



COMMISSION INTERNATIONALE DE L'ÉCLAIRAGE
INTERNATIONAL COMMISSION ON ILLUMINATION
INTERNATIONALE BELEUCHTUNGSKOMMISSION

ELECTRICALLY CALIBRATED THERMAL DETECTORS OF OPTICAL RADIATION

(ABSOLUTE RADIOMETERS)

PUBLICATION CIE N° 65 (1985)
BUREAU CENTRAL DE LA CIE
52, BOULEVARD MALESHERBES 75008 PARIS — FRANCE

This report has been prepared by CIE Technical Committee 2.2 (Detectors). It has been approved by the majority of the Technical Committee and is recommended for study and application. The report is not an Officially Agreed CIE Recommendation approved by the National Committees of the Member Countries of the CIE, and it should be noted that any recommendation which it contains is advisory and not mandatory. The latest CIE Proceedings or CIE Journal should be consulted regarding the current status of the report and possible subsequent amendments.

Ce rapport a été préparé par le Comité Technique 2.2 (Détecteurs) de la CIE. Il a été approuvé par la majorité du Comité Technique et il est recommandé pour étude et application. Ce rapport n'est pas une Recommandation officielle de la CIE, approuvée par les Comités Nationaux des Pays Membres de la CIE. Il doit être noté que toute recommandation y figurant est donnée à titre de conseil et non d'obligation. En ce qui concerne la situation présente de ce Rapport et d'éventuelles modifications, il faut consulter le plus récent Compte Rendu de Session ou Journal de la CIE.

Dieser Bericht wurde vom Technischen Komitee 2.2 (Detektoren) der CIE ausgearbeitet. Er wurde durch die Mehrheit des Technischen Komitees gebilligt und wird zum Studium und zur Anwendung empfohlen. Dieser Bericht ist keine offiziell anerkannte CIE Empfehlung, der die Nationalen Komitees der Mitgliedsländer der CIE zugestimmt haben. Es sei darauf hingewiesen, dass jede Empfehlung in diesem Bericht als Anleitung dient und nicht verbindlich ist. Was den gegenwärtigen Status dieses Berichtes und mögliche Nachfolge-Ausgaben angeht, ziehe man die neuesten CIE-Tagungsberichte oder das CIE-Journal zu Rate.

© CIE 1984

FOREWORD

The following members of Committee TC-2.2 took part in the preparation of the technical report:

Les membres suivant du comité TC-2.2 ont participé à la préparation du rapport technique:

Die folgenden Mitarbeiter des Komitees TC-2.2 haben sich an der Ausarbeitung des Technischen Berichtes beteiligt:

Chairman:

Hengstberger, F*

South Africa

Cogno, J A*

Argentina

Farmer, A J D

Australia

Reiter, H*

Austria

Pastiels, R

Belgium

Andreytchine, R

Bulgaria

Budde, W

Canada

Krtíl, J

Czechoslovakia

Nielsen, O

Denmark

Janest, A

France

Timonen, T

Finland

Riemann, M

Germany, Dem. Rep.

Geutler, G

Germany, Fed. Rep.

Betts, D B*

Great Britain

Schanda, J*

Hungary

Artom, M

Italy

Nanjo, M

Japan

Balder, J J

Netherlands

Hisdal, B

Norway

Lipowski, M

Poland

Musa, G

Romania

Corrons, A*

Spain

Ottoson, A

Sweden

Blaser, P*

Switzerland

Zalewski, E F

U S A

Ignatiev, V G

U S S R

Subcommittee on "Electrically calibrated thermal detectors of optical radiation":

Chairman:

Hengstberger, F

South Africa

Lozano, R D
 Blevin, W R
 Brown, W J
 Crommelynck, D
 Boivin, L P
 Zatkovic, J
 Bastie, J
 Bonhoure, J
 Bischoff, K
 Möstl, K
 Gentile, C
 Ono, A
 Ooba, N
 Belsey, D C
 Fröhlich, C
 Doyle, W M
 Geist, J
 Willson, R C

Argentina
 Australia
 Australia
 Belgium
 Canada
 Czechoslovakia
 France
 France
 Germany, Fed. Rep.
 Germany, Fed. Rep.
 Italy
 Japan
 Japan
 New Zealand
 Switzerland
 U S A
 U S A
 U S A

and members of TC-2.2 marked * above

Editorial committee:

Chairman:

Hengstberger, F

South Africa

Key, P

Great Britain

Zalewski, E F

U S A

SUMMARY

The report summarizes the operating principle of electrically calibrated thermal detectors of optical radiation. It also describes their main components, lists their error sources, suggests experimental procedures to determine their systematic errors and discusses their main application areas. An extensive list of references enables the reader to refer to specialist literature should he require more detailed information. The report is intended as a guide for non-specialist users of such instruments, giving them the background required for using these devices and an objective means for assessing their performance.

RESUME

DETECTEURS DE RADIATIONS OPTIQUES A ETALONNAGE PAR SUBSTITUTION ELECTRIQUE

Ce rapport résume le principe de fonctionnement des détecteurs de radiations optiques à étalonnage par substitution électrique. Il décrit également leurs principaux composants, donne la liste des sources d'erreurs, suggère des méthodes expérimentales pour déterminer leurs erreurs systématiques et discute leurs principaux domaines d'application. Une importante bibliographie permet au lecteur de se reporter à des textes spécifiques s'il désire des informations plus détaillées. Ce rapport a pour but de servir de guide aux utilisateurs non spécialistes de tels instruments, en leur donnant les connaissances de base nécessaires pour utiliser ces appareils et des moyens objectifs pour améliorer leurs performances.

ZUSAMMENFASSUNG

ELEKTRISCH KALIBRIERTE THERMISCHE EMPFÄNGER OPTISCHER STRAHLUNG

Dieser Technische Bericht beschreibt das Arbeitsprinzip von elektrisch kalibrierten thermischen Empfängern optischer Strahlung. Er behandelt auch ihre wichtigsten Komponenten, erläutert ihre Fehlerquellen, beschreibt experimentelle Methoden zur Bestimmung der systematischen Fehler und gibt ihre Hauptanwendungsgebiete an. Eine umfassende Bibliografie ermöglicht es dem Leser die Spezialliteratur auf diesem Gebiet zu studieren falls mehr detaillierte Informationen erforderlich sind. Der Bericht ist als Einführung für Verwender von solchen Instrumenten gedacht, die nicht Spezialisten auf diesem Gebiet sind. Er vermittelt ihnen das zur Verwendung der Instrumente nötige Wissen und ermöglicht ihnen auch eine objektive Bewertung ihrer Güte.

TABLE OF CONTENTS

1. INTRODUCTION	1
1.1 Radiant power scales	1
1.2 Scope	1
2. THE OPERATING PRINCIPLE OF AN ABSOLUTE RADIOMETER	2
3. ABSORBERS	4
3.1 General	4
3.2 Absorber types	5
3.2.1 Cavity absorbers	5
3.2.2 Disk absorbers	5
3.2.3 Disk absorbers with reflector	5
3.2.4 Conical absorbers	5
3.3 Common absorber materials	5
3.3.1 3M Black Velvet Paint	5
3.3.2 Eppley-Parsons Optical Black Lacquer	6
3.3.3 Kodak Black Baking Lacquer	6
3.3.4 Krylon Ultra Flat Black Spray Enamel No 1602	6
3.3.5 Metal absorbers	6
3.3.6 Carbon blacks	7
3.3.7 Comparative data	7
4. TEMPERATURE SENSORS	8
4.1 General	8
4.2 Thermopile sensors	9
4.3 Bolometric sensors	9
4.4 Pyroelectric sensors	10
5. REFERENCE POWER	10

6. ERROR SOURCES IN ABSOLUTE RADIOMETRY	11
6.1 General	11
6.2 Environmental factors	12
6.2.1 Diffraction	13
6.2.2 Atmospheric absorption	14
6.2.3 Filters	15
6.3 Instrumental factors	16
7. CORRECTION EXPERIMENTS	18
7.1 General	18
7.2 Reflection Loss	18
7.3 Lead-heating	19
7.4 Case-heating	21
7.5 Non-equivalence of the heat losses from the absorber	22
7.6 Responsivity variations across the detector surface	23
8. APPLICATION AREAS FOR ABSOLUTE RADIOMETERS	23
8.1 Realization of radiometric scales	23
8.2 Realization of photometric scales	23
8.3 Basic research	24
REFERENCES	25

1. INTRODUCTION

1.1 RADIANT POWER SCALES

The difference between a radiometer and an absolute radiometer is evident from the fact that the first instrument can only measure radiation in absolute units when it has been calibrated against a standard source or a standard detector. An absolute radiometer, on the other hand, does not need a calibration against another device. It is itself a standard detector which can be used, amongst other things, to calibrate common (non-absolute) radiometers. As is to be expected for a class of instruments used for the realization of the absolute radiation scale, the approach towards corrections and error sources differs fairly substantially from that used for non-absolute radiometers (a subject covered by CIE Technical Report No 53). There are two main methods by means of which absolute optical radiation scales can be realized. One is by reference to the radiant flux emitted by a black body. Here the accuracy depends on the accuracy with which the thermodynamic temperature scale can be realized and on the validity of the black body radiation laws. The alternative approach is known as "absolute radiometry", but it should be understood that neither of the two methods is more absolute than the other, and that both methods are valid. Other absolute methods under development at present include the absolute spectral response self-calibration of silicon photodiodes (see CIE Technical Report No 64) and the use of electron-synchrotrons as sources with a theoretically predictable radiant power spectrum. Absolute radiometric measurements are usually made with thermal detectors, which are built in such a way that they can also be heated with some form of reference power. This reference power is virtually always electrical power, and in that case such instruments are sometimes known as "Electrically Calibrated Radiometers" or "ECR's", especially in North America. In the field of meteorology the name "Compensation Pyrheliometer" is often used for absolute radiometers, but not all of the instruments referred to in this way are based on the "absolute" electrical power scale. In many instances "Compensation Pyrheliometers" measure in terms of relative power scales, based on a particular construction. However, instruments of this type seem to be on the way out as references and today meteorological radiation measurements are also referred to the absolute power scale.

1.2 SCOPE

The subject matter to be covered in this technical report is the field of "classical" absolute radiometry, which deals with the measurement of non-coherent optical radiations. Methods for measuring coherent optical radia-

tions or radiations in an arbitrary state of coherence are presently hampered by the fact that the basic theoretical relationships for the propagation of energy by coherent or partially coherent radiation are only now being established. The measurement of the power output of CW lasers by means of absolute radiometers is, however, quite feasible with the techniques described in this report, provided some extra precautions are observed. These mainly centre on the increased importance of spatial responsivity variations due to the often very localised heating produced by the laser beam and the avoidance of interference effects in windows (e.g. by the use of wedge shaped windows) [1-5].

This report is intended to serve as a guide for non-specialist users of absolute radiometers. It should enable them to grasp the operating principles of such instruments, make them aware of the main error sources and experimental techniques and provide them with objective guidelines for assessing their performance.

2. THE OPERATING PRINCIPLE OF AN ABSOLUTE RADIOMETER

Absolute radiometers are used to measure the incident radiant power (also referred to as radiant flux) in absolute units (watts). If the irradiated area is accurately known, the incident power per unit area (irradiance) can also be deduced. In a measurement with an absolute radiometer the unknown radiant flux is absorbed by the detector (generally a thermal detector). The resulting temperature rise causes an electrical output signal, which is then reproduced by heating the detector with a known amount of reference power. After correcting for a number of imperfections in the practical (as opposed to the ideal) measuring process, the incident radiant flux can be derived. The ideal measuring process is depicted schematically in Fig. 1a), from which the principle functions required of a detector element can be identified as [6]:

- a) radiant flux to thermal power (heat) conversion,
- b) equivalent reference power to thermal power (heat) conversion and
- c) thermal power (heat) sensing.

In an ideal radiometer all these functions are served by a single component. The fact that they have to be assigned to different, specialized components in practical instruments gives rise to most of the imperfections referred to above. A schematic diagram for this (non-ideal) case is given in Fig. 1b). In a very general way the instrumental corrections for one

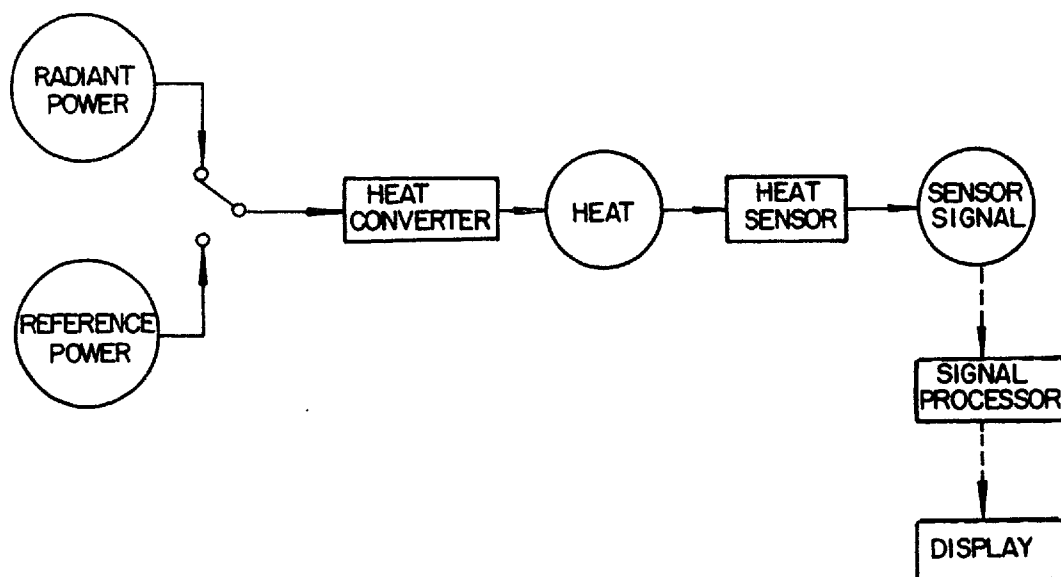


Fig. 1a. Ideal absolute radiometer

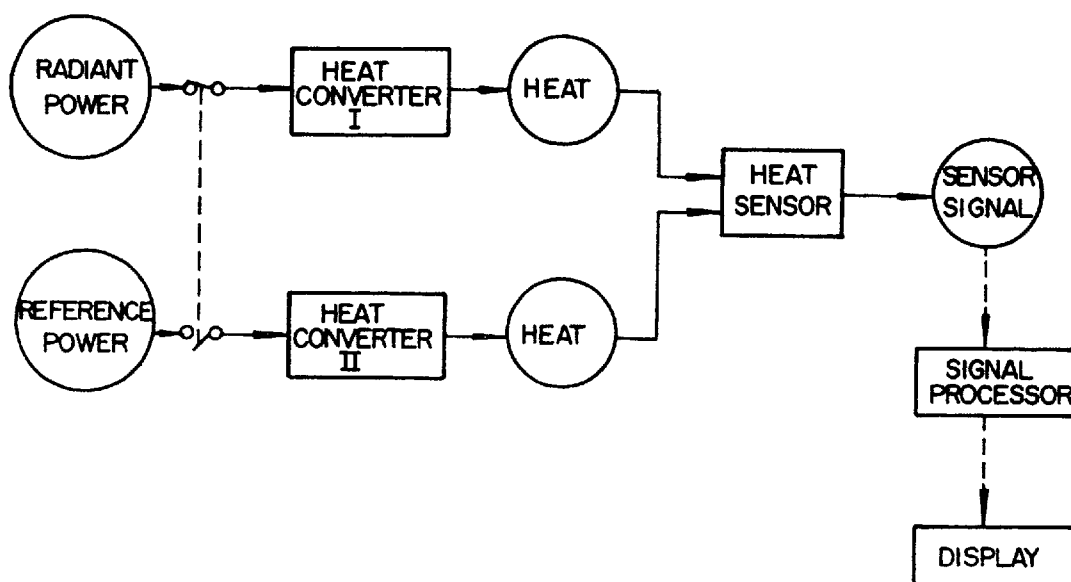


Fig. 1b. Real absolute radiometer

type of radiant power source and for one set of environmental conditions can be shown to refer to two principal causes:

- 1) differences in the conversion efficiencies of converters 1 & 2,
- 2) different heat paths to the sensor.

3. ABSORBERS

3.1 GENERAL

When optical radiation is incident on matter a number of different physical processes can occur, e.g. absorption, reflection, transmission, luminescence, photoelectric phenomena, structural changes in the matter, etc. While some of these processes can be observed under specific conditions with common absorber materials (e.g. photo-electron emission at vacuum-ultraviolet wavelengths, structural changes in high-power beams), they will be insignificant for most applications.

For the present purpose the term "absorber" will characterize a material for which the predominant interaction process with optical radiation is conversion of radiant energy into heat.

If one can assume that the material is opaque, its quality as absorber is mainly described by the spectral absorption factor $\alpha(\lambda)$ and the spectral reflection factor $\rho(\lambda)$. They are related by the equation

$$\alpha(\lambda) = 1 - \rho(\lambda) \quad (1)$$

The absorption factor $\alpha(\lambda)$ can be interpreted as the heat-conversion efficiency of the absorber for radiation with wavelength λ .

For use in an absolute radiometer it is desirable to select an absorber with a high absorption factor $\alpha(\lambda)$, which is as constant as possible with wavelength. Since the heat generation by absorption takes place in the absorber material and the measurement of the resulting temperature rise at another location in the receiver, the absorber's thermal conductivity should be high and uniform. In order to achieve a low thermal time-constant the absorber should preferably also have a low heat capacity.

Good adhesion to the substrate, mechanical durability and long-term stability are other desirable features.

3.2 ABSORBER TYPES

3.2.1 CAVITY ABSORBERS

If a blackened cavity with a small entrance aperture is used as the absorber, one can achieve absorptance factors which approach unity to within 0.001 [7,8,9,10,11,12]. In addition the deviations from unity can be calculated with good accuracy [13]. A disadvantage of cavity absorbers is their generally bigger heat capacity and the difficulty of achieving a uniform response and identical distribution of radiant and electrical heating powers. On the other hand the thermal resistance of the absorber layer has very little influence since the heat losses by conduction and convection are small. Significant advantages can be gained with cryogenic operation [11,12].

3.2.2 DISK ABSORBERS

Disk absorbers consist of a disk-shaped substrate covered by an absorber layer. They can be made with a low heat capacity, but the thermal conductivity of the absorber and the substrate should be as high as possible. The absorption factor is mainly determined by the layer of absorber material (see 3.3).

3.2.3 DISK ABSORBERS WITH REFLECTORS

The effective absorption factor of a disk absorber can be increased significantly by placing the disk in the centre of a hemispherical reflector [14,15,16]. Expressions for the effective absorption factor can be found in the literature [17,18].

3.2.4 CONICAL ABSORBERS

Cones are used frequently as absorbers [19,20,21,22]. In this technique it is advantageous to use a specularly reflecting absorber rather than a diffusely reflecting one. A critical factor for the performance is the radius of curvature achievable at the apex. Special techniques to minimize the apex effect and accurate procedures for measuring cavity reflectances [23] have been developed.

3.3 COMMON ABSORBER MATERIALS

3.3.1 3M BLACK VELVET PAINT [24]

This paint has excellent mechanical stability, a reasonably high