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DETERMINATION OF THE SPECTRAL RESPONSIVITY OF OPTICAL RADIATION DETECTORS

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SUMMARY

This Technical Report outlines procedures for determining the spectral responsivity function of photodetectors.

The report is divided into two parts:

1. The determination of the relative spectral responsivity function.

Various methods are presented and instrumental details are discussed. Sources of errors are listed together with diagnostic tests and proposals for remedial action.

2. The absolute calibration.

Three different methods are presented for transforming the relative spectral data into absolute values.

This report is intended to serve as a guide for anyone wishing to assemble, test or modify new or existing instruments. Its purpose is to stimulate critical judgement of various options in every phase of the development of such instrumentation rather than to present a single solution.

RÉSUMÉ

Ce rapport technique décrit les procédures à suivre afin de déterminer la courbe de réponse spectrale d'un photodétecteur. Le rapport est divisé en deux parties:

1. La détermination de la courbe de réponse spectrale relative.

Plusieurs méthodes sont présentées, et les détails instrumentaux sont discutés. Les sources d'erreur sont cataloguées, avec différents essais pour fins de vérification et des suggestions pour corriger les problèmes.

2. L'étalonnage absolu.

Trois méthodes différentes sont présentées pour transformer les données spectrales relatives en valeurs absolues.

Ce rapport a été conçu pour servir de guide à quiconque désirerait monter, vérifier ou modifier des instruments nouveaux ou déjà en opération. Le but de ce rapport est de permettre au lecteur de faire un jugement critique des différentes options possibles à toutes les phases de développement de ce genre d'instrumentation, plutôt que de présenter une seule solution.

ZUSAMMENFASSUNG

Dieser Technische Bericht beschreibt Methoden zur Bestimmung der spektralen Empfindlichkeitsverteilung von Photoempfängern.

Der Bericht ist in zwei Teile geteilt:

1. Bestimmung der relativen spektralen Empfindlichkeitsverteilung.

Verschiedene Methoden werden vorgeschlagen und instrumentelle Details werden besprochen. Fehlerquellen werden aufgezählt zusammen mit diagnostischen Experimenten und mit Methoden zur Korrektur.

2. Die absolute Kalibrierung.

Drei verschiedene Methoden zur Umwandlung relativer Daten in absolute werden besprochen.

Der Zweck dieses Berichtes ist es, als Anleitung für Personen zu dienen, die beabsichtigen neue oder existierende Geräte zu entwickeln oder zu modifizieren. Er will kritische Beurteilung verschiedener Möglichkeiten in allen Phasen der Entwicklung solcher Instrumente anregen.

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0. INTRODUCTION

Knowledge of the spectral responsivity function of photoelectric detectors is a fundamental requirement for many radiometric, photometric and colorimetric applications. Instrumentation for the determination of this function has been assembled in a number of institutes. However, in various intercomparisons organized by the CIE and other organizations, unexpectedly large differences were found between the data from the participating laboratories (Budde and Sanders, 1973; Budde, 1984).

The members of CIE Technical Committee TC-2.2 agreed that a CIE Technical Report should be prepared in which spectral responsivity measurements are discussed. This report is based on the knowledge and opinions of the members of the Committee. It represents to some extent the present status of the subject and therefore is of temporary significance. Future developments may supersede present-day technology and may render some aspects of this report obsolete. Such development is encouraged and this report should not be considered the last word on the measurement of spectral responsivity functions, thereby inhibiting further work on improving the technology. Instead, it is hoped that periodic reviews of the report will incorporate such new developments and that such revisions will keep this document up to date and useful.

0.1 Purpose of the report

The purpose of this report is to discuss methods and instrumentation for spectral responsivity measurements. It is intended

as a guide for anyone wishing to assemble, test or modify instrumentation for such measurements. There is no ideal scheme or instrumentation for this purpose; consequently for several aspects, various options are presented. However, strong recommendations are made on certain points and preferred methods are pointed out. Special attention is given to sources of errors, diagnostic tests and corrections.

It is emphasized that this report does not suggest one universal scheme for spectral responsivity measurements because such a scheme does not appear to be known yet. The underlying purpose of this report is to stimulate a critical judgement of various options in every phase of the development of new instrumentation or of various aspects of existing instrumentation.

0.2 Organization of the report

The determination of a spectral responsivity function can be, and is usually, made in two stages: First, the relative spectral responsivity function is determined by means of a thermal or other reference detector; in the second stage the absolute calibration is performed, usually at one wavelength. Consequently the main body of this report is organized in two parts:

Part 1. The determination of the relative spectral responsivity function

Part 2. Methods for absolute calibration.

It is, of course, feasible to combine the two operations in one step if the absolute spectral responsivity function of the

reference detector is known and certain instrumental conditions are met. However, in many applications only the relative spectral responsivity function is required. On the other hand a simple procedure may be required to verify the absolute calibration of a detector after some period of use. Therefore the division into the two separate operations appears quite useful and is adopted.

0.3 Terminology

The definitions presented in this Section are taken from existing CIE documents (CIE Publication No. 53) and/or the draft of the revised CIE Vocabulary. In some cases parts of the definitions which are not relevant for this document have been omitted.

Detector (of optical radiation)

Device in which incident optical radiation produces a measurable physical effect.

Photoelectric detector

Detector of optical radiation that utilizes the interaction between radiation and matter resulting in the absorption of photons and the liberation of electrons from their equilibrium states, thereby generating an electrical potential or current, or a change in electrical resistance, excluding electrical phenomena caused by temperature changes.

Thermal detector of radiation; thermal (radiation) detector

Detector of optical radiation in which a measurable physical effect is produced by the heating of the part that absorbs radiation.

Photoemissive cell, phototube

Photoelectric detector that utilizes emission of electrons caused by optical radiation.

Photomultiplier

A photoelectric detector comprising a photocathode, an anode, and an electron-multiplication device that uses the secondary emission of dynodes or channels between photocathode and anode.

Photoresistor, photoconductive cell

Photoelectric device that utilizes a change of electrical conductivity produced by electrons liberated by the absorption of optical radiation.

Photodiode

Photoelectric detector in which a photocurrent is generated by absorption of optical radiation in the neighbourhood of a p-n junction between two semiconductors, or of a junction between a semiconductor and a metal.

(Radiation) thermocouple [(radiation) thermopile]

Thermal detector of optical radiation in which the electromotive force produced in a single thermovoltaic junction [in several thermovoltaic junctions] is used to measure the heating effect produced by absorbed radiation.

Input (for a detector of optical radiation)

Radiometric or photometric quantity that a detector of radiation is being used to measure or detect.

Pyroelectric detector

Thermal detector of optical radiation that utilizes the time rate of change of the temperature dependence of the spontaneous

electric polarization, or of long-lived polarization, of certain dielectric materials.

Output (for a detector of optical radiation)

Change in a physical quantity, usually electrical, yielded by a detector in response to an optical input.

Note: This electrical quantity may, for example, be current, voltage or resistance; the output may also be chemical, as in a photographic film or actinometer, or mechanical such as in a Golay detector.

Photocurrent, I_{ph}

That part of the current yielded by a photoelectric detector that is caused by incident radiation.

Note: In photomultipliers a distinction must be made between the cathode photocurrent and the anode photocurrent.

Dark current, I_o

Current yielded by a photoelectric detector or by its cathode in the absence of input.

Responsivity, s (of a detector)

Quotient of the detector output Y by the detector input X

$$s = \frac{Y}{X}$$

Spectral responsivity, $s(\lambda)$ (of a detector)

Quotient of the detector output $dY(\lambda)$ by the monochromatic detector input $dX_e(\lambda) = X_{e,\lambda}(\lambda) \cdot d\lambda$ in the wavelength interval $d\lambda$ as a function of wavelength λ

$$s(\lambda) = \frac{dY(\lambda)}{dX_e(\lambda)}$$

Relative spectral responsivity (of a detector)

Ratio of the spectral responsivity $s(\lambda)$ of the detector at wavelength λ to a given reference value s_m .

$$s(\lambda)_r = s(\lambda)/s_m.$$

Note: The given reference value s_m can be an average value, a maximum value or an arbitrarily chosen value of $s(\lambda)$.

Response time (of a detector)

Time required for the detector output to reach, after a step variation of a steady detector input, a given percentage of its final value.

Rise [fall] time (of a detector)

Time required for the detector output to rise [fall] from a stated low [high] percentage to a stated higher [lower] percentage of the maximum value when a steady input is instantaneously applied [removed].

It is usual to consider a low percentage of 10% and a high percentage of 90%.

Time constant (of a detector whose output varies exponentially with time)

Time required for the detector output to vary, after a step variation from a steady input to another steady input, from its initial value to the fraction $(1-1/e)$ of its final change.

Linearity (of a detector)

The property that the output quantity of the detector is proportional to the input quantity. Then the responsivity is constant over a specified range of inputs.

Note 1: A detector is usually linear to a given percentage only over a certain range of input levels. Outside this range it may become nonlinear. The range must be stated.

Note 2: The linearity range of a detector may be affected by the use of unsuitable electronic circuitry.

1. DETERMINATION OF THE RELATIVE SPECTRAL RESPONSIVITY FUNCTION

In this part methods and instrumentations for determining the relative spectral responsivity function of a photoelectric detector are presented. Various methods, which have been described, are summarized and then the elements of the instrumentation are discussed, together with some problems which are related to the operation. Finally a list of possible sources of error is given with diagnostic tests and suggestions for correction.

1.1 The calibration quantity

A detector may be calibrated either for spectral flux responsivity or for spectral irradiance responsivity. If a calibration is made in the two steps outlined in the introduction, the first step, that is, the determination of the relative spectral responsivity function, is not affected by this distinction provided the responsivity is uniform across the sensitive area. However, in the second phase, the absolute calibration, this point has a bearing on the instrumentation. It is therefore discussed in detail in part 2.

If the two calibration steps are combined into one operation, the relevant considerations of part 2 must be kept in mind.

1.2 Basic methods

For the purposes of this report the various techniques which have been described in the literature are classified into three basic methods. This classification is arbitrary and other schemes are equally valid. However it will be seen that the proposed classification is practical and useful for the discussions below. The three methods are listed here only briefly. Details are given in the Section 1.3.

1.2.1 Direct comparison method: At each wavelength the monochromatic radiation is switched from the reference detector to the sample detector by means of a moving mirror. This switching may be done either by means of a spinning semi-circular or multi-sector mirror, Fig. 1 (mirror M4), in which case AC or lock-in signal amplification is required (Mitsuhashi and Nakayama, 1956), or by means of a two-position mirror, Fig. 2 (mirror M1, three versions) which switches the beam only once at each wavelength (Kaase, 1980; Eppeldauer et al, 1977). A direct comparison by means of a beam splitter is also possible and requires no moving parts, but it poses several other problems which require careful consideration.

1.2.2 Substitution method: An auxilliary detector, (Fig. 3: detector AS), is calibrated against the reference detector T, which is mounted at the slit image, by any of the direct comparison techniques or using a stationary beam splitter. The reference detector T is then removed and the sample detector D is mounted in the same position and measured against the auxiliary detector. In this method sample and reference detector are irradiated under identical conditions and the

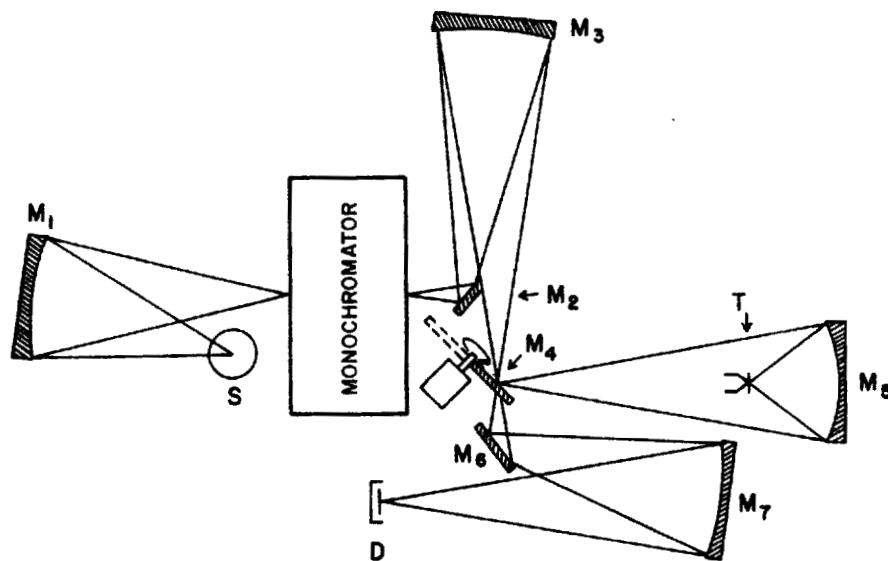


Fig. 1: Comparison method with spinning mirror.
 S = source; M = mirrors; T = reference detector
 D = sample detector.

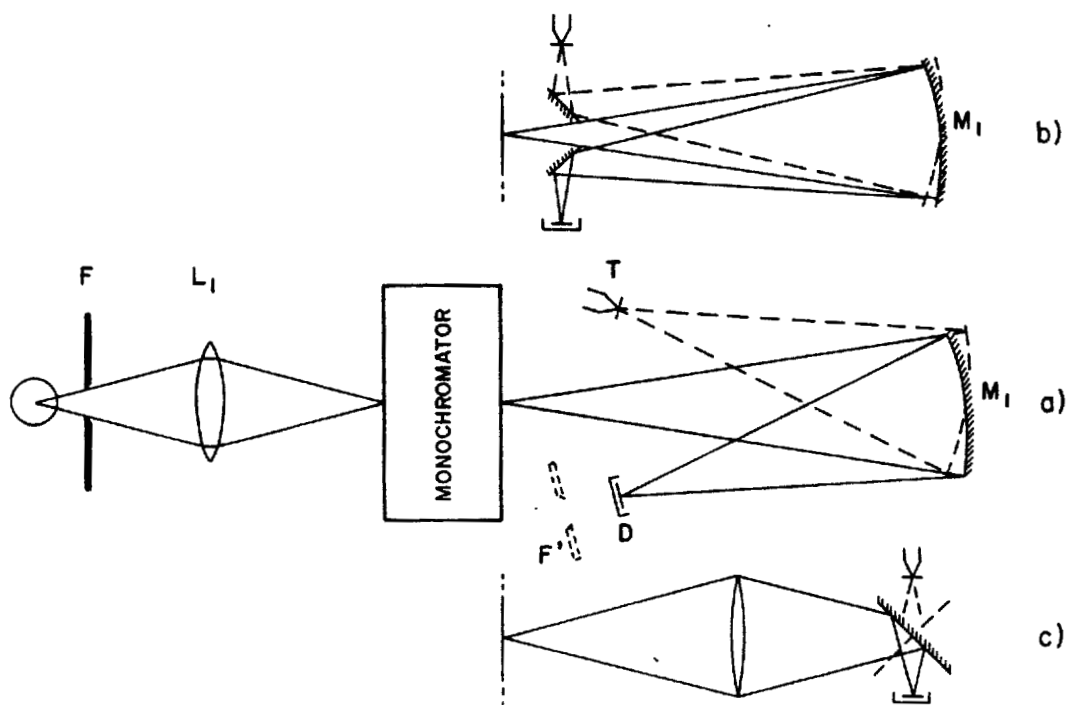


Fig. 2: Comparison method with three different arrangements
 of a switching mirror. L_1 = lens; F = aperture;
 F' = image of aperture. Other symbols as in Fig. 1.

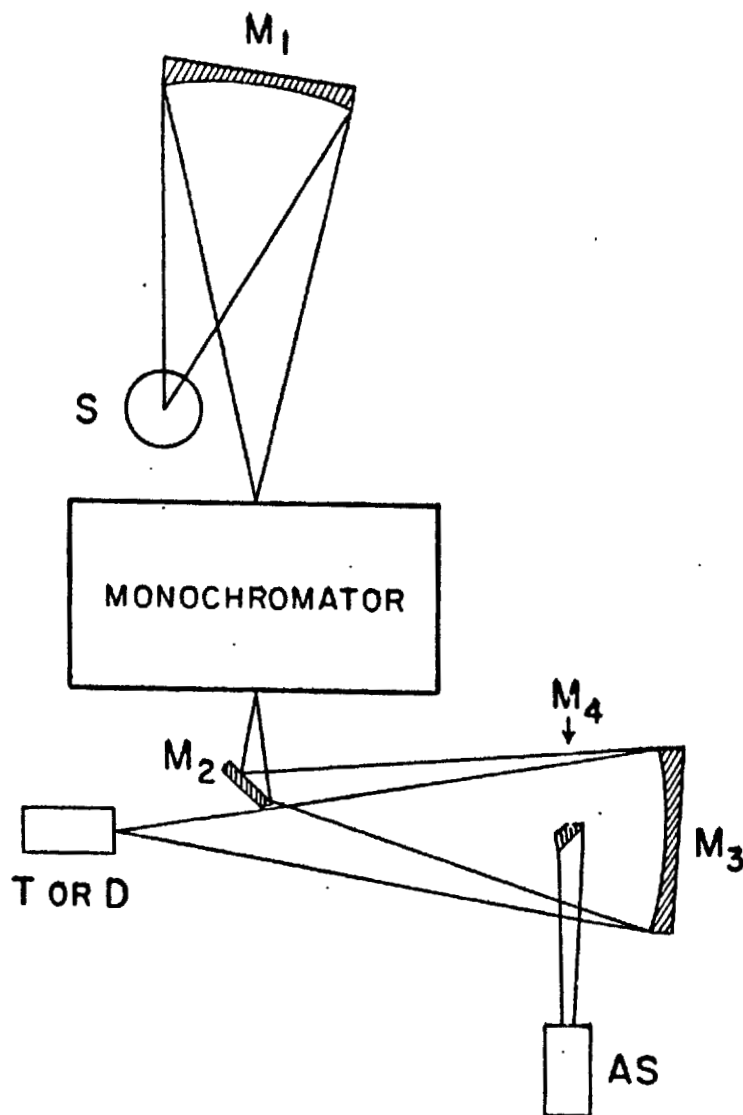


Fig. 3: Substitution method. AS = auxiliary standard; reference detector T and sample detector D are mounted consecutively at position "T or D"; M_4 = beamsplitter.

properties of the switching mirror or beam splitter cancel out, (Budde and Dodd, 1971; Ramadan et al, 1982). The important condition is that the spectral responsivity function of the auxiliary standard remains constant.

1.2.3 Broad-band-filter method: The sample detector is irradiated successively by the combination of a source of known spectral power distribution and a set of n filters of known spectral transmittance functions. The proper evaluation of the signals yields the spectral responsivity at n wavelengths (Wyszecki, 1960; Mori, 1961; Fleming and Wark, 1965). This method is not to be confused with methods 1 or 2 where interference filters serve for the isolation of narrow wavelength bands. The filters used in this method cover considerably larger, partly overlapping wavelength bands.

The advantage of this method is that no reference detector is required. However, certain difficulties limit the precision and accuracy of this method (Hahn and Weidemann, 1965). It does not seem to have been used to any extent and therefore this method will not be discussed further in this report.

1.3 Basic elements of the instrumentation

1.3.1 Sources of radiation

Incandescent lamps are the preferred sources of radiation because they can be stabilized or controlled by means of suitable power supplies. Stabilization to better than 0.1% is easily achieved with dc-power supplies that have stabilities of 0.01% or better. Current regulation rather than voltage regulation should be employed in order

to avoid the effects of contact-resistance changes. For uniform irradiation of a monochromator entrance slit, ribbon-filament lamps are the most suitable source. However, coil-filament lamps may be operated at higher temperatures and yield higher irradiance at the entrance slit, particularly at short wavelengths.

One inconvenience of incandescent lamps is the shape of their spectral power distribution with its strong increase towards longer wavelengths. This may be overcome by varying the lamp current or by means of suitable filters between lamp and monochromator. Occasionally efforts have been made to control the lamp current in a feedback loop from a thermal detector so that the spectral power is constant throughout the spectrum. This constant-spectral-power spectrum has the advantage that the signals from the sample detector show immediately the spectral responsivity function. Two conditions must be met in this case: 1. that the spectral responsivity function of the reference detector is completely nonselective; 2. that the optical systems for reference and sample detector are spectrally identical.

Xenon arcs, although useful for their high output in the UV and blue spectral region, pose serious problems if high stability and uniform irradiance of a monochromator slit are required (Budde, 1962a). For high stability a feedback-controlled power supply is required where the sensing photodetector must be mounted inside or behind the monochromator to stabilize the power entering the entrance slit.

For the near-UV-range deuterium lamps or argon arcs may be used.

1.3.2 Wavelength selection

For the isolation of the various wavelengths either monochromators or sets of narrow-band filters are suitable. One

consideration for the selection of the wavelength selecting medium is that spectral purity, that is absence of stray radiation of different wavelength, is more important than high resolution because most spectral responsivity functions are rather smooth and do not show superimposed line structures such as those of the spectral power distribution of fluorescent lamps. However, out-of-band stray radiation may cause considerable errors if it comes from the wavelength range where the detector has high responsivity.

Monochromators may be prism or grating instruments. Prism-double monochromators offer the highest spectral purity whereas in the case of grating instruments great care must be taken to eliminate higher-order stray radiation. This must be done either with filters or with a prism pre-disperser. Such hybrid prism-grating monochromators are commercially available and offer the nearly constant dispersion of the grating type with suitable spectral purity. The spectral bandwidth of the system is not as critical as in spectroradiometry. However, if the slopes of the spectral response function of sample and reference detector differ considerably in some wavelength region, a larger bandwidth causes wavelength errors and corrections or a reduction of bandwidth are necessary. Bandwidth-related errors are especially a problem in the case of $V(\lambda)$ -corrected photodetectors.

Sets of interference filters (Moran, 1955; Horwitz and Wendland, 1979), are particularly useful in cases where a higher monochromatic irradiance is desired. They are instrumentally less demanding and particularly suitable in situations where reference and

sample detector have about the same spectral responsivity function, for example in production control. However, it is important that these filters be mounted perpendicular to the optical axis to avoid wavelength shifts with angle of incidence. This also must be considered if the radiation passing through such a filter is highly convergent. Unless the bandwidth of such filters is extremely narrow, wavelength corrections based on the spectral power distribution of the source, the spectral transmittance function of the filter and the spectral responsivity function of the detector must be incorporated (Krochmann, 1982).

Lasers, tunable or multiwavelength-types, such as the argon or krypton models, are also suitable, provided they are stabilized and coherence and polarization of the radiation do not affect the results. They offer power levels which are considerably higher than those achievable with monochromators, but tunable lasers are complex to operate for a moderate or large wavelength range, and multiwavelength models have only a limited and unevenly distributed number of wavelengths available. The latter are very suitable for absolute calibrations, see Section 2.2.

1.3.3 Beam-switching mechanisms

Essentially four different techniques are feasible for directing the monochromatic beam to reference or sample detector.

A) Mechanical exchange of the two detectors into the stationary optical beam: this must be done either at each wavelength or the total spectrum is scanned first with the reference detector and then with the sample detector. The first method requires high mechanical precision

of the exchange movement, particularly if small detectors and/or large housings are involved, whereas the second method requires high stability of the spectral condition of the system, that is, high stability of the source, high precision of the wavelength drive of the monochromator, and high stability of reference detector and amplifier.

B) Two-position switching mirrors. Several versions are shown in Fig. 2. Version a) usually requires a larger movement of the mirror which may cause larger distortions of the slit image. In version b) the mirror movement is smaller but the two flat mirrors either must have identical spectral reflectance functions or the ratio of these two functions must be known. Version c) is suitable if the imaging element is a lens or, in case mirrors are used, if the exchange is done perpendicular to the original direction. In all three versions high mechanical precision of the mirror movement is required, particularly if long distances and small detectors are involved. This is discussed further in Section 1.5.

C) Spinning sector mirrors: This method is shown in Fig. 1, where mirror M4 is a semi-circular or multi-sectored mirror disc which alternately reflects and transmits radiation. The mirror may be either rotating slowly or spinning rapidly, in the latter case presenting chopped radiation to both detectors.

D) Beamsplitters have the advantage that no movement of parts is required. However, they may introduce various sources of errors, for example 1. the ratio of transmitted to reflected beam changes with wavelength; 2. the polarization of both beams changes with wavelength. [These two sources of error are discussed by Mielenz (1979)] 3. some