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STANDARD PROCEDURE FOR TESTING INFRARED DETECTORS AND FOR DESCR--ETC(U)

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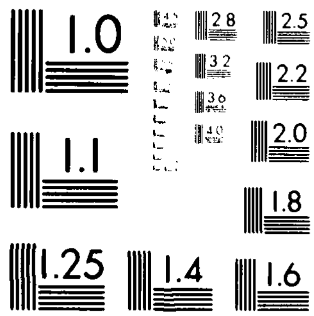

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SUBCOMMITTEE ON NON-ATOMIC MILITARY RESEARCH AND DEVELOPMENT

STANDARD PROCEDURES FOR TESTING INFRARED DETECTORS AND FOR DESCRIBING THEIR PERFORMANCE

REVISED 1975

OFFICE OF THE DEPUTY SECRETARY OF DEFENSE

20 May 1980

MEMO FOR DTIC

This report is a revision of a 196[illegible] report with the same title. It is also in the Commerce collection for sale to the public.

Since the master is none too good, we are including that so you and Commerce won't be making third generation copies.

If you have questions, contact Jim Terrell in OUSDRE

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6 STANDARD PROCEDURE FOR TESTING INFRARED DETECTORS AND FOR DESCRIBING THEIR PERFORMANCE. Revision,

~~REVISED 1975~~

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Prepared for
The Technical Cooperation Program
Subgroup J (Infrared)

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PREFACE

In the late 1950's the lack of uniformity in reported performance data on infrared detectors indicated a need for a joint measurement standard. A working panel was established to prepare a suitable document dealing with definitions, measurement methods and data format. The panel consisted of R. C. Jones, Chairman and United States representative; D. W. Goodwin, United Kingdom representative; and G. T. Pullan, Canadian representative. Their document Standard Procedure For Testing Infrared Detectors and For Describing Their Performance was subsequently published in September 1960. This standard has been widely used by the infrared community and it is considered the definitive document for detector testing.

Over the past fifteen years many new detector materials, fabrication techniques and modes of operation have been developed. Detectors have been improved until the performance of several types of detectors approaches the theoretical limit. The availability of infrared lasers, sampling oscilloscopes, digital processing equipment, etc., has provided many new and useful detector measurement tools.

In view of the extensive development in infrared technology since 1960 it seemed desirable to review the original standard. A new panel consisting of W. L. Eisenman, Chairman and United States representative; E. H. Putley, United Kingdom representative; and J. L. Lachambre, Canadian representative was established to generate a current joint measurement standard.

Upon reviewing the original joint standard, the panel concluded that much of the original document was still applicable and since it has been widely used the panel felt it would be advantageous to adhere to the original format whenever possible. Except for a few minor changes, the section dealing with definitions and terms has been retained. The sections on test equipment and test procedures have been updated to include current equipment and measurement techniques. In the section on test results the panel has recommended several changes in data format.

Anyone attempting to use a new type of detector would like measured data on every detector parameter. However, detector testing represents a significant fraction of the manufacturing costs of a detector. For some applications a single measurement of detector responsivity and noise might suffice. However, in mosts cases a knowledge of how responsivity and noise depend on modulation frequency, wavelength, bias, operating temperature, etc., will be necessary to effectively utilize a detector. Unfortunately, economic considerations often require some compromise in the amount and type of data provided by the manufacturer.

1. INTRODUCTION

1.1 PURPOSE

It is the purpose of this document to present a recommended procedure for the quantitative evaluation of infrared photodetectors and to give a recommended uniform reporting format.

Because there are various types of infrared detectors, and each type has several characteristics which must be evaluated, a complete description of the operating characteristics of the detector would require an excessive number of measurements as well as the presentation of an enormous quantity of data. Consideration must be given in any set of procedures for minimizing the number of measurements, the types of measurements, and the quantity of data presented in a manner consistent with accuracy and completeness. We consider only those detectors having an electrical output. The procedures outlined in the documents have evolved over a period of several years and are based on the experiences of several laboratories which have been concerned with the evaluation of infrared photodetectors.

The recommended measurement and reporting procedures of this document are intended to be applied to those detectors having two general properties: (1) the electrical output is a continuous and linear function of the radiant power incident on the sensitive area; (2) the detector characteristics are factorable (see para. 2.15).

It is the purpose of this document that the procedures recommended will permit meaningful comparison to be made between a set of measurements by personnel of one laboratory with another set of measurements by personnel in a different laboratory. Beyond this immediate goal, however, there is a greater one: that sufficient data presented in a suitable format will provide a concise and accurate description of the detector enabling the application engineer to predict, with accuracy and precision, the performance of a given detector for his particular application.

1.2 SCOPE

This document consists of a set of definitions, and recommended standard test equipment, test procedures, and standard report. This document is <u>not</u> intended to replace or restrict procedures for measurement programs designed for any particular detector having special characteristics and which are to be examined in a unique manner.

2. DEFINITIONS

2.1 THE DETECTOR AND ITS COMPONENTS

2.1.1 <u>Detector</u>: The word "detector" is used in this standard to denote a device that provides an electric output that is a useful measure of the radiation incident on the device. It is intended to include not only the responsive element, but also the physical mounting of the responsive element, as well as any other elements—such as windows, area-limiting apertures, dewar flasks, internal reflectors, etc.—that form an integral part of the detector as it is received from the manufacturer. If, as an integral part of the device, the manufacturer includes equipment for amplification or impedance transformation, then the term detector applies to the combination of the responsive element, the other elements listed in the foregoing sentence, and the amplifier or transformer.

2.1.2 <u>Responsive Element</u>: The term "responsive element" indicates that part of the detector which, when radiation falls on it, undergoes a change in physical properties that results in an electrical signal.

2.1.3 <u>Individual Detector</u>: An "individual detector" is a single sample of a given type of detector. An example is: indium antimonide cell No. 3483 manufactured by X Corporation.

2.1.4 <u>Type of Detector</u>: A type of detector is a class of individual detectors that have one or more relevant properties in common. Examples are: heat detectors, bolometers, thermistor bolometers, photoconductive cells, evaporated lead sulfide photoconductive cells with evaporated gold electrodes mounted in stainless steel capsules having silver chloride windows.

2.2 THE RADIATION INCIDENT ON THE DETCTOR

This section is concerned primarily with the radiation, not with the detector.

The radiation incident on a detector is characterized by the distribution of the radiant power with respect to wavelength, modulation frequency, position on the responsive element, and the direction of arrival.

(1) The power that is instantaneously incident on the responsive element of a detector is denoted P and is measured in watts.

(2) The power per unit area incident on the responsive element of the detector is called the irradiance H and is measured in watts per square centimeter.

(3) In testing radiation detectors, one causes to be incident on the responsive plane of the detector a signal power P_s. When the radiation is uniformly incident on the responsive plane of the detector, the radiation can also be described in terms of the signal irradiance H_s. The signal power is usually modulated by a chopper.

(4) The ambient power P_a and the ambient irradiance H_a describe the steady radiation incident on the detector. Examples are: radiation emitted by the mounting and the windows and steady radiation arising outside of the detector. It is usually not feasible to make the ambient radiation zero.

(5) The signal power and the ambient power are completely described by stating the distribution of the incident power with respect to radiation wavelength λ, modulation frequency f, position coordinates x, y on the adopted responsive plane (see section 2.4) and angular coordinates θ, ϕ.

(a) The radiation wavelength λ is the value in vacuum and is measured in micrometers.

(b) The modulation frequency f is measured in Hz.

(c) The peak wavelength λ_p and the peak modulation frequency f_p are the values of λ and f that simultaneously maximize the detectivities D_1 and D* (see section 2.11).

(6) The distribution of the radiant power with respect to radiation wavelength λ is described by stating the spectral power P_λ, defined as the power per unit wavelength interval. More precisely, if ΔP is the power in the wavelength interval $\Delta\lambda$, P_λ is the ratio $\Delta P/\Delta\lambda$ with $\Delta\lambda$ suitably small compared with λ. P_λ is measured in watts per micrometer.

(7) The power P normally incident on the detector is calculated by multiplying the irradiance H in the adopted responsive plane of the detector by the adopted area A_a.

$$P = A_a H \tag{2.2-1}$$

(8) The distribution of the irradiance with respect to radiation wavelength λ is described by stating the spectral irradiance H_λ, defined as the irradiance per unit wavelength interval. More precisely, if ΔH is the irradiance in the wavelength interval $\Delta\lambda$, H_λ is the ratio $\Delta H/\Delta\lambda$, $\Delta\lambda$ being suitably small compared with λ. H_λ is measured in the unit: watt/cm^2-micrometers.

(9) In testing detectors, the radiation incident on the detector is usually modulated periodically in time. The usual way to achieve this modulation is to place a multibladed wheel between the radiation source and the detector and rotate the wheel at a constant angular velocity. The modulating device is called a chopper. The basic repetition frequency produced by the chopper is denoted f. The instantaneous power P(t) incident on the detector can be represented as the sum of Fourier components:

$$P(t) = P_o + P_1 \cos (2\pi ft + \Psi_1) + P_2 \cos (4\pi ft + \Psi_2) + \ldots \qquad (2.2\text{-}2)$$

where each component has an amplitude P_k and phase angle a Ψ_K. Each component represents a sinusoidally modulated radiation signal, and the components have the frequencies f, 2f, 3f, etc. The fundamental component is the sinusoidal component with the frequency f. The root-mean-square amplitude of the fundamental component is defined as the peak-to-peak amplitude of this component divided by $2^{3/2}$:

$$P_{rms} = 2^{-1/2} P_1 \qquad (2.2\text{-}3)$$

(The peak-to-peak amplitude is $2P_1$.)

A second method for producing an amplitude modulated signal of radiation is to use a combination of a laser source and an electro-optic modulator. This equipment can be used to generate transient as well as repetitive waveforms and can usually operate at higher frequencies than is possible with a mechanical modulator. This type of arrangement can provide a sinusoidally modulated light source from DC to approximately 1 GHz of existing laser wavelength in the infrared spectrum.

Another way to realize a sinusoidal modulation of a light source is to vary the frequency of the voltage applied to a laser diode.

2.3 THE ELECTRICAL OUTPUT OF THE DETECTOR

It is convenient to distinguish two additive components in the electrical output of the detector--the signal voltage V_s (or signal current I_s) and the noise voltage V_n (or the noise current I_n). Over a sufficiently long period of time, the two voltages (or currents) can be distinguished exactly by the criterion that the signal voltage is fully coherent with the signal power, whereas the noise voltage is completely incoherent with the signal power. The output can be described by giving the distribution of the voltage (or current) with respect to time or frequency.

In this section and in sections 2.8 and 3.6 the fundamental frequency f of the chopper must be distinguished from the frequency ν of any component in the output of the detector. In all other sections to distinguish between f and ν is unnecessary, however, and the symbol f is used for both types of frequency. The frequencies f and ν are both measured in Hz.

(1) The electrical signal voltage V_s (or current I_s) in the output of the detector is the part of the output that is coherent with the signal power incident on the detector.

(2) In the special case where the radiation power is periodic in time, the electrical signal output is also periodic in time. The instantaneous signal voltage V(t) can be represented as the sum of Fourier components:

$$V(t) = V_o + V_1 \text{ cps } (2\pi ft + \theta_1) + V_2 \cos (4\pi ft + \theta_2) + \ldots \qquad (2.3\text{-}1)$$

The root-mean-square amplitude of the fundamental component is defined as the peak-to-peak amplitude of this component divided by $2^{3/2}$:

$$V_{s,\ rms} = 2^{-1/2} V_1 \qquad (2.3\text{-}2)$$

(The peak-to-peak amplitude is $2V_1$.)

(3) In addition to the signal voltage V_s appearing at the output of the detector, electrical noise also is always present. When there is no signal power, the only electrical output from the detector is the electrical noise.

(4) Unlike the electrical signal which has components only at frequencies ν equal to f, 2f, 3f, etc., the electrical noise has components at every frequency--that is to say, the spectrum of the electrical noise is continuous. The magnitude of the noise voltage as observed by a suitable voltmeter depends on the range of

frequencies accepted by the voltmeter. To define the band of frequencies accepted by the voltmeter, we let $g(\nu)$ denote the gain of the voltmeter as a function of the frequency ν. Then, the noise bandwidth $\Delta\nu$ of the measuring equipment is defined by:

$$\Delta\nu = \int_0^\infty [g(\nu)]^2 d\nu / g_m^{\ 2} \tag{2.3-3}$$

where g_m is the maximum value of the gain with respect to frequency ν. The frequency ν_m that maximizes $g(\nu)$ is called the center frequency of the passband.

(5) The root-mean-square voltage (or current) of the electrical noise is defined as the square root of the time average of the square of the difference between the instantaneous voltage (or current) and the time average voltage (or current).

$$\begin{aligned} V_{n,rms} &= [<(V_n - <V_n>_{Av})^2>_{Av}]^{\frac{1}{2}} \\ I_{n,rms} &= [<(I_n - <I_n>_{Av})^2>_{Av}]^{\frac{1}{2}} \end{aligned} \tag{2.3-4}$$

The average values of $<V_n>_{Av}$ and $<I_n>_{Av}$ will nearly always be zero in practice, since the voltage or current will usually have passed through an amplifier whose dc gain is zero. When this condition holds, the above two equations reduce to:

$$\begin{aligned} V_{n,rms} &= [<(V_n)^2>_{Av}]^{\frac{1}{2}} \\ I_{n,rms} &= [<(I_n)^2>_{Av}]^{\frac{1}{2}} \end{aligned} \tag{2.3-5}$$

(6) The power spectrum $W(\nu)$ of the electrical noise is defined as the time average of the square of the difference between the instantaneous noise voltage (or current) and the time average voltage (or current), divided by the noise bandwidth $\Delta\nu$ of the measuring equipment.

$$W(\nu) = (V_{n,rms})^2/\Delta\nu$$

$$W(\nu) = (I_{n,rms})^2/\Delta\nu \qquad (2.3\text{-}6)$$

In this definition, it is supposed that the voltmeter has a bandwidth $\Delta\nu$ that is small compared with ν. $W(\nu)$ is measured in volt^2/Hz or in ampere^2/Hz.

(7) If the distribution of the noise voltage (or current) about the time average mean value is Gaussian and if the statistical properties are stationary in time, then the statistical properties of the noise are fully described by the power spectrum. But if the distribution is not Gaussian, further description is necessary for a complete characterization of the statistical properties of the noise.

(8) The root power spectrum $N(\nu)$ is the square root of the power spectrum $W(\nu)$. $N(\nu)$ is measured in volt/(Hz)$^{\frac{1}{2}}$ or in ampere/(Hz)$^{\frac{1}{2}}$.

(9) The term "voltmeter" as used in this section is equivalent to the combination of the low-noise amplifier, tunable filter, and voltmeter, as described separately in sections 3.5, 3.6, and 3.7.

2.4 GEOMETRICAL PROPERTIES OF THE DETECTOR

(1) The responsive properties of a detector are defined in terms of the radiation incident on a selected plane/surface associated with the detector. The plane selected by the testing laboratory is called the adopted responsive plane, and is denoted S.

(2) Usually there is no ambiguity in selecting the responsive plane S. If the responsive element itself is in the form of a thin flat layer, as with evaporated photoconductive cells or metal bolometers, the adopted responsive plane is simply the plane in which the responsive element lies. But there are detectors where the responsive plane must be chosen otherwise. Examples: With doped germanium detectors in which the responsive element is more or less cubical and is located within a chamber with reflecting walls, the adopted reference plane S is the plane that contains the entrance aperture of the chamber. With photoemissive tubes with curved photocathodes, the adopted reference plane is the plane that contains the straight edges of the photocathode.

(3) With some detectors the selection of the adopted reference planes is more or less arbitrary. With a detector that incorporates a number of refracting elements, for example, the testing laboratory may find it convenient to refer the measurements to the plane that contains the rim of the most accessible optical element.

(4) Let a coordinate system x,y be established on the adopted responsive plane S.

(5) Let the direction of incidence of a pencil of radiation that is incident at the point x,y, be defined by the two angles θ,ϕ of a spherical coordinate system, with the polar angle θ measured from the normal to the adopted responsive plane.

(6) Detector Area A. The several kinds of detector areas measured on the adopted reference plane need to be distinguished:

(a) The nominal area A_n is any value of the responsive area, quoted by a source other than the testing laboratory, that purports to represent an approximation of the actual responsive area of the detector. Thus, for example, the nominal area may be the manufacturer's design-center values for the area of an evaporated-film detector, or the nominal area may be an area quoted to one significant figure that is used as a label to distinguish between the given detector and other detectors of widely different area.

(b) The adopted area A_a is the area that is adopted by the test laboratory to convert the irradiance H on the detector to the power P incident on the detector:

$$P = A_a H \tag{2.4-1}$$

The test laboratory will often select either the nominal area or the effective area as the adopted area.

(c) The effective area A_e of a detector is defined by physical measurements, as follows: The position on the adopted responsive plane S of the detector is defined by a rectangular cartesian x,y coordinate system. The responsivity R(x,y) is measured with a very small spot of radiation at each point of the plane. The effective area A_e is defined by

$$A_e = \int_S \int R(x,y)\,dxdy/R_{max} \tag{2.4-2}$$

where R_{max} is the maximum value of R(x,y).

(7) Detector solid angle. It is often desirable to know the solid angle from which the detector can receive radiation from outside the detector. This information is needed to calculate D** for at least two situations of practical interest: Cooled detectors equipped with cooled radiation shields and room temperature detectors whose responsive element is immersed in a lens of high index. Actually, the solid angle that one wishes to know for a flat detector element is

the solid angle weighted at each angle by the cosine of the angle of incidence. This is called the weighted solid angle and is denoted by Ω. Several kinds of weighted solid angles need to be distinguished.

(a) The nominal weighted solid angle Ω_n of a detector may be a value used in the specification of the detector or it may be the value used to identify the detector.

(b) The adopted weighted solid angle Ω_a of a detector is the solid angle that is adopted by the test laboratory to calculate the value of D**.

(c) The effective weighted solid angle Ω_e of a detector is defined by physical measurements, as follows: The responsivity at the point x,y on the adopted responsive plane S of the detector for radiation coming from the direction θ,ϕ is denoted $R(x,y,\theta,\phi)$. The angles θ and ϕ are the polar and azimuthal angles of a spherical coordinate system with the axis normal to the surface of the responsive plane. The effective weighted solid angle Ω_e of the detector in steradians is defined by:

$$\Omega_e = \int_S\int dxdy \int_0^{\pi/2} \cos\theta \sin\theta \, d\theta \int_0^{2\pi} R(x,y,\theta,\phi)d\phi / [A_e R_{max}(0\ 0)] \quad (2.4\text{-}3)$$

where $R_{max}(0,0)$ is the maximum value of $R(x,y,0,0)$. It is, of course, scarcely contemplated that any laboratory will ever measure $R(x,y,\theta,\phi)$ as a function of all four variables and then perform the quadruple integration. But the above expression for Ω_e does indicate (in a way that no words can) the exact conceptual meaning of the effective weighted solid angle.

(8) If the responsivity of a detector is independent of the angles θ and ϕ, the detector is called a Lambertian detector.

(9) With some detectors, it is considered to be an adequate approximation to suppose that the responsivity is independent of the azimuthal angle ϕ. Then, the detector is said to have circular symmetry.

(10) For detectors with circular symmetry, the total cone angle Θ may be used instead of the weighted solid angle Ω. The total cone angle Θ is defined in terms of Ω by:

$$\Omega = \pi \sin^2 (\Theta/2) \tag{2.4-5}$$

The relation between the total cone angle and the ordinary unweighted solid angle ω is:

$$\omega = 2\pi \, [1 - \cos(\Theta/2)] \tag{2.4-6}$$

As the solid angle Ω in equation 2.4-5 is identified with the nominal, adopted, or effective weighted solid angle, the equation defines the nominal, adopted, or effective total cone angle, respectively.

(11) The weighted solid angle of a Lambertian detector is $\Omega = \pi$. The unweighted solid angle of a Lambertian detector is $\omega = 2\pi$.

2.5 THE DETECTOR AS A CIRCUIT ELEMENT

Most detectors have two electrical terminals. When the radiation incident on the detector is steady, the detector may be considered a circuit element and can be described as a circuit element. It should be held in mind, however, that the properties of the detector as a circuit element will usually depend on the frequency and will sometimes depend on the amount of ambient power P_a and on the dc current I_o through the detector.

(1) The impedance Z of the detector is defined by:

$$Z = \frac{dE}{dI} \tag{2.5-1}$$

where E is the instantaneous voltage across the terminals of the detector and I is the instantaneous current through the detector. The impedance Z is complex:

$$Z = \overline{R}_z + iX_z \tag{2.5-2}$$

(2) The value of $\overline{R}_z$ at zero frequency is called the dc impedance and is denoted $\overline{R}_{zo}$.

(3) The unqualified term resistance $\overline{R}$ is used to describe the ratio of the dc voltage to the dc current:

$$\overline{R} = E_o/I_o \tag{2.5-3}$$

(4) The impedance Z, both its real and imaginary parts, and the resistance $\overline{R}$ are measured in ohms.

(5) The impedance Z of some detectors may be conveniently represented by an equivalent circuit that is appropriate to the detector in question. For example, as a capacitance C and resistance $\overline{R}_d$ in parallel for high impedance photoconductive cells, or as an inductance L and resistance $\overline{R}_d$ in series for thermistor bolometers.

(6) When radiation detectors are tested the detector is connected to an amplifier and in some cases to bias sources. The load impedance Z_L is the impedance of the external circuit as seen from the terminals of the detector. Often, the impedance is almost purely resistive. In this case, the load impedance can be represented by the load resistance $\overline{R}_L$. Z_L and $\overline{R}_L$ and measured in ohms.

2.6 DETECTOR TEMPERATURE

Detectors that operate without refrigeration have responsive elements that have a temperature equal to or slightly higher than the ambient temperature. The actual temperature of the responsive element is often nonuniform and is difficult to measure experimentally. The user of the detector normally has little interest in the actual temperature of the responsive element.

In this standard, the term detector temperature T indicates the ambient temperature if the detector is not refrigerated or the nominal temperature of the coolant if the detector is refrigerated.

The detector temperature T is measured in Kelvin.

2.7 DETECTOR BIAS

Most kinds of individual detectors have externally adjustable parameters that permit a variation of the responsivity (and of the detectivity). Examples of these adjustable parameters are the biasing current in bolometers and photoconductive cells, the applied potentials in multiplier phototubes and simple phototubes, the biasing voltage in back-biased junctions, the emitter current in phototransistors, the several adjustable parameters of the Golay detector, and the magnetic field in photoelectromagnetic detectors.

All of these parameters have the effect of varying the performance of the detector. The term "bias" will be used as a generic term to refer to any of these adjustable parameters. When the bias is the biasing current of a photoconductive cell, the recommended unit is the ampere and the recommended symbol is i.

(1) The optimum bias b_p is the bias that maximizes the detectivity when it is measured with radiation with a wavelength near λ_p and a chopping frequency near f_p. The optimum bias b_p for a single element detector at temperature T_d is the bias that maximizes the detectivity when it is measured with radiation with a wavelength near λ_p and a chopping frequency near f_p. If the detector has to be operative over a range of temperature or is one element in an array it may not be practicable to use the optimum bias as defined. In these cases the criterion to be used for selecting the bias value must be specified by the manufacturer or the design authority responsible for drawing up the detector specification.

(2) The maximum value of the bias b_m is the maximum value recommended by the manufacturer.

2.8 RADIATION SOURCES AND VOLTMETERS

2.8.1 Radiation Sources: In measuring the responsivity of radiation detectors, it is customary to use three different kinds of sources: A blackbody source, a monochromatic source and a modulated source. The first and second types may be equipped with choppers or other modulators but the third is specifically used for measuring the modulation response of the detector.

(1) With the blackbody source, the wavelength distribution from the blackbody is supposed to be known on an absolute basis and is described by the spectral irradiance $H_{\lambda,rms}$.

(2) The monochromatic source is characterized by the wavelength λ of its output.

(3) The variable frequency source is characterized by the time dependence of its radiant output. Two main types are used: Periodically modulated (or chopped) and pulsed. The latter may be periodic or repetitive but is considered separately because the very small fraction of time that the source radiates makes it useful to measure each individual pulse. The fundamental frequency of the periodically modulated radiation is denoted by f, the reciprocal of the repetition period. The amplitude of the power (or irradiance) of the chopped radiation is measured by the root-mean-square amplitude of the Fourier component at the fundamental frequency. The pulsed source is characterized by the envelope P(t) of one pulse of radiation. Often it will be sufficient to specify only the peak pulse power P_p and a pulse width t.

2.8.2 Voltmeters: The term voltmeter as used in this section is equivalent to the combination of the low-noise amplifier, tunable filter, and voltmeter as described in sections 3.5, 3.6, and 3.7.

The signal voltage (or current) in the output of the detector is measured with a voltmeter such that the gain $g(\nu)$ of the voltmeter has its maximum value when ν is equal to the chopping frequency f, and such that the gain $g(\nu)$ is negligible relative to g (f) when ν is equal to any of the harmonics of f—that is to say, when ν is equal to 2f, 3f, 4f, etc.

The voltmeter is to be such that it indicates the root-mean-square voltage of the component of frequency f.

(Note: Henceforth, in this standard except in section 3.6 it is unnecessary to distinguish between the chopping frequency f and the frequency ν of the electrical output of the detector. The symbol f will be used to denote both ν and f.).

2.9 THE RESPONSIVITY

The responsivity is here defined only for periodically modulated radiation. Furthermore, it is supposed that, as described in section 2.8, the electrical measuring equipment has its maximum gain at the chopping frequency of the radiation input and a negligible gain at the harmonic frequencies.

The responsivity of a detector is usually measured with an amplifier connected between the detector output terminals and the instrument that measures the voltage. If the output of the amplifier is (mistakenly) taken as the output of the detector, one obtains a responsivity R_{zg} that is increased by the gain g of the amplifier and is influenced by the finite load impedance Z_L.

(1) The responsivity, in general, is the ratio of the rms value of the fundamental component of the electrical output of the detector to the rms value of the fundamental component of the input radiation power when the power is incident, normally, on the adopted responsive plane. The responsivity is measured in volts per watt or in amperes per watt.

(2) The responsivity R_z is the responsivity referred to the terminals of the detector but influenced by the finite load impedance Z_L.

(3) The responsivity R is the responsivity referred to the terminals of the detector and referred to an infinite load impedance. R may be termed the open-circuit responsivity.

(4) The responsivities defined above may be called absolute responsivities to distinguish them from a relative responsivity. A relative responsivity is an absolute responsivity multiplied by a constant whose value may or may not be known.

(5) The responsivity R of an individual detector usually depends on all of the following parameters:

(a) The spectrum of the radiation (λ)

(b) The chopping frequency (f)

(c) The detector temperature (T)

(d) The bias (b)

(6) The responsivity $R_m(f)$ is the responsivity R at the peak wavelength λ_p. The responsivity R and detectivity D have their maxima with respect to wavelength at the same wavelength λ_p.

(7) The responsivity $R_\mu(\lambda)$ is the responsivity R at the peak modulation frequency f_p, which is defined as the frequency that maximizes the detectivity D with respect to the modulation frequency f. The use of the subscript μ instead of m is intended to emphasize that $R_\mu(\lambda)$ is not the maximum value of R with respect to the modulation frequency f.

(8) The responsivity $R_{m\mu}$ is the value of the responsivity R at the peak wavelength λ_p and the peak modulation frequency f_p. R has its maximum at the same wavelength λ_p as does D, but unless the root power spectrum of the noise is flat, the responsivity R and the detectivity D do not have their maxima at the same modulation frequency.

2.10 THE DETECTOR NOISE

The electrical noise in the output of a detector is usually measured with an amplifier connected between the detector output terminals and the instrument that measures the noise. If the output of the amplifier is (mistakenly) taken as the output of the detector, the measurement yields a root power spectrum N_{zng} that is influenced by the gain g and the noise n of the amplifier and by the finite load impedance Z_L.

(1) The root power spectrum N_{zn} is the root power spectrum referred to the terminals of the detector but not corrected for the noise of the amplifier and not referred to an infinite load impedance.

(2) The root power spectrum N_n is the root power spectrum referred to the teminals of the detector and referred to an infinite load impedance but not corrected for the noise of the amplifier.

(3) The root power spectrum N_z is the root power spectrum referred to the terminals of the detector and corrected for amplifier noise but not referred to infinite load impedance.

(4) The root power spectrum N is the root power spectrum referred to the terminals of the detector, referred to an infinite load impedance, and corrected for amplifier noise.

(5) A simple and widely used procedure permits the measurement of N_n directly without first measuring N_{zng}. This procedure involves the injection of a calibrating voltage in series with the detector under test, by the mechanism of a small, known resistance connected between the detector's ground terminal and ground. The details are given below in sections 3 and 4. This procedure is not always practicable with very fast detectors or with detectors having very high output impedance. In these cases R_{zg} must be measured with the amplifier gain determined by a separate measurement. In some detectors (for example the Golay

cell and some types of pyroelectric detectors) an amplifier stage is built as an integral part of the detector so that it may not always be practicable to arrive at a true value of R. When there is any doubt, this should be clearly stated in the test report.

2.11 THE DETECTIVITY

The detectivity of a detector can be defined in any of three equivalent ways: As the reciprocal of the noise equivalent input, as the signal-to-noise ratio divided by the incident power, or as the responsivity divided by the noise. The last definition is used in this standard.

(1) The detectivity D is defined, in general, as the ratio of the responsivity to the rms noise

$$D = \frac{R}{N} \tag{2.11-1}$$

where R is in volts/watt or

$$D = \frac{R}{N} \tag{2.11-2}$$

where R is in amperes/watt. This ratio does not depend on whether the right-hand quantities are measured at the output of the amplifier or at the detector terminals, nor does it depend on whether the quantities are referred to a finite or infinite load resistance. But the value obtained for D does depend on whether the rms noise is corrected for the noise of the amplifier. If uncorrected, the detectivity is denoted D_n, and if corrected, D. D is measured in reciprocal watts.

$$D_n = \frac{R_{zg}}{N_{zng}} = \frac{R_z}{N_{zn}} = \frac{R}{N_n} \tag{2.11-3}$$

$$D = \frac{R_{zg}}{N_{zg}} = \frac{R_z}{N_z} = \frac{R}{N} \qquad (2.11\text{-}4)$$

There is sometimes a danger of unrealistic values of D being reported. The detector has to be used with an amplifier, and if the best available state-of-the-art amplifiers contribute noise then D_n cannot be bettered. On the other hand, if the amplifier noise is negligible, $D_n = D$. In some cases there is a danger of reporting a value of D far better than anything which can be realized in practice. This remark applies to pyroelectric detectors, the sub mm detectors and can also be relevant for some shorter wavelength photo detectors.

The detectivity D*, pronounced "D star", is the detectivity D reduced to unit area by the root-area relation

$$D^* = A_a^{1/2} D \qquad (2.11\text{-}5)$$

D* is measured in the units: cm-$(Hz)^{1/2}$/watt.

The detectivity D**, pronounced "D double star", is the detectivity D reduced to unit area and to a weighted solid angle of π steradians.

$$D^{**} = (A_a \Omega_a / \pi)^{1/2} D \qquad (2.11\text{-}6)$$

D** is measured in the units: cm-$(Hz)^{1/2}$/watt.

The detectivities D, D*, and D** of an individual detector usually depend on all of the following parameters:

(a) The spectrum of the radiation (λ)

(b) The chopping frequency (f)

(c) The detector temperature (T)

(d) The ambient power (P_a)

(e) The spectrum of the ambient power (λ)

(f) The bias (b)

The detectivity D depends also on the noise bandwidth $\Delta\nu$ used in the measurement.

The detectivities D, D*, and D**, as well as the corresponding quantities not corrected for the noise of the amplifier, all differ by factors that depend neither on the wavelength λ nor on the modulation frequency f. Therefore, the wavelength and frequency that maximize one of these detectivities maximize all of the others. The peak wavelength λ_p and the peak modulation f_p are the values of λ and f that simultaneously maximize the detectivity. The values of the detectivities at the peak wavelength λ_p and at the peak modulation frequency f_p are denoted by D_{mm}, D^*_{mm}, D^{**}_{mm}.

The detectivities measured at the peak modulation frequency f_p are denoted by $D_m(\lambda)$, $D^*_m(\lambda)$, $D^{**}_m(\lambda)$.

The detectivities measured at the peak wavelength λ_p are denoted by $D_m(f)$, $D^*_m(f)$, $D^{**}_m(f)$.

The reciprocal of each of the detectivities is a noise equivalent power. For example, the noise equivalent power P_N may be defined as the reciprocal of D:

$$P_N = 1/D \tag{2.11-7}$$

The concept of D* is not applicable to all types of detectors since there are some cases where D does not vary as $A_a^{\frac{1}{2}}$. If there is any doubt, test reports should be expressed in terms of D (or P_N) with the value of A_a being clearly stated.

2.12 ENERGY DETECTIVITY

(1) The concepts of responsivity and detectivity defined in the preceding sections have been formulated in terms of a periodically modulated radiation

signal. In this section, the radiation signal is supposed to be in the form of a pulse. E denotes the total energy of the pulse and is measured in joules.

(2) The detector is supposed to be connected to a noiseless amplifier with the gain g(f). At the output of the amplifier, the total rms noise voltage is denoted V_n. The maximum voltage of the electrical signal pulse with respect to time is denoted V_{sp}. The energy detectivity is defined by:

$$\Delta = \frac{V_{sp}}{EV_n} \tag{2.12-1}$$

The energy detectivity Δ is measured in reciprocal joules.

(3) The energy detectivity Δ is the reciprocal of the noise equivalent energy E_N, which is defined as the value of the pulse energy E that makes the signal-to-noise ratio V_{sp}/V_n equal to unity.

(4) The value of the energy detectivity Δ depends on the shape of the radiation pulse and on the amplifier gain function g(f). It can be shown that the maximum possible value of Δ is achieved if the following three conditions are satisfied:

(a) The pulse is very short--specifically, the duration of the pulse is very small compared with the detective time constant τ_d.

(b) The gain g(f) is of the form:

$$g(f) = \text{constant } R/N^2 \tag{2.12-2}$$

(c) The sum of the phase shift in the detector and the phase shift of the amplifier is directly proportional to the frequency.

When these three conditions are satisfied, the energy detectivity is given by:

$$\Delta_m(\lambda) = 2\left(\int_0^\infty [D(\lambda, f)]^2 df\right)^{\frac{1}{2}} = D_m(\lambda)/\tau_d^{\frac{1}{2}} \qquad (2.12\text{-}3)$$

$\Delta_m(\lambda)$ is measured in reciprocal joules.

(5) The energy detectivity Δ^*, pronounced "delta star", is the energy detectivity Δ reduced to unit area by the root area relation:

$$\Delta^* = \frac{A^{\frac{1}{2}} V_{sp}}{V_n E} \qquad (2.12\text{-}4)$$

Δ^* is measured in cm/joule.

(6) The energy detectivity $\Delta^*_m(\lambda)$ is the energy detectivity $\Delta_m(\lambda)$ reduced to unit area by the root area relation:

$$\Delta^*_m(\lambda) = 2\left(\int_0^\infty [D^*(\lambda, f]^2 df\right)^{\frac{1}{2}} = D^*_m(\lambda)/\tau_d^{\frac{1}{2}} \qquad (2.12\text{-}5)$$

(7) The energy detectivity Δ^*_{mm} is the energy detectivity $\Delta^*_m(\lambda)$ measured at the peak wavelength λ_p.

2.13 TIME CONSTANT

If the complex responsivity depends on the frequency in accordance with the relation:

$$R(f) = R_o/(1 + 2\pi i f\tau) \qquad (2.13\text{-}1)$$

then there is general agreement that the (responsive) time constant is equal to τ. Other than in this paragraph, all of the responsivities dealt with in this standard represent the modulus of the complex responsivity rather than complex responsivity per se.

When the responsivity does not depend on the frequency in accordance with the above relation, controversy sets in. Some persons believe that no effort should be made to define a time constant. Others assert that some particular definition should be used. Among the definitions that have been proposed are the following:

(a) The reciprocal of the angular frequency at which the responsivity is 0.707 times the zero frequency responsivity.

(b) The reciprocal of the angular frequency where the low-and high-frequency asymptotes intersect (in a plot of log R versus log f).

(c) The reciprocal of the angular frequency where the slope of the log R versus log f curve is minus one-half (minus 3 decibels per octave).

(d) The reciprocal of the angular frequency where the phase lag is 45 degrees.

(e) Any of the times required for approach to a steady state after a transient radiation signal.

All of these time constants are equal when the above equation holds; otherwise all of them may differ.

All of the time constants represent an effort to measure the speed of response of the detector or, in different words, to measure the bandwidth of the detector. Accordingly, the writers of this standard have elected to define the time constant in terms of the bandwidth.

The time constants defined in (3) and (4) below involve measurements made over the entire frequency range of the detector. To determine whether a detector satisfies a specification, such measurements are not always desirable. Accordingly, (5) and (6) provide a pair of alternative definitions for use only in specifications. These two alternative definitions are based on measurements made at two pre-assigned frequencies.

With a mechanical modulator chopping frequencies up to about 50,000 Hz are considered to be practical for achievement in a small testing laboratory. Time constants greater than about 5×10^{-6} seconds can be measured on the basis of the definitions given in (3) and (4) below. Modulation frequencies of up to 1 GHz can be realized with the aid of a laser and an electro-optic modulator; a time constant of about 0.5 ns can be deduced with this technique on the basis of the definitions given in (3) and (4) below. Time constants shorter than 0.5 ns are not easy to measure. A direct method to measure such a time constant is to use a continuously mode-locked laser when available at the desired wavelength and a sampling oscilloscope.

Because of the distributed and shunt capacities of the detector itself, all of the time constants defined in this section will depend to a greater or lesser extent on the value of the load resistor R_L. Although the method of measurement recommended in section 4.1 completely eliminates the effect of the shunt capacity of the input of the preamplifier, it does not eliminate the effect of the shunt capacity of the detector itself. When the bandwidth of a detector is limited by the capacitance of the detector and the external shunt resistance, the value of this shunt resistance must be given with the specifications. This situation generally prevails in the pyroelectric detector case when the bandwidth changes with the load resistor.

(1) The responsive bandwidth $(\Delta f)_r$ is defined by:

$$(\Delta f)_r = \int_0^\infty [R(f)]^2 df/[R_{max}]^2 \tag{2.13-2}$$

where R(f) is the responsivity and R_{max} is the maximum value of R with respect to frequency. Note that R_{max} is not identical with $R_\mu(\lambda)$

(2) The detective bandwidth $(\Delta f)_d$ is defined by:

$$(\Delta f)_d = \int_0^\infty [D^*(\lambda,f)]^2 df / [D^*_m(\lambda)]^2 \qquad (2.13\text{-}3)$$

Both bandwidths are measured in Hz.

(3) The responsive time constant τ_r is defined by:

$$\tau_r = 1/(4(\Delta f)_r) \qquad (2.13\text{-}4)$$

(4) The detective time constant τ_d is defined by:

$$\tau_d = 1/(4(\Delta f)_d) \qquad (2.13\text{-}5)$$

(5) The specification-type responsive time constant τ_{rs} is defined by:

$$\tau_{rs} = \frac{1}{2\pi}\left[\frac{[R(f_1)]^2 - [R(f_2)]^2}{[f_2 R(f_2)]^2 - [f_1 R(f_1)]^2}\right]^{\frac{1}{2}} \qquad (2.13\text{-}6)$$

where f_1 and f_2 are frequencies that must be included in the specification. (For some specifications it may be convenient to define f_1 and f_2 by:

$$f_1 = \frac{1}{20\tau'_{rs}} \qquad f_2 = \frac{1}{2\tau'_{rs}} \qquad (2.13\text{-}7)$$

where τ'_{rs} is a specified design-center responsive time constant).

(6) The specification-type detective time constant τ_{ds} is defined by:

$$\tau_{ds} = \frac{1}{2\pi}\left[\frac{[D^*(f_1)]^2 - [D^*(f_2)]^2}{[f_2 D^*(f_2)]^2 - [f_1 D^*(f_1)]^2}\right]^{\frac{1}{2}} \qquad (2.13\text{-}8)$$

where f_1 and f_2 are frequencies that must be included in the specification. (For some specifications it may be convenient to define f_1 and f_2 by:

$$f_1 = \frac{1}{20\tau'_{ds}} \qquad f_2 = \frac{1}{2\tau'_{ds}} \tag{2.13-9}$$

where τ'_{ds} is a specified design-center detective time constant.)

(7) The pulse time constant τ_p is measured by exposing the detector to a rectangular pulse of radiation. Because the pulse time constant is a type of responsive time constant, the result depends on the gain-versus-frequency curve of the amplifier used and on the magnitude of the resistance that is in shunt with the detector. The gain should be flat up to frequencies that are large compared with $2\pi/\tau_p$. The result usually depends markedly on the value of the shunt resistance. When the shunt resistance is made so small that the RC time constant is small compared with the value measured, the pulse time constant is called the intrinsic time constant. When this is not the case (ex. pyroelectric detector) the value of the shunt resistor used in the measurement should accompany the quoted rise time.

The rise and fall times of the radiation pulse must be short compared with the pulse time constant being measured. When the rise and decay time of the pulse are pure exponentials, the rise time constant is equal to the time required for the signal voltage (or current) to rise to 0.63 times its asymptotic value. The fall time constant is equal to the time required for the signal voltage to fall to 0.37 of the asymptotic value. If the rise and decay time of the measured pulse are not exponential, the rise time and decay time of the detector should be given by the time required for the pulse to vary from 10% to 90% of its maximum value and inversely. In this case, the specified time constant value of a given detector should be accompanied by the following notation (10% to 90%). It must be noted that in this last situation, there is no direct relationship between the measured time constant and the responsive bandwidth. If the detector and amplifier are linear, the rise and fall time constants are equal and are called the pulse time constant τ_p. If the rise and fall times are unequal, the detector-amplifier system is nonlinear and the system lies outside the scope of this standard.

2.14 DETECTIVE QUANTUM EFFICIENCY

(1) If nearly monochromatic radiation from an unmodulated thermal source is incident on a detector, the mean square fluctuation in the power is given by:

$$<(\Delta P)^2>_{Av} = 2EP_a \Xi \Delta f \qquad (2.14\text{-}1)$$

where Ξ is the Bose-Einstein coherence factor that may be taken as equal to unity for all practical purposes. (The formal condition for Ξ to be close to unity is that the product of the wavelength and the temperature of the source be less than about 5000 micrometer-degrees.) E is the energy of a photon of the wavelength in question, P_a is the ambient power, and Δf is the noise bandwidth.

(2) If there is no other radiation incident on the detector <u>and</u> if the power emitted by the detector is negligible compared with P_a <u>and</u> if there is no other source of noise in the detector, then the detectivity D is the reciprocal of $[<(\Delta P)^2>_{Av}]^{\frac{1}{2}}$:

$$D = 1/(2EP_a\Delta f)^{\frac{1}{2}} \qquad (2.14\text{-}2)$$

In the presence of the given ambient radiation, the expression 2.14-2 indicates the maximum possible detectivity. No actual detector can have a higher detectivity, and all detectors in practice have a lower detectivity.

(3) The detective quantum efficiency is defined in general by:

$$Q_D = \left[\frac{\text{Measured detectivity D}}{\text{Maximum possible detectivity D}} \right]^2 \qquad (2.14\text{-}3)$$

(4) In the special case of sections (1) and (2) where the incident unmodulated radiation is nearly monochromatic, the detective quantum efficiency is given by:

$$Q_D = 2EP_a(\text{Measured D})^2 \qquad (2.14\text{-}4)$$

(5) When the incident radiation is not nearly monochromatic, the calculation of the maximum possible detectivity becomes more complex--the result depending both on the way the detectivity depends on the wavelength and on the spectrum of the incident power. For the very special case in which the incident radiation has the spectrum of a blackbody with temperature T_{bb}, one has:

$$Q_D = 8kT_{bb}P_a(\text{Measured D})^2 \qquad (2.14\text{-}5)$$

where k is the Boltzmann constant.

(6) The detective quantum efficiency $Q_{Dm}(\lambda)$ is the detective efficiency Q_D measured at the peak modulation frequency f_p.

(7) The detective quantum efficiency $Q_{Dm}(f)$ is the detective quantum efficiency Q_D measured at the peak wavelength λ_p.

(8) The detective quantum efficiency Q_{Dmm} is the detective quantum efficiency Q_D measured at the peak modulation frequency f_p and at the peak wavelength λ_p.

2.15 FACTORABILITY PROPERTY

The factorability property permits the responsivity of a detector, considered as a function of the wavelength and of the modulation frequency, to be represented as the product of two factors, one of which depends only on the wavelength, and the other of which depends only on the frequency:

$$R(\lambda,f) = \text{constant } L(\lambda)F(f) \tag{2.15-1}$$

The factorability property is nearly always assumed (often without comment) in the description of the performance of radiation detectors.

(1) For a detector that has this property, a very important simplification is possible in the measurement and definition of the responsivity. It permits the detector's responsivity to be completely determined by measurement of the responsivity as a function of wavelength at a single frequency and by measurement of the responsivity as a function of the frequency at a single wavelength.

(2) Many important detectors have the factorability property, but there is an important class of photoconductive detectors whose responsivity is not at all factorable.

3. RECOMMENDED TEST EQUIPMENT

3.1 STANDARD TEST EQUIPMENT

The test laboratory shall use equipment that conforms with the requirements of this section or alternative equipment that is capable of equivalent precision of measurement for the detectors under test.

3.2 CALIBRATED SIGNAL GENERATOR

The calibrated signal generator shall produce at its output terminals a sine wave voltage with a frequency adjustable over the range on which the responsivity of the detector is to be measured. In a comprehensive test laboratory, this range will be from about 1 Hz to about 100 MHz. The output voltage should be adjustable and the generator should be capable of delivering approximately 10 volts rms into a 50 ohm load.

3.3 CALIBRATED ATTENUATOR

The calibrated attenuator receives a voltage from the signal generator and delivers a voltage of accurately known rms amplitude to its output terminals. The amplitude of the output voltage should cover the range from 1 microvolt to 1 volt. The output impedance of the attenuator shall be negligible compared to its load impedance.

3.4 BIAS SUPPLIES

The bias supplies produce the biasing voltages or currents that the detector requires for its operation. The internal impedance of each voltage supply shall be negligible compared to its load impedance. The power supply shall be equipped with a high impedance voltmeter and a low impedance current meter. These meters shall be placed in the bias circuit such that their internal impedances do not affect the accuracy of the measurements.

3.5 EQUIPMENT FOR MEASURING IMPEDANCE

The test laboratory shall have the usual equipment needed to measure the impedance of the detector and other circuit elements. It shall also maintain calibration equipment for the test equipment. In particular, the test laboratory shall have equipment to calibrate the output of the signal generator.

3.6 REFERENCE DETECTOR

The test laboratory shall use a reference detector for spectral response measurements. The variation with wavelength of the responsivity of the reference detector shall be known as accurately as possible. Low frequency narrow-band tuned amplifiers or lock-in amplifiers are suitable indicating devices if the reference detector is a radiation thermocouple, thermistor bolometer, or pyroelectric detector.

3.7 THE DETECTOR CIRCUIT

The detector circuit includes the detector, the detector's load resistor, a means of connection to the bias sources, and a means of coupling the detector to the amplifier. The circuit may also include a resistor, R_{cal}, to inject the signal from the calibrated attenuator. The resistance, R_{cal}, should be very small compared with the impedance Z of the circuit. A one-ohm resistor is often used. The detector circuit shall be placed in a well-shielded enclosure.

3.8 LOW NOISE AMPLIFIER

The low noise amplifier increases the signal received from the detector circuit to a level where it may be filtered and measured without introducing appreciable noise. The gain of the low noise amplifier shall be stable with time and reasonably independent of frequency over the entire range of frequencies being measured. It is often necessary to place the first stage of the low noise amplifier in the shielded enclosure with the detector circuit.

3.9 TUNABLE FILTER

The tunable filter shall have a center frequency f_m that can be varied as a function of frequency over the entire frequency range of interest. The tunable filter shall have stable gain and, preferably, this gain shall be independent of frequency. The gain of the filter to harmonics of its center frequency should be negligible. The bandwidth of the tunable filter should be reasonably narrow--the order of 1/10 the center frequency.

3.10 MULTIRANGE VOLTMETER

The multirange voltmeter measures the signal voltages and the noise voltages. The calibration of the voltmeter shall be known over the frequency range over which the responsivity and noise are to be measured. Since the noise and signal may differ by several orders of magnitude, the voltmeter must be equipped with accurate attenuators covering a range of at least four decades. It is desirable that the voltmeter be of the type which reads the true root-mean-square amplitude of an arbitrary wave form. The noise bandwidth Δf (as defined in 2.3-4) of the combination of low noise amplifier, tunable filter, and multirange voltmeter shall be known as a function of the frequency setting of the tunable filter. If the low noise amplifier and the multirange voltmeter have gains which are independent of frequency, then, of course, the overall noise bandwidth is that of the tunable filter. Heterodyne type spectrum analyzers can serve as both the tunable filter and multirange voltmeter. However, it is necessary to measure the noise bandwidth Δf and to correct the meter readings to true RMS when these instruments are used for noise measurements.

3.11 RADIATION SOURCES

The test laboratory shall use the following three radiation sources:

(1) Blackbody Source

The blackbody source shall be stable in temperature and shall be provided with a modulator. The modulator may be for a fixed frequency (f_c); however, it would be convenient if modulation frequencies of approximately 10, 100, and 1000 Hz are available. The blackbody source shall produce an accurately known spectral irradiance in the reference plane of the detector and the irradiance shall be uniform over the sensitive area of the detector. The measure of spectral irradiance to be used is the rms amplitude of the fundamental component produced by the modulator.

This amplitude is denoted $H_{\lambda,rms}$. In the process of determining $H_{\lambda,rms}$ the radiation from the modulator must be taken into account. Furthermore, if radiation filters are used to eliminate radiation outside the chosen factorability band, the spectral absorptance and transmittance of the filters must be known and taken into account. The total irradiance H_{rms} is given by:

$$H_{rms} = \int_{o}^{\infty} H_{\lambda,rms} d\lambda \qquad (3.11\text{-}1)$$

The means used to secure an accurate calibration of the blackbody source lie outside the scope of this standard, which requires only that the best available physical procedures be used.

(2) Monochromatic Source

The monochromatic source shall consist of a stable source of radiation and a monochromator (preferably a double monochromator) with a modulator placed between the source and the entrance aperture.

The monochromator shall be capable of providing a wavelength band of radiation that is not wider than 1/30 of the center wavelength. The modulator may be for a single frequency, which shall be the same as the frequency (f_c) of the blackbody source. When feasible, the irradiance produced by the monochromatic source shall be uniform over the responsive surface of the detector. The out-of-band energy (scattered radiation) produced by the monochromator must be known over its entire wavelength range. The measurement laboratory shall have its wavelength calibration methods documented.

(3) Variable Frequency Source

The variable frequency radiation source shall consist of a stable source of radiation and a variable frequency modulator. Several sources may be used to cover the entire frequency range of interest, but if so, the frequency ranges should overlap. The irradiance produced by the variable frequency source shall be uniform over the responsive surface of the detector. The frequency of the variable frequency source need not be continuously adjustable. A series of fixed frequencies may be used.

3.12 EQUIPMENT FOR MEASURING RESPONSIVITY CONTOURS

The test laboratory shall have means of irradiating a very small spot on the surface of the detector. This device shall consist of a source, a modulator, and a microscope equipped with a mechanical stage (or other suitable means of producing the X-Y motion) and shall have provisions for inserting factorability filters. The irradiance produced by the microscope shall be limited to the factorability band of interest.

3.13 EQUIPMENT FOR MEASURING PULSE TIME CONSTANTS

If pulse time constants are to be measured, the test laboratory should have appropriate equipment, including a wide-band amplifier and oscilloscope, such as the Hewlett-Packard Model 8447F Amplifier or an Avantek Amplifier and a Tektronix Oscilloscope 7904. If a rise-time shorter than 1 ns is to be measured, a sampling oscilloscope should be used.

As far as the radiation sources are concerned, the use of any monochromatic source in conjunction with a mechanical modulator is sufficient for low rise-time measurement. For short rise-time measurement a Q-switched laser or a combination of a laser and an electro-optic modulator should be used. The subnanosecond time constant is detectable with the use of a continuously mode-locked infrared laser and a sampling oscilloscope.

4. RECOMMENDED TEST PROCEDURE

4.1 STANDARD TEST PROCEDURE

This section recommends a straightforward set of test procedures; other test procedures than those recommended here may be employed, but if departures are made from the recommended procedures, the test laboratory making the departures must establish, by actual test, that the modified procedures produce results of equivalent accuracy or better. Further, if procedures are employed which differ from those described herein, these departures shall be described in the standard report, or in the explanation that accompanies the standard report (see section 5).

The test procedures may be divided into two independent groups. In the first group are the measurements that yield the responsivity, and in the second group are the measurements that yield the root power spectrum of the noise. From these results the detectivity is calculated.

4.2 THE RESPONSIVITY

The determination of the responsivity involves three separate series of measurements with radiation sources and one numerical integration. In all of the measurements described in section 4.1, the signal radiation shall normally be incident on the detector. Specifically, the signal radiation shall have a direction of propagation within 10 degrees of the normal to the adopted responsive plane of the detector. In all of the measurements described in section 4.1, the amount of signal radiation shall be confined to the range in which the output signal (V_s or I_s) is proportional to the incident power P_{rms}. Confirmation of this linearity shall be obtained with each detector.

(1) The measurement of the responsivity involves the use of the factorability property. For those detectors where this property does not hold for the entire wavelength range of interest, the blackbody source and the variable frequency source shall both be equipped with a factorability filter that confines the radiation to one of the bands of wavelength within which the factorability property holds.

(2) The first step is to establish the range of bias value to be used with the detector being measured. Experience with similar detectors will usually indicate the approximate range of bias values. The range will normally cover at least one decade of bias voltage or current. The highest value of bias will normally be the "manufacturer's maximum recommended bias for continuous operation". Considerable care should be exercised if measurements are to be made at biases greater than the manufacturer's maximum value. The detector noise should be carefully

monitored and the bias should be increased in small steps. Operating some types of detectors in this region of high bias is very risky and experience must be relied upon to a great extent.

(3) The blackbody source equipped with the factorability filter, if needed, is used to irradiate the detector. The tunable filter is set at f_c and signal generator is set to zero output. The reading E of the multirange voltmeter is noted. Then the irradiation is removed, the signal generator is set to the frequency f_c and the attenuator is adjusted to the value which gives the same reading E on the multirange voltmeter. The open circuit detector signal $V_{s,rms}$ is the voltage across the calibrating resistor R_{cal}. These readings are then repeated for the various values of bias until the complete range of bias values has been covered. In general, these points should be taken at intervals of one octave.

(4) The power P_{rms} incident on the adopted responsive area of the detector is obtained from the known irradiance H_{rms} upon multiplication by the adopted area A_a:

$$P_{rms} = A_a H_{rms} \tag{4.2-1}$$

The corresponding responsivity is given by:

$$R_{\beta\beta}(b,f) = \frac{V_{s,rms}}{P_{rms}} \tag{4.2-2}$$

where the subscript $\beta\beta$ is used (instead of the more obvious bb) to emphasize that the spectrum of the radiation produced by the blackbody source is not necessarily a blackbody spectrum.

(5) With the tunable filter set at f_c and bias applied, the detector is irradiated by the monochromatic source. The center wavelength of the monochromator is varied over the wavelength range of interest and the relative signal voltage $E_{s,rms}$, indicated by the multirange voltmeter is recorded as a function of wavelength. The detector under test is then replaced by the reference detector and the relative signal voltage $E_{s,rms,re}$ of the reference detector is recorded as a function of wavelength. Some detectors may exhibit changes in spectral response as a function of bias. If these changes are significant, then several spectral response curves must be obtained for different bias values.

(6) The relative response $L(\lambda)$ as a function of the wavelength is then calculated by:

$$L(\lambda) = \frac{E_{s,rms}\,\varepsilon(\lambda)}{E_{s,rms,re}} \tag{4.2-3}$$

where $\varepsilon(\lambda)$ is the relative responsivity of the reference detector, if it is known to differ from a constant.

(7) The frequency response of some detectors may vary as a function of applied bias. If this change in frequency response is significant, then several frequency response curves must be obtained over the entire range of useful bias values. The relative frequency response of a detector can be measured by three different means:

(a) Measurement with an amplitude modulated source.

The variable frequency source, equipped with a factorability filter, if needed, is used to irradiate the detector. As the frequency of the source is varied, the center frequency of the tunable filter is continuously adjusted to the modulation frequency. The signal voltage $E_{s,rms}$ read on the multirange voltmeter is recorded as a function of the frequency. The source is then removed and the signal generator or the signal applied to the electro-optic modulator is varied over the same range of frequencies with a fixed attenuator setting. As the frequency is varied, the center frequency of the tunable filter is continuously adjusted to the same frequency. The voltage $E_{c,rms}$ read on the multirange voltmeter is recorded as a function of frequency. (If a chopper is employed that modulates the radiation sinusoidally so that P_2, P_3, P_4, etc. of equation (2.2-2) are all zero, then the tunable filter may be removed from the electronic system. This method provides an appreciable simplification of the measurement).

The relative response F(f) as a function of frequency is then computed by:

$$F(f) = \frac{E_{s,rms}\, e(f)}{E_{c,rms}} \qquad (4.2\text{-}4)$$

where e(f) is the relative voltage produced by the signal generator if the voltage is not the same at all frequencies.

(b) Heterodyne measurement

The frequency response of a detector can be determined by measuring the beating signal produced by two frequency tunable lasers. The experimental arrangement consists in adding two laser beams on a beam splitter and directing the superposed beam on the detector under test. The frequency of one of the two lasers is then varied and the frequency f and amplitude E(f) of the resulting beat signal is recorded. If the amplitude of the tunable laser varies in amplitude during the sweep, a reference detector should be used to continuously monitor the laser output I(f).

The relative response F(f) as a function of frequency is then computed by:

$$F(f) = \frac{E(f)}{\sqrt{I(f)}}\, F_o \qquad (4.2\text{-}5)$$

where F_o is a normalizing constant.

(c) Measurement of the shot noise frequency spectrum

A very simple and attractive method of measuring the frequency response of a detector is to create in the detector a white-noise source having a spectrum much wider than the detector bandwidth. It consists essentially in exposing the detector to a radiant flux strong enough to induce a shot noise level well above any other noise source in the detector-amplifier combination. A simple measurement of that noise as a function of frequency gives a very good estimate of the frequency response of the detector in the condition where the responsive bandwidth is not limited by the electron transit in the detector.

A laser beam is directed on the sensitive area and the noise level is read on an electronic voltmeter. The amplitude of the laser beam incident on the detector is slowly increased from a very low value to a higher value for which the noise level at the output of the system is four or five times greater than the level obtained without illumination. The noise spectrum P(f) is then recorded as a function of frequency and the frequency response F(f) of the detector is deduced from the relation:

$$F(f)\ F^*\ (f) = F_o P(f) \qquad (4.2\text{-}6)$$

where F_o is a normalizing factor.

(8) From the experimental results described in foregoing paragraphs the absolute responsivity as a function of the wavelength (λ) and the modulation frequency (f) is given by:

$$R(\lambda,f) = R_{\beta\beta} \bullet \frac{L(\lambda)P_{rms}}{\int L(\lambda)P_{\lambda,rms} d\lambda} \bullet \frac{F(f)}{F(f_c)} \qquad (4.2\text{-}7)$$

where $P_{\lambda,rms}$ is the spectral power of P_{rms}. Note that the value of $R(\lambda,f)$ is not changed if either $L(\lambda)$ or $F(f)$ is multiplied by a constant. Nor is $R(\lambda,f)$ changed if P_{rms} and $P_{\lambda,rms}$ are multiplied by the same constant.

4.3 THE NOISE

In the measurement of the noise of a radiation detector, good judgment and experience are essential for ensuring that the only noise which appears at the multirange voltmeter is that generated in the detector and in the amplifier. Continuous vigilance is required to prevent other sources of noise from influencing the results. It may be found convenient to place a wide-band oscilloscope in the electronic system ahead of the tunable filter. The appearance of the noise trace on the oscilloscope is helpful in determining the presence of extraneous noise signals.

In particular, the bias supplies must not contribute appreciable noise. The bias source can be checked for internal noise by substituting a wire wound resistor in place of the detector in the detector circuit. The resistance of the wire-wound resistor should be approximately equal to the detector resistance. Bias is then applied to the circuit and the noise noted on the multirange voltmeter. The noise generated in the wire-wound resistor should be independent of the current flowing through the resistor.

(1) Bias is applied to the detector, all radiation sources are removed, and with the signal generator producing zero signal, the root-mean-square noise voltage indicated by the multirange voltmeter is recorded as a function of the center frequency of the tunable filter. The voltage read is denoted $E_{o,rms}$.

(2) The detector and load resistor are replaced by a wire-wound resistor having approximately the same resistance as the parallel combination of the detector and load resistor. The temperature of this wire-wound resistor is maintained such that the thermal noise generated in the resistor is small compared to

the noise generated in the amplifier. The root-mean-square noise voltage indicated by the output meter is again recorded as a function of frequency. This voltage is denoted $E_{a,rms}$.

(3) The calibrated attenuator is now adjusted to produce a calibration signal ($E_{c,rms}$ approximately 100 times larger than the detector noise) across the calibrating resistor R_{cal}. The tunable filter is tuned to the frequency of the calibration signal and the rms voltage shown on the multirange voltmeter is recorded. This procedure is repeated over the entire frequency range of interest. The system gain (g) is thus determined as a function of frequency.

(4) The root power spectrum N, referred to the terminals of the detector, referred to an infinite load impedance, and corrected for amplifier noise, is calculated from the following formula:

$$N(f,b) = \frac{\left[E^2(f,b)_{o,rms} - E^2(f)_{a,rms} - E^2_{th}\ \frac{R^2}{R_L^2}\right]^{\frac{1}{2}}}{g(f) \bullet (\Delta f)^{\frac{1}{2}}} \qquad (4.3\text{-}1)$$

Where E_{th} is the thermal noise of the load resistor in a bandwidth Δf.

(5) At frequencies where the difference between $E_{o,rms}$ and $E_{a,rms}$ cannot be measured reliably, the root power spectrum, and thus the detectivity of the detector, cannot be measured with the equipment used.

(6) The measurement in paragraphs 1, 2, and 3 above are repeated for each value of bias used in the responsivity measurements over the entire useful range of bias values. Several bias points over the entire range should be used so that a reasonable family of root power spectra is obtained.

4.4 THE DETECTIVITY

The various kinds of detectivity are all calculated from the responsivity $R(\lambda,f,b)$ and the root power spectra $N(f,b)$.

4.5 MEASUREMENT OF RESPONSIVITY CONTOURS

The definition of the effective area A_e of the detector involves the measurement of the variation of responsivity over the sensitive area of the detector.

The method of measuring $R(x,y)$ is not ready for standardization at this time. However, some steps toward standardization are listed below:

The microscope used to focus the radiation of the detector shall use reflection optics. Extreme care shall be exercised to ensure that the detector is responding linearly to the radiation. The large numerical aperture of microscope optics can easily produce very high irradiance of the spot.

4.6 IMPEDANCE

The methods used to measure the impedance, resistance and capacity of the detector are well known and do not require description here. These parameters shall be measured as a function of bias.

4.7 TIME CONSTANT

The measurement of the detector rise-time and decay time is straight forward if an equipment equivalent to the one described in 3.13 is available. For a time constant longer than 1 ns, the measurement is made in real time. Shorter time constants are recorded with the aid of a sampling oscilloscope. In all these measurements the time constant of the light pulse and of the electronic instrumentation must be shorter than the measured detector time constant. If the measured time constant is limited by the load resistance, the value of this load must accompany the specification. The determination of the time constant is done according to the definition given in section 2.13 (7).

5. THE STANDARD REPORT

5.1 DETECTOR DESCRIPTION

Description of the detector in the standard report shall list as many of the following items as is feasible:

1. Type of detector
2. Name of manufacturer
3. Detector serial number
4. Date of measurement
5. Window material
6. Shape of sensitive area (cm)
7. Detector area (cm^2)
8. Dark resistance (ohms)
9. Field of view
10. Detector capacity (pfd)

5.2 CONDITIONS OF MEASUREMENTS

The standard report shall list the following items with respect to the test conditions:

1. Blackbody temperature (K)
2. Blackbody irradiance (μ watts/cm^2, rms)
3. Modulation frequency (Hz)
4. Noise bandwidth $(Hz)^{\frac{1}{2}}$
5. Detector temperature (K)
6. Detector current for D^*_{mm} (μa)
7. Load resistance (ohms)
8. Transformer (if used)
9. Relative humidity (%)
10. Responsive plane (from window) (cm)

11. Ambient temperature (°C)

12. Ambient radiation on detector (K)

5.3 INPUT CIRCUIT

The standard report shall include a diagram of the input circuit used in the test. This diagram shall show the detector, its bias supply, and the connection to the first stage of the amplifier. The diagram shall show the way the calibration voltage is introduced. The values of all important components shall be indicated.

Components used in the input circuit may be referred to by the manufacturer's type number, but a brief description of these components should also be included in the report. This is particularly important for any transformers that might be used in the input circuit.

If the method of correcting for the noise of the low noise amplifier differs from that described in section 4.3 the method used shall be described in detail.

5.4 STANDARD TEST RESULTS

5.4.1 Plots

The standard report shall contain five plots.

(1) Response vs. Frequency (frequency response): This is a plot of the response of the detector as a function of modulation frequency. The plot will be made with logarithmic scales. The ordinate shall be relative response F and the abscissa shall be modulation frequency f in Hz. If the frequency response of the detector varies with applied bias, then the plot shall be a family of curves. Curves over the entire range of useful bias values shall be plotted.

(2) Root Power Spectrum of the Noise (noise spectrum): This is a plot with logarithmic scales, the ordinate to be the root power spectrum N in volts/$(Hz)^{\frac{1}{2}}$ and the abscissa to be frequency in Hz. In general, this plot shall be a family of curves. Curves over the entire range of useful bias values shall be plotted.

(3) Response vs. Wavelength (spectral response): This is a plot with a logarithmic ordinate scale and a linear abscissa scale. The ordinate will be relative response L and the abscissa will be wavelength λ. The curve shall be for the modulation frequency f_c. If the spectral response of the detector varies with applied bias, then the plot shall be a family of curves. Curves over the entire range of useful bias values shall be plotted.

(4) Determination of Bias: This is a plot with logarithmic scales. The abscissa is the bias for two curves labeled V_s and N. The first curve shows the signal V_s measured at the modulation frequency f_c (radiation shall be limited to the factorability range). The second curve shows the noise N measured at the modulation frequency f_c.

(5) Detectivity vs. Frequency: This is a plot with logarithmic scales. D^*_m is plotted as the ordinate and modulation frequency f is plotted on the abscissa. This plot should be a family of curves covering the entire range of useful bias values.

5.4.2 Tabular Data

The standard report shall also include the following tabular data:

1. $R_{\beta 3}$ (f_c,b)
2. $H_{N,33}(f_c,b)$
3. $P_{N,33}(f_c,b)$
4. D^*_{33} (f_c,b)
5. Responsive time constant
6. R_m/R_{33}
7. Peak wavelength
8. Peak detective modulation frequency
9. D^*_{mm}

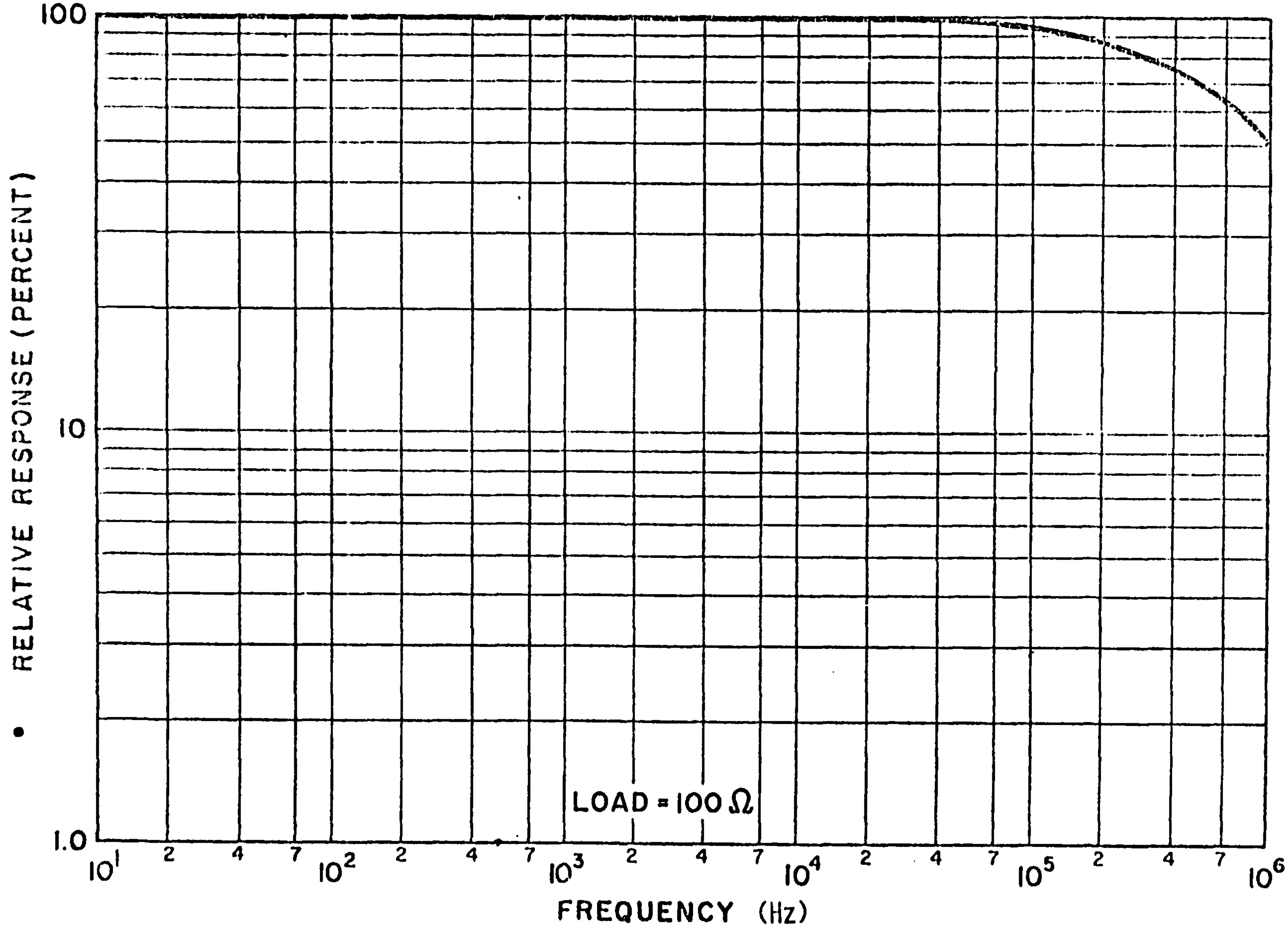
APPENDIX A

MODEL REPORT

TEST RESULTS	
$R_{\beta\beta}$ (volts/watt) (500, 860)	5.3×10^{3}
$H_{N,\beta\beta}$ (watts/Hz$^{1/2}\cdot$cm^{2}) (500, 860)	7.8×10^{-9}
$P_{N,\beta\beta}$ (watts/Hz$^{1/2}$) (500, 860)	7.1×10^{-13}
$D^*_{\beta\beta}$ (cm$\cdot$Hz$^{1/2}$/watt) (500, 860)	1.4×10^{10}
Responsive time constant (μsec)	0.3
$\frac{R_m}{R_{bb}}$	2.0
Peak wavelength (μ)	13.5
Peak detective modulation frequency (cps)	$> 1 \times 10^{3}$
D^*_{mm} (cm$\cdot$Hz$^{1/2}$/watt)	2.8×10^{10}

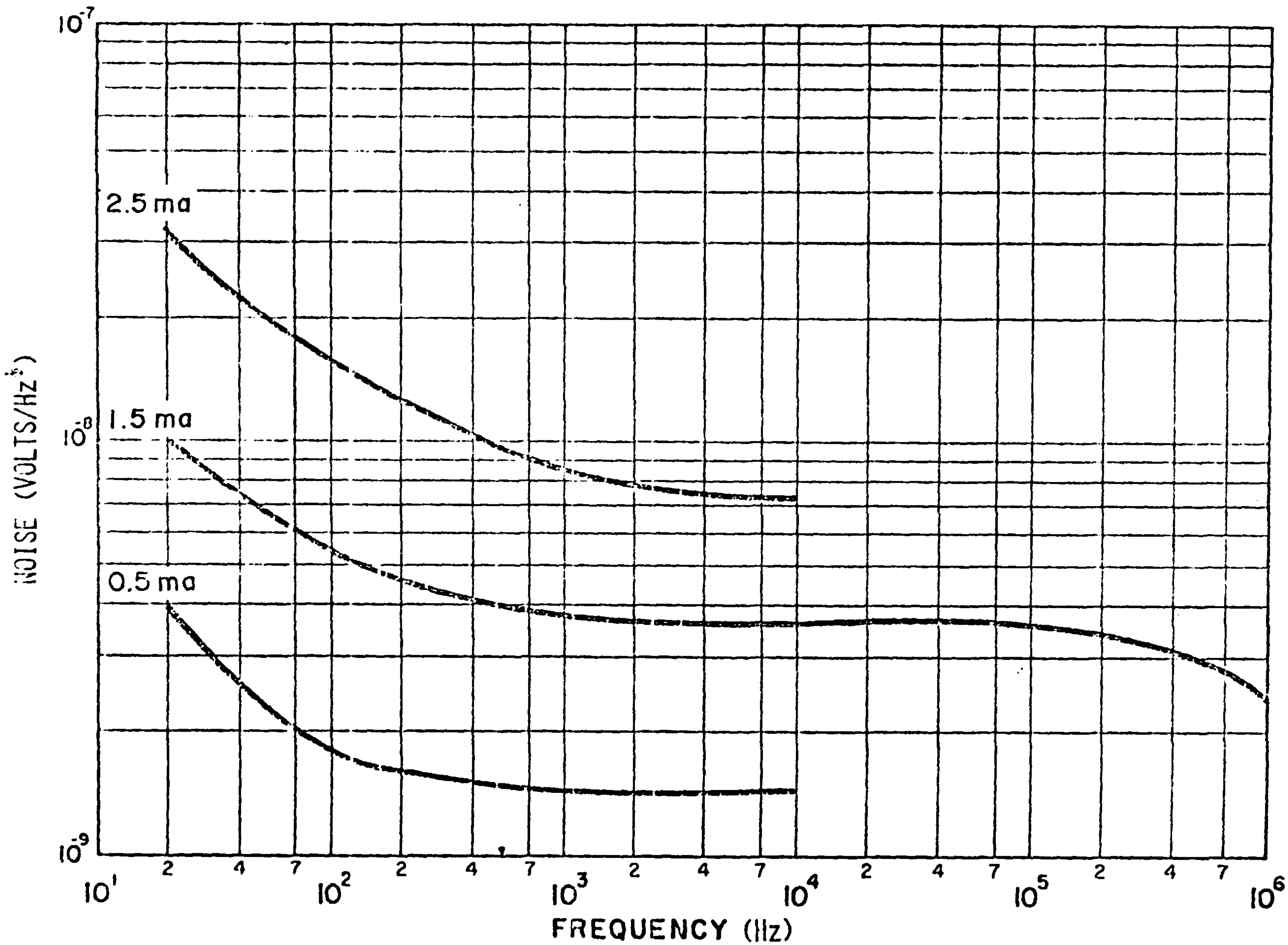
CELL DESCRIPTION	
Type	HgCdTe
Manufacturer	Honeywell Inc.
Detector Serial Number	A4
Date of Measurement	30 July 1969
Dark resistance (ohms)	40
Shape of sensitive area (cm)	0.009 X 0.01
Area (cm^2)	9.05×10^{-5}
Field of view	~ 40°
Window material	Cold IRTRAN 2
Detector Capacity (Pf)	- - -

CONDITIONS OF MEASUREMENT	
Blackbody temperature (K)	500
Blackbody flux density (μwatts/cm^2, rms)	9.0
Chopping frequency (Hz)	860
Noise bandwidth (Hz)	6.5
Cell temperature (K)	77
Cell current for 860 cps data (μa)	1.5×10^{3}
Cell current for D^*_{mm} (μa)	1.5×10^{3}
Load resistance (ohms)	1.0×10^{2}
Transformer	- - -
Relative humidity (%)	39
Responsive plane (from window)	- - -
Ambient temperature (°C)	23
Ambient radiation on detector (K)	296



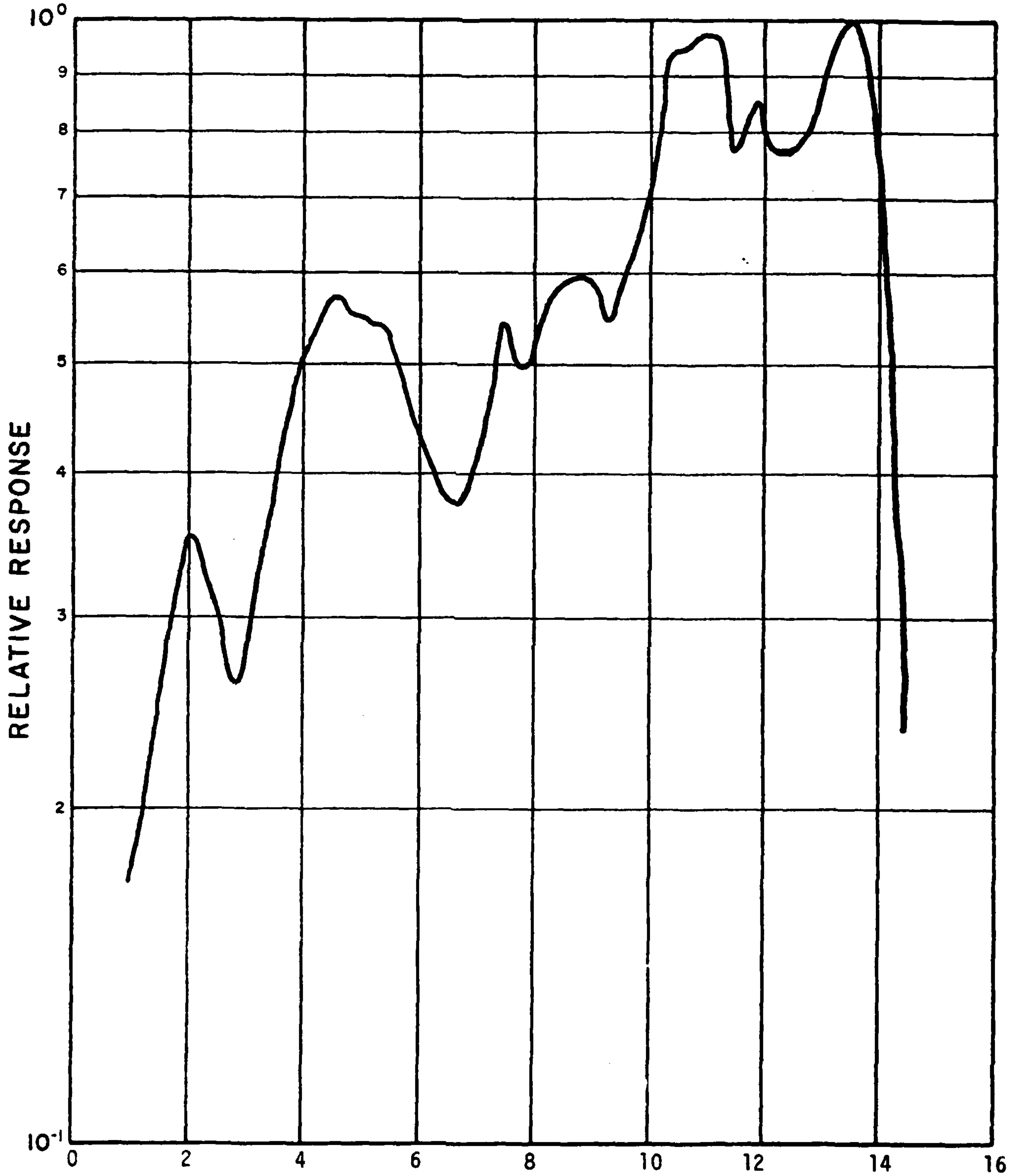
FREQUENCY RESPONSE

FIGURE 1



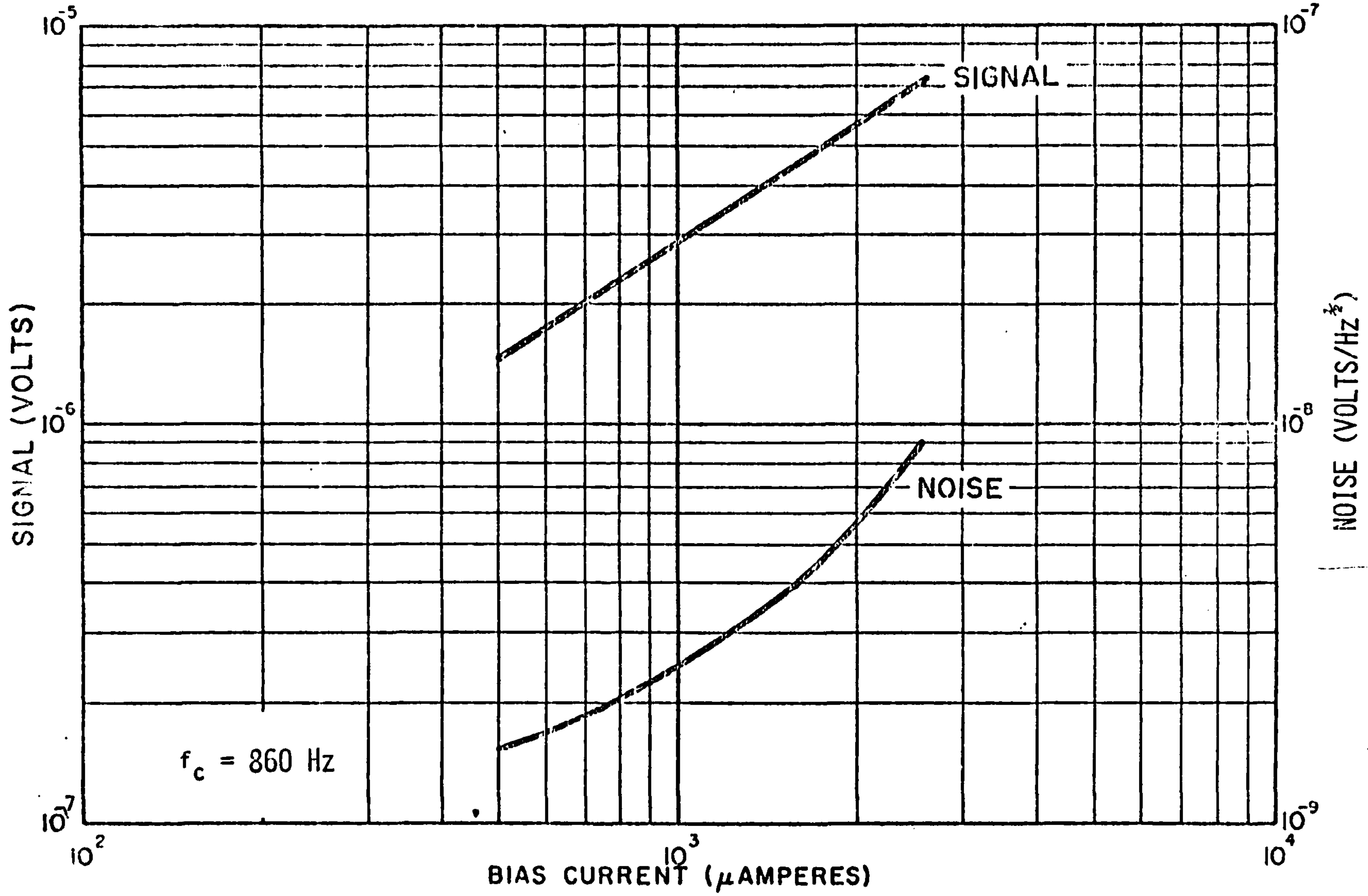
NOISE SPECTRUM

FIGURE 2



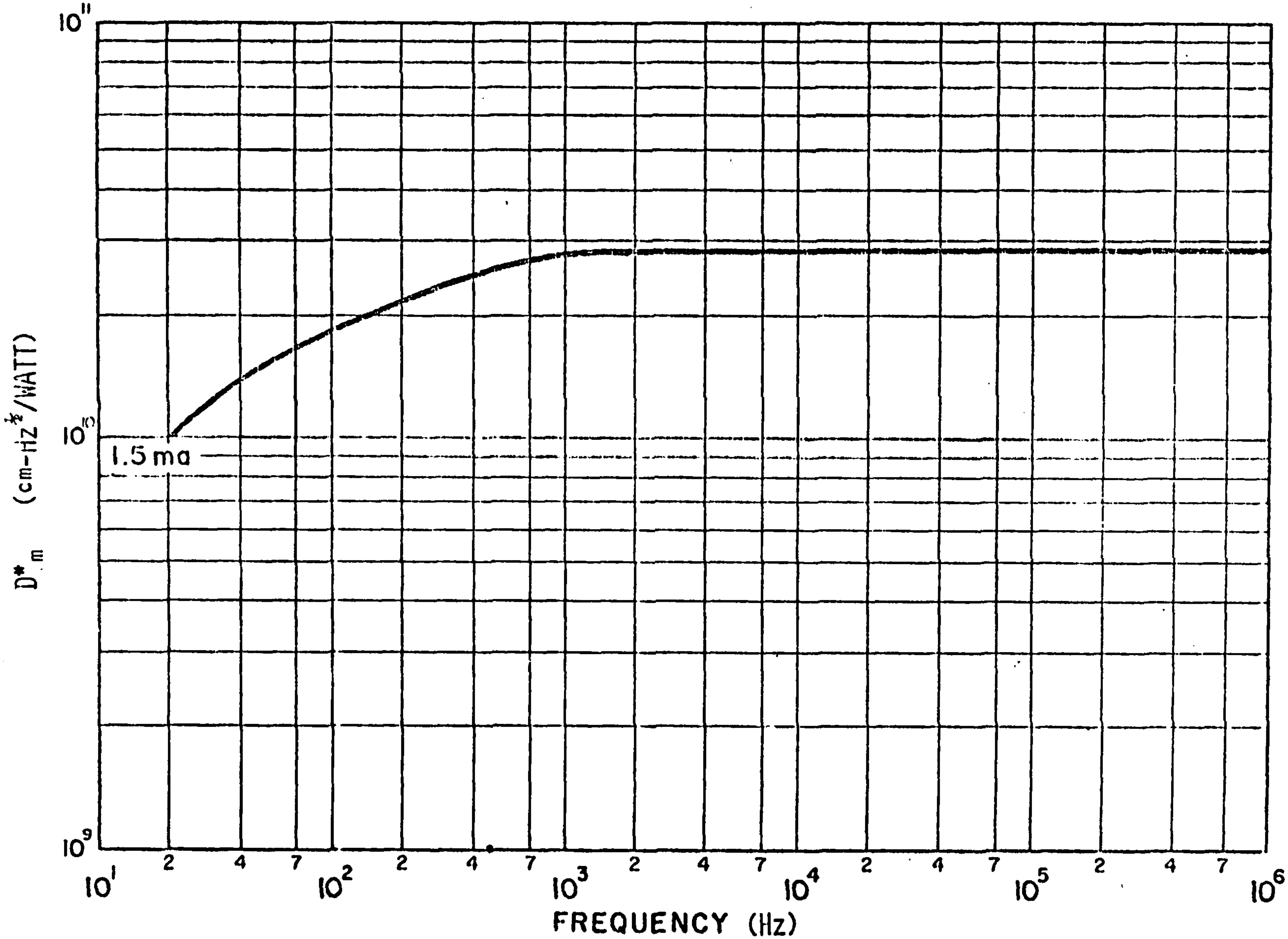
SPECTRAL RESPONSE

FIGURE 3



DETERMINATION OF OPTIMUM BIAS

FIGURE 4



DETECTIVITY vs FREQUENCY

FIGURE 5

APPENDIX B

D* AND SOME ALTERNATIVE FIGURES OF MERIT

by

E. H. Putley (RRE Malvern)

Of all the detector figures of merit which have been proposed, (D*) has proved to be the most generally useful and has therefore found general acceptance amongst detector manufacturers and users.

However there are certain limitations to the usefulness of D*. For some purposes other figures of merit are more appropriate whilst in some cases no generally useful figure of merit can be formulated.

One objection to D* is that it does not indicate directly how close the performance of a detector approaches the ideal limit. The difficulty is that the "ideal limit" depends not only on the type of detector but also on the precise way it is used. The performance of a perfect detector is limited by the fluctuations in incident background radiation to which the detector responds. This therefore depends not only upon the spectral response of the detector but also upon the field of view which will be determined by the optics and the detector encapsulation-factors which are independent of the detector responsive element itself. One consequence of this is that one often sees plots of measured detector performance compared with idealized background limited performance in which real detectors apparently have higher D*s than the ideal. This arises usually because the real detectors have smaller fields of view than that chosen for the idealized curve. When, of course, an ideal curve is drawn for the same field of view as the detector it always shows a higher detectivity than that observed. To overcome this objection to the use of D*, the concept of "Detector Quantum

Efficiency" (Q_D) was developed by Clark Jones[1]. An indication of the significance of Q_D is obtained by considering an almost-ideal detector which contains no internal source of noise but which can only respond to a fraction η (the quantum efficiency) of the incident radiation. Since the noise will all be associated with the incident radiation this will also be reduced as a function of η. It turns out that the detectivity of this detector is

$$D^* = \eta^{\frac{1}{2}} \; D^*_{IDEAL} \tag{B-1}$$

where D^*_{IDEAL} is the value which would be obtained if all the radiation were utilized ($\eta = 1$). Thus we see

$$\eta = (D^*/D^*_{IDEAL})^2 \tag{B-2}$$

By considering more general departures from ideal behaviour, we obtain equation 2.14-3 which shows that the actual detectivity can be related to that of the corresponding ideal detectivity by a factor analogous to a quantum efficiency. Although this concept has a certain logical attractiveness it has the serious practical disadvantage that it may not be easy to say precisely what the appropriate D^*_{IDEAL} is for a given detector since to do this the optical configuration must be characterized precisely.

A situation, now becoming of wider interest, in which D* is inappropriate is that in which the detector is being used in a laser heterodyne receiver. For optimum performance sufficient local oscillator power must be applied to make the dominant source of noise the shot noise of the local oscillator radiation. We then find that the detectivity is

$$D = \eta / h\nu\Delta f \qquad \text{(B-3)}$$

where ν is the frequency of the radiation, h Planck's constant and Δf is the bandwidth. Note that D is independent of the area A, varies inversely as Δf and not as $\Delta f^{1/2}$, and that D is proportional to η (contrast equations B-1 and B-2). η is the only detector parameter upon which D depends directly. It is clear that in this case D* is not meaningful. For a laser application the most suitable detector, other things being equal, is the one with the highest quantum efficiency η. The quantum efficiency is the parameter which is most useful as a figure of merit for this case.

In choosing detectors for applications such as thermal imaging where a high level of performance over a broad spectral band is required, a mean value of D* weighted both by the detector's spectral response and by the atmospheric transmission characteristics of the operational spectral band is required. The situation is made more difficult by the fact that the spectral response of modern alloy semiconductors such as mercury cadmium telluride or lead tin telluride depends upon the composition, and so may vary significantly between detectors of the same nominal composition. It is not therefore possible to calculate a universal spectral multiplying factor for each type of detector but it is necessary to calculate the factor for each sample. A figure of merit denoted M* has been defined to include all these considerations(2). It is defined by the equation

$$M^*(f,T_{BB},L) = \int_0^\infty D^*(\lambda,f)\tau(\lambda) \left.\frac{dH_\lambda}{dT}\right|_{T_{BB}} d\lambda \qquad \text{(B-4)}$$

where T_{BB} is the temperature of the blackbody source, f the modulation frequency, λ the wavelength, $D^*(\lambda,f)$ is the value of D^* at the wavelength λ and modulation frequency f, $\tau(\lambda)$ is the atmospheric transmittance at the wavelength λ and for the desired range of the target, L.

H_λ is the hemispherical spectral radiant emittance. The factor M* is not a true detector figure of merit since it depends upon optical and meteorological factors determined by the intended application. The usefulness of M* is that it enables the system designer to assess the best choice of detector as weighted by his operational requirement. The accurate calculation of M* relies upon a reliable measurement of $D^*(\lambda,f)$, which can be achieved by following the procedures of this specification.

D* is only meaningful when the noise sources vary as $A^{\frac{1}{2}}$ (A the detector's area). Except when used in the heterodyne mode, this applies to practically all the important noise sources, including the background, thermal G-R noise and Johnson noise in the detector. The major source of noise to which this does not apply is the amplifier noise. It is now possible to design amplifiers for most detectors which do not contribute significantly to the noise, but when this cannot be achieved the D* concept becomes invalid. Two examples are some of the sub-mm detectors, such as the various forms of InSb sub-mm detector, and pyroelectric detectors. Standardization of the sub-mm detectors is still very difficult so that the best procedure is to report all the details of measurements. The problem with the pyroelectric detectors is that the amplifier noise has a complex dependence both on the modulation frequency and the impedance presented to it by the detector[3]. As a result, at low frequencies and small areas, D is independent of A, at intermediate frequencies and detector sizes $D \propto A^{-\frac{1}{2}}$, whilst at high frequencies or large areas $D \propto A^{-1}$. Luckily with the best available pyroelectric detectors, most applications fall in the intermediate region so that D* is now meaningful, but it must be used much more carefully than with Johnson noise limited thermal detectors or with the photon detectors.

To summarize, D* is the most generally useful figure of merit, but it does not indicate directly how closely a detector's performance approaches the ideal, and it does not apply to heterodyne detection nor to amplifier noise limited detectors. When comparing detectors for thermal imaging systems it is useful to derive a spectrally weighted value averaged over the relevant waveband (M*).

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