NBS MEASUREMENT SERVICES: THE NBS PHOTODETECTOR SPECTRAL RESPONSE CALIBRATION TRANSFER PROGRAM

Edward F. Zalewski

Center for Radiation Research
National Measurement Laboratory
National Bureau of Standards
Gaithersburg, MD 20899

U.S. DEPARTMENT OF COMMERCE, C. William Verity, Secretary
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, Director
Issued March 1988

Library of Congress Catalog Card Number: 88–600509

National Bureau of Standards Special Publication 250-17
Natl. Bur. Stand. (U.S.), Spec. Publ. 250-17, 65 pages (Mar. 1988)
CODEN: XNBSAV

Commercial products—materials and instruments—are identified in this document for the sole purpose of adequately describing experimental or test procedures. In no event does such identification imply recommendation or endorsement by the National Bureau of Standards of a particular product; nor does it imply that a named material or instrument is necessarily the best available for the purpose it serves.

U.S. GOVERNMENT PRINTING OFFICE
WASHINGTON: 1988

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402–9325

PREFACE

The calibration and related measurement services of the National Bureau of Standards are intended to assist the makers and users of precision measuring instruments in achieving the highest possible levels of accuracy, quality, and productivity. NBS offers over 300 different calibration, special test, and measurement assurance services. These services allow customers to directly link their measurement systems to measurement systems and standards maintained by NBS. These services are offered to the public and private organizations alike. They are described in NBS Special Publication (SP) 250, NBS Calibration Services Users Guide.

The Users Guide is being supplemented by a number of special publications (designated as the "SP 250 Series") that provide a detailed description of the important features of specific NBS calibration services. These documents provide a description of the: (1) specifications for the service; (2) design philosophy and theory; (3) NBS measurement system; (4) NBS operational procedures; (5) assessment of measurement uncertainty including random and systematic errors and an error budget; and (6) internal quality control procedures used by NBS. These documents will present more detail than can be given in an NBS calibration report, or than is generally allowed in articles in scientific journals. In the past NBS has published such information in a variety of ways. This series will help make this type of information more readily available to the user.

This document (SP 250-17), NBS Measurement Services: The NBS Photodetector Spectral Response Calibration Transfer Program, by E. F. Zalewski, is the seventeenth to be published in this new series of special publications. It describes the methods and procedures for calibrating a silicon-photodiode-based radiometer and explains how to apply the radiometer to the measurement of absolute spectral response in the 250 to 1064 nm region of the spectrum (see test number 39060C in the SP 250 Users Guide). Inquiries concerning the technical content of this document or the specifications for these services should be directed to the author or one of the technical contacts cited in SP 250.

The Center for Radiation Research (CRR) is in the process of publishing 21 documents in this SP 250 series, covering all of the calibration services offered by CRR. A complete listing of these documents can be found inside the back cover.

NBS would welcome suggestions on how publications such as these might be made more useful. Suggestions are also welcome concerning the need for new calibration services, special tests, and measurement assurance programs.

Joe D. Simmons
Acting Chief
Measurement Services

Chris E. Kuyatt
Director
Center for Radiation Research

ABSTRACT

A silicon-photodiode-based radiometer is supplied to transfer the calibration of absolute spectral response in units of A/W (Amperes/Watt) and A cm^2/W in the 250 to 1064 nm region of the spectrum. The radiometer is also characterized for linearity over the four-decade range of the amplifier gain settings. Also included with the radiometer are components and a procedure for measurement error diagnosis. The methods for obtaining and using this calibrated radiometer are described, as well as the calibration and characterization procedures used at NBS.

KEY WORDS: calibration, linearity, photodetector, photoelectric effect, quantum efficiency, radiometry, responsivity, silicon photodiode, spectral response.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

The NBS Photodetector Spectral Response Calibration Transfer Program

1) Introduction

1.1) Description of the calibration

The NBS photodetector spectral response calibration transfer program is a means of obtaining an absolute spectral response calibration in the visible and near-visible spectral region. It is listed as item number 39060C (formerly 7.5H) in NBS Special Publication 250 [1] and its Appendix.

The instruments used to transfer the calibration are rented from NBS rather than purchased. During the rental period the user transfers the responsivity calibration from the NBS instrument to his own set of in-house secondary standard photodetectors. To do the spectral comparison the user needs to have a tunable monochromatic source, such as a monochromator or a set of narrow-band filters combined with a suitable light source. The range of radiant power levels at which the spectral comparison can be performed is 10^{-3} to 10^{-7} W. The linearity of the photodetectors and amplifiers is calibrated over this range.

The NBS photodetectors are calibrated in units of A/W (Amperes/Watt) in 10 nm intervals from 250 to 960 nm. The photodetectors are also calibrated at two additional spectral lines in the infrared: 1014 and 1064 nm. A calibrated 0.5 cm^2 aperture is included to enable the calibration to be transfered in units of A cm^2/W. In the first case the output beam from the spectral comparator is focussed into a spot, i.e. underfills the active area of the photodetector. In the second case the output beam overfills the detector aperture.

1.2) Historical perspective

In the early 1970s NBS ceased to offer detector spectral response calibrations. Before that time only relative, not absolute, photodetector spectral response calibrations were offered. That program was halted for several reasons. The photodetectors then available were judged to be unreliable as calibration transfer standards; radiometric-quality silicon photodiode technology was just emerging. The NBS photodetector comparison instrumentation had deficiencies requiring major revisions. The number of calibration requests was very small. And, finally, it was thought that the NBS-calibrated spectral irradiance lamps could serve as the calibration base for detectors.

The photodetector calibration picture changed quickly because of the rapid advances made in photodetector technology, particularly with respect to silicon photodiodes. Some types of silicon photodetectors were reported to have superior radiometric characteristics, such as linearity over a large dynamic range, spatial response uniformity [2], no light memory (hysteresis) effects [3], and long-term stability. Furthermore, large measurement differences arising from using lamp standards for photodetector calibrations were demonstrated by the newly formed Council for Optical Radiation Measurements (CORM). Under the aegis of CORM, Franc Grum of the Eastman Kodak Co. organized an intercomparison of detector spectral response measurements [4]. The differences among the participating laboratories were much larger than expected. It was clear that suitable detector standards were needed by the optical radiation community and that NBS had to take steps to remedy the situation.

Because of the very encouraging reports on the characteristics of silicon photodiodes and earlier work at NBS [3], these detectors appeared to be the most suitable choice as calibration transfer standards. However, their behavior in regards to all the critical radiometric characteristics, especially long-term stability, were not yet well understood. Furthermore, it was not clear from the CORM intercomparison what portion of the problem was due to the lack of a standard detector, and what portion was due to inadequate calibration transfer measurement techniques. Therefore, a pilot program was undertaken in which silicon photodiodes were used as the calibration transfer standards and an experiment was designed to test the state-of-the-art of detector calibration transfer measurements. Concurrently, lasers and other electro-optic devices were being applied to radiometry [5] and new absolute response measurement techniques [6] were being developed at NBS.

The pilot calibration program and measurement diagnosis experiment showed that a number of laboratories could perform detector spectral response transfer measurements with an uncertainty of +/- 2% or less [7], and that silicon photodiodes could serve as reliable calibration transfer standards. The results of other work at NBS [2,8], however, indicated that the behavior of silicon photodiodes was not well enough understood and that there might yet be some hidden problems. One of the findings of the measurement diagnosis experiment [7] was that many laboratories did not have the appropriate electronics to correctly amplify the output of a silicon photodiode.

The successor to the pilot calibration program is now called the NBS Detector Response Transfer and Intercomparison Program*. In this program, calibrated silicon detectors are not issued as separate entities. Rather, the DRTPs [9] are complete radiometers

---

* The acronym is DRTIP, but, the calibration transfer instruments are commonly referred to as the more pronounceable DRIPs. Since we are referring only to the calibration transfer and not the intercomparison aspect of the program in this publication, the acronym we will use is DRTP.

(temperature-controlled silicon photodiode, amplifier, and power supplies) that are characterized for other critical parameters besides the absolute spectral response. Because of the large expense of development and characterization, the DRTPs are not sold but rented. The rental period, one month scheduled in advance, is sufficient to enable a laboratory to transfer the calibration to several of its in-house standard detectors and to perform the diagnostic tests that are the "Intercomparison" part of the program (see Appendix A).

It should be noted that, because of staff and funding limitations, the NBS portion of the intercomparison has not been completed. Even though the measurement diagnosis portion of the NBS detector calibration program has not been implemented, the DRTPs have served over the years to significantly improve the state-of-the-art in absolute spectral response measurements of photodetectors.

Recently, the addition of new staff members has facilitated the development of the instrumentation that will enable NBS to complete its part of the DRTIP intercomparison. It is hoped that this important part of the NBS photodetector calibration program, the measurement diagnosis service, will be reactivated shortly.

1.3) Overview of this document

Section 2 contains most of the information needed by the general user of the NBS detector response transfer package (DRTP). It includes the physical description of the instrument as well as a description of the range and accuracy of the calibration. Other pertinent information in Section 2 includes how to obtain, use, and return a DRTP.

Readers interested in more details regarding the photodetector calibration and characterization methods can find them in Section 3. It includes discussions of the instrumentation and experimental procedures used in characterizing the DRTPs, the absolute spectral response calibration procedure, the interpolation procedure, verification experiments, and the estimation of the uncertainties associated with this calibration.

1.4) Acknowledgements

Many people have worked with the author on the development and improvement of the NBS photodetector spectral response transfer program over the years. Most of them are recognized in the list of references. However, much of the work exists as unpublished data. The many contributions to the NBS photodetector calibration program are hereby gratefully acknowledged. Redesign and ruggedization of the electronic circuitry: Joel B. Fowler. Radiometric characterization measurements: A. Russell Schaefer and Warren K. Gladden. Spectral response interpolation/extrapolation calculations: Warren K. Gladden and Jon Geist. Interpolation/extrapolation verification measurements: Warren K. Gladden and Robert L. Booker. Spectral comparator instrument development and quality control measurements: Robert D. Saunders and Jeanne B. Houston.

2) Essential information for the user

2.1) Precautions

Before beginning a description of the instrument, several precautions must be noted regarding the care and handling of the detector, aperture, and filters. The user is cautioned to observe the following instructions:

DO NOT TOUCH the surface of the detector, the filters or the inner rim of the aperture.

DO NOT EXPOSE these components to a dusty environment or contaminating vapors.

DO NOT OPEN THE DRTP EXCEPT IN A NO SMOKING AREA

DO NOT ATTEMPT TO CLEAN these surfaces except by a stream of dry, oil-free nitrogen or other inert gas (compressed freon is generally NOT oil-free).

KEEP THE LENS CAP ON the detector whenever it is not in use. Also keep the filters wrapped in lint-free lens tissue and in their containers when they are not in use.

DO NOT OPEN THE RADIOMETER HEAD. The aperture holder may be removed if an active detector area of greater than 8 mm diameter is required. Please exercise care when doing so.

In order to insure the most accurate transfer measurements, NO ELECTRONIC ADJUSTMENTS OR ALTERATIONS TO THE INSTRUMENT SHOULD BE MADE IN THE FIELD BY THE USER.

2.2) How to rent a detector response transfer package (DRTP)

Current price and ordering information for the DRTP is published in the Appendix to NBS Special Publication 250 [1]. The Appendix to SP 250 is updated semi-annually. To obtain a current copy contact the NBS Office of Physical Measurement Services by phone: (301) 975-2007; or by mail: Room B-362 Bldg. 221; National Bureau of Standards; Gaithersburg, MD 20899.

Presently the Radiometric Physics Division staff member to contact regarding a DRTP rental is Ms. Jeanne Houston: phone number, (301) 975-2327; mail address, Room A-222 Bldg. 221. Six months is a typical lead time.

The instrument is shipped by second-day-delivery air freight from NBS and it should be returned to NBS by air freight. The special shipping crate should be saved and used to return the instrument. We have found that, besides saving time, the instruments arrive in better condition when shipped by an air freight service.

2.3) Physical description of the DRTP

The detector response transfer package consists of the radiometer, three broad-band absorbing glass filters, and two narrow-band interference filters. The radiometer consists of a cylindrical head 6.35 cm in diameter by 18 cm long, connected by a 1.5 m umbilical cord to a power supply (15 cm x 33 cm x 46 cm). All the sensitive electronics are contained in the radiometer head (see Figure 1). These are a temperature-stabilized silicon photodiode, current-to-voltage amplifier, gain control, and output buffer amplifier. The gain settings vary in decade steps from 10^4 to 10^7 V/A and are adjustable by means of a rotary switch at the rear of the radiometer head. The output voltage connection is a female BNC connector also located at the rear of the radiometer head.

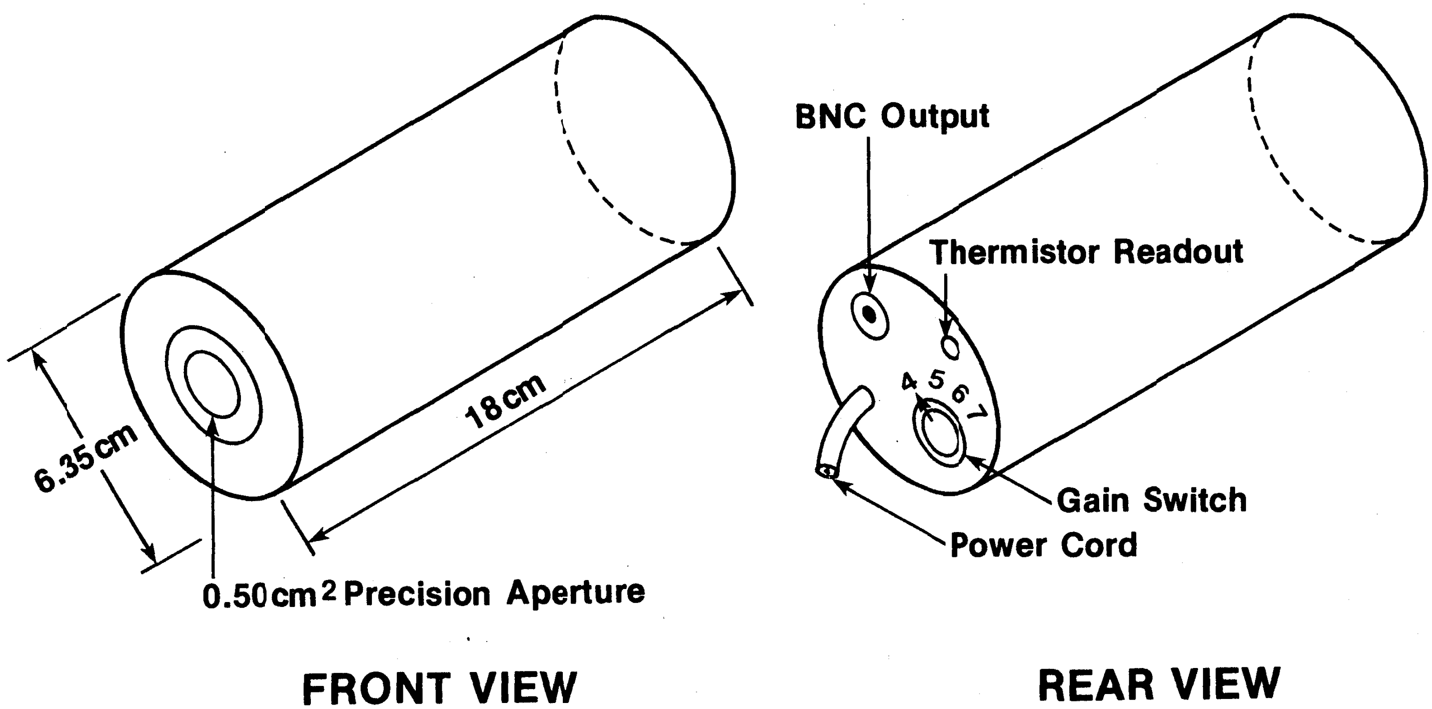


Fig. 1. Detector response transfer radiometer head.

Explicit mechanical and electronic descriptions of the DRTPs can be found in NBS Tech Note 950 [9]. Some features of the instrument have been changed, however, to ruggedize the control box for shipping. The digital panel meter, overload indicator, and variable-time-constant circuits described in reference [9] have been eliminated. The control box now contains simply the power supplies for the radiometer head. As noted above, the amplifier gain adjustment and the amplifier output are now at the rear of the radiometer head. Also at the rear of the radiometer head is a miniature gold-plated connector for a thermistor readout that is used only for calibrations at NBS. The radiometer head can not be disconnected from the control box. Finally, because the plastic lens cap was suspected to be a possible source of contamination it has been replaced by an aluminum cap which is held in place by a single #2-56 screw.

The instrument operates on 110 to 130 VAC at 50 to 60 Hz.

2.4) Other required instrumentation

A calibrated voltmeter and a male BNC connector cable will be needed to read the amplifier output at the rear of the radiometer head.

A stable mounting assembly will be required to hold the radiometer head. This mounting should have adjustable pitch and yaw motions. A 6.4 cm inside diameter clamping ring with a 1.27 cm diameter protruding rod is included in the DRTP package to facilitate mounting the radiometer.

The user is expected to have a detector response comparator instrument to transfer the DRTP calibration to a set of in-house detector standards. Descriptions of this type of instrumentation along with complete discussions of possible sources of error are given in CIE Publication 64 [10].

NBS Technical Note 988 [11] is a study of the characteristics of a particular spectral comparator instrument based on a pair of grating monochromators. This NBS Tech Note is similar in some respects to CIE Publication 64 [10] in that it deals with the pitfalls in designing and working with a detector spectral comparator. Also included in reference [11] is some early work on the use of a spectral irradiance standard lamp as a standard for detector calibrations via a black coated thermopile. It demonstrates the problems encountered in assuming the spectral non-selectivity of black thermal detectors. and may be a useful reference for those applications where a black thermal detector is used to extend the spectral range of the DRTP calibration. Other useful references for extending the spectral range of the DRTPs are [12, 13 and 14] where gold-black coatings and electrically calibrated pyroelectric radiometers are discussed.

2.5) How to use the DRTP

This calibration transfer standard has been made as rugged as possible to minimize physical damage to the instrument. However, as with any calibrated instrument, special care should be taken to protect the instrument from physical abuse. In particular the protective cap that covers the detector should always be replaced when the detector is not in use. In order to insure the highest accuracy, it is essential that the detector surface be kept free of contamination and that the aperture not sustain any physical damage.

The actual operation of the device has been kept as simple as possible to avoid operator error. Switch the power (110-130 V, 50-60 Hz) and the temperature control at the front of the power supply box to the ON positions. Allow 30 minutes for the detector temperature to stabilize to its operating temperature of 30°C. Over the course of the calibration transfer measurements, it is preferable to leave the instrument on continuously to insure maximum temperature stability. The ambient temperature must be below 30°C for proper operation.

Set the spectral comparator source to the wavelength of maximum radiant power output. Remove the protective cap from the detector head and adjust the amplifier gain to 10^4, the least sensitive setting. Initial measurements should be made using this range and then changing to more sensitive ranges if necessary. If the output voltage reads 12 V, the amplifier in the detector package is saturated and the incoming beam of radiation must be attenuated, typically with neutral density filters. For optimum linearity at any gain setting, the amplifier output should be 10 V or less.

The linearity of the detector response is a function of the radiant power density [15, 16]. That is, a high power density focused spot may cause the detector to be non-linear even though the photocurrent is below the maximum allowable for the amplifier. To avoid saturation, the radiant power density on the detector should not exceed 25 mW/cm^2.

The detector should be mounted so that the incident radiation is normal to the surface and underfills the active area. Because the detector uniformity degrades near the edges of the active area [2], the radiation should be restricted to the central 8 mm diameter area within the confines of the precision aperture. However, for images larger than 8 mm but not larger than the active area of the detector (11 mm diameter) the aperture can be removed -- exercising care as noted above. The accuracy of the calibration transfer will of course be degraded.

In order to use the calibration values as supplied in units of A/W, the radiation should always underfill the aperture (or the active area) of the photodiode. If the radiation field is larger than this, the precision aperture should be used. The calibration will then be in units of amps per irradiance (A cm^2/W) and the measured area of the aperture as supplied in the calibration report should be used to determine these calibration values.

In the irradiance measurement mode, the non-uniformities of the source irradiance and detector responsivity could lead to large, position dependent errors [11]. As noted above, the active area of the detector is not the correct limiting area.

Careful attention must be given to the geometry of the incoming radiation and the placement of lenses and filters. Since the detector has an optical quality surface, the user must be mindful of possible stray radiation due to inter-reflections between the detector and lenses or filters.

As a simple example of the use of the DRTP calibration, the following is a typical calculation for an optical power measurement at a mercury emission line.

$$P = \frac{X}{G * R} \quad , \tag{1}$$

where P is optical power; R is 0.2137 A/W (a typical interpolated value for the DRTP responsivity at 436 nm); G is 10^4 V/A (gain factor for the DRTP amplifier); and X is 3.756 V (DRTP output). Therefore, P equals 1.758 mW.

By placing another detector in this beam and reading its output, say 3.626×10^{-4} A, its responsivity at 436 nm is determined to be 0.2063 A/W.

If the radiation had overfilled the aperture of the DRTP, then the measurement is one of irradiance responsivity. If the aperture area is 0.5113 cm^2, then the irradiance measured by the DRTP is 3.438 mW/cm^2. The irradiance responsivity of the transfer detector is 0.1055 A cm^2/W.

Because the detectors are linear, they can be used to verify the linearity of other detectors. In addition, they can be used to characterize the irradiance versus distance behavior of light sources such as spectral irradiance or luminous intensity standards. That is, the DRTP can be used to check the inverse square "law" behavior of lamp standards [8], thereby extending the dynamic range of a lamp calibration.

2.6) Range of calibration

The silicon photodiode is calibrated for spectral response (A/W) at 10 nm intervals from 250 to 960 nm and at two discrete wavelengths in the infrared: 1014 and 1064.2 nm. The responsivity calibration of a typical photodiode is listed in Table 1. The typical uncertainties in the calibration relative to SI (absolute units) are listed in Table 2. The uncertainties summarized in Table 2 are the upper bound of the total error. They are more completely described in Section 3.12.

TABLE 1

Typical DRTP Responsivity

Wavelength (nm)	Spectral Responsivity (A/W)	Wavelength (nm)	Spectral Responsivity (A/W)
250	0.115	620	0.4457
260	0.109	630	0.4562
270	0.097	640	0.4660
280	0.091	650	0.4756
290	0.093	660	0.4850
300	0.098	670	0.4940
310	0.100	680	0.5024
320	0.100	690	0.5113
330	0.102	700	0.5196
340	0.101	710	0.5275
350	0.098	720	0.5352
360	0.095	730	0.5429
370	0.102	740	0.5503
380	0.117	750	0.5572
390	0.132	760	0.5641
400	0.148	770	0.5708
410	0.162	780	0.5773
420	0.177	790	0.5838
430	0.192	800	0.5903
440	0.207	810	0.597
450	0.222	820	0.602
460	0.237	830	0.608
470	0.251	840	0.614
480	0.266	850	0.620
490	0.281	860	0.625
500	0.2940	870	0.630
510	0.3077	880	0.636
520	0.3223	890	0.641
530	0.3364	900	0.646
540	0.3504	910	0.651
550	0.3632	920	0.656
560	0.3762	930	0.659
570	0.3886	940	0.661
580	0.4011	950	0.661
590	0.4126	960	0.656
600	0.4246	1014	0.577
610	0.4353	1064.2	0.277

TABLE 2

Summary of the DRTP Uncertainties

Wavelength	Uncertainty
250 to 390mm	+/- 6.0%
400 to 490mm	+/- 1.9%
500 to 850mm	+/- 0.8%
860 to 960mm	+/- 2.2%
1014mm	+/- 5.9%
1064.2mm	+/- 5.7%

A complete description of the calibration and interpolation method along with a discussion of the various sources of uncertainty are presented in Section 3.

A typical calibration report is presented in Appendix B. The most recent calibration results of each DRTP are included with the instrument as it is sent to the user. After checking the stability of the absolute response of the DRTP upon return to NBS, a report is issued of the actual calibration of the DRTP at the time that it was in the hands of the user.

2.7) Description of the diagnostic intercomparison

An accurate absolute spectral response calibration of a detector from NBS will enable other laboratories to determine the absolute spectral response of many other different detectors and radiometers. However, the other key component in the quality of the measurement chain, besides the accuracy of the NBS calibration and the various pertinent characteristics of the detector and the electronics, is the accuracy of the user's transfer of this calibration. The detector response transfer package contains several components selected to diagnose and intercompare each laboratory's response transfer capabilities. The diagnostic tests have been designed to evaluate the performance of monochromator based detector comparators, since these are by far the most common type.

Two of the most common sources of error in detector response transfer measurements are inaccuracy in the monochromator wavelength readings and out-of-band (stray) radiation transmitted by the monochromator. To test for the accuracy of the wavelength setting, two mounted interference filters are supplied with each instrument. One filter has a transmission peak at approximately 410 nm (serial numbers begin with WV) and the other at approximately 940 nm (WR serial numbers). Each laboratory is requested to use its monochromator and source to measure the wavelength at the 20% transmission points of each filter when mounted on the DRTP radiometer head.

The other principal source of error, stray radiation, is of two types: radiation from all other wavelengths scattered into the monochromator's transmission band and the second order diffraction present in grating instruments. For instruments employing an incandescent source, the first type of stray radiation is usually a big problem in the blue and uv spectral regions whereas the second type is most apparent in the red and ir. Instruments employing arc sources with intense uv lines are a special case since the second order scatter will occur in the visible. To test for stray radiation two absorbing glass cut-off filters are supplied. The filter to check for stray radiation at wavelengths shorter than 400 nm (SV serial number) is a 1 mm thick Schott VG-5 glass. For stray radiation at wavelengths longer than 800 nm the filter (SR serial number) is a 1 mm thick Schott BG-18 glass. The nominal transmittances of these filters are displayed in Fig. 2. Each laboratory is requested to measure the output of its monochromator at specified uv and ir wavelengths using the NBS detector both with and without the cut-off filters.

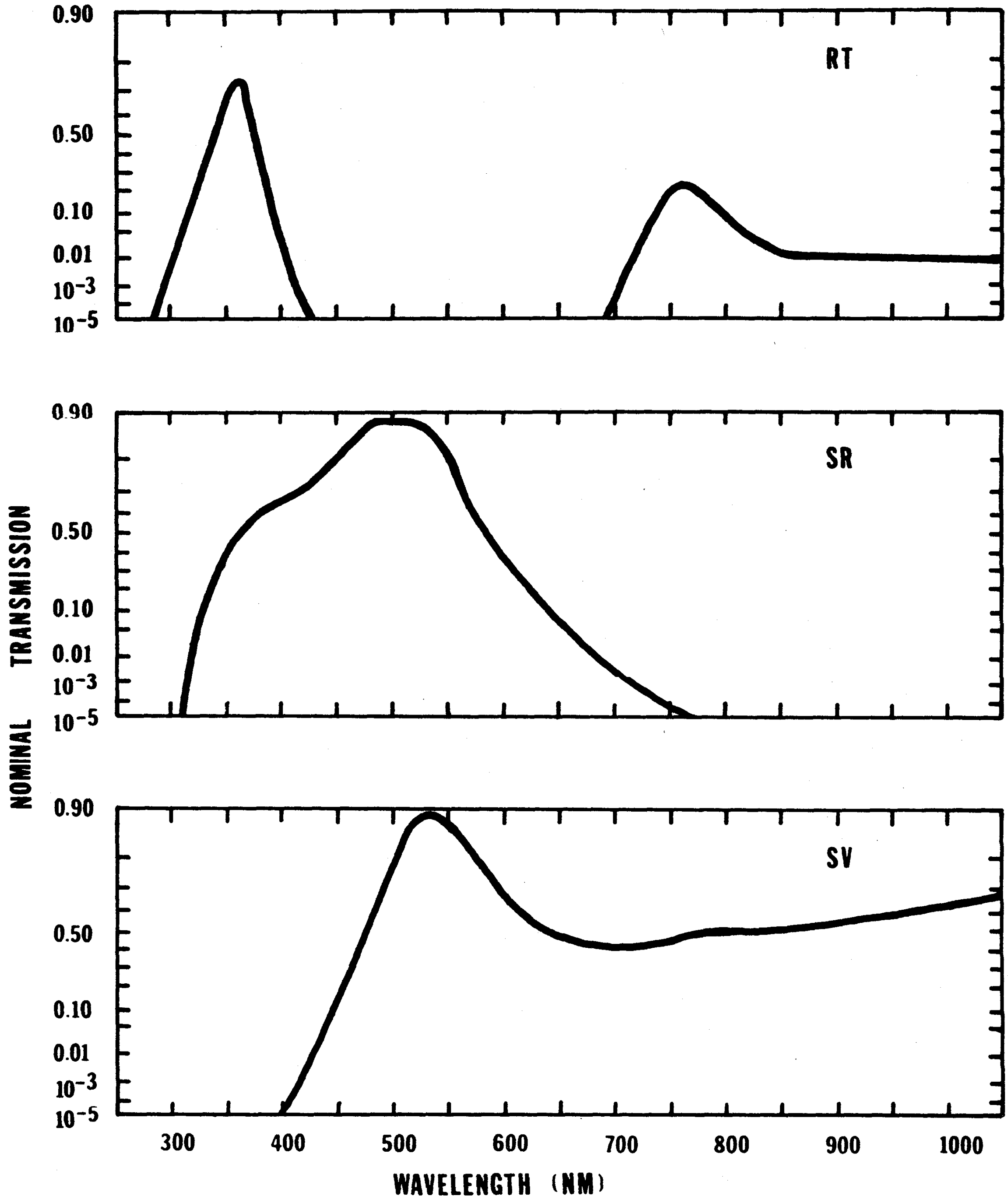


Fig. 2. Typical transmittances of the diagnostic filters.

A good indicator of each laboratory's response transfer capability is how well it can transfer the absolute spectral response from the calibrated silicon detector to another detector having a very different spectral sensitivity. The third absorbing glass filter in the detector response transfer package (RT serial number) is a 2 mm thick filter of Schott UG-1 glass. This is a visible absorbing filter that has transmission peaks in both the uv and ir. (See Fig. 2.) Each laboratory is requested to measure the spectral response of a "test" detector (the NBS detector with the RT filter in place) against that of the DRTP detector calibration as supplied by NBS. When the SR and SV filters are used in tandem with the silicon detector the response is limited to only visible wavelengths. The laboratories are also requested to measure the response of this combination at specified wavelengths.

From the data on the above two test response functions as supplied by the various laboratories, it is possible to compare interlaboratory spectral response capabilities in three distinct spectral regions: near uv, visible and near ir.

The intercomparison format along with the instructions are presented in Appendix A.

3) <u>NBS calibration and characterization procedures</u>

3.1) <u>Overview of the calibration procedure</u>

This Section covers the procedures followed at NBS in the characterization and calibration of the DRTPs. The procedures described here are not to be undertaken on the DRTP by the user. In order to insure the most accurate transfer measurements, **no electronic adjustments or alterations to the instrument should be made in the field by the user.**

Before the DRTPs were radiometrically characterized, the electronic circuits were adjusted and the temperature control set as described below. These adjustments do not have to be repeated.

The key radiometric characteristics of linearity, uniformity, and aperture area were then measured. These were followed by the principal calibration of reflectance and absolute spectral response.

The experimentally determined values of the spectral response and reflectance were used to calculate the internal quantum efficiency at each measurement wavelength. Using theoretical models of the internal quantum efficiency of silicon and the reflectance of a thin film dielectric on a conductor, the internal quantum efficiency and reflectance were interpolated over the spectral range of the calibration: 250 to 960 nm in 10 nm intervals. These two spectral functions were combined to yield the absolute spectral response as presented in each DRTP calibration report.

The stability of the calibration of the DRTPs is checked each time they are returned to NBS by intercomparing their spectral responsivities by means of a conventional monochromator spectral comparator. Changes in the spectral response of each DRTP relative to the group are monitored.

The radiometric characterizations were all performed using the laser-based facility described in NBS Tech Note 954 [5]. The heart of the facility is the amplitude-stabilized cw laser. This is a nearly ideal source of monochromatic radiation due to its high degree of collimation and high power. The associated optics are simpler and the dynamic range of radiant power available for most experiments is orders of magnitude greater than from conventional monochromatic sources. For many experiments, the concentrated radiant power in the laser beam is too great and must be attenuated. Neutral density filters can be used if the attendant scattered radiation is acceptable. A preferred technique is to use a beam expanding telescope and spatial filter to provide a more uniform laser beam and reduce its radiant power density.

In some experiments it is important that there be very low scatter around the collimated beam. One successful method of forming a well collimated and clean beam of radiation is to defocus the microscope objective in the beam expanding telescope so that it slightly overfills the spatial filter pinhole. This produces a circular diffraction pattern. The central spot of the diffraction pattern can be selected by intersecting the first dark ring in the pattern with an iris diaphragm. In this way diffraction from the iris diaphragm and other subsequent apertures is avoided. An aperture might be needed close to the experimental area to remove the small amount of scattered radiation from the telescope or other optical components.

It should be noted that for optimum performance of the laser power stabilizer system, the beamsplitter and monitor detector should be positioned close to the experimental area. It may be necessary to position the final aperture after the beamsplitter in order to reduce the scatter from it.

3.2) Safety considerations

The main hazards that occur in the calibration and characterization of the DRTPs arise from the electrical instrumentation and from the high intensity light sources, such as lasers and arc lamps. In addition, high pressure arc lamps can explode and may produce hazardous levels of ozone during operation.

Electrical connections on all equipment are well insulated and these instruments are connected with approved grounded power cords. High voltage sources are well shielded.

Laser and ultraviolet (from the arc lamp) radiation hazard signs are posted appropriately. In addition the lasers and arc lamps are shielded to reduce the level of exposure as a protection for the personnel working in the area. Protective goggles should be worn by the working personnel and additional sets are readily available for visitors.

Adequate shielding is especially important when working with high pressure arc lamps because of the danger of explosion. Such precautions are especially important when the lamps have to be handled during replacement.

3.3) Current amplifier calibration

Access to the detector head electronics is achieved in the following manner. Remove the aperture plate by removing the three countersunk Allen screws. Next remove the three outer countersunk Allen screws in the detector plate. Replace the lens cap to protect the detector. Loosen the Allen set screw on the side near the back (cable) end of the detector head and slide the outer shell back over the cables.

With the silicon detector covered to insure zero light input, attach the positive side of a stable current generator capable of a 1 mA to 100 nA output to the cathode of the silicon detector SD1, through a 1 KW standard resistor. The anode side of the detector should be connected to the negative side of the generator.

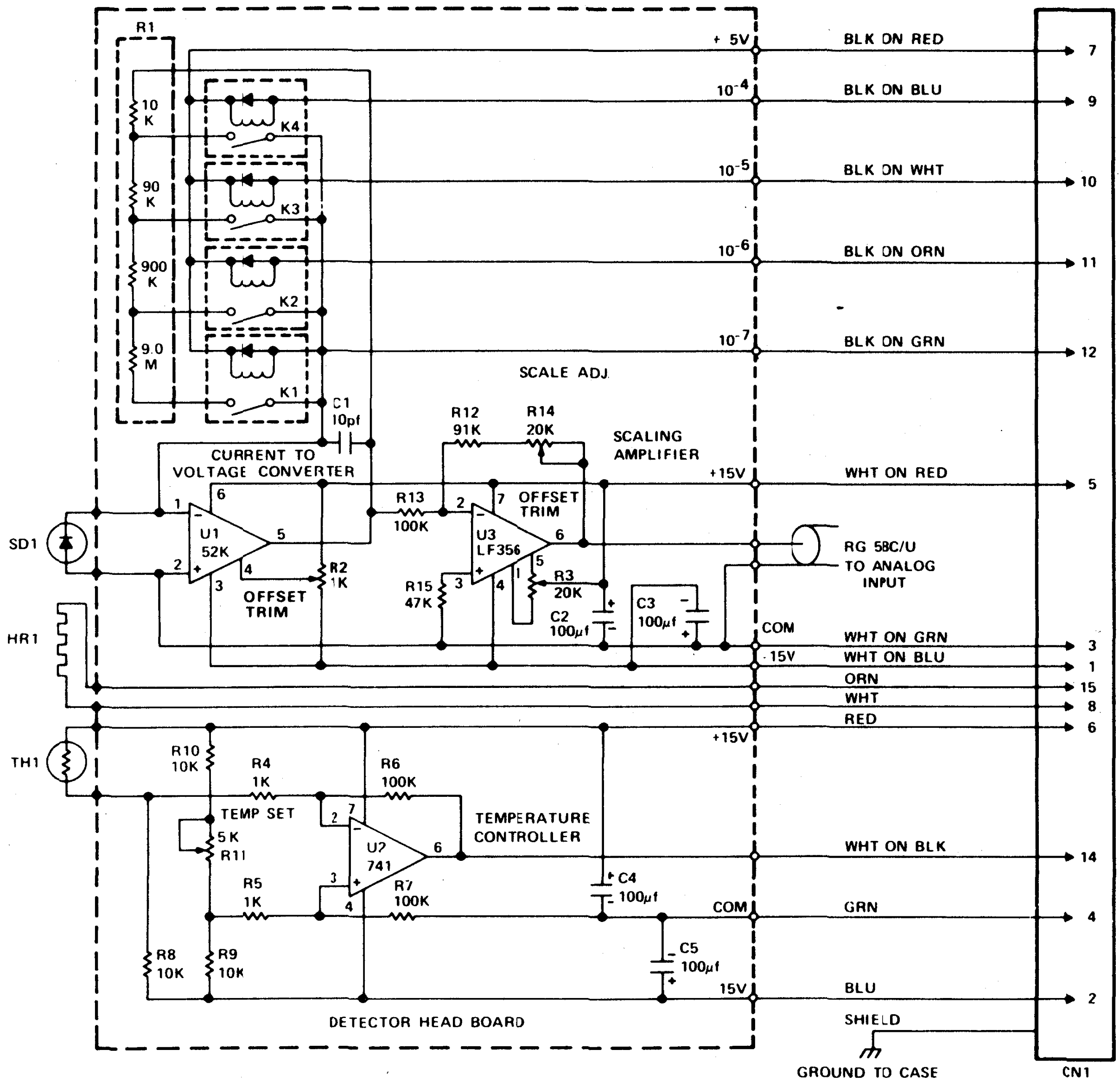
A high accuracy DVM is then used to monitor the current output of the generator by measuring the voltage drop across the standard resistor. Locate R2 and R3 using the diagram in Fig. 3. With the current generator set for zero current output, adjust R2 for a minimum voltage at the output of U1. Next adjust R3 for a minimum output of U3.

Adjust the current generator to 1.0000 mA with the gain switch set to the 10^4 V/A position. Adjust R14 to read 10.000 V at the output of U3 (the detector head BNC connector). Next adjust the current to 1.0000 mA and set the gain switch to the 10^7 V/A position. The output of U3 should again read 10.000 V. Readjust R14 slightly if necessary. Try the other gain settings to insure that the amplifier is scaling properly. Using an iterative procedure it is possible to bring the output of U3 to the correct value within 0.01% for all gain settings.

The linearity of the amplifiers was measured by checking the amplifier calibration over an output range of 0.1 to 13 V. In the range from 0.1 to 10 V, the amplifiers were linear to within +/- 0.01%. For an output above 10 V, the amplifier begins to saturate showing a one percent effect at about 12 V. The linearity between ranges is +/- 0.01%. The uncertainty in the amplifier gain, i. e. the absolute accuracy of the current to voltage conversion, is +/- 0.03%. The uncertainty in the amplifier gain does not contribute to the uncertainty of the absolute response calibrations. Rather, it is a contribution to the linearity uncertainty that is included in the detector linearity measurement.

3.4) Temperature controller adjustments

The temperature is set by adjusting R11 in the detector head (Fig. 3). In order to insure the best possible transfer measurements, all characterizations of the detectors have been performed with the temperature of the substrate set at approximately 30°C and controlled to better than +/- 0.1°C.



SPECIAL PARTS

SD1	SILICON DETECTOR EG&G UV444B SELECTED AND CHARACTERIZED
HR1	HEATING ELEMENT MINCO NO. HK6010 - 0189.48
TH1	THERMISTOR FENWAL ELECTRONICS INC NO. GB41J1
CN1	15 PIN CONNECTOR CYNCH DA 15P
CB1	15 COND SHIELDED CABLE ALPHA NO 3315
K1, K2 K3, K4	SPST REED RELAY MAGNACRAFT NO. W171 DIP 7
U1	OP AMP ANALOG DEVICES NO. 52K
U3	OP AMP NATIONAL SEMICONDUCTOR LF356CH
R1	DECADE RESISTOR DIVIDER CADDOCK NO. 1776-1
C1	SILVER MICA 10pf
C2, C3 C4, C5	100µf 20V TANT.
	ALL RESISTORS ¼ WATT 2% TIN OXIDE
	ALL TRIM POTS 15 TURN CERMET

Fig. 3. Circuit diagram, radiometer head.

A thermistor probe (Fenwal GB41J1) has been installed in each DRTP to enable the temperature set point to be read easily. This thermistor is connected to the minature gold-plated connector at the rear of the radiometer head. At the temperature set point the resistance of the thermistor in each of the six DRTPs was as follows:

DR-10, 8.08 +/- 0.02 KΩ; DR-11, 6.64 +/- 0.04 KΩ;

DR-12, 6.77 +/- 0.02 KΩ; DR-13, 6.63 +/- 0.01 KΩ;

DR-14, 6.89 +/- 0.05 KΩ; DR-15, 5.43 +/- 0.02 KΩ.

The uncertainty in the absolute response calibration due to temperature fluctuations (+/- 0.1°C) is only significant in the ir spectral region. From the temperature coefficient of the responsivity at 1064 nm the upper bound on the systematic error due to temperature fluctuations is estimated to be +/- 0.2%.

3.5) Linearity measurements

The linearity of the DRTP photodiodes was checked at several wavelengths using amplitude stabilized [17] laser lines as the monochromatic source. The wavelengths used were: 406, 530, 647 and 799 nm. Significant departures from linear responsivity (greater than 0.1% per decade) were observed only for DR-14 and only at 799 nm. This nonlinearity was manifest as an increase in responsivity at high radiant power input, the phenomenon known as super-responsivity [15, 16].

Besides super-responsivity, the other non-linearity effect is saturation of the photodiode at high radiant power densities. Saturation at the 0.1% level occured in all the DRTPs (except DR- 14) at radiant power densities above 25 mw/cm^2. The radiant power density in the case of DR-14 should not exceed 5 mW/cm^{-2}.

Two linearity measurement methods were used: the AC-DC method [15, 16] and a beamsplitter reflectance measurement versus power. In the

AC-DC method the laser output is split into two beams. One beam is chopped (AC) and then superimposed with the steady (DC) beam on the detector. The AC output of the detector is measured with a lock-in amplifier. The radiant power in the DC beam is varied. If the detector is non-linear the responsivity, R, will be a function of the input power.

$$i = R(p)\ p, \qquad (2)$$

where i and p are the output current and input power respectively. The AC measurement is analogous to the first derivative of Eq. 2;

$$\frac{\Delta i}{\Delta p} = R + \frac{p\ \Delta R}{\Delta p} \qquad (3)$$

If the AC output of the detector remains constant as the power in the DC beam changes, the derivative of i with respect to p must be a constant. The right-hand side of Eq. 3 is therefore also a constant function of radiant power, i. e. the detector must be linear.

The advantage of the AC-DC method is that it is simple to implement. The disadvantage is that if the detector is non-linear then there is no clear-cut way to obtain a correction factor for the non-linearity.

The second method, the beamsplitter reflectance measurement versus power, was used to compare linear and non-linear detectors to determine a correction for the latter. The measurements for DR-14 at 799 nm are shown in Fig. 4. This shows a super-responsivity non-linearity of about 0.5% per decade at about 1 mW, the highest input power where the DRTP is calibrated. The non-linearity decreases rapidly at lower power levels. The super-responsivity non-linearity effect is greater at longer wavelengths. From these and other measurements made with a conventional spectral comparator, the non-linearity corrections to the absolute response calibration values were obtained for DR-14. The corrections to

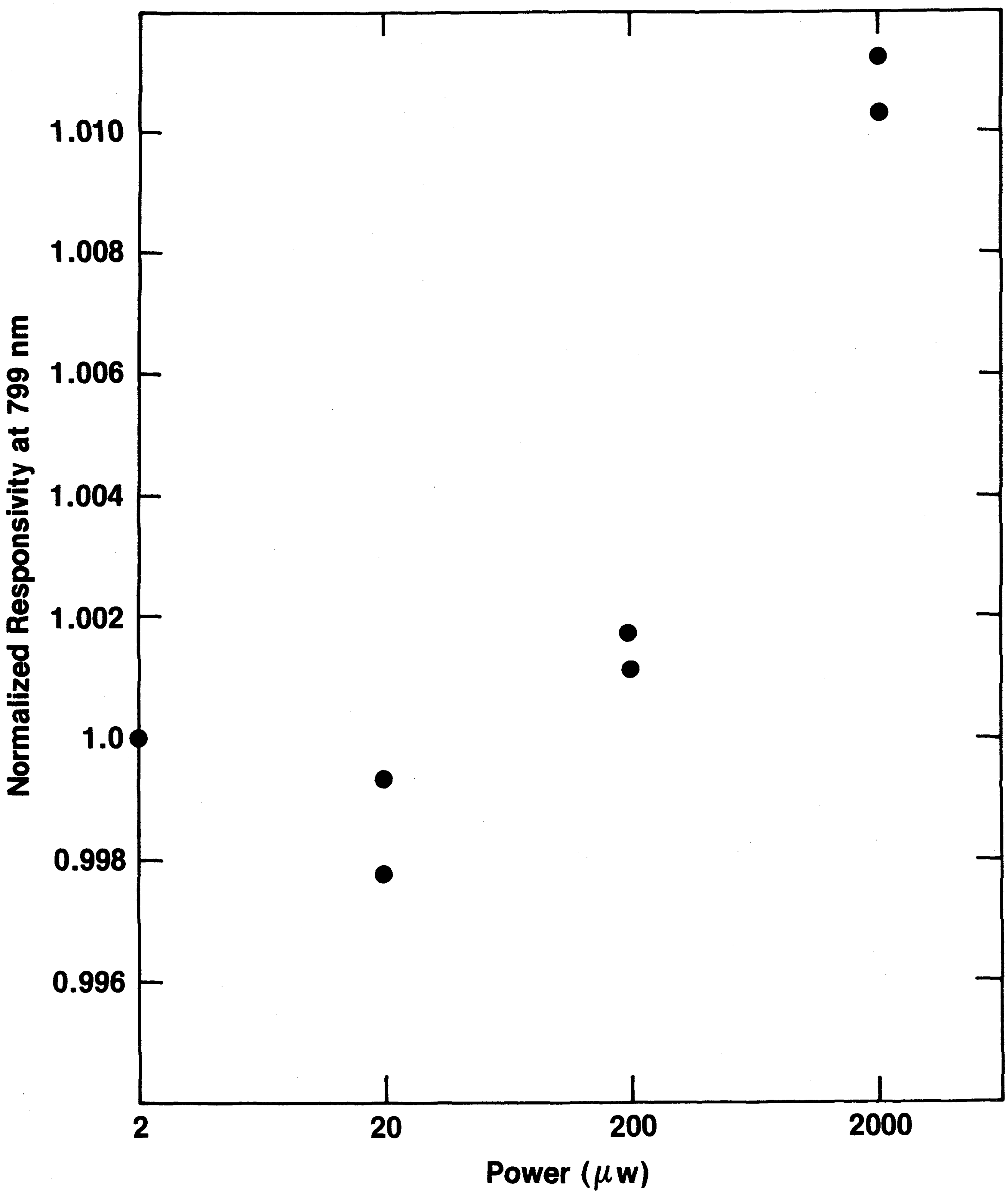


Fig. 4. Non-linearity of DR-14 at 799 nm.

be applied when operating at any power level less than 0.1 mW: - 0.5% at 800 nm; - 1% at 900 nm; and - 2% at 950 nm.

At the long wavelength end of the calibration range (700 nm and up) all the other DRTPs were found to be reasonably linear over the entire range of the amplifier gain settings; i. e. no extreme super-responsivity effect. The non-linearity uncertainty (upper bound) that applies when using any of the DRTPs at short wavelengths and at radiant power levels less than 0.1 mW, is +/- 0.1% per decade. At wavelengths longer than 700 nm the linearity uncertainty (upper bound) for all the DRTPs, including DR-14 with the correction as stated above, increases to +/- 0.3% for the first decade, from 1 to 0.1 mW, and for radiant power levels below 0.1 mW it reduces to 0.1% per decade.

3.6) Measurement of spatial and angular characteristics

Spatial uniformity was measured by focussing a 1 mm square spot on the detector and then recording its output while moving the detector in a 1 mm step, two dimensional scan. Translation of the detector, rather than scanning the beam by tilting mirrors, was preferred because of the possible fluctuations introduced by the variable reflectance of a rotated mirror. A square 1 mm x 1 mm spot was obtained by expanding the laser beam onto a 1 mm square aperture. The image of this aperture was then focussed on the detector. The detector output was AC amplified.

The detectors all showed similar spatial uniformity of response. As an example, the uniformity maps for one of the DRTPs at four wavelengths (257.3, 406.7, 632.8 and 1064.0 nm) are shown in Figs. 5, 6, 7 and 8. In the blue and uv spectral regions, the maximum variations observed ranged from 2% across the detector to as much as 6%. In the mid-visible to red spectral region the variation in response ranged from 0.5 to 2%. The uniformity does not vary monotonically across the surface but exhibits peaks and valleys.

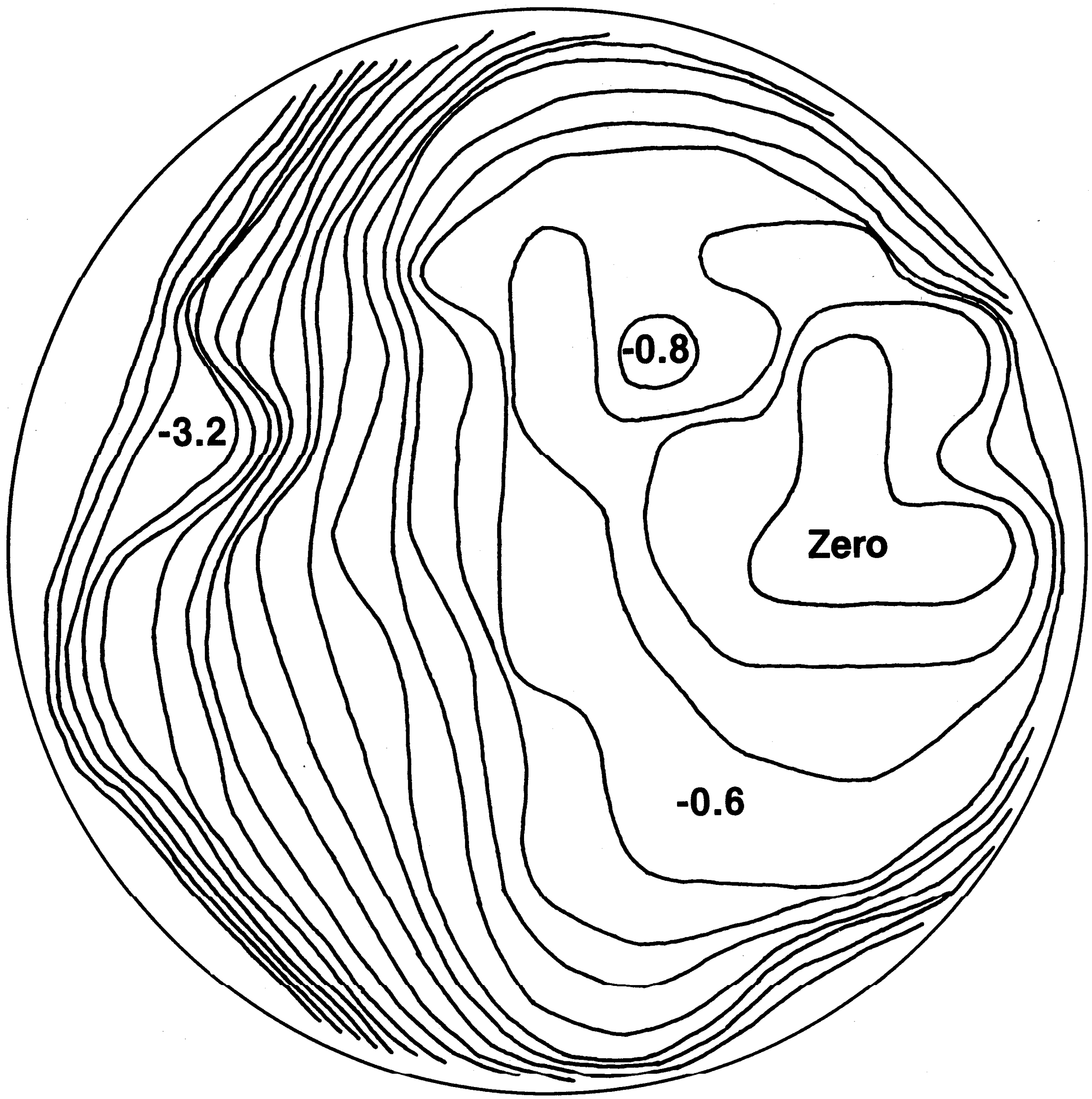


Fig. 5. Typical detector uniformity map at 254 nm.

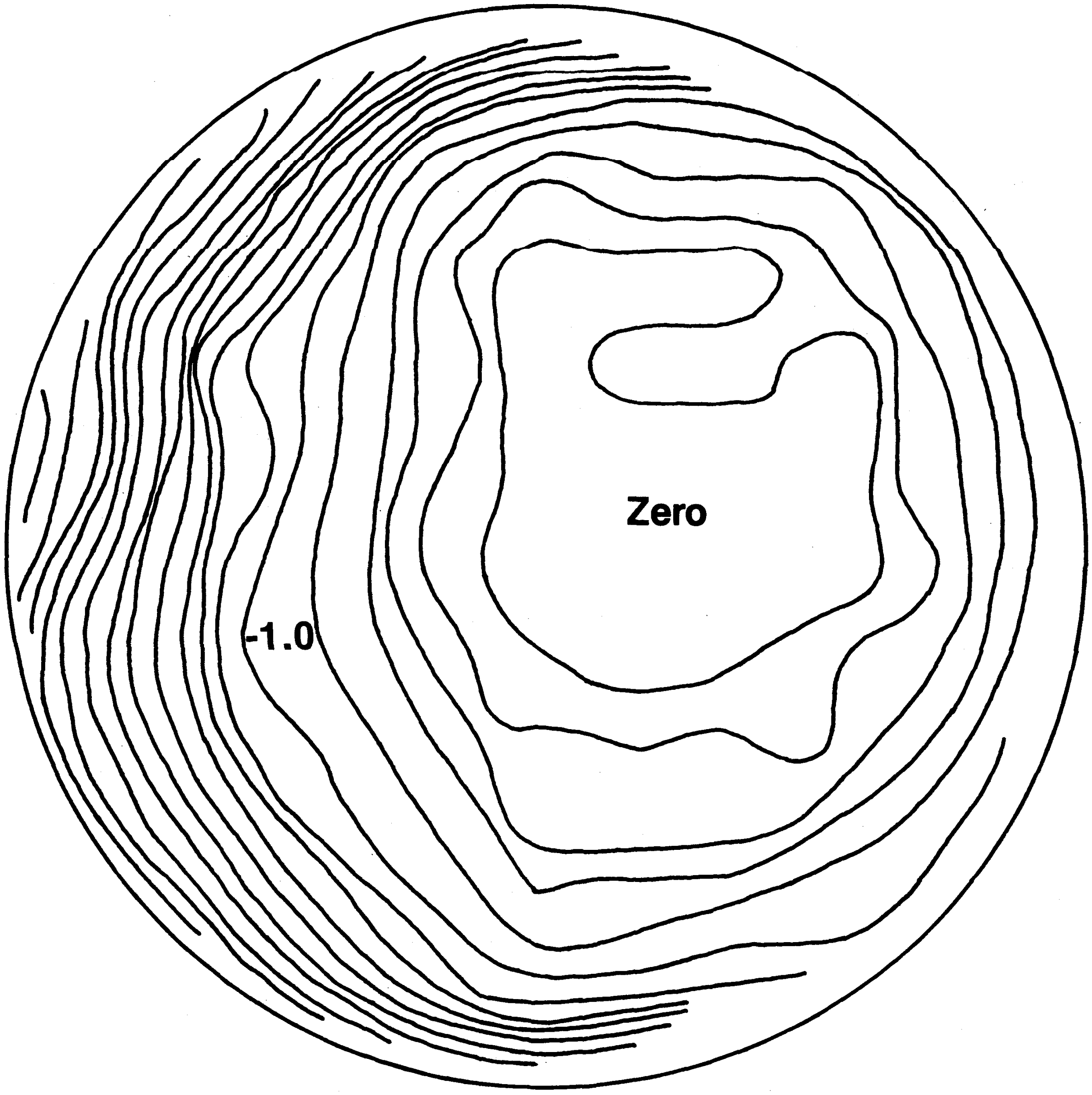


Fig. 6. Typical detector uniformity map at 407 nm.

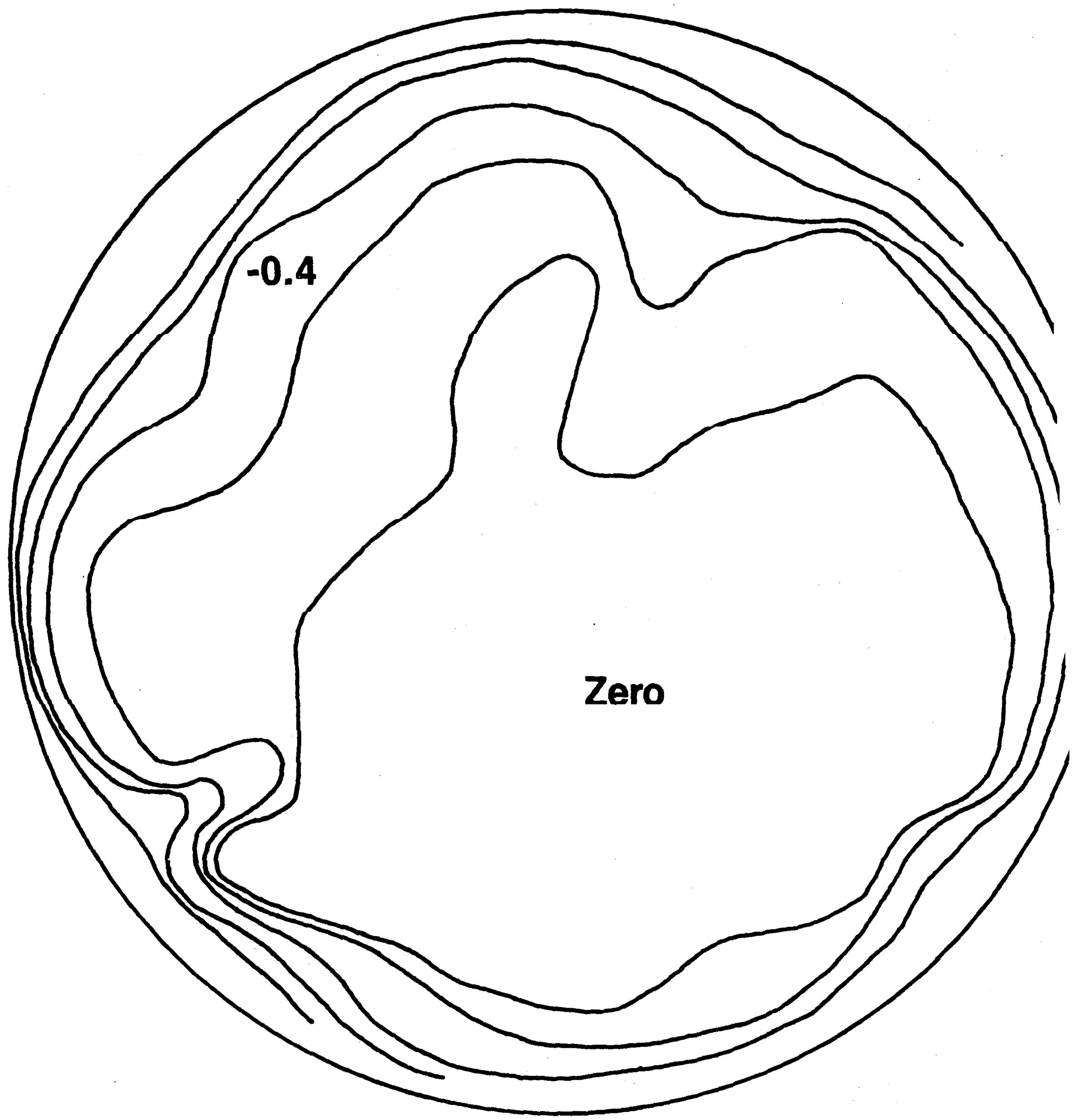


Fig. 7. Typical detector uniformity map at 633 nm.

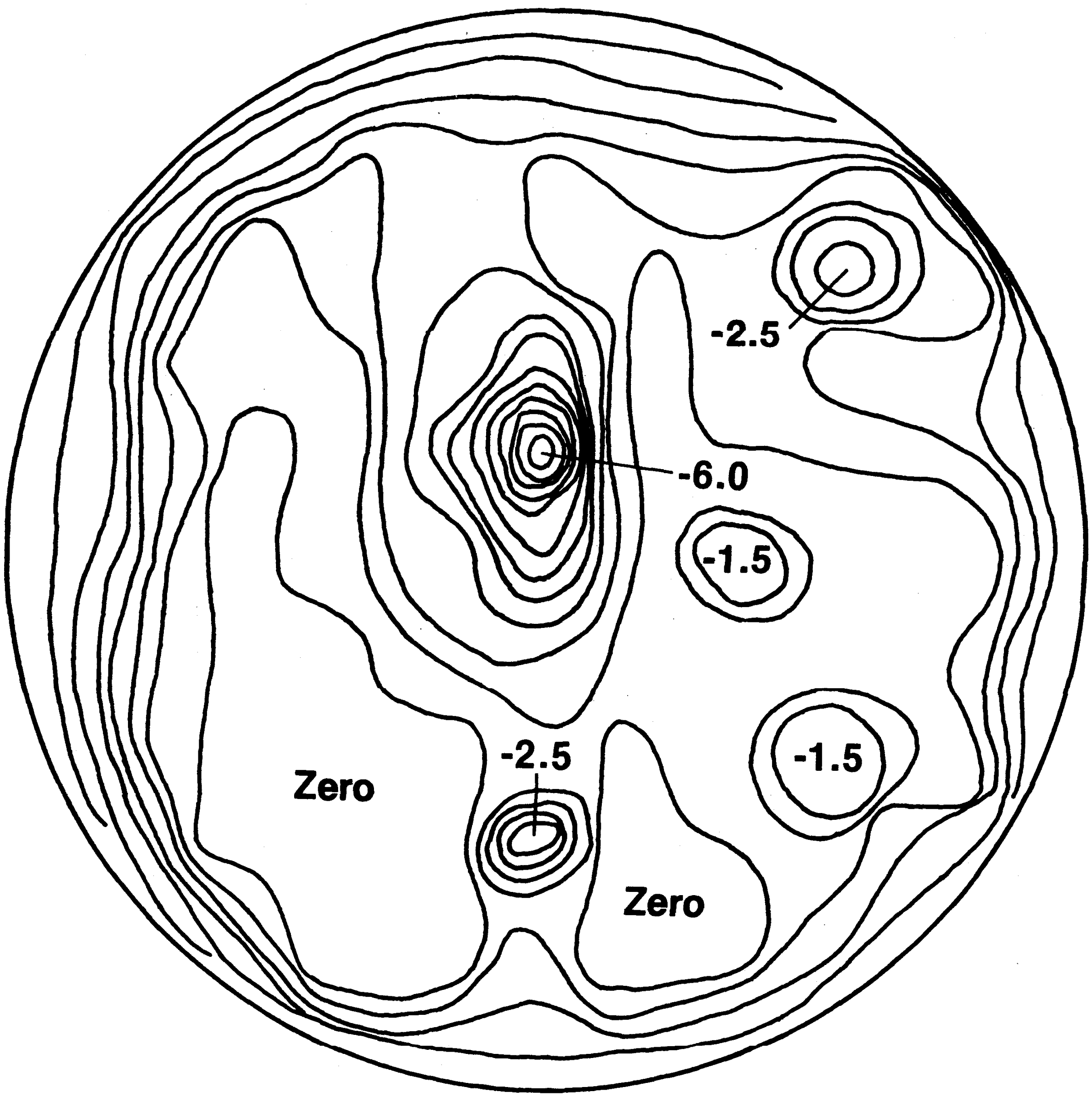


Fig. 8. Typical (except DR-14, see text) detector uniformity map at 1064 nm.

At 1064 nm the character of the uniformity variations is markedly different. Typically, the maximum variations of response at 1064 nm ranged from 5 to 8%, except for DR-14 which varied by 39%. See reference [16] for an explanation of the large ir non-uniformity in some silicon photodiodes.

The uncertainty due to the non-uniformity of response depends on the size of the spot of radiation used in measuring the DRTP and also the wavelength of the radiation. In the responsivity calibration, the spot size was 4 +/- 1 mm in diameter. The upper bound of the systematic error associated with the non-uniformity of the photodiode was estimated to be one-half of the maximum observed non-uniformty.

Angular responsivity was measured by irradiating a small region (approximately 3 mm diameter spot) in the center of the detector and recording the output while rotating the detector about an axis in the plane of its surface. Rotation of +/- 5 degrees from normal incidence produced negligible, less than 0.1%, change in the detector output.

3.7) Aperture area measurements

The area of the apertures was measured [18] by a microprobe analysis of the roundness of the opening (Tallyround method). The average diameter was then used to calculate the area. From the variations in the diameters, the upper bound on the systematic error in the area of the apertures is estimated to be +/- 0.02%. The measured value for the area of each DRTP aperture is included in the calibration report.

The distance to which the plane of the aperture is recessed from the front of the holder was also measured and is included in each calibration report. The exact position of the plane of the aperture is, of course, important in transferring detector response in the irradiance mode (A cm^2/W).

3.8) <u>Specular and diffuse reflectance measurements</u>

Specular reflectance (within a 1° cone around a 5° angle of reflection) was measured with an amplitude stabilized HeNe laser at 632.8 nm and a HeCd laser at 441.6 and 325.0 nm. These measurements were performed with a separate silicon detector as the sensor to receive the reflected radiation. The sensor detector was then moved to intercept and measure the incident beam. Care was taken to insure that the incident and reflected spots were approximately the same size and in the same position on the sensor detector to preclude any non-uniformity effects. The sensor detector's linearity was verified over the dynamic range of this measurement. The measurements were performed in the AC mode (with a lock-in amplifier).

Diffuse reflectance (specular excluded) was measured with a 50 mm diameter silicon detector that had a 9 mm diameter hole in the center [19]. This detector was checked for linearity by comparing it to detector DR-10 and for uniformity by the method described in Section 3.6. With the laser radiation passing through the hole and reflected back out of the hole from one of the DRTP detectors, the diffusely reflected radiation could be detected. By increasing the distance between the two detectors, the collection angle was reduced so as to measure the radiation that had escaped through the center hole when the detectors were at the closer position. The diffuse reflectance was measured from within 1° of specular (at nearly normal incidence) to 68°.

It was found that the diffuse reflectance was approximately proportional to the specular reflectance. The estimate used was that the diffuse component was 0.009 times the value of the specular component of reflection. The upper bound on the systematic error in the absolute response calibration due to this approximation of the diffuse reflection component is negligible.

3.9) Absolute spectral response measurements

The absolute spectral response of the DRTPs was measured by comparison to an absolute detector [20, 21, 22] at 325.0, 441.6, 632.8 and 951 nm. The first two lines are from a HeCd laser and the third from a HeNe laser. The fourth line is a xenon emission line obtained from a high pressure arc lamp and interference filter. The laser lines were amplitude stabilized [17] with the experimental set-up as described in NBS Tech Note 954 [5]. The filtered image of the high pressure arc lamp was focussed through a beamsplitter simultaneously onto a monitor detector and the detectors being calibrated. The active areas of the detectors were underfilled; the image size ranged from 3 to 5 mm diameter.

In addition to the calibrations at the above mentioned wavelengths, the DRTPs were measured at 1014 and 1064 nm [23]. The first wavelength is that of a mercury emission line and the second is that of a NdYAG laser. The absolute basis for these measurements was the Electrically Calibrated Pyroelectric Radiometer (ECPR) [13, 14]. These data were not used in the interpolation process (see below), but are reported as measured.

Since these are radiant power calibrations, care was taken to insure that all the radiation was collected and that the image spot was not surrounded by appreciable scattered radiation. In the case of the laser-based measurements, this was checked by measuring the radiant power along the beam with an apertured DRTP. Radiant power variations were much less than 0.1%; therefore, the error from this effect was negligible. In the case of the arc source, the image quality was visually inspected (in the green spectral region) by passing the image through a hole in a white card and estimating the amount of scatter around the beam. By comparison with the visual appearance of the laser based measurements, the scatter observed from the arc source was estimated to be no more than 0.1%.

The absolute detectors upon which the response measurements are based are of the 100% quantum efficient type [20]. These are standards based on the silicon photodiode self-calibration or predictable quantum efficiency technique [21, 22]. The upper bound on the systematic error in the absolute response of these devices is +/- 0.2% with respect to SI base units [20, 24] in the 360 to 700 nm wavelength range.

Direct comparison to a 100% quantum efficient device was done at only 441.6 and 632.8 nm. At the uv and ir lines the comparison detector was an ECPR that previously had been calibrated with the 100% quantum efficient device [23]. The upper bound on the systematic error of the ECPR calibration, i.e. the maximum range of the variation of the correction factor is +/- 0.5%.

The worst case estimate of the standard deviation of the mean (one sigma value) at each wavelength was: 325.0 nm, 0.22% (5); at 441.6 nm, 0.07% (4); at 632.8 nm, 0.10% (5); and at 951 nm, 0.58% (5). At 1014 and 1064 nm, the estimated standard deviations of the mean were somewhat higher: 0.99% (8) at 1010 nm and 0.88% (8) at 1064 nm. The number of measurements in each set is given in parentheses.

3.10) Interpolation of the external quantum efficiency

The absolute spectral response $R(\lambda)$ in A/W is directly proportional to the external quantum efficiency $Q_{ext}(\lambda)$ in electrons/photon [21, 22] as follows:

$$R(\lambda) = Q_{ext}(\lambda) \frac{\lambda}{1239.5} \qquad (4)$$

where the wavelength λ is in nm units. The external quantum efficiency is related to the internal quantum efficiency via the reflection loss, $r(\lambda)$,

$$Q_{ext}(\lambda) = [1 - r(\lambda)]\ Q_{int}(\lambda). \qquad (5)$$

The spectral variation of reflectance was calculated as follows. The value of the reflectance as measured at 441.6 nm was used with the literature values of the indices of refraction of SiO_2 [25] and Si [26] in the Fresnel reflection equations [27] to calculate the thickness of the oxide layer. The SiO_2 thicknesses obtained ranged from 115 to 122 nm.

The calculated values of the SiO_2 thickness were used in the Fresnel equations to calculate the spectral variation of the reflectance at 10 nm intervals over the range from 250 to 960 nm. The reflectance curves for 115 and 122 nm thickness of SiO_2 on Si are shown in Fig. 9.

The effect on absorptance (one minus the reflectance) due to a 2 nm error in a 120 nm thick oxide is shown in Fig. 10. It can be seen in Fig. 10 that the fitting errors in the absorptance are expected to be greatest in the blue and uv.

Using the values of the oxide layer thicknesses obtained from the 441.6 nm data, the reflectances at 325.0 and 632.8 nm were calculated to check the goodness of the fit. Since the SiO_2 layer acts as an antireflection coating in the red-visible region, the agreement was quite good at 632.8 nm. The largest difference in terms of the effect on absolute response in this region was 0.5%. However, the opposite is true in the blue-visible and ultraviolet. The reflection is near a maximum so that an error in the estimation of the oxide thickness has a more pronounced effect. At 325.0 nm the largest difference in the reflectance fitting was 3.5% in terms of the absolute response.

From the measurements of the absolute spectral response and the calculated values of the spectral reflectance, the internal quantum efficiency of each DRTP was obtained at 325.0, 441.6, 632.8, and 951 nm.

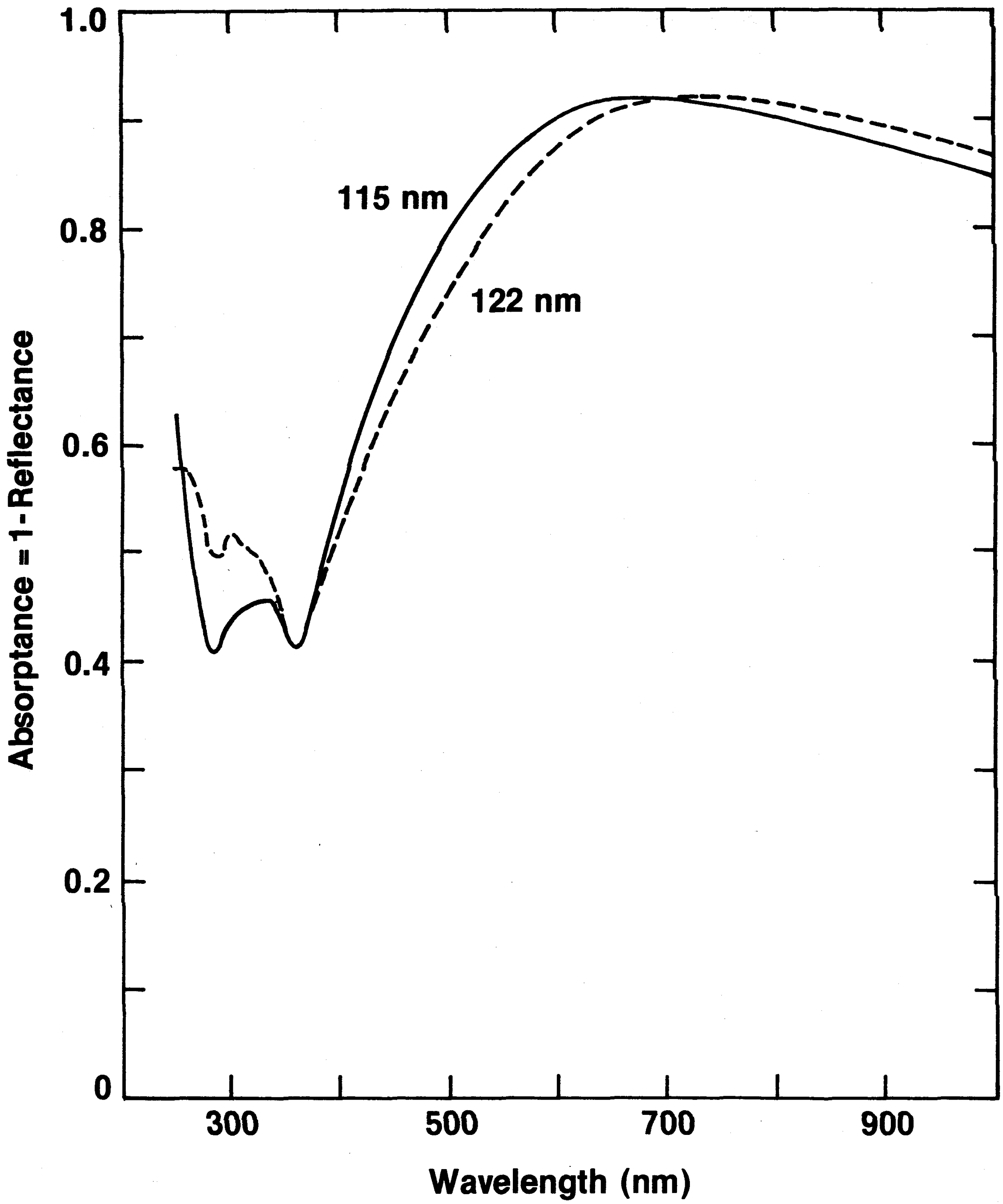


Fig. 9. Spectral absorptance of the DRTP photodiodes.

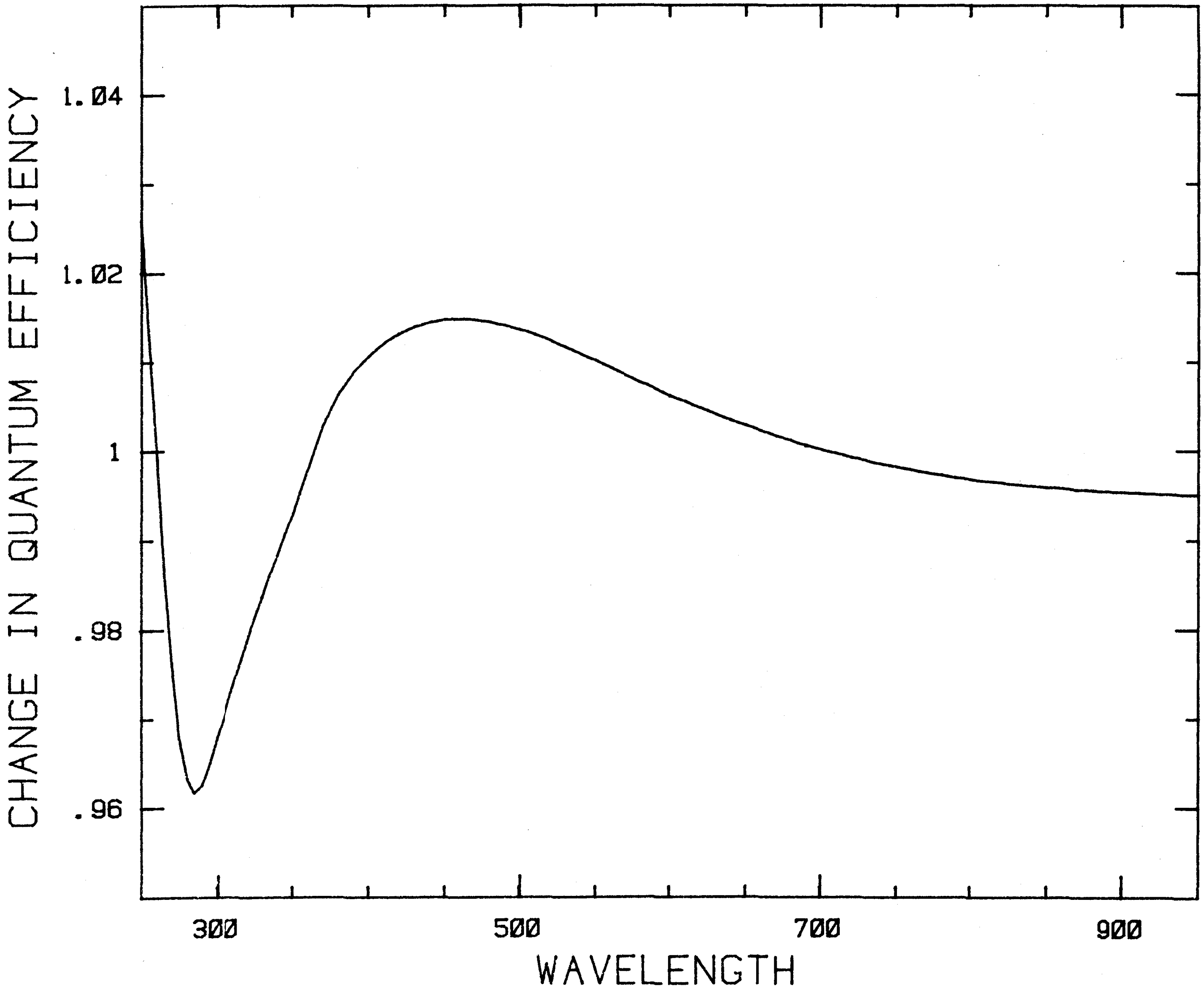


Fig. 10. Change in quantum efficiency (absorptance) due to 2 nm change in the thickness of the SiO_2 layer.

The experimental values of the internal quantum efficiency were used to determine the P, T and L parameters in the theoretical model [28] of the internal quantum efficiency, $e(\lambda)$.

$$e(\lambda) = P + \frac{(1 - P)}{\alpha(\lambda)\ T} [1 - \exp\{-\alpha(\lambda)T\}] - \frac{h}{\alpha(\lambda)\ L^2} \qquad (6)$$

Here α is the wavelength dependent absorption coefficient of silicon. From the literature values of the wavelength dependence of α [26], the spectral dependence of e was calculated at 10 nm intervals from 250 to 960 nm.

The quantum yield of silicon (production of electron-hole pairs per photon absorbed) is unity in the 360 to 960 nm region; however, it becomes greater than unity below 360 nm. In the ultraviolet region of the spectrum from 250 to 360 nm, the values of the quantum yield of silicon as measured by Wilkinson, Farmer, and Geist [29] were used to calculate the internal quantum efficiency. The upper bound on the systematic error contribution to the uncertainty of the absolute response is +/- 3% at 250 nm and decreasing to effectively zero at 360 nm.

From the spectral variation of the reflectance and internal quantum efficiency, the external quantum efficiency was calculated at 10 nm intervals from 250 to 960 nm. These values were then converted to the conventional units of absolute spectral response, A/W. The resulting quantum efficiency curves are shown for DR-14 in Fig. 11 and for DR-15 in Fig. 12. These two DRTPs were at the extremes of the fitting parameters, that is, their SiO_2 thicknesses and P, T, and L values differed by the greatest amounts.

The accuracy of the interpolation (and extrapolation) was checked experimentally by measuring the absolute spectral response of the DRTPs at several laser lines and atomic (mercury and xenon) emission lines.

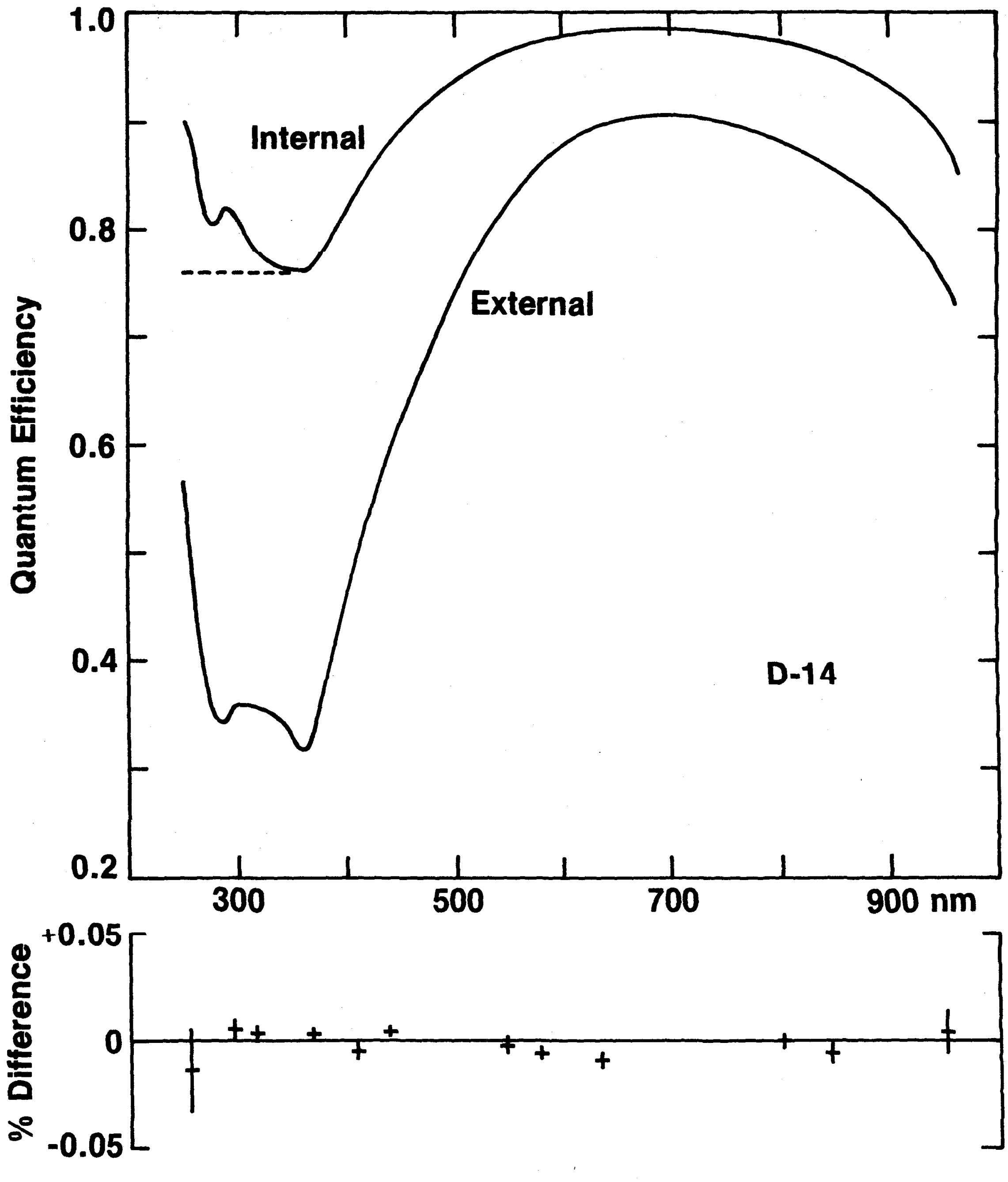


Fig. 11. Calculated quantum efficiency of DR-14 (upper curve) and comparison to measured values (lower curve).

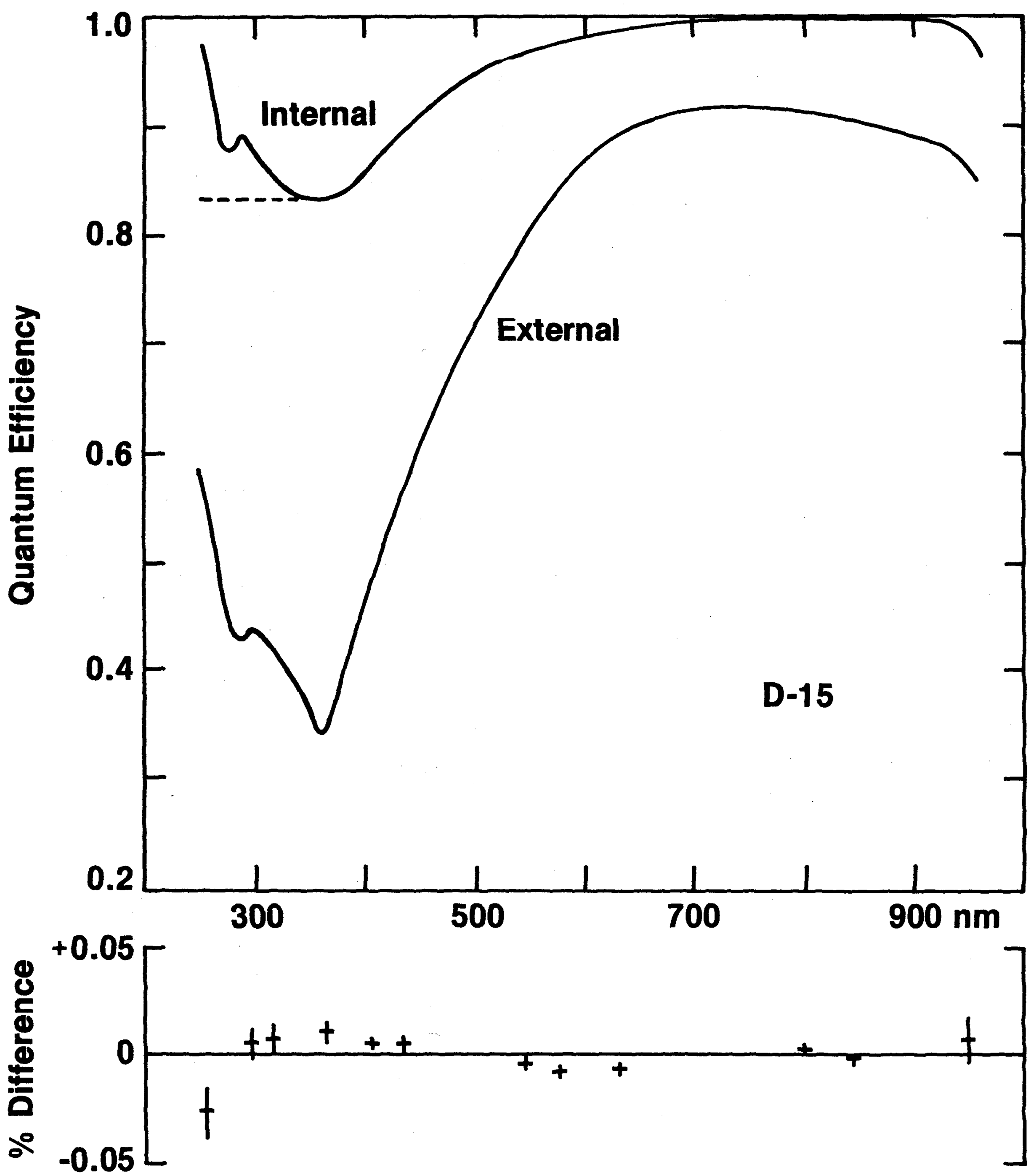


Fig. 12. Calculated quantum efficiency of DR-15 (upper curve) and comparison to measured values (lower curve).

The absolute detector in these measurements was the ECPR or the 100% quantum efficient detector depending on the wavelength (see Section 3.9). The results at several laser lines including those used in the interpolation are shown for DR-14 and DR-15 in Table 3.

TABLE 3

Difference between measured and interpolated responsivities

Wavelength	DR-14	DR-15
325.0 nm	-0.8%	-0.4%
406.7	+0.9	+0.3
441.6	+0.2	+0.1
568.2	-0.7	-0.4
632.8	-0.9	-0.7
799.3	-0.1	+0.1

The results in Table 3 as well as the results of the measurements at the atomic emission lines are shown in the bottom portion of Figs. 11 and 12. The error bars on the data points represent the three sigma precision of the DRTP-absolute comparison measurements.

3.11) <u>Spectral comparator measurements - quality control</u>

In addition to the absolute detector based measurements discussed at the end of the last Section, the responsivities of all the DRTPs were intercompared by means of a conventional (monochromator-based) spectral comparator. See reference [10] for a description of this type of instrument. The results of those measurements are shown in Fig. 13.

Here DR-15 was chosen as the "standard" detector and the responsivity of the other DRTPs calculated with respect to DR-15. The

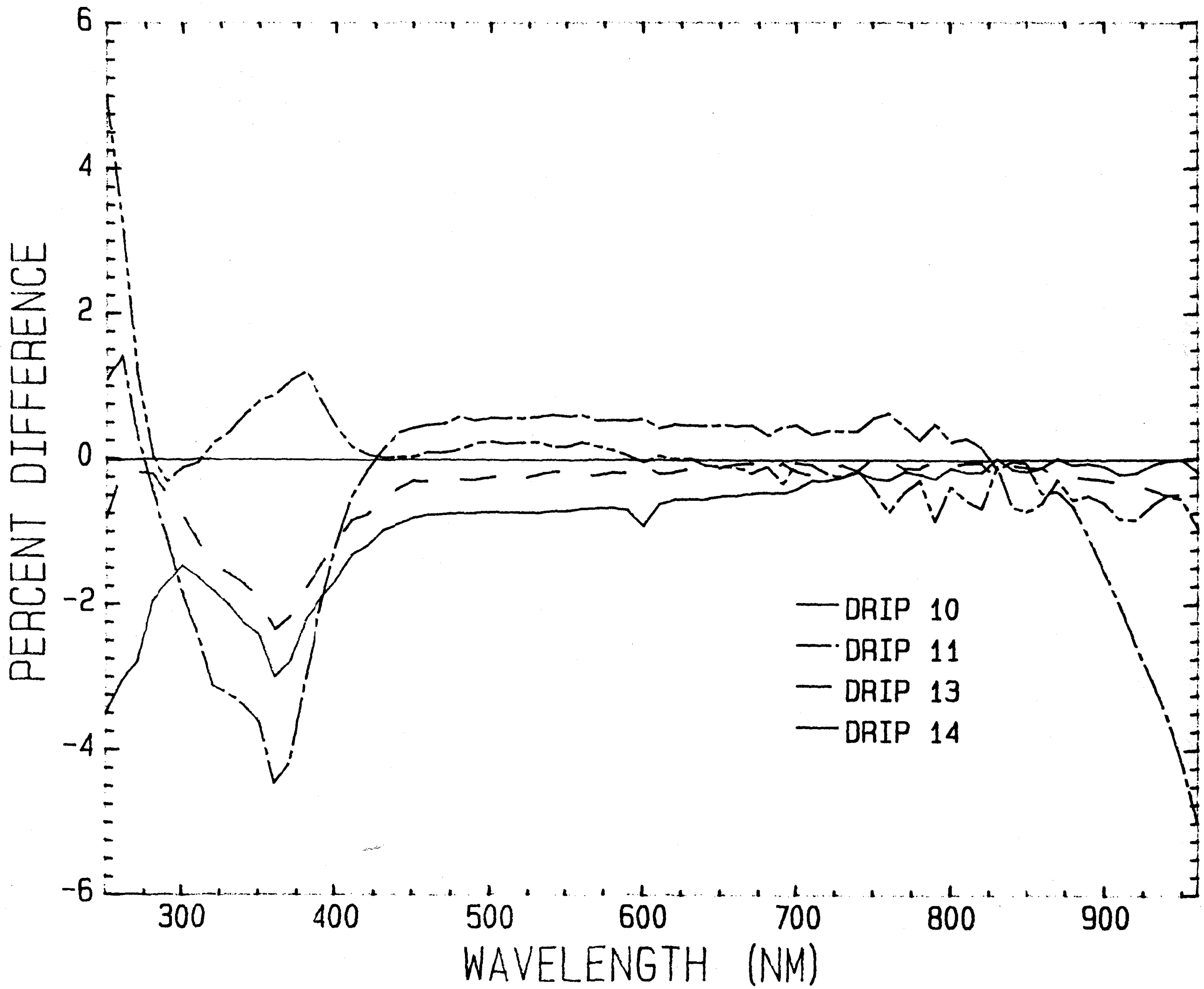


Fig. 13. Spectral comparator measurements versus DR-15 as the standard.

calculated DRTP responsivity was then compared to the responsivity as determined by the interpolation procedure described in the previous Section. The percent differences between the comparator measurements based on DR-15 and the actual calibration of each DRTP are plotted in Fig. 13.

3.12) Estimation of the overall uncertainty

The verification of the estimation of the uncertainties of the DRTP calibrations is contained in Table 3 and Figs. 11, 12 and 13. The major components of the uncertainty at short wavelengths are the quantum yield of silicon (peak at 250 nm) and the reflectance fitting (peaks around 300 and 450 nm). In the visible region of the spectrum all the contributions to the uncertainty go to a minimum. At long wavelengths the uncertainty is dominated by the imprecision of the response comparison and the non-uniformity effects. A summary of the uncertainty estimates for the DRTPs is presented in Table 4.

TABLE 4

Summary of the DRTP Uncertainty Estimates

Wavelength (nm)	250 to 390	400 to 490	500 to 850	860 to 960	1014	1064
QED accuracy	---	0.2%	0.2%	---	---	---
ECPR accuracy	0.5%	---	---	0.5%	0.5%	0.5%
Response comparison precision*	0.7	0.2	0.3	1.7	3.0	2.7
Silicon quantum yield	3.0	0.0	0.0	0.0	---	---
Reflectance fitting	4.0	1.5	0.5	0.7	---	---
Quantum efficiency fitting	1.0	0.5	0.2	0.5	---	---
Non-uniformity (DR-14)	3.0	1.0	0.5	1.0	5.0 (20	5.0 20)
Temperature fluctuations	0.0	0.0	0.0	0.0	0.2	0.2
Linearity, 0.1 mW and below, % per decade except DR-14, see Section 3.5)	(250 to 700 nm, 0.1; 700 to 1064 nm, 0.3:					
TOTAL (quadrature addition) (DR-14)	6.0%	1.9%	0.8%	2.2%	5.9% (20%	5.7% 20%)

* This is a three sigma estimate of the precision (three times the standard deviation of the mean). All the other uncertainty estimates are upper bounds of a systematic error and are considered to have the nature of a three sigma confidence limit.

References

1) G. A. Uriano, E. L. Garner, R. K. Kirby, and W. P. Reed eds. "NBS Calibration Services User's Guide 1986-88", Natl. Bur. Stand. (U. S.) Spec. Publ. 250 (1986).

2) M. A. Lind and E. F. Zalewski "Silicon Photodetector Instabilities in the UV" Appl. Opt. 15, 1377 (1976).

3) K. Mohan, A. R. Schaefer, and E. F. Zalewski, "Stability and Temperature Characteristics of Some Silicon and Selenium Photodetectors" NBS Tech. Note 594-5, (1973).

4) F. Grum and J. Cameron, "Detector Intercomparison Results" Electro-Optical Systems Design, (Kiver Publications Inc., 222 W. Adams, Chicago, IL; November, 1974) p. 82.

5) J. Geist, M. A. Lind, A. R. Schaefer, and E. F. Zalewski, "SPECTRAL RADIOMETRY: A New Approach Based on Electro-Optics" NBS Tech. Note 954, (1977).

6) M. A. Lind, "Measurement of the Absolute Spectral Response of Detectors", Proc. Electro-Optics System Design Conf. (Industrial and Scientific Conference Management, Chicago, 1976) p. 55.

7) E. F. Zalewski and M. A. Lind,"Improving the Accuracy of Radiant Power Measurments Based on Photodetector Instrumentation", Symp. on Bio. Effects and Meas. of Light Sources, D. G. Hazzard, Ed. HEW Publication (FDA) 77-8002 (U. S. Government Printing Office, Washington, DC, 1977) p. 117.

8) A. R. Schaefer and E. F. Zalewski, "Measurement of the Energy Irradiance from Single Pulse Sources" NBS Tech. Note 935, (1977).

9) M. A. Lind, E. F. Zalewski, and J. B. Fowler, "The NBS Detector Response Transfer and Intercomparison Package: The Instrumentation", NBS Tech. Note 950, (1977).

10) CIE Publication No. 64 (1984) "Determination of the Spectral Responsivity of Optical Radiation Detectors". To obtain a copy of this publication contact Mr. Robert A. McCully, North American Philips Lighting Corp., Philips Square, CN6800, Somerset, NJ 08873-6800; phone (201) 563-3471.

11) A. Corrons and E. F. Zalewski, "Detector Spectral Response from 350 to 1200 nm Using a Monochromator Based Spectral Comparator", NBS Tech. Note 988, (1978).

12) W. R. Blevin and W. J. Brown, "Black Coatings for Absolute Radiometers", Metrologia, 2, 139 (1966).

13) J. Geist and W. R. Blevin, "Chopper-Stabilized Null Radiometer Based on an Electrically Calibrated Pyroelectric Detector", Appl. Opt. 12, 2532 (1973).

14) W. M. Doyle, B. C. McIntosh, and J. Geist, "Implementation of a System of Optical Calibration Based on Pyroelectric Radiometry", Opt. Engr. 15, 541 (1976).

15) A. R. Schaefer, E. F. Zalewski, M. A. Lind, and J. Geist, "Linearity Studies on Silicon Photodiodes", Proc. Electro-Optics System Design Conf.(Industrial and Scientific Conference Management, Chicago, 1977) p. 459.

16) A. R. Schaefer, E. F. Zalewski, and J. Geist, "Silicon Detector Nonlinearity and Related Effects", Appl. Opt. 22, 1232 (1983).

17) J. B. Fowler, M. A. Lind, and E. F. Zalewski, "A Servo Controlled Electro-Optic Modulator for cw Laser Power Stabilization and Control", NBS Tech. Note 987, (1979).

18) These measurements were performed by Mr. Ralph Veale of the Mechanical Processes Division of NBS.

19) E. F. Zalewski, J. Geist, and R. C. Willson "Cavity Radiometer Reflectance", Proc. of the SPIE, 196, 152 (1979).

20) E. F. Zalewski and C. R. Duda, "Silicon Photodiode Device with 100% External Quantum Effiency", Appl. Opt. 22, 2867 (1983).

21) E. F. Zalewski and J. Geist, "Silicon Photodiode Absolute Spectral Response Self-Calibration", Appl. Opt. 19, 1214 (1980).

22) J. Geist, E. F. Zalewski, and A. R. Schaefer "Spectral Response Self-Calibration and Interpolation of Silicon Photodiodes", Appl. Opt. 19, 3795 (1980).

23) E. F. Zalewski and M. Rufino, "Silicon Photodiode Self-Calibration as a Basis for Radiometry in the Infrared", Proc. of the SPIE, 308, 2 (1981).

24) L. P. Boivin and F. T. McNeely, "Electrically Calibrated Absolute Radiometer Suitable for Measurement Automation", Appl. Opt. 25 554 (1986).

25) I. H. Malitson, "Interspecimen Comparison of the Refractive Index of Fused Silica", J. Opt. Soc. Am. 55, 1205 (1965).

26) H. R. Philipp, "Influence of Oxide Layers on the Determination of the Optical Properties of Silicon", J. Appl. Phys. 43, 2835 (1972), and personal communication.

27) M. Born and E. Wolf, "Principles of Optics" (Pergamon Press, NY, 1964), 3rd ed., p. 61.

28) J. Geist and E. F. Zalewski, "The Quantum Yield of Silicon in the Visible", Appl. Phys. Lett. 35, 503 (1979).

29) F. J. Wilkinson, A. J. D Farmer, and J. Geist "The Near Ultraviolet Quantum Yield of Silicon", J. Appl. Phys. 54, 1172 (1983).

Appendix A

Intercomparison Format

On the following pages are the instructions for the intercomparison phase of the detector response transfer program. This intercomparison consists of three parts: a wavelength accuracy measurement, a scattered light measurement, and spectral response transfer measurements in the ultraviolet, visible and infrared spectral regions.

The detailed information requested on the first page will be kept confidential and will be used only by NBS staff members to elucidate possible systematic errors in the measurements. The data requested on the subsequent pages will likewise be kept confidential. When the results of these intercomparisons are prepared for publication the laboratories will not be identified except by code numbers.

Description of Instrumentation

NBS Detector Number DR- ________Date:________

Laboratory ____

Person(s) to contact regarding measurements: _________________

______________________________Phone Number: (   )___________

Address: ____

____

Monochromator:

/_/Grating /_/Prism /_/Interference Filters /_/Other, identify

/_/Single Monochromator /_/Double Monochromator

If Double, /_/Additive or /_/Subtractive Dispersion?

Bandpass (full width at half-maximum). Is the bandpass the same throughout the spectrum? If not please identify the wavelength or clarify below.

____

Wavelength calibration (which lines) _________________________

Size and Shape of Output Beam on Detector Surface ____________

Clarification of above information or other pertinent instrument characteristics

____

Light Source:
Description of light source (i.e. incandescent strip lamp, mercury arc, etc.)

____

Was an image of the light source focussed or diffused on the entrance slit of the monochromator? __________________________

Did you use a monitor detector to adjust the intercomparison data for possible light source fluctuations?__________________________

Wavelength Accuracy Intercomparison

NBS Detector Number DR- _____ Date: ____________

Laboratory ____

Wavelength Calibration Filter Numbers WV-________ and WR-______

The nominal peak transmission wavelength is 410 nm for the WV filter and 940 nm for the WR filter. You are asked to identify the wavelengths of the 20% transmission points on both of these filters. That is, measure the detector output both with and without the filter at the smallest wavelength intervals you can obtain. Compute the following ratio

$$T(l) = \frac{\text{Filtered Detector Output}}{\text{Bare Detector Output}}$$

then report the two wavelengths (for each filter) at which T = 0.200. Please repeat this procedure at three different times (different days if possible) and preferably after some change in the instrument such as switching gratings.

For WV, T = 0.200 at:

WAVELENGTHS

RUN1	RUN 2	RUN 3
____________	____________	____________
____________	____________	____________

For WR, T = 0.200 at:

WAVELENGTHS

RUN1	RUN2	RUN 3
____________	____________	____________
____________	____________	____________

Scattered Light Intercomparison

NBS Detector Number DR- ________ Date: ________________

Laboratory ____

The three absorbing glass filters have been selected to enable a test of out-of-band radiation in three separate regions: the uv from 200 to 350 nm (SV filter), the visible from 450 to 650 nm (RT filter), and the ir from 750 to 1150 nm (SR filter). You are asked to first measure the output of your monochromator in each of these regions using the bare detector. Then repeat the measurements with the appropriate filter in place and the gain set at 10^{-7} A/V or as high as possible.

	Bare Detector		Filter	Filtered Detector	
Wavelength	Output	Gain	Number	Output	**Gain**
200 nm	______	____	SV-____	______	___
250	______	____	SV-____	______	___
350	______	____	SV-____	______	___
450	______	____	RT-____	______	___
550	______	____	RT-____	______	___
650	______	____	RT-____	______	___
750	______	____	SR-____	______	___
850	______	____	SR-____	______	___
950	______	____	SR-____	______	___
1050	______	____	SR-____	______	___
1150	______	____	SR-____	______	___

Visible Response Transfer Intercomparison

NBS Detector Number Dr-______________ Date: ____________

Laboratory ____

Filter Numbers SV-__________ and SR-______________

The SV and SR filters when used together on the detector result in a response function limited to the visible spectral region. The order of stacking the filters may be significant (because of interreflections) so put the SV filter in place first, then the SR filter over that. You are asked to measure the absolute spectral response of the filtered detector, basing the measurements on the values of response as supplied for the bare detector. Please repeat these measurements at three different times (different days if possible) in order that an estimate of your precision can be made.

ABSOLUTE RESPONSE (A/W)

WAVELENGTH	RUN 1	RUN 2	RUN 3
450 nm	________	________	________
475	________	________	________
500	________	________	________
525	________	________	________
550	________	________	________
575	________	________	________
600	________	________	________
625	________	________	________
650	________	________	________
675	________	________	________

Has a correction been made for the effect of the monochromator bandpass?

____

Was the aperture in place between the detector and the filters? filters?

____

UV and IR Response Transfer Intercomparison

NBS Detector Number Dr-_____________ Date: ____________

Laboratory ____

Filter Number RT-____________

The RT filter when placed on the detector results in a two part response function: one section in the uv and one in the ir. You are asked to measure at three different times the detector output both with and without the filter in place. Then report the response transfer ratio:

$$T(l) = \frac{\text{Filtered Detector Output}}{\text{Bare Detector Output}}$$

RESPONSE TRANSFER RATIO

WAVELENGTH	RUN 1	RUN 2	RUN 3
320 nm	________	________	________
340	________	________	________
360	________	________	________
380	________	________	________
400	________	________	________
700	________	________	________
800	________	________	________
900	________	________	________
1000	________	________	________
1100	________	________	________

FORM NBS-443
(REV. 11-65)

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
Gaithersburg, MD 20899

REPORT OF CALIBRATION

of
Photodetector Absolute Spectral Response

Requested by:
Company Name
Company Address

(See your purchase order number ###### dated: .)

The NBS detector response transfer radiometer [ ] No. DR- has been supplied to the above-mentioned laboratory for the purpose of transferring the NBS scale of detector spectral response. The responsivity in amps/watt of this radiometer is presented in the accompanying table as a function of wavelength. A second table lists the estimated uncertainty relative to absolute (SI) units as a function of wavelength. Also included is the measured area of the aperture supplied with the radiometer to enable measurements of radiant power density (irradiance).

The absolute spectral response of the NBS detector response transfer radiometer is based on electrical power versus radiant power substitution measurements [2,3] and on the silicon photodiode self-calibration method [4,5]. Amplitude stabilized cw lasers [6] and a HgXe arc lamp with narrow-band filters were used as the monochromatic sources. The incident radiation was normal to the detector surface and underfilled the active area. Each time the radiometer is returned to NBS, a measurement of the absolute spectral responsivity is performed at a few key wavelengths to verify the stability of the calibration. For maximum accuracy in the detector response transfer measurements, detector uniformity must be considered. It is recommended that the incident radiation be restricted to the central 8 mm diameter area of the detector. Further recommendations for performing detector response transfer measurements can be obtained in reference [7].

Prepared by:

Jeanne M. Houston
Radiometric Physics Division
Center for Radiation Research

Approved by:

Donald A. McSparron
Radiometric Physics Division
Center for Radiation Research

NBS Test No.:
Date:

REFERENCES:

[1] "The NBS Detector Response Transfer and Intercomparison Package: The Instrumentation," M. A. Lind, E. F. Zalewski and J. B. Fowler, NBS Technical Note 950 (1977).

[2] "Fundamental Principles of Absolute Radiometry and the Philosophy of This NBS Program (1968 to 1971)," J. Geist, NBS Technical Note 594-1 (1972); also "Comparison of the Laser Power and Total Irradiance Scales Maintained by the National Bureau of Standards," J. Geist, L. B. Schmidt and W. E. Case, Applied Optics 12, 2773 (1973).

[3] "Spectral Radiometry: A New Approach Based on Electro-Optics, " J. Geist, M. A. Lind, A. R. Schaefer, and E. F. Zalewski, NBS Technical Note 954 (1977).

[4] "Silicon Photodiode Absolute Spectral Response Self-Calibration", E. F. Zalewski and J. Geist, Applied Optics 19, 1214 (1980).

[5] "Spectral Response Self-Calibration and Interpolation of Silicon Photodiodes", J. Geist, E. F. Zalewski, and A. R. Schaefer, Applied Optics 19, 3795 (1980).

[6] "A Servo Controlled Electro-Optic Modulator for cw Laser Power Stabilization and Control," J. B. Fowler, M. A. Lind and E. F. Zalewski, NBS Technical Note 987 (1979).

[7] "Detector Spectral Response from 350 to 1200 nm Using a Monochromator Based Spectral Comparator", A. Corrons and E. F. Zalewski, NBS Technical Note 988 (1978).

NBS Test No.: 534/
Date:

Radiometer No. DR

Wavelength (nm)	Spectral Responsivity $(A \cdot W^{-1})$	Wavelength (nm)	Spectral Responsivity $(A \cdot W^{-1})$
250	0.105	640	0.462
260	0.104	650	0.471
270	0.095	660	0.481
280	0.091	670	0.490
290	0.093	680	0.500
300	0.097	690	0.508
310	0.100	700	0.517
320	0.099	710	0.526
330	0.101	720	0.534
340	0.099	730	0.541
350	0.100	740	0.549
360	0.098	750	0.555
370	0.099	760	0.562
380	0.112	770	0.569
390	0.128	780	0.575
400	0.143	790	0.581
410	0.158	800	0.588
420	0.173	810	0.594
430	0.188	820	0.599
440	0.204	830	0.605
450	0.219	840	0.610
460	0.234	850	0.616
470	0.248	860	0.621
480	0.263	870	0.626
490	0.277	880	0.631
500	0.292	890	0.636
510	0.306	900	0.640
520	0.320	910	0.646
530	0.334	920	0.650
540	0.347	930	0.653
550	0.361	940	0.654
560	0.373	950	0.654
570	0.384	960	0.649
580	0.397		
590	0.409		
600	0.422	1014	0.57
610	0.431	1064.2	0.26
620	0.442		
630	0.452		

Radiometer No. DR

ESTIMATED UNCERTAINTY IN ABSOLUTE RESPONSE MEASUREMENTS

Wavelength	
250nm - 390nm	± 6.0%
400nm - 490nm	± 1.9%
500nm - 850nm	± 0.8%
860nm - 960nm	± 2.2%
1014nm	± 5.9%
1064.2nm	± 5.7%

Aperture Dimensions

Area: 0.5150 ± 0.0005 cm^2

Distance from aperture plane to front of holder: 4.85 ± 0.05 mm