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INFRARED TARGET AND BACKGROUND RADIOMETRIC MEASUREMENTS—CONCEPTS, UNITS, AND TECHNIQUES

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Abstract—This report discusses concepts, units, and techniques for making and describing measurements of radiation from targets and backgrounds.

1. INTERPRETATION OF TARGET AND BACKGROUND

1.1. *Introduction*

SINCE the terms "target", "background", and "atmospheric phenomena" are used throughout this report, it is necessary to establish some basic definitions or concepts for these terms. The following paragraphs present the Working Group on Infrared Background's interpretation of them to make sure that the reader is properly oriented.

1.2. *Target and Background*

A target is an object to be detected, located, or identified by means of infrared techniques. A background is any distribution or pattern of radiant flux, external to the observing equipment, which may interfere with this process.

An object may thus at one time be a target and at another be part of the background, according to the intent of the observer. An electric-power generating plant is part of the background if the target is a ship moving in a nearby river, but is not if the generating plant itself is the target. Likewise, all terrain features are of interest to the users of certain reconnaissance devices and hence are targets. However, information obtained by such equipment is useful background data to other investigators. In short, one man's target is another man's background.

1.3. *Atmospheric Phenomena*

Some major problems in correlating target and background data are caused by atmospheric phenomena. Effects such as the attenuation of emitted and reflected radiation from background objects, and self-emission and scattered radiation from the atmosphere itself, contribute to the interfering radiation pattern seen by the observing instrument and so are included with the background. The attenuation of radiation from a target, however, is a separate effect; the problem of accounting for this is treated in subsequent sections of this report. Scintillation and refraction in the atmosphere, which cause difficulties in the detection and location of targets at long ranges, are not considered.

2. RADIOMETRIC UNITS AND CONCEPTS

2.1. *Introduction*

The nomenclature, units, and descriptions of the primary physical quantities considered most important to infrared technology are given here so that workers in this field may communicate in a common language. The WGIRB prefers the names, symbols, and units given in Table I, most of which are taken from the American Standards Association.(1)

2.2 *Radiometric Units*

The preferred units are based on the metric system. Units differing from the given units by factors which are integral powers of 10 are desirable when the size of the measured quantity makes such a change convenient.

2.3. *General Concepts and Descriptions of Radiometric Quantities*

The concepts of radiant emittance, radiant intensity, and radiance are usually considered in reference to a radiating source and are measures of the properties of a source. These properties can be determined by measurements made at a distance from the source if the intervening space contains a nonattenuating medium. Let us consider for the present that the measurements are made in a nonabsorbing and nonscattering medium; the difficulties caused by an intervening attenuating medium will be discussed later.

2.3.1. *Radiometric Quantities Referred to a Source in Vacuum*

The average *radiant emittance* of a source is the ratio of the total power radiated away from the source, to the total area of the source. The average radiant emittance of a small portion of a source is the ratio of the total power radiated from that small portion of the source, to the area of that small portion. The limiting value of the average radiant emittance of a small portion of a source as the area is reduced in size about a point is the radiant emittance of the source at that point. The total radiation from the elemental area includes all that which is radiated into the hemisphere (2π sterad). Radiant emittance measures the power radiated into the hemisphere per unit of the source and is then $W = \partial P/\partial A$, where A is a measure of area.

The average *radiant intensity* of a source is the total power radiated by the source, divided by the total solid angle about the source (4π sterad). The average radiant intensity within a given solid angle is the ratio of the power radiated within the given solid angle to the size of the solid angle. The limiting value of the average radiant intensity in a solid angle, as the solid angle is reduced in extent about a particular direction, is the radiant intensity J in that direction. Radiant intensity measures the power radiated per unit solid angle in a particular direction, and it is $J = \partial P/\partial \Omega$, where Ω is the measure of the solid angle.

The average *radiance* of an area of a source in a given solid angle is the total amount of power radiated from that area into that solid angle, divided by the product of the area and the solid angle. The limiting value of the average radiance as both the area and the solid angle are reduced in extent is the radiance at a point in a direction. The radiance measures

TABLE 1. SYMBOLS, NOMENCLATURE, AND UNITS

Symbol	Name	Description	Unit
U	Radiant energy		joule
u	Radiant energy density		joule/cm^3
P	Radiant power	Rate of transfer of radiant energy	watt
W	Radiant emittance	Radiant power per unit area emitted from a surface	W/cm^2
H	Irradiance	Radiant power per unit area incident upon a surface	W/cm^2
J	Radiant intensity	Radiant power per unit solid angle from a source	W/sterad
N	Radiance	Radiant power per unit solid angle per unit area from a source	W/sterad per cm^2
P_λ	Spectral radiant power	Radiant power per unit wavelength interval	W/μ
W_λ	Spectral radiant emittance	Radiant emittance per unit wavelength interval	W/cm^2 per μ
H_λ	Spectral irradiance	Irradiance per unit wavelength interval	W/cm^2 per μ
J_λ	Spectral radiant intensity	Radiant intensity per unit wavelength interval	W/sterad per μ
N_λ	Spectral radiance	Radiance per unit wavelength interval	W/sterad per cm^2 per μ
ϵ	Radiant emissivity	Ratio of "emitted" radiant power to the radiant power 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		μ

the radiant power per unit area per unit solid angle in a particular direction, and it is $N = \partial^2 P/\partial A \partial \Omega$. From this definition it follows that $J = \int N dA$, where the integral is over the source area, and also that $W = \int N d\Omega$ where the integral is over 2π sterad.

Determination of the value of the radiance at a point on a source necessitates a determination of the size of a small elemental area of the source. Since the measurement is made from a distance, as it always must be, the orientation of the elemental area with respect to the line of observation may be unknown, and therefore the area may be undetermined. The projection of the area on to a plane perpendicular to the direction of the measurement can usally be determined, however. If the projected area rather than the true area is used in the definition of radiance, then the orientation of the source need not be known for the radiance to be determined. The use of the projected area leads to the useful concept that the radiance of a source which obeys Lambert's cosine law is independent of the direction of measurement. It also allows a sensible measure of the radiance of a rough or tortuous surface. In measurements and other considerations of background radiances, this projected area of the background is usually assumed. The sky does not have a uniquely associated true area—it does not even have a distance away from the observer—yet there is a good measure for the radiance of such a background. Any work should make clear which of these area concepts is being used.

Irradiance is a measure of the radiant power per unit area received by an elemental surface area. It has the same units as radiant emittance but refers to the radiation incident upon a receiving surface rather than that leaving an emitting surface. Both radiant emittance and irradiance are measures of the areal density of radiant power (often called flux density). The radiation incident upon the receiving surface may be limited, in a particular situation, to that which originates from a given source or which arrives within a given solid angle. When so restricted, the receiver surface irradiance is the areal density of the power from the source under consideration, and this power need not arrive from a full 2π sterad of solid angle. It is sufficient then to speak of the irradiance of a radiometer collecting mirror produced by a particular source under measurement simply as the irradiance of the collecting mirror if the actual source and its extent have been implied by previous remarks.

2.3.2. *Spectral radiometric quantities*

The radiometric quantities *radiant emittance*, *irradiance*, *radiant intensity*, and *radiance* are used to help specify a particular portion—that within a particular solid angle, or passing through a particular area—of all the radiation being considered. These quantities are differential with respect to solid angle and area and must be integrated over the appropriate variable in order to obtain the radiant power.

There are also quantities which are differential with respect to wavelength. One of these is the spectral radiant power, which is the radiant power per unit wavelength interval, or $\partial P/\partial\lambda = P_\lambda$. The value of P_λ will ordinarily vary with λ, and the radiant power between λ_1 and λ_2 is given by $\int_{\lambda_1}^{\lambda_2} P_\lambda d\lambda$.

Other useful spectral quantities are as follows: spectral radiant emittance, $\partial W/\partial\lambda\ W_\lambda$; spectral irradiance, $\partial H/\partial\lambda = H_\lambda$; spectral radiant intensity, $\lambda J/\partial\lambda = J_\lambda$; and spectral radiance, $\partial N/\partial\lambda = N_\lambda$. (It is to be noted that the subscript notation for the partial derivative with respect to wavelength for these particular quantities has had almost universal acceptance, and therefore the subscript λ should not be used on these particular quantities in any other context.)

These spectral quantities are measured by spectroradiometers, but may be crudely measured by radiometers equipped with filters.

2.3.3. *Other radiometric quantities*

The absorptance α of a system measures the fraction of the incident radiation which is absorbed by the system. The absorptance must be distinguished from an "absorption constant", which measures the fraction absorbed per unit path length or per unit concentration.

The meaning of a value of the reflectance ρ for a single, specularly reflecting surface is well understood. The meaning of a value of ρ for a diffusely reflecting surface or for a partially transparent body with internal scattering is not easily specified. This difficulty arises from the complicated angular dependence of the "reflected" radiation and from the inability to separate, in a general definition, the transmitted, scattered, and reflected portions of the radiation. When the reflection is nonspecular or involves more than one surface, the reporter should carefully specify what he means by "reflectance".

The meaning of a value of the transmittance τ of a nonscattering homogeneous medium is well understood. As in the case of reflectance, however, the meaning of transmittance can be confusing, particularly when a medium exhibits diffuse reflection and scattering. The investigator, therefore, should be careful to specify what he means by "transmittance".

The absorptance of a system is usually calculated from measurements of the reflectance and transmittance by the relation $\alpha = 1 - \rho - \tau$. When there is no scattering and when the reflection is specular, calculation is simple. If there are diffuse reflections and scattering, then the calculations will be complex, necessarily including all of the incident radiation which escapes from the system without absorption.

The emissivity of a body at some certain temperature is the ratio of the radiant emittance of the body to the radiant emittance of a blackbody at the same temperature. If a body does not have a single recognizable temperature, then its "emissivity" will be meaningless.

Physical systems have values of α, ρ, τ, and ϵ which are dependent upon the spectral distribution of the radiation used in the measurement of these quantities. If the radiation used for the measurement is confined to an infinitesimally small wavelength range about wavelength λ, then the particular values $\alpha(\lambda)$, $\rho(\lambda)$, $\tau(\lambda)$, and $\epsilon(\lambda)$ are determined. (The subscript notation α_λ, ρ_λ, ϵ_λ, τ_λ, etc., is apt to be confused with the differential notation, P_λ, W_λ, H_λ, J_λ, N_λ. Hence, the parenthetic notation is preferable.)

2.3.4. *Radiometric quantities as field concepts*

As has been indicated, the concepts of radiant emittance and radiance are normally thought of as referring to a source of radiation, and that of irradiance as referring to a sink, or receiver, of radiation. These radiometric concepts can also be applied to the radiation in a radiation field away from sources and sinks, however, and it is often convenient to do so. One could place in the radiant field a barrier surface containing an aperture. This aperture has the essential radiant properties both of a source for the radiation leaving the aperture and of a sink for the radiation incident on the aperture. At the point in the radiation field defined by reducing the size of the aperture, there is a sensible measure of the radiant emittance, irradiance, and radiance of the "aperture", and thus of the radiation field. These radiometric quantities will be dependent upon the orientation of the aperture in the radiation field. For the usual consideration of the radiation field produced by a single, distant small source, it is natural to specify the radiometric quantities only along the direction of rays from the source.

It can be seen that, ideally these radiometric field quantities can be measured at a point in a radiation field by a properly calibrated radiometer placed at that point.

It is very useful to extend the definitions of these radiometric quantities to measure the properties of a radiant field, as well as the properties of a source. These field quantities can be evaluated, for example, at lenses, mirrors, apertures, entrance pupils, exit pupils, real images, or virtual images in a variety of ways to make calculations simpler or more understandable. Of special importance in this connection is the fact that the radiance from a source measured at any point along a ray in an image-forming system, is a constant. (To be correct for radiation passing through several media without loss, the constant quantity is N/n^2, where n is the index of refraction of the medium at the point of evaluation of the radiance N.) It is because these radiometric quantities have meaning in the radiation field away from the source that it is necessary to modify the names of the quantities carefully when they are used away from the true source. Without such modification it would normally be assumed that the values were those of the actual source of the radiation.

In practice, the measurement of the radiometric properties of a source by a radiometer at a distance from the source is equivalent to the measurement of some radiant field quantity together with certain geometrical factors, such as the field of view, the entrance pupil area, or the distance from the radiometer to the source. For example, when a small source is at a large distance s from the radiometer, the radiant intensity J of the source is related to the entrance pupil irradiance H by the equation $J = s^2H$. Thus, determining H at the radiometer and the distance s allows one to calculate J at the source. Such determinations of the source properties will be valid only to the approximation that the intervening medium is nonabsorbing and nonscattering. For attenuating media, exact calculation of the source quantities from the distant field quantities is difficult—and usually impossible.

2.3.5. *Radiometric quantities referred to a source in an attenuating medium*

Calculating radiometric characteristics of a source in an attenuating medium from measurements made at a distance always involves some assumptions about the nature of the attenuation, emission, and scattering of the intervening medium. Thus, the calculated source characteristics may be in error by an unknown amount. If, in calculating the source characteristics, no attempt is made to include the effects of the intervening medium, then the calculated quantities are "apparent" quantities. The radiant intensity of a target calculated from measurements made one mile away with no correction for atmospheric attenuation would be the *apparent* radiant intensity of the target. If, on the other hand, the calculation corrects for the attenuation and other effects of the atmosphere to the satisfaction of the investigator, then it may be called the radiant intensity of the target. Likewise, without considering the intervening medium, one can calculate the apparent radiant emittance or the apparent radiance of a target. The calculation of the radiant emittance or the radiance would include some consideration of the intervening medium.

When the infrared targets being measured are distant, as is usual, the investigator has limited confidence in the available methods of adjusting the apparent radiometric quantities for the effects of the intervening atmosphere. He should point out this uncertainty and describe the method of computation.

2.3.6. *Terminology for source and field radiometric quantities*

In this report distinctions between radiometric quantities attributed to source and those which are a property of the radiation field are made as follows:

2.3.6.1. *Targets.* Radiance, radiant intensity, etc., when used in connection with a well defined source, such as a target, are considered properties of the source. Accordingly, the radiation field quantities of a target measured by the radiometer at a distance are called *apparent radiance*, *apparent radiant intensity*, etc., of the target. This distinction emphasizes the difficulties in determining intrinsic source properties by measurements through the atmosphere. (Since irradiance is a field quantity by concept, "apparent" irradiance would be redundant.)

2.3.6.2. *Backgrounds.* An infrared background is defined to include the contributions of the emission, absorption, and scattering of the atomsphere to the radiant flux pattern that interferes with the detection process. Thus the background is a nonlocalized source extending from the observing instrument outward. Thus, for backgrounds, in contrast with the case for targets, it is not possible to distinguish between the concepts of *radiance*, an intrinsic property of a specific source, and *apparent radiance*, a field quantity. Since "apparent" implies the existence of possible corrective procedures, the field quantity measured for backgrounds will normally be called *radiance.*

2.3.6.3. *Calibration of radiometers.* Radiometers can measure only field quantities. No special terminology will be used to emphasize this. Therefore, a radiometer is calibrated in radiance responsivity in order to measure the apparent radiance of a target.

3. SOURCE CHARACTERISTICS AFFECTING INSTRUMENT CHOICE

3.1. *Introduction*

The preceding section discussed the mathematical and physical relationships among the various radiometric quantities. Section 4 discusses at some length the characteristics of specific types of instruments, and Sections 5 and 6 treat the detailed techniques and procedures that can be used most appropriately with specific classes of instruments. This section deals primarily with the source characteristics to be measured and their influence upon the choice of instruments.

3.2. *The Measurement Problem*

In general, the purpose of the measurement is to establish some relationship between the radiation from some physical source and the various parameters governing that source. The major problem of measurement is emphasizing the relationship of greatest interest. This problem arises because of the large number of independent variables which may affect the radiation measurements. Therefore, careful judgment must be exercised in selecting the most significant variable or variables.

Among these variables are wavelength, time, aspect, altitude, power setting, fuel, etc. Realizing that wavelength is not under control, the observer may fix power setting and altitude as he determines the wavelength dependency of radiant power.

3.3. *Basis for Instrument Choice*

Generally, four broad classifications of source characteristics are of interest in radiometric measurements: (1) spectral distribution, (2) spatial distribution, (3) temporal variations of the spectral and/or spatial distribution, and (4) the level of radiation and its dynamic range. The characteristic to be measured determines the choice of instrumental technique.

3.3.1. *Spectral distribution*

To obtain the spectral distribution of radiant power from a source, one uses a spectroradiometer designed so that the spectral irradiance or radiance is measured as a continuous function of wavelength.

The amount of irradiance that an instrument can sense,

$$\Delta H = \int_{\lambda}^{\lambda+\Delta\lambda} H_\lambda d\lambda \tag{1}$$

is a function of the spectral bandwidth used.

In order to obtain a useful measurement, the amount of irradiance in a chosen spectral region must exceed the noise of the spectroradiometer; thus, the bandwidth $\Delta\lambda$ may be made small when the irradiance is large, but $\Delta\lambda$ must be made larger when the irradiance is smaller. In some cases it must be so large that a dispersing-type instrument cannot be used. The use of a broadly filtered radiometer is the next best solution. Also, if the time during which the source is constant is too short to permit continuous and detailed spectral scanning, a filtered radiometer may be used.

3.3.2. *Spatial distribution*

If the target or background to be examined is larger than the field of view of the measuring instrument, the *radiance* of the target or background is of primary interest. The angular resolution of the instrument should be chosen so that the examination is made with a resolution element of the desired area at the target or background. Usually, the smallest instantaneous field of view obtainable is desired. However, the time to search a field of view of fixed size depends upon the number of looks required and the system response time. If the latter is fixed, the time of search is inversely proportional to the solid angle of the instantaneous field. Thus, to accomplish a measurement in a reasonable time, one may wish to use a moderate-sized field of view. Very small fields of view and limited time impose the requirement for increased electrical bandwidth, which reduces the system detectivity. If a scanning instrument is used, the bandwidth of the amplifiers should be just broad enough so that the geometrical resolution is not degraded.

Where the field of view is large enough to permit integration of all target radiance, the *radiant intensity* is the quantity of primary interest. While in general one would choose the smallest field of view consistent with the capability to sight, track, and contain the entire target, it must be kept in mind that the angular subtense of infrared targets may vary during a given measurement.

A closely associated problem is that of the aspect angle. Simple symmetrical bodies may pose only small aspect problems. However, complicated shapes such as modern aircraft present problems requiring the investigator to use his experience and judgment to determine the resolution with which aspect data are to be collected.

3.3.3. *Temporal variation*

The spectral characteristics and radiance level of the target, the background, and the intervening media may vary with time. If there is sufficient irradiance at the instrument, and sufficient bandwidth in the amplifiers and recorders, the temporal measurements would be limited primarily by the frequency response of the detector. It is obvious, however, that temporal effects are often more closely associated with long-time variations such as the diurnal cycle than with detector time constants. Small values of such slow changes may be measured by using narrow bandwidths and long integration times.

3.3.4. *Radiation levels*

The observer should obtain a reasonable estimate of those levels of radiation that must be measured in order to select an instrument with adequate detecting ability. The instrument with the very highest detectivity may not be the best choice. Important also are dynamic range and speed of response.

4. GENERAL ATTRIBUTES OF RADIOMETRIC INSTRUMENTS

4.1. *Introduction*

The preceding section discussed characteristics of sources encountered in infrared radiometry, as well as the types of measurements to be made and some of the factors to be considered in choosing an instrument for making the measurements. This section considers the several classes of instruments and discusses some common features that need to be understood so that their relevance to the resulting data will be taken into account.

4.2. *Instrument Classification*

In general, an infrared radiometer is an instrument that gives a response dependent on the power of infrared radiation impinging on the instrument within the wavelength band to which it is sensitive. Infrared radiometers may be classified according to their spectral response characteristics. In one clas s arethe "total radiation" radiometers, which have a flat, or relatively equal, response over all parts of the useful infrared spectrum. In another class are the "broadband" radiometers, which respond to radiation within a relatively broad wavelength band such as the lead sulfide region. In a third class are the "filter" radiometers, which respond to a band of wavelengths restricted by the use of optical filters. The fourth class consists of "spectral" radiometers or "spectroradiometers", which, by means of dispersing prisms or diffraction gratings, respond to power within extremely narrow bands of wavelengths. Interferometric radiometers may also be included in this fourth class. Each class of instrument has its own advantages and disadvantages, depending upon its application in any given measurement problem; so the choice of the proper class of radiometer must be determined by the problem at hand.

4.3. *Basic Radiometer Components and Their Characteristics*

All radiometers have the following basic components, although some may be in a rudimentary form:

(1) A detector element which responds to radiant power.

(2) Optical components which, together with the detector's spectral response, determine the wavelength interval in which radiant power is measured.

(3) An optical system which determines the amount of radiation that can be collected and, together with the detector size, determines the angular resolution of the radiometer. In a simple system this is a collecting mirror, or lens, which focuses the radiation from a distant field of view onto the detector surface.

(4) An output indicator and amplifier which, together with the detector, determine the response of the radiometer to the temporal variations of the radiation.

The construction and use of the radiometer may intermix the functions of these components so that they are not independent. For example, the spatial direction of the radiometer may be changed with time by a scanning process so that the spatial information is modified by the temporal characteristics. A radiometer that is slow to respond will not record spatial variations of radiance which are passed over too rapidly. Likewise, a slow response will blur the wavelength spectrum of a source if the spectrum is scanned too rapidly. It is essential, therefore, to have information about all the characteristics of the radiometer in order to evaluate properly the results of measurements made with it. In the following paragraphs some of the features of these components will be discussed, with emphasis upon the instrument specifications that should be determined in order to allow full use of the radiometric data.

Radiometer performance is dependent upon the kind of detector, its size and shape, its spectral responsivity, its time constant, and such operating conditions as temperature, etc. Two detectorrelated concepts are considered next: reference radiation and reference temperature, and temperature as a radiometric unit.

4.3.1. *Reference radiation and reference temperature*

The calibration of a radiometer should include information about the position of the zero on the scale—a fact frequently forgotten by radiometer operators. This zero is sometimes built into the radiometer in an obscure manner. A thermocouple, for example, gives an electrical output signal which depends upon the difference between the temperatures of the warm, exposed junction and the cool, compensating junction. Zero electrical output means, therefore, that the amount of radiation on the exposed junction is just enough to keep its temperature the same as that of the compensating junction. The amount of this reference radiation which produces zero output signal should be stated when reporting results from such a device. It is convenient to specify the amount of this reference radiation by giving the reference temperature of the radiometer. The reference temperature is the temperature of a blackbody filling the entrance pupil and field of view of the radiometer that produces zero output response.

Many radiometers are constructed so that the detector alternately receives the radiation from a black chopper and that from the field of view, and thus they respond to the difference between these two amounts of radiation. The reference temperature of such radiometers is usually close to the temperature of the black chopper. Some radiometers have a controlled reference blackbody whose radiation reaches the detector by reflection from a chopping mirror. *The reference radiation must have a spectral radiance closely approximating that of a blackbody if one is to use a reference temperature to indicate the amount of reference radiation.*

If the calculated results of radiometric measurement are to be proportional to the incident radiant power, then the reference radiation must be added properly to the radiometer response. For amounts of incident radiation which are large compared to that of the reference radiation, this correction could be unimportant, but this should be demonstrated, not assumed.

Some radiometers are designed to use the radiation from a neighboring region of the background as the reference radiation. Such devices measure the difference between the radiation of the two space elements, and as such they have no reference temperature.

Still other specialized radiometers are constructed to have no zero frequency response; instead, the radiation during a previous period is used as the reference for the measurement. A radiometer used in this manner does not have a reference temperature. Such radiometers may be used to measure the rate at which the radiation changes.

4.3.2. *Temperature as a radiometric unit*

If the source measured by a radiometer is a blackbody, then a unique description of the radiance is given by the temperature of the source. The temperature scale is a substitute for the scale of radiant power. It is a good scale for sources closely approximating a blackbody. For radiometers having equal responsivity for all wavelengths, the temperature value does indeed uniquely determine the total radiance from the source, but it cannot verify that the spectral distribution is that of a blackbody. If, however, the responsivity of the radiometer depends on the wavelength, *and* if the spectral radiance of the source is not that of a blackbody, then the "temperature" of the radiation will depend on the response-vs.-wavelength characteristics of the radiometer; accordingly, under these conditions a statement of the "temperature" is ambiguous and is not recommended to describe the radiance. The information given by the "temperature" should instead be given by stating a value of one of the radiometric power units.

4.3.3. *Spectral characteristics*

Measurement with an infrared instrument implies a spectral selection for radiation in the infrared region. The many infrared detectors have widely different spectral responses, and, in addition, most infrared devices have filters of some sort which further limit the wavelength range of operation. Sometimes the spectral limits are determined by the source; e.g., the radiation in a molecular band emitted by a hot gas. It is important, therefore, to have a good measure of the spectral response of the instrument in order to interpret properly the data obtained.

Where sources of unknown and nonuniform spectral output are observed with a radiometer whose spectral response is nonuniform, the output is not a unique determination of the input. Widely varying inputs may produce the same output. It is common to treat the data by a process known as "normalization to the peak" or "normalization to an average value". Normalization accepts the ambiguities in the measurement in a reasonable manner so that the data may be treated consistently and understandably. Since there is more than one method, it is important to specify the method used.

The following treatment of normalization refers primarily to irradiance. However, the principles apply equally well to any of the other radiometric concepts, such as radiant power, apparent radiance, radiant intensity, etc.

4.3.3.1. *Normalization to the Peak.* The response of a radiometer is a function of the wavelength. For example, in Fig. 1 a typical irradiance responsivity is shown as a function of wavelength by the function $R_H(\lambda)$. This quantity is stated in V/W per cm². The output response V of such a radiometer to spectral irradiance $H_\lambda(\lambda)$ is

$$V = \int R_H(\lambda) H_\lambda(\lambda) \mathrm{d}\lambda \tag{2}$$

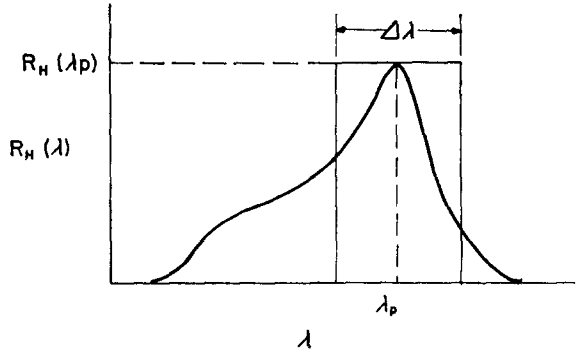

FIG. 1

Given the irradiance responsivity $R_H(\lambda)$ and the response V, one cannot calculate the spectral irradiance $H_\lambda(\lambda)$ as a function of the wavelength λ. All one knows is the value of the integral in the above expression. Clearly, however, the measurement gives some information about the irradiance H. The information that the measurement does give is usually stated by "normalizing to the peak" the responsivity function.

The responsivity $R_H(\lambda)$ has a maximum value $R_H(\lambda_p)$ at the wavelength λ_p. The process or normalizing to the peak means that the value of irradiance H inferred from the measurement is

$$H = V/R_H(\lambda_p) \tag{3}$$

The actual input irradiance produces the same effect (or output) as wou an amount H of nearly monochromatic irradiance at wavelength λ_p. This value of the irradiance has full significance only if it is accompanied by the responsivity-vs.-wavelength curve of the radiometer.

If $R_H(\lambda)$ is relatively constant over the spectral range in which the source has significant output, or if the spectral output of the source is relatively constant over the range of $R_H(\lambda)$, then under certain conditions additional information may be determined from the radiometer measurements.

In the first situation, the total radiant output from the target may be determined with an uncertainty depending on the constancy of $R_H(\lambda)$.

In the second situation, it is possible also to make some inferences about the value of the spectral irradiance at the wavelength λ_p. In particular, if the bandwidth of the radiometer is defined by

$$\Delta\lambda = \int R_H(\lambda)d\lambda/R_H(\lambda_p) \tag{4}$$

then the peak-normalized value of the spectral irradiance $H_\lambda(\lambda)$ is

$$H_\lambda(\lambda_p) = V/R_H(\lambda_p)\Delta\lambda \tag{5}$$

and, as indicated, this value is assigned to the wavelength λ_p at which the responsivity $R(\lambda)$ has its maximum value.

As a numerical example, let it be supposed that a given radiometer has the responsivity of 3000 V/W per cm^2 at the wavelength $\lambda_p = 3{\cdot}5\ \mu$ where the responsivity has its maximum value. A response of 45 volts would then indicate an irradiance, normalized to the peak, of 0·015 W/cm^2. Suppose further that the bandwidth $\Delta\lambda$ of the responsivity curve, as defined by Equation 4 above, is 0·2 μ. Then the spectral irradiance H_λ, normalized to the peak, is 0·075 W/cm^2 per μ and this value of H_λ is assigned to the 3·5 μ wavelength.

4.3.3.2. *Other methods of normalization.* Although normalization to the peak is the usual method of normalization, in a number of special situations this method may not be the best. We cite two such situations in which it is desirable to normalize to a wavelength interval.

First Example. The responsivity-vs.-wavelength curve may have a flat top marred by "waves", as suggested by Fig. 2. Such waves may be produced by a thin film in the optical system. In this special case, it is clear that normalization to the "average" responsivity, indicated by the dashed line, is preferable to normalization to the peak. If the responsivity corresponding to the dashed line is denoted $R_{H,\mathrm{av}}$, then the value of the irradiance inferred from the measurements is

$$H = V/R_{H,\mathrm{av}} \tag{6}$$

and the corresponding spectral irradiance, if the target spectral output is nearly constant over $\Delta\lambda$, is

$$H_\lambda = V/(R_{H,\mathrm{av}}\Delta\lambda) \tag{7}$$

in which

$$\Delta\lambda = \int R_H(\lambda)d\lambda/R_{H,\mathrm{av}} \tag{8}$$

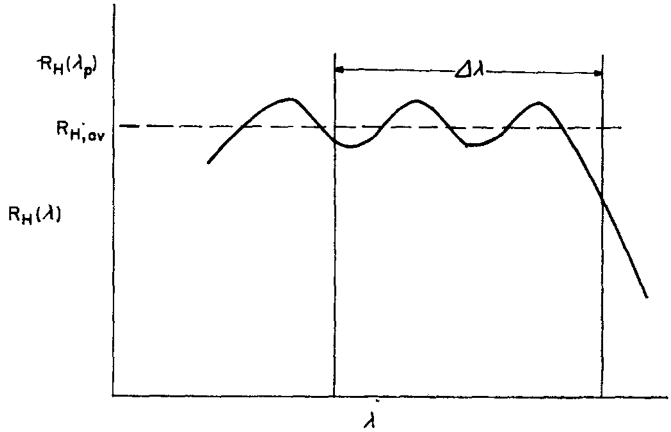

FIG. 2

If $\Delta\lambda$ is a large spectral interval, the inferred value of H_λ will be a poor description of the source. Since only the product $R_{H,\mathrm{av}}\Delta\lambda$ is determined by the response $R_H(\lambda)$, an infinite set of values of $R_{H,\mathrm{av}}$ and $\Delta\lambda$ is possible. In this technique of normalization to the average, the $\Delta\lambda$ is usually chosen to correspond to the spectral region of interest, and the $R_{H,\mathrm{av}}$ is computed from Equation 8. In this sense, normalization to the average is normalization to a chosen bandwidth, and the chosen bandwidth is essential information.

Second Example. Most doped germanium detectors have an essentially flat responsivity

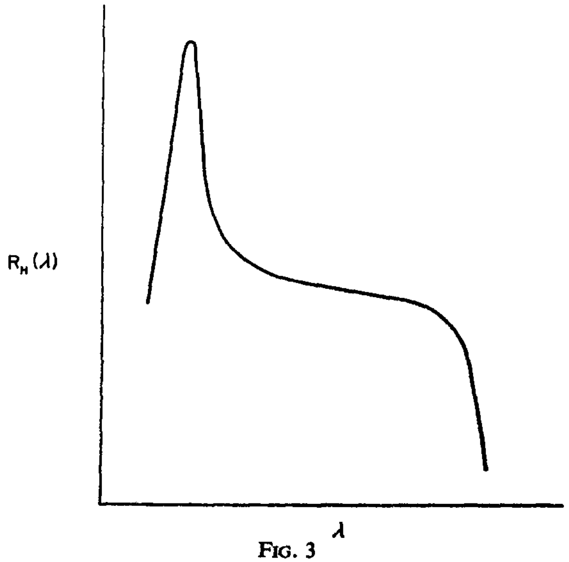

FIG. 3

at wavelengths greater than 2 μ, with a high peak at about 1·8 μ, as shown in Fig. 3. If it is known that the high peak contributes only a negligible amount of the response to the radiation, then it is clearly the longer wavelength responsivity that is relevant. If, as in Fig. 3, there is no secondary peak at longer wavelengths to which to normalize, then it is necessary to select some arbitrary responsivity to obtain values of H and H_λ within a specified bandwidth. The value selected will depend on one's estimate of the wavelength distribution of the radiation being measured.

It is important that the method of normalization be carefully described.

4.3.4. *Optical system characteristics*

The field stop of a radiometer, often determined by the detector size and shape, determines the geometry of the measured field of view. Knowledge of this geometry is a part of the complete calibration of a radiometer. The field-of-view information is particularly important in evaluating the geometry of the source from the radiometric measurements.

For a simple optical system that focuses a distant region of space on the whole of the sensitive area of a detector, the field of view measures the angular extent of the spatial region being examined. Thus, the geometry of the system, that is, focal length and detector size, will give information about the angular extent of the field of view. If the response of the radiometer were the same for small, distant sources anywhere in this field, then a statement of the angular extent of the limits of this field would adequately describe the field of view. Most radiometers, however, because of aberrations of the optical system and/or variations of the responsivity of the detector over the detector area, have a nonuniform response over the field of view. Therefore the description of this responsivity variation over the field of view is necessary, particularly when measurements are made of nonuniform source distributions such as a target which only partially fills the field of view. This complete field-of-view description is also important in evaluating the possible resolution of spatial structure by the radiometer measurements.

If the radiometer is constructed to scan a region of space, then it may have a definite size for its field of scan, as well as one for its instantaneous field of view. Both fields should be specified. The operation of sophisticated radiometers—for example, those using episcotisters (rotating reticles)—will need to be described in detail so that the data they obtain will be amenable to evaluation.

4.3.5. *Temporal characteristics*

A radiometer not only has filters for spectral and spatial distribution, but also has "filters" for signal distribution in the time domain. The response of a radiometer to a pulse of radiant power will depend upon the ability of the detector element and/or the amplifier and output system to respond quickly. Information about the system response to fluctuating incident radiant power is important for the evaluation of the measuring capabilities of the system. These capabilities can be determined if the response for all frequencies of sinusoidally varying incident radiant power is known. Such information can be presented as a temporal frequency spectrum of both the amplitude and the phase of the radiometer's output response. It is good to know whether this function is determined in the main by the detector alone, the amplifier alone, or the output recorder alone.

4.3.5.1. *Time constant.* Sometimes the frequency response may be characterized by a single number, called the time constant. That is, the complex responsivity $R(f)$ depends on the frequency f in accordance with

$$R(f) = R_0/(1 + 2\pi i f \tau) \tag{9}$$

in which τ is the time constant, and the responsivity is defined as the ratio of the amplitude of a sinusoidal output component to the corresponding component of the radiation power input. For some purposes it is not necessary to know the relative phase of the voltage output versus the radiation input, and it is therefore sometimes sufficient to state the absolute value of $R(f)$.

Replacing a responsivity-vs.-frequency curve by a statement of the time constant is a proper procedure only if the responsivity is closely represented by Equation 9.

4.3.5.2. *Zero-frequency response.* If the radiometer does not respond to a constant, unvarying incident radiant power, then the frequency response has a zero value at zero frequency. Such radiometers respond to fluctuating radiant inputs only, and knowledge of this fact is important. A radiometer that responds to the time rate of change of the radiant power has a frequency response which increases with and is proportional to the frequency (and to a constant value of phase shift). The responsivity of a radiometer whose frequency response approximates this linear relationship to sufficiently high frequencies is measured in volts per (radiation unit per second), where "radiation unit" represents irradiance, apparent radiance, or received power.

5. CALIBRATION OF A RADIOMETER

5.1. *Introduction*

The calibration of a radiometer must be known in order to interpret the results of measurements made with it. The usual direct result of a radiometer measurement is a voltage. In order to convert this voltage into a radiometric quantity, it is necessary to know the *responsivity* of the radiometer. It is also desirable and sometimes necessary to know a number of other parameters describing the performance of the radiometer. These include (1) the size and shape of the field of view, (2) the way that the responsivity depends on the modulation frequency, (3) the way that the responsivity depends on the wavelengths of the radiation, and (4) the amount of electrical noise in the output of the radiometer.

Calibration is the process of measuring these quantities.

The responsivity is measured by using a source that emits a known amount of radiation. Such sources are called calibration sources. The usual standard calibration source is a blackbody source. Since a perfectly black source cannot be obtained in practice, it is important to select the closest possible approximation to it. An imperfectly black source will reflect some undesirable and usually unknown radiation into the instrument. Where feasible and convenient, it is desirable to use a blackbody calibration source with a temperature not too far from the temperature of the objects to be measured.

The characteristics of available sources must be considered carefully. Suitable extended sources with areas of about one square foot are available if high temperatures (i.e., above 250°C) are not necessary. A few experimental sources have been made in conical shapes with apertures one foot in diameter, but these are limited to temperatures below 100°C. Commercially available extended sources are made as flat, blackened plates with emissivities slightly greater than 0·9.

Sources with temperatures as high as 1000°C to 1500°C are available with apertures on the order of one inch in diameter. Emissivities very close to 1·0 are expected on the basis of theoretical calculations following the methods of DeVos (2) and Gouffe (3).

5.2. *The Three Kinds of Responsivity*

The three radiometric concepts that are of primary interest in connection with radiometer calibration are radiant power P, irradiance H, and radiance N.

It will be supposed that the output of the radiometer is a voltage, so that the responsivity of the radiometer is a dimensional number that is the ratio of the output voltage V to some input radiometric quantity, either power P, irradiance H, or apparent radiance N.

Thus, there are three responsivities:

$R_p \equiv V/P$, the power responsivity, V/W
$R_H \equiv V/H$, the irradiance responsivity, V/W per cm^2
$R_N \equiv V/N$, the radiance responsivity, V/W per cm^2 per sterad.

The irradiance responsivity is of interest primarily in the measurement of the apparent radiant intensity of targets that do not fill the field of view of the radiometer. If J' is the apparent radiant intensity, s is the distance from target to radiometer, and V is the output voltage of the radiometer, then J' is given by

$$J' = s^2 V R_H \tag{10}$$

The radiance responsivity is of interest primarily in the measurement of the apparent radiance of a target that fills the field of view of the radiometer, and in the measurement of the radiance of backgrounds.

As will be seen in the next section, some methods of calibration enable one to measure the irradiance responsivity or the radiance responsivity without knowing the size of the field of view. But if one does know the effective solid angle ω of the field of view, then knowledge of either of these two responsivities enables him to calculate the other by the relation

$$R_N = \omega R_H \tag{11}$$

It is always sound procedure, other things being equal, to calibrate one's equipment in the mode in which it will be used. Thus, it is sound practice to measure the irradiance responsivity directly if one wishes to measure point targets, and to measure the radiance responsivity if one wishes to measure apparent radiance. However, it is often more difficult to measure the irradiance responsivity R_H than to measure the radiance responsivity R_N. Therefore, it is often preferable to measure R_N and ω, and then to compute R_H by Equation 11. The choice between these two procedures will often depend on which can be measured more accurately, R_H or ω.

If the effective area of the entrance pupil of the radiometer is denoted A_p, then the power responsivity R_P is related to R_N by

$$\omega A_p R_P = \omega R_H = R_N \tag{12}$$

The power responsivity is sometimes of interest because it is so to speak, neutral ground with respect to R_H and R_N. If both ω and A_p are known with adequate accuracy, all three of the responsivities can be computed from the value of any one of them.

5.3. *The Several Methods of Responsivity Calibration*

The basic requirement of a calibration procedure is that it provides a known increment of radiant input. Since, on earth at least, a background of zero radiance is not available for calibration purposes, precautions must be taken to insure that unknown amounts of radiation emitted or reflected from the background are not included with the test radiation.

One generally applicable procedure is to observe a source which, having a given aperture and temperature, produces a measurable output. The temperature or the aperture of the source is increased by an accurately known amount to produce a considerably larger output. The radiometer may then be calibrated from the incremental output which results from the incremental input. In this procedure the contribution from the background, although unknown, is the same for each measurement, and the incremental input is the difference between the two source inputs.

An obvious modification of this procedure, appropriate in the radiance calibrations described below where the test source fills the radiometer field of view and uniformly irradiates the entrance aperture, is to direct the radiometer successively at test sources of different known temperatures.

When the calibration source is effectively a point source, one may use a high temperature source with a chopper located behind the defining aperture of the source. The incremental input to the radiometer is then the difference between the input due to the radiant intensity of the source and that due to the radiant intensity of the chopper, which includes both emitted and reflected radiation, as seen through the defining aperture. The contribution of the chopper, although not precisely defined, should be so small that it may be neglected when compared with that of the source. The source radiation is then considered to be the incremental input. When radiometers employing an internal chopper are calibrated by this method, the frequency with which the source is chopped should be small compared with the internal chopping frequency.

The methods of calibration may be classified according to the position of the calibration source with respect to the measuring instrument.

In the first class, the source is located at a distance from the entrance aperture and is usually imaged on the field stop (often coincident with the detector). In the "distant small source method", the source image covers only a portion of the field stop; in the "distant extended source method", the source fills the field of view and uniformly irradiates the field stop.

In a second class, the source is located at or near the entrance aperture and uniformly irradiates the field stop. The source may completely fill the entrance aperture or, as in the Jones method (see Section 5.3.4.), only partially fill the entrance aperture.

In a third class, the calibration source is located within the measuring instrument behind the entrance aperture. The source usually irradiates the field stop uniformly and may or may not completely fill the optical cone between itself and the field stop.

When the source is at a distance, the radiation collected by the radiometer has two components: that from the source itself, attenuated by the intervening atmosphere, and that from the background. (In the distant extended source method, the background consists of the emission from the intervening atmosphere, which may or may not be significant.) With the source at or near the entrance aperture, there is little or no atmospheric attenuation, but in the Jones method there is radiation from the background. In all of the methods, there is radiation from the optical elements, from the chopper (if the radiometer contains one), and from the instrument housing. None of these sources of steady radiation are important in the calibration process, because the radiation from the calibration source is tagged by its modulation.

Much of the following discussion assumes that the radiometer is linear (i.e., that its output voltage is strictly proportional to the radiation input). Because in practice this linearity should not be assumed, it is necessary to calibrate at several different radiation levels in the range where measurements will be made, or to confirm the linearity in some other way.

As indicated in Section 2.3.1, radiant intensity and radiance are the two important radiometric concepts associated with a specific source. The corresponding quantities in the radiation field measured at the aperture of the radiometer are the irradiance, for objects that do not fill the field of view, and the apparent radiance, for objects larger than the field of view. In the distant small source method, the source does not fill the field of view and may be considered to calibrate the radiometer directly in irradiance. In the other methods of calibration, the field stop is uniformly irradiated, thus filling the field of view, the radiometer may be considered to be calibrated directly in radiance. These two calibrations are related through the field of view of the instrument. However, since many radiometers have a nonuniform response over the field of view (see Section 4.3.4), an averaged or effective value of the field of view must be used to relate one calibration to the other. Because of the uncertainty in determing this effective value, the method of calibration employed should be selected, when feasible, on the basis of the type of measurement to be made.

5.3.1. *Distant small source method*

A source is placed at a distance such that it lies within the field of view of the radiometer. Often the radiometer is focused at infinity, in which case the source must be so distant that its image lies completely within the field stop. In terms of rays, a ray from any point of the source through any part of the entrance pupil must pass through the field stop.

A salient feature of this method is that all the power in the irradiation of the radiometer by the source is incident on the detector.

The radiant intensity of the calibration source is given by

$$J_c = A_c \int_0^\infty N_{\lambda,c}(\lambda) d\lambda \tag{13}$$

in which J_c is in W/sterad; A_c is the area of the calibration source in cm^2; $N_{\lambda,c}(\lambda)$ is the spectral radiance of the calibration source in W/cm^2 per sterad per μ; and λ is the wavelength in μ.

When there is no attenuating atmosphere between the source and the radiometer, the apparent radiant intensity of this distant small target is the same as its radiant intensity, as given by the above equation. But in the presence of an attenuating medium, the apparent radiant intensity J'_c is given by

$$J'_c = A_c \int_0^\infty N_{\lambda,c}(\lambda) \tau_c(\lambda) d\lambda \tag{14}$$

in which $\tau_c(\lambda)$ is the transmittance of the intervening atmosphere.

We now note that the calibration source will be modulated in one of the ways described in Section 5.3. We let $\Delta N_{\lambda,c}$ denote the amplitude of this modulation. If the source is modulated by a chopper that gives a square-wave modulation, the difference $\Delta N_{\lambda,c}$ would suitably be set equal to the difference between the value of $N_{\lambda,c}$ when the target is "on", and the value of $N_{\lambda,c}$ when the target is "off". If the modulation is sinusoidal, $\Delta N_{\lambda,c}$ may be set equal to the rms modulation of $N_{\lambda,c}$ or to the peak-to-peak modulation.

Whatever measure is used to denote the amplitude of the modulation of $N_{\lambda,c}$, this measure must be used consistently throughout the calibration. We denote the corresponding amplitude of the modulation of J'_c by $\Delta J'_c$.

The amplitude of the modulation of the irradiance is given by

$$\Delta H_c = \Delta J'_c/s_c^2 = (A_c/s_c^2)\int_0^\infty \Delta N_{\lambda,c}(\lambda)\tau_c(\lambda)d\lambda = \int_0^\infty \Delta H_{\lambda,c}(\lambda)d\lambda \tag{15}$$

in which s_c is the distance from the calibration source to the radiometer.

The modulation of the source produces a radiometer output voltage modulation denoted ΔV.

The irradiance responsivity of the radiometer is then given by

$$R_{Hc} = \Delta V/\Delta H_c \tag{16}$$

This is, of course, the irradiance responsivity for the particular source that is used. If the relative responsivity of the radiometer is known as a function of the wavelength and is denoted $L(\lambda)$, the irradiance responsivity for monochromatic radiation is given by

$$R_H(\lambda) = \frac{L(\lambda)\Delta V}{\int_0^\infty L(\lambda)\Delta H_{\lambda,c}d\lambda} = \frac{L(\lambda)R_{Hc}\int_0^\infty \Delta H_{\lambda,c}d\lambda}{\int_0^\infty L(\lambda)\Delta H_{\lambda,c}d\lambda} \tag{17}$$

The irradiance responsivity, normalized to the peak, is $R_H(\lambda_p)$, where λ_p is the wavelength that maximizes $L(\lambda)$.

Of the four methods of calibration, only this one gives the irradiance responsivity directly, without the need to know either ω or A_p. The other three methods give the radiance responsivity directly.

This method, like the distant extended source method, has the disadvantage that the transmittance $\tau_c(\lambda)$ of the intervening atmosphere must be known in order to calculate the value of ΔH_c.

By use of a collimator, it is possible to secure the equivalent of a distant small source without its attending atmospheric absorption. Certain precautions should be observed. The collimator aperture should be larger in diameter than the entrance pupil of the radiometer. The angular size of the source image should be small compared with the radiometer field of view so that any spreading of the source image due to aberrations introduced by the collimator will not be significant. Focusing is critical, and the collimator should be checked for uniform flux density over the beam.

Another method of reducing the problem of determining the transmittance of the intervening atmosphere is to use a narrowband filter in the optical path to limit the test radiation to an atmospheric window. The transmission of the filter must be accurately known. Since appropriate filters will most probably be of the interference type, the filter should be placed over the source to minimize difficulties with oblique rays.

5.3.2. *Distant extended source method*

The distant source is large enough to fill the field of view of a radiometer focused on it. If, however, the radiometer is focused on infinity, the finite distance of the source will produce an image with blurred edges in the plane of the field stop. In this case, the uniformly irradiated part of the image must cover the open area of the field stop. In terms of rays, a ray from any point in the field stop through any point in the entrance aperture must pass through the calibration source.

As in the previous section, let $\varDelta N_{\lambda,c}$ denote the modulation of the spectral radiance of the source. Then the modulation of the apparent spectral radiance at the radiometer is given by

$$\varDelta N'_{\lambda,c}(\lambda,T) = \varDelta N_{\lambda,c}(\lambda,T)\tau_c(\lambda) \tag{18}$$

and the modulation of the apparent radiance by

$$\varDelta N'_c = \int_0^\infty \varDelta N_{\lambda,c}(\lambda,T)\tau_c(\lambda)d\lambda \tag{19}$$

Also, as in Section 5.3.1, let $\varDelta V$ denote the modulation of the output voltage of the radiometer.

Then the radiance responsivity of the radiometer is given by

$$R_{Nc} = \varDelta V/\varDelta N'_c \tag{20}$$

This is the radiance responsivity for the particular source that is used. The radiance responsivity for monochromatic radiation is given by

$$R_N(\lambda) = \frac{L(\lambda)R_{Nc}\int \varDelta N'_{\lambda,c}d\lambda}{\int L(\lambda)\varDelta N'_{\lambda,c}d\lambda} \tag{21}$$

and the radiance responsivity, normalized to the peak, is $R_N(\lambda_p)$.

This method, like the distant small source method, has the disadvantage that one must know the transmittance $\tau(\lambda)$ of the intervening atmosphere; but it has the advantage that it yields the radiance responsivity directly, with no need to know either ω or A_p.

A collimator may be used with this method also. The angular size of the source image should be substantially larger than the radiometer field of view to insure that the detector will be irradiated by a uniform part of the image. Other precautions for the use of a collimator (see Section 5.3.1.) should be followed.

This method yields the radiance responsivity directly, with no need to know either ω or A_p.

5.3.3. *Near extended source method*

A calibration source is placed close to the radiometer. The active area of the source must fill the entrance aperture of the radiometer. Thus, for a radiometer with an 8-in. mirror, the source must have a diameter greater than 8 in. In terms of rays, every ray from the field stop through the entrance aperture must pass through the calibration source.

The method of calculation is the same as in Section 5.3.2, except that the transmittance $\tau_c(\lambda)$ is taken equal to unity, so that $\varDelta N_{\lambda,c}'$ and $\varDelta N_{\lambda,c}$ are equal.

5.3.4. *The Jones method*(4)

A calibration source with a small area (small compared to the area of the radiometer's entrance pupil) is placed close to the entrance aperture. Thus, this method might be called the "near small source method". The radiometer is focused on infinity.

The position of the source must be carefully adjusted. Every point on the source must be able to "see" every point of the field stop. In terms of rays, every ray that passes through the field stop and through the calibration source must pass through an unobstructed part of the entrance area.

When the above conditions on the placement of the source are satisfied, one may show that the detector is uniformly irradiated, just as it is by a distant or near extended source, and that the modulation of the spectral irradiance of the detector is the same as that which would be produced by a near extended source of spectral radiance modulation

$$\Delta N_{\lambda,e} = (A_c/A_p)\Delta N_{\lambda,c} \tag{22}$$

in which $\Delta N_{\lambda,c}$ is the modulation of the actual spectral radiance of the source, A_p is the area of the entrance pupil of the radiometer, and A_c is the area of the calibration source.

It is perhaps obvious that Equation 22 is valid if the calibration source is located in the plane of the entrance pupil; but perhaps less obvious is that it remains rigorously true as the source is moved away, as long as the conditions stated in the second paragraph of this section hold.

The placement of the calibration source in the Jones method must be considered in more detail. Fig. 4 shows a simple optical system in which the field of view is determined by the area of the detector UV and in which the entrance area is determined by the open area of a lens XY of focal length F. Rays that diverge from a point on the detector surface become parallel on the right side of the lens; two such bundles of rays are shown in the figure.

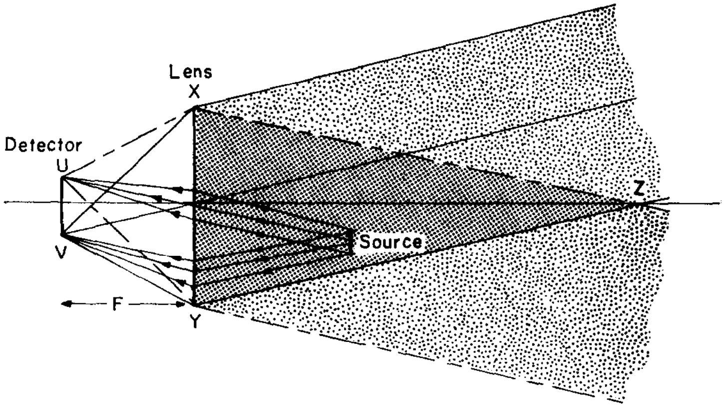

FIG. 4

The limiting upper and lower rays UXZ and VYZ are shown in Fig. 4. These rays intersect at the point Z, and the angle between these rays at Z is the angle of the field of view in the plane shown.

A small calibrating source that lies entirely within the cone XZY will be entirely visible from every point on the surface of the detector, and conversely.

Most radiometers involve mirrors, however, and usually there is some central obscuration. In this case, it is necessary to make a careful calculation of the optical system to obtain satisfactory positions for the source.

Assuming correct placement of the source, Equation 22 shows that the modulation of the irradiance of the detector is the same as would be produced by a near-extended source, whose modulation of the radiance is given by

$$\Delta N_e = (A_c/A_p) \int_0^\infty \Delta N_{\lambda,c} d\lambda \tag{23}$$

The radiance responsivity of the radiometer is then given by

$$R_{Ne} = \Delta V/\Delta N_e \tag{24}$$

The radiance responsivity for monochromatic radiation is found by the use of Equation 21, and is normalized to the peak as in Section 5.3.2.

Three possible difficulties to the Jones method must be mentioned.

First, an unstated assumption in the foregoing description of the Jones method is that the *transmittance* is the same for every ray that passes through the entrance aperture and through the field stop. This is not true of all radiometers. The assumption may fail because of nonuniform reflectance of the mirrors or variation of the focal length when different portions of the entrance aperture are used. Parabolic mirrors having steep curves often exhibit this last effect. The assumption can be tested by placing the source at a number of places in the entrance aperture and checking to see that the responsivities so obtained are all the same. If they are different, they must be averaged.

Second, if the chopper in the radiometer is not imaged on the detector, the phase and/or waveform obtained by the Jones method may differ from that obtained by the near extended source method. If the radiometer employs a synchronous detector, this variation of phase will not introduce error if the responsivity is averaged over the entrance aperture as described in the preceding paragraph, but there will be errors if the electrical detector is not synchronous.

Finally, just as with the distant small source method, the radiometer sees all of the calibration source, not just the part that is labeled the source. It is therefore essential that the calibration source produce no modulated radiation except that from the source aperture.

5.4. *Spectroradiometer Calibration*

Everything stated so far in Section 5 is valid for spectroradiometers; but two more parameters, the center wavelength λ_0 of the passband and the bandwidth $\Delta\lambda$ of the radiometer, must also be considered, since they can usually be adjusted continuously and independently in a spectroradiometer. Further, the field view of a spectroradiometer will depend on the width of the entrance slit if the entrance slit determines the field stop of the spectroradiometer.

In addition, some restrictions are placed on the location and temperature of the calibration source. If one wishes to calibrate through the strong atmospheric absorption bands, the calibration source should be located at the entrance aperture or within the instrument Also, the spectral radiance of the calibration source should not change rapidly within the spectral slit width of the spectroradiometer; in particular, one should not calibrate with a blackbody whose spectral peak is at a wavelength longer than that of the center of the instrument spectral bandpass. Thus, a high-temperature blackbody (1100° or above) is needed for calibration in the 1 to 3 μ region. It should be kept in mind that spectroradiometers are usually calibrated in terms of the response to *spectral* radiance or *spectral* irradiance, instead of radiance or irradiance.

This section assumes that the spectroradiometer is of the kind that contains a prism or grating as the dispersing element. In particular, filter-type radiometers are excluded from this section.

In regions of wavelength spectrum where the responsivity of the radiometer is substantially independent of wavelength, it may be permissible to suppose that the spectral irradiance responsivity is proportional to the width of the exit slit, and that the spectral radiance responsivity is proportional to the product of the widths of the entrance and exit slits. But in this report, it is supposed that the radiometer is first calibrated for fixed (or programmed) slit settings, and then recalibrated, independently, for other slit settings (or programs).

5.4.1. *Spectral radiance responsivity of a spectroradiometer*

The spectral radiance responsivity is defined as the ratio of the modulation of the output voltage V to the modulation of the apparent spectral radiance of the source:

$$R_{N\lambda} = \Delta V / \Delta N_\lambda \qquad (25)$$

5.4.2. *Spectral irradiance responsivity of a spectroradiometer*

The spectral irradiance responsivity is defined as the ratio of the modulation of the output voltage V to the modulation of the spectral irradiance:

$$R_{H\lambda} = \Delta V / \Delta H_\lambda \qquad (26)$$

5.4.3. *The calibration procedure*(5,6,7,8)

It is customary to calibrate the wavelength scale of spectroradiometers in the laboratory. The wavelength calibration gives the relation between the wavelength of the center of the passband, and the position of the adjusting dial.

The responsivity is then measured as a function of the wavelength setting. If a large range of wavelengths is to be covered, it may be desirable to employ a number of calibration sources of different temperatures, each of which has a nearly constant spectral radiance in the band in which it is used.

Because of the many sharp absorption bands of the atmosphere, it is usually impractical to use distant sources in the calibration. If a collimator is not used, one may employ the near extended source method for the low-temperature sources; but for the higher temperature sources with small area, it is necessary to employ the Jones method.

5.4.4. *Warnings*

In the use of a spectroradiometer, one should always be alert for the effects of stray radiation. Short-wavelength stray radiation is particularly apt to be troublesome when the radiometer is used outdoors in daylight, but is less likely to be a problem if the calibration is done indoors or at night.

If the slit is the aperture stop of the instrument and the width of the entrance slit is varied, the spectral irradiance responsivity will not change, but the spectral radiance responsivity will change.

5.5. *The Instantaneous Field of View*

The field of view of a radiometer is sometimes calculated by assuming perfect imaging by the optical system and uniform responsivity over the surface of the field stop. The condition of uniform responsivity may be approximated by the use of an aperture to define the field of view and a field lens to image the entrance aperture upon the detector. This configuration when wavelength considerations permit.

It is always desirable to measure the field of view, especially when the detector element is the field stop. No optical system is free of aberrations, and some detectors depart significantly from uniform responsivity over the surface. The field of view may be measured by moving a point source or the radiometer in a television-type scanning raster, and plotting the responsivity along each line of the scan. Contours of equal responsivity can also be measured and are more useful.

A radiometer to be used for measuring the radiant intensity of small distant targets should have a central region in the field of view within which the irradiance responsivity is substantially constant. This region should be indicated in the reticle of an associated boresighted telescope; some means should be provided so that targets being measured are viewed within this central region.

In dispersing-type spectroradiometers, the field of view depends on the width of the entrance slit of the monochromator.

If the irradiance responsivity depends on the position (α,β) of the source in the field of view, an effective solid angle of the instantaneous field of view may be defined as follows:

$$\omega = \iint R_H(\alpha,\beta)d\Omega / R_{H,\max}$$

in which $R_{H,\max}$ is the maximum value of the irradiance responsivity (Fig. 5). It may be noted that the measurement of the effective solid angle by use of this equation or any other method requires only the measurement of *relative* responsivities.

The periphery of the response pattern, because of the two-dimensional geometry, may make a larger contribution to the solid angle ω than is suggested by examination of one-dimensional profiles.

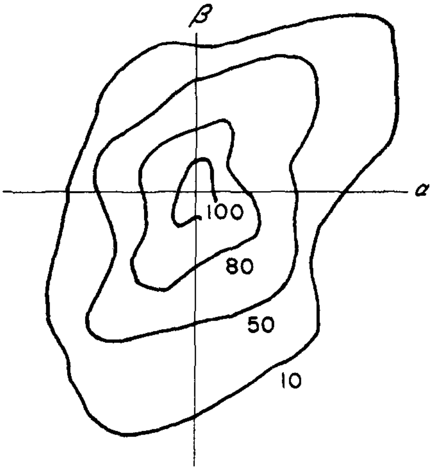

FIG. 5

5.6. *Frequency Response*

Most radiometers have d.c. response and are calibrated at modulation frequencies so low that the response at these frequencies is equal to the d.c. response. Usually, one needs to know the frequency response only roughly, and a statement of the "time constant" of the radiometer is sufficient. If one is using the radiometer to measure modulation of the output of the target, it is necessary to know the actual responsivity as a function of frequency.

It is often assumed that the relative response-versus-frequency characteristic of a radiometer is independent of the wavelengths involved. Actually, this is not always true, especially for doped germanium detectors.

5.7. *Wavelength Response*

The responsivity vs. wavelength curve of a radiometer (Section 5.4.3.) depends not only on the properties of the detector, but also on the wavelength dependence of the transmittance and reflectance of the mirrors, lenses, and filters.

The overall responsivity vs. wavelength curve is often calculated by combining the curves of each of the components. Indeed, the properties of the components are sometimes assumed without measurement. For one example, freshly coated mirrors may be supposed to have the same reflectance at all wavelengths. For another, the wavelength dependence of the transmittance of the filters and the responsivity of the detectors is sometimes approximated by typical curves.

The use of typical filter-response curves may lead to substantial errors. Transmission filters are usually measured in a collimated beam. When they are used in a radiometer in convergent radiation, the transmission may be quite different. This is particularly true for interference filters, which have a shift in the wavelength of maximum transmittance for oblique rays. Scattering-type filters have a transmittance that depends on the solid angle within which the transmitted radiation is accepted. Many kinds of filters have a transmittance that depends importantly on the temperature of the filter. To avoid mistaken measurements due to spectrally stray radiation, account should be taken of the transmission of the filters far from the nominal passband, particularly at short wavelengths.

It is of course highly desirable to measure directly the relative responsivity of the complete radiometer as a function of the wavelength. In principle, the calibration can be done with the aid of a source, a monochromator, and a reference heat detector with a responsivity substantially independent of the wavelength; but with this method it is difficult to secure enough radiant power for the calibration. A collimator may be used to secure more radiant power.

The overall responsivity may be calculated by multiplying the transmittances and reflectances of the elements by the responsivity of the detector. Much care is required if this method is to give reliable results.

5.8. *Noise*

The electrical noise in the output of a radiometer is here defined as any voltage that arises from causes other than the radiation field external to the radiometer. Thus, the term noise includes not only the statistically random component in the output, but also other components such as hum and electrical pickup.

The noise is important in several ways. Accurate measurements can be made only when the signal is well above the effective noise level. Since the noise is relevant to the results, the noise level should be reported in a form such that its influence can be determined.

The linearity of the measuring system may fail at low levels because of quadratic addition of signal and noise in nonsynchronous electrical detectors.

5.9. *Measurements*

The preceding has covered the broad principles of calibration. Specific measurement problems and correspondingly artificial solutions, we strongly recommmend that the reader review the excellent works(8,9,10,11) which illustrate the orderly, systematic, and scientific approach to real problems encountered in radiometric research.

6. DATA PRESENTATION

6.1. *Introduction*

This chapter discusses methods for presenting the data measured by the calibrated equipment and subsequently reduced by the investigator to a useful form. It includes methods for describing targets which are completely within the field of view of the measuring equipment and targets which more than fill the field; it also includes both statistical and non-statistical methods for describing the distributions of background radiance.

6.2. *Targets Completely within the Field of View*

The primary data to be presented are the values of H_T, the irradiance due to the target T. A frequently used method of presenting data consists of plots of H_T, together with values of range R and other important auxiliary data, as functions of time. A variation of this method differs only in that the apparent radiant intensity $J' = H_T R^2$ is plotted as a function of time rather than of the irradiance H_T. Presenting all data as functions of time makes the task of deriving a particular form relatively easy.

Most often for such targets J (or J') is a function of aspect as well as of the operating conditions of the target. The display of J' as a function of aspect for a given set of altitudes or other operational characteristics is an example of a useful data presentation method.

Although such target radiation patterns are usually three-demensional, in many cases the patterns are sufficiently rotationally symmetrical to permit their presentation in conventional two-dimensional polar diagrams. Data valid for one aspect can then also be reduced easily to describe the radiation from other aspects.

This procedure is not satisfactory if symmetry exists only with respect to a plane rather than with respect to an axis, as, for example, is always true for multiple-engine airborne targets where obscuration or reflections from wings, fuselage, and other structural parts affect the pattern. In such cases the pattern can be presented in the form of a *set* of polar diagrams, each for a different rotational angle with respect to the direction of flight of the target. Presentation of the complete "global" or "4π" pattern around the target then requires plotting of a multiplicity of polar diagrams and/or presentation on several graph sheets.

6.3. *Methods of Describing the Spatial Distribution of Radiance*

This section describes a number of methods, both statistical and nonstatistical, for describing the spatial distribution of radiance. The nonstatistical methods, which include the infrared picture, the line scan, and the contour map, are useful for describing backgrounds and for describing targets larger than the field of view of the radiometer. The statistical methods were developed for describing backgrounds. These methods include the amplitude distribution function, and the one- and two-dimensional Wiener spectra.

6.3.1. *Nonstatistical methods*

6.3.1.1. *The infrared picture.* One very good way of describing a radiance distribution is to show an infrared picture of the extended targets or of the background. It has many advantages, particularly if high-quality equipment is available. The thermal picture shows the high-radiance points in the field of view, and a glance suffices to show what they are associated with. One can see the size and shape of the objects of interest. Furthermore, one can put the picture in a simulator and find out how any infrared device will react to the given field of view.

The problem of recording the large amount of information in an infrared picture is considerable. Photographic film is the most feasible means, but it is limited in dynamic range, its readout accuracy is low, and linearity between input and output is difficult to attain. The limited dynamic range often results in loss of small radiance variations associated with the finer details of the background. Additional loss of detail results from limitations on angular resolution due to design compromises among the field of view, scanning time, threshold sensitivity, and instantaneous field of view.

One can ease the problem of limited dynamic range by the use of electrical compression, but this makes the linearity problem much worse. For use in simulators, it is very desirable to have the image on the film arranged so that the radiance is directly proportional to the reflectance or transmittance of the film. This is difficult at best, and it conflicts with the desire to compress in order to increase the dynamic range.

The infrared picture, then, is suitable for extended targets and nonrandom spatial backgrounds, particularly ground backgrounds in which landmarks and works of man are prominent. It is not the preferred method for sky or water backgrounds.

6.3.1.2. *The line scan.* In order to avoid the difficulties just mentioned, some workers have used line scans. Fig. 6 shows a chart recording of a line scan. The upper record was obtained by scanning a bolometer-equipped radiometer over a partially cloudy sky at night. The lower record shows the results of an identical scan made with the shutters closed; it thus shows the electrical and microphonic noise of the system.

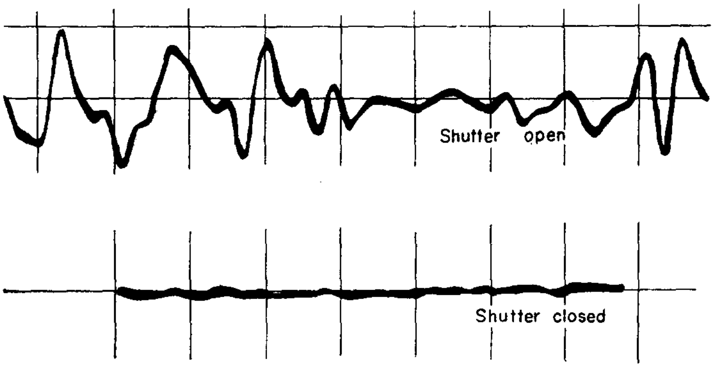

Chart recording of a line scan

FIG. 6

This line-scan method does succeed in mitigating some of the limitations of the infrared picture. One big advantage is that one can use electrical equalizers. Increasing the gain at the higher frequencies makes the fine detail show up better in the record, and thus improves both the effective resolution and the effective dynamic range of the record. A record of a line scan made on a chart recorder, or perhaps on magnetic tape, is much closer to being perfectly linear than a film record, for example. (Those who work with sound on film know how hard it is to keep the distortion down.) Finally, a strip-chart record is directly readable (a magnetic-tape record, obviously, is not).

Thus, the line-scan method has a number of attractive features even though it does lack some of the outstanding advantages of the infrared picture.

6.3.1.3. *Contour maps.* The information from many line scans can be presented in the form of iso-radiance plots or contour maps. These maps are useful for describing the radiance distribution of targets and backgrounds and determining the effective size of targets.

6.3.2. *Statistical methods*

Statistical methods are of value in describing the variations among targets of a given type or class. Often, however, targets are described by non-statistical means. The following statistical methods are described with respect to backgrounds.

6.3.2.1. *Amplitude distribution function.* The amplitude distribution function $P(N)$ is the probability that the measured radiance lies in the range between N and $N + \Delta N$, divided by ΔN. The probability $P(N)$ has the property that its integral with respect to N is unity.

The amplitude distribution of a background can be measured in a given band of wavelengths and with a given shape of the scanning aperture. This is a very powerful method for measuring a background, and gives the designer the information he needs to calculate the probability of target detection as a function of the false alarm rate.

The limitation of the method is that the amplitude distribution must be measured separately for each different aperture.

6.3.2.2. *The one-dimensional Wiener spectrum.* The one-dimensional Wiener spectrum is heuristically described elsewhere(9). It may be visualized as follows. Imagine that one looks at a background with a scanning aperture that is very narrow in the direction of scan. If $N(x)$ is the radiance as a function of x, then the one-dimensional Wiener spectrum of the background bears the same relation to $N(x)$ that the power spectrum of electrical bears to $V(t)$, where V is the voltage as a function of the time. The one-dimensional Wiener spectrum has the dimensions of radiance^2 per (cycle per dimension), where the "dimension" can be radian, degree, or meter and is the same as the dimension of x.

6.3.2.3. *The two-dimensional Wiener spectrum.*

(a) *Sinusoidal radiance distributions.* Basic to the notion of the Fourier transform and of the Wiener spectrum is the concept of a two-dimensional sinusoidal distribution of radiance.

If one imagines part of the surface of a lake to be covered with a series of parallel waves with uniform spacing, the wave height (as a function of two cartesian coordinates in the surface of the water) represents a sinusoidal distribution of wave height.

Figures 7 and 8 are an artist's effort to represent a sinusoidal distribution of reflectance.

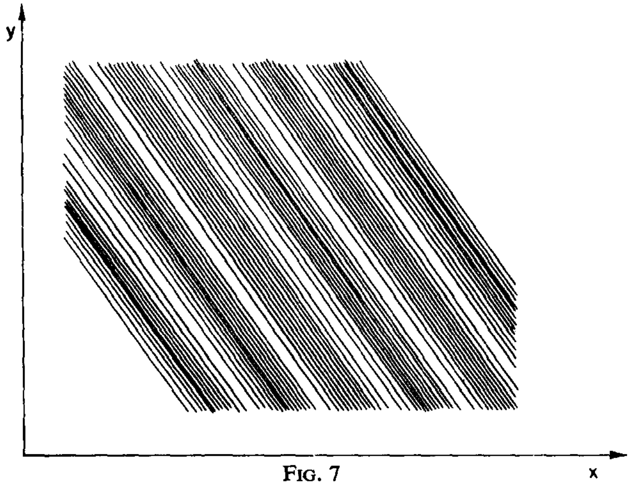

FIG. 7

In the scale in which they appeared in their publication in the *Journal of the Optical Society*,(10) the pattern in Fig. 7 can be described mathematically as follows:

$$R = \mathbf{R} + R_0 \cos 2\pi(1{\cdot}59x + 1{\cdot}08y) \tag{28a}$$

and that in Fig. 8 by

$$R = \mathbf{R} + R_0 \cos 2\pi(0{\cdot}49x - 0{\cdot}41y) \tag{28b}$$

where **R** and R_0 are constants of no interest in this discussion, and where x and y are measured in centimeters.

(b) *The Wavenumbers.* Any given sinusoidal pattern can be described by two wavenumbers, k_x and k_y. Physically, the two wavenumbers (aside from their signs) are the number of cycles per centimeter along the intersection of the patterns with the x and y axes. In Fig. 7, for example, the wavenumber k_x is 1·59 c/cm, and k_y is 1·08 c/cm. In Fig. 8, the wavecrests have a negative slope; if this is to be indicated by the wavenumbers, one of them must be negative. If k_x is taken to be plus 0·49 c/cm, then k_y is $-0·41$ c/cm.

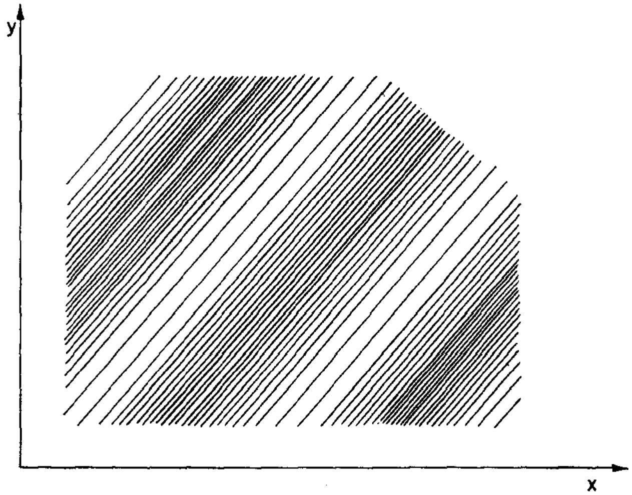

FIG. 8

Figure 9, reproduced from an article by Mertz and Gray[11] published more than 25 years ago, shows a whole array of sinusoidal patterns (represented by black and white bars) of differing values of both k_x and k_y.

(c) *The Fourier transform of a radiance distribution.* Any distribution whatever of radiance on a plane surface can be represented as a sum of sinusoidal radiance distributions. This is the two-dimensional form of the basic theorem of Fourier analysis.

If $N(x,y)$ is the radiance distribution over a region A of the plane, the Fourier transform of the radiance distribution is defined by the following equation:

$$F(k_x,k_y) = \iint_A N(x,y)\{e^{-2\pi i(xk_x + yk_y)}\}dx\,dy \tag{29a}$$

where the factor in the braces is a way of writing a two-dimensional sinusoid with the wavenumbers k_x and k_y.

The Fourier transform $F(k_x,k_y)$, which is complex, is the transform of the radiance distribution $N(x,y)$, and contains all of the information that is in the original distribution; indeed, one can calculate $N(x,y)$ from $F(k_x,k_y)$ by the following equation:

$$N(x,y) = \iint F(k_x,k_y)\{e^{2\pi i(xk_x + yk_y)}\}dk_x\,dk_y \tag{29b}$$

Equations 29a and 29b constitute the mathematical formulation of the basic theorem of Fourier analysis.

Equation 29b presents the original radiance distribution as a sum of sinusoidal patterns with a weighting factor $F(k_x,k_y)$. The Fourier transform $F(k_x,k_y)$ gives the amplitude and the phase of the sinusoidal components that are required to reconstruct $N(x,y)$.

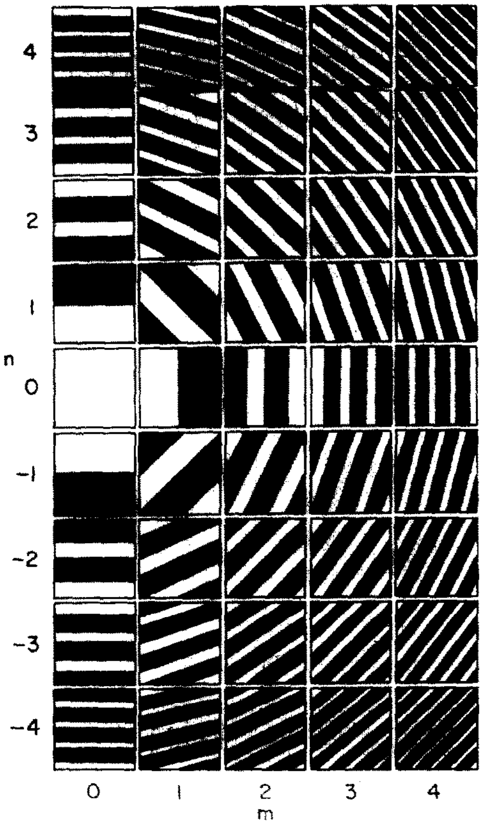

FIG. 9

(d) *Definition of the Wiener spectrum.* It is now possible to define the Wiener spectrum. One takes the absolute value of $F(k_x,k_y)$, squares it, and divides by the area of the region A. This is almost the Wiener spectrum, and indeed it is the Wiener spectrum of the given background. Any given sample of a background, however, usually contains certain idiosyncrasies not characteristic of that class of background. It is customary, therefore, to define the Wiener spectrum as the average of $|F(k_x,k_y)|^2/A$ over an ensemble of similar backgrounds. Thus, the definition of the Wiener spectrum of an ensemble of backgrounds is

$$W(k_x,k_y) = <A^{-1}|F(k_x,k_y)|^2> \text{ ensemble average} \tag{30}$$

In words, the Wiener spectrum is the mean square fluctuation of the radiance of those components of the background that have a wavenumber vector with an x component lying between $k_x - 1/2$ and $k_x + 1/2$, and a y component lying between $k_y - 1/2$ and $k_y + 1/2$.

It is essential for the definition of the Wiener spectrum that the radiance $N(x,y)$ have a mean value of zero. Thus, before computing the Wiener spectrum, one should first subtract the mean value of $N(x,y)$ from $N(x,y)$.

The Wiener spectrum and the two-dimensional autocorrelation function of the background and the Wiener spectrum are Fourier transforms of each other, and thus any statement about the advantages or disadvantages of the Wiener spectrum is equally relevant for the autocorrelation function.

(e) *Utility and limits of Wiener spectra.* The data obtained from the Wiener spectrum may be brought into play along with the design parameters of the system, such as noise equivalent irradiance and instantaneous field of view, in order to calculate the probability that the device will record a target when it is not there, or not locate it when it is there. In the calculation one must assume that the amplitude distribution function of the background radiance is gaussian. We have excellent indications that the amplitude distribution function is probably not gaussian, but so far we lack data sufficient to define the statistics that do apply.

If the amplitude distribution for a given aperture differs widely from a gaussian distribution, the mean square estimate provided by the Wiener spectrum does not give a reliable estimate of the false alarm rate, particularly when the threshold setting provides a very low false alarm rate. Under the latter condition, to obtain a good estimate of the false alarm rate, one must know the amplitude distribution function, including its extremes, for the given aperture.

The Wiener spectrum may be of considerable value for purposes of preliminary design, or if it is not necessary to obtain extremely low false alarm rates.

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