NBS Measurement Services:

Spectral Radiance Calibrations

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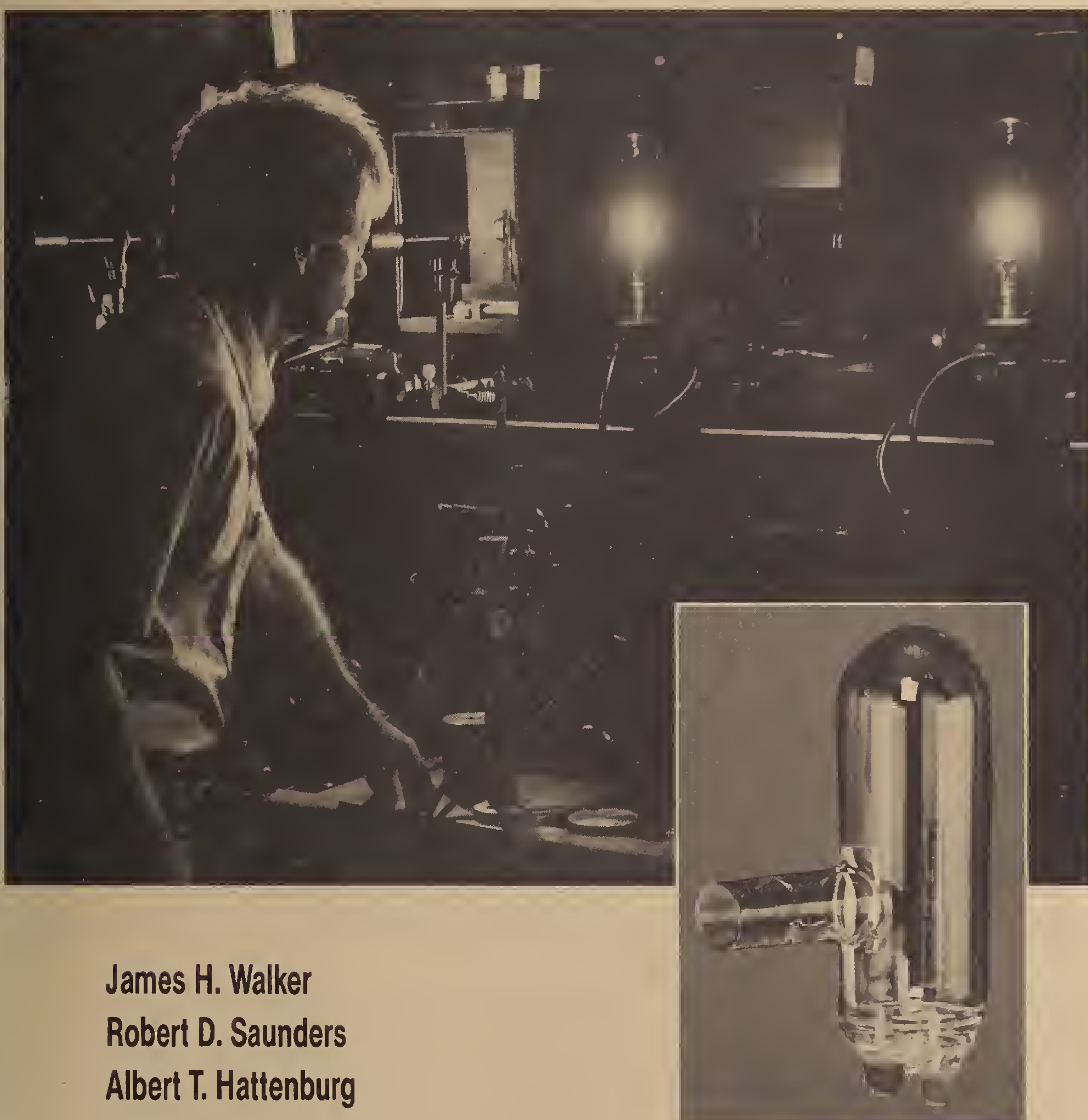

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U.S. Department of Commerce
National Bureau of Standards

Center for Radiation Research

The Center for Radiation Research is a major component of the National Measurement Laboratory in the National Bureau of Standards. The Center provides the Nation with standards and measurement services for ionizing radiation and for ultraviolet, visible, and infrared radiation; coordinates and furnishes essential support to the National Measurement Support System for ionizing radiation; conducts research in radiation related fields to develop improved radiation measurement methodology; and generates, compiles, and critically evaluates data to meet major national needs. The Center consists of five Divisions and one Group.

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- Radiation Chemistry and Chemical Dosimetry
- Neutron Measurements and Research
- Neutron Dosimetry
- Radioactivity
- X-Ray Physics
- Dosimetry

Nuclear Physics Group

Engages in forefront research in nuclear and elementary particle physics; performs highly accurate measurements and theoretical analyses which probe the structure of nuclear matter; and improves the quantitative understanding of physical processes that underlie measurement science.

NBS MEASUREMENT SERVICES: SPECTRAL RADIANCE CALIBRATIONS

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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 250-1), NBS Measurement Services: Spectral Radiance Calibrations, by J. H. Walker, R. D. Saunders, and A. T. Hattenburg, is the first to be published in this new series of special publications. It covers the calibration of the spectral radiance of tungsten ribbon filament lamps over the wavelength range of 225 to 2400 nm (see test numbers 39010C-39030C 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.

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ABSTRACT: This report describes the measurement methods and instrumentation used in the realization and transfer of the NBS scale of spectral radiance. The application of the basic measurement equation to both blackbody and tungsten strip lamp sources is discussed. The polarizance, spectral responsivity function, linearity of response and "size-of-source effect" of the spectroradiometer are described. The analysis of sources of error and estimates of uncertainty are presented. The assigned uncertainties in spectral radiance range from about 1.75% at 225 nm to 0.25% at 2400 nm.

KEY WORDS: calibrations; blackbody; response linearity; slit-scattering function; spectral radiance; standards.

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INTRODUCTION

Spectral radiance, denoted L_λ, is defined as the radiant flux at a given point, direction, and wavelength per unit of projected area, solid angle, and wavelength interval. Mathematically,

$$L_\lambda = d^3\Phi/(dA\cdot\cos\theta\cdot d\omega\cdot d\lambda) \qquad (1)$$

where Φ is the radiant flux, A is the surface area at that point, θ is the angle between the normal to the surface and the direction of propagation, ω is the solid angle about the direction subtended at A, and λ is the wavelength. Spectral radiance is the basic quantity for specifying the distribution of radiant flux relative to position, direction, and wavelength, and all other classical radiometric quantities may be derived from it. The National Bureau of Standards (NBS) issues lamp standards of spectral radiance calibrated at 34 wavelengths over the spectral range 225 to 2400 nm. These lamp standards are designated in NBS Special Publication 250 as items 39010c, 39020c, and 39030c (former designations 7.5b, 7.5c and 7.5d respectively).

The NBS scale of spectral radiance is based upon the radiant flux emitted by a blackbody of known temperature. In 1960, Stair [1] developed tungsten strip lamp standards of spectral radiance in the 250 to 2600 nm spectral range by comparison to blackbody sources, whose temperature was measured with visual optical pyrometers. Estimated accuracies ranged from 8% at 250 nm to 3% at 2600 nm. In 1965, Kostkowski [2] developed more accurate lamp standards in the 210 to 850 nm range, using a spectroradiometer which doubled as a photoelectric pyrometer. The pyrometer was calibrated in accordance with the definition of the International Practical Temperature Scale [3]. A variable temperature blackbody, operable at temperatures up to about 2700 K, was used as the comparison source, and all radiometric matches were made between sources of nearly equal spectral radiance (null measurement). The present NBS spectral radiance scale derives from these procedures and instrumentation, but has undergone many refinements: determination of the spectroradiometer response linearity allows accurate comparison of unequal sources, the temperature of the variable temperature blackbody is determined by nearly direct comparison to the gold point blackbody, the wavelength range has been extended to 2400 nm, accuracy estimates have been more rigorously evaluated, and the instrument has been incorporated into an automated calibration facility, utilizing a computer for operational control, data acquisition, and data reduction. This report is a detailed description of the present scale realization and its associated uncertainties.

SCALE DERIVATION AND TRANSFER: A GENERAL DESCRIPTION

Planck's law defines the spectral radiance L_λ of an isothermal cavity, or blackbody, as

$$L_\lambda = c_1 / \pi \cdot n^2 \cdot \lambda^5 \cdot \{[\exp(c_2 / n \cdot \lambda \cdot T)] - 1\} \quad (W/cm^3 \cdot sr) \qquad (2)$$

where $c_1 = 3.7418 \cdot 10^{-12}$ $(W \cdot cm^2)$ and $c_2 = 1.4388$ $(cm \cdot K)$ are the first and second radiation constants, n is the refractive index of air, λ (cm) is the wavelength in air and T is the thermodynamic temperature (K). For a blackbody at the temperature of equilibrium between melting and freezing gold (gold point), the temperature is defined as 1337.58 K on the International Practical Temperature Scale (the best estimate of the thermodynamic temperature) [3]. In principle, such a blackbody establishes a spectral radiance scale, but the energy is too weak at wavelengths below about 500 nanometers for practical use. Measurement of the ratio of spectral radiance of the gold point blackbody to that of another blackbody at known wavelength determines the temperature of the second blackbody, and therefore its spectral radiance at any wavelength. These values can be transferred to other sources by direct comparison at selected wavelengths, thereby establishing a practical scale of spectral radiance.

The ratio of spectral radiance of two sources is deduced from the corresponding ratio of signals from a linear spectroradiometer set at a selected wavelength. For each source, the resulting signal is [4]

$$S = \int_{\Delta\lambda} \int_A \int_\omega R(\lambda_0, \lambda) \cdot L_\lambda \cdot \cos\theta \cdot d\omega \cdot dA \cdot d\lambda \qquad (3)$$

where $R(\lambda_o,\lambda)$ is the spectral responsivity function of the spectroradiometer and depends on the instrument wavelength setting λ_o and on the wavelength λ of the measured radiation, L_λ is the spectral radiance of the source, $\cos\theta \cdot d\omega$ is an element of projected solid angle, and dA is an element of source target area. In general, both $R(\lambda_o,\lambda)$ and L_λ vary with ω, A, λ, and state of polarization. Each element of flux is weighted by the corresponding value of the responsivity. Thus the indicated spectral radiance is an instrument-weighted average which may vary from instrument to instrument, and $R(\lambda_o,\lambda)$ must be determined over the spectral range of the spectroradiometer.

When the sources being compared are both blackbodies, the spectral radiance is unpolarized and is uniform over ω and A. Thus the responsivity weighting over these parameters is the same for both sources, so that

$$S = \int_{\Delta\lambda} L_\lambda \cdot \left[\int_A \int_\omega R(\lambda_0,\lambda) \cdot \cos\theta \cdot d\omega \cdot dA\right] \cdot d\lambda \tag{4}$$

and the ratio of signals is given by

$$S_2/S_1 = \int_{\Delta\lambda} R_a(\lambda_0,\lambda) \cdot L_{2,\lambda} \cdot d\lambda \Big/ \int_{\Delta\lambda} R_a(\lambda_0,\lambda) \cdot L_{1,\lambda} \cdot d\lambda \tag{5}$$

where $R_a(\lambda_0,\lambda)$ is the responsivity averaged over ω and A (the bracketed integral in Eqn. 4). When source 1 is the gold point blackbody, $L_{1,\lambda}$ is given by eqn 2, and the value of the integral in the denominator is determined. By estimating a temperature for the second blackbody, and inserting the corresponding expression for $L_{2,\lambda}$ from eqn. 2 in the integral in the numerator, the temperature which satisfies eqn. 5 can be found by iteration.

If the sources being compared are not both blackbodies, the spectral radiance variations over ω and A generally will not be weighted equally by the instrument responsivity, and the variation of spectral radiance over wavelength for a non-blackbody source will not be a known function. The errors due to the variations over ω and A may be minimized by making ω and A small, and treating L_λ as a weighted average $(L_\lambda)_{av.}$ over these parameters. If the two sources are operated so that their relative spectral distributions are identical over the instrument bandpass, i.e. so that

$$(L_{1,\lambda})_{av.} = K_1 \cdot D_\lambda \tag{6}$$

and

$$(L_{2,\lambda})_{av.} = K_2 \cdot D_\lambda \tag{7}$$

where D_λ is the relative spectral distribution and is the same for each source, then [4]

$$\frac{S_2}{S_1} = \frac{K_2 \cdot \int_{\Delta\lambda} R(\lambda_0,\lambda) \cdot D_\lambda \cdot d\lambda}{K_1 \cdot \int_{\Delta\lambda} R(\lambda_0,\lambda) \cdot D_\lambda \cdot d\lambda} = \frac{K_2}{K_1} = \frac{(L_{2,\lambda})_{av.}}{(L_{1,\lambda})_{av.}} \tag{8}$$

and the ratio of weighted-average spectral radiances is equal to the signal ratio. Any polarization of the non-blackbody source requires a correction to the observed signal.

These procedures are used in the realization and transfer of the NBS scale of spectral radiance. Calibration of lamp standards at wavelengths as low as 225 nm requires a blackbody temperature of about 2600 K, nearly twice the temperature of the gold point blackbody. The resultant spectral distribution mismatch occurring in the comparison of the two blackbodies requires an accurate determination of the spectral responsivity function that is used in eqn. 5. The transfer of spectral radiance from the blackbody to another source, using Eqn. 8, requires small values of ω and A, selection of a source with minimal variation in these parameters and minimal polarization, and close matching of the relative spectral distributions of the two sources. The transfers at the shortest wavelengths also require a low value for the long-wavelength wing of the spectral responsivity function to avoid large spectral scattering contributions from the visible region, where the source spectral radiances are about 10^4 times greater than in the short wavelength region. Both comparisons require a high degree of response linearity in the spectroradiometer for the valid determination of those signal ratios which depart significantly from unity.

MEASUREMENT APPARATUS

A block diagram of the measurement apparatus is shown in figure 1. The principal components of the system are:

1. Gold Point Blackbody

2. Variable Temperature Blackbody

3. Lamp sources
   a. Vacuum Lamps
   b. Gas-filled Lamps

4. Spectroradiometer
   a. Fore-optics
   b. Monochromator
   c. Detectors

5. Control and data acquisition system

1. Gold Point Blackbody.

The gold point blackbody was developed for the purpose of realizing the International Practical Temperature Scale above the gold point at NBS, and its construction and characterization have been detailed in reports of this work [5]. The estimated emissivity is 0.99999. The duration of a melt or freeze plateau is approximately 5 minutes, and the time delay between these observation periods is about 5 minutes.

2. Variable Temperature Blackbody

A schematic cross-section of the variable-temperature blackbody is shown in figure 2. The blackbody cavity is located in the central portion

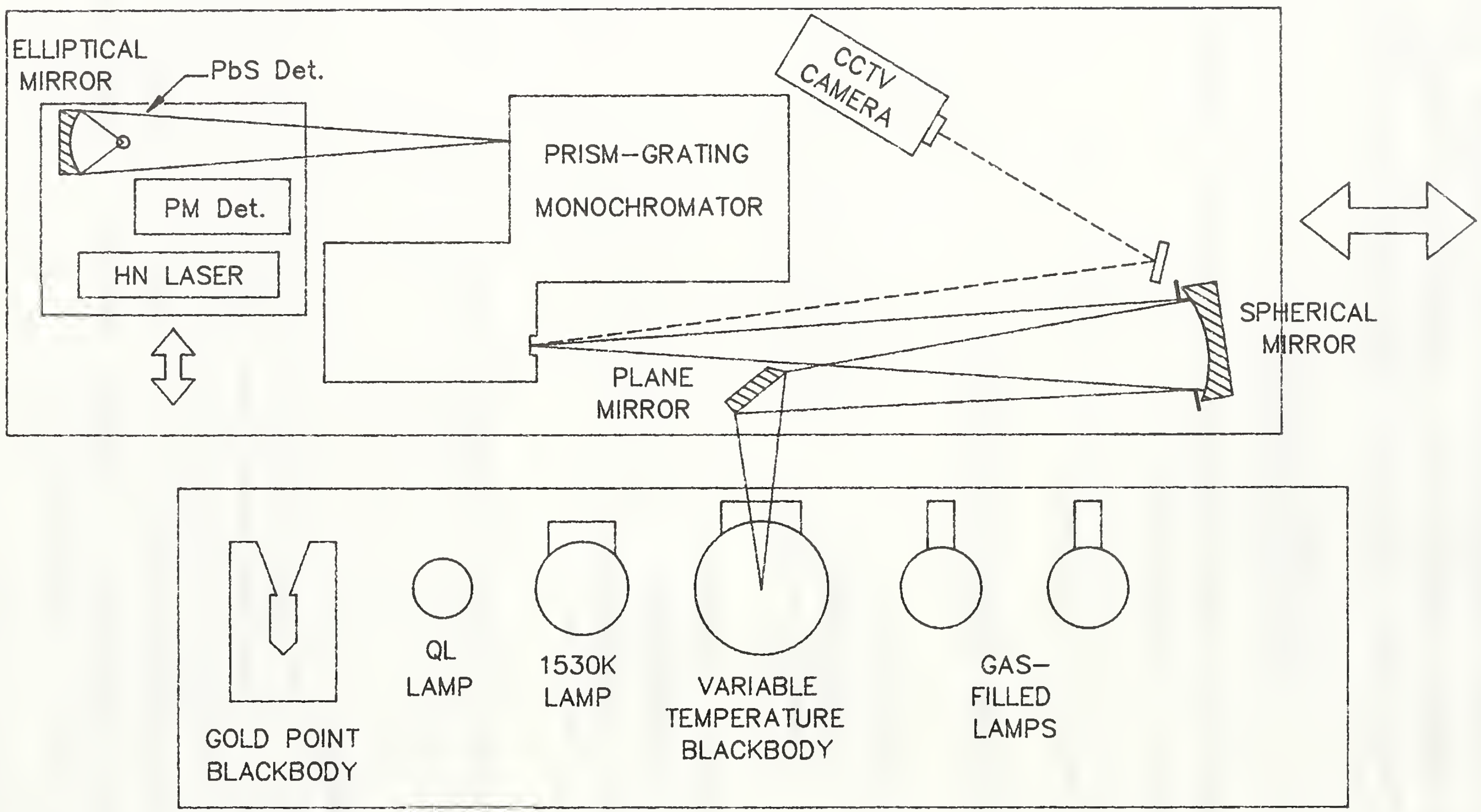

FIGURE 1. Spectral Radiance Measurement Apparatus

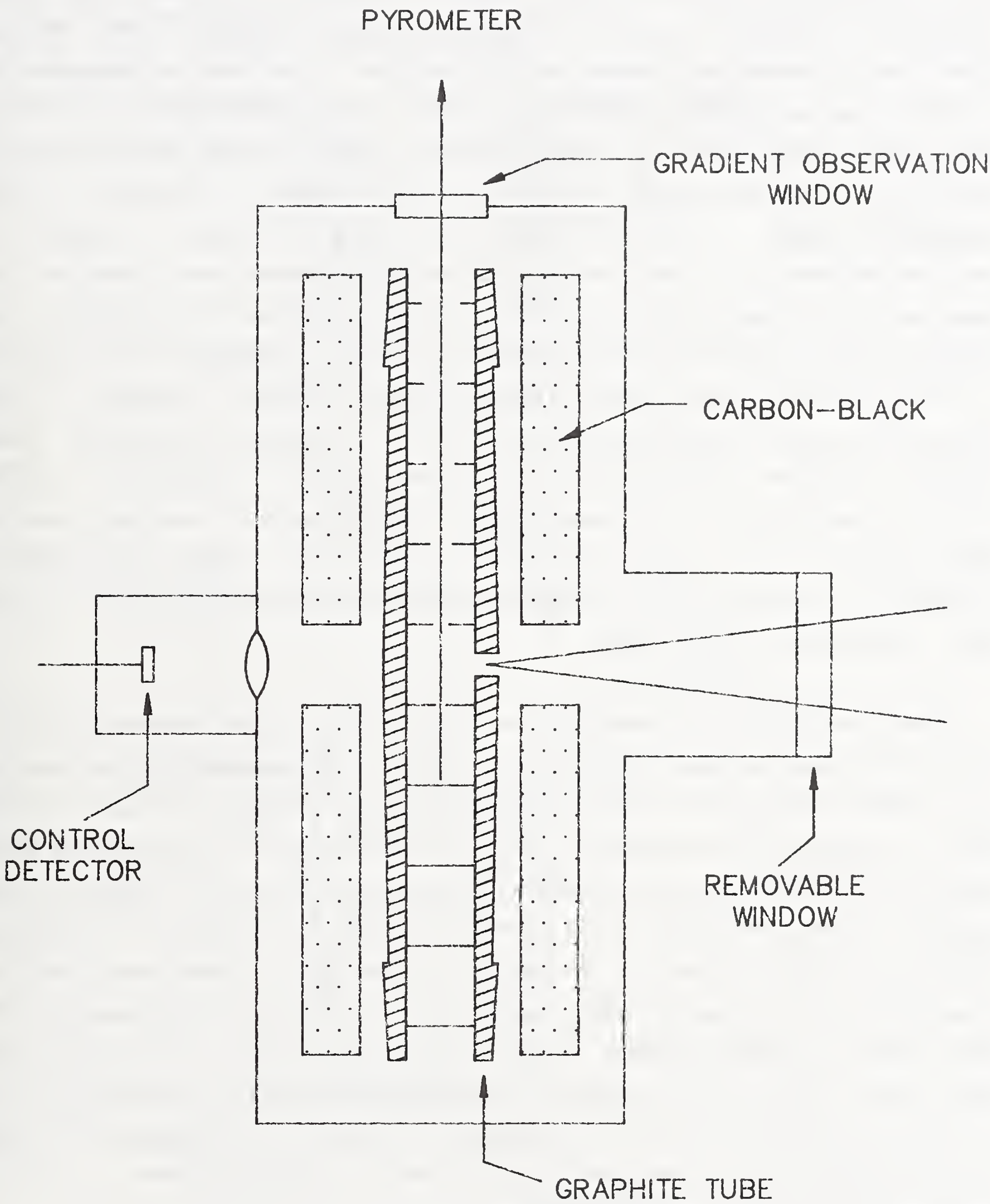

FIGURE 2. Variable Temperature Blackbody Schematic

of a high density graphite tube, which is resistively heated in an argon atmosphere. Electric current is supplied to the graphite tube through water-cooled electrical connections at each end The tube is surrounded by a double-walled graphite radiation shield, with carbon black fill between the walls. This assembly is surrounded by a water-cooled metal housing, with an observation port which can be sealed during evacuation of the atmosphere within the housing prior to flushing with argon. A window is provided at the top of the housing for visual pyrometer observation of the temperatures along the tube interior. A second window at the rear of the housing allows radiation from the rear wall of the graphite tube to fall on a silicon photodiode, whose signal provides automatic control of the saturable-reactor power supply for the tube. A germanium photodiode, whose response extends further into the infrared region, replaces the silicon cell for operation at low temperatures. The blackbody mounting provides adjustment in two angular and three translational degrees of freedom, allowing for precise positioning and radiometric scanning over the target area and the beam solid angle.

The graphite tube is about 200 mm long, with an inner diameter of about 11 mm. The outer surface is tapered to improve temperature uniformity along its length. The wall is about 4 mm thick at mid-length. A 2 mm diameter hole in the wall at this point allows for observation of the emitted flux. The tube is partitioned into small cylindrical sections by a series of thin graphite disks separated by thin graphite cylinders located at intervals along the bore. Holes in the graphite disks permit measurement of the temperatures in the middle and upper sections with a visual pyrometer. The holes vary in diameter from 6 mm for the uppermost disk to 0.75 mm for the disk below the central section. The central cylindrical section, which provides the observed flux, is 9 mm high and has a 10 mm diameter. The wall is threaded to reduce the partial reflectivity. Figure 3 shows a cross-sectional view of the central section.

The blackbody emissivity has been assessed by measurements of its solid angle subtended by the cavity opening, partial reflectivity of the graphite material [6], temperature gradients, and absorption by gases [2]. The solid angle subtended at the rear wall of the cavity by the inner edge

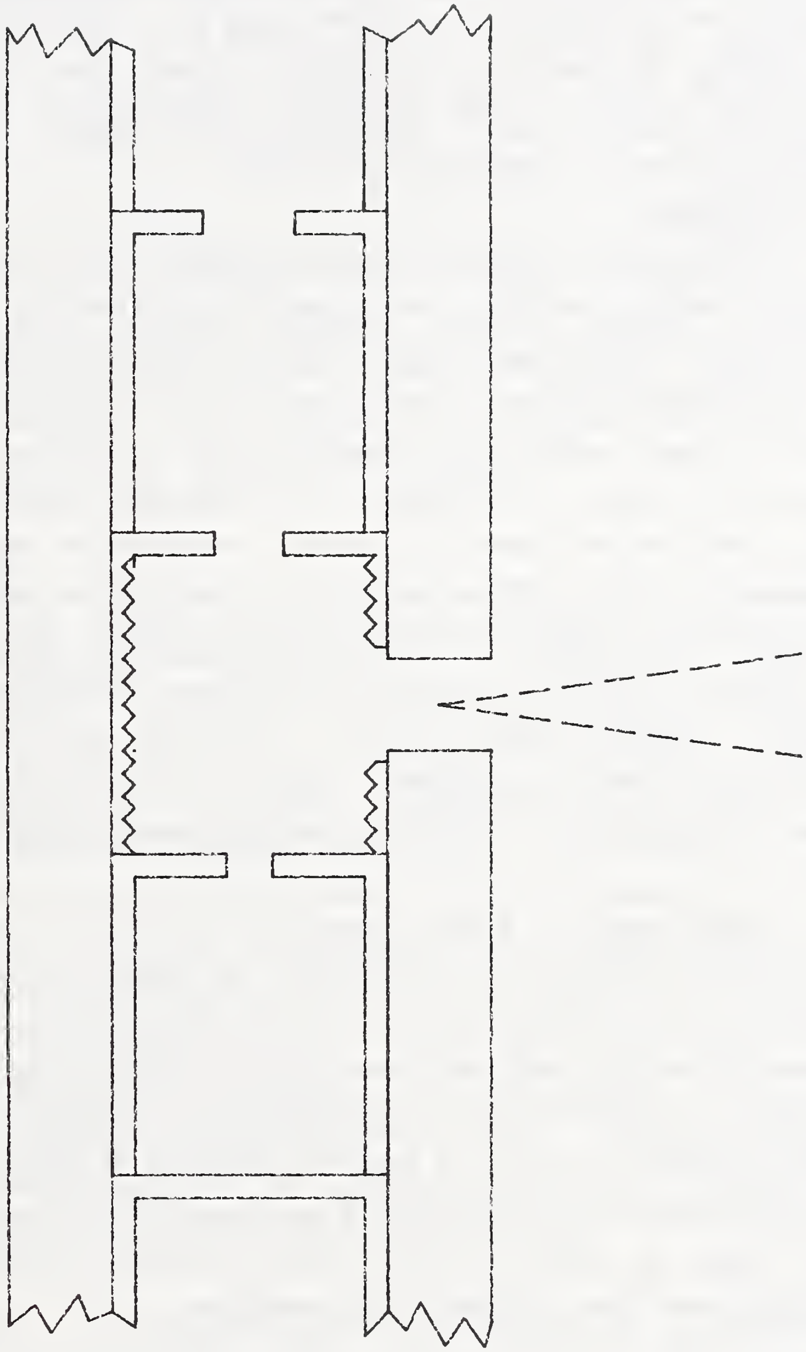

FIGURE 3. Central Section of Variable Temperature Blackbody

of the observation hole is about 0.03 sr. The measured partial reflectivity of the graphite is 0.02 sr^{-1}. The measured temperature gradient over the length of the viewing cavity is less than 1 K. Experimental investigations of possible absorption of radiation by gases has disclosed only weak absorption lines at 589 and 589.6 nm (Na) and at 766.5 nm (K). The resulting estimate of emissivity is 0.999.

3. Lamp Sources.

Tungsten-strip filament lamps are used both in the realization of the spectral radiance scale and as secondary standards for scale dissemination. Each filament has a small notch in one edge, about midway along its length, to aid in determination of the filament portion to be calibrated (target area). A small mark is placed on the rear of the lamp envelope to permit reproducible angular positioning. The lamps are rigidly fastened in source mounts which allow translation along, and rotation about, three mutually perpendicular axes. These motions are required for precise alignment and for radiometric scans in translation and rotation. The lamps are operated at constant current, provided by stabilized (0.005% regulation) DC power supplies. Manganin shunts (0.01 or 0.001 ohms) and a 5-1/2 digit voltmeter provide the current measurement. Lamps are allowed to stabilize at the set current for about 1 to 1-1/2 hours before measurements are begun.

a. Vacuum Lamps. Vacuum tungsten-strip lamps of two types are used in the scale realization to facilitate the temperature measurement of the blackbody. A Quinn-Lee lamp [7,8] is operated at a single current to produce a spectral radiance equal to that of the gold-point blackbody at 654.6 nm. A commercial vacuum lamp with plane windows [8] is operated at a single current to produce a spectral radiance of about eight times that of the gold-point blackbody at 654.6 nm (about 1530 K radiance temperature). Both lamps are stable to better than 0.02% over two hundred hours when operated under these single-level conditions.

b. Gas-Filled Lamps. Gas-filled tungsten-strip lamps are calibrated as secondary standards for dissemination of the spectral radiance scale. The lamps have a quartz window to transmit near-ultraviolet radiation. They are operated at a single current, chosen to produce a radiance temperature of about 2470 K at 654.6 nm. Prior to calibration, lamps are annealed at a radiance temperature of 2620 K (at 655 nm) for 2 to 3 hours. Each lamp is examined for the variations in spectral radiance with time, with position within the central area, and with angle of emission. The amount and orientation of polarization are also determined. Lamps selected for calibration display a degree of polarization of 0.005 or less and a drift rate of less than 0.04% per hour at 654.6 nm. The drift rate is measured at two wavelengths over a 20-hour period by comparison with a stable vacuum lamp, and included in the calibration report. Typical values in percent change per hour are 0.025 ± 0.004. Appendix A shows a typical calibration report and accompanying descriptive material which provide a table of L_λ values versus wavelength, and variations in spectral radiance with position, angle, polarization, time, and lamp current.

4. Spectroradiometer

a. Fore-optics. Sources are imaged with unit magnification at the entrance slit of the monochromator by the two front-surface aluminized mirrors shown in figure 1. The mirror surfaces are stripped and recoated at intervals to reduce signal loss due to oxidation. The plane mirror directs the beam to the spherical mirror (radius of curvature 1220 mm) along a line about 1.5 degrees from the spherical mirror axis. The spherical mirror focuses the beam onto a mirror-surfaced mask, placed immediately in front of the entrance slit. The mask is engraved with horizontal and vertical scales with 0.1 mm divisions, and is viewed at high magnification by either a telescope or a video camera to allow for precise positioning of the sources. The mask determines the height of the system field stop (source target area). The entrance slit determines the width. The stop dimensions are 0.8 mm high by 0.6 mm wide for the scale realization and transfer. The system aperture stop is located within the monochromator.

b. Monochromator. A prism-grating double monochromator is employed to minimize spectral scattering and avoid multiple orders. The wavelength range is 200 to 2600 nm. The dispersion varies with wavelength from about 1 to 4 nm/mm. The entrance aperture (solid angle) is rectangular in shape, with a vertical angle of 0.125 radians and a horizontal angle of 0.0625 radians. The wavelength setting is calibrated against spectral line standards (H_g, thorium, neon, helium) and is repeatable to within 0.05 nm.

The entrance, intermediate, and exit slits are adjustable from 0.01 to 3.0 mm as a unit, resulting in a nearly triangular-shaped spectral responsivity function.

c. Detectors. Two interchangeable detectors are used to cover the wavelength range of the spectroradiometer. For the 200 to 850 nm range, an end-on 11-stage photomultiplier with quartz window and S-20 spectral response is placed behind the exit slit. The detector is cooled to 258 K with a thermoelectric cooler. The anode current is amplified and converted to a 0-10 volt signal by a programmable amplifier. The current is normally restricted to a maximum of 500 nanoamperes, by selection of detector applied voltage, to ensure linearity of response. A lead sulfide detector, cooled to 240 K by a thermoelectric cooler, is used for the 800 to 2600 nm range. The detector and the exit slit are placed at the foci of an ellipsoidal mirror, which images the slit upon the detector with a demagnification of 7. The detector output is amplified and converted to a 0-1 volt signal by a phase-sensitive lock-in voltmeter, which is keyed to a 78 hertz sector disk placed just before the plane mirror. The signal from either detector-amplifier combination is fed to a 5 1/2 digit voltmeter, capable of integration times ranging from one second to several minutes. To facilitate alignment of optics or sources, a He-Ne laser is placed at the detector position, so that its beam passes through the monochromator and fore-optics in the reverse direction.

5. Control and Data Acquisition System.

The spectral radiance calibrations are carried out on the NBS Facility for Automated Spectroradiometric Calibrations (FASCAL). After initial alignment, the FASCAL system permits control of the entire measurement process from a remote operator console. Component positions, instrument settings, sequence of operations, and data collection are effected by either stored computer programs, operator commands, or a combination of the two.

The system is directed by a microcomputer equipped with a CRT terminal and keyboard, and a high-speed disk system for program and data storage. A modular interface controller [9] provides the link between instruments and computer. All measurement signals are multiplexed into the digital voltmeter through the interface scanner, and the instruments are remotely programmed and controlled through interface modules. All instrument settings and signal outputs are printed and stored on disk for later analysis. Additional details on the FASCAL system are given in Appendix B.

The spectroradiometer (fore-optics, monochromator, and detectors), a closed-circuit TV camera, and a photoelectric pyrometer are mounted on a carriage. The carriage can be positioned by remote command along a linear track, to align the spectroradiometer with one of the sources mounted at fixed stations along the track. The average move time between stations is a few seconds, and positions are repeatable to about 0.1 mm. The TV camera presents a highly magnified image of the monochromator entrance slit mask to displays at the spectroradiometer and at the operator console, for initial source alignment and subsequent monitoring. The pyrometer is used for the initial setting of the variable temperature blackbody to its approximate temperature.

MEASUREMENT OF INSTRUMENT AND SOURCE PARAMETERS

Spectral Responsivity Function

The relative spectral responsivity function of the spectroradiometer is determined by the indirect method [10]. In this method, the relative responsivity function is treated as the product of two terms, the responsivity factor and the slit-scattering function, where the responsivity factor depends only upon the wavelength of the observed flux and the slit-scattering function depends only upon the difference between the wavelength setting of the monochromator and the wavelength of the flux. This factorization of the spectral responsivity function is valid if the instrument dispersion, aberrations, scattering, and diffraction are constant over the wavelength region of interest. This assumption is valid in the central portion of the relative responsivity function, but values for the distant wings are subject to error due primarily to changes in scattering and dispersion.

The responsivity factor is obtained by spectrally scanning a continuous source standard of spectral radiance with narrow (0.1 mm) slits. To determine the slit-scattering function, an integrating sphere irradiated by a high-powered laser is spectrally scanned by the spectroradiometer, with the slit widths set at the 0.6 mm width used in the scale realization and transfer. The plot of the output signal versus wavelength is the mirror image of the plot of the slit-scattering function versus wavelength. For a 647 nm krypton laser, the function is nearly triangular in shape with a width at half-height of 2.5 nm. Relative to the peak value, the measured values decrease to about 10^{-3} at 3 nm, 10^{-4} at 15 nm, and 10^{-7} at 70 nm from the central wavelength. At 150 nm from the central wavelength, the value decreases to 10^{-8} in the short-wavelength wing and to 10^{-9} in the long-wavelength wing. Scans with 488 nm, 514 nm (argon), and 676 nm (krypton) yield similar results. These values were confirmed over the central and near wings portion of the function by measurements with the direct method, using a dye laser tuned through a series of wavelengths with the spectroradiometer set at a fixed wavelength [11].

The measurement at 647 nm yields the slit-scattering function at 654.6 nm, where the spectral distribution mismatch of the two blackbodies requires an accurate determination of the relative responsivity function. However, the measurements in the visible cannot be applied with confidence to the short-wavelength region, since the dispersion varies by about a factor of 2½. For this region, the central portion and near wings of the slit-scattering function are determined by scans of a spectral line discharge source, and values in the distant long-wavelength wing are deduced from a measurement of the integrated spectrally-scattered radiation. With the wavelength set at a selected value in the 200 to 250 nm region, the signal from a calibrated lamp (radiance temperature 2475 K at 654.6 nm) is recorded. A glass filter which blocks all radiation in the vicinity of the wavelength setting and passes about 90% of the radiation at longer wavelengths is inserted into the beam. The ratio of signals with and without filter is taken as the fractional contribution of spectrally scattered radiation to the signal. A second (identical) filter is added to insure that only scattered light is being observed in the filtered beam. Results with filters of different cut-off wavelengths (Corning filters CS

0-56 and CS 0-52) both indicate an integrated scattered light contribution of less than 0.2% at 225 nm. The slit scattering function calculated from this result and the known source distributions and responsivity factor is less than 10^{-9} at wavelengths greater than 200 nm from the central wavelength, in good agreement with the values measured in the visible.

Linearity of Response

The degree of linearity of the spectroradiometer response is determined with an automated beam conjoiner [12]. A beam from a constant source is split into two branches, whose fluxes are independently attenuated or blocked before recombination and further attenuation. The flux contributions from both branches is equal to the sum of the fluxes from each branch when measured separately (additivity). The device provides ninety-six levels of flux ranging over a factor of about five hundred. The levels are presented in random order to avoid systematic errors, and are interspersed with twenty-nine zero flux levels. A micro-computer controls the attenuating filters and records the filter positions and radiometer signals. The data is least-squares fitted to a polynomial response function, to determine a correction factor by which the radiometer output signal must be multiplied to obtain a quantity proportional to radiant flux.

The response function of the spectroradiometer is dependent upon the detector-amplifier employed. With the photomultiplier tube in place (spectral range 200 to 850 nm), the instrument response at all wavelengths is linear to within 0.2% for a range of anode currents from 1 to 500 nanoamperes. For currents much less than 1 nanoampere, the signal is limited by noise. For currents greater than one microampere, the correction increases rapidly, rising to 3% at 7 microamperes. The anode current is restricted to less than 500 nanoamperes during measurements by selection of appropiate tube voltage. Correction factors for the amplifier ranges are determined from measurement of a known electrical current and combined with the linearity correction factor. Linearity tests of two PbS detectors resulted in a correction factor which is a linear function of the signal over the range 1 to 280 millivolts. The correction varies from 0.1% at 3 mv to about 9% at 300 mv. To avoid reliance on large corrections, the sources are typically operated at near equality in the PbS spectral region.

Polarization

The polarization properties of the spectroradiometer and the gas-filled lamps are measured with the aid of sheet (linear) polarizers positioned in motorized rotating mounts. The sheet polarizer properties and those of the spectroradiometer are determined in an initial set of experiments, using an illuminated integrating sphere as a source of unpolarized radiation. The characterized polarizer and spectroradiometer are then used to measure the polarization properties of the lamp sources.

The determination of spectroradiometer and sheet polarizer properties consists of spectral radiance measurements of the sphere source alone, with a pair of similar polarizers interposed in the beam and set at a number of angular positions (rotations about the optic axis), and with each polarizer separately in the beam at the same angular positions. A Mueller transmittance matrix [13] containing six parameters is assumed for the sheet polarizers, to account for departure from ideal behavior. Circular polarization is assumed to be negligible. The spectroradiometer polarization direction is determined in a preliminary experiment and chosen as the polarization reference direction, leaving only the degree of polarization to be determined for the instrument. Our measurements provide about 200 equations involving ten unknowns, which are then obtained by a non-linear least-squares solution.

The sphere source is replaced by the lamp source whose properties are to be measured using a characterized sheet polarizer and spectroradiometer. Measurements are made with the lamp alone and with the polarizer set at the same angular positions as before, resulting in 25 equations involving the two source unknowns, which are obtained by a least-squares solution. The polarization of the lamp source is specified by the direction of maximum linear polarization γ, and the degree of polarization

$$p = (L_{max} - L_{min}) / (L_{max} + L_{min}) \qquad [9]$$

where L_{max} and L_{min} are the maximum and minimum readings of a polarization-indifferent radiometer when an ideal linear polarizer is rotated in the source beam. The correction factor required to reduce the signal ratio of Eqn. 8 to a value which would be obtained with a polarization-indifferent radiometer is

$$(1 + Bp_1)^{-1}$$

where $p_1 = p\cdot\cos 2\gamma$ and B is the spectroradiometer polarizance (degree of linear polarization introduced by the spectroradiometer). For the spectroradiometer employed here, the polarizance varies from zero at 225 nm to 0.26 at 655 nm and 0.85 at 2400nm. The degree of polarization of a typical lamp selected for calibration is about 0.003. The uncertainty in the radiometer polarizance B is estimated as .0005 in the visible and .001 in the extremes of the wavelength range. The lamp polarization uncertainties are estimated as 0.002 in the visible and 0.003 at extreme wavelengths. A more detailed description of the measurement process and data analysis is given in Appendix C.

Size of Source

The "size of source" effect (signal contribution due to flux which originates outside the target area and is scattered into the measured beam by the fore-optics) is determined by observing the signal from a 0.6 by 0.8 mm segment of a uniform diffuse source, and noting the change in signal when the surrounding area of the source is changed by placing various masks on the diffuse source. The masks expose source areas which closely approximate the radiant areas of the lamp and blackbody sources used in the scale realization and transfer. As a check, the effect is also evaluated by observing changes in the near-zero signal from a "black hole" (an absorbing cavity slightly larger than the 0.6 by 0.8 mm field stop) as the various surrounding area masks are positioned. The observed differences are used to apply a correction to the signals observed in source comparisons. The effect is measured at wavelengths of 654.6 and 350 nm, and values for other wavelengths are estimated from the assumption of an inverse wavelength dependence. The correction varies from 0.04% to 0.1% at 654.6 nm depending upon the elapsed time since the last mirror recoating.

PROCESS OF REALIZATION AND TRANSFER

The process of realization and transfer consists of the temperature determination of the variable temperature blackbody (VTBB) at a reference wavelength, a spectral radiance comparison of the VTBB and the gas-filled test lamps at chosen calibration wavelengths, and a redetermination of the VTBB temperature.

The temperature determination of the VTBB is composed of three steps. In step one, the gold point spectral radiance is transferred to a Quinn-Lee vacuum lamp. In step two, a second vacuum lamp at about 1530 K radiance temperature (about eight times the gold point spectral radiance) is compared to the first vacuum lamp. In step three, the second lamp is compared to the VTBB. If the vacuum lamps remain constant between observations, the product of the signal ratios from the three comparisons is the signal ratio of the blackbodies, from which the spectral radiance and thus the temperature of the VTBB can be evaluated from eqns. 5 and 2. The polarization and the spectral radiance distributions over ω, A, and λ of the vacuum lamps are of no concern here, since the lamps serve only to reproduce the spectroradiometer signal between comparisons. The only requirement is that the lamp parameters remain constant between comparisons with the gold-point blackbody (GPBB) and with the VTBB. This is satisfied by the constant-current operation of the stable (0.02% per 200 hours) vacuum lamps. Comparison with the GPBB is performed about every 50 to 100 hours of lamp operation, the vacuum lamps are compared with each other weekly during experiments, and the 1530 K lamp is compared to the VTBB before and after each set of comparisons of the VTBB to the gas-filled lamps. The use of the first vacuum lamp avoids the inconvenience of manipulating the GPBB through its melting and freezing point cycles and provides a continuous measure of gold point radiance. It also increases the number of experiments allowed between maintenance or replacement of the gold point furnace. The use of the second vacuum lamp keeps all signal ratios within the linear response region of the spectroradiometer (i.e., within the 1 to 500 nanoampere range of anode current).

In principle, the three comparisons comprising the VTBB temperature determination can be performed at any wavelength within the signal-to-noise limitations of the instrument. At present, they are done at a wavelength setting λ_0 of 654.6 nm (location of a convenient thorium line), where a long history of vacuum lamp behavior has been accumulated, and where comparisons with the IPTS temperature scale are facilitated.

The spectral radiance comparisons of the VTBB and the test lamps are typically carried out on a group of lamps, each operated at its chosen calibration current throughout the experiment. For the 800 to 2400 nm spectral range the VTBB is set at various temperatures to yield spectral radiances within 10% of those of the lamps, in order to avoid reliance upon large linearity corrections. In the ultra-violet and visible spectral region, the VTBB is operated at a temperature of about 2580 K. At this temperature, the VTBB spectral radiance is about half that of the lamps at 225 nm and about twice that of the lamps at 800 nm, well within the linear range of the photomultiplier detector. Under these conditions, the spectral distribution similarity in the two sources over the central instrument bandpass permits the use of Eqn. 8 to within 0.05%. Spectral scattering from the distant wings of the slit-scattering function requires a correction of about 0.1% for the comparisons below 250 nm. Spectral radiance comparisons are made at 654.6 and 250 nm at the start and finish of the full range of comparisons, to detect and correct for any effects of lamp drift. Detailed procedures of the process are listed in Appendix D.

Scale Stability

The calibrations resulting from this process are derived in principle from a complete realization of the spectral radiance scale, and therefore are not dependent upon the maintenance of in-house standards. In practice, the realization often omits the GPBB comparison and relies upon the value of gold point spectral radiance which is maintained on the stable Quinn-Lee vacuum lamp. The long-term record of this lamp's comparison with the GPBB (each 50-100 hours of operation) is monitored to detect any deviation from normal.

The spectral radiance values of each group of calibrated lamps are compared wavelength by wavelength to the values of earlier calibrations in order to disclose any apparent shifts in the scale. Recalibration of a few lamps which are retained at NBS for the realization of other radiometric or photometric scales provide further checks on scale stability.

DATA ANALYSIS AND UNCERTAINTIES

The signal ratio of the VTBB to the GPBB is obtained from the product of the signal ratios measured in the first vacuum lamp comparison with the GPBB, the second vacuum lamp comparison to the first, and the average of the VTBB comparisons to the second lamp. The ratio is then multiplied by correction factors to account for the size-of-source disparity, the estimated departure from unity emissivity, and the departure from linear response where appropriate (total correction 0.1 to 0.6%). An estimated VTBB temperature is then calculated from the ratio of Planck functions for the two blackbodies. This temperature can then be used to determine by iteration the exact temperature which satisfies Eqn. 5. For the spectral responsivity function of this spectroradiometer, this exact temperature differs from the ratio of Planck functions approximation by an amount which is small (less than 0.2 K) and is a simple function of the temperature. Therefore, to avoid the repetitive integration process, the temperature calculated from the Planck function ratios is corrected to the desired Eqn. 5 value by this known difference.

For each calibration wavelength, the measured signal ratio of the test lamp-VTBB comparison is corrected for the size-of-source, non-unity emissivity, and polarization factors (total correction less than 0.5%). The spectral radiance of the test lamp is then obtained by using the measured VTBB temperature in Eqn. 2 to determine the spectral radiance of the VTBB at the calibration wavelength, and inserting this spectral radiance and the corrected signal ratio into Eqn. 8. The spectral radiance values at each wavelength are corrected for any lamp drifts determined by the initial and final measurements at 654.6 and 250 nm.

Uncertainty estimation

The uncertainties in the spectral radiance values assigned to the calibrated lamps are obtained from the observed imprecision of the measurements and the estimated systematic error in both the measured and the provided quantities (e.g., temperature of melting gold). Uncertainties obtained from observed imprecision and from published values of the physical constants are based upon three standard deviations. Uncertainties of systematic errors are estimated at the equivalent of three standard deviations.

In order to examine the contributions of the various errors to the uncertainty in spectral radiance, an approximate equation for the complete measurement process can be developed by using the Wien approximation to Eqn. 2,

$$L_\lambda \simeq (c_1/\pi)\cdot\lambda^{-5}\cdot\exp(-c_2/\lambda\cdot T) \tag{10}$$

The signal ratio of the VTBB to the GPBB at the reference wavelength can then be expressed as

$$S_V/S_{Au} \simeq \exp[(c_2/\lambda_r)\cdot(1/T_{Au} - 1/T_V)] \quad , \tag{11}$$

and the spectral radiance of the test lamp at a calibration wavelength as

$$L_\lambda \simeq (S_L/S_V)\cdot L_V \simeq (S_L/S_V)\cdot(c_1/\pi)\cdot\lambda^{-5}\cdot\exp[-c_2/(\lambda\cdot T_V)] \tag{12}$$

where L_V is the spectral radiance of the VTBB. Solving Eqn. 11 for T_V, substituting this expression into Eqn. 12, inserting the various correction factors heretofore omitted, and rearranging, we have

$$L_\lambda \simeq \left[s_\lambda\cdot\epsilon_B\cdot d\cdot M_\lambda/(1+B\cdot p_1)\right]\left[c_1/[\pi\cdot\lambda^5\cdot\exp[c_2/(\lambda\cdot T_{Au})]\right]\left[s_r\cdot f_r\cdot M_r/\epsilon_B\right]^{\lambda_r/\lambda} \tag{13}$$

where the definitions of the quantities and their estimated uncertainties are:

M_λ, signal ratio of the VTBB-test lamp comparison (0.16 to 1.27%)

M_r, signal ratio of the GPBB-VTBB comparison (0.2%)

s_λ, size-of-source correction for the VTBB-test lamp comparison (0.1%)

ϵ_B, effective emissivity of the VTBB (0.1%)

d, correction for lamp drift during calibration (0.1%)

B, spectroradiometer polarizance (0.05 to 0.1%)

p_1, lamp polarization component (0.2 to 0.3%)

s_r, size-of-source correction for the GPBB-VTBB comparison (0.1%)

f_r, linearity-range factor correction (0.04 to 0.1%)

T_{Au}, IPTS-68 temperature of melting gold (0.4 K)

c_1, first radiation constant ($0.0006 \cdot 10^{-12}$ W-cm^2)

c_2, second radiation constant (0.000135 cm-K)

λ, wavelength of the VTBB-test lamp comparison

λ_r, wavelength of the GPBB-VTBB comparison

Spectral radiance uncertainties due to the factors of Eqn. 13 are obtained from the partial derivative with respect to those factors and the estimated uncertainty in the factor. Thus the percent uncertainty in spectral radiance at 300 nm due to the 0.4 K uncertainty in T_{Au} is

$$100 \cdot \Delta L_\lambda / L_\lambda = 100 \cdot [c_2 / \lambda \cdot T_{Au}^2] \cdot \Delta T_{Au} = 100 \cdot [1.4388/3 \cdot 10^{-5} \cdot (1337.58)^2] \cdot (0.4)$$

or 1.07%, while the percent uncertainty at 900 nm due to the uncertainty in the VTBB emissivity is

$$100 \cdot \Delta L_\lambda / L_\lambda = 100 \cdot [1-(\lambda_r/\lambda)] \cdot \Delta\epsilon_B = 100 \cdot [1-(654.6/900)] \cdot (0.001)$$

or 0.03%. Differences between errors calculated by Eqn. 13 and those calculated by the exact Planck relation are negligible. Note that for the wavelengths λ and λ_r this process yields the error due to inserting the wrong wavelength in the spectral radiance calculation, not the error due to an incorrect wavelength setting.

In addition to the factors which appear explicitly in this relation, uncertainties in the ratios M_λ and M_r arise from errors in the wavelength settings λ (0.1 nm) and λ_r (0.05 nm), in the current measurements of the vacuum (0.2 ma) and gas-filled (1 ma) lamps, and in the measured spectral responsivity function. The uncertainties in the ratios due to wavelength setting and current are assessed at a number of wavelengths by measurement of the change in signal ratio when varying these quantities. The effect upon the signal ratios due to the uncertainties in the measured spectral responsivity function is determined by solving Eqn. 5 for a range of $R(\lambda_0,\lambda)$ values, using the known spectral radiance distributions of the blackbodies and an approximate test lamp distribution derived from the calibration values. The spectral radiance uncertainties due to these factors are then deduced from the ratio uncertainties as before. The signal ratio, lamp current and wavelength setting errors are considered random; the remaining errors are systematic.

Table I lists the uncertainties obtained by this process. The calculated uncertainties in percent of spectral radiance are tabulated for a number of wavelengths over the calibration range. The individual values are combined in quadrature to yield the combined uncertainty for each wavelength. These uncertainties apply to the reported values at the conclusion of the calibration.

CONCLUSION

The realization of the NBS scale of spectral radiance and its transfer to calibrated lamp standards has been described in this report. This spectral radiance scale also serves as the basis for the NBS scales of spectral irradiance, luminous intensity, luminous flux, and color temperature. It has therefore been the subject of continuing investigations to decrease and assess uncertainties and to increase its efficiency. Recent improvements in the process are the determination of the system response linearity, the polarization characterization of instrument and sources, and accurate measurement of the spectroradiometer spectral responsivity function. The thermodynamic temperature of melting gold remains as the chief source of uncertainty in the scale realization.

The calibrated lamp standards of spectral radiance are provided to the user with a report of calibration and an attachment which briefly describes

TABLE I

SPECTRAL RADIANCE UNCERTAINTY (%)

Source of Error	Wavelength (nm) 225	250	350	655	900	1550	2400
T_{Au} (s)	1.43	1.29	0.92	0.49	0.36	0.21	0.13
M_r (r)	0.60	0.52	0.37	0.23	0.20	0.11	0.12
M_λ (r)	1.27	0.61	0.46	0.19	0.22	0.17	0.16
s_r (s)	0.29	0.26	0.19	0.10	0.07	0.04	0.03
s_λ (s)	0.10	0.10	0.10	0.10	0.10	0.10	0.10
f_r (s)	0.29	0.26	0.19	0.10	0.07	0.04	0.03
d (s)	0.10	0.10	0.10	0.10	0.10	0.10	0.10
ϵ_B (s)	0.19	0.16	0.09	0.00	0.03	0.06	0.07
c_2 (s)	0.15	0.13	0.10	0.05	0.04	0.02	0.01
p_1 (s)	0.01	0.01	0.03	0.05	0.06	0.17	0.25
λ_r setting (r)	0.03	0.04	0.03	0.01	0.02	0.01	0.01
λ setting (r)	0.24	0.22	0.16	0.08	0.06	0.03	0.01
Spectral Resp. (s)	0.09	0.08	0.06	0.03	0.02	0.02	0.01
Lamp currents:							
Quinn-Lee (r)	0.12	0.11	0.08	0.04	0.03	0.02	0.01
1530 K (r)	0.06	0.06	0.04	0.02	0.02	0.01	0.01
Test (r)	0.11	0.10	0.07	0.04	0.03	0.02	0.01
B, c_1 (s)	-------------(less than 0.001%)--------------						
Total 3σ Uncertainty (%) (square root of sum of squares)	2.09	1.61	1.16	0.62	0.51	0.38	0.39

Note: Random errors denoted by (r), systematic by (s).

the calibration method, the lamp positioning, orientation, target area and solid angle, and dependence upon lamp current. A typical report with attachment is shown in Appendix A. In addition to the uncertainties which apply at the conclusion of the calibration, additional uncertainties accrue as the lamp is operated as a standard source. The reported spectral radiance values may be adjusted with operating time by use of the reported drift rate, but this rate cannot be assumed to remain constant over a long time period. Therefore, it is recommended practice to promptly transfer the calibration values to other lamps, use such lamps as working standards, and monitor their changes by occasional comparison to the original lamp.

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FORM NBS-443
(REV. 11-68)

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

REPORT OF CALIBRATION

LAMP STANDARD OF SPECTRAL RADIANCE

Requested by

Department of The Navy
Commanding Officer
Naval Rework Facility
North Island, San Diego, CA 92135

(See your Letter dated 10/16/84 signed by J. B. Mackinnon.)

1. Material

One gas-filled General Electric type 30/T24/13 tungsten ribbon filament lamp has been supplied by NBS for this test and bears the designation Q93.

2. Calibration

The lamp was calibrated using the equipment and procedures described in the enclosed document, "Lamp Standards of Spectral Radiance-1984". The selection and preparation of test lamps are described in paragraph II of this document. Note particulary paragraph III.B which describes the orientation and operation of the test lamp. The calibration was performed with the lamp operating at a direct current of 40.370 amperes with the longer filament support post at positive potential. The environmental temperature was 26°C and the relative humidity was 55%.

3. Results

Table I gives the measured spectral radiances of the test lamp. Table II gives the uncertainties of the calibration. Figures 1 through 5 show the results of the lamp mappings described in paragraph IV of the enclosed document.

The stability measurements at 654.6 nm and 350 nm described in paragraph II of the enclosed document showed that the spectral radiance of the test lamp changed at a rate of -0.029% per hour and -0.055% per hour, respectively. The relative change in spectral radiance at other wavelengths is expected to be approximately inversely proportional to the wavelength. It is therefore recommended that the shortest wavelengths be transferred to other lamps first.

NBS Test No. 534/G-44928-2
September 23, 1985

The polarization measurements at 655 nm, described in paragraph II of the enclosed document, showed that the degree of polarization was 0.0020. The direction of polarization of the larger component was approximately 6 degrees counterclockwise from the horizontal when viewed from the spectroradiometer.

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Approved by:

D M

Donald A. McSparron
Radiometric Physics Division
Center for Radiation Research

TABLE I

Measured Values of Spectral Radiance and Blackbody Temperature for Q93 at 40.370 amperes

Wavelength in air (nm)	Spectral Radiance ($W\ cm^{-3}\ sr^{-1}$)	Blackbody Temperature K (IPTS-68)
225	7.150E+00	2654.2
230	1.073E+01	2653.3
240	2.286E+01	2651.8
250	4.542E+01	2650.2
260	8.513E+01	2648.8
270	1.499E+02	2646.3
280	2.518E+02	2643.8
290	4.061E+02	2641.4
300	6.268E+02	2638.2
325	1.607E+03	2629.4
350	3.490E+03	2619.9
375	6.633E+03	2609.5
400	1.136E+04	2598.5
450	2.626E+04	2575.4
475	3.649E+04	2563.6
500	4.834E+04	2551.6
550	7.570E+04	2526.9
575	9.049E+04	2514.4
600	1.054E+05	2501.6
654.6	1.373E+05	2473.4
675	1.486E+05	2463.1
700	1.614E+05	2450.2
750	1.836E+05	2423.6
800	2.003E+05	2396.2
900	2.185E+05	2340.6
1050	2.147E+05	2254.4
1200	1.913E+05	2169.3
1300	1.719E+05	2114.0
1550	1.241E+05	1981.0
1700	1.002E+05	1906.2
2000	6.507E+04	1770.0
2100	5.641E+04	1727.9
2300	4.204E+04	1642.9
2400	3.709E+04	1610.7

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September 23, 1985

TABLE II

Summary of Estimated Uncertainties in Percent of Spectral Radiance Values

SOURCE OF UNCERTAINTY	WAVELENGTH (nm) 225	250	350	654.6	900	1550	2400
1) Blackbody quality	0.29	0.24	0.13	0.00	0.04	0.09	0.11
2) Calibration of Pyrometer Lamp relative to the International Practical Temperature Scale (IPTS-68)	0.70	0.63	0.45	0.24	0.17	0.10	0.07
3) Temperature determination of blackbody and transfer of blackbody spectral radiance to lamp (3σ)	1.05	0.90	0.36	0.27	0.36	0.30	0.24
4) Polarization effects	0.00	0.00	0.01	0.04	0.06	0.09	0.15
5) Current measurement	0.14	0.13	0.09	0.05	0.04	0.02	0.01
6) Wavelength measurement	0.11	0.10	0.08	0.01	0.01	0.01	0.01
7) Temperature scale	1.43	1.28	0.93	0.49	0.40	0.20	0.13
Total estimated uncertainty relative to S.I. units (square root of the sum of the squares of the individual uncertainties)	1.9	1.7	1.1	0.6	0.6	0.4	0.3

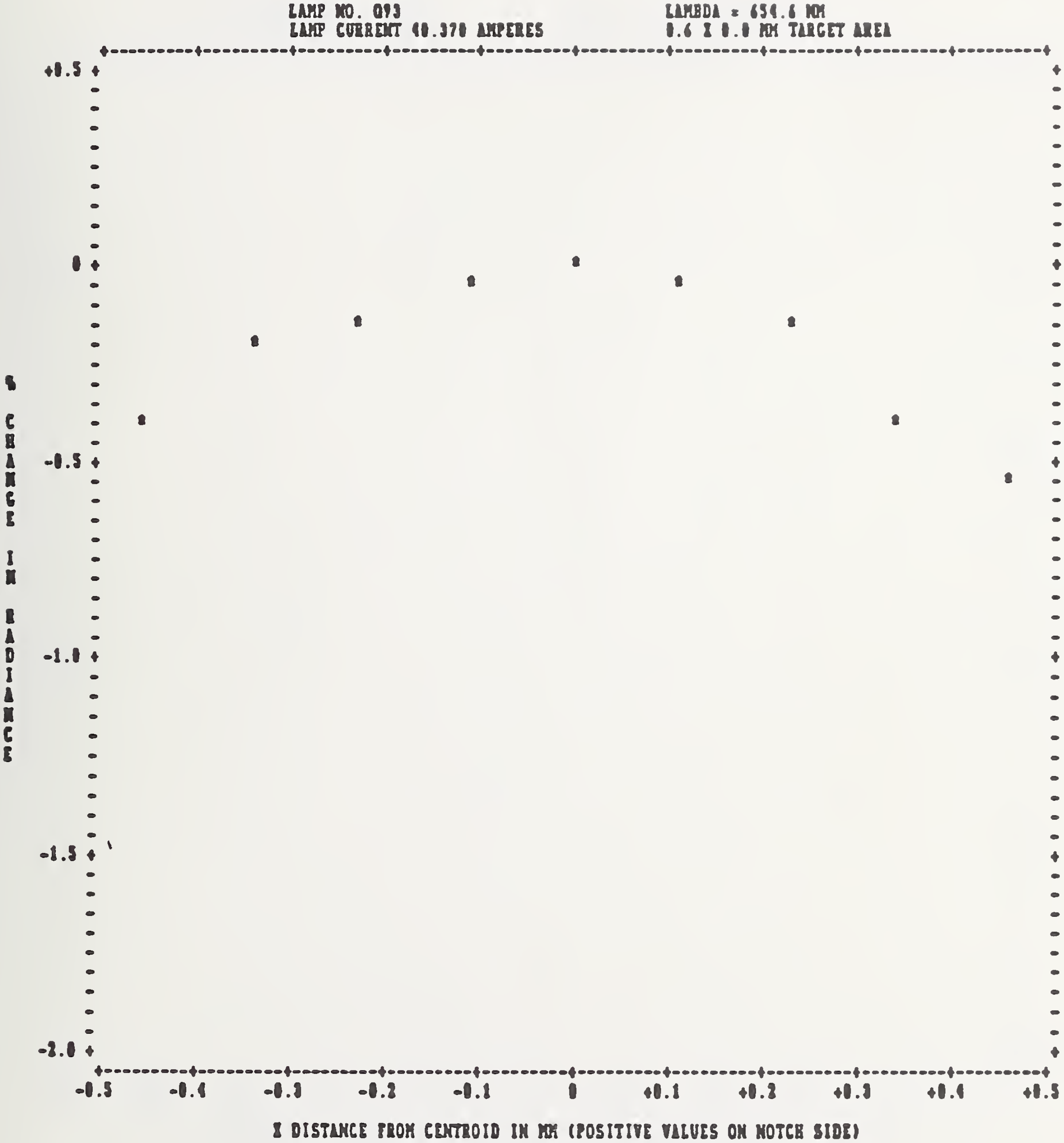
LAMP NO. Q93
LAMP CURRENT 40.370 AMPERES
LAMBDA = 654.6 NM
0.6 X 0.8 MM TARGET AREA
+0.5
0
-0.5
-1.0
-1.5
-2.0
% CHANGE IN RADIANCE
-0.5
-0.4
-0.3
-0.2
-0.1
0
+0.1
+0.2
+0.3
+0.4
+0.5
X DISTANCE FROM CENTROID IN MM (POSITIVE VALUES ON NOTCH SIDE)

FIG. 1

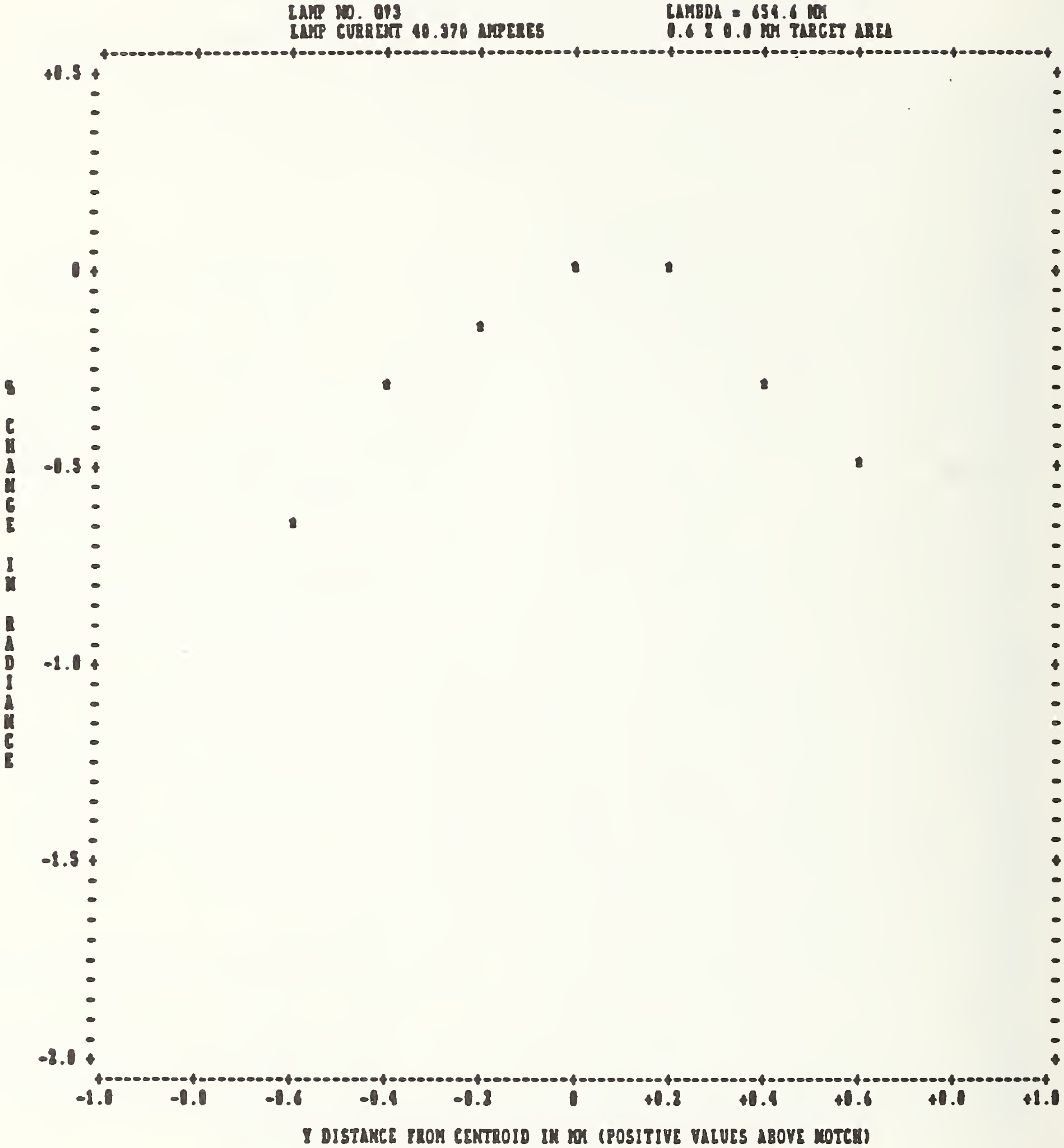
LAMP NO. Q93
LAMP CURRENT 40.370 AMPERES
LAMBDA = 654.6 NM
0.6 X 0.8 MM TARGET AREA
+0.5
0
-0.5
-1.0
-1.5
-2.0
% CHANGE IN RADIANCE
-1.0
-0.8
-0.6
-0.4
-0.2
0
+0.2
+0.4
+0.6
+0.8
+1.0
Y DISTANCE FROM CENTROID IN MM (POSITIVE VALUES ABOVE NOTCH)

FIG. 2

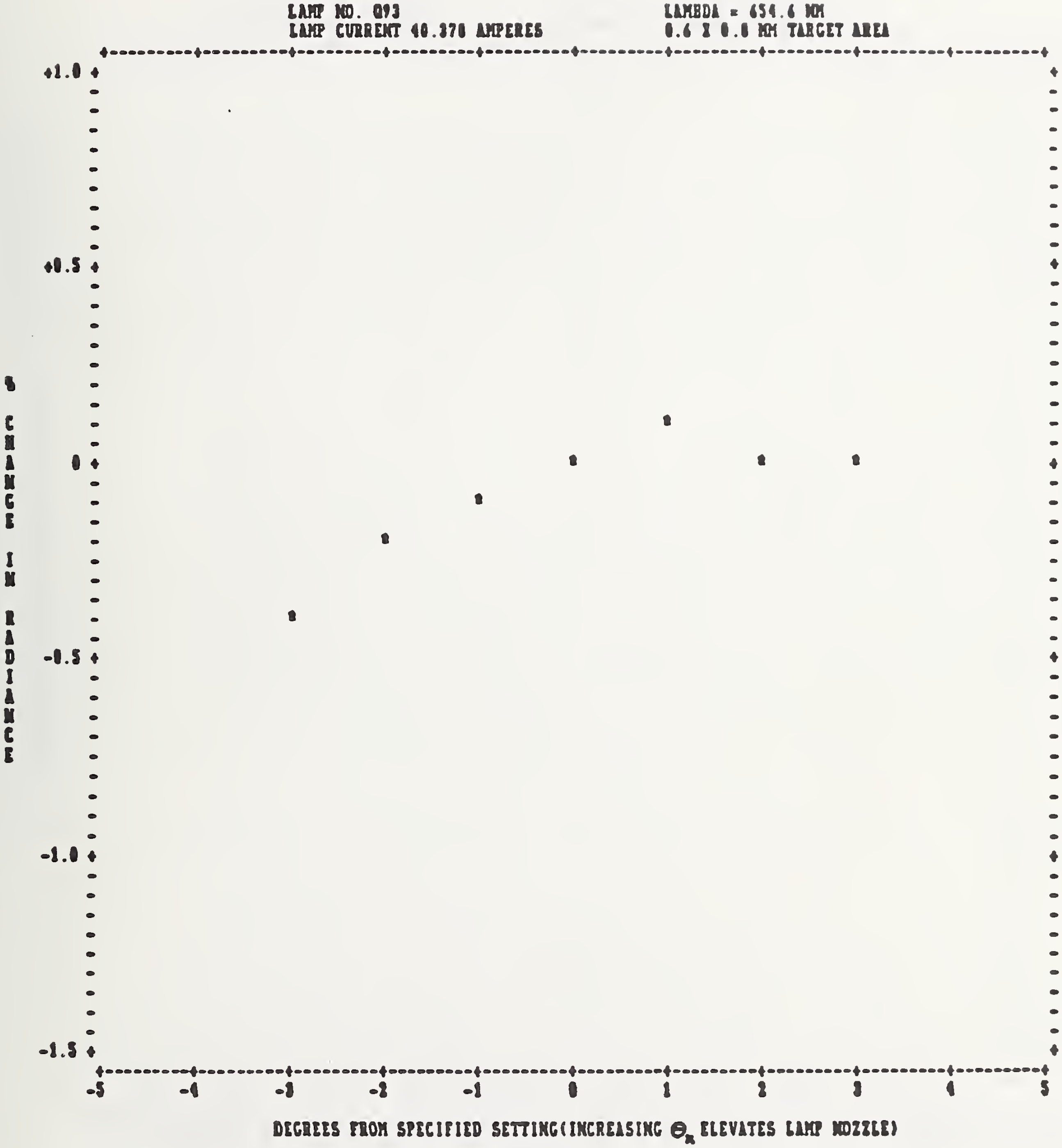
LAMP NO. Q93
LAMP CURRENT 40.370 AMPERES
LAMBDA = 654.6 NM
0.6 X 0.8 MM TARGET AREA
% CHANGE IN RADIANCE
+1.0
+0.5
0
-0.5
-1.0
-1.5
-5
-4
-3
-2
-1
0
1
2
3
4
5
DEGREES FROM SPECIFIED SETTING(INCREASING Θ_x ELEVATES LAMP NOZZLE)

FIG. 3

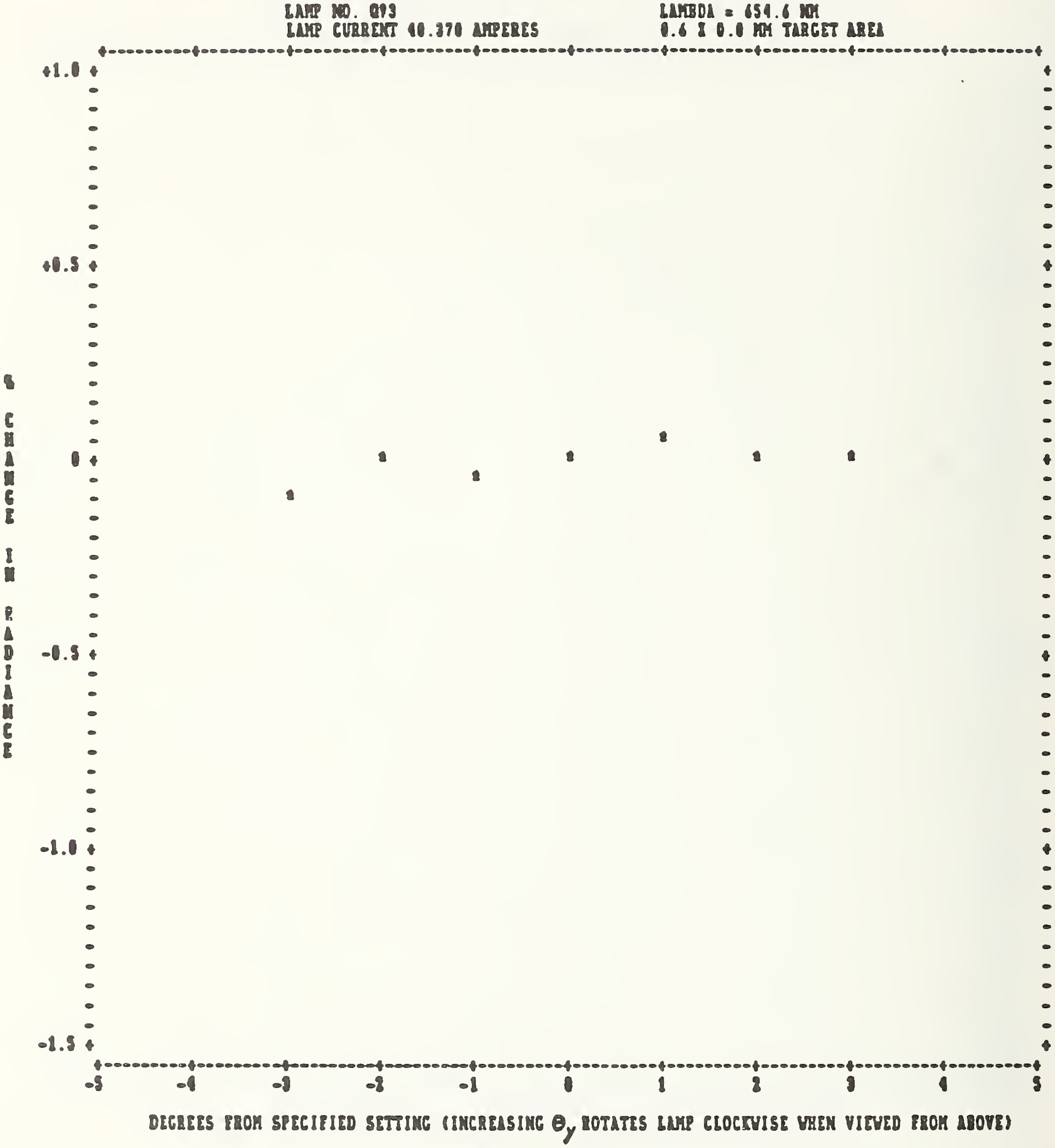
LAMP NO. Q93
LAMP CURRENT 40.370 AMPERES
LAMBDA = 654.6 NM
0.6 X 0.8 MM TARGET AREA
+1.0
+0.5
0
-0.5
-1.0
-1.5
% CHANGE IN RADIANCE
-5
-4
-3
-2
-1
0
1
2
3
4
5
DEGREES FROM SPECIFIED SETTING (INCREASING θy ROTATES LAMP CLOCKWISE WHEN VIEWED FROM ABOVE)

FIG. 4

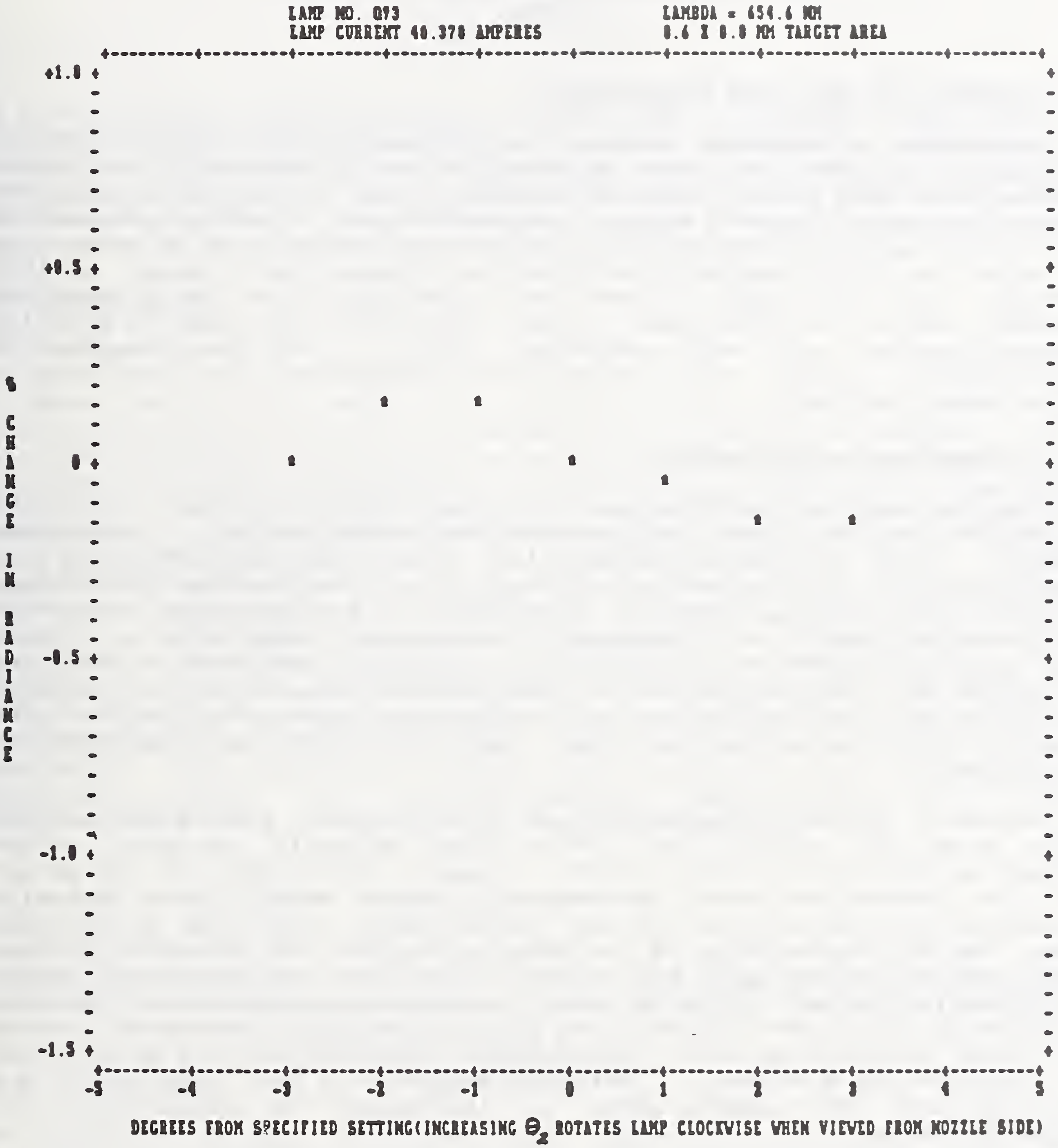
LAMP NO. Q93
LAMP CURRENT 40.370 AMPERES
LAMBDA = 654.6 NM
0.6 X 0.8 MM TARGET AREA
+1.0
+0.5
0
-0.5
-1.0
-1.5
% CHANGE IN RADIANCE
-5
-4
-3
-2
-1
0
1
2
3
4
5
DEGREES FROM SPECIFIED SETTING(INCREASING θ_z ROTATES LAMP CLOCKWISE WHEN VIEWED FROM NOZZLE SIDE)

FIG. 8

LAMP STANDARDS OF SPECTRAL RADIANCE
1984

I. Introduction and Lamp Description

Standards of spectral radiance are issued by the National Bureau of Standards to cover the spectral range 225 nm to 2400 nm. Gas-filled tungsten filament lamps (General Electric type 30/T24/13 with quartz windows and mogul bipost bases) are calibrated by direct comparison with a high quality blackbody. The blackbody temperature is determined in terms of the International Practical Temperature Scale of 1968 (IPTS-68) [1] for each of the 34 wavelengths for which spectral radiance values are reported. The calibration includes a detailed characterization of the radiation field, and the degree of polarization). Such characterization measurements are performed at approximately 655 nm.

II. Preparation and Screening

At the beginning of testing, an identification number is painted on the rear surface (the side opposite the quartz window) of each lamp envelope. All test lamps are annealed at a brightness temperature of about 2620 K at 655 nm for 2 to 3 hours on direct current (the longer filament support post at positive potential). A calibration current is then chosen to produce a brightness temperature of about 2480 K. Drift rates are determined by monitoring the spectral radiance at 654.6 nm and 350 nm for a 20 hour period. Lamps exhibiting a drift rate of less than 0.04% per hour at 654.6 nm are selected for calibration. The measured drift rates for individual lamps are given in the Report of Calibration.

Spectral radiance calibrations are performed for a rectangular target area 0.6 mm wide by 0.8 mm high which is centered on the filament at the height of the notch. Angular orientation of the target area is determined from goniometric scans about three mutually perpendicular axes centered on the target area. The lamp orientation chosen for the calibration is one which minimizes the variation in lamp output while maintaining the optical axis of the spectroradiometer approximately normal to the filament and passing approximately through the center of the quartz window. An arrow is etched on the rear surface of the lamp envelope to allow reproducible alignment of this orientation (see section III.B below). Detailed mappings of the lamp output are performed and the results given in the Report of Calibration (see section IV below).

For lamps of the type used for this calibration, the radiation from the target area as viewed through the quartz window has been found to be slightly polarized. At 655 nm, the degree of polarization, P, defined as

$$P = \frac{L(max) - L(min)}{L(max) + L(min)}$$

and the direction of polarization of the larger component, L(max), are determined. L(max) and L(min) are the maximum and minimum readings of a polarization-indifferent radiometer when an ideal linear polarizer is rotated in the source beam. Only lamps with P less than or equal to .005 are calibrated. The measured value of P and the direction of polarization of L(max) are given in the Report of Calibration.

III. Calibration

A. Method

Measurements are made with a spectroradiometer [2] incorporated into the NBS Facility for Automated Spectral Calibrations (FASCAL) [3]. In the infrared, the spectroradiometer uses a lead sulfide detector and the measured spectral radiance* is determined by a spectral comparison of the test lamp to a high-quality variable temperature blackbody of approximately equal spectral radiance. In the visible and ultraviolet the spectroradiometer uses a photomultiplier tube. The photmultiplier-amplifier combination was determined to be linear [7] to better than 0.1% over a photmultiplier current range from 1 X 10^{-9} amperes to 5 X 10^{-7} amperes. Therefore, in the visible and ultraviolet, it is not necessary to closely match the blackbody to the test lamp. The blackbody temperature is determined by using a pyrometer lamp calibrated at 654.6 nm in terms of the International Practical Temperature Scale (IPTS-68) [1]. Within the present state of thermometry, this scale is the best approximation to the Thermodynamic Temperature Scale. The reported spectral radiance (in air**) and blackbody temperature are related by the Planck equation [5]

$$L = (C_1 / n^2\lambda^5) / [\exp(C_2/n\lambda T) - 1]$$

where C_1 is 3.741832 x 10^{-12} W cm^2 sr^{-1}, n is the index of refraction of air [6], is the wavelength (in air) in cm, C_2 is 1.4388 cm K, and T is the IPTS-68 blackbody temperature in K.

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*The spectral radiance values in this report are average values over the target area and solid angle set by the spectroradiometer. Detailed descriptions of these parameters are given later in this documentation.

**If the spectral radiance in a medium other than air is desired, it can be obtained from the Planck equation and the L n^{-3} invariance relationship [4].

B. Conditions

The values of spectral radiance measured for the test lamp are associated with a specific target area on the filament surface and with a specific solid angle of the radiation emitted from the target area. These values of spectral radiance apply when the lamp has reached thermal stability at a specified operating current (about a one-hour warm-up is sufficient*) and has then been aligned to a specified orientation. The test lamp is operated on direct current with the longer filament support post at positive potential.

The lamp is oriented base down with the filament vertical and the optical axis of the spectroradiometer passing through the quartz window and intersecting the center of the filament at the height of the notch. The exact location of the target area and rotational alignment of the lamp are as follows.

The calibration is performed for a rectangular target area 0.6 mm wide by 0.8 mm high. The height dimension of the target area is approximately parallel to the sides of the lamp filament. The centroid of the target area is located at the intersection of two lines, both of which lie on the viewed filament surface. The lines are perpendicular to each other, one line bisecting the filament along its length and the other passing through the point centered at the mouth of the V-notch.

The centroid of the target area on the filament is viewed along the horizontal axis of the spectroradiometer. The lamp is positioned so that the long filament support is to the left and the etched arrow is to the rear, as viewed from the spectroradiometer. A plumb line is used to make the notch side of the filament vertical. The lamp is then successively rotated about the horizontal axis through the centroid of the target area and normal to the line of sight, and about the vertical axis through the centroid of the target area, until the tip of the arrowhead appears centered at the mouth of the filament's V-notch.

The solid angle used is a rectangular pyramid whose longer base dimension is vertical. The size of the solid angle is defined by the vertex angles at the apex of the pyramid. The vertex angles are 0.125 radians (7.16 degrees) in the vertical plane and 0.0625 radians (3.58 degrees) in the horizontal plane.

The bandpass of the spectroradiometer varies from 0.6 nm at 225 nm, to 2.2 nm at 655 nm, to 1.6 nm at 2400 nm.

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*For lamps that have not been burned for more than three weeks, a warm-up time of at least two hours is recommended.

IV. Mapping

Translational and rotational mapping about the aligned position are performed on each test lamp at 654.6 nm. The variation in spectral radiance is measured as the filament is translated horizontally and vertically along lines which intersect at the centroid of the target area. The horizontal translation is done along a line, x, parallel to the width of the filament and the vertical translation is done along a line, y, parallel to the length of the filament. The variation in spectral radiance of the target area is mapped as a function of the angle of rotation about three mutually perpendicular axes which intersect at the centroid of the target area. Rotation about the horizontal axis in the filament plane is denoted θ_x. Rotation about the vertical axis in the filament plane is denotated θ_y. Rotation about the optical axis is denoted θ_z.

V. Discussion

Table I gives typical values of spectral radiance for lamps of this type and typical values of the associated uncertainties. For each calibration run, the uncertainties are redetermined and these results are given in the Report of Calibration.

The change in spectral radiance for a change in lamp current has been measured at 654.6 nm for a typical lamp of the type issued for calibration. A one milliampere change corresponded to approximately a 0.013% change in spectral radiance. To calculate the approximate percent change per milliampere at other wavelengths, the following formula can be used:

$$\frac{\Delta L_\lambda}{\Delta i} \simeq \left(\frac{654.6}{\lambda} \times 0.013 \right) \text{\% per milliampere.}$$

The transmittance of the quartz window may be non-uniform. For a solid angle that is different from the one described above, the user must determine, by measurement, the appropriate corrections.

VI. References

[1] "The International Practical Temperature Scale of 1968", Metrologia, Vol. 5, p. 35-44 (1969).

[2] Kostkowski, H.J., D.E. Eriminy, and A.T. Hattenburg, "High-Accuracy Spectral Radiance Calibration of Tungsten-Strip Lamps", Advances in Geophysics, Vol. 14, p. 111-127 (1970).

[3] NBS Optical Radiation News No. 18, November 1976.

[4] Nicodemus, F.E., H.J. Kostkowski, and A.T. Hattenburg, Self-Study Manual on Optical Radiation Measurements: Part I -- Concepts, Chapters 1 to 3, Nat. Bur. Stand. (U.S.), Tech Note 910-1, p. 52 (March 1976).

[5] Blevin, W.R., "Corrections in Optical Pyrometry and Photometry for the Refractive Index of Air", Metrologia, Vol. 8, p. 146-147 (1972).

[6] Coleman, C.C., W.R. Bozman, and W.F. Meggers, Table of Wavenumbers, Vols. 1 and 2, Nat. Bur. Stand. (U.S.), Monograph 3 (May 1960).

[7] Saunders, R.D. and J.B. Shumaker, "An Automated Radiometric Linearity Tester", (submitted to Applied Optics).

TABLE I

SAMPLE OF DATA AND UNCERTAINTIES

Typical Spectral Radiance Values and Estimated Uncertainties (Percent)

	Wavelength (nm) 225	350	654.6	800	1550	2400
Spectral Radiance ($W\ cm^{-3}\ sr^{-1}$)	6.679	3.427×10^3	1.369×10^5	1.999×10^5	1.237×10^5	3.756×10^4
Blackbody Temperature (K IPTS-68)	26[illegible].7	2616.9	2472.7	2395.5	1979.7	1616.1
SOURCE OF UNCERTAINTY						
1) Blackbody quality	0.29%	0.1[illegible]%	0[illegible]	0.03%	0.09%	0.11%
2) Calibration of Automatic Optical Pyrometer relative to the International Practical Temperature Scale (IPTS-68)	2.09	1.34	0.74	0.62	0.36	0.25
3) Temperature determination of blackbody and transfer of blackbody spectral radiance to lamp	1.16	0.48	0.2[illegible]	0.[illegible]	[illegible].17	0.21
4) Polarization effects	--	0.01	0.04	0.05	0.08	0.13
5) Current measurement	0.14	0.09	0.05	0.04	0.02	0.01
6) Wavelength measurement	0.04	0.02	0.01	0.01	0.01	0.01
7) Thermodynamic Temperature Scale relative to IPTS-68	1.43	0.93	0.49	0.40	0.20	0.13
Total estimated uncertainty relative to S.I. (square root of the sum of the squares of the individual uncertainties)	2.8%	1.7%	0.9%	0.8%	0.5%	0.4%

Optical Radiation News

Prepared by the staffs of the Optical Radiation and the Radiometric Physics Sections of NBS to report on items of interest in optical radiation measurements. Inquiries may be directed to Robert L. Booker, B308 Metrology Bldg., NBS, Washington, D.C. 20234 (301) 921-3864.

U.S. DEPARTMENT OF COMMERCE National Bureau of Standards

NO. 18 November 1976

FASCAL

The Facility for Automated Spectroradiometric Calibrations (FASCAL), the most recent and ambitious product of the Optical Radiation Section's automation efforts, has reached a stage of development whereby routine spectral irradiance calibrations have been automatically performed on this equipment since June.

Since there have been no previously published descriptions of this facility, its main technical features will be described here in some detail along with a description of current usage.

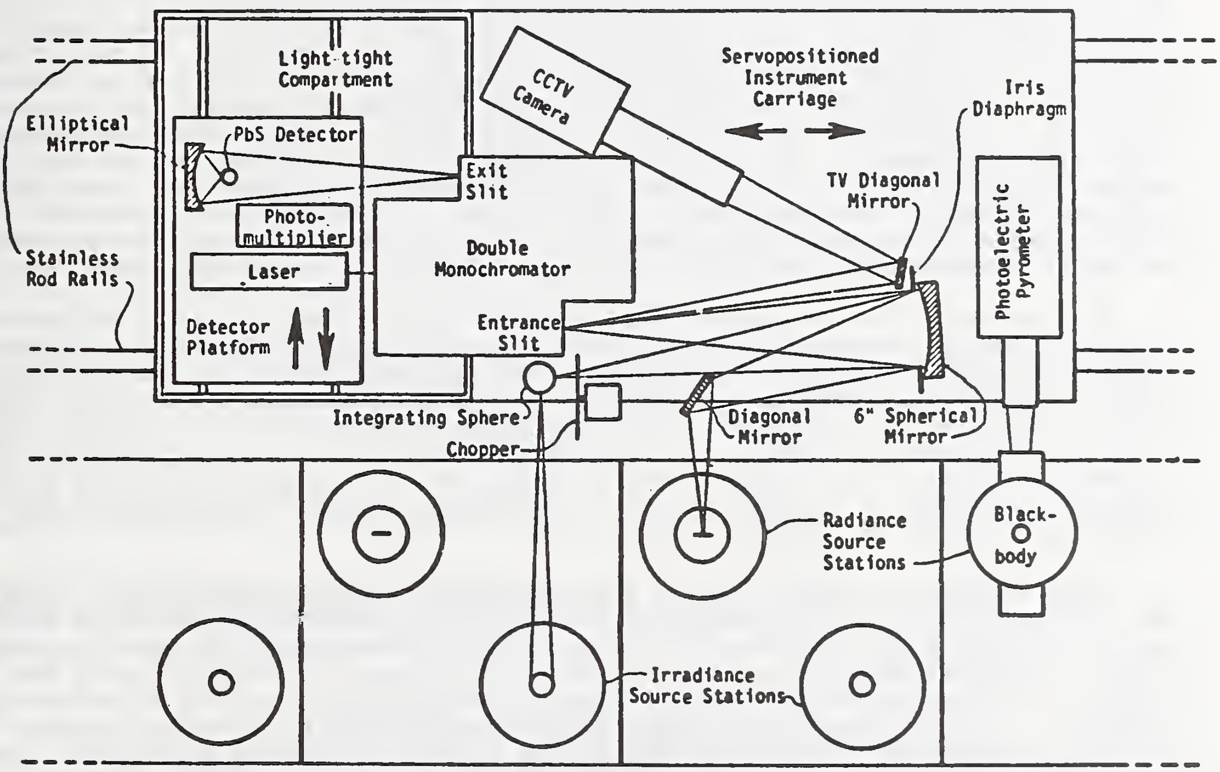

Figure 1. OPTICAL ARRANGEMENT OF FASCAL SYSTEM

Top View

The FASCAL facility incorporates all of the usual elements required for precision temperature-based radiometry. They are configured in a linear arrangement, dominated by a heavy truss bridge structure 7.3 m long supporting a pair of ground 1¼-inch diameter stainless steel rails. These rails were carefully aligned by a laser beam to within ±.03 mm tolerance in straightness and parallelism. Riding the rails on linear ball bushings is an instrument carriage in the form of a rectangular box 240 cm long, 68 cm wide and 50 cm in height. All optical elements, dispersers and detectors are mounted within the carriage and can be positioned along the track to intercept the radiation from various radiation sources placed at stationary points alongside the rail structure. There are twenty-five available source mounting stations spaced along the length of the structure.

The instrument carriage is driven through roller chains by a digital servo-positioning system and may be automatically positioned with a resolution of 0.1 mm and a repeatability of 0.01 mm. Positioning speed is sufficiently rapid that an average move between two stations takes only about two seconds. The actual carriage position is tracked by an incremental rotary encoder which has a digital visual display. The digital position information is also entered into a minicomputer. There is a unique central position, designated the "home" position, to which the carriage may be driven at any desired time to verify the functioning of the incremental encoder and to reference it to an absolute scale.

The instrument carriage is divided into two compartments. One is light-tight and houses detectors, and the other contains optics and associated electronics. The latter compartment is almost entirely enclosed to minimize dust collection and scattered light. The optical arrangement of the instrument carriage is shown schematically in Figure 1. The dispersing element is a prism-grating double monochromator, mounted so that the exit slit is within the light-tight detector compartment. Monochromatic radiation from the exit slit can be directed to either of two detectors on a detector platform that can be positioned remotely. Radiation in the visible and ultraviolet is detected by a thermoelectrically cooled photomultiplier having an extended S-20 response, while infrared radiation is detected by a thermoelectrically cooled PbS detector placed at the focus of an elliptical mirror. The wavelength of the monochromator may be remotely set by a high-speed stepping motor with a resolution of .025 nm through a range of 200 nm to 2500 nm. An absolute encoder having .025 nm resolution permits the actual wavelength setting to be visually displayed and entered into the computer. A He-Ne laser, also mounted on the detector platform, can be automatically positioned so that its beam passes through the monochromator and optics in the reverse direction to facilitate alignment of optics and sources.

The fore-optics are arranged to enable measurements to be made on either radiance or irradiance sources. Radiance sources are focused on the entrance slit by a 6-inch diameter spherical mirror with the optical path being turned approximately 90° by a flat diagonal mirror. The spherical mirror is rotated a few degrees for irradiance measurements. This allows the exit aperture of a small integrating sphere to be imaged on the entrance slit of the monochromator. Irradiance sources are placed 50 cm from the entrance aperture of the integrating sphere, and extensive light baffling of the irradiance sources and sphere minimizes the effects of scattered light. A motor-driven chopper is positioned in the optical path when the PbS detector is used.

The monochromator entrance slit is almost completely inaccessible to direct viewing due to the enclosures, baffling and closely packed optical elements and associated equipment. To provide a view of this slit, a closed-circuit television (CCTV) camera is mounted within the carriage and focused on the monochromator entrance slit through a small flat mirror mounted near the 6-inch spherical mirror. This has been invaluable in the initial alignment of radiance sources and in monitoring the positioning of the source image on the slit (or slit mask used to limit the slit height) during the course of experiments. The image of the entrance slit is magnified some twenty-five times such that the notch on tungsten strip lamps imaged onto the slit is readily observable on the monitor screens.

The instrument carriage also houses ancillary equipment such as power supplies for the thermoelectric coolers, a remotely programmable high-voltage power supply for the photomultiplier, and an automatic photoelectric pyrometer. The latter is focused on the radiance sources, including a variable-temperature, graphite-tube blackbody source that occupies the "home" position.

Cables from all equipment housed in the instrument carriage are bundled and passed through the bottom of the carriage, where they ride in a smooth trough between the rails as the carriage passes back and forth. All control and measurement cables from the carriage and source supplies lead to the operator's console.

Measuring instruments and equipment to communicate with the operator and the computer are housed in the console. The operator interface consists of analog and digital displays, a CCTV monitor displaying the monochromator entrance slit and a CRT terminal and keyboard. Instrumentation includes a 5½ digit DVM, a lock-in amplifier, a picoammeter, and remote controls for eight source power supplies. A MIDAS system[1,2] provides the interface between instruments and computer. All measurement signals are multiplexed into the DVM through the MIDAS scanner, and all instruments may be remotely programmed and controlled through MIDAS modules. In addition, the current supplied to the lamp sources can be automatically monitored and controlled.

The MIDAS controller communicates serially at a rate of 1200 baud with a minicomputer having 32 K of core memory. The computer is equipped with a high-speed disk system for program and data file storage. It is operated in a time-shared mode so that it can service other experiments, in addition to FASCAL, simultaneously. Programming is done exclusively in BASIC interactive language.

FASCAL is currently being used for routine spectral irradiance calibrations. These calibrations are carried out on groups of twelve 1000 W tungsten-halogen lamps preselected for stability, spectral composition, and directional uniformity. Three lamps from the group and one of our in-house standards (calibrated as described in the soon-to-be-published NBS Tech Note 594-13) are mounted in four of the outer row of lamp stations shown in Figure 1. Lamp alignment is accomplished with "reverse optics" using the laser in the detector compartment and a special alignment jig that is interchangeable with the integrating sphere. This jig includes a diagonal mirror that directs the laser beam to the lamp station for positioning the lamp in the plane perpendicular to the optical axis, and a 50 cm arm terminating in a dial gauge for setting the lamp-to-detector distance. Using the integrating sphere input to the monochromator, these four lamps are then intercompared automatically by FASCAL at our twenty-six customary wavelengths. Then another three lamps and a different in-house standard are measured in the same way. This process is performed sixteen times, with permutations of lamps and stations, until each of the twelve lamps has been compared against each in-house standard and each of the sixteen lamps has been measured in each of the four lamp stations. The redundancy of these measurements permits us to sense any systematic errors. For example, any dependence upon lamp station, or discrepancy among our four in-house standards would be thoroughly investigated.

We are now in the process of adding routine spectral radiance calibrations to FASCAL's repertoire. This is a more complicated problem requiring the rest of the features of FASCAL and we hope to report on these calibrations in the near future.

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[1] Optical Radiation News, No. 8 (March 1975).

[2] C. H. Popenoe and M. S. Campbell, MIDAS, Modular Interactive Data Acquisition System -- Description and Specification, NBS Tech Note 790 (August 1973).

A NEW TECHNIQUE FOR TRANSLUCENCY EVALUATION

The translucent phenomenon that causes flux loss in spectrophotometric measurements involving a finite-size sample port is well recognized. A technique utilizing an integrated point spread function and laser and conventional light sources has been developed by J. J. Hsia of the spectrophotometry group in the Radiometric Physics Section. The details of the method, mathematical derivation, experimental set ups, and results are described in NBS Technical Note 594-12, "The Translucent Blurring Effect - Method of

Evaluation and Estimation", which is now available. Inquiries concerning this technique and its possible use in error evaluation and estimation should be directed to:

Dr. Jack J. Hsia
Room A317, Metrology Building
National Bureau of Standards
Washington, D.C. 20234

Phone: (301) 921-2791.

Copies of Tech Note 594-12 are now being distributed to CORM members. Copies may also be obtained from the Superintendent of Documents, U. S. Government Printing Office, Washington, D.C. 20402. Order by SD Cat. No. C13.46:594-12, Price 75¢. Contact the editor of this newsletter if difficulty is encountered.

Appendix C. Measurement of Instrument and Source Polarization

The measurement of source polarization and the determination of its effect on the measurement of spectral radiance is carried out with a sheet polarizer mounted in a motorized rotating mount. This mount fits a slot milled into a bracket attached to the front of the spectroradiometer. By this means the polarizer can be reproducibly positioned in the same location between the source and the spectroradiometer whenever required.

Before the polarizer can be used for source polarization measurements its polarization and that of the spectroradiometer must be measured. This is accomplished with the help of an integrating sphere and a second polarizer similar to the first. The integrating sphere is mounted in the radiometer source plane so that its exit port serves as a source of unpolarized radiance. Its entrance port, located at about 90° from the exit port, is irradiated with a suitable light source, such as a quartz-halogen lamp. Then a series of spectral radiance measurements of this source is recorded: a) with no polarizer, b) with the first polarizer in its slot, c) with the second polarizer added in a second milled slot in the mounting bracket between the first polarizer and the source, and, d) with the first polarizer removed leaving only the second polarizer. At each wavelength of interest measurements are taken as a function of polarizer orientation as the polarizers are rotated about the optic axis. The first polarizer is typically sampled every 15° and the second every 30°. The second polarizer is tilted in its mount by about 10° to avoid polarizer-polarizer interreflections. All of these measurements are automated and require typically about an hour at each wavelength.

In the analysis of this data we write the first row Mueller matrix elements of the spectroradiometer responsivity as

$$R = R_o \begin{vmatrix} 1 & B & 0 & 0 \end{vmatrix} \qquad (1a)$$

where R_o is the ordinary responsivity neglecting polarization and we take the reference direction for polarization to be in whatever direction the radiometer polarizance lies, thus forcing the 45^{o} component to vanish. The reference direction was determined to be horizontal by simply observing the effect of a hand-held polarizer of known polarization axis upon a lamp measurement. The polarization axis of the polarizer, in turn, was confirmed by viewing sunlight reflected at glancing incidence through the polarizer. Circular polarization is assumed to be negligible for the type of instrument and sources employed here. The quantity B represents the degree of linear polarization of the spectroradiometer. The Mueller matrix of a polarizer is taken to be of the form

$$P = \begin{vmatrix} s & dC & dS & 0 \\ dC & eC^2+f & gSC & 0 \\ dS & X & X & X \\ 0 & X & X & X \end{vmatrix} \qquad (2a)$$

where $C = \cos 2(\phi - \phi_0)$, $S = \sin 2(\phi - \phi_0)$ and the parameters s, d, e, f, g, and ϕ_0 are obtained by least-squares fitting of the measurements. The angle ϕ is the orientation angle of the polarizer read from a scale on the polarizer mount. The matrix elements marked X are not involved in these measurements. This form of the Mueller matrix was found, by trial and error, to fit our data well. The simpler model of an ideal dichroic polarizer in which e = s and g = s-f (where, in terms of the principle transmittances k_1 and k_2, we have $s=[k_1+k_2]/2$ and $d=[k_1-k_2]/2$) is adequate for our visible and infrared polarizers but fails to fit the ultraviolet polarizer data. Finally, the Stokes vector of the unpolarized source is given by

$$L = L_o \begin{vmatrix} 1 \\ 0 \\ 0 \\ 0 \end{vmatrix} \qquad (3a)$$

The various measurements then lead to equations of the following forms.

$$\text{No polarizer:} \quad V = \mathbf{R} \cdot \mathbf{L} = R_o L_o \tag{4a}$$

$$\text{Polarizer \#1:} \quad V(\phi) = \mathbf{R} \cdot \mathbf{P} \cdot \mathbf{L} = R_o L_o (s+BdC) \tag{5a}$$

$$\text{Both polarizers:} \quad V(\phi,\phi') = \mathbf{R} \cdot \mathbf{P} \cdot \mathbf{P'} \cdot \mathbf{L} \tag{6a}$$

$$= R_o L_o (ss'+Bs'dC+dd'CC'+Bd'fC'+dd'SS'+Bd'gSCS'+Bd'eC^2C')$$

$$\text{Polarizer \#2:} \quad V(\phi') = \mathbf{R} \cdot \mathbf{P'} \cdot \mathbf{L} = R_o L_o (s'+Bd'C') \tag{7a}$$

where $C' = \cos 2(\phi' - \phi_0')$, $S' = \sin 2(\phi' - \phi_0')$, and V represents the recorded radiometer signal output as a function, in general, of polarizer orientation angles. Altogether our measurements produce about 200 equations. The values of the ten unknowns s, s', d, d', e, f, g, B, ϕ_0 and ϕ_0' are then obtained by a non-linear least squares solution. As far as polarization is concerned the parameters s, d, e, f, g, and ϕ_0 completely characterize the first polarizer, at least within the accuracy of the model represented by the Mueller matrix of eq. (10), and the parameter B characterizes the spectroradiometer. Since the factor $R_o L_o$ is common to all equations these measurements yield no information about it.

Using the characterized polarizer and radiometer we are now able to measure the polarization of an unknown source by recording spectroradiometer measurements obtained from the source: a) without a polarizer, and b) with the first polarizer again mounted on the bracket as when it was characterized. As before, the measurements are made at 15^o intervals of the polarizer. We take the Stokes vector of the unknown source to be

$$L = L_o \begin{vmatrix} 1 \\ p_1 \\ p_2 \\ 0 \end{vmatrix} \qquad (8a)$$

where, as always, we have neglected circular polarization. p_1 and p_2 are given by $p_1 = p \cdot \cos 2\gamma$ and $p_2 = p \cdot \sin 2\gamma$, where γ is the direction of polarization measured from the reference direction of the radiometer and p is the degree of polarization,

$$p = (Lmax - Lmin)/(Lmax + Lmin) \; . \qquad (9a)$$

In Eqn. 17 Lmax and Lmin are the maximum and minimum readings of a polarization-indifferent radiometer when an ideal linear polarizer is rotated in the source beam. Then our measurements lead to a no-polarizer equation:

$$V = R_o L_o (1+Bp_1) \qquad (10a)$$

and to 24 equations:

$$V(\gamma) = R_o L_o [(s+BdC) + (dC+BeC^2+Bf)p_1 + (dS+BgSC)p_2] . \qquad (11a)$$

Aside from the factor $R_o L_o$ which is common to all equations and cancels out, the only unknowns in these 25 equations are p_1 and p_2 which we can then obtain by a least-squares solution. These two parameters completely characterize the state of (linear) polarization of the source. Normally, only the second described experiment of 25 measurements need be performed to measure the polarization of a source since the polarizers and radiometer are relatively stable and, once characterized, will only infrequently need to be remeasured.

Equation (10a) gives the relationship between the spectral radiance of a source, L_o, and the radiometer output signal, V, assuming linearity of response and only linear polarization. If we apply this equation both to the measurement of an unknown source and to the measurement of a spectral radiance standard used to calibrate the radiometer we obtain:

$$L_o = L_o^s[V/V^s][(1+Bp_1^s)/(1+Bp_1)] \qquad (12a)$$

where L_o^s is the known spectral radiance of the standard, V/V^s is the measured signal ratio, B is the radiometer polarizance, and p_1^s and p_1 are the relative Stokes components measured as described above for the standard and for the unknown source. (For a blackbody standard, presumably, $p_1^s = 0$.) This shows that the presence of polarization introduces the extra factor

$$(1+Bp_1^s)/(1+Bp_1)$$

into the simple measurement relationship which is valid in the absence of source polarization or if the radiometer is indifferent to polarization.

The polarization measurement uncertainty by this process can be judged by the statistics of the least-squares fitting and by the measurement reproducibility when different polarizers are used. Both indications suggest typical uncertainties (one standard deviation) in the visible where the polarizers are very good and the noise level very low of ± 0.0003 in the radiometer polarizance B and uncertainties of ± 0.001 in the source relative Stokes components p_1 and p_2.

DETAILED PROCEDURES FOR ROUTINE SPECTRAL RADIANCE CALIBRATIONS

A. Lamp Preparation

1. Visual Inspection

The lamp that is issued as a spectral radiance standard is a specially made lamp from General Electric designated type 30A/T24/13. Upon unpacking, each lamp is inspected to see that

a. the quartz nozzle has a clear window
b. the filament is within 2mm of being centered in the window
c. the area of the lamp envelope opposite the window does not have striations which distort the view of the filament
d. the filament has electrical continuity with the electrodes.

2. Initial Lighting

Each lamp is positioned in a lamp mount, power is applied, and the current is set at 35 amperes. If the lamp does not fail, then the next step in the lamp preparation procedure is performed.

3. Annealing

An automatic pyrometer is used to set each lamp at approximately 2350°C where it is annealed for 2 hours.

4. Arrowing

In order to accurately reproduce the alignment of each lamp, an alignment arrow is etched on the rear of the lamp envelope.

a. Turn the lamp on and set it at approximately 1700°C.

b. Position and orient the lamp so that the Helium Neon laser beam defining the optical axis of the spectroradiometer (see A.5.b.) is normal to the viewing window and passes through the notch on the lamp filament.

c. Make a small dot with a marking pen on the rear of the lamp envelope at the point where the laser beam strikes.

```
******************************************
*                 CAUTION                *
******************************************
* Great care should be taken to avoid    *
* any direct eye contact with the laser  *
* beam.  Either position a blocking      *
* finger on the 45 degree plane mirror   *
* to block the direct beam or translate  *
* the lamp horizontally so that the lamp *
* filament blocks the beam.              *
******************************************
```

d. Align a viewing scope behind the lamp so that the scope is normal to and views along the optical axis of the spectroradiometer defined by the laser beam (see A.5.h.).

e. Block off the laser beam.

f. Using the scope (with a small aperture on the objective lens to improve the depth of field), view the position of the dot relative to the notch in the filament and draw a picture of the relationship.

g. Draw an arrow on the picture with its tip centered on the mouth of the notch and pointing into it.

h. Turn off the lamp and remove it from the mount.

i. Paint an etching wax solution on the area of lamp envelope containing the small dot.

j. Allow the etching wax to dry for at least 20 minutes and then using a sharp needle and a transparent straightedge, scribe a small arrow in the wax at the location relative to the dot indicated by the drawing.

k. Position a small wax ring around the area to be etched to prevent acid from etching unwaxed portions of the lamp envelope.

l. Using a small paintbrush, put a droplet of hydrofluoric acid on the scribed arrow.

```
******************************************
*                 CAUTION                *
******************************************
* Do not allow the hydrofluoric acid to  *
* contact the skin. Rinse thoroughly     *
* with cold water if skin contact occurs.*
******************************************
```

m. After 3 minutes, rinse off the acid with cold water, clean off the etching wax with xylene, and wash the entire lamp envelope and nozzle with Sparkleen and hot water. Then dry thoroughly with Kimwipes to remove any waterspots.

```
*****************************************
*               CAUTION                 *
*****************************************
* Avoid any direct breathing of the     *
* xylene vapors.                        *
*****************************************
```

5. Lamp Alignment

A precise technique for lamp alignment has been developed and must be followed each time a lamp is aligned. A highly polished stainless steel mask with an 0.8 mm square cut in it is positioned just in front of the entrance slit of the monochromator (with the cutout square centered on the slit). The image of a source is focussed onto this mask and is reflected back toward a low light level TV camera. The image from the camera is viewed on a TV monitor and is used when performing alignments. Neutral density filters can be placed in front the objective lens of the TV camera to prevent high level sources from saturating the vidicon tube.

a. Set the monochromator wavelength to 632.8 nm (the Helium Neon laser wavelength).
b. Turn on and position the alignment laser located in the detector box portion of the monochromator.
   1) Push the LASER button on the detector positioning controller circuit.
   2) Position a white card in front of and centered on the focussing mirror of the spectroradiometer.
   3) Manually rotate the detector positioning wheel about 1 and 1/3 turns clockwise until a maximum signal from the laser beam appears on the white card.
   4) The laser beam exiting from the entrance slit of the monochromator and reflecting off the mirror surfaces defines the optical axis of the spectroradiometer. The laser beam can now be used to aid in source alignment.
c. Let the alignment laser stabilize for 20 minutes.
d. With the lamp off, orient it so that the laser beam passes through the notch in the lamp filament and the tip of the arrowhead on the rear of the lamp envelope.

e. Turn on the lamp and let it stabilize for 20 minutes.

```
******************************************
*                CAUTION                 *
******************************************
* When turning a lamp on or off the      *
* current should be slowly increased or  *
* decreased.  A period of 40 seconds to  *
* 1 minute should be taken to slowly     *
* increase the lamp current to its       *
* operating value or to slowly decrease  *
* the lamp current to turn it off.       *
******************************************
```

f. Use a plumb line to make the notch side of the lamp filament vertical.

g. Focus the lamp filament onto the entrance slit of the monochromator to plus or minus 2.5 mm.
   1) Replace the reflective mask in front of the monochromator slits with a white opaque mask.
   2) Remove any neutral density filters from in front of the TV camera.
   3) While viewing the image of the lamp filament on the TV monitor, translate the lamp in a direction parallel to the optical axis of the spectroradiometer. Continue to perform this translation until the filament is at its best focus on the TV monitor.
   4) Replace any neutral density filters removed in step 2).
   5) Replace the white opaque mask in front of the monochromator with the reflective mask.

h. Position a viewing scope behind the lamp looking along the optical axis of the spectroradiometer. Orient the scope so that the laser beam passes through the center of the objective lens when the lamp filament is in focus at the center of the field of view.
   1) Translate the lamp filament horizontally so that the laser beam passes along side it and exits through the rear of the lamp envelope.
   2) Position a viewing scope behind the lamp and looking toward the spectroradiometer.
   3) Adjust the viewing scope so that the laser beam passes through the center of the objective lens (a small aperture can be placed on the objective lens to help locate its center).
   4) Translate the lamp filament to block the laser beam.
   5) Adjust the scope so that the image of the lamp filament at the notch is centered in the field of view.

6) Repeat steps 3) to 5) until the laser beam is centered on the objective lens while the image of the filament notch is centered in the field of view.

i. Position a "blocking finger" on the 45 degree plane mirror on the spectroradiometer. Rotate the arrow 2 degrees out from the notch and translate the lamp so that the monochromator slit image can be viewed.

j. Translate the lamp vertically until the filament notch is vertically centered on the slit image.

k. Translate the lamp horizontally to approximately center the slit image behind the lamp filament.

l. Put a small aperture on the objective lens of the scope to improve the depth of field, adjust the focus of the scope, and adjust the rotation and the tilt of the lamp filament until the tip of the arrow is aligned at the notch.

m. Set the dial setting to read zero for the lamp base rotation adjustment.

n. Remove the aperture, rotate the arrow out 2 degrees, and translate the lamp horizontally to view the slit image.

o. Translate the lamp vertically until the filament notch is vertically centered on the slit image.

p. Rotate back to the zero setting on the rotation adjustment.

q. Translate the lamp horizontally to get a left edge and a right edge reading of the slit image on the horizontal translation scale.

r. Calculate the reading for which the slit image will be centered on the lamp filament then translate in the horizontal and set that reading.

s. Recheck the focus.

t. Repeat steps k. and l.

u. If the rotation or tilt was changed significantly, then repeat steps m. to r.

B. Preliminary Measurements

1. Stability Measurements

Stability measurements are made in order to determine an approximate drift rate on each lamp. The measurements are performed at 654.6 nm and at either 400 or 350 nm. The computer program used to perform the stability measurements is "RCSTAB2.LIN". (This program reads lamp currents, sets wavelength, positions the spectroradiometer takes the detector readings for the lamps and a shutter position, and performs the calculations to determine the ratios of the test lamp readings to the reference lamp readings.)

a. Test lamps are set at a current to give them a radiance temperature of about 2470 K at 654.6 nm. (This current is usually between 38 and 43 amperes.)
b. The test lamps are allowed to stabilize at this level for about one hour.
c. The radiometric output of the test lamps is then measured and compared to the radiometric output from a highly stable reference lamp at 654.6 nm and also at either 400 or 350 nm.
d. The reference lamp is turned off and the test lamps are burned overnight (20 to 24 hours).
e. The reference lamp is turned back on and the radiometric output from the test lamps is measured again and compared to the output from the reference lamp at the same two wavelengths.
f. The two ratios of each test lamp to the reference lamp are used to determine the percent change in the output of each test lamp and a drift rate is calculated.

2. Mapping Measurements

Translational and rotational mappings about the aligned position are performed on each test lamp at 654.6 nm. The lamp mounts have been motorized so that automated mappings can be performed. The computer program used to perform the mapping measurements is "RADMAP3.CRO". The mappings performed are

a. Translation along the horizontal axis
b. Translation along the vertical axis
c. Rotation around the horizontal axis
d. Rotation around the vertical axis
e. Rotation around the optical axis

Mapping is not performed for focussing because spectral radiance is not critical with respect to focus.

3. Polarization Measurements

Because the spectroradiometer has significant polarization (0.26 at 654.6 nm and 0.85 at 2400 nm), it is necessary to measure the polarization of each test lamp so that a polarization correction can be made.

a. Use two polarizers to characterize the polarizers and the spectroradiometer (see Appendix 3). Two motorized polarizers are used to do an automated characterization at 654.6 nm. The computer program used to perform these measurements is "TWOPOL.JW".

b. Use one polarizer to characterize the polarization of the test lamp. The computer program used to perform these measurements is "ONEPOL.JW".

C. Calibration Procedures

1. Blackbody Turn On Procedure

a. Turn on cooling water and check for flow.
b. Turn blackbody power switch ON.
c. Turn null detector microvoltmeter ON.
d. Zero null detector on 100 microvolt scale and check batteries.
e. Blackbody Flushing Procedure
   1) Turn on vacuum line and wait 30 seconds.
   2) Turn on Argon flow using valve on the copper line.
   3) Turn off vacuum line, let Argon flow until pressure gauge on vacuum line reads 1 atmosphere and turn off Argon flow.
   4) Wait 2-3 minutes to allow Argon to diffuse within the blackbody housing.
   5) Turn on vacuum line and let pump for 30-60 seconds.
   6) Repeat steps 2) to 5) three more times.
   7) Turn on Argon flow, turn off vacuum line and when the pressure gauge reads 1 atmosphere, unplug the vacuum line and check for Argon exhaust flow.
   8) Adjust the Argon flow valve on the copper line so that the flow gauge reads 8 CFH.
f. Plug in blackbody alarm and turn switch ON. This alarm will output a warning signal if the Argon flow is too low or if blackbody housing starts heating up.

```
*******************************************
*                 CAUTION                 *
*******************************************
* If the blackbody alarm sounds:          *
*   1) Check the Argon flow.              *
*   2) If Argon flow is normal then turn *
*      down blackbody by pushing the red *
*      button and throw breaker on back  *
*      wall to OFF position.              *
*   3) If  Argon flow is low then connect*
*      up a new tank of Argon and adjust *
*      the flows.                         *
*******************************************
```

g. Throw 208V breaker on the wall behind the spectroradiometer to ON position (Up).
h . Depress yellow button on C.A.T. control unit until meter reads about 30 and check that the top of the blackbody housing is cool and that the cooling water is flowing. (If not flowing, depress red button and return meter reading to zero.)
i. Let blackbody run at this level for 5-10 minutes.
j. Check for wanted temperature on the "T(BB) vs. O/P Current Read" plot and depress the yellow and red buttons until the O/P Current Read meter at the blackbody displays the wanted setting.
k. Allow about 10 minutes for the blackbody to stabilize at this setting.
l. Set the null detector to the 10 millivolt range and adjust the potentiometer setting until the monitor detector signal is nulled to zero.
m. Push the "AUTO" button to go into the automatic control mode.
n. Turn the null detector scale sensitivity switch counterclockwise until oscillation occurs and then back off one scale setting.
o. Allow 5-10 minutes for the blackbody to stabilize.
p. When ready to view the blackbody with the spectroradiometer
    1) Adjust the Argon flow valve on the green line so that its flow gauge reads 8 CFH.
    2) Adjust the Argon flow valve on the copper line so that its flow gauge reads 4 CFH.
    3) Open the blackbody window (turn counterclockwise).

2. Standard Lamp and Test Lamp Turn On and Alignment

Perform as described in A.5.

3. Adjust Blackbody Level

The blackbody level is adjusted so that its output approximately matches the output of the test lamps at 654.6 nm. The adjusting procedure is the same as described in C.1. j. to o.

4. Blackbody Alignment

Once the blackbody has stabilized at its operating temperature it is aligned as follows:

a. The spectroradiometer detector signal is converted to an analog voltage which is displayed on a strip-chart recorder.
b. The full scale signal is biased to about 5% of its original value and then is amplified by a factor of 10 so that one division on the strip-chart represents about 0.1% in radiance.
c. The blackbody is translated horizontally (in a direction perpendicular to the optical axis of the spectroradiometer) until the 1% drop offs are found on each side of center. These horizontal scale position readings are noted and the blackbody is translated until the scale reading is half way between the two readings.
d. A similar procedure is done using the vertical translation of the blackbody.
e. Step c. is repeated one more time.
f. The blackbody is rotated around the vertical axis passing approximately through the center of the blackbody rod until the 1% drop offs are found on each side of center. The rotational scale position readings are noted and the blackbody is rotated until the scale reading is half way between the two readings.
g. A similar procedure is done using rotation around the horizontal axis passing through the viewing opening of the blackbody rod.
h. Steps c. through e. are repeated one more time.

5. Data Taking Procedure

The computer program used to perform the routine spectral radiance calibration is "RCBB2A.LIN". The general data taking procedure is as follows.

a. Adjust the 1530 K standard lamp to its calibrated current.
b. With the spectroradiometer wavelength set at 654.6 nm, the spectral radiance output from the blackbody is compared to the spectral radiance output from the standard lamp.
    1) The spectroradiometer is positioned so that it is viewing the calibrated target area of the standard lamp. The photomultiplier output is amplified and converted to a voltage which is read with an integrating digital voltmeter (DVM). The DVM reading is recorded.
    2) The spectroradiometer is positioned so that it is viewing the opening in the blackbody rod. The DVM reading is recorded.
    3) The spectroradiometer is alternately positioned to view the standard lamp and the blackbody until a set of three readings is taken on each source.

4) The spectroradiometer is positioned in front of a shutter position and the DVM reading is recorded.
5) For each source the mean of the three DVM readings is calculated and the shutter reading is subtracted from it.
6) The resulting signal is corrected for the amplifier range on which it was taken and for the polarization of the source.
7) The ratio of the blackbody signal to the standard lamp signal is determined.

c. Set the spectroradiomter to the test wavelength and compare the spectral radiance output from each test lamp to the spectral radiance output from the blackbody. (The procedure is similar to the steps listed in section b. except the signals from several test lamps are compared to the signal from the blackbody.)
d. Set the spectroradiomter to 654.6 nm and repeat step b.
e. Using the mean ratio of the blackbody to the standard lamp and the known radiance temperature of the standard lamp, the Planck equation is used to determine the temperature of the blackbody. A small temperature correction is applied to account for the finite spectral bandpass.
f. The Planck equation is used to determine the spectral radiance of the blackbody at the test wavelength and the spectral radiance of the test lamps is determined.
g. For each test wavelength the spectral radiance and the blackbody temperature of each test source is saved to to one data file and the precision of the source comparisons is saved to a second data file.

6. Data Taking Sequence

a. Adjust blackbody level to approximately match the output of the test lamps at 654.6 nm.
b. Measure the test lamps at 654.6 nm using the photomultiplier tube.
c. Adjust blackbody level to approximately match the output of the test lamps at 250 nm.
d. Measure the test lamps at 250 nm using the photomultiplier tube.
e. Measure the test lamps from 2400 to 900 nm using PbS detector.
   1) Set at the test wavelength, position the PbS detector and adjust the blackbody level to approximately match (within 5%) the output of the test lamps. This is necessary because the responsivity of the PbS detector has not been accurately determined and it is being used at a signal level where saturation is beginning to occur.

2) Return to 654.6 nm, position the photomultiplier tube and determine the blackbody temperature by comparing its output to the output of the standard lamp.
3) Set at the test wavelength, position the PbS detector and compare the output from the test lamps to the output from the blackbody.
4) Repeat step 2).
5) Set at the next test wavelength and repeat steps 1) to 4).

f. Adjust blackbody level to approximately match the output of the test lamps at 654.6 nm.
g. Measure the test lamps from 900 to 300 nm using the photomultiplier tube.
h. Adjust blackbody level to approximately match the output of the test lamps at 250 nm.
i. Measure test lamps from 300 to 225 nm using the photomultiplier tube.
j. Adjust blackbody level to approximately match the output of the test lamps at 654.6 nm.
k. Measure test lamps at 654.6 nm using the photomulti- multiplier tube.

7. Standard Lamp and Test Lamp Turn Off

Turn lamps down slowly as described in CAUTION after section A.5.d.

8. Blackbody Turn Off Procedure

a. Turn null detector to the 100 millivolt scale.
b. Depress red button on the C.A.T. control unit and hold down until the meter reads zero and then continue to hold down for 4 more seconds.
c. Throw 208V breaker on the wall behind the spectroradiometer to OFF position (Down).
d. Turn the potentiometer setting to read zero.
e. Leave the cooling water and Argon flow on for at least 10 more minutes to give the blackbody time to cool down.
f. Turn off cooling water.
g. Turn off and unplug blackbody alarm.
h. Close blackbody window (turn clockwise).
i. Turn off the Argon flow on the green line.
j. Reconnect the vacuum and turn it on.
k. Turn off the vacuum line and allow the Argon to flow until the vacuum pressure gauge reads 1 atmosphere and then turn off the Argon flow valve on the copper line. Turn off valve at Argon supply tank.
l. Turn null detector microvoltmeter OFF.
m. Turn blackbody power switch OFF.

n. Read over "End of Day Check List" (located on K-6 Pot) and perform the necessary operations.
   1) Turn off the blackbody.
      a) Throw main breaker on back wall to off.
      b) Turn off cooling water.
      c) Close blackbody window and turn off Argon flow at the blackbody and at Argon tank.
      d) Turn off power switch on blackbody control panel and turn pot to zero.
      e) Turn off null detector microvoltmeter.
      f) Turn off and unplug blackbody alarm.
   2) Turn off auto pyrometer and cover objective with a lens cover.
   3) Turn off power supplies for positioning spectroradiometer and for setting wavelength.
   4) Turn off TV monitors (2) and TV camera.
   5) Turn off lamp power supplies and record off time.
   6) Shutter photomultiplier tube.
   7) Turn off potentiometer null detector.
   8) Turn off stepping motor power supplies.
   9) Cover 45° plane mirror with dust cover.
   10) Cover V25 with dust cover.
   11) Put back panel on spectroradiometer box.
   12) Address MIDAS using CRT keyboard:
      a) Open all switches (I8,J8).
      b) Push Clear button on MIDAS control board.
      c) Turn CRT power off.
   13) Remove floppy disks from disk drives.
   14) Turn printer off.
   15) Turn computer terminal power off.
   16) Turn all water off.

D. Data Reduction Procedures

1. Analysis of Spectral Radiance Data

Several computer programs are used to perform the analysis of the spectral radiance data.

a. Run "SPLITRAD.1" to split the main data file into a separate data file for each test lamp.

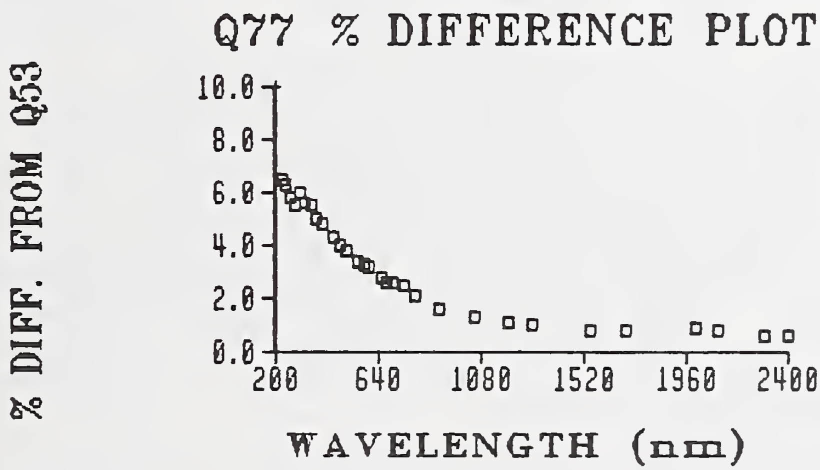
b. Run "REPDIF.1" to calculate the percent differences in repeat measurements during the calibration.

   Measurements are made at 654.6 nm at the start, near the middle, and at the end of the calibration. Measurements are made at 250 nm at the start and near the end of the calibration. Calculating the the differences for these repeat measurements allows for drift rates to be calculated and for drift corrections to be made if necessary.

c. Run "ORDERFL.1" to order the data by wavelength.

d. Run "FLANAL.1" to calculate the following statistics
   1) Number of measurements at each wavelength
   2) Range for repeat measurements
   3) Mean value
   4) Standard deviation of the mean

   and to store the wavelength, mean spectral radiance, and mean blackbody temperature in a data file.
e. Run "DELRAD.1" to calculate and store the percent difference at each wavelength between the spectral radiance of the test lamp and the spectral radiance of a reference lamp measured several years ago.
f. Run "PLOT" to plot the percent difference as a function of wavelength on the HP plotter.
g. The plot should form a smooth curve to about plus or minus 0.5% if the test data is good. Here is an example:



2. Analysis of Precision Data

The computer program "RAD'SD.RED" is used to calculate the the overall precision the source comparisons. This result is used in combination with the repeat measurement standard deviation of the mean in order to derive an overall uncertainty in the temperature determination of the blackbody and the transfer of the blackbody spectral radiance to a test lamp.

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[ ] Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

This report describes the measurement methods and instrumentation used in the realization and transfer of the NBS scale of spectral radiance. The application of the basic measurement equation to both blackbody and tungsten strip lamp sources is discussed. The determinations of the spectral responsivity function, response linearity, polarizance and "size-of-source effect" of the spectroradiometer are described. The analysis of sources of error and estimates of uncertainty are presented. The assigned uncertainties in spectral radiance range from about 1.75% at 225 nm to 0.25% at 2400 nm.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

blackbody; calibrations; response linearity; slit-scattering function; spectral radiance; standards.

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