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U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

Optical Radiation Measurements:

The 1973 NBS Scale of Spectral Irradiance

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PREFACE

This is the thirteenth issue of a series of Technical Notes entitled OPTICAL RADIATION MEASUREMENTS. The series will consist primarily of reports of progress in, or details of, research conducted in radiometry, photometry and spectrophotometry in the Optical Radiation Section and the Radiometric Physics Section of the Optical Physics Division.

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Any suggestions readers may have to improve the utility of this series are welcome.

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THE 1973 NBS SCALE OF SPECTRAL IRRADIANCE

R.D. Saunders and J.B. Shumaker

This note describes the measurement apparatus and techniques used in deriving the 1973 scale of spectral irradiance. The uncertainty of this scale is believed to be less than 2% in the spectral region 250 nm - 500 nm and less than 1% in the spectral region 500 nm - 1600 nm. This uncertainty represents a three-fold improvement over the previous NBS scale of spectral irradiance. The complete derivation of the projected solid angle, which is crucial when transferring from radiance to irradiance, is given. Also described in this note is a model for interpolating the spectral irradiance at wavelengths between the wavelengths measured. Measurement details are presented and sources of error are discussed.

Key words: Calibrations; interpolation formula; irradiance drift formula; projected solid angle; spectral irradiance; standards.

1. Introduction

Spectral irradiance, denoted E_λ, is defined as the radiant flux incident on a surface per unit wavelength and per unit area on the surface. Mathematically

$$E_\lambda = \frac{d^2\phi}{d\lambda\ dA}$$

where $d^2\phi$ is the element of flux and $d\lambda$ and dA are the elements of wavelength and area respectively.

In 1963, the National Bureau of Standards established a scale of spectral irradiance [1][1] using a group of 200-watt, quartz-halogen, tungsten coiled-coil filament lamps. Although these lamps were compact and relatively easy to use, the spectral irradiance below 400 nm was inadequate for many applications. For this reason, the scale was transferred to a group of 1000-watt, quartz-halogen lamps which increased the spectral irradiance by a factor of 5. The uncertainties assigned to this scale were about 3% in the visible-infrared spectral region and 8% in the ultraviolet spectral region.

A widespread need for higher accuracy led NBS, in the early 1970's to initiate development of an improved scale of spectral irradiance. The new scale, with estimated uncertainties about 1/3 that of the earlier scale, was first disseminated in September 1973. There have been 10 realizations of the scale, and the scale was used in an international

[1]Figures in brackets indicate the literature references on page 19.

comparison involving 8 national laboratories [2]. The current Tech Note is a detailed description of the realization of this new scale and of the uncertainties associated with it.

2. Derivation of Scale: An Overview

The National Bureau of Standards scale of spectral irradiance is derived from its scale of spectral radiance [3]. This is done by determining the average spectral radiance of a tungsten strip lamp image which is formed by an optical system subtending a well defined and measurable solid angle. Since the spectral irradiance at this image can be calculated from its spectral radiance and the solid angle, this establishes a spectral irradiance scale. As a matter of convenience the scale is transferred to a group of four 1000-watt quartz-halogen lamps using an integrating sphere - monochromator combination designed for spectral irradiance measurements. These lamps, then, which are recalibrated at roughly 100-burning-hour intervals, embody the 1973 NBS scale of spectral irradiance.

3. Measurement Apparatus

Figure 1 shows a schematic block diagram of the measurement apparatus. For purposes of discussion it is presented as consisting of the following six functional units:

1. Lamp Image System
2. Monochromator Fore-optics
   a. Integrating sphere
   b. Imaging optics
3. Monochromator
4. Detection System
5. Data Acquisition System
6. Lamp Mounts and Power Suppliers

1. Lamp Image System The lamp image system consists of a tungsten strip lamp in a holder and a spherical mirror in a three-point adjustable mount both attached to a three-legged adjustable table. An aluminum fast-coated (peak reflectance is obtained if aluminized in less than 10 seconds) front surface mirror forms an image of the strip filament of the radiance lamp with approximately unit magnification. Directly in front of the spherical mirror is a calibrated aperture used to define the solid angle from which the flux irradiates the sphere.

In the method developed for realizing the improved scale of spectral irradiance, the current of the tungsten strip lamp is adjusted until the output signal from the measurement apparatus is equal when observing either the irradiance lamp or the image of the strip lamp. The equality of output signals is represented mathematically by

$$\int_{\Delta\lambda}\int_{\Delta A} E_{\lambda}\ dA\ d\lambda\ R \ = \ \int_{\Delta\lambda}\int_{\Delta A}\int_{\omega} L_{\lambda}\ \cos\theta\ d_{\omega}\ dA\ d\lambda\ R,$$

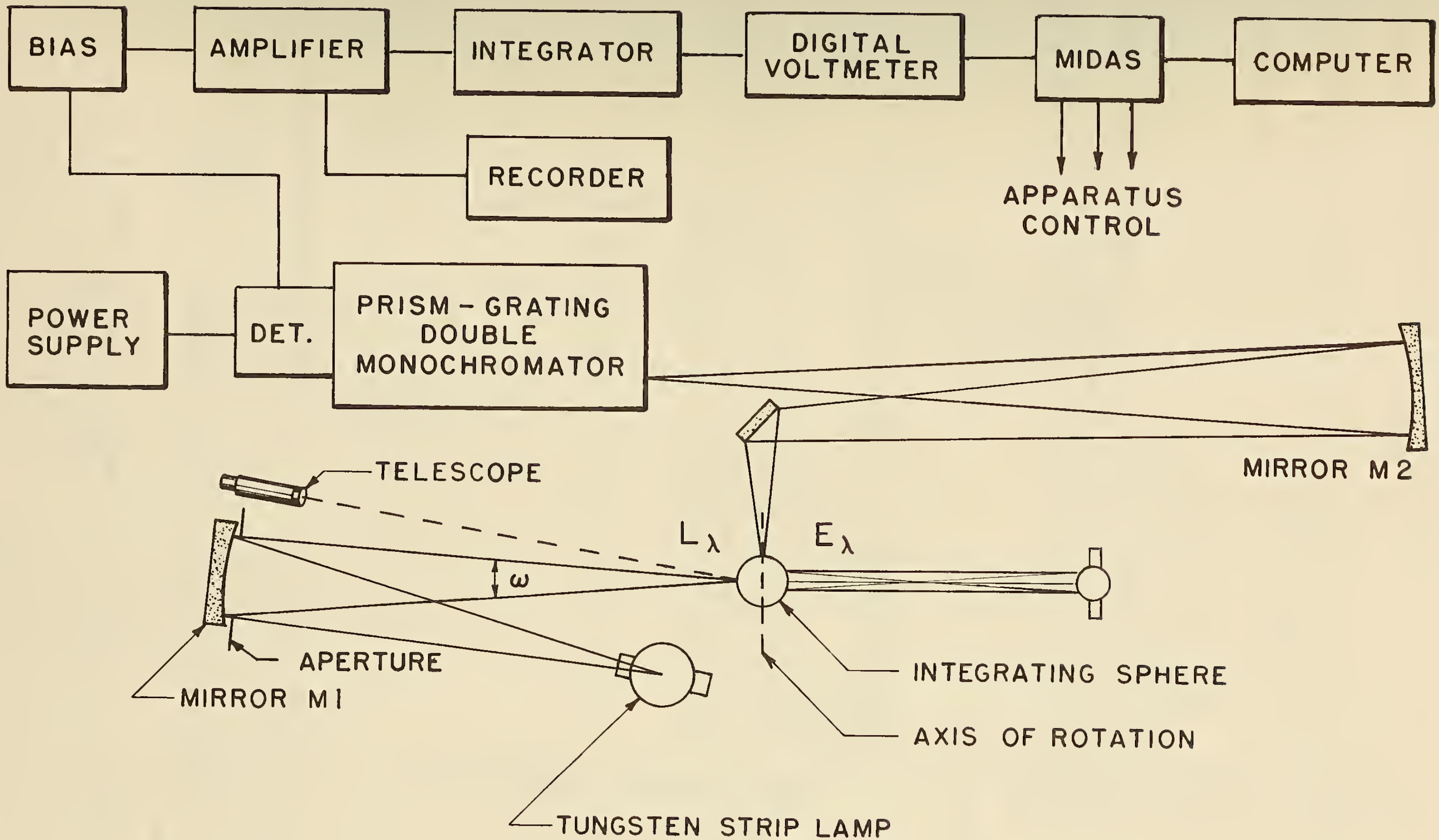

Figure 1. Block Diagram of the Measurement Setup used to Realize the Scale of Spectral Irradiance from the Scale of Spectral Radiance.

where

E_λ = spectral irradiance at a particular point of the integrating sphere entrance aperture.

L_λ = spectral radiance of the strip lamp image at a particular point and direction at the sphere entrance aperture.

ω = solid angle subtended by the calibration aperture at the sphere entrance aperture.

ΔA = area of sphere entrance aperture.

$\Delta\lambda$ = spectral band pass of monochromator.

R = responsivity of measurement apparatus; that is, element of output signal per element of flux incident on sphere entrance aperture.

θ = the angle between a ray from the mirror and the normal to the plane surface of the entrance aperture.

This equation can be rewritten as

$$\bar{E}_\lambda \int_{\Delta\lambda}\int_{\Delta A} dA\, d\lambda\, R = \bar{L}_\lambda \int_{\Delta\lambda}\int_{\Delta A}\int_\omega \cos\theta\, d\omega\, dA\, d\lambda\, R,$$

where $\bar{E}_\lambda$ and $\bar{L}_\lambda$ are average values weighted by the two integrands respectively. Assuming that the responsivity is independent of the direction of incidence of an element of flux and that $\int_\omega \cos\theta\, d\omega$ has the same value at every point of ΔA,

$$\bar{E}_\lambda \int_{\Delta\lambda}\int_{\Delta A} dA\, d\lambda\, R = \bar{L}_\lambda \left(\int_{\Delta\lambda}\int_{\Delta A} dA\, d\lambda\, R\right) \left(\int_\omega \cos\theta\, d\omega\right)$$

and

$$\bar{E}_\lambda = \bar{L}_\lambda \int_\omega \cos\theta\, d\omega.$$

The projected solid angle, $\int_\omega \cos\theta\, d\omega$, has been numerically integrated with an estimated calculation uncertainty of less than 0.01%. A detailed discussion of the evaluation of this integral is given in the appendix. For the 75 cm radius of curvature and 14 cm aperture of the imaging mirror used in this work the projected solid angle varies by less than .01% over the .06 × 5.6 mm area ΔA.

The average spectral radiance of the image, $\bar{L}_\lambda$, is determined by comparison to a calibrated tungsten strip lamp as shown in figure 2. Ideally in performing this measurement, ΔA and ω should be the same as when making the spectral irradiance comparison with the integrating sphere. Otherwise the averaged spectral radiance may be different

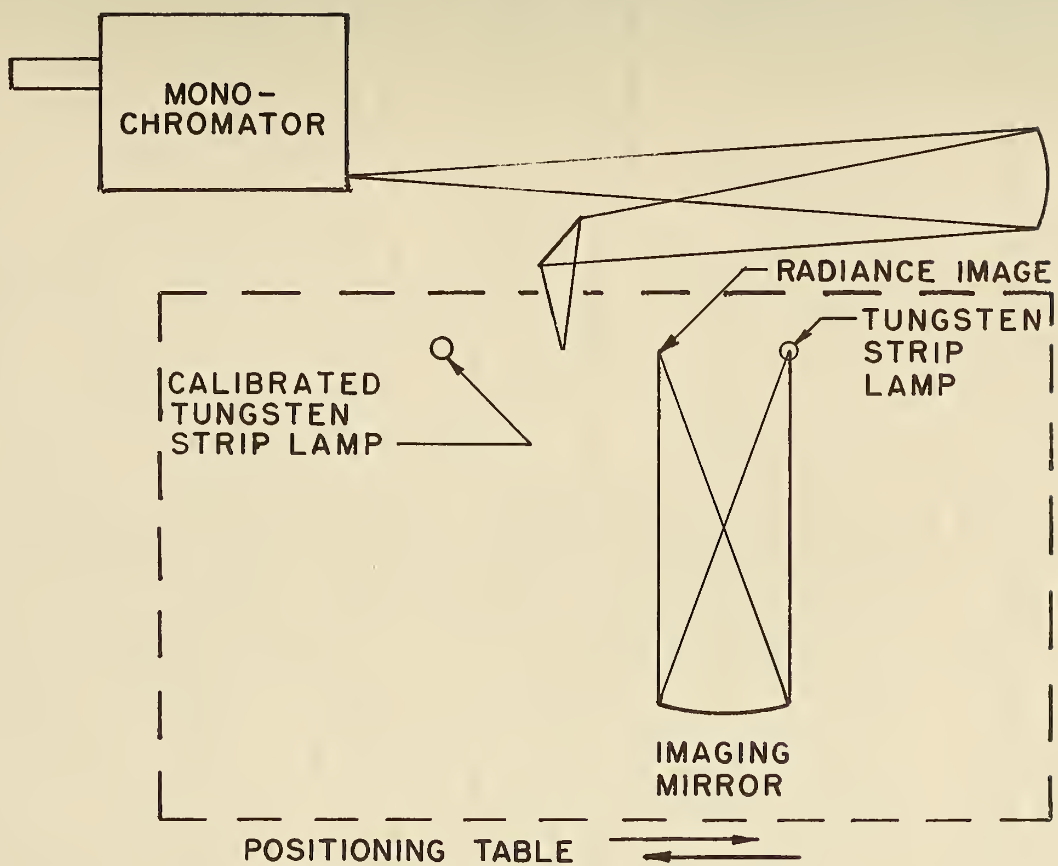

Figure 2. Measurement Setup for Calibrating the Radiance of the Image.

in the two cases. The area ΔA was essentially the same but the solid angle was limited by the entrance pupil of the monochromator rather than the somewhat larger aperture at the imaging mirror. However, it was experimentally demonstrated that the radiance of the image was uniform over the larger solid angle to within 0.1% so that the two averages would be identical regardless of the difference in solid angles. This uniformity was demonstrated by mapping the calibrated aperture.

2. Monochromator fore-optics

a. Integrating sphere The major problems in applying this method are related to the geometric size and shape differences between the irradiance and radiance sources and the configurations in which they must be used. The irradiance sources are 1000-watt type DXW coiled-coil tungsten filament quartz envelope halogen lamps placed at a distance of approximately .5 meters from the point at which the irradiance is measured. These sources are used without imaging optics. The radiance source is a tungsten strip lamp and a spherical mirror for imaging the filament onto the area ΔA. These two sources may differ in polarization, uniformity of field, and the solid angle of irradiation. Since the transmittances of optical systems and the responses of detectors generally depend on these factors, direct comparison of a radiance and irradiance flux generally has an uncertainty of at least two or three percent and sometimes considerably more. These three areas of difficulty are avoided by using an integrating sphere.

The integrating sphere is 2.5 cm in diameter with a .6 × 5.6 mm rectangular entrance port and a 3 × 10 mm exit port located 90° from the entrance port. By rotating the sphere about an axis through the exit port the radiometer can be made to view either of two sources as shown in figure 1. The inside sphere wall is coated with pressed high purity $BaSO_4$ using no binders (most binders lower the reflectance significantly in the UV) to insure a high sphere transmittance. The pressed $BaSO_4$ approximates a Lambertian surface (i.e., each incoming ray of flux is reflected diffusely). Because of multiple reflections in the integrating sphere, entering radiation is randomized, producing uniform, depolarized radiant flux at the exit port. Thus even a non-uniform source can be made uniform with the use of an integrating sphere. This was verified to within the measurement precision of 0.1% by radiometrically scanning the exit port of the sphere. Depolarization was tested at 500 nm and 650 nm using an unpolarized source and a linear polarizer. As in the test for uniformity, depolarization was complete within the precision of the measurements (0.1%). The difference in solid angle of irradiation for the irradiance lamp and the radiance image is only a problem when the reflectance of the integrating sphere wall is not uniform. The high purity, 3 mm thick $BaSO_4$ sphere coating provides this uniformity, and it was verified by determining the spectral irradiance of one of the quartz-halogen lamps with different sized apertures in front of mirror M1. These apertures had diameters ranging from 2.5 cm to 14 cm and simulated the difference in solid angles of irradiation for the irradiance and radiance sources. No significant (>.1%) difference in the results was observed.

b. Imaging optics The exit port of the integrating sphere is imaged, using the plane and spherical mirrors shown in figure 1, onto a polished stainless steel mask (field stop) placed directly in front of the slits of the monochromator. The mirrors are front surfaced with a fast coat of aluminum. The 45° plane mirror is used to divert flux from the integrating sphere onto the spherical mirror, M2. The spherical mirror then images the exit port of the integrating sphere onto the mask in front of the monochromator slits. The exit port of the integrating sphere and the slits of the monochromator are at a distance from the spherical mirror approximately equal to its radius of curvature. The monochromator slits and the 45° plane mirror are also kept as close as possible (3°) to the axis of the spherical mirror to minimize aberrations.

3. Monochromator The double monochromator is a prism-grating instrument (2 nm/mm dispersion at 250 nm to 4 nm/mm at 1600 nm and wavelength error about .1 nm) exhibiting very low spectral scattering. The optical chain of the monochromator consists of a collimating mirror, a quartz prism predisperser, an intermediate slit, a grating and a second mirror which forms an image at the exit slit.

4. Detection System A thermoelectrically cooled (-15°C) EMI 9558QB (S-20 cathode) photomultiplier tube is placed behind the exit slit of the monochromator to measure flux in the spectral region 250 nm - 800 nm. The photo current is converted to a 0-1 volt signal by a picoammeter. A photo current of less than 10^{-8} amperes is maintained by adjusting the voltage across the dynode chain of the photomultiplier. Past experience has demonstrated that the photomultiplier will remain stable (0.1%) and linear (1%) under these conditions. For the spectral region 700 nm - 1600 nm, a concave ellipsoidal mirror is used to collect the flux from the exit slit. The monochromator exit slit is located at one focus of the ellipsoidal mirror and a demagnified image (factor 7) of the slit appears at the other focus. A PbS detector is placed at this focus to measure the flux. The signal from the PbS detector is amplified to a 0-1 volt signal by a phase sensitive lock-in type voltmeter. A sector disk operating at a modulating frequency of 78 hertz is placed at the entrance slit of the monochromator. The signal-to-noise ratio of the detector is optimized by cooling the detector to liquid freon temperature (-113°C). It was found that further cooling decreased the signal while the noise remained at approximately the same level.

5. Data Acquisition The data acquisition system consists of a capacitor type integrator, MIDAS [4] data acquisition system and a 5½-digit voltmeter. Depending on which detector is being used, the picoammeter output or the lock-in voltmeter output is integrated. Integration times can be set to any desired interval; typically 60 seconds is used. The integrated signal, lamp current, lamp voltage, and ambient temperature are measured and recorded by the MIDAS system. The MIDAS system under control of a minicomputer, operates the integrator, sets the wavelength drive and positions the integrating sphere. The data collected is sent directly to the minicomputer for processing.

6. Lamp Mount and Power Supplies The irradiance sources (type DXW quartz-halogen lamps) are mounted in U-shaped holders as shown in figure 3. Each irradiance lamp has its own holder including a recessed lamp socket which is spring loaded to allow the lamp to expand and contract when heating and cooling.

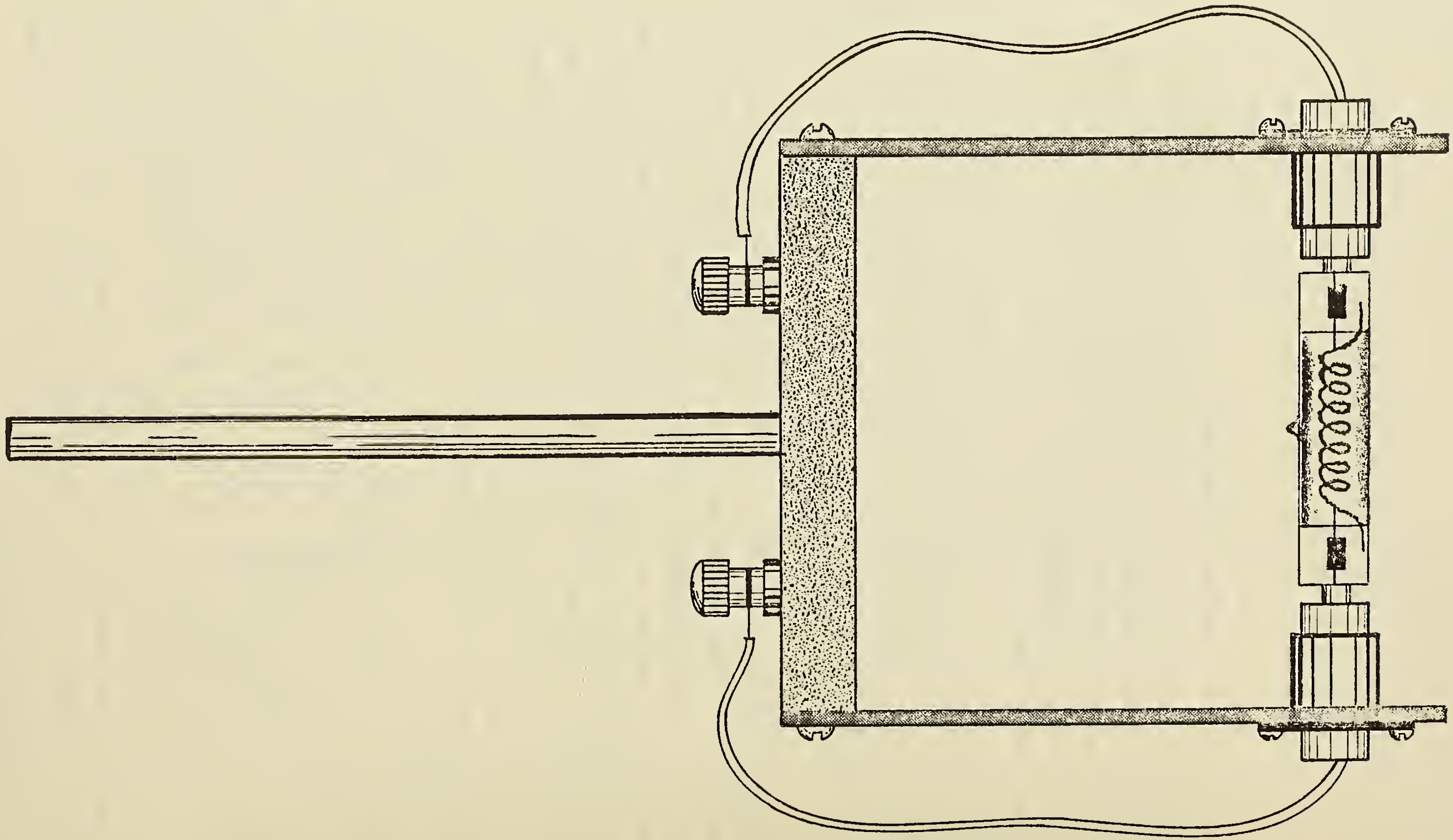

Figure 3. Quartz-Halogen Type DXW Lamp used for Spectral Irradiance Standards.

The radiance lamps are mounted in holders that can be adjusted in height, pitch, yaw, x direction, and y direction. These adjustments are necessary to align and keep aligned the radiance lamp during measurements.

Both radiance and irradiance lamps are operated at a constant direct current (.01% measurement accuracy .001% current regulation).

4. Process of Realization

In order to avoid making any critical assumptions about the linearity of the detector response, the spectroradiometer is used in a null mode, i.e., the test source and reference source produce equal output signals. In practice, the sources are matched to within 2%. Since the detector non-linearity has been shown to be less than 0.5%, and this non-linearity applies only to the differences in output signals, the error due to the 2% mismatch is negligible.

One gas-filled strip lamp (250 - 800 nm) and one vacuum strip lamp (700 - 1600 nm) are used to represent the scale of spectral radiance. A second gas-filled lamp and a second vacuum lamp are used with spherical mirror M1 to form the radiance image. These lamps have been selected from a larger group of lamps that were specially designed to maximize radiance stability and the selected lamps have been checked for radiance stability, radiance gradient, and polarization.

Radiance stability was checked by operating the lamps continuously for approximately 30 hours and checking the radiance during this time. The drift rate for the gas-filled lamps was approximately .01%/hr at 654.6 nm. No drift in radiance of the vacuum lamps could be detected. Similar vacuum lamps have exhibited a radiance drift rate of about 0.0001%/hr at 654.6 nm.

A well-defined .6 × 5.6 mm filament area on each of the radiance lamps was mapped for radiance. The lamps were first mapped vertically by dividing the defined filament area into seven .6 by .8 mm areas. Using the measurement configuration shown in figure 2, the spectral radiance of each area was measured and normalized to the center area. Depending upon the filament brightness temperature and the wavelength, the radiances over this area for the gas-filled lamps varied by 2% to 10% while those for the vacuum lamps varied by 1% to 5%. The radiances horizontally across the filament were also mapped by dividing the defined area into six .1 mm by 5.6 mm areas. The variations of the spectral radiance horizontally across the filament of all the lamps were about 1%. In all cases the radiances were smooth functions of position.

The selected lamps were also chosen such that their directions of polarization were approximately the same. In general the radiances of strip lamps are slightly polarized. Measurements with a polarization sensitive instrument (such as a monochromator) can therefore yield incorrect results. Possible errors due to polarization have been minimized by selecting, for comparison, those lamps which had nearly identical polarization.

The gas-filled strip lamps have a plane quartz window so that they can be used in the

UV spectral region. These lamps are operated at brightness temperatures up to 2400 K. Although the radiance of these lamps fluctuates about 1.5% in a few seconds, the average radiance over ten seconds is repeatable to a few tenths of a percent. Some of this fluctuation is thought to be caused by the snout on the lamp envelope (see fig. 4) which disrupts the normal flow of gas around the filament causing changes in refraction and in the filament temperature. In the spectral region 700 - 1600 nm, the vacuum strip lamps are used. Because there is no gas in these lamps, the radiance fluctuations are very small (<.1%/s).

Four 1000-watt, type DXW quartz-halogen lamps were selected as irradiance sources. The lamps were chosen from a group of lamps that had been screened for emission lines and absorption bands. At the time this group was chosen, there were very few DXW quartz-halogen lamps that had no absorption bands and emission lines. Lamps with the weakest absorption bands and emission lines were chosen. The average drift rate of the four lamps is less than .02%/hr at 654.6 nm (see fig. 5).

With the irradiance lamp and strip lamp image positioned as in figure 1, the flux entering the integrating sphere from the irradiance lamp at a single fixed current can be matched by the flux from the radiance lamp only if the radiance lamp current is varied with wavelength. Therefore, before the scale realization process was started the reverse of the process was carried out to determine the strip lamp current needed at each wavelength to match the flux from the irradiance lamp.

The measurement process is now performed in three basic steps at each wavelength. First, the spectral radiance of the lamp image at the lamp current determined above is measured in the measurement configuration shown in figure 2 using the other strip lamp carrying the spectral radiance scale as the reference lamp. Second, the radiance image is positioned on the mask (0.6 × 5.6 mm) of the integrating sphere as in figure 1 and one of the four irradiance lamps is placed at a distance of 50 cm on the opposite side of the rotatable integrating sphere. Using the relationship $\bar{E}_\lambda = \bar{L}_\lambda (\int_\omega \cos\theta \, d\omega) \, S_E/S_L$ (where S_E/S_L is the ratio of the irradiance signal to the radiance image signal) the spectral irradiance of the irradiance lamp is measured. Third, the radiance image system is replaced by an irradiance lamp chosen from one of the remaining three irradiance lamps, and the four irradiance lamps are intercompared using the following measurement scheme:

Left Side	Right Side
I_K	I_{K+1}
I_{K+2}	I_K
I_K	I_{K+3}
I_{K+1}	I_K

At each repetition, a different irradiance lamp is calibrated using the radiance image. (In the above measurement design a repetition is equivalent to selecting a different value for K. I_{k+j-4} is used whenever $K + j > 4$). The complete process yields five independent

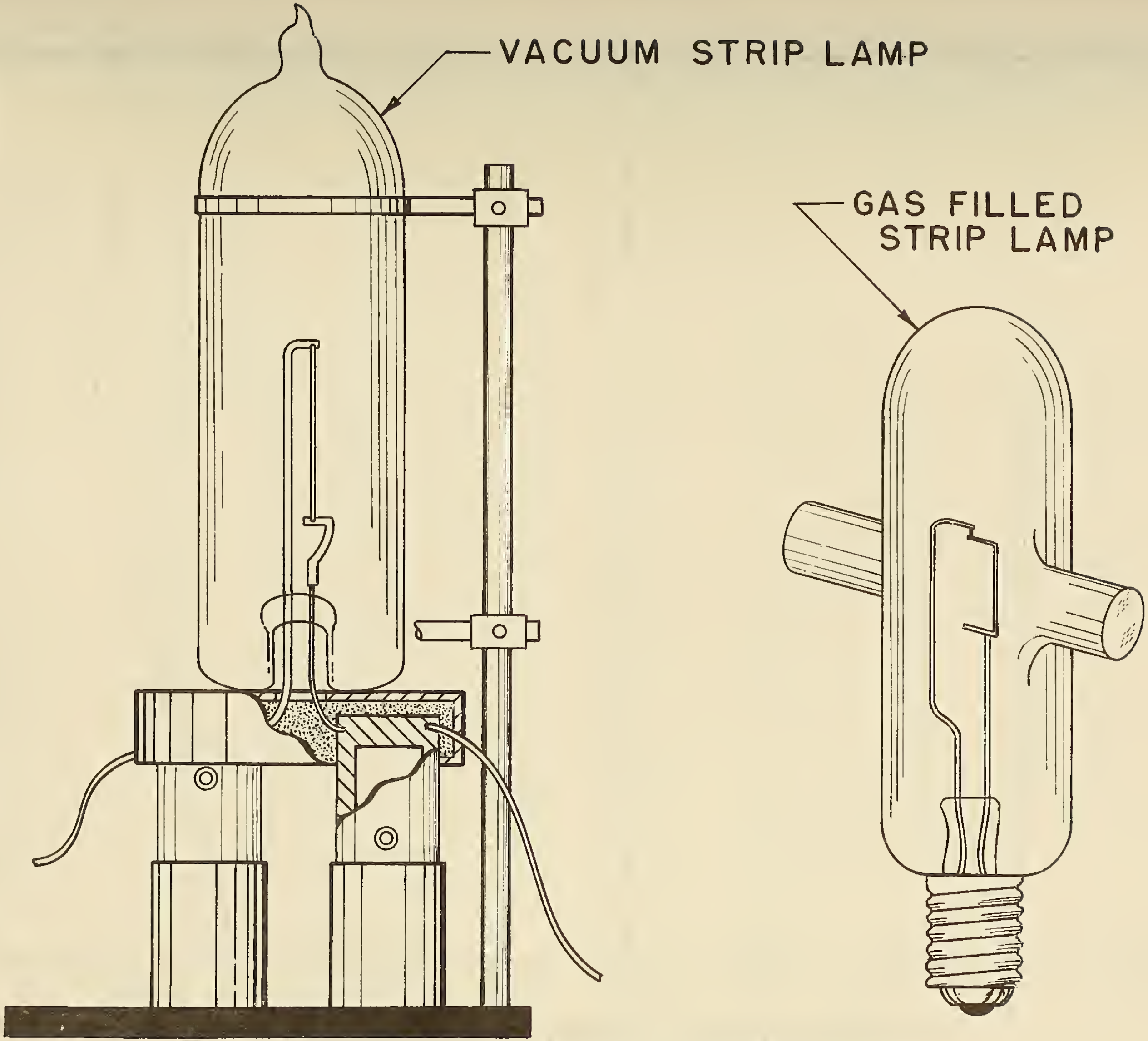

Figure 4. Tungsten Strip Lamps Used for Radiance Standards.

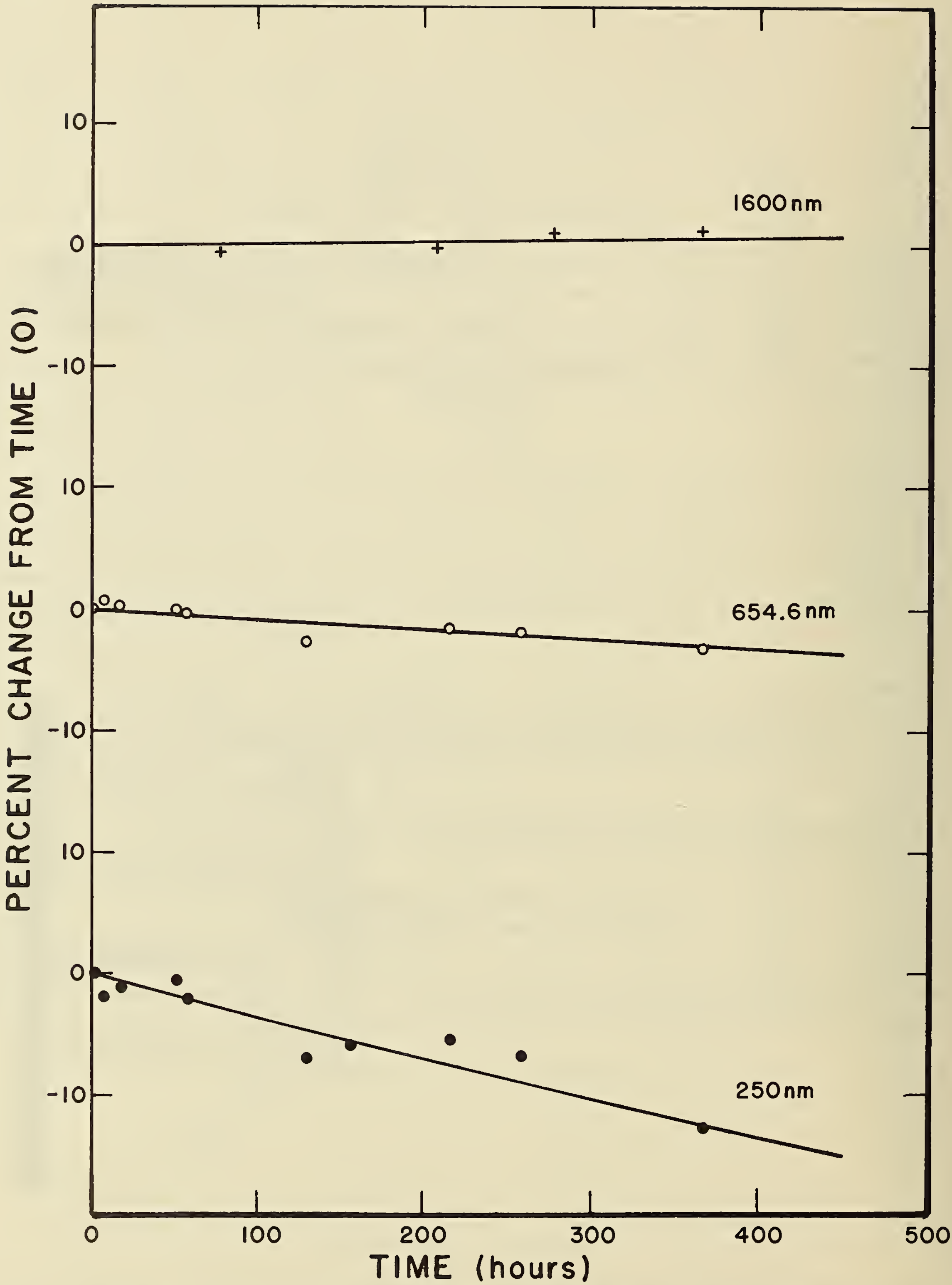

Figure 5. Typical Drift Curves for Type DXW Spectral Irradiance Standards.

measurements on each irradiance lamp.

5. Data Reduction

Twenty-six wavelengths were chosen for this realization. Eight of the wavelengths in the UV spectral region, however, were used to check the validity of an equation (discussed below) defining spectral irradiance as a function of wavelength and computed blackbody temperature. These eight wavelengths (260 nm, 270 nm, 280 nm, 290 nm, 310 nm, 320 nm, 330 nm and 340 nm) have only been measured twice. The gas-filled strip lamps are used at the wavelengths 250 nm, 300 nm, 350 nm, 400 nm, 450 nm, 500 nm, 555 nm, 654.6 nm, 700 nm and 800 nm. Vacuum strip lamps are used at the wavelengths 700 nm, 800 nm, 900 nm, 1050 nm, 1150 nm, 1200 nm, 1300 nm, 1540 nm, and 1600 nm.

Because of stabilization times (20 min) and the integration time required to smooth short-term radiance fluctuations, the total time for each wavelength is approximately an hour for the first two steps of the realization. In step 3 (irradiance to irradiance) the measurement time for all wavelengths on an irradiance lamp is approximately two hours. The large number of operating hours involved means that lamp drift cannot be ignored. Therefore, for each lamp an equation was developed to allow its spectral irradiance to be calculated at any time t.

Based upon the drift data exemplified by figure 5 an adequate model for the drift of spectral irradiance of constant current tungsten halogen lamps is given by the equation

$$E_\lambda = \lambda^{-5} \exp (A_\lambda + Ct + (D + Bt)/\lambda).$$

Comparing this equation with Wien's law for a gray body: $E_\lambda = \varepsilon\lambda^{-5} \exp (C_2/\lambda T)$ one sees that $\exp (A_\lambda + Ct)$ represents the effective emissivity (and envelope transmission) which is assumed to change with time. The term $(D + Bt)$ represents C_2/T, again assumed to change with time. D was set at 4.7 μm corresponding to $T = 3061$ K. The remaining coefficients (B, C, and one A_λ for each of the twenty-six wavelengths) were determined by least-squares fitting techniques.

In a similar way an interpolation formula was developed for calculating the spectral irradiance of tungsten-halogen lamps at wavelengths intermediate between the 26 calibrated wavelengths. This formula is:

$$E_\lambda = (A_0 + A_1\lambda + A_2\lambda^2 + \ldots + A_n\lambda^n)\, \lambda^{-5} \exp (a + b/\lambda).$$

The quantities a and b are determined by fitting the data to $\ln(E_\lambda \lambda^5) = a + b/\lambda$ in which it will be recognized that $\exp (a)$ is an effective gray-body emissivity and b is closely related to the reciprocal of the distribution temperature. With a and b thus fixed

A_0, A_1, . . . A_n are least squares fitted using $1/E^2_\lambda$ weighting (assuming constant percentage measurement error). In practice it has been found that the final fit is considerably improved if the spectrum is broken into two spectral regions, 250 - 400 nm and 350 - 1600 nm, for separate fitting.

Figures 6, 7 and 8 show the different fittings to the equations given above. This method is only valid for the continuous spectrum and does not predict the emission lines and absorption bands.

6. Uncertainties

The significance of this new method for determining the spectral irradiance is best appreciated by examining the basic uncertainties associated with the method. These are listed in Table 1. The total absolute uncertainties in the last two lines of the table are obtained by adding all the uncertainties at a given wavelength in quadrature.

The systematic uncertainty in the radiance-to-irradiance transfer (line II a) is obtained by adding in quadrature estimated contributions from a number of error sources. Each of the following error sources contributed 0.01% or less: Non-linearity of the detector-amplifier system, wavelength error, stray light, lamp polarization, lamp current measurements, and the integrating sphere response to the different solid angles of the radiance image and irradiance sources. Each of the following contributed less than 0.05%: The projected solid angle determination, uniformity of mirror M1, and spectral light scattering due to the slit function wings. Finally, the non-uniformity of the radiance sources over the viewing area contributes an uncertainty varying from 0.12% in the UV to .05% in the IR.

The uncertainties listed in Table 1 are the uncertainties assigned to the mean value of the four working standards at the time that the standards are calibrated. Because lamps drift with time, the spectral irradiance at any other time is obtained from the spectral irradiance vs. time formula described above for the working standards group. The possibility that this drift model may be wrong introduces an additional uncertainty not included in Table 1. This model uncertainty for a particular lamp is estimated as 0.8%. This uncertainty was obtained by comparing the calculated extrapolated spectral irradiance with further scale realizations. When the working group is used between scale realizations, this 0.8% uncertainty must be combined in quadrature with the total uncertainties in Table 1.

7. Conclusion

The method described in this report has made the frequent realization of the spectral irradiance scale feasible. This, in turn, has significantly reduced the uncertainty of the scale by eliminating the reliance upon long-term predictability of the NBS working lamp standards. The method is valid for generating a spectral irradiance scale of any magnitude; the magnitude can be altered either by changing the radiance levels or by changing the solid-angle-defining aperture at mirror M1. At present a scale realization requires about 40 hours to complete. Most of this time is spent stabilizing the strip lamps, which must be done because the lamp current is changed for each wavelength. Other sources of spectral radiance are being investigated which will require less stabilization time. A radiance source requiring

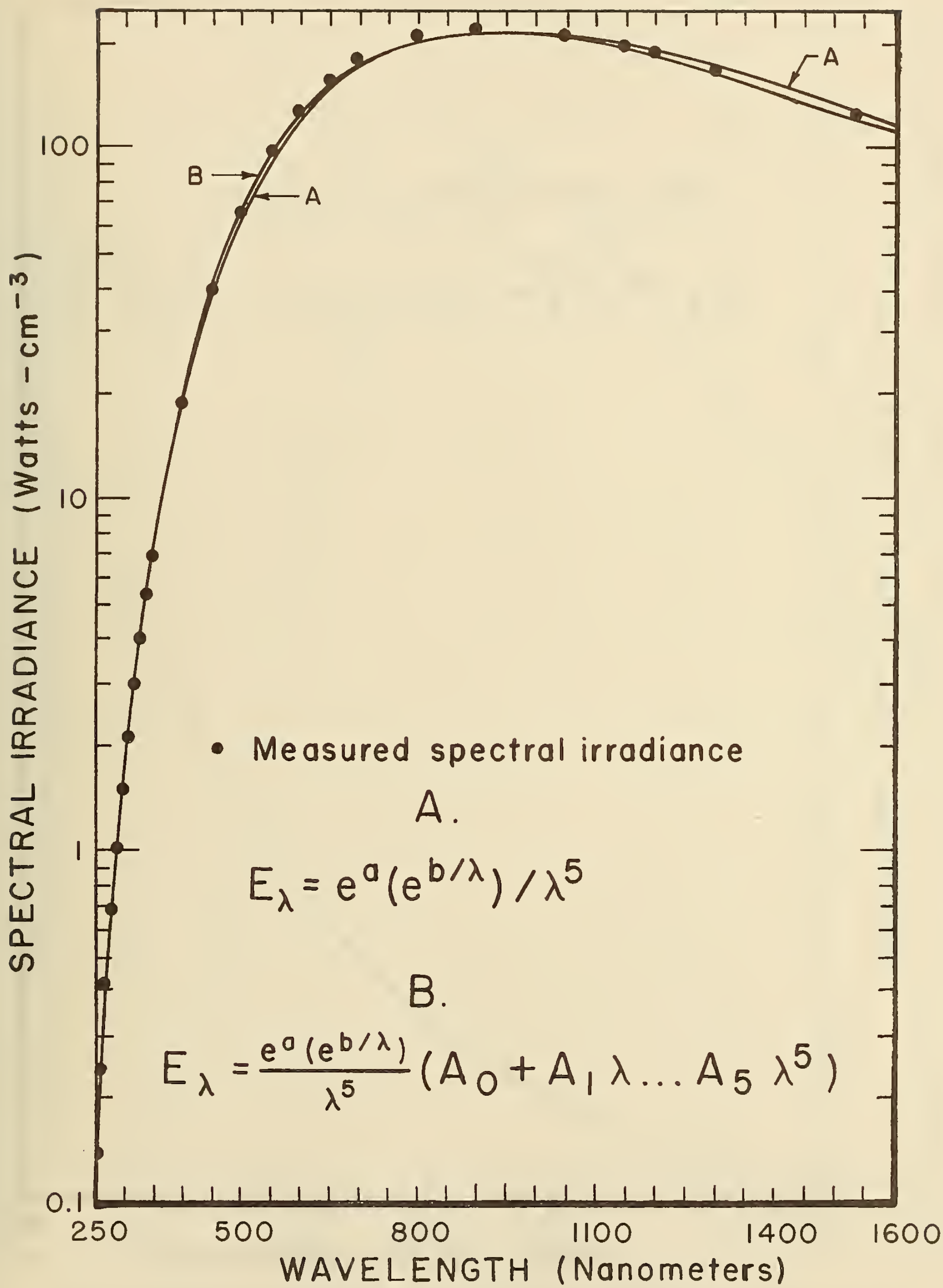

Figure 6. Spectral Irradiance Fit in Spectral Region 250 - 1600 nm.

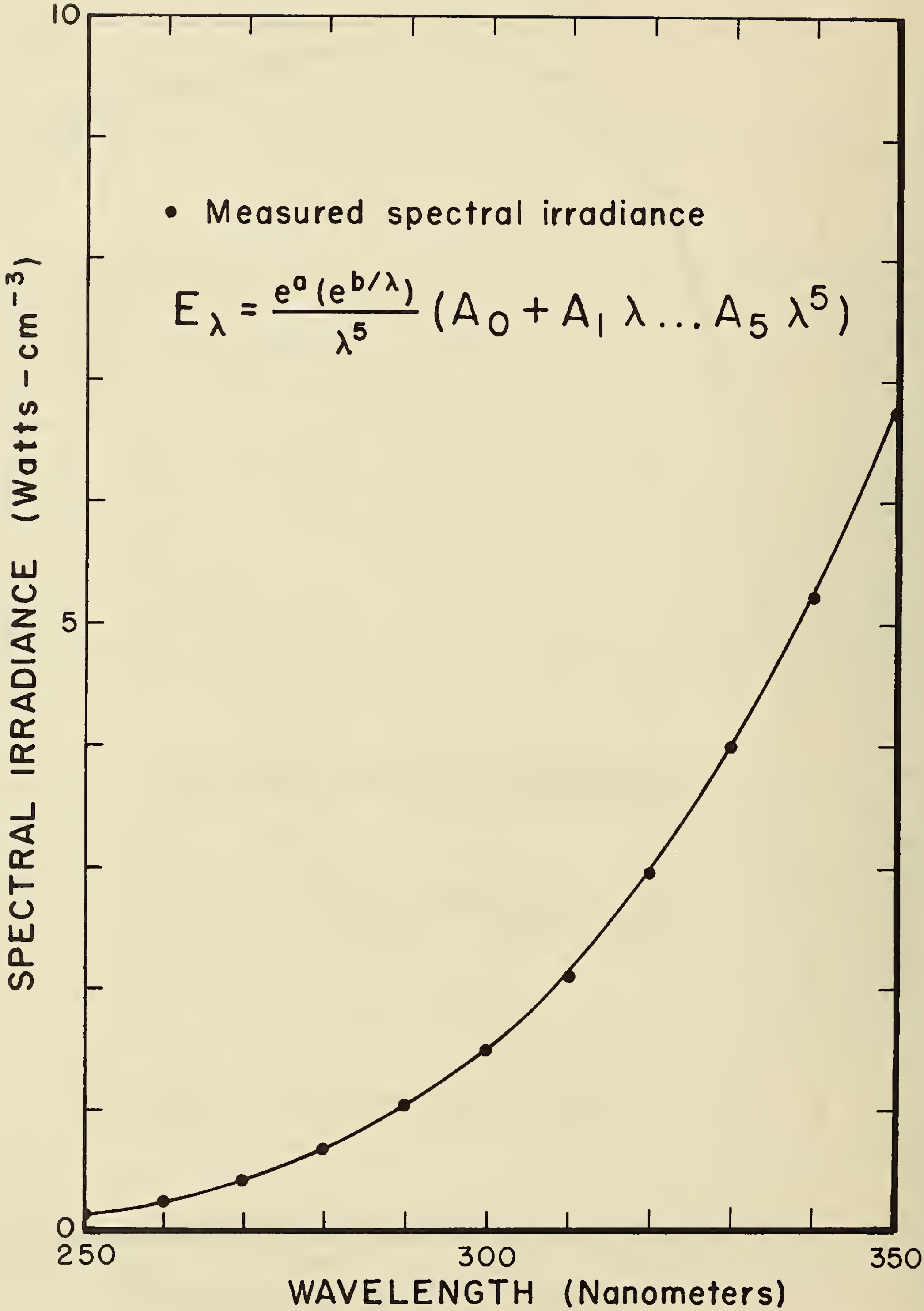

Figure 7. Spectral Irradiance Fit in Spectral Region 250 - 350 nm.

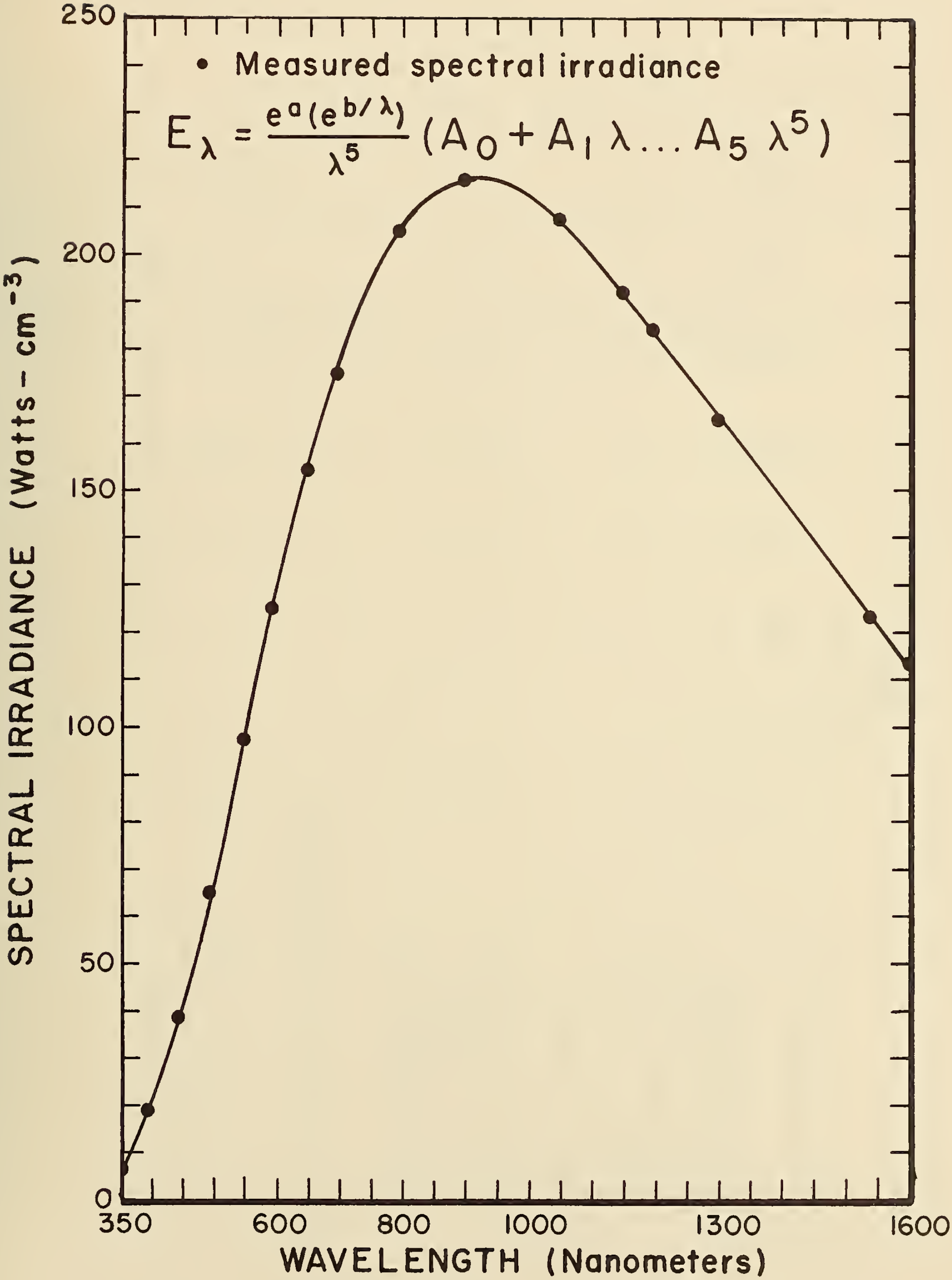

Figure 8. Spectral Irradiance Fit in Spectral Region 350 - 1600 nm.

TABLE 1

UNCERTAINTY (%)

	250 nm	350 nm	450 nm	555 nm	654.6 nm	800 nm	1300 nm	1600 nm
I. NBS SPECTRAL RADIANCE SCALE								
a. Absolute uncertainty respect to SI units	1.66	1.20	.93	.65	.65	.46	.28	.27
b. NBS long term reproducibility	1.06	.76	.61	.30	.26	.22	.12	.18
II. NBS SPECTRAL IRRADIANCE								
a. Systematic uncertainty	.16	.16	.10	.10	.08	.08	.07	.07
b. Precision (estimated reproducibility of the mean of standards I_1-I_4, 3-σ)	.72	.55	.53	.56	.54	.51	.80	.80
III. SPECTRAL IRRADIANCE SCALE UNCERTAINTIES								
a. With respect to SI units	1.8	1.3	1.1	.86	.84	.69	.85	.85
b. NBS long term reproducability term reproducibility	1.26	.95	.81	.64	.60	.56	.81	.82

little or no stabilization would decrease the scale realization time to about 8 hours for four working standards.

8. References

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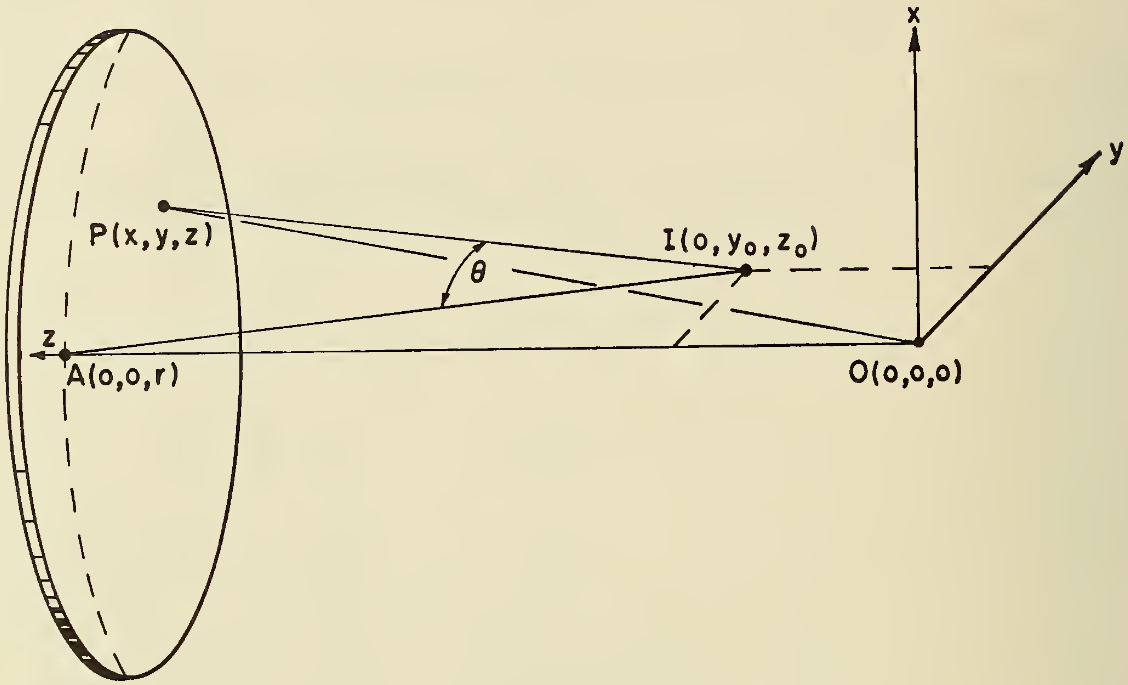
9. Appendix

Evaluating the Projected Solid Angle at the Image Point

The Projected Solid Angle Integral



Consider a spherical mirror of radius of curvature (r) whose center of curvature is at 0 . The center of the mirror aperture and point 0 define the z axis of a rectangular coordinate system. The point A is the center of the mirror surface; the point P is an arbitrary point on the mirror; and the point I is an image point in the yz plane. The projected solid angle is

$$F = \int_{\omega} \cos\theta \; d\,\omega \tag{1}$$

where ω is the solid angle subtended at I by a portion of the mirror and θ is the angle between AI and the solid angle element $d\,\omega$. This can be expressed as

$$F = \iint_{S} \cos \overline{AIP} \; \frac{\cos \overline{OPI} \; dS}{\overline{PI}^2} \tag{2}$$

where S is the surface of the mirror, $\overline{OPI}$ is the angle between the viewing direction and the normal to the mirror surface, and $\overline{PI}$ is the distance to the surface element dS. The x, y and z coordinates of the four labeled points are

O: o, o, o

A: o, o, r

I: o, y_o, z_o (The assumed position at the image point)

P: x, y, z (where $z = \sqrt{r^2-x^2-y^2}$).

The following vectors

$$\vec{IA} = -y_o \vec{j} + (r-z_o) \vec{k}$$

$$\vec{IP} = x\vec{i} + (y-y_o) \vec{j} + (z-z_o) \vec{k}$$

$$\vec{PO} = x\vec{i} + y\vec{j} + z\vec{k}$$

and the distances

$$\overline{PI} = (x^2 + (y-y_o)^2 + (z-z_o)^2)^{\frac{1}{2}}$$

$$\overline{IA} = (y_o^2 + (r-z_o)^2)^{\frac{1}{2}}$$

$$\overline{PO} = r$$

are needed.

Now since $\vec{V_1} \cdot \vec{V_2} = \overline{V_1}\,\overline{V_2} \cos \theta$ the cosine factors appearing in (2) can be calculated.

$$\cos \overline{AIP} = \frac{\vec{IA} \cdot \vec{IP}}{\overline{IA} \cdot \overline{PI}} = \frac{y_o (y_o-y) + (r-z_o)(z-z_o)}{\sqrt{(y_o^2 + (r-z_o)^2)(x^2 + (y-y_o)^2 + (z-z_o)^2)}}$$

$$\cos \overline{OPI} = \frac{\vec{IP} \cdot \vec{PO}}{\overline{PI} \cdot \overline{PO}} = \frac{x^2 + y(y-y_o) + z(z-z_o)}{r\sqrt{x^2 + (y-y_o)^2 + (z-z_o)^2}}$$

The element of surface area is given by

$$ds = dx\,dy\sqrt{1 + \left(\frac{\partial z}{\partial x}\right)^2 + \left(\frac{\partial z}{\partial y}\right)^2}$$

$$= dx\,dy\sqrt{1 + \frac{x^2}{z^2} + \frac{y^2}{z^2}} \qquad \text{(using } z = (r^2-x^2-y^2)^{\frac{1}{2}}$$

$$= dx\,dy\,\frac{r}{z}\,.$$

Now integral (2) can be expressed as:

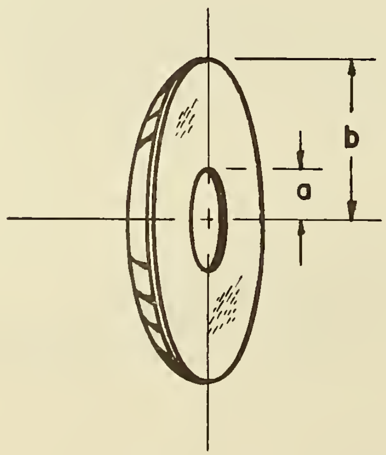
$$F = \iint_S \frac{[y_o(y_o-y) + (r-z_o)(z-z_o)][x^2 + y(y-y_o) + z(z-z_o)]\,dx\,dy}{\sqrt{y_o^2 + (r-z_o)^2}\,[x^2 + (y-y_o)^2 + (z-z_o)^2]^2\,z} \qquad (3)$$

in which the notation z is simply a shorthand for $(r^2-x^2-y^2)^{\frac{1}{2}}$. The limits of integration, S, remain to be defined.

<u>The Integration Limts: The area S</u>

Consider an aperture plane perpendicular to the z axis which cuts the mirror surface in a circle with radius b. The equation of this plane is

$$z = \sqrt{r^2-b^2}.$$



The line PI to an arbitrary mirror point (temporarily denoted as x_m, y_m, z_m) is:

$$\begin{cases} x = \dfrac{z-z_o}{z_m-z_o}\, x_m \\ \\ y-y_o = \dfrac{z-z_o}{z_m-z_o}\, (y_m-y_o)\ . \end{cases}$$

The intersection of this line and the aperture plane is:

$$x = u\, x_m$$

$$y-y_o = u\, (y_m-y_o)$$

$$u = \frac{\sqrt{r^2-b^2}\ -z_o}{\sqrt{r^2-x_m^2-y_m^2}\ -z_o}$$

Writing ξ and η for the x and y coordinates in the aperture plane and dropping the subscript m for coordinates on the mirror surface gives:

$$\xi = u\, x$$

$$\eta-y_o = u\, (y-y_o) \tag{4}$$

$$u = \frac{\sqrt{r^2-b^2}\ -z_o}{\sqrt{r^2-x^2-y^2}\ -z_o}$$

as the relation connecting any point ξ , η in the aperture plane to the corresponding point x,y on the mirror surface defined by the ray from the image point, I, through ξ , η. For a circular aperture with radius a the image point can "see" all mirror points x,y which satisfy $\xi^2 + \eta^2 \leq a^2$. Similarly the object point will illuminate all mirror points x',y' which satisfy $\xi^2 + \eta^2 \leq a^2$ with

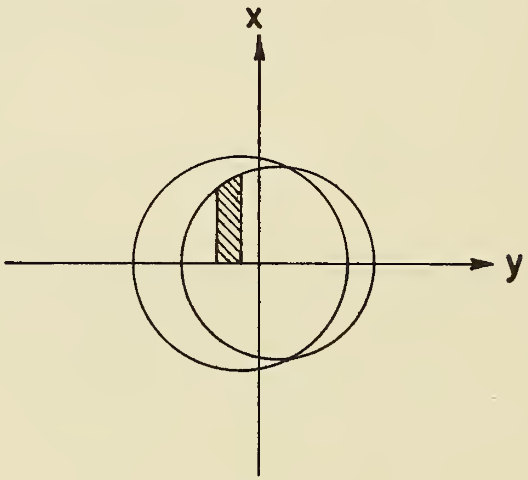
$$\xi = u'x'$$

$$\eta - y_o = u'(y' - y'_o) \tag{5}$$

$$u' = \frac{\sqrt{r^2-b^2} - z'_o}{\sqrt{r^2-x'^2-y'^2} - z'_o}$$

where y'_o and z'_o are the coordinates of the object point.

If the mirror is viewed from the origin with the source to the left and image to the right the areas "seen" by object and image will look like*



The area over which the integration is to be performed is the central area common to both object and image viewing.

The integration over x is straightforward: the integral is symmetric about $x = o$ so, for a given y, the integral runs from o to the smaller of x and x' where

$$x = x(y_o, z_o, y)$$

$$x' = x(y'_o, z'_o, y)$$

---

*In this illustration the image point is assumed closer to the mirror than the object point, thus resulting in a slightly larger area "seen" by the image point.

are solutions of $\xi^2 + \eta^2 = a^2$ using (4) for x and (5) for x'. The integration over y runs from the negative branch of the solution $y' = y(y_o', z_o', 0)$ to the positive branch of the solution $y = y(y_o, z_o, 0)$ where these are solutions of the same equations ($\xi^2 + \eta^2 = a^2$, etc.) with $x = 0$.

Numerical Evalution

For the numerical calculation of F, equation (3) can be rewritted so as to leave terms of order y_o/r and z_o/r as correction terms:

$$F = \frac{2}{r\sqrt{y_o^2 + (r-z_o)^2}} \int_{y_-^o}^{y_+^o} dy \int_{o}^{x^o(y)} (1 + p)(1 + q)\, dx$$

$$p = \frac{(z_o^2 - z_o(2z + r) + y_o^2 - y_o y)(r-z) + y_o yz}{z\,(r^2 - 2yy_o + y_o^2 - 2zz_o + z_o^2)}$$

$$q = \frac{z_o(z-z_o) + y_o(y-y_o)}{(r^2 - 2yy_o + y^2 - 2zz_o + z_o^2)}$$

$$z = \sqrt{r^2 - x^2 - y^2}\ .$$

The limits of integration are determined by numerical solution of equations like:

$$\xi^2(x,y) + \eta^2(x,y) = a^2$$

or

$$u^2x^2 + u^2(y - y_o(1-1/u))^2 = a^2$$

$$\text{with} \quad u = \frac{\sqrt{r^2-b^2} - z_o}{\sqrt{r^2-x^2-y^2} - z_o}$$

If u were known the equations would be simple; hence the technique is to assume a trial value for the unknown (x or y) in u, then solve for an improved value of the unknown, etc. Specifically

$$x^o(y) = \text{Min}\,(x_a, x_a')$$

where

$$x_a = \sqrt{a^2/u^2 - (y - y_o(1-1/u))^2}$$

$$x_a' = \sqrt{a^2/u'^2 - (y - y_o'(1-1/u'))^2}$$

and
$$u = \frac{\sqrt{r^2-b^2} - z_o}{\sqrt{r^2 - x_a^{o\,2} - y^2} - z_o}, \quad u' = \frac{\sqrt{r^2-b^2} - z_o'}{\sqrt{r^2 - x_a^{o'\,2} - y^2} - z_o'}$$

and x_a^o and $x_a^{o'}$ denote trial values of x_a and x_a'. x_a^o and $x_a^{o'}$ are replaced by x_a and x_a' and new values for x_a and x_a' are computed; the process being repeated to convergence. For the y limits set $x = o$ and solve the following equations

$$y_-^o = \text{Max}\,(y_a^-, y_a^{-'})$$

$$y_+^o = \text{Min}\,(y_a^+, y_a^{+'})$$

where

$$y_a^- = y_o\,(1-1/u) - a/u\,, \quad y_a^{-'} = y_o'\,(1-1/u') - a/u'$$

$$y_a^+ = y_o\,(1-1/u) + a/u\,, \quad y_a^{+'} = y_o'\,(1-1/u') + a/u'$$

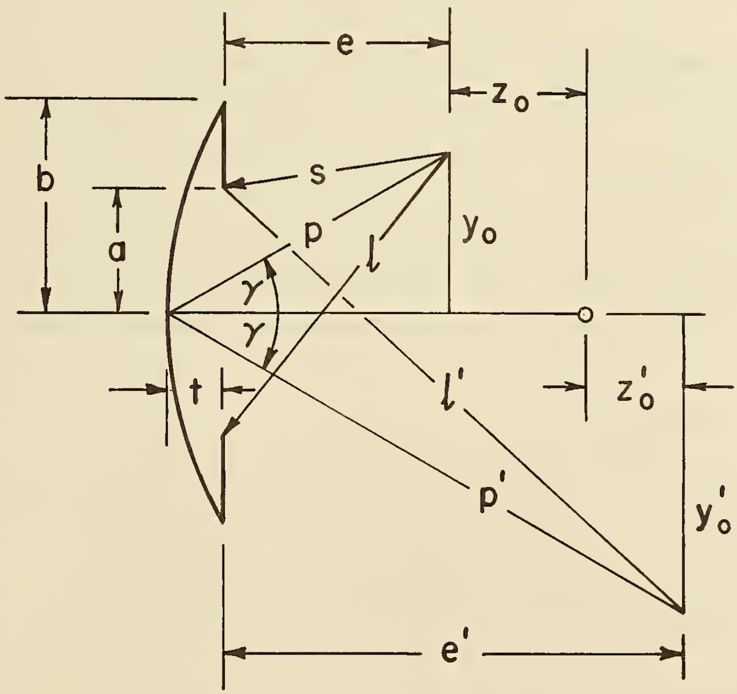
and

$$u = \frac{\sqrt{r^2-b^2}-z_o}{\sqrt{r^2-y_a^{o2}}-z_o} \quad , \quad u' = \frac{\sqrt{r^2-b^2}-z_o'}{\sqrt{r^2-y_a^{o'2}}-z_o'}$$

y_a^o and $y_a^{o'}$ are trial values which are repeatedly refined to convergence.

<u>Geometrical Relationships</u>

The distances r, b, y_o, z_o, y_o', and z_o' which appear in the expressions for F are difficult to measure. Therefore, the following equations are used to calculate them from the more easily measured quantities, s, ℓ, ℓ', t, and a. s is the distance from the image point to the closest point of the aperture opening; ℓ is the distance to the most remote point of the aperture opening. ℓ' is the distance from the object point to the most remote point of the aperture opening as seen from the object point. t is the distance from the plane of the aperture to the center of the mirror surface. a is the radius of the aperture.



$$y_o = \frac{\ell^2 - s^2}{4a}$$

$$e = \sqrt{s^2 - (4a^2 - \ell^2 + s^2)^2/16a^2}$$

$$\tan \gamma = \frac{y_o}{e+t}$$

$$P/\cos \gamma = \frac{y_o^2 + (e+t)^2}{e+t}$$

$$\frac{P'}{\cos \gamma} = t - a \tan \gamma + \sqrt{\ell'^2/\cos^2 \gamma - (a+t \tan \gamma)^2}$$

$$r = \frac{2}{P/\cos \gamma + P'/\cos \gamma} \left(\frac{P\ P'}{\cos^2 \gamma} \right)$$

$$b = \sqrt{r^2 - (r-t)^2}$$

$$y_o' = -y_o\ P'/P$$

$$z_o = r - e - t$$

$$z_o' = r - (r - z_o)\ P'/P.$$

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15. SUPPLEMENTARY NOTES

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This note describes the measurement apparatus and techniques used in deriving the 1973 scale of spectral irradiance. The uncertainty of this scale is believed to be less than 2% in the spectral region 250 nm -500 nm and less than 1% in the spectral region 500 nm - 1600 nm. This uncertainty represents a threefold improvement over the previous NBS scale of spectral irradiance. The complete derivation of the projected solid angle, which is crucial when transferring from radiance to irradiance, is given. Also described in this note is a model for interpolating the spectral irradiance at wavelengths between the wavelengths measured. Measurement details are presented and sources of error are discussed.

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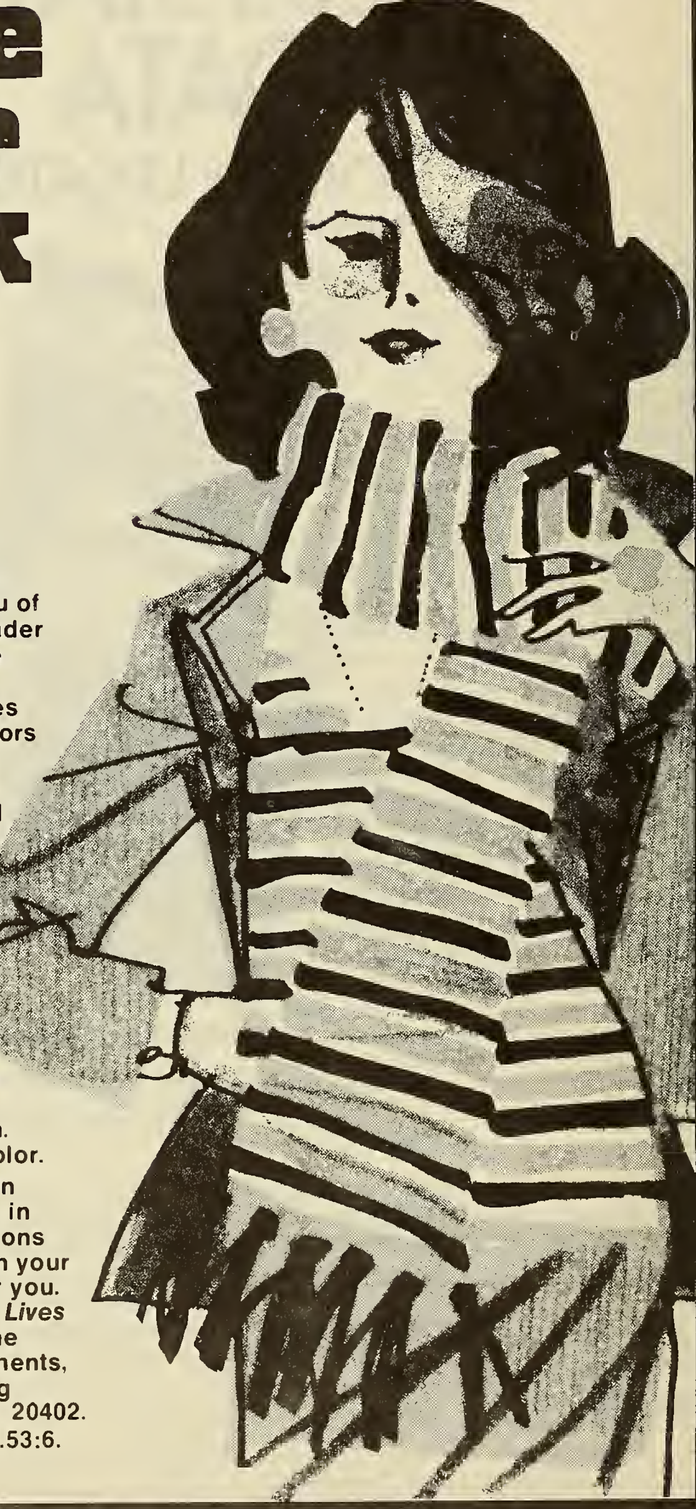

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