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AN INTEGRATING SPHERE SPECTRORADIOMETER FOR SOLAR SIMULATOR MEASUREMENTS

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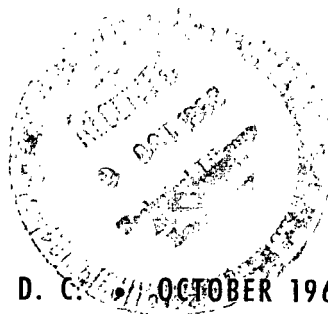NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • OCTOBER 1968

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FOR SOLAR SIMULATOR MEASUREMENTS

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ABSTRACT

A spectroradiometer, utilizing an integrating sphere and a grating monochromator, and a technique for performing low-error spectral measurements of solar simulators are described, together with their evaluation tests.   A point-by-point technique is used in which the spectroradiometer is calibrated with an NBS spectral irradiance standard at each wavelength. Evaluation consisted of checking the calibration of several NBS spectral irradiance standards. Accuracy was also checked by correlating these measurements with measurements obtained with a filter radiometer. Results of the measurements of a carbon-arc solar simulator and a xenon-arc solar simulator are presented.

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SUMMARY

A spectroradiometer and a technique for performing low-error measurements of the spectral irradiance of solar simulators are described. Results of the measurements of two solar simulators are presented and discussed.

The radiant power flowing past a given plane within the beam of a solar simulator is a function of five parameters: wavelength, position in the given plane, direction, polarization, and fluctuations with time. The first four radiation parameters were controlled by use of a grating monochromator in conjunction with an integrating sphere and a spectral irradiance standard. The fifth parameter was controlled by comparing the unknown with a standard at each wavelength in turn. In addition, due consideration was given to the proper selection and use of appropriate filters, detectors, and electronic apparatus to further ensure that the spectroradiometer calibration remained constant.

The spectroradiometer was experimentally evaluated for repeatability at all wavelengths within its operating range, 250 to 2100 nanometers. Measurements of a tungsten standard of spectral irradiance performed with this spectroradiometer and with a filter radiometer were compared to check the accuracy. The accuracy of measurement of the tungsten standard was better than 2 percent.

The spectroradiometer was used to measure the spectrum of two solar simulators – a carbon-arc unit, and a xenon-compact-arc unit. These two measurements were compared with the results obtained by a broadband filter radiometer. The method whereby narrow-band and broadband measurements may thus be compared is discussed.

INTRODUCTION

The NASA Lewis Research Center has been investigating techniques for improving the solar simulator component of space environment test facilities for several years.

All solar simulators fail to match the irradiance of the sun in each of several important characteristics. Each class of research experiment establishes the order of importance of these characteristics, and the amount of variance which can be allowed. The experimenter must know how accurately his source duplicates the desired solar irradiance (the source must be calibrated), or he must be able to make field measurements to properly evaluate research results.

In many experiments, the spectral distribution delivered by the source to the test object is of first order importance. These experiments result in a requirement for the spectrum of the source to have an uncertainty of the order of 5 percent of the spectral irradiance in bandwidths that contain 10 percent of the total energy. Measurements made on several solar simulators at Lewis with three of the best available instruments (a prism spectrometer, a modified infrared spectrophotometer, and a filter radiometer) yielded measurements that differed by as much as 25 percent in the visible region. As a result of these measurements, it was obvious that a considerable improvement in measurement accuracy would be necessary to satisfy research requirements. A program was therefore instituted at Lewis whose objective was to develop a spectroradiometer and measurement technique to satisfy research requirements. Concurrent with this investigation, the National Bureau of Standards (NBS) was requested to aid in developing methods to improve the measurement accuracy of spectral irradiance from solar simulators. Partial results of the NBS study are given in reference 1. The results of both the NBS and of this program were incorporated in a spectroradiometer and a measurement technique by which high resolution measurements of spectral irradiance of solar simulators can be obtained within predictable uncertainty. Measurement techniques and some apparatus are also described in reference 2.

The purposes of this report are to (1) describe the spectroradiometer and list the considerations in the selecting of its parts, (2) describe the measurement technique, and (3) describe and discuss the evaluation tests that were performed. In addition, results of the measurement of two solar simulators are presented and discussed.

THEORY

The radiant power flowing past a given plane within the beam of a solar simulator is a function of five parameters: wavelength, position in the given plane, direction, polarization, and fluctuations with time.

The first parameter of this discussion concerns the wavelength λ for which a spectroradiometer is necessary. The spectroradiometer requires three main systems: a radiation gathering system that includes the disperser (monochromator), a transducer (detector), and data processing and presentation components.

Spectrally, the combined effect of the spectroradiometer is to produce a signal voltage:

$$V_i = G \int_0^\infty H_\lambda(\lambda) R_i(\lambda) T(\lambda) \tau(\lambda) d\lambda \qquad (1)$$

where

V_i voltage at spectroradiometer wavelength setting λ_i and spectral slit width $\Delta\lambda$ ($\Delta\lambda = \lambda_2 - \lambda_1$, where λ_1 and λ_2 are the 50-percent transmission points of the monochromator pass band)

G gain setting of amplifying and recording system

$H_\lambda(\lambda)$ spectral irradiance of incident energy

$R_i(\lambda)$ instrument irradiance transfer function

$T(\lambda)$ spectral transmission of various order-blocking and stray light filters

$\tau(\lambda)$ spectral transmission of neutral density filter

The irradiance transfer function includes all the spectral reflections, absorptions, and dispersion in the radiation collection system, the slit function, and the spectral sensitivity of the detector. If $R_i(\lambda)$ is not known, the measured value of V_i is meaningless. A known value of $H_\lambda(\lambda)$ must be used to determine $R_i(\lambda)$ at λ_i.

A solution of equation (1) is not readily obtained; therefore, a method using an approximation of the integral equation is used. Although the method is subject to errors and requires certain precautions, it is relatively simple to use. The form of the equation is

$$V_i = GH_\lambda(\lambda_i) R_i(\lambda_i) T(\lambda_i) \tau(\lambda_i) \Delta\lambda \qquad (2)$$

where the terms $H_\lambda(\lambda_i)$ and $R_i(\lambda_i)$ are the spectral irradiance and transfer function at the wavelength setting (λ_i). Equation (2) is valid for narrow intervals $\Delta\lambda$ in which the variation of $H_\lambda(\lambda)$ is small. Where the variation in $H_\lambda(\lambda)$ is large because of emission lines, the $\Delta\lambda$ must be kept very small. When this is not possible, some error in measurement results.

The calibration to obtain the transfer function is performed with a tungsten standard of spectral irradiance. The transfer function is then used to obtain the irradiance of the solar simulator $H_\lambda(\lambda_i)$ from the measured voltage V_i. With the proper conditions of measurement to ensure no change in the transfer function when the standard and the solar simulator are measured, the spectral irradiance of the solar simulator is

$$H_\lambda(\lambda_i) = \frac{G_S}{G} \frac{H_{S,\lambda}(\lambda_i)}{\tau(\lambda_i)} \frac{V_i}{V_{S,i}} \tag{3}$$

where the subscript S is for the calibration standard, and the nonsubscripted quantities for the solar simulator. The spectral transmission $T(\lambda_i)$ is used in both the standard and unknown measurements and cancels. The neutral density filter $\tau(\lambda_i)$ is used only in the unknown source.

So that the spectral irradiance can be measured as a function only of wavelength, the effect of the other four radiation parameters must be eliminated to ensure that the transfer function does not change and that the use of equation (3) is valid. This elimination is accomplished by the proper choice of system components and measurement technique.

MEASUREMENT PROCEDURE

The basic elements of the system are shown in figure 1. Spectral irradiance measurements are performed with this spectroradiometer by using a wavelength point by wavelength point method. At each wavelength setting of the monochromator, the irradiance of the standard lamp is measured and then that of the unknown source is measured.

Before an accurate measurement of an unknown source is attempted, however, the operator makes a quick measurement to obtain a look at its spectrum. This acquaints him with the interim program of slit widths, detectors, filters, and gain settings that must be used.

A typical spectroradiometer program is shown in figure 2. The choice of blocking filter is dictated by the wavelength alone; the choice of detector is dictated by both the wavelength and, more important, the standard-lamp intensity.

Wide slits are needed in the ultraviolet and visible regions, because of low standard-lamp irradiance, and in the infrared region, because of reduced energy from the grating. This enforced large slit width requires the use of a neutral density filter in the ultraviolet and visible regions for the unknown source.

This program is then modified to fit the additional limitations imposed by the standard lamp. The final program is thus formed by trade-offs between limitations due to source-intensity variations, detector sensitivities, and resolution.

For purposes of curve fittings, obtaining data with both detectors in the region from 600 to 700 nanometers is not necessary, since the same value of $H_\lambda(\lambda)$ is obtained at the transition point with each detector to within 2 percent.
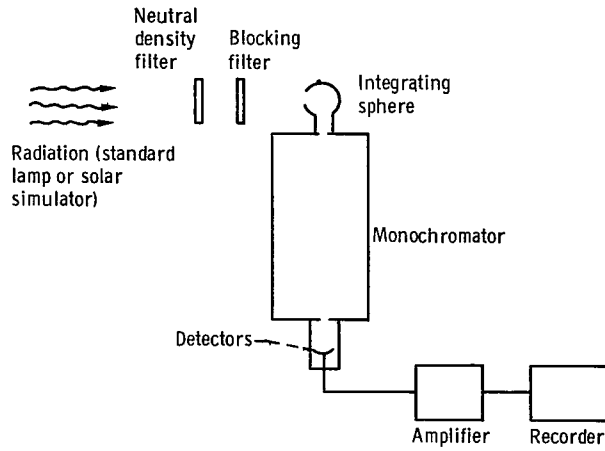
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Neutral
density
filter

Blocking
filter

Integrating
sphere

Radiation (standard
lamp or solar
simulator)

Monochromator

Detectors

Amplifier   Recorder

Figure 1. – Elementary diagram of spectroradiometer.

Detector

Multiplier–
phototube
(1 P 28)

Lead sulfide (PbS)

Slitwidth, mm

1.25

0.25   0.5   3.0   6.0   12.0

Wavelength, nm

300   600   700   1000

410   1200   1600   2100

250   650

Blocking filter

2 - 61   7 - 56   Lo-Pass

7 - 54

3 - 75

Neutral density
filter (unknown
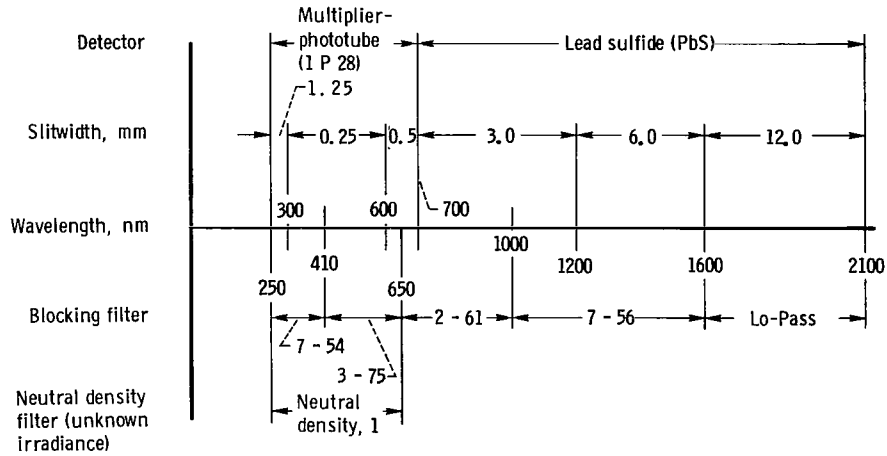irradiance)

Neutral
density, 1

Figure 2. – Typical program of detector, slit width, and filter.

Irradiance of the standard lamp was given by NBS at a distance of 50 centimeters from the filament. At this distance, the full spectral range of the spectroradiometer could not be covered because of an insufficient signal, especially in the infrared region. As a compensation for this insufficient energy, the standard lamp was used at a distance of 27.9 centimeters. Therefore, $H_{S,\lambda}(\lambda_i)$ must be multiplied by $(50/27.9)^2$ to obtain $H_\lambda(\lambda_i)$ by equation (3).

The spectral irradiance of the solar simulator at wavelength λ_i is then

$$H_\lambda(\lambda_i) = \frac{G_S}{G} \frac{H_{S,\lambda}(\lambda_i)}{\tau(\lambda_i)} \frac{V_i}{V_{S,i}} \left(\frac{50}{27.9}\right)^2 \tag{4}$$

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The validity of inverse-square correction was confirmed by measurements of lamp irradiance at both 27.9 and 50 centimeters.

The data that consitute the right side of equation (4) are entered directly onto FORTRAN IV sheets, and the irradiance is then obtained by computer reduction. Data reduction by computer is used because a typical solar simulator measurement requires over 100 spectral data points to adequately define the spectrum.

SELECTION OF SYSTEM COMPONENTS

Radiation Collection System

Integrating sphere. - For maximum accuracy, the spectroradiometer is calibrated while it is being used to measure the spectral irradiance of a solar simulator. The available sources for performing this calibration are tungsten lamps, which are des- cribed in references 3 and 4. Errors may be introduced by the geometrical differences between the lamp and the solar simulators - namely, differences in the position, direc- tion, and polarization of radiation.

The effects of position and direction are cancelled by use of an integrating sphere that receives radiation from either source along the same line of sight. No mirrors or lenses are used in the optical system before the integrating sphere so that the irradiance of the solar simulator may be compared directly with the irradiance of the calibrating standard.

The integrating sphere also provides a means by which the spectroradiometer can be made insensitive to polarized light. Reference 5 shows how an instrument transfer function can change with the plane of polarization.

Monochromator. - A grating monochromator was chosen because it offers the following advantages over a prism-type instrument:

(a) Constant reciprocal linear dispersion

(b) Linear wavelength readout

(c) High resolution

(d) Large light-gathering power because large-area gratings are available

(e) High ratio of detector flux to entering flux

The particular monochomator chosen had the added advantage of being practically free of anomalies because of the low ruling error of the grating.

Filters. - Since the monochromator is a single-grating instrument, optical filters are used to give a spectrum that is free of radiation outside the selected bandwidths. Stray light from mirror imperfections and multiple orders of diffraction has been mini- mized or eliminated by use of a variety of colored glasses and interference filters as

blocking filters. Where stray light cannot be eliminated, it is measured and used for data correction.

A solar simulator resembles a 6000 K blackbody radiator, whereas the standard lamp is a 3000 K tungsten filament. Also, arcs radiate much of their energy in emission lines, the radiant intensity of which may be several orders of magnitude larger than the continuous radiation from a tungsten filament at the same wavelength. The detectors must operate linearly over this range of intensities to provide a nonchanging transfer function. Rather than an attempt to develop a stable detection system with a large linear range, the solar simulator flux was optically attenuated by use of a neutral density filter. The technique whereby the monochromator slit widths are changed to provide optical attenuation was considered but was then discarded because the slits widths were not resettable to better than 5 percent.

Transducer

Two detectors were required to give an adequate signal-to-noise ratio over the wavelength range of the instrument: a multiplier phototube was used from 250 to 700 nanometers, and a photoconductor was used from 700 to 2100 nanometers. The following precautions were taken to eliminate any condition that might produce an error:

(1) Nonlinearity - The response of each of the detectors is not linear at high irradiance levels (refs. 6 and 7). A low irradiance on the detector is maintained by a predetermined combination of the monochromator slit width, neutral density filter, and amplifier gain. The resultant signal output of the detectors is thereby maintained below the value where nonlinearity becomes appreciable.

The multiplier-phototube response becomes nonlinear when the amplification changes because of changes in the accelerating voltage (ref. 8). Such changes can occur with changes in the signal (anode) current, if this current is excessive, and with a poorly regulated power supply. The effect of excessive signal current on the accelerating voltage is minimized by making the ratio between the divider-network current and the signal current always greater than 100. Fluctuations in the accelerating voltage supply are eliminated by use of a doubly regulated dc supply with 0.01-percent regulation.

The photoconductor response may also become nonlinear if it is operated beyond its power-dissipating capability for extended periods of time (ref. 6); such excessive power operation is avoided. The power-dissipating capability is not exceeded even during a 1-hour operating interval.

(2) Fatigue - Multiplier phototubes show a sensitivity loss due to fatigue (ref. 7) because of continued operation at high irradiance levels or because of large, abrupt changes in irradiance. This effect is eliminated by operating at low flux levels and by

exposing the detector to irradiance of a comparable level for approximately 30 minutes before a measurement is performed. This same irradiance is also applied to the detector in the period between measurements of the standard-lamp irradiance and the simulator irradiance.

(3) Temperature effects - Both detectors exhibit a change in sensitivity with temperature; however, both are enclosed in heavy brass sinks so that ambient temperature fluctuations during the measurement period have no effect on the results. Cooling by refrigeration was not used since the signal-to-noise capability of the detectors was adequate for the wavelength range being studied.

(4) Variation in surface sensitivity - Reference 1 shows how the sensitivity varies across the surface of photoconductors and multiplier-phototubes. In the present study, this shortcoming was eliminated by the measurement technique. The spectroradiometer was calibrated, and the solar simulator irradiance was measured with identical monochromator slit widths.

Amplifying and Recording System

An electronic amplifying system was used to transform the transducer output to a readable signal. This system comprises an ac amplifier, an ac to dc converter, and a recording dc potentiometer. This amplifying method was chosen because the photoconductor requires operation in an ac mode. For the detection of the low-level signal generated by the incident radiation, this radiation is chopped and the resultant pulsating electrical signal from the detector is recovered from the dc bias by capacitor coupling to the ac amplifier.

DESCRIPTION AND USE OF COMPONENTS

In the final assembled form (fig. 3), the optical components of the spectroradiometer consists of a radiation chopper, filter holder, limiting aperture, integrating sphere, grating monochromator, and interchangeable detectors in their individual light-tight enclosures. The electrical accessories are an ac to dc converter and a strip-chart-recording null-millivoltmeter. All the optical components are in a single rigid assembly that is shifted in its entirety to receive radiation from the standard or the unknown source.
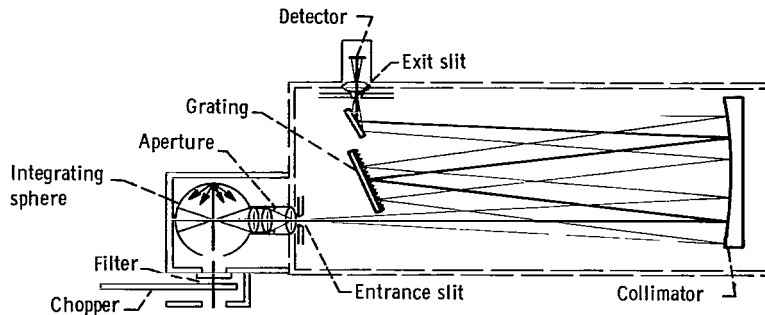
Figure 3. – Optical layout of spectroradiometer.

Integrating Sphere

The integrating sphere is 5.0 centimeters in diameter and is composed of two spun aluminum hemispheres bolted together after receiving a magnesium oxide (MgO) coating. Each hemisphere is initially coated with a flat black paint on the outside and with a flat white paint on the inside to provide a surface to which the MgO will readily adhere. The MgO coating is deposited according to the method described in reference 9. This coating method is implemented by an electrodeposition technique (described in ref. 10), which aids in producing a thicker and smoother coating, 3 to 4 millimeters thick, that remains firmly affixed to the walls for long periods of time.

The entire sphere and the lens system at the entrance slit are contained in a light-tight enclosure that has all surfaces painted with a flat black paint. The two apertures of this enclosure, the opening in the chopper blade, and the sphere opening are circular with diameters of 2.5, 2.2, 2.5, and 1.9 centimeters, respectively. The opening of the sphere is the limiting aperture in the system and is therefore the plane at which the radiation is measured.

Monochromator

An Ebert-type, 500-millimeter grating monochromator with an equivalent aperture of f/4.4 is used. A detailed description is given in appendix A.

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Filters

Stray light. - While measurements below 400 nanometers were made, a 7-54 glass filter was introduced at the entrance of the sphere. This filter, the spectral transmission of which is shown in figure 4, is almost completely opaque to visible light, but, because it is not completely effective in removing stray light, the remaining stray light is measured at 250, 270, and 290 nanometers by use of glass filters 0-53, 0-54, and 0-52, respectively. Typically, the ratio of stray light to the signal is 0.5 at 250 nanometers, 0.06 at 270 nanometers, and 0.01 at 290 nanometers.

Stray light may also be a source of error in the region between 600 and 700 nanometers because of the rapid decrease of multiplier-phototube sensitivity. The stray light in this region was determined by use of a tungsten lamp and a xenon-arc solar simulator with a set of color glass filters. The stray light was 1 percent of the signal at 700 nanometers and decreased to the limit of detectability at 650 nanometers. These low levels are obtained because the order-blocking filter used in this region transmits no radiation below 580 nanometers.

Order blocking. - To provide for elimination of the multiple orders of grating dif-
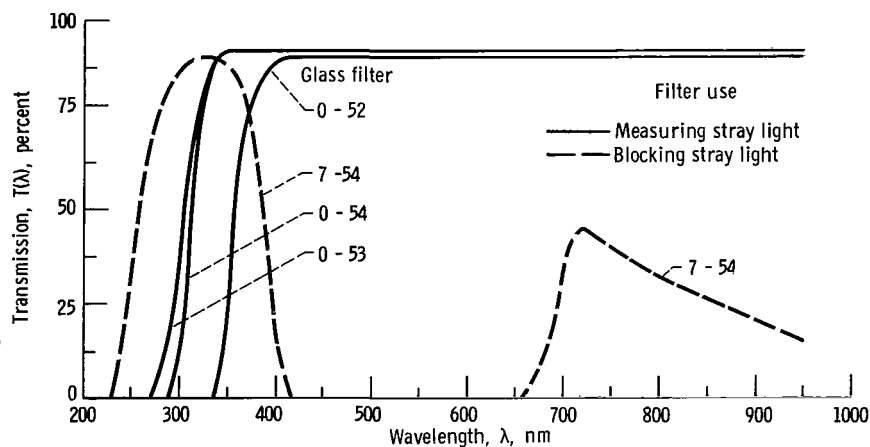

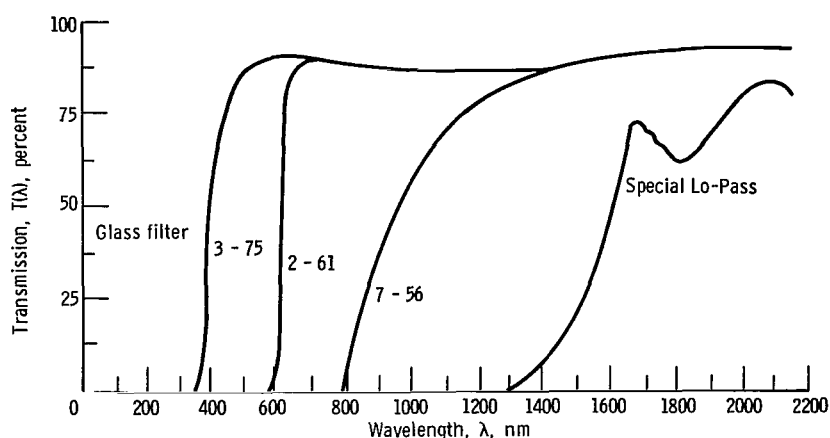Figure 4. - Approximate spectral transmission of filters for stray light.

Figure 5. - Approximate spectral transmission of order-blocking filters.

fraction, a set of four filters (fig. 5) was selected for use in the wavelength region from 410 to 2100 nanometers. The filters were inserted, one at a time, into the holder at the sphere housing in the sequence shown in the following table:

Filter	Wavelength when filter is inserted, nm	Percent of transmission at insertion wavelength	Wavelength of less than 0.5 percent trasmission, nm
3-75	410	50	365
2-61	650	85	580
7-56	1000	60	800
Lo-pass	1600	50	1250

The 3-75, 2-61, and 7-56 are all standard filters. The Lo-pass filter was specially constructed for this work.

Knowledge of the exact transmission characteristics of these filters is not necessary because they are used in the optical paths of both sources, and the transmission factor cancels out. However, as a double check, the spectral transmission of all filters was measured on a spectrophotometer.

Caution must be exercised in use of the 2-61 filter when hot sources are being measured. This filter exhibits a shift of its cutoff point toward the infrared region as its temperature increases. The effect was quite noticeable when the 1000-watt tungsten lamps were used at distances of 28 centimeters. This effect was minimized by using

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the 2-61 filter on the long wavelength side of the 650-nanometer knee. In addition, measurements were performed more rapidly in the region between 650 and 700 nanometers to minimize the heating time.

Irradiance matching. - The neutral density filter used for optical attenuation consists of a thin coating of Inconel sandwiched between two pieces of quartz. This construction proved to be quite stable over long periods of use. The spectral density of the filter is flat in the visible region and then decreases uniformly to 0.1 at 250 nanometers. This decrease is desirable because the fraction of the ultraviolet energy in the simulator beam increases tenfold over that in the lamp spectrum. The spectral density of this filter must be accurately known since it is used only in the solar simulator irradiance measurement. The density was measured on a spectrophotometer, which has a photometric accuracy of ±0.002 at a density of 1 and ±0.005 at a density of 2.

Detectors

A type 1P28 multiplier phototube, selected for low noise, and a lead sulfide (PbS) cell were used. Each produced an alternating signal as a result of mechanical modulation of the entering flux at 39 hertz. This frequency was selected to minimize hum pickup and to be compatible with the detector time constant and the amplifier frequency response. Each of the detectors is permanently mounted in a separate light-tight enclosure, and each has its own power supply.

Electronics

The ac coupled amplifying system, which has a gain adjustable in decade steps from 5 to 500, feeds a conventional strip-chart servo-balanced recorder with a 10-millivolt span. The gain accuracy is 1.0 percent and nonlinearity is negligible. The system is allowed a 30-minute warmup period to ensure that no drift occurs in the amplifier, and the ac supply voltage for all electrical equipment is regulated to 0.25 percent.

EXPERIMENTAL EVALUATION

The spectroradiometer was checked by performing two tests that are described in the following sections.

Reproducibility

The purpose of the reproducibility test was to determine whether or not the transfer function changed with time or with wavelength. Measurements were made on two 1000-watt NBS tungsten-iodine-lamp standards of spectral irradiance (ref. 4) over a period of 2 days. The lamps were located 27.9 centimeters from the sphere and were operated in series so that slight undetected changes in current would have no effect on the measurement. The spectrum of these lamps was measured at 31 calibrated wavelength points from 250 to 2100 nanometers. Each spectrum was determined 5 times over the 2-day period.

If the transfer function changes during the measurement, its fractional deviation at wavelength λ_i is

$$1 - \frac{R_{2,i}(\lambda_i)}{R_{1,i}(\lambda_i)} \tag{5}$$

where the subscripts 1 and 2 refer to the two lamps. If the amplifier gain settings for the measurements are equal, equation (5) becomes

$$1 - \frac{\dfrac{V_{2,i}}{V_{1,i}}}{\dfrac{H_{2,\lambda}(\lambda_i)}{H_{1,\lambda}(\lambda_i)}}$$

To obtain these data requires that a ratio be taken of the two voltages $V_{1,i}$ and $V_{2,i}$ produced by the spectroradiometer as it views the radiation from the two lamps at the same wavelength and bandwidth. The values of $H_{1,\lambda}(\lambda_i)$ and $H_{2,\lambda}(\lambda_i)$ are known from the NBS calibrations. The results of the reproducibility test are shown in figure 6.
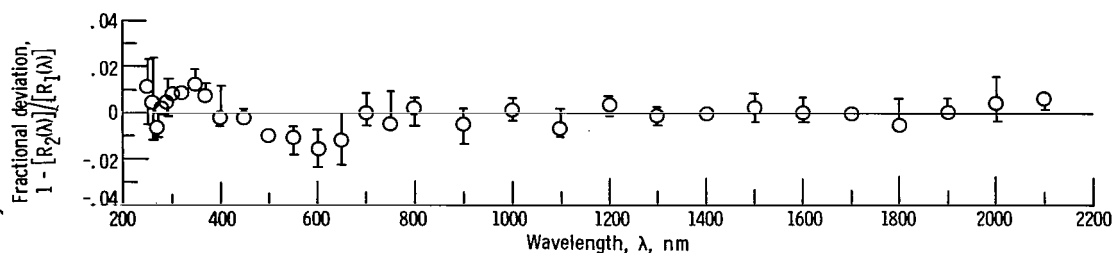

Figure 6. – Comparison of instrument repeatability and reproducibility for two 1000-watt lamps.

Each circle is the average of the five measurements at each wavelength over a 2-day period. The range of data scatter is indicated by the length of the vertical lines at each wavelength. The least-squares line differs from the zero line by less than 0.2 percent. This difference indicates that no systematic wavelength-dependent effect exists. The standard deviation of the averages represented by the circles is 0.7 percent. The average half-height of the vertical lines is 0.5 percent, representing the average variation over a 2-day period.
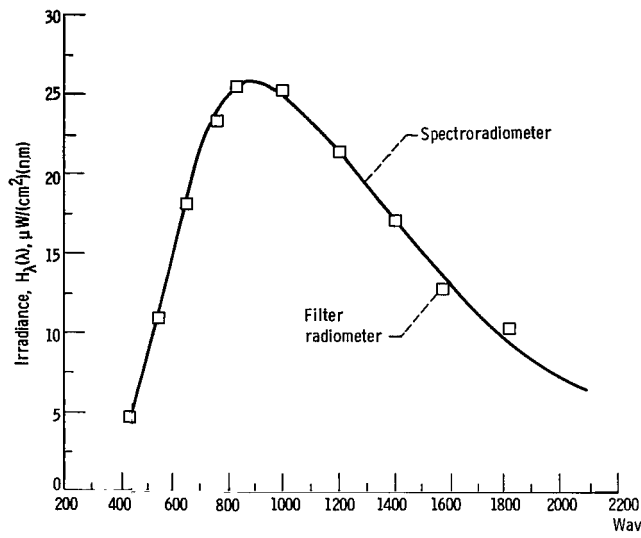
Correlation with Filter Radiometer

The measurement of the spectral irradiance of a solar simulator could be accepted with greater confidence if agreement were obtained between two independent measurements. One could be a high resolution method using this spectroradiometer, and the other could be a low resolution method using a filter radiometer. The particular advantage of using the filter measurement as an independent check is the fact that it has few errors in common with the spectroradiometer. The filter radiometer is described in appendix B.

The results of such a comparison would be a relatively smooth filter radiometer spectrum and a less smooth spectroradiometer spectrum, if the source had strong emission lines. For purposes of comparing the two spectra, the method of reference 11 can be further extended so that a linear equivalent spectrum of the spectroradiometer measurement is obtained. This linear equivalent spectrum, in effect, is the spectrum that the filter radiometer would give if it were receiving energy from a source having the spectrum defined by the spectroradiometer output.
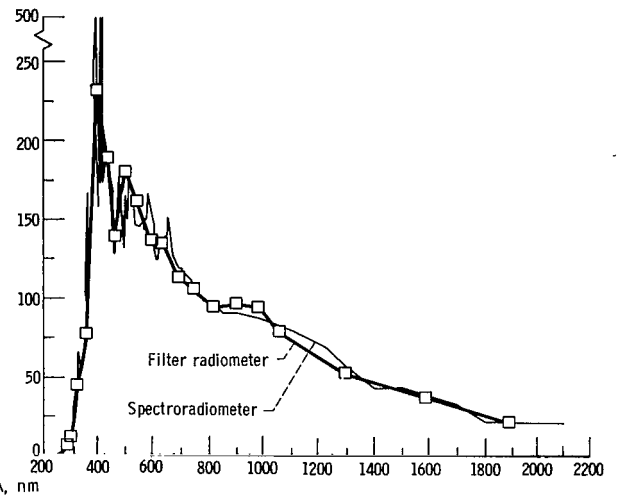
Figures 7(a) to (c) show the spectra obtained with the two instruments on a NBS tungsten-lamp standard of spectral irradiance, a carbon-arc solar simulator, and a xenon-arc solar simulator, respectively. Figures 8(a) to (c) show the differences that would be obtained between filter radiometer readings when the filter radiometer observed the source directly and when it observed the spectroradiometer output (linear equivalent spectrum).

The upper wavelength limit of 2100 nanometers in figures 7 and 8 is set by the cutoff of the spectroradiometer. The lower wavelength limit is 450 nanometers for the tungsten lamp, which produces very little irradiance below 450 nanometers, so that the signal-to-noise ratio for the filter radiometer becomes marginal. The higher irradiance of the solar simulators permits a lower limit of 250 nanometers.
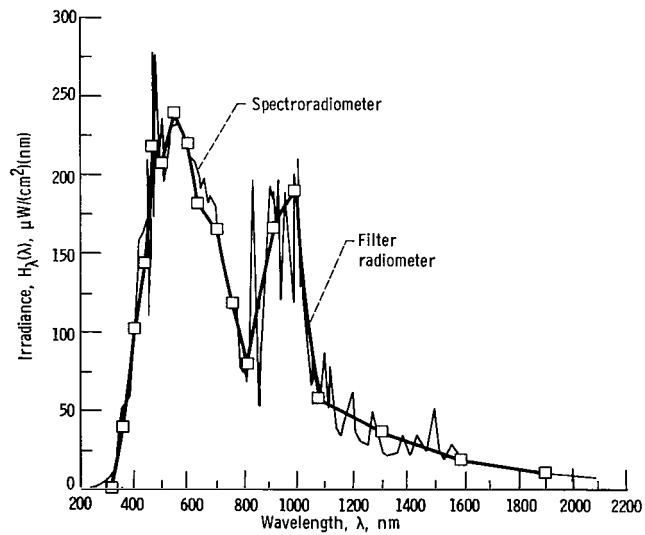
The root-mean-square deviation of the data shown in figures 8(a), (b), and (c) is 2.3, 4.7, and 5.2 percent, respectively. Additional details of the solar simulator measurements are presented in the next section
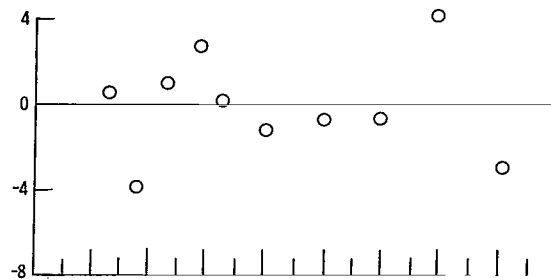
(a) Spectral irradiance of 1000-watt tungsten lamp.
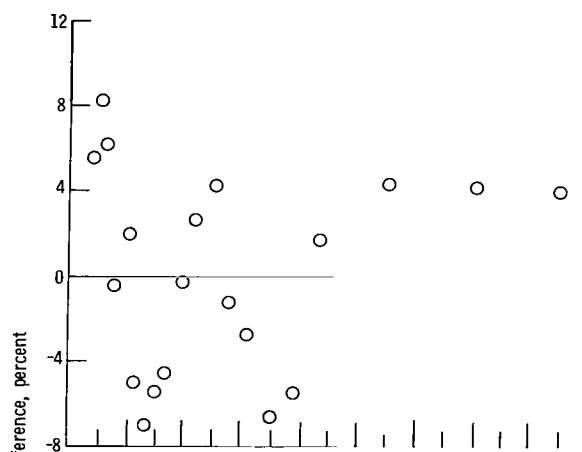
(b) Spectral irradiance of carbon-arc solar simulator.

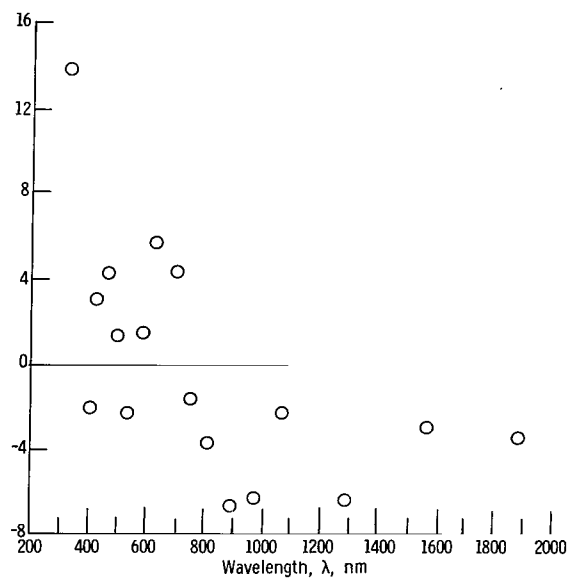(c) Spectral irradiance of xenon-arc solar simulator.

Figure 7. – Spectra obtained with spectroradiometer and filter radiometer from three radiation sources.

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(a) 1000-Watt tungsten lamp.

(b) Carbon-arc solar simulator.

(c) Xenon-arc solar simulator.

Figure 8. - Difference between linear equivalent forms of spectrora-
diometer and filter radiometer measurements of irradiance from
three radiation sources.

MEASUREMENTS ON SOLAR SIMULATORS

Spectral measurements on two simulators at the NASA Lewis Research Center were made in the target plane of each system where the irradiance level was 1 solar constant (140 mW/cm^2).

Carbon-Arc Solar Simulator

The carbon-arc solar simulator is a modified theatre projection carbon-arc lamp. It is essentially as described in reference 12, except that the theatre lamp uses 160-ampere rather than 400-ampere electrodes, and the optics are scaled down to irradiate a 30-centimeter-diameter target area.

While spectral measurements are made with the monochromator (which requires approximately $1\frac{1}{2}$ hr), the total irradiance is monitored with a thermopile detector because the total value of irradiance does not remain constant but varies by as much as 3 percent. Readings are made only when the total irradiance is at the nominal value. The time constant of the thermopile monitor is approximately 1/4 second and is adequate to follow the temporal variations of the carbon arc.

A photograph of the setup used to measure the spectrum of the carbon-arc system is presented in figure 9. The thermopile monitor is out of view; it was located near an aperture in the shield that allowed the central portion of the beam to irradiate the sphere. The filter radiometer, which was also used in these measurements, was located so that its detector was positioned in the same plane as that occupied by the entrance aperture of the sphere.

The results of the spectral measurements on this simulator are shown in figure 7(b). The emission lines shown on the spectroradiometer output were defined by slowly scanning the spectrum and selecting the wavelengths where peaks and valleys occurred. This scanning results in a presentation where the line structure is triangular in shape. The line structure shown in this figure is undoubtedly wider and shorter than the true shape because the slit widths used were relatively large.

The ordinates of figure 7(b) were checked by the following procedure. The area under the curve (which is the total irradiance) is determined by measuring the total irradiance in the solar simulator beam with the calibrated thermopile of the filter radiometer. The total irradiance would be 140 milliwatts per square centimeter over the wavelength limits (180 to 3500 nm) of the solar simulator and thermopile detector, the infrared responses of which are limited by quartz windows. However, since the spectral measurements are made only out to 2100 nanometers, a smaller area must be used. The assumption is made that 5 percent of the energy in the simulator lies beyond
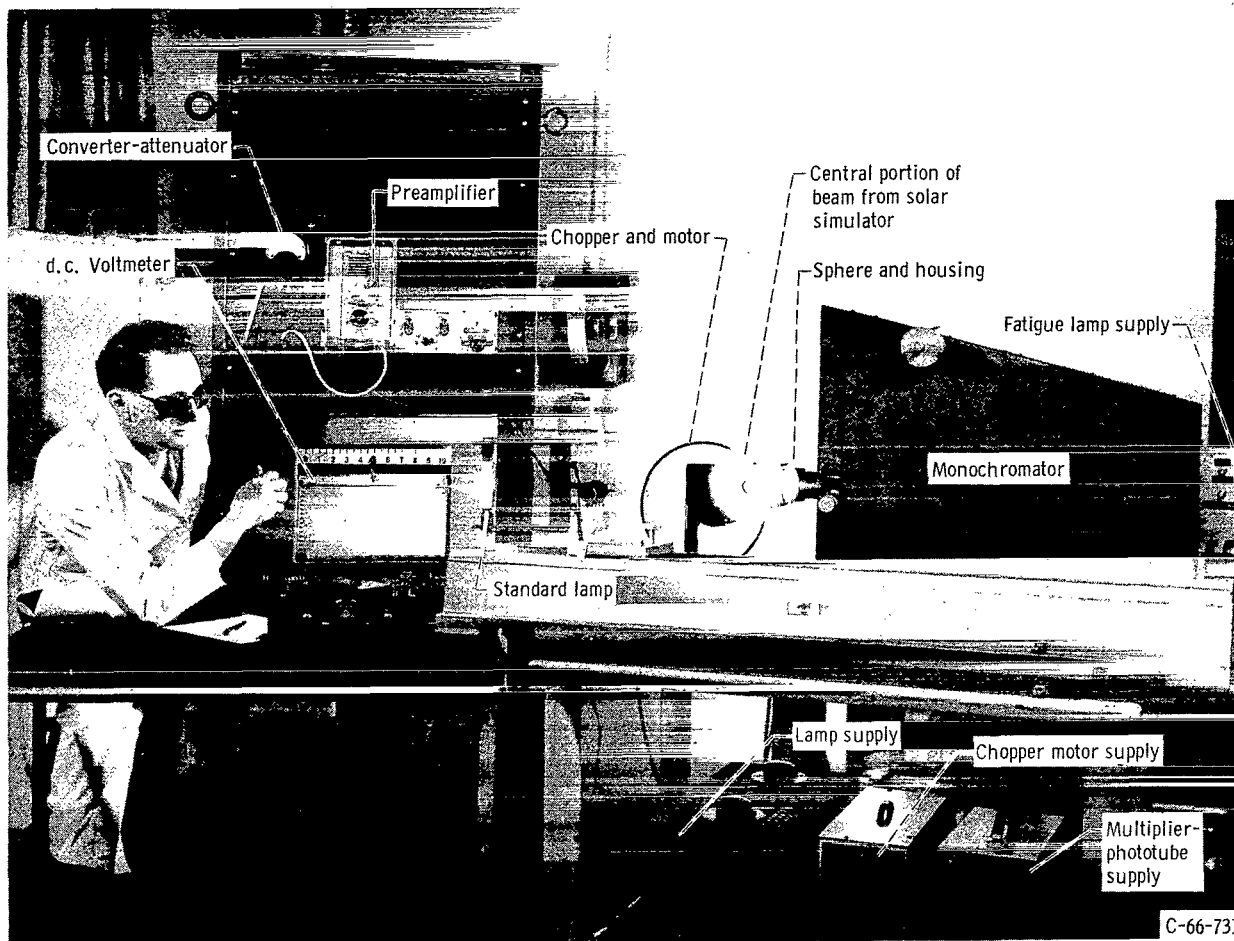
Figure 9. – Spectroradiometer system for measurements on solar simulator.

2100 nanometers; therefore, 95 percent of the irradiance measured by the thermopile is 0.95×140 or 133 milliwatts per square centimeter, and it is the irradiance assigned to the area under the spectral curve from 250 to 2100 nanometers. The result obtained with this procedure agrees within 5 percent with the result of the procedure using the absolute values of $H_{S,\lambda}(\lambda_i)$ of equation (4); this 5 percent also represents the predicted combined uncertainties of the two methods.

The root-mean-square deviation between the filter radiometer and linear equivalent spectrum of the spectroradiometer, as shown in figure 8(b), is 4.7 percent. A spectrum that has a reduced uncertainty can be obtained if both measurements are combined into one composite spectrum, as described in reference 11. A correction term that is obtained from the filter radiometer measurements is applied to the spectroradiometer measurement to give the composite result of figure 10. Some idea of the improvement to the monochromator measurement can be seen from the fact that the
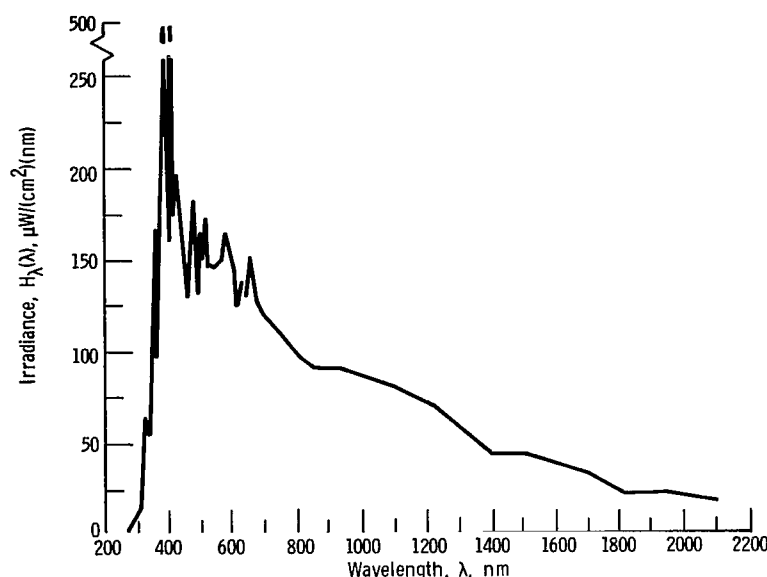
18

Figure 10. – Spectral irradiance of carbon-arc solar simulator composite spectrum.

root-mean-square deviation between the linear equivalent spectrum of this composite curve and the filter radiometer curve is 3.8 percent instead of the previous value of 4.7 percent. The curve of figure 10 differs only slightly from that of figure 7(b) because the correction is not localized but is distributed over the entire spectrum.

Xenon-Arc Solar Simulator

The xenon-arc solar simulator is a commercially available unit that uses a 6.5 kilowatt xenon-compact-arc lamp plus filters to reduce the intensity of the emission spectrum between 800 and 1050 nanometers.

The result of the spectral measurements is shown in figure 7(c). The spectral bandwidth of the monochromator was as shown in figure 2. The emission lines were defined as for the carbon arc by measurements made at the peaks and valleys, and the same triangular shapes resulted. Because of the relatively wide (10 nm) bandpass in the region between 800 and 1050 nanometers, the xenon emission spectrum in this region is not accurately resolved.

The filter radiometer measurements, also shown in figure 7(c), were made with 17 of the 20 filters used for the carbon-arc lamp measurement. The ultraviolet filters used in the carbon-arc lamp measurement were not used because of the low ultraviolet content of the xenon arc.

A comparison of the filter radiometer result with the linear equivalent spectrum of the spectroradiometer measurement is shown in figure 8(c). The greatest difference in the two ordinates occurs at 355 nanometers and is 13.9 percent. This large difference occurs because a comparison is made by a linear extrapolation of the filter-measured spectrum out to the limits of the filter spectral transmission. Obviously, the curve is not linear below 355 nanometers. Most of the other data agreed to approximately 2 to 4 percent with the exception of the values at 902, 975, and 1297 nanometers, which are near strong emission lines of xenon. The differences here are -6.7, -6.3, and -6.3 percent, respectively. The root mean square of the deviations is 5.2 percent.

As was done for the carbon arc, a composite spectrum of the xenon arc was obtained and is shown in figure 11. The differences at the wavelengths of 902, 975, and 1297 nanometers were reduced to -3.0, -2.0, and -1.6 percent, respectively, that is, the irradiance measured by the spectroradiometer in the regions of strong line emission was increased slightly. This result confirmed the known fact that the broadband pass of the monochromator had reduced the true line height. However, the shape of the line emission had not been so greatly distorted that the composite spectrum method could not give improved results. The root mean square of the deviations of the composite spectrum had been reduced from 5.2 to 3.5 percent.
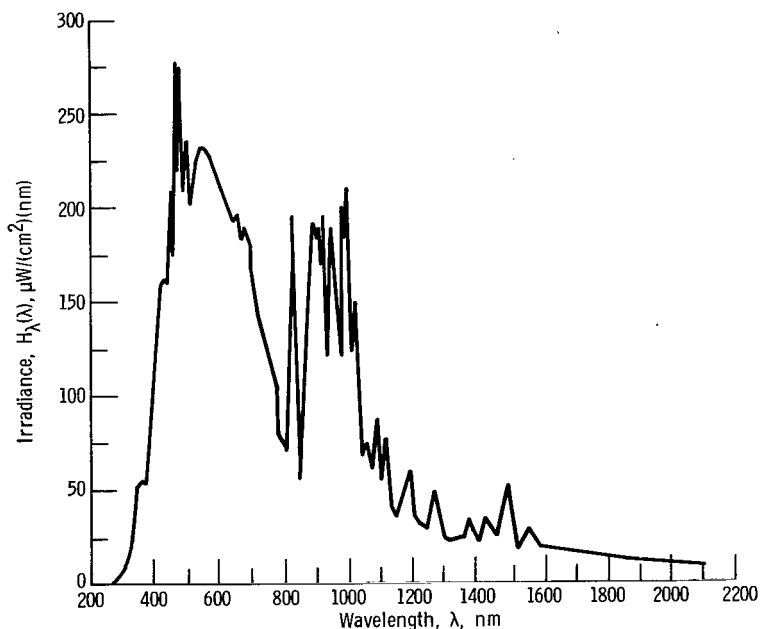

Figure 11. - Spectral irradiance of xenon-arc solar simulator composite spectrum.

CONCLUSION

The spectroradiometer developed as a result of this program gives low-error spectral measurements of solar simulators in the wavelength region from 250 to 2100 nanometers. The investigation established that this instrument system would reproduce the spectrum of a tungsten-lamp standard to better than 2 percent. Also established by means of the linear equivalent spectrum (which permits comparison of the spectrum obtained with instruments giving high and low resolution measurements) was that the spectrum of a tungsten lamp obtained with this spectroradiometer and one obtained with a filter radiometer agree to better than 2 percent. This spectroradiometer would, therefore, give spectral measurements of tungsten standards to an accuracy of 2 percent. The root-mean-square difference between the linear equivalent spectrum of the spectroradiometer measurement and the filter radiometer measurement of two entirely different solar simulator systems (a carbon arc and a xenon arc) was approximately 5 percent. This difference was reduced to approximately 3.5 percent by combining the two measurements into a composite spectrum that contained the desirable qualities of both measurement methods. The degree of agreement is representative of what might be expected in measurements of other solar simulators.

For the obtainment of these low-error spectral irradiance measurements, consideration was given to the past difficulties associated with geometrical factors, instrument range, and technique. From a preliminary study, it was determined that these sources of errors can be and are, in fact, eliminated by the following considerations:

1. The dependence on position and direction of the radiation is eliminated by use of an integrating sphere, the desirable features of which are enhanced when it is used with a high-irradiance source for calibration. This sphere also minimizes errors that may result from polarization.

2. The linear range of the spectroradiometer is optically extended by use of a stable, accurately measured neutral density filter having a spectral transmission that varies smoothly with respect to wavelength.

3. At each wavelength point, the spectral irradiance of the solar simulator is compared with that of a standard lamp. Since a grating monochromator is used as a disperser, this technique provides a spectroradiometer that has a transfer function which is essentially constant at any specific wavelength, even for spectrally different sources.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, June 6, 1968,
124-09-05-03-22.

APPENDIX A

MONOCHROMATOR

The monochromator disperses the radiation received from the sphere. The radiation to be measured enters the sphere after passing through the apertures, the optical chopper, and the filter. The quartz triple-lens system at the entrance slit collects the diffuse radiation from the sphere walls and directs it into the monochromator so that the entrance slit and gratings are uniformly irradiated. The aperture in this lens system is focused by the slit lens onto the grating, and thereby eliminates stray radiation due to spillage about any optical element. The collimator has a focal length of 500 millimeters and gives the monochromator an equivalent aperture of f/4.4. Actually, the grating is located above the horizontal plane extending through the slits. The collimator is slightly tipped so that the first reflection will be above the plane of the figure. The grating is also tipped so that energy reflected from it will return to the collimator. The quartz lens placed at the exit slit facilitates the use of two different detectors. Because this lens is not color corrected, its refractive index decreases by approximately 5 percent from 250 to 2100 nanometers. A change in size of the image at the detector results but is of no consequence because in the measurement technique both sources are compared at the same wavelength. The detector thereby makes a comparison at the same refractive index of the quartz. These conditions hold for the triple-lens system at the entrance slit. The size of the aperture within this lens system is such that all radiation is kept within the limits of the grating surface for all wavelengths.

The diffraction grating has 600 grooves per millimeter and gives (in the plane of the exit slit) a reciprocal linear dispersion of 3.2 nanometers per millimeter. The grating is blazed for maximum efficiency at 400 nanometers in the first order. The diffracted energy traverses the exit slit by rotation of the grating through a sine-bar drive that produces a linear relation between wavelength and rotation.

Three physical modifications were made to the monochromator. First, for coverage of the wavelength region from 250 to 2100 nanometers, the upper-limit wavelength stop was removed (normal operating range of this instrument was 200 to 1400 nm) and the grating was reset. A wavelength calibration (i.e., the grating position against rotation) was made by use of the emission lines from a low pressure mercury-arc source. The calibration was checked through the full operating range by using the multiple orders of the strong mercury lines and was linear to better than one-half the minimum scale division, 0.5 nanometer.

Second, the standard physical construction made bringing the radiation into the entrance slit difficult. The uses of the two slits were therefore reversed, so that

radiation entered the original exit slit and left at the original entrance slit. This reverse use (optically) of the monochromator is possible because the Ebert mount is optically symmetrical about the grating. The slits were also inverted so that the flat faces of the beveled jaws faced the oncoming radiation to minimize scattering.

Third, inside surfaces of the instrument that introduced reflections were painted with a flat black paint which has an absorptance of 0.98 or better.

APPENDIX B

FILTER RADIOMETER

The filter radiometer is composed of a series of interference filters (each used individually) and a blackened thermopile detector having a response that is insensitive to the three space-related parameters (direction, position, and polarization). The parameter of time is minimized by the measurement technique used with the instrument. The transfer function is not as complex as that of the spectroradiometer and is simply the transmission of the interference filter. This simplicity is seen in the defining equation of the measured voltage which is obtained when a filter is used in the radiometer:

$$V = GS \int_0^\infty H(\lambda)\tau(\lambda)d\lambda \tag{B6}$$

where

G   gain of voltmeter

S   sensitivity of detector and independent of wavelength

$H(\lambda)$ unknown spectral irradiance

$\tau(\lambda)$ spectral transmission of filter

The transfer function can be determined if a calibration that uses a known irradiance is performed and the equation is changed to the approximation form of equation (2). However, this approximation is subject to error because the $\Delta\lambda$ of the filter is relatively broad. Also, using a calibrating standard reduces the effectiveness of the method as an independent check on the spectroradiometer, because the same source must be used for calibrating the spectroradiometer. Instead, an iterative data reduction program, described in reference 10, is used to obtain a filter-measured spectrum. This filter spectrum is formed by a series of straight line segments that join the spectral irradiance values at wavelengths determined by the centroid of the filter spectral transmission. In reference 11, the spectrum formed by this method is called the linear equivalent spectrum because the calculated spectrum, if measured with the filter radiometer, would give the same voltages as would the actual spectrum, provided that such a measurement were performed on the calculated spectrum.

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