NATIONAL BUREAU OF STANDARDS REPORT

8619

An Artificial Star Source for the OAO

By

D. Sirota and L. Chernoff

NBS

U.S. DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

THE NATIONAL BUREAU OF STANDARDS

The National Bureau of Standards is a principal focal point in the Federal Government for assuring maximum application of the physical and engineering sciences to the advancement of technology in industry and commerce. Its responsibilities include development and maintenance of the national standards of measurement, and the provisions of means for making measurements consistent with those standards; determination of physical constants and properties of materials; development of methods for testing materials, mechanisms, and structures, and making such tests as may be necessary, particularly for government agencies; cooperation in the establishment of standard practices for incorporation in codes and specifications; advisory service to government agencies on scientific and technical problems; invention and development of devices to serve special needs of the Government; assistance to industry, business, and consumers in the development and acceptance of commercial standards and simplified trade practice recommendations; administration of programs in cooperation with United States business groups and standards organizations for the development of international standards of practice; and maintenance of a clearinghouse for the collection and dissemination of scientific, technical, and engineering information. The scope of the Bureau's activities is suggested in the following listing of its four Institutes and their organizational units.

Institute for Basic Standards. Electricity. Metrology. Heat. Radiation Physics. Mechanics. Applied Mathematics. Atomic Physics. Physical Chemistry. Laboratory Astrophysics.* Radio Standards Laboratory: Radio Standards Physics; Radio Standards Engineering.** Office of Standard Reference Data.

Institute for Materials Research. Analytical Chemistry. Polymers. Metallurgy. Inorganic Materials. Reactor Radiations. Cryogenics.** Office of Standard Reference Materials.

Central Radio Propagation Laboratory.** Ionosphere Research and Propagation. Troposphere and Space Telecommunications. Radio Systems. Upper Atmosphere and Space Physics.

Institute for Applied Technology. Textiles and Apparel Technology Center. Building Research. Industrial Equipment. Information Technology. Performance Test Development. Instrumentation. Transport Systems. Office of Technical Services. Office of Weights and Measures. Office of Engineering Standards. Office of Industrial Services.

---

* NBS Group, Joint Institute for Laboratory Astrophysics at the University of Colorado.
** Located at Boulder, Colorado.

NATIONAL BUREAU OF STANDARDS REPORT

NBS PROJECT 2120420

NBS REPORT 8619

An Artificial Star Source for the OAO

By

D. Sirota and L. Chernoff

Prepared for
National Aeronautics and Space Administration
Goddard Space Flight Center
Greenbelt, Maryland 20771

NBS

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

Table of Symbols

$\underline{d}$	the distance between the filament of the tungsten projection lamp and the aperture of the OAO star-simulator
$\underline{D}$	the distance between the aperture of the OAO star-simulator and the receiver
$\underline{D_{OAO}}$	the value of $\underline{D}$ necessary to produce an illuminance of 3.1×10^{-8} footcandle at the receiver
$\underline{E}'$	the illuminance at the flashed opal glass
$\underline{E}$	the illuminance at the receiver
$\underline{F_c}$	the focal length of the optic of the collimated star-simulator
$\underline{F_T}$	the focal length of the objective of the star-tracker
$\underline{H_{OAO}}$	the spectral irradiance produced by the OAO star-simulator at the receiver which yields an illuminance of 3.1×10^{-8} footcandle
$\underline{H_{xenon}}$	the spectral irradiance produced by a star-simulator having a xenon lamp light source at the receiver required to yield an illuminance of 3.1×10^{-8} footcandle
$\underline{H_{10,700}}$	the spectral irradiance from a type AO star
$\underline{I_A}$	the intensity of the aperture of the OAO star-simulator
$\underline{I_L}$	the intensity of the tungsten projection lamp
$\underline{J}$	the diameter of the source of light in the collimated star-simulator
$\underline{K}$	the diameter of the image of the collimated star-simulator produced by the objective of the star-tracker
$\underline{\bar{N}_{xenon}}$	the relative spectral energy distribution from a xenon lamp

$\bar{N}_{3,000}$ the relative spectral energy distribution of color temperature 3,000°K from the tungsten projection lamp and opal glass combination

P_{OAO} the relative output with respect to wavelength of a star-tracking receiver irradiated by the OAO star-simulator

P_{star} the relative output with respect to wavelength of a star-tracking receiver irradiated by a type AO star

P_{xenon} the predicted relative output with respect to wavelength of a star-tracking receiver when irradiated by a star-simulator having a xenon lamp light source

r the radius of the aperture of the OAO star-simulator

R_D the relative spectral response of the photodetecting surface in the star-tracking receiver

R_r the relative spectral response of the star-tracking receiver

s_u the object distance when the OAO star-simulator is focussed by the objective of the star-tracker

s_v the image distance when the OAO star-simulator is focussed by the objective of the star-tracker

T_F the luminous transmittance of the two triple-layered, blue-glass color temperature altering filters

T_G the luminous directional transmittance of the flashed opal glass

T_{MBC} the spectral transmittance of M.B.C. optical glass (20 mm thick)

T_{6G} the spectral transmittance of the two triple-layered, blue-glass color temperature altering filters

U the diameter of the aperture of the OAO star-simulator

V the diameter of the image of the aperture of the OAO star-simulator produced by the objective of the star-tracker

1. Introduction

Under contract order S-60407-G dated June 5, 1964, the National Bureau of Standards constructed for the National Aeronautics and Space Administration a prototype of a low-intensity, uncollimated light source. This light source is the standard for calibrating star-tracking equipment of the OAO (Orbiting Astronomical Observatory) Project.

Light from this source simulates the illuminance and "color temperature" of a visual second magnitude AO star. The stellar magnitude of a source with an intensity of one candela when viewed at a distance of one meter is -14.18.[1/] From this value and the definition of stellar magnitude, the illuminance of a second magnitude star was calculated to be 3.1×10^{-8} footcandle. The "color temperature" of a type AO star has been defined as 10,700°K.

In the star-simulator, the source of light is a tungsten lamp. The "color temperature" of this light is altered by means of a special blue filter. The light is then diffused by a flashed opal glass which produces a light source of uniform luminance at a fixed distance $\underline{d}$ from the lamp. The light then passes through a small aperture which restricts the area of the flashed opal glass viewed by the receiver. The arrangement of the components of the star-simulator is shown in figures 1 and 2.

2. Spectral Energy Distribution of the OAO Star-Simulator

2.1 Spectral Irradiance Produced by a Type AO Star

Star-tracking receivers used in the OAO project make use of S-4 or S-20 type photodetector surfaces and glass optical systems. For calculation purposes, it was assumed that the receiver optical system consisted of 20 mm of type M.B.C. optical glass.[2/] As the range of spectral response for this type of receiver is 0.35 to 0.75 micron, duplication of the spectral energy distribution of the type AO star by the OAO star-simulator is desired within this spectral range.

Strictly speaking, the term color temperature refers only to visible flux (0.40 to 0.70 micron). Since the range of spectral response of star-tracking receivers is broader than the visible spectrum, the type AO star color temperature requirement was interpreted to mean that the spectral energy distribution from the OAO star-simulator should as closely as possible correspond to the spectral energy distribution from a type AO star for the 0.35 to 0.75 micron range. The relative spectral energy distribution of a 10,700°K blackbody for this range was therefore used as a definition of the relative spectral energy distribution of a type AO star.[3/]

By use of this definition for the relative spectral energy distribution of a type AO visual second magnitude star and the fact that the illuminance on the surface of the earth from such a star is 3.1×10^{-8} footcandle, the spectral irradiance of this type of star, $\underline{H_{10,700}}$, was calculated and is shown in figure 3.

2.2 Spectral Irradiance Produced by the Star-Simulator

In the OAO star-simulator it is necessary to use a tungsten lamp with the highest color temperature consistent with lifetime considerations in order to obtain a significant ultraviolet component. After examination of several different types of lamps, a 500-watt clear projection lamp of ASA type DNK was selected for use. Three seasoned lamps of this type were calibrated to have a color temperature of 3,000°K when viewed respectively through the flashed opal glass LS 631.

The relative spectral energy distribution of the combination of one of these lamps and the flashed opal glass, $\underline{\bar{N}_{3,000}}$, was measured by using a monochromator and photomultiplier. The output of the photomultiplier was calibrated with respect to wavelength by means of a standard tungsten projection lamp of known relative spectral energy distribution operated at 2,854°K. This output was monitored by a picoammeter.

Because of practical considerations, only filters readily available were considered for the star-simulator. It was found that the combination of two triple-layered, blue-glass filters available from Corning Glass Works have the most suitable spectral transmission characteristics. These glasses are sold commercially with identification numbers C.S. 1-71 and C.S. 1-72. The spectral transmittance for this combination filter was measured by means of a spectrophotometer and is represented by $\underline{T_{6G}}$.

The relative spectral energy distribution of the star-simulator, therefore, is given by $\underline{\bar{N}_{3,000} T_{6G}}$. By use of this distribution and the required illuminance at the receiver, the spectral irradiance, $\underline{H_{OAO}}$, produced by the star-simulator at the receiver was calculated. $\underline{H_{OAO}}$ is shown in figure 3 compared to $\underline{H_{10,700}}$.

These curves are somewhat similar in most of the visible region (0.4 to 0.7 micron) of the spectrum but deviate markedly in the ultraviolet and infrared regions. The data of figure 3 can be used to evaluate the difference in the output as a function of wavelength of a receiver of known spectral response when the receiver is irradiated by the star-simulator instead of by a type AO star.

2.3 Relative Output with Respect to Wavelength of a Receiver with an S-4 Or S-20 Surface

The criterion for selecting the color-temperature altering filter was a visual judgment of the closeness of the match between the relative output with respect to wavelength, P_{star}, of the receiver when irradiated by the type AO star, with that, P_{OAO}, when irradiated by the OAO star-simulator. The relative output with respect to wavelength of the OAO star-simulator and of a type AO star are respectively,

$$P_{OAO} = H_{OAO}R_r \tag{1}$$

and

$$P_{star} = H_{10,700}R_r \tag{2}$$

where R_r is the relative spectral response of the receiver. But since the receiver consists of optical glass of spectral transmittance, T_{MBC}, and a photodetector of relative spectral response, R_D,

$$R_r = T_{MBC}R_D \,. \tag{3}$$

Therefore,

$$P_{OAO} = H_{OAO}T_{MBC}R_D \tag{4}$$

$$P_{star} = H_{10,700}T_{MBC}R_D. \tag{5}$$

Figures 4a and 4b are comparisons of P_{OAO} and P_{star} for two different photodetectors. In figure 4a the response is that of an S-4 type photodetector surface,and in figure 4b the response is that of an S-20 type.[4/] Note that the spectral match is good in most of the visible region (0.4 to 0.7 micron),but a significant mismatch exists in the region below 0.4 micron.

Because the spectral response of photodetector surfaces varies widely, comparison of P_{OAO} and P_{star} are made in figures 5a and 5b where R_D is respectively the spectral response of an extreme red- and extreme blue-shifted S-4 photodetector surface.[5/] The differences between P_{OAO} and P_{star} as shown in figures 5a and 5b are not appreciably greater than the differences between P_{OAO} and P_{star} as shown in figure 4a.

3. Consideration of the Use of a Xenon Lamp in the Star-Simulator

The use of a xenon lamp as a light source instead of a tungsten projection lamp was investigated because of the large ultraviolet component of xenon lamps. The relative spectral energy distribution from a star simulator having a xenon lamp light source is then given by $\underline{\overline{N}_{xenon} T_{6G}}$. By use of this distribution, the spectral irradiance, $\underline{H_{xenon}}$, produced by a star simulator having a xenon lamp light source at the receiver required to yield an illuminance of 3.1 x 10^{-8} footcandle was calculated. For this calculation the data for $\underline{\overline{N}_{xenon}}$ were taken from reference 6.

Figures 6a and 6b show a comparison of $\underline{P_{xenon}}$ and $\underline{P_{star}}$ where

$$P_{xenon} = H_{xenon} T_{MBC} R_{D}, \qquad (10)$$

and $\underline{R_D}$ is the relative spectral response of the S-4 and S-20 surfaces, respectively. A large mismatch occurs between $\underline{P_{xenon}}$ and $\underline{P_{star}}$ in the spectral region between 0.375 and 0.475 micron. This mismatch is due to the large blue spectral component of a xenon lamp and the fact that S-4 and S-20 surfaces have higher response in the blue region than they have in the rest of the visible region of the spectrum.

When used with the xenon source, the predicted relative output with respect to wavelength of the receiver, $\underline{\overline{N}_{xenon} T_{MBC} R_{D}}$ could be normalized so that the receiver has the same output whether irradiated by a star-simulator having a xenon light source or by an AO star.* Curves with this kind of normalization are shown in figure 7. While the match of these curves is better than in figure 5, it is still too poor to permit the use of a xenon lamp in the star-simulator without the addition of a correcting filter. In addition, a xenon lamp emits a line spectrum not shown in the above figures. It was, therefore, decided that a tungsten filament lamp was more suitable for the star-simulator than was a xenon lamp.

4. Construction

The OAO star-simulator is constructed as a single unit box of dimensions as shown in figure 2. The box is made of aluminum and is portable. All seams of the box are light-tight. The inside of the box is painted with a flat black paint while the outside is painted spackled black. A baffle which is situated between the tungsten projection lamp

---

* This normalization differs from the one used in figure 5 of "Progress Report July 1, 1964 to September 30, 1964 For an Artificial Star Source for the OAO" (NBS 8565). In that report the curves were normalized to have equal peak values.

and the aperture implements the black interior in reducing the amount of stray light from internal reflections reaching the aperture. The tungsten projection lamp is cooled by an internally-mounted fan. The filter, flashed opal glass, and aperture are fastened securely in holders by means of set screws.

5. Illuminance Produced by the OAO Star-Simulator

Note: The star-simulator has been discussed with respect to spectral irradiance. However, the output of the star-simulator was to be specified in photometric terms. In this section, therefore, photometric definitions and units are used.

With reference to figure 2, if the thickness of the opal glass is assumed to be small with respect to d, the illuminance on the flashed opal glass is given by

$$E' = I_L \, T_F / d^2 \qquad (6)$$

where I_L is the intensity of the lamp, and T_F is the luminous transmittance of the blue filter. The intensity of the aperture is

$$I_A = E' \, T_G \pi r^2 / \pi = E' T_G r^2 \qquad (7)$$

where T_G is the luminous directional transmittance of the flashed opal glass and r is the radius of the aperture.

The luminous directional transmittance of the flashed opal glass is defined as the ratio of the luminance of the surface of the opal glass facing the aperture to the luminance of an ideal perfect diffuser identically illuminated. The luminance is measured in a direction along an axis through the center of the opal glass. The glass is illuminated along this same axis.

When a receiver is placed at a distance D from the aperture, the illuminance at the receiver is

$$E = I_A / D^2 \; . \qquad (8)$$

Therefore,

$$E = I_L T_F T_G r^2 / d^2 D^2 \; . \qquad (9)$$

It was decided that the star-simulator would be used at a distance, D, of about 30 feet. Appropriate values of the other parameters of equation 9 were then chosen to give the desired value of E. Each of the three tungsten projection lamps has an intensity, I_L, of about 1,400 candelas. The other components of the star-simulator have values:

$$T_F = 0.065$$
$$T_G = 0.5$$
$$d = 14.0 \text{ inches}$$
$$\text{and } r = 0.01 \text{ inch.}$$

The intensity, I_A, of the aperture of the star-simulator was measured with each of the lamps as the source of light. The measurement was made by means of a PJ-14B vacuum phototube photometer calibrated by use of three different standard lamps.[7] The output of the photometer was amplified by means of an electrometer amplifier, and the deflection of the amplifier was monitored by means of a recorder. The lamp current was set, and the lamp voltage was measured by means of a potentiometer.

From the measured values of I_A, the distance, D_{OAO}, between the aperture of the star-simulator and the receiver needed to produce an illuminance of 3.1×10^{-8} footcandle at the receiver was calculated by using equation 8. The results of the measurements and the calculated values of D_{OAO} are given in Table I.

Table I

Lamp	Current (amperes)	Voltage (volts)	I_A (candela)	D_{OAO} (feet)
NBS 7544	4.263	113.7	2.32×10^{-5}	27.2
NBS 7557	4.238	113.2	2.20×10^{-5}	26.6
NBS 7552	4.184	114.2	2.32×10^{-5}	27.2

6. Instructions for Use

1. The star-simulator is placed on a level table and adjusted so that the line of sight to the receiver is perpendicular to the aperture of the star-simulator.

2. A small, bright light source is placed behind the lamp to cast shadows on the internal baffle of the two phi-lines inscribed on the lamp. The star-simulator lamp is then adjusted until the shadows of the two phi-lines coincide with the line inscribed on the baffle.

3. The lid of the star-simulator box is fastened down securely to prevent any light leaks from occurring at its edges. As a further precaution against light leaks, a black cloth is draped over the box, leaving the aperture unobstructed.

4. The lamp current is set with a potentiometer, and the lamp voltage is periodically checked. The star-simulator is not used for calibrating until the voltage and current of the lamp are stable.

5. A visible check is then made to insure that only light directly transmitted from the aperture of the star-simulator reaches the receiver.

6. The intensity of the tungsten lamps must be remeasured after each four hours of operation to determine any effects of aging. A record of operation time, therefore, must be kept.

7. <u>Discussion</u>

As the OAO project is presently conceived, the star-simulator will be used to calibrate a photometer, and the photometer will be used to calibrate a collimated light source for use in testing star-trackers. However, use of the OAO star-simulator directly in testing star-tracking equipment should be considered.

In any star-tracking system, information about the position of a source depends upon the ability of the optical system of the star-tracker to focus light from the source to a small defined image. When the source is at an infinite distance from the receiver as is an actual star, the image will be formed at the focus of the objective of the optical system of the tracker.

When a source of uncollimated light is placed at an object distance greater than 26 times the focal length of a lens system, the source is effectively at infinity*. Since the OAO star-simulator can be placed at object distances in excess of 26 times the focal length of the tracker's objective, the image of the star-simulator will also be formed at the focus of the objective.

If $\underline{U}$ is the mean diameter of the aperture of the star-simulator, $\underline{V}$ is the diameter of its image, $\underline{s_u}$ is the object distance, and $\underline{s_v}$ is the image distance (which, for this case, does not differ significantly from the focal length of the objective of the star-tracker), then

$$V = U \frac{s_v}{s_u} . \qquad (10)$$

---

* This factor is variously given as between 15 and 26 times the focal length depending on the reference. For the purposes of this report the factor 26 is used.[8]

For a representative set of values of the parameters of the optical system,

$$U = 2.0\times10^{-2} \text{ inch},$$

$$s_v = 8.0 \text{ inches},$$

$$\text{and} \quad s_u = 3.26\times10^{2} \text{ inches},$$

the image size $\underline{V}$ is 4.9×10^{-4} inch.

The fact that the object diameter is small with respect to the focal length, and that the object lies on or close to the optical axis at a distance greater than 26 times the focal length means that any of the various lens aberrations would be essentially the same as that for an object at infinity. Effectively, therefore, the image of the OAO star-simulator would be the same diameter as that of a star.

In a star-simulator producing collimated light, an optic collimates light from a small source located at its focus. In the testing of star-trackers, the collimated light is focussed to an image at the focal length of the objective of the star-tracker.

If $\underline{F_c}$ is the focal length of the optic of the collimated star-simulator, $\underline{F_T}$ is the focal length of the objective of the star-tracker, $\underline{J}$ is the diameter of the source of light in the collimated star-simulator, and $\underline{K}$ is its image diameter, then

$$J = K\frac{F_T}{F_c} \quad . \tag{11}$$

Considering representative values for a collimated star-simulator,

$$K = 2.0 \times 10^{-3} \text{ inch},$$

$$F_T = 8.0 \text{ inches},$$

$$F_c = 30.0 \text{ inches},$$

one obtains an image diameter $\underline{J}$ of 5.3×10^{-4} inch.

The diameter and character of the image of the OAO star-simulator that would be formed in a star-tracker is not significantly different from the image of a collimated star-simulator source. Use of the OAO star-simulator directly in testing star-trackers would remove the necessity of taking the additional steps involved in calibrating both the photometer and the collimated star-simulator as now proposed.

References

1. Smithsonian Physical Tables, 9th rev. ed., p. 730 (Smithsonian Institution, Washington, D. C., 1954).

2. H. B. Hallock, Prediction of the Response of Spacecraft Optical Control Devices to Stars of Various Classes and Magnitudes, Grumman Aircraft Engineering Corporation, Bethpage, Long Island, N. Y. (1962).

3. M. Pivovonsky and M. Nagel, Tables of Blackbody Radiation Functions (Macmillan Company, New York, N. Y., 1961).

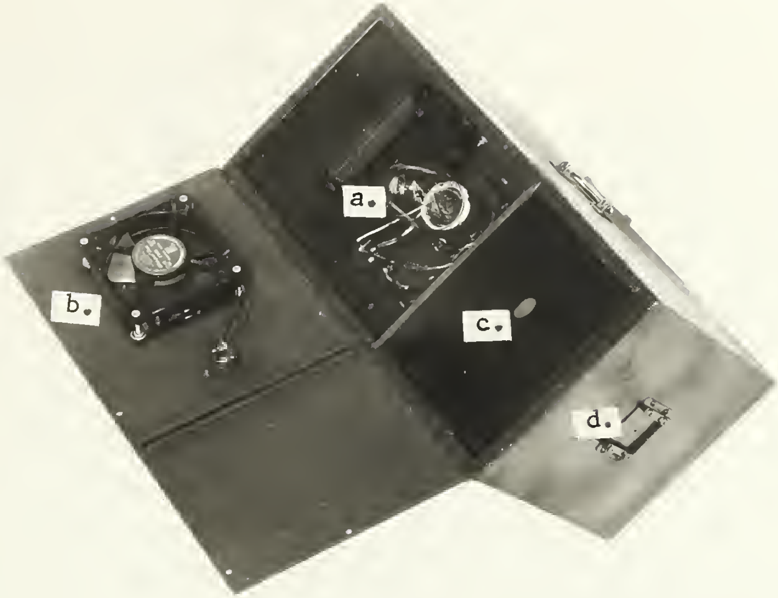
4. R.C.A. Tube Handbook (Radio Corporation of America, Harrison, N.J.)

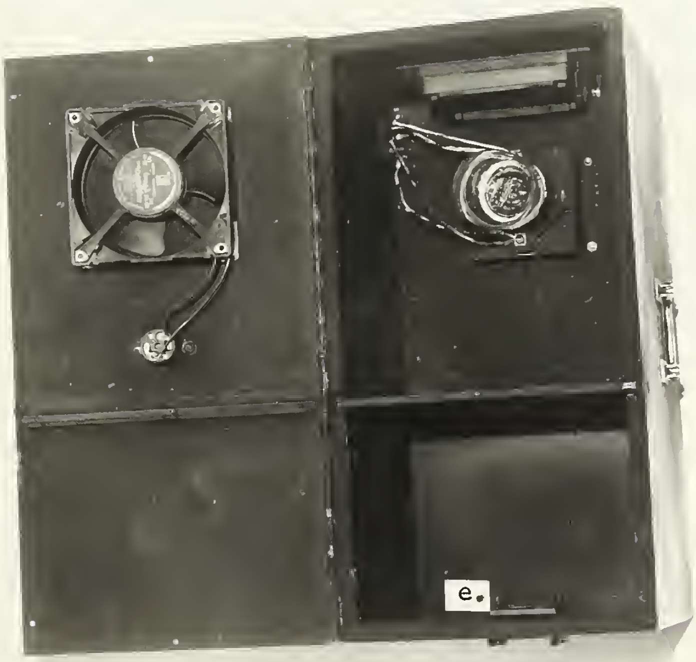
5. T. R. Vogt and M. L. Baker, A Star Magnitude Calibration for the OAO Star Tracker, General Electric Company, TIS 63SD206, p. 5 (1963).

6. IES Lighting Handbook 3d ed., p. 8-37 (Illuminating Engineering Society, New York, N. Y., 1959).

7. L. Chernoff, Photometry of Projectors at the National Bureau of Standards, NBS Technical Note 198 (1963).

8. F. E. Washer and I. C. Gardner, Method for Determining the Resolving Power of Photographic Lenses, NBS Circular 533, p. 13 (1953).





TWO VIEWS OF THE OAO STAR-SIMULATOR SOURCE- Seen are the a. lamp, b. fan, c. baffle, d. aperture, and e. filter-opal glass holder.

DIMENSIONAL DIAGRAM OF THE OAO STAR-SIMULATOR SOURCE

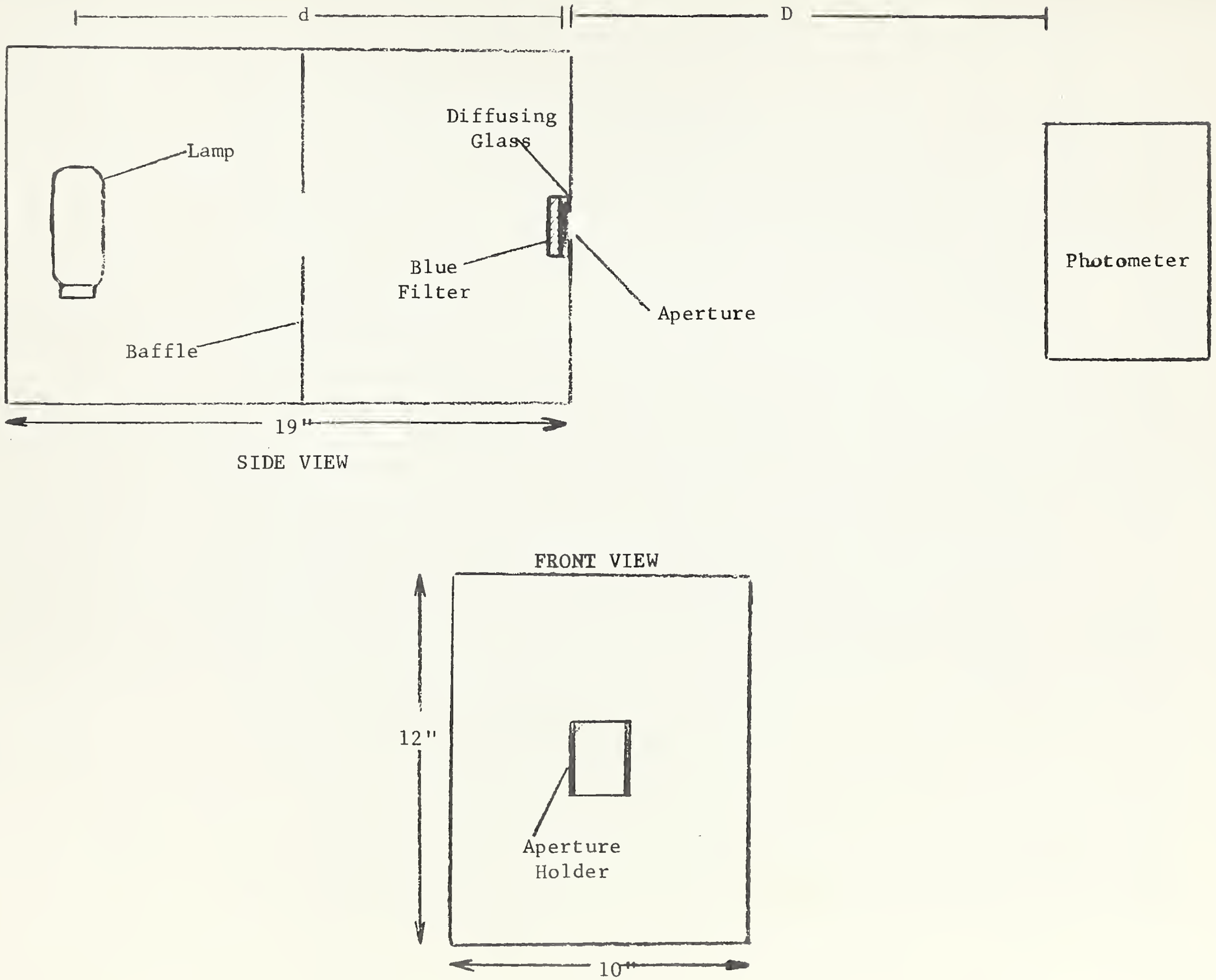
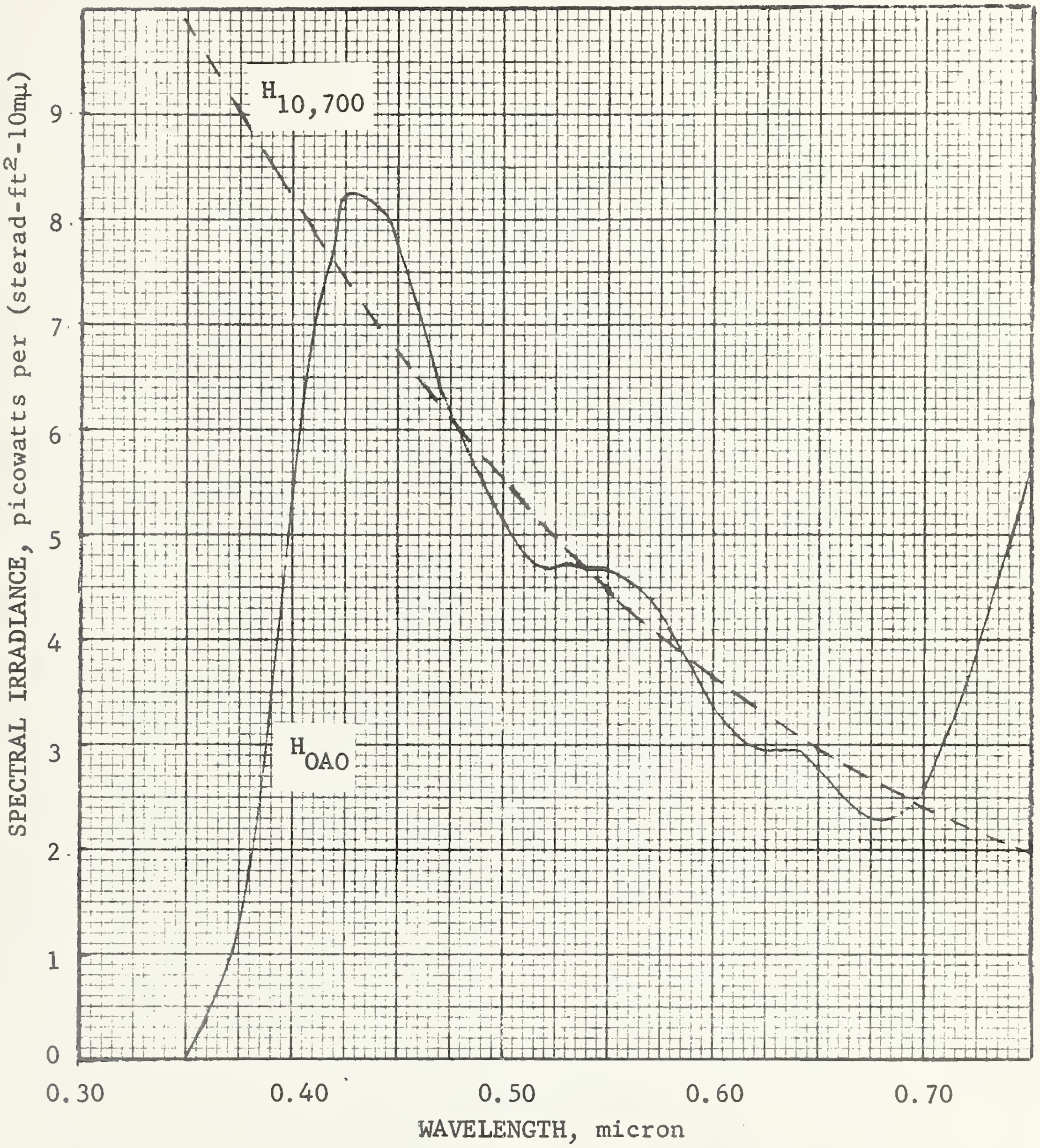


Figure 2

Spectral Irradiance
From
a Second Magnitude, Type AO (10,700°K) Star
and From
the OAO Star-Simulator Source at Distance D_{OAO}



NBS Report 8619

Figure 3

Relative Output With Respect to Wavelength
of a
Receiving System Containing an Average S-4 Surface
Irradiated by a Type AO (10,700°K) Star
and
Irradiated by the OAO Star-Simulator Source

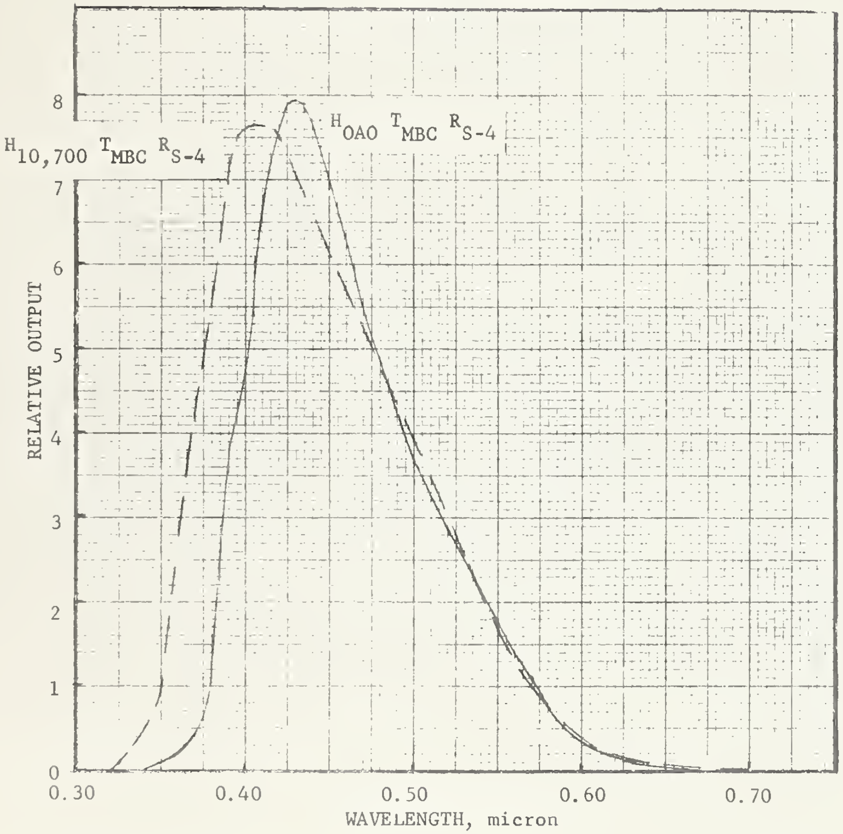


Figure 4a

Relative Output With Respect to Wavelength
of a
Receiving System Containing an Average S-20 Surface
Irradiated by a Type AO (10,700°K) Star
and
Irradiated by the OAO Star-Simulator Source

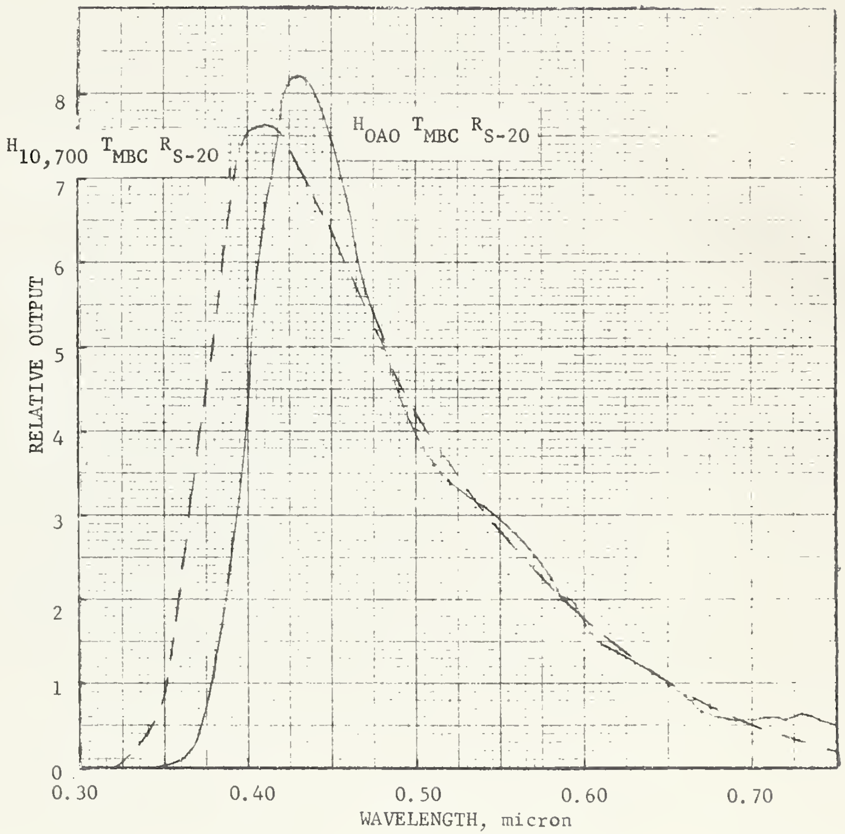
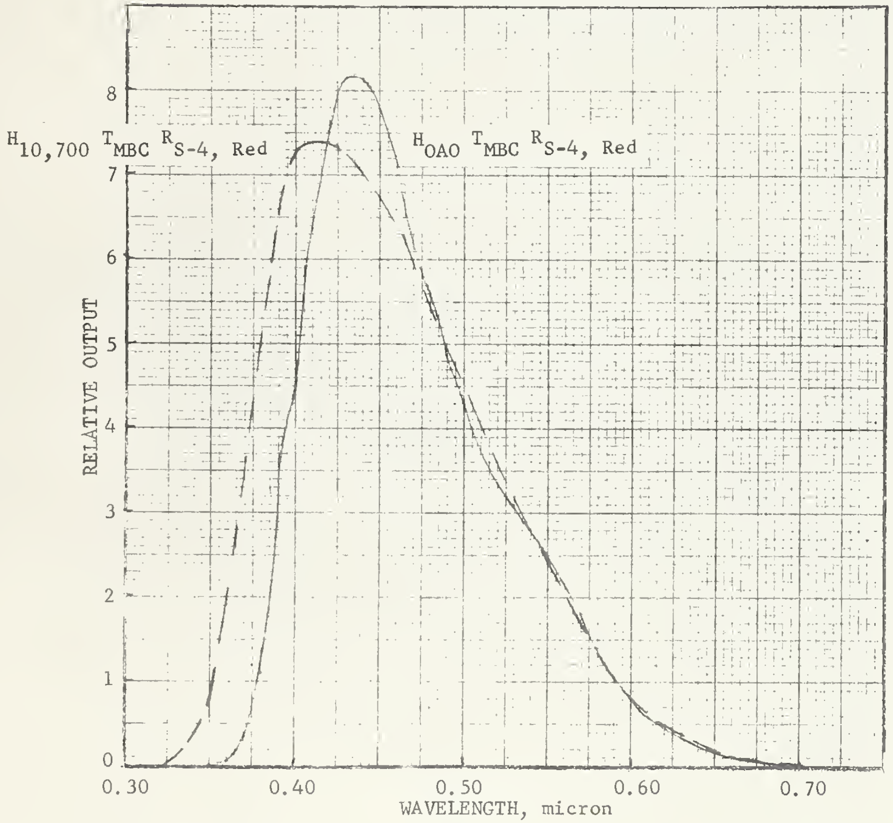


Figure 4b

Relative Output With Respect to Wavelength
of a
Receiving System Containing
an Extreme Red-Shifted S-4 Surface
Irradiated by a Type A0 (10,700°K) Star
and
Irradiated by the OAO Star-Simulator Source



NBS Report 8619

Figure 5a

Relative Output With Respect to Wavelength
of a
Receiving System Containing
an Extreme Blue-Shifted S-4 Surface
Irradiated by a Type A0 (10,700°K) Star
and
Irradiated by the OAO Star-Simulator Source

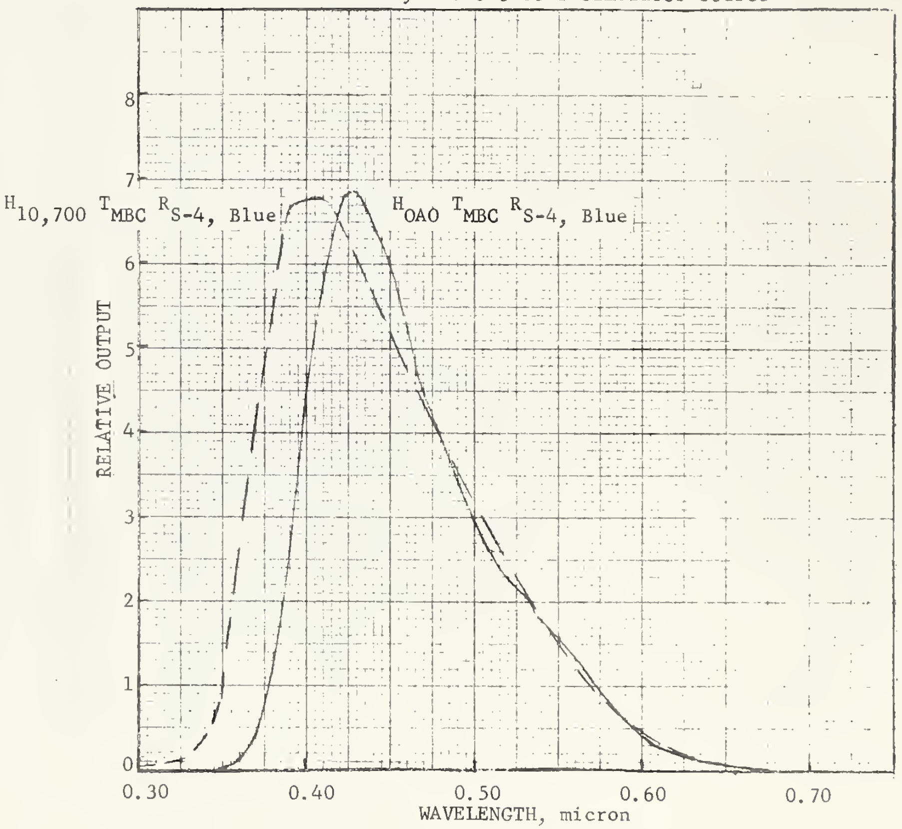


Figure 5b

Predicted Output With Respect to Wavelength
of a
Receiving System Containing an Average S-4 Surface
Irradiated by a Type AO (10,700°K) Star
and
Irradiated by a Xenon-Lamp, 6G Filter Combination
(These Curves Have Been Normalized For
Equal Illuminance at the Receiver)

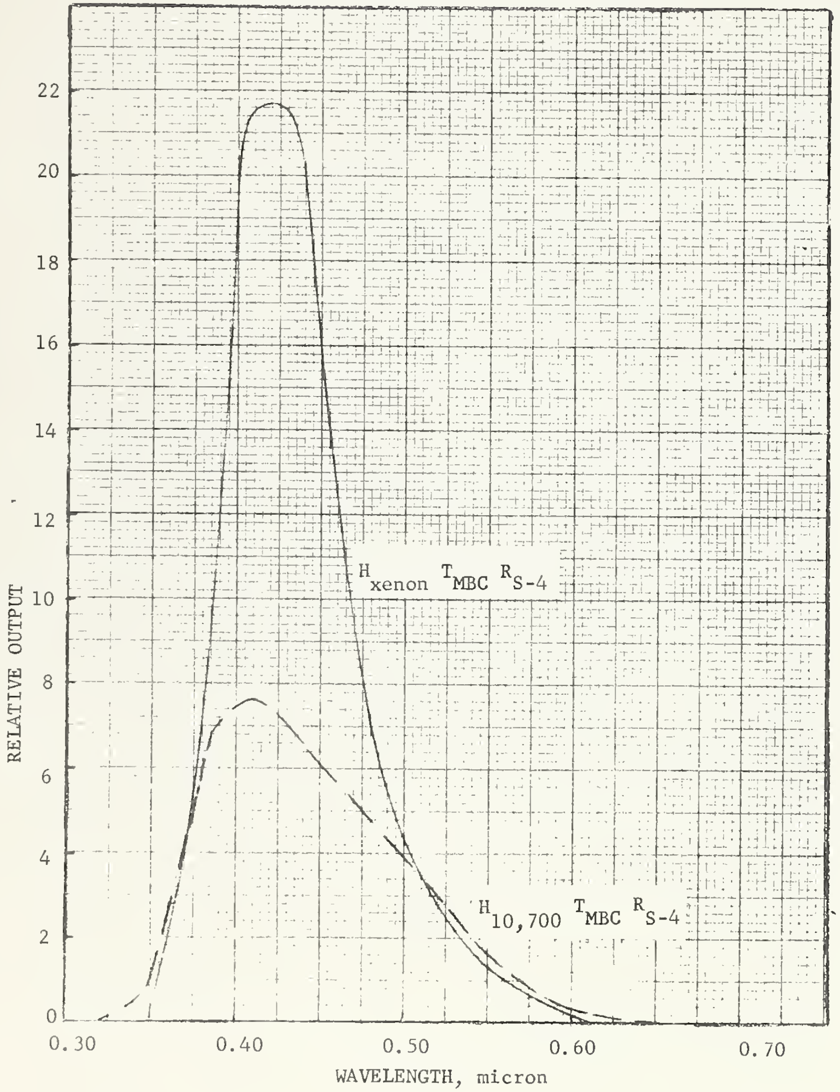


Figure 6a

Predicted Output With Respect to Wavelength
of a
Receiving System Containing an Average S-20 Surface
Irradiated by a Type AO (10,700°K) Star
and
Irradiated by a Xenon-Lamp, 6G Filter Combination
(These Curves Have Been Normalized For
Equal Illuminance at the Receiver)

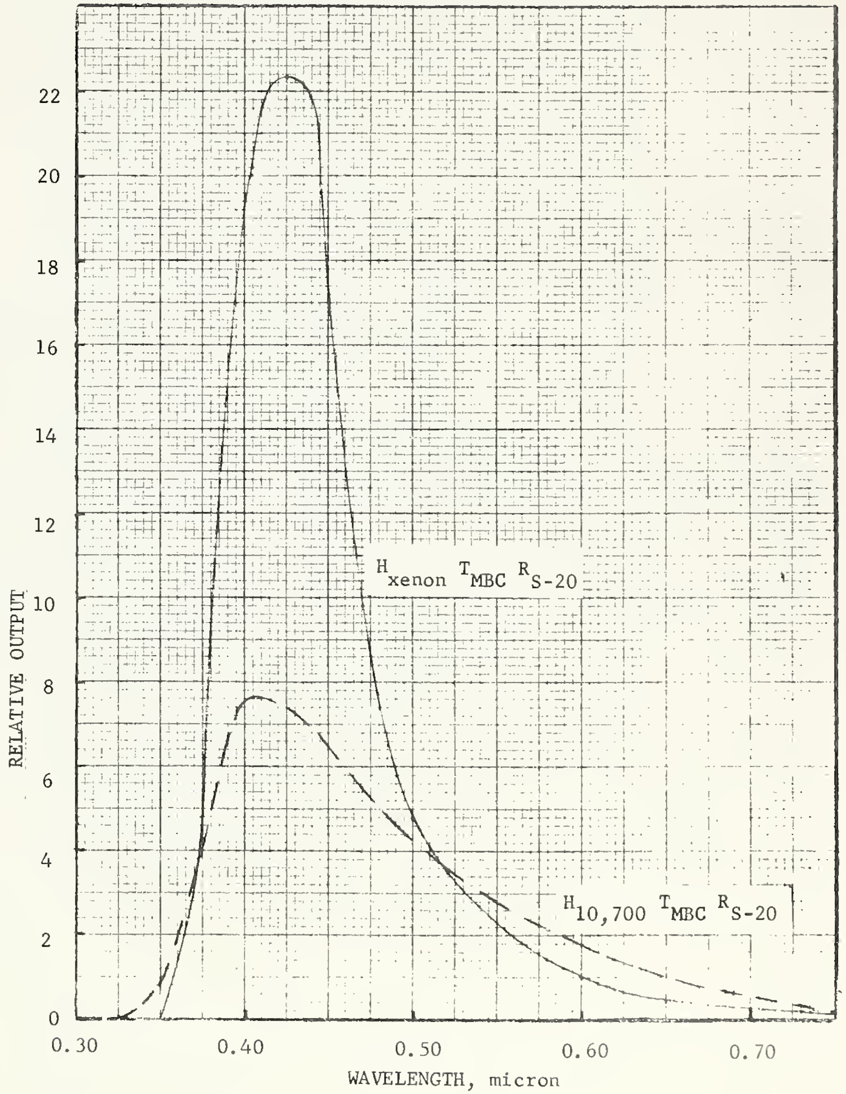


Figure 6b

Predicted Output With Respect to Wavelength
of a
Receiving System Containing an Average S-4 Surface
Irradiated by a Type AO (10,700°K) Star
and
Irradiated by a Xenon-Lamp, 6G Filter Combination
(These Curves Have Been Normalized
For Equal Receiver Output)

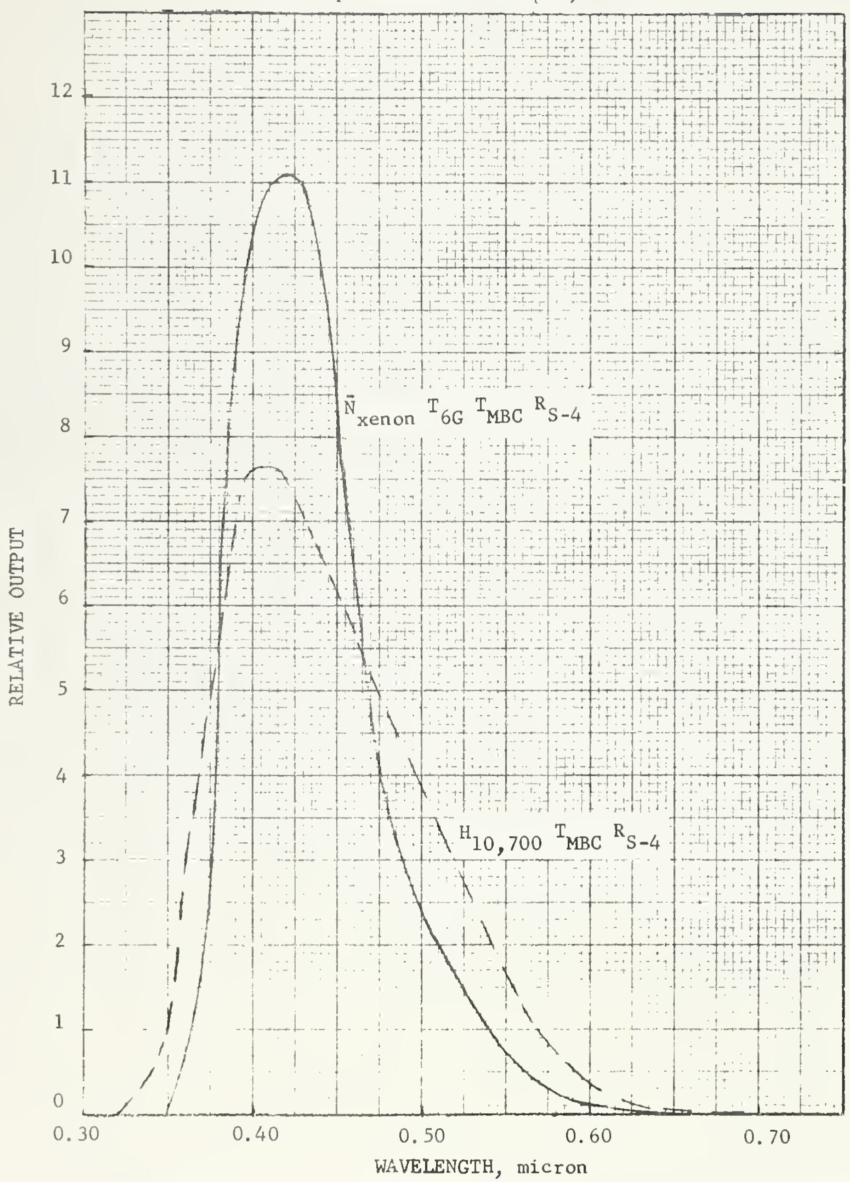


Figure 7a

Predicted Output With Respect to Wavelength
of a
Receiving System Containing an Average S-20 Surface
Irradiated by a Type AO (10,700°K) Star
and
Irradiated by a Xenon-Lamp, 6G Filter Combination
(These Curves Have Been Normalized
For Equal Receiver Output)

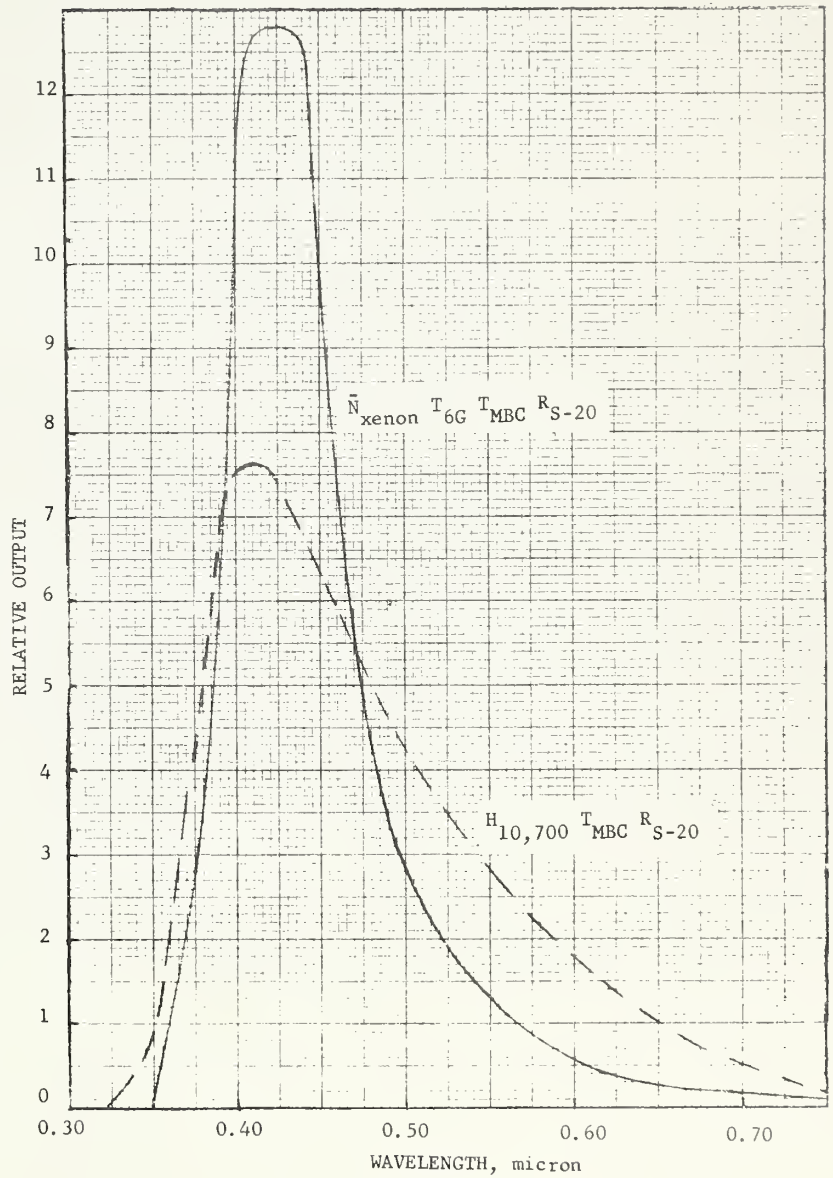


Figure 7b

DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS