INFRARED PHYSICS AND ENGINEERING

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Frederick Emmons Terman

PREFACE

The purpose of this book is to provide a basic understanding of the physical background and engineering considerations required for the design of infrared systems. The book is written for engineers, physicists, and mathematicians. It is hoped that anyone with an undergraduate training in any of these fields can understand the various chapters of the book provided that they are read in proper sequence. On the other hand the book is also meant to be useful to infrared practitioners with advanced training in the field, as the current state of knowledge is discussed and summarized in each chapter.

The basic principles are emphasized in each chapter, as these will always be useful in the development and understanding of new infrared devices. Today an engineer is no more satisfied than a physicist with a superficial treatment of a subject. For each topic the authors have presented the important facts as they understand them. Naturally their selection of topics has been biased to some extent by their own research. The presentation is not meant to be encyclopedic or to be a mere catalogue of all the results obtained in a given field. In particular, the list of references at the end of each chapter is meant to suggest some important sources where the authors feel that it is profitable to look for additional information; it is not a complete bibliography.

The various authors were selected so that they could provide an authoritative treatment for all the subjects covered in this book. A single writer can rarely provide a similar understanding of many diverse subjects. However, the advantage of multiple authorship is often negated by a lack of coordination between the work of different contributors. In an attempt to avoid this difficulty the authors have held numerous meetings, which helped to provide a unified point of view. It is hoped that any remaining differences of style and presentation between the various chapters have been minimized.

The plan of the book is as follows: An introductory chapter describes briefly the philosophy and historical background of the infrared field. The laws which govern the radiation of electromagnetic energy from molecules and solid objects are reviewed in Chapter 2. A discussion of the many factors which influence the transmission of infrared radiation through the atmosphere is given in Chapter 3. These two chapters should be read in order. Chapter 4 is about backgrounds and targets and describes the various spectral characteristics of radiation emitted by various natural and man-made sources.

A description of the different types of infrared detectors and their methods of operation is given in Chapter 5. The optical principles of infrared systems are considered in Chapters 6 and 7, which describe infrared optics and infrared optical materials.

The subjects considered in Chapters 8 to 13 all require the use of probability theory. The background of mathematical statistics needed for the other chapters in this group is summarized in Chapter 8. Chapter 9 deals with the aspects of operations analysis which are useful in dealing with infrared systems. Chapter 10 deals with some important topics concerning the physical sources of noise, including a discussion of Gaussian noise and other stochastic processes. Topics of electronic engineering where the signal-to-noise ratio is of primary importance are considered in Chapter 11.

Chapter 12 deals with the theory of space filtering as applied to the discrimination between targets and random backgrounds on the basis of size and shape. Chapter 13 describes the design of systems from the point of view of information theory and the theory of statistical hypothesis testing, with emphasis on the calculation of detection probabilities and false-alarm rates. The choices made in designing a scanning system together with applications of the theory and principles which are described in the previous chapters are given in Chapter 14 on Infrared Systems.

The authors wish to thank the many persons who have permitted the use of their material in this book. It is impossible to mention individually all those who have made suggestions about the many topics presented. Finally the authors wish to thank their secretaries for their aid in typing and preparing the material for publication.

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CHAPTER 1

INTRODUCTION

1-1. The Present Significance of Infrared Technology. Among the many new techniques which have become of significance in applications beyond the laboratory is the field known as *infrared.* The term infrared is generally applied to devices which depend for their basic information upon the electromagnetic energy of wavelength between 0.7 and 1,000 μ (0.7 to $1{,}000 \times 10^{-4}$ cm) which is reflected from, absorbed by, or emitted by objects of interest. The comparatively recent rise in interest and importance of infrared is due to the appearance of military operational applications of some significance. One of the more dramatic demonstrations of the effectiveness of infrared was the destruction of several aircraft by infrared-guided Sidewinder missiles over the Chinese offshore islands in 1958.

Infrared detection techniques have been employed for many years for instrumentation in the laboratory and industry. However, the application of infrared detection to devices which must meet a host of requirements as operational equipment under conditions never faced in the laboratory or plant has generated a new field of engineering unlike any other in its combination of specialty areas.

Infrared engineering, like radar engineering, has evolved under cover of military security. Many current applications are still highly classified, and details cannot be divulged. As the art progresses, more of the basic concepts become common knowledge and a coherent picture can now be assembled of the field of design of operational infrared systems. Unlike radar, which received a monumental development effort during World War II, operational infrared has evolved rather slowly, on a limited-budget basis. With the advancement of military strategy into environments which are more favorable to the infrared technique, such as high altitude and space, infrared devices are receiving more serious attention.

The unique capabilities of infrared devices, with the expenditure of relatively little in weight, complexity, and power, have become significant in relation to the operational requirements of modern armament.

By making use of the natural emission of thermal or molecular radiation from objects of military interest, most infrared systems operate as passive detectors of their presence and direction. No energy is required to be transmitted by the observer in order to observe the target by reflection, as is the situation with radar systems. The feasibility of the infrared technique has been improved by the development of more sensitive detectors, a greater variety of infrared optical materials, and a large number of new scanning system designs.

Infrared devices are basically optical in nature; that is, they use lenses and mirrors to direct and concentrate the radiation for detection. The high angular resolution afforded by the relatively short wavelength of the infrared radiation detected by operational equipment has allowed the design of equipments which provide directional information on targets to a degree of precision which cannot be duplicated by microwave devices of many times their size.

The infrared technique has its limitations, however, as have all available methods. Although infrared can penetrate atmospheric haze more effectively than can visible light because of its longer wavelength relative to the scattering haze, particle size, transmission through fog and clouds is very little better than for visible radiation. Atmospheric gases absorb severely at some wavelengths in the infrared region, although there are relatively clear spectral bands, known as atmospheric "windows," which can be utilized over great path lengths (see Chap. 3).

The fact that all objects of temperatures above absolute zero radiate energy, much of it in the infrared, means that there is always present a certain quantity of radiation from the background, either external or internal, which must be contended with in the detection of a weak or distant target. In the near infrared ($<3\ \mu$) reflected sunlight becomes a serious problem as in the important situation of the detection of aircraft against a cloud background in the daytime. These characteristics may mean that the infrared system may have a limited daytime or all-weather capability, unless special techniques for discriminating in favor of the target against the background are brought to bear.

As operational aerial tactics move steadily to higher and higher altitudes with the development of improved-performance aircraft, the feasibility of infrared techniques of target detection and tracking has grown to the degree where in some applications it replaces a heavier, more power-consuming radar. Other applications make use of the high angular accuracy of infrared devices to supplement radar equipment, which can provide better target-range information. Outer space provides a highly favorable environment for infrared techniques, with relation to the propagation of radiation. With no absorption or scattering of the intervening medium, a free selection may be made of the operating wavelength region, based on considerations other than the transmission of the path between source and receiver.

1-2. Historical Development of Infrared Applications. After the discovery of the existence of the infrared region of the electromagnetic spectrum by Sir William Herschel in 1800,[1,*] the nineteenth-century effort in the field consisted in the study and understanding of the nature of infrared. With the gradual evolution of detection devices for this region of the spectrum, the extent and structure of infrared spectra became more and more evident. A thorough review of the history of the science of infrared has been given by Smith, Jones, and Chasmar.[2]

By 1900, many techniques for the dispersion and detection of infrared radiation had been devised. The radiation thermocouple, its multiple version, the thermopile, and the bolometer constituted the available means of detection at that time. Except for the near infrared, where glass could be used as a transmitting material, optical systems were largely made up of reflecting elements.

As the understanding of the characteristics of infrared and the techniques to detect and measure the radiation became available, applications began to appear. At first, infrared techniques were used only in the laboratory in the experimental investigations on the radiation itself. Later, astronomers began to use infrared detectors with their telescopes to obtain estimates of the temperature of stars and planetary surfaces by measuring the infrared radiation from them. The study of the physics of the sun has been aided considerably by the use of infrared detectors in radiometer telescope systems.

The powerful tool of infrared spectroscopy for chemical analysis has been employed for many years. The method has grown into a highly developed science, with a variety of instruments for the analysis of gases and liquids by their infrared absorption spectra. Williams[3] has related in detail the development of the techniques of infrared spectrochemical analysis.

The system designs of the infrared spectroscopic instruments, such as the spectrograph, spectrophotometer, and monochromator, have

* References, indicated by superscript numbers in the text, are listed at the end of the chapter.

been, and still are, direct evolutions from the physics laboratory designs. Usually, the additional design features imposed by the requirements of industrial application have been limited to those concerned with packaging, reliability, and stability. Recently, more attention has been paid to convenience of operation and data handling.

With the advent of military infrared applications, additional requirements were brought to bear, which were related to the size, weight, power consumption, and field maintenance of the devices. In general, the military devices were required to operate at speeds much greater than those demanded of the laboratory instruments. New detection problems were encountered because of the nonideal conditions obtaining in the military situations. Arnquist[4] has given a detailed account of the early military developments.

Military infrared did not receive much attention until World War II. With the availability of more sensitive and effective detectors of infrared radiation early in the war, developments slowly began to appear. The most advanced infrared equipments, which reached operational status during the war, were the active Sniperscope and Snooperscope systems. These devices used photoemissive image tubes, sensitive to 1.2 μ, to observe the reflected infrared from scenes illuminated by searchlights filtered to cut out the visible light. Sniperscopes were used successfully as part of the gunsight for rifles fired at night. Snooperscopes were particularly useful for driving vehicles at night by invisible headlight illumination.

The first of the photoconductive detectors began to appear in practical form during World War II. Thallous sulfide (thalofide) detectors, highly sensitive out to 1.2 μ, were developed for application in visible-light signaling systems. Substantially independently, lead sulfide detectors were developed during the war in Germany (1939–1945) by Gudden and others and in the United States by Cashman.[5] The PbS detector, with high sensitivity and rapid response in the infrared to about 3 μ, allowed for the first time the development of effective detection devices operating from the passive radiation from military targets, such as aircraft. Improved forms of thermal-type detectors, thermocouples and bolometers, were developed during World War II and were employed in a variety of military devices.

Several equipments reached limited operational status during the war. None of these, however, were developed to the degree where they constituted major military-armament subsystems. The German equipments produced during the war reflected the approach characteristic of the superb German optical capability. Several near-infrared devices, employing glass optics and photoemissive detectors, reached limited production status. Some were actually used in the field for gun laying by reflected radiation from targets such as tanks.[6]

Among the American devices were an infrared-guided bomb which used a bolometer as the sensor, several varieties of communication devices, scanning systems for detection of heat-radiating targets, such as tanks or ships, and a thermal mapping device. The operation of these equipments left much to be desired at that time, owing mainly to limitations of the available components and techniques.

Since World War II, both the interest in and the capabilities of infrared equipment have steadily increased. Improvements in the characteristics and reproducibility of detectors in the intermediate (1.5 to 10 μ) region have allowed the design of passive detection devices of progressively more useful capabilities. Spectacular performance by such equipments as the Sidewinder infrared-guided missile has helped to focus attention on the military possibilities of the infrared technique.

Current military applications have taken the form of missile guidance systems, fire control subsystems, bomber-defense devices, thermal reconnaissance equipment, and other devices whose existence and designs are still kept under military security classification. Klass[7] has given a review of the recent status of unclassified military infrared.

Infrared has also found application in industrial instrumentation and control systems. The infrared spectrometer has been used for many years as an analytical tool in industrial laboratories for purposes of determination of the nature and quantity of a great variety of organic substances in liquids and gases. The petroleum industry relies heavily on the infrared spectrometer for the qualitative and quantitative analysis of hydrocarbons by means of the unique infrared spectra of the various constituents of the complex mixtures.

The radiation pyrometer, a device which responds in proportion to the quantity of radiation incident upon it, has been used for some time as a remote temperature measuring device as well as an automatic temperature-control system component.

The infrared radiation from flames has been employed in devices for the automatic shutdown of industrial gas- or oil-fired boilers in case of flame failure. The lead sulfide infrared detectors in these controls monitor the presence of the flickering infrared radiation peculiar to flames. Similar devices are at present on the market which use infrared as a fire-alarm system component. A single infrared detector can be located at a strategic position in an area such as a warehouse and can detect the appearance of a fire remotely by its flickering infrared radiation.

Short-wavelength infrared is also used in invisible photography. Photographic emulsions can be made with sensitivity extending into the infrared to about 1.3 μ. If filters are used to block off radiation shorter than 0.7 μ, pictures can then be taken with invisible radiation only.

1-3. Infrared Physics and Engineering. Infrared physics, as defined for the purpose of this book, includes the description and analysis of the basic phenomena related to the emission, transmission, direction, and detection of infrared energy. The thermodynamics of the emission of radiation, the absorption and scattering of radiation through the atmosphere and through optical elements, the influence of optical elements on infrared radiation, and the physical phenomena associated with the process of detection of infrared radiation represent various aspects of the physics of infrared technology. Infrared engineering we have defined as that field of engineering which includes the design, development, and construction of devices which perform functions based on information gained from the detection of infrared radiation.

Underlying both infrared physics and engineering is the necessary foundation of mathematical techniques. The basic understanding of the phenomena and processes involved in the detection of radiation and the subsequent extraction of the available information requires the application of mathematical analysis at several points in the design. Discussions will be given in later chapters of the mathematical techniques as related to the problems of the design of infrared systems.

Infrared engineering has evolved from the applied physics-research approach to equipment construction into a mature engineering operation of somewhat unique characteristics. Several fields of physics and engineering are drawn upon in combination to produce the optimized design for the application. Infrared detectors, still under active development, are the subject of research in solid-state physics, since most of the important detectors employ some form of semiconductor as the sensitive element. Optics, physical as well as geometric, is heavily involved in infrared equipment design. Beyond the basic design, optical engineering must be brought to bear in order that the lenses, mirrors, filters, and other optical elements be capable of useful operation under environmental conditions experienced by equipment in the field. Electronic circuit design, although less complex than radar equipment designs, must be provided with characteristics which serve to make use of the information available from the detector in a form suitable for the presentation means.

All the many techniques which have been developed for high-reliability military electronic gear are applicable for infrared systems. The mechanical design of many infrared systems involves numerous sometimes conflicting requirements imposed by scanning operations, gimbals, slip rings, packaging, etc.

The infrared system designer should be sufficiently familiar with all the above fields in order to achieve the most nearly optimum combination of characteristics. Frequently this can be accomplished by use of a team of specialists, but the project engineer should be versed in all aspects of infrared engineering.

1-4. Procedure in Development of an Infrared System. The process of arriving at a thoroughly developed production model of an infrared system from the initial operational requirements is similar in principle to that of the development of many other types of systems. In order to indicate the roles of the various areas of discussion to be given in the following chapters, let us review the detailed procedure to be followed in the development of a typical infrared system. The flow diagram given in Fig. 1-1 shows how the system is evolved from the operational requirements through the various design and model construction stages to the production model. It should be mentioned that this procedure is not necessarily followed for all system developments. Simple devices may well be developed without necessity for construction and testing of all three models, breadboard, engineering, and prototype, before the production model is built. Also, systems which represent variations or departures from previously developed devices may not require a return to the early development phases.

Operations analysis is applied as a first step in the development for the purpose of assuring the effectiveness of the equipment in its application. This type of analysis is used to interpret the operational requirements into specifications for infrared equipment, on the one hand, and to indicate the operational significance of infrared equipment of a certain set of characteristics, on the other. A set of specifications is established which then represents the best compromise between the desires of the equipment user in his operational application and the capabilities of the infrared art. The techniques of operations analysis as applied to infrared systems are discussed in detail in Chap. 9.

The preliminary design phase is often separated from the principal design activity, in order to establish the most promising design direction while some flexibility may still exist in the determination of the system specifications. The procedure of compromising is properly carried out in conjunction with the operations analysis in the process of laying out the basic design of the infrared system. This operation may be performed by an individual or group of specialists, who

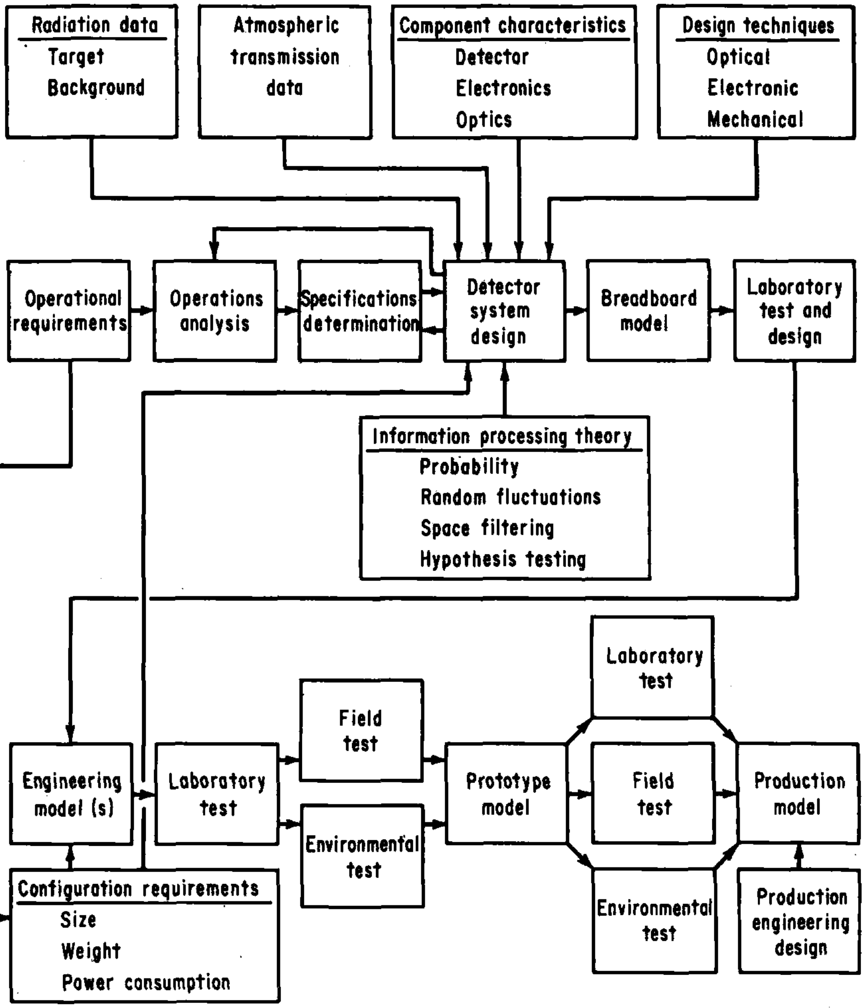

FIG. 1-1. Flow diagram of the development of an infrared system.

will relinquish the design function to the development project engineer after the preliminary approach has been established.

With the initial design approach determined, the project takes over the function of working out the detailed detector system design. The system is broken down into subsystems, each of which is designed in detail by specialist groups operating under coordination by the project engineer. Infrared systems are usually divided into optics, detector, electronics, and mechanical subsystems. Each of the subsystem designers draws upon the components and techniques that have become available to him. Information on the magnitude and conditions of observation of the available radiation to be detected is also made available to the designer.

With the crystallization of the infrared system design, the first model is constructed. Where the design is a relatively new, untried one, an experimental ("breadboard") model is usually put together for preliminary evaluation of the design principles in the laboratory. A process of laboratory testing and "debugging" is then carried out with the breadboard model. Often, the design principles are changed as a result of experience with the first model.

At the point where the basic design is established, a second model, sometimes called an "engineering" model, is built. In addition to the basic performance specifications, approximate configuration requirements are also fed into the engineering model. The device should conform roughly to the size, shape, and weight requirements indicated by the application. The engineering model, after laboratory tests to define its basic performance characteristics, is usually put through preliminary field tests. If the equipment is to be airborne, flight tests may be made. Basic environmental tests are made on the engineering model to determine its ability to withstand shock, vibration, temperature and humidity extremes, etc., as required. Design changes are made if failure in the tests occurs.

After the engineering model has successfully passed the requirements, the prototype model is designed and constructed. Occasionally, in cases where a great deal of development is required, several stages of engineering models may be required before the prototype is arrived at. The prototype design represents the optimum combination of performance characteristics and a configuration suitable for installation and maintenance. The model must pass a full set of tests representative of the operational application.

After the development of a satisfactory prototype, the production model is designed. According to the expected quantity of production, techniques of fabrication and testing are employed to reduce costs and ensure reproducibility. Various degrees of production engineering may be required as large-quantity production is demanded.

1-5. The Detector System Design. The procedure of arriving at a complete infrared detector system design involves a complex combination of techniques and data unique to this field. It is the primary purpose of this book to present the design and analytical techniques and physical data which make up the process of detector