inches—or may be many miles in length. So intense is the absorption at certain wavelengths by atmospheric constituents such as carbon dioxide and water vapor that their effect on the transmitted radiation must always be taken into account in extrapolating back from the measured radiation to the true target radiation.

Then the radiation from the target or source, as transmitted by the atmosphere, is intercepted and gathered in by an optical system, which system constitutes one of the most challenging parts of the overall problem to the optical-mechanical design engineer or physicist.

The very heart, or perhaps I should say Achilles heel, of the system is the radiation detector, located at the focal point of the optical system. As a matter of fact, the advanced state in which infrared technology finds itself today is largely due to a break-through that occurred in Germany in the 1930's with the discovery of lead sulfide photoconductivity at near-infrared wavelengths, and the development during the following twenty years of photoconductors sensitive to longer wavelength infrared radiation. Thus the old thermodynamic-type detectors such as bolometers and thermocouples could be replaced by rapid-acting, ultra-sensitive, quantum-type detectors.

The weak signal from the detector must be suitably amplified with the addition of a minimum of electrical noise, and this process is sometimes treated as a separate problem, although at other times the detector-preamplifier is considered as a single unit. Following the preamplifier there are further stages of amplification, and finally there is the display,

[1]Warren N. Arnquist, "A Survey of Early Infrared Developments," *Proc. IRE* 47, 1420–1430 (1959).

[2]E. Scott Barr, "Historical Survey of the Early Development of the Infrared Spectral Region," *Am. J. Phys.* 28, 42–54 (1960).

the read-out, the servo motor, or whatever output is desired from the infrared system.

Thus the five "elements" of the infrared system are the target or source; atmospheric absorption; the optical system; the detector-preamplifier; and finally the read-out or display. All of these items are covered in detail in the present book. In addition, considerable space is given to some other items such as techniques for the measurement of infrared radiation, evaluation and test procedures for detectors, signal processing techniques, and design procedures for specific types of equipments. Also, there are appendixes which deal in more detail with certain specialized subjects. Of special note is Appendix C, "Sources of Information about Infrared Technology," which should be of great practical value to persons doing research and development work in this broad field.

It must be realized that no one person could be expected to have the knowledge and the ability to write a complete book on infrared technology—the subjects involved are too diverse and the amount of detail needed to do an adequate job in each one is overwhelming. Therefore it is not surprising that this book represents the joint efforts of five authors, each of whom is particularly qualified in a special field. (Two additional contributors are authors of Appendixes A and B.) Despite the fact that several persons are involved, there has been a serious effort made to achieve uniformity of style and format.

It is a great pleasure to witness the appearance, at long last, of an extensive, inclusive, satisfying treatment of the vigorous new field of infrared technology.

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PREFACE

Twice each summer since 1959 we have given a one-week accelerated course in modern infrared technology at The University of Michigan. This book is an outgrowth of the notes used in teaching that course. We hope that it will meet the needs for a text covering the relatively new field of infrared technology as applied to military and civil problems.

The level of the material presented is approximately that of the senior undergraduate year of a typical university curriculum in the physical sciences. It is desirable that the reader's background include experience with elementary and intermediate college physics, mathematics through elementary differential equations, and those elements of communications included in electrical engineering.

The book is made up of four major sections. The first section, Chapters 1 through 4, covers basic radiation concepts: sources and the nature of the radiation processes, radiation measurements, and transmission through various media with particular emphasis on the earth's atmosphere. Chapter 1 also discusses commonly accepted nomenclature for radiation quantities recommended by the Working Group on Infrared Backgrounds; this nomenclature has usually been followed throughout the book. Chapters 5 through 7, which comprise the second part, are devoted to optics, optical materials, and optical instruments. The next section, Chapters 8 through 12, includes that part of solid-state physics appropriate to detectors, physical mechanisms suitable for detection, the interaction of radiation and matter, noise processes in semiconductors, and detector measurements. Finally, Chapters 13 and 14 deal with applications; design procedures are discussed and applied to typical problems. One Appendix describes the major sources of infrared information; another contains atmospheric spectra.

The authors are indebted to the following distinguished scientists for helpful comments on the material of the course and in this book: L. Biberman, M. Krasno, D. Lowe, J. Morgan, L. Mundie, R. Powell, W. Weihe, T. Whitney, and E. Wormser. Each of them presented a guest lecture for the course and made suggestions regarding content. Appendices A and B to this book were contributed by Mr. L. Biberman and Mr. E. Wormser respectively, and are based on lectures given during the course.

We are indebted to the Engineering Summer Conferences of The University of Michigan for support while we prepared several drafts of the notes which were the forerunners of the final manuscript. We also acknowledge with gratitude several government agencies which supported the research programs that provided part of the background for the material in this book. In particular, the Office of Naval Research, Physics Branch; the Army Signal Corps; the Air Force Aeronautical Systems Division; the Air Force Cambridge Research Laboratories; and the Advanced Research Projects Agency have all contributed in this regard.

We gratefully acknowledge the contributions of Professors Stanley S. Ballard and Kathryn A. McCarthy on optical materials; the members of the Working Group on Infrared Backgrounds and Anthony J. LaRocca, who contributed ideas and criticisms on radiometric concepts; and Dr. R. Clark Jones and many members of The University of Michigan Infrared Laboratory staff who have contributed to the discussions on space-filtering techniques. Finally, Professor Ballard's criticisms of the over-all scope and content of the book have been very helpful.

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CONTENTS

CHAPTER 1

THE EMISSION AND ABSORPTION OF INFRARED RADIATION

1.1 Definitions, Units, and Nomenclature

The adjective *infrared* has been defined as "pertaining to or designating those rays lying just beyond the red end of the visible spectrum... wavelengths... longer than those of visible light and shorter than those of radio waves." Commonly, the infrared region of the electromagnetic spectrum is said to extend from wavelengths of about 0.75 μ to 1000 μ. A brief but interesting history of the development of this spectral region has been written by E. Scott Barr.[1]

The electromagnetic spectrum may also be classified by division into three different types of wavelength distributions. These are continuous, band, and line spectra. If these are observed as dispersed by a low-resolution instrument, the distributions are described as:

(a) A continuum, a continuous variation in radiant power as a function of wavelength.

(b) Bands, a set of wavelength regions ($\Delta\lambda_1 = \lambda_2 - \lambda_1$; $\Delta\lambda_2 = \lambda_3 - \lambda_2$; $\Delta\lambda_3 = \lambda_4 - \lambda_3$; $\Delta\lambda_4 = \lambda_5 - \lambda_4$; ...) with discontinuous changes in power at the edges ($\lambda_1, \lambda_2, \lambda_3, \lambda_4, \ldots$).

(c) Lines, a set of wavelengths ($\lambda_1, \lambda_2, \lambda_3, \ldots$) each corresponding to a single value of power.

If high-resolution instrumentation is used, each line is seen to span a region of wavelength values in a continuous variation of radiance, often with more than one maximum. Thus one can observe fine structure, or even hyperfine structure, within what first appeared to be a single line. Similarly, the bands are found to be made up of many lines so that structure is found to exist here also. A true continuum, however, even under high resolution, shows no internal structure.

Table 1-1 lists the symbols, names, units, and descriptions of the radiometric quantities of greatest utility to infrared technology. The symbols are those recommended by the American Standards Association,[2] with units based on the metric system and names as recommended by the Working Group on Infrared Backgrounds*[3,4] (reported by E. Bell[5]). Thus the unit of radiant energy U is the joule, while radiant energy density u is expressed in joule $\cdot$ cm^{-3}. The rate of transfer of radiant energy, or the radiant power P, may be indicated as U_t, where the subscript is used to denote the partial derivative with respect to time. Thus

$$P = \frac{\partial U}{\partial t} = U_t \qquad (1\text{-}1)$$

Radiant emittance, radiant intensity, and radiance are usually considered in reference to a radiating source, and are measures of the proper-

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*The Working Group on Infrared Backgrounds (WGIRB) was established in 1954, by an *ad hoc* committee representing the three Services, for the purpose of studying significant problems in the field of infrared backgrounds and to make recommendations for their solution. Since that time, the Group has been considering targets, atmospheric transmission, and other related aspects of military infrared technology. The present membership is:

[Niel Beardsley] (deceased)	Raytheon, Santa Barbara
Ely Bell	Ohio State University Research Foundation
Lucien Biberman	University of Chicago Laboratories for Applied Sciences
George Brown	Engineering Research and Development Laboratories
John Hamilton	General Mills, Inc.
R. Clark Jones	Polaroid Corporation
Gilbert Kelton	Emerson Research Laboratories
George Levy	Marquardt Aircraft Company
Donald Lowe	Bendix Systems Division, Bendix Corporation
Max Nagel	SHAPE Air Defense Technical Center, SHAPE, The Hague, Netherlands
Lawrence Nichols	U.S. Naval Ordnance Test Station
Roy Paulson	Syracuse University
John Sanderson	Naval Research Laboratory
Edward Sevadjian	Aerojet-General Corporation
Eric Wormser	Barnes Engineering Company
George Zissis	The University of Michigan

The published reports of the WGIRB,[3,4] as well as extracts of an as-yet-unpublished report by the Group covering infrared target and background measurements, were extremely useful in many of the considerations presented in Chapters 1, 2, and 3.

ties of a source. These properties can be directly determined by measurements made at a distance from the source if the radiation is propagated through a nonattenuating medium.

Table 1-1

Radiometric Quantities[a]

Symbol	*Name*	*Description*	*Unit*
U	Radiant energy		Joule
u	Radiant energy density		Joule-cm^{-3}
P	Radiant power (radiant flux)	Rate of transfer of radiant energy	Watt
W	Radiant emittance	Radiant power per unit area emitted from a surface	Watt-cm^{-2}
H	Irradiance	Radiant power per unit area incident upon a surface	Watt-cm^{-2}
J	Radiant intensity	Radiant power per unit solid angle from a source	Watt-sterad^{-1}
N	Radiance	Radiant power per unit solid angle per unit area from a source	Watt-sterad^{-1}-cm^{-2}
P_λ	Spectral radiant power	Radiant power per unit wavelength interval	Watt-micron^{-1}
W_λ	Spectral radiant emittance	Radiant emittance per unit wavelength interval	Watt-cm^{-2}-μ^{-1}
H_λ	Spectral irradiance	Irradiance per unit wavelength interval	Watt-cm^{-2}-μ^{-1}
J_λ	Spectral radiant intensity	Radiant intensity per unit wavelength interval	Watt-sterad^{-1}-μ^{-1}
N_λ	Spectral radiance	Radiance per unit wavelength interval	Watt-sterad^{-1}-cm^{-2}-μ^{-1}
ε	Radiant emissivity	Ratio of "emitted" radiant power from a source to that from a blackbody at the same temperature	
α	Radiant absorptance	Ratio of "absorbed" radiant power to incident radiant power	
ρ	Radiant reflectance	Ratio of "reflected" radiant power to incident radiant power	
τ	Radiant transmittance	Ratio of "transmitted" radiant power to incident radiant power	
λ	Wavelength		Micron (μ)

[a]Reproduced with the permission of the Institute of Radio Engineers from Reference 5.

The basic quantity involving radiant power is the spectral radiance. This is defined as the limit of the ratio of ΔP to the product $\Delta A \cdot \Delta\Omega \cdot \Delta\lambda$, where ΔP is the increment of radiant power lying between λ and $\lambda + \Delta\lambda$ radiated away from the projection of an element of area ΔA into a solid angle $\Delta\Omega$ in a direction θ from the normal to the area, as all of these elements are reduced in size. Thus

$$N_\lambda = \lim_{\substack{\Delta A \to 0 \\ \Delta\Omega \to 0 \\ \Delta\lambda \to 0}} (\Delta P/\Delta\lambda \cdot \Delta\Omega \cos\theta \cdot \Delta A) = \partial^3 P/\partial\lambda\,\partial\Omega \cos\theta\,\partial A \quad (1\text{-}2)$$

From this radiometric quantity all of the others involving power may be defined by integration. For example, the radiant intensity of a Lambertian source can be found by

$$\int_\lambda \int_A N_\lambda \cos\theta\, dA\, d\lambda = J \quad (1\text{-}3)$$

If the wavelength region is only a portion of the total spectrum, then $J_{\Delta\lambda}$ is found where

$$J_{\Delta\lambda} = \int_{\lambda_1}^{\lambda_2} \int_A N_\lambda \cos\theta\, dA\, d\lambda \quad (1\text{-}4)$$

(In the following paragraphs differential definitions of the radiometric quantities are presented; these, however, are equivalent to the integral formulation of the functions defined.)

The limit of the ratio of the increment of radiant power ΔP radiated away from an element of area ΔA, as the area is reduced in size about a point, is defined as the radiant emittance W at that point. Thus

$$\lim_{\Delta A \to 0} \Delta P/\Delta A = W = \partial P/\partial A = P_A \quad (1\text{-}5)$$

It should be noted that in this definition the radiant power considered is that radiated into the hemisphere (2π steradians) from a point of the source. If we restrict the power considered in the definition to that in an increment of solid angle $\Delta\Omega$ about a particular direction, and reduce this small angle in size, then the limit of the ratio of radiant power to area and solid angle is the radiance of the source at the point and in the particular direction, i.e.,

$$\lim_{\substack{\Delta\Omega \to 0 \\ \Delta A \to 0}} \Delta P/\Delta A\,\Delta\Omega = N = P_{A,\Omega} \quad (1\text{-}6)$$

The power radiated by an entire source per unit solid angle in a particular direction is the radiant intensity J in that direction and may be defined as

$$\lim_{\Delta\Omega\to 0} \Delta P/\Delta\Omega = J = P_\Omega \tag{1-7}$$

Obviously,

$$J = \int_{\substack{\text{Area}\\ \text{of Source}}} N \cdot dA \tag{1-8}$$

and

$$W = \int_{\substack{2\pi\\ \text{steradian}}} N \cdot d\Omega. \tag{1-9}$$

A determination of radiance from measurements made at a distance from a source, which for simplicity is considered to be *in vacuo*, involves a knowledge of the orientation of the observation direction with respect to the normal at the observed point. This knowledge is often difficult, if not impossible, to obtain. Modification of the definition so that the projected area is used, i.e., so that ΔA is replaced by the projection of the elemental area perpendicular to the direction of observation, offers a simpler and more easily determined quantity. In addition, sources which obey Lambert's cosine law (so that $\partial J/\partial A$ varies as the cosine of the angle θ between the normal to the surface and the direction of the observation) will have a radiance which is independent of the direction of measurement. This modification could be written as:

$$N = \frac{\partial^2 P}{\partial\Omega\, \partial A \cdot \cos\theta} \tag{1-10}$$

and this definition of radiance will be used throughout this book.

Finally, the amount of radiant power per unit area received by a surface is given by the irradiance H defined as:

$$H = \partial P/\partial A = \lim_{\Delta A\to 0} \Delta P/\Delta A \tag{1-11}$$

The specification of H is not complete, however, without some statement about the directions of the incident radiation. Two cases illustrating this point are the irradiation of a surface by radiation from an extended source such as an overcast sky (so that the radiation comes from the full 2π steradians of the hemisphere), and the irradiance on a surface due to radiation from a point source such as a distant star. Such statements describing the source-receiver geometry are usually sufficient to complete the definition of the particular irradiance measured.

In the definitions presented so far no consideration has been given to wavelength. If ΔP is the increment of radiant power in the interval λ to $\lambda + \Delta\lambda$ in each of the definitions given, then the limits of $\Delta W/\Delta\lambda$, $\Delta N/\Delta\lambda$, $\Delta J/\Delta\lambda$, and $\Delta H/\Delta\lambda$, as $\Delta\lambda$ becomes smaller, will define the spectral quantities

$$W_\lambda = \partial W/\partial\lambda \tag{1-12}$$

$$N_\lambda = \partial N/\partial\lambda \tag{1-13}$$

$$J_\lambda = \partial J/\partial\lambda \tag{1-14}$$

and

$$H_\lambda = \partial H/\partial\lambda \tag{1-15}$$

Similarly,

$$P_\lambda = \lim_{\Delta\lambda \to 0} \Delta P/\Delta\lambda \tag{1-16}$$

The other radiometric quantities listed in Table 1-1 are considered to be defined by the statements listed in the column entitled "Description." However, certain qualifications and cautions should be noted. The absorptance α is a measure of the fraction of incident radiation absorbed by a receiver, and should be distinguished from other concepts, such as the fraction absorbed per unit path or unit concentration. Specification of the reflectance of a single, specularly reflecting surface requires additional statements. The angle of incidence, the curvature of the incident wavefronts, polarization, and other conditions need to be stated. For diffusely reflecting surfaces the situation is more complicated. A common, although by no means universally accepted, concept has been named the partial reflectance. This is the ratio of the radiant power reflected in some angle β to the radiant power incident at some angle γ. The reflectance is then the ratio of the total reflected power, in all directions, to that incident on the surface. Again, for transmittance, several qualifying statements are needed to ensure the complete specification of the particular quantity considered. The definition of emissivity requires a specification of the thermodynamic variable, temperature, of the body. If a single recognizable temperature of the body does not exist, then "emissivity" is a meaningless concept for that body.

All of the quantities α, ρ, τ, and ε may depend upon the spectral distribution of the radiation used in the measurement of these quantities. The wavelength dependencies may be determined by measurements of radiation in very small wavelength regions since

$$\varepsilon(\lambda) = \lim_{\delta\lambda \to 0} \left\{ \frac{\int_{\lambda-\delta\lambda}^{\lambda+\delta\lambda} W_\lambda(\lambda)\, d\lambda}{\int_{\lambda-\delta\lambda}^{\lambda+\delta\lambda} [W_\lambda(\lambda)]_{\text{Blackbody}}\, d\lambda} \right\} \tag{1-17}$$

is the emissivity at λ. Since $\varepsilon(\lambda) \neq \partial\varepsilon/\partial\lambda$, the subscript notation ε_λ is not correct here. Similar considerations apply to the spectral reflectance, transmittance, and absorptance.

1.2 Effects of Attenuating Media

Although the quantities just discussed are generally cited in connection with a source or receiver, it is often useful to be able to specify some radiometric quantities in the radiant field between the source and receiver. This may be easily done by the introduction of a "test" receiver at the point under consideration. Thus, for a point source of intensity J in a nonattenuating medium, a test receiver at a distance s from the source receives an irradiance,

$$H = J/s^2 \tag{1-18}$$

The receiver aperture can next be considered a source with rays limited to those angles that fit the geometry. Now the values of W and N can be stated (in accordance with the previous definitions), and thus the radiometric quantities may be meaningfully applied at any point in the radiant field. This concept is most useful in connection with optical systems, since radiant power, emittance, irradiance, and radiance can be calculated at lenses, mirrors, images, and the like. By the law of conservation of energy the invariance of radiance in a lossless medium can be shown. Even in lossless media with different indexes of refraction, the ratio of the radiance (measured at any point along a ray in an image-forming system) to the square of the relative index of refraction at that point (i.e., N/n^2) is a constant.

These considerations must be modified greatly if the media considered are not lossless. The processes of absorption, scattering, and emission may occur in the medium between source and receiver. The adjective "apparent" is used to modify any quantity describing the source which has been calculated, with no attempt at inclusion of the effects of the intervening medium. For example, if Eq. (1-18) were used to calculate J for a source when actually half the source radiation was lost by absorption in an intervening medium (i.e., $\tau = 1/2$), then the quantity $H \cdot s^2$ would yield the apparent radiant intensity J', while the radiant intensity would be given by

$$J = 2 \cdot J' = 2H \cdot s^2 \tag{1-19}$$

Similarly, one may measure the apparent radiance or emittance of a source. It is of interest to note here that, since an infrared background is defined to include the emission, scattering, and absorption of the atmosphere, measurement of infrared backgrounds can never yield an apparent radiance. The adjective may be applied to the irradiance at a receiver in some