NATIONAL BUREAU OF STANDARDS REPORT

8565

Progress Report July 1, 1964 to September 30, 1964

For an Artificial Star Source for the OAO

By

D. Sirota and L. Chernoff

U.S. DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

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Prepared for

National Aeronautics and Space Administration

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Table of Symbols

$\underline{d}$ the distance between the filament of the standard tungsten projection lamp and the aperture of the designed OAO star-simulator

$\underline{D}$ the distance between the aperture of the designed OAO star-simulator and 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

$\underline{I_A}$ the intensity of light leaving the aperture of the designed OAO star-simulator

$\underline{I_L}$ the intensity of the standard tungsten projection lamp

$\underline{J}$ the linear size of the source of light in the collimated star-simulator

$\underline{K}$ the linear size of the image of the collimated star-simulator produced by the objective of the star-tracker

$\underline{\bar{N}_{xenon}}$ the relative spectral distribution of flux from a xenon lamp

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

$\underline{\bar{N}_{10,700}}$ the relative spectral distribution of flux from a type AO star

$\underline{\bar{N}_{3,000}T_{6G}}$ the relative spectral distribution of flux from the designed OAO star-simulator

$\underline{P_{OAO}}$ the predicted relative spectral output of a star-tracking receiver illuminated by the designed OAO star-simulator

$\underline{P_{star}}$ the predicted relative spectral output of a star-tracking receiver illuminated by a type AO star

$\underline{P_{xenon}}$ the predicted relative spectral output of a star-tracking receiver illuminated by a xenon star-simulator

$\underline{r}$ the radius of the aperture of the designed OAO star-simulator

$\underline{R_D}$ the relative spectral response of the photodetecting surface in the star-tracking receiver

$\underline{R_r}$ the relative spectral response of the star-tracking receiver

$\underline{s_u}$ the object distance of the designed OAO star-simulator when focussed by the objective of the star-tracker

$\underline{s_v}$ the image distance of the designed OAO star-simulator when focussed by the objective of the star-tracker

$\underline{T_F}$ the transmittance of the blue filter

$\underline{T_G}$ the luminous directional transmittance of the flashed opal glass

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

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

$\underline{U}$ the linear size of the aperture of the designed OAO star-simulator

$\underline{V}$ the linear size of the image of the aperture of the designed 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 was requested by the National Aeronautics and Space Administration to build a prototype of a low-intensity, uncollimated light source which will be the standard for calibrating star-tracking equipment. Light from this source is to simulate the illuminance and color temperature of a visual second magnitude AO star. A second magnitude star has an illuminance of 3×10^{-8} footcandle. The "color temperature" of a type AO star has been defined as 10,700°K.

2. Illuminance Produced by the Designed OAO Star-Simulator

In the designed star-simulator, the source of light is a standard tungsten projection 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 is a uniform light source at a fixed distance 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 figure 1.

If the thickness of the opal glass is assumed to be small with respect to d, the illuminance on the flashed opal glass may be given by

$$E' = I_L \, T_F/d^2 \tag{1}$$

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

$$I_A = E' \, T_G \pi r^2/\pi = E' T_G r^2 \tag{2}$$

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 in a direction along an axis through the center of the opal glass. The glass is illuminated along this same axis.

The receiver is placed at a distance D from the aperture. The illuminance at the receiver is

$$E = I_A/D^2 \, . \tag{3}$$

Substituting equations (2) and (1) in equation (3) yields

$$E = I_L T_F T_G r^2/d^2 D^2 \, . \tag{4}$$

The estimated values of the parameters to be used to obtain a value of $\underline{E}$ equal to 3×10^{-8} footcandle are:

$$I_L = 1{,}100 \text{ candelas}$$

$$T_F = 0.05$$

$$T_G = 0.5$$

$$r = 0.001 \text{ foot}$$

$$d = 1.0 \text{ foot}$$

$$D = 30.0 \text{ feet.}$$

3. Spectral Distribution of the Designed OAO Star-Simulator

Star-tracking receivers contain 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 M.B.C. optical glass.[1] As the range of spectral sensitivity for this type of receiver is 0.35 to 0.75 micron, comparison of the spectral distribution of flux from the type A0 star and that from the OAO star-simulator is required within this range.

Strictly speaking, the term color temperature refers only to visible flux (0.40 to 0.70 micron). Since the range of spectral sensitivity of star-tracking receivers is broader than the visible spectrum, the type A0 star color temperature requirement was interpreted to mean that the spectral distribution of flux from the designed OAO star-simulator should as closely as possible correspond to the spectral distribution of flux from a type A0 star for the 0.35 to 0.75 micron range. The relative spectral distribution of flux from a 10,700°K blackbody[2] $\underline{N}_{10,700}$ will then be used as a definition of the relative spectral distribution of flux from a type A0 star for this range.

It is necessary to use a standard lamp of highest possible color temperature consistent with lifetime considerations in order to obtain a significant ultraviolet component. After examination of a few different types of lamps, a 120-volt, 500-watt clear projection lamp operated at 113.7 volts was found to be suitable. Light from this lamp when viewed through the flashed opal glass was found to have a color temperature of 3,000°K. In the calculations of this report the relative spectral distribution function of a 3000°K blackbody[3] $\underline{N}_{3,000}$ will represent the spectral distribution of flux from the lamp and flashed opal glass combination in the range under consideration.

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 had 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 is represented by T_{6G}, and the relative spectral distribution of flux from the designed OAO star-simulator is therefore given by $\underline{N_{3,000}T_{6G}}$.

Figure 2 is a comparison of the relative spectral distribution of flux from the designed star-simulator $\bar{N}_{3,000}T_{6G}$ with that of a type AO star $\bar{N}_{10,700}$. The curves are normalized to have equal value at 0.56 micron. 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 2 can be used to evaluate the difference in response of a receiver of known spectral sensitivity when the receiver is illuminated by the designed star-simulator instead of by a type AO star.

The criterion for selecting the color temperature altering filter was the visual judgment of the closeness of the match between the predicted relative spectral output of the receiver when illuminated by the type AO star P_{star} with that when illuminated by the designed OAO star-simulator P_{OAO}. The predicted relative spectral output of the OAO star-simulator ~~and~~ of a type AO star are respectively

$$P_{OAO} = \bar{N}_{3,000}T_{6G}R_r \tag{5}$$

and

$$P_{star} = \bar{N}_{10,700}R_r \tag{6}$$

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

$$R_r = T_{MBC}R_D \; . \tag{7}$$

Substituting (7) in (5) and (6) yields

$$P_{OAO} = \bar{N}_{3,000}T_{6G}T_{MBC}R_D \tag{8}$$

and

$$P_{star} = \bar{N}_{10,700}T_{MBC}R_D \; . \tag{9}$$

Figures 3a and 3b are comparisons of P_{OAO} and P_{star} for two different photodetectors of response R_D. In figure 3a the response is that of an S-4 type photodetector surface while in figure 3b the response is that of an S-20 type.[4] The outputs, P_{OAO} and P_{star} are normalized to have equal peak values. It can be observed 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 4a and 4b 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 4a and 4b are not appreciably greater than the differences between P_{OAO} and P_{star} as shown in figure 3a.

The attainment of a color temperature of 10,700°K by use of a xenon lamp of relative spectral distribution $\bar{N}_{xenon}$ as a light source instead of a tungsten projection lamp was investigated. In figures 5a and 5b there is a comparison of P_{star} and P_{xenon} where

$$P_{xenon} = \bar{N}_{xenon} T_{6G} T_{MBC} R_D . \qquad (10)$$

The data for $\bar{N}_{xenon}$ are taken from reference 6. There is better agreement below 0.4 micron between P_{star} and P_{xenon} in figures 5 than between P_{star} and P_{OAO} in figures 3 because a xenon lamp contains a larger component of ultraviolet than does a tungsten lamp. There is, however, a large deviation in the visible region between P_{star} and P_{xenon} caused by the rather flat spectral distribution of flux from a xenon lamp in this region. In addition, the xenon lamp emits a line spectrum not shown in figures 5. It was decided that it was advantageous to use the tungsten-filament rather than the xenon lamp, and construction proceeded on this basis.

4. Construction

The designed OAO star-simulator is constructed as a single unit box of dimensions as shown in figure 1. 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 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.

The construction of the OAO star-simulator is underway and is expected to be completed shortly.

5. Discussion

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 U is the mean size of the aperture of the star-simulator, V is the linear size of its image, s_u is the object distance, and 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

$$V = U \frac{s_v}{s_u} \quad . \tag{11}$$

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

$$U = 2.4 \times 10^{-2} \text{ inch,}$$

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

and

$$s_u = 3.60 \times 10^{2} \text{ inches,}$$

the image size V is 5.3×10^{-4} inch.

The fact that the object size 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 those for an object at infinity. Effectively, therefore, the image of the OAO star-simulator would be the same size 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 F_c is the focal length of the optic of the collimated star-simulator, F_T is the focal length of the objective of the star-tracker, J is the size of the source of light in the collimated star-simulator, and K is its image size, then

$$J = K \frac{F_T}{F_c} \quad . \tag{12}$$

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*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 will be used.[7]

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 size $\underline{J}$ of 5.3×10^{-4} inch.

The size 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.

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

3. Ibid, p. 92.

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

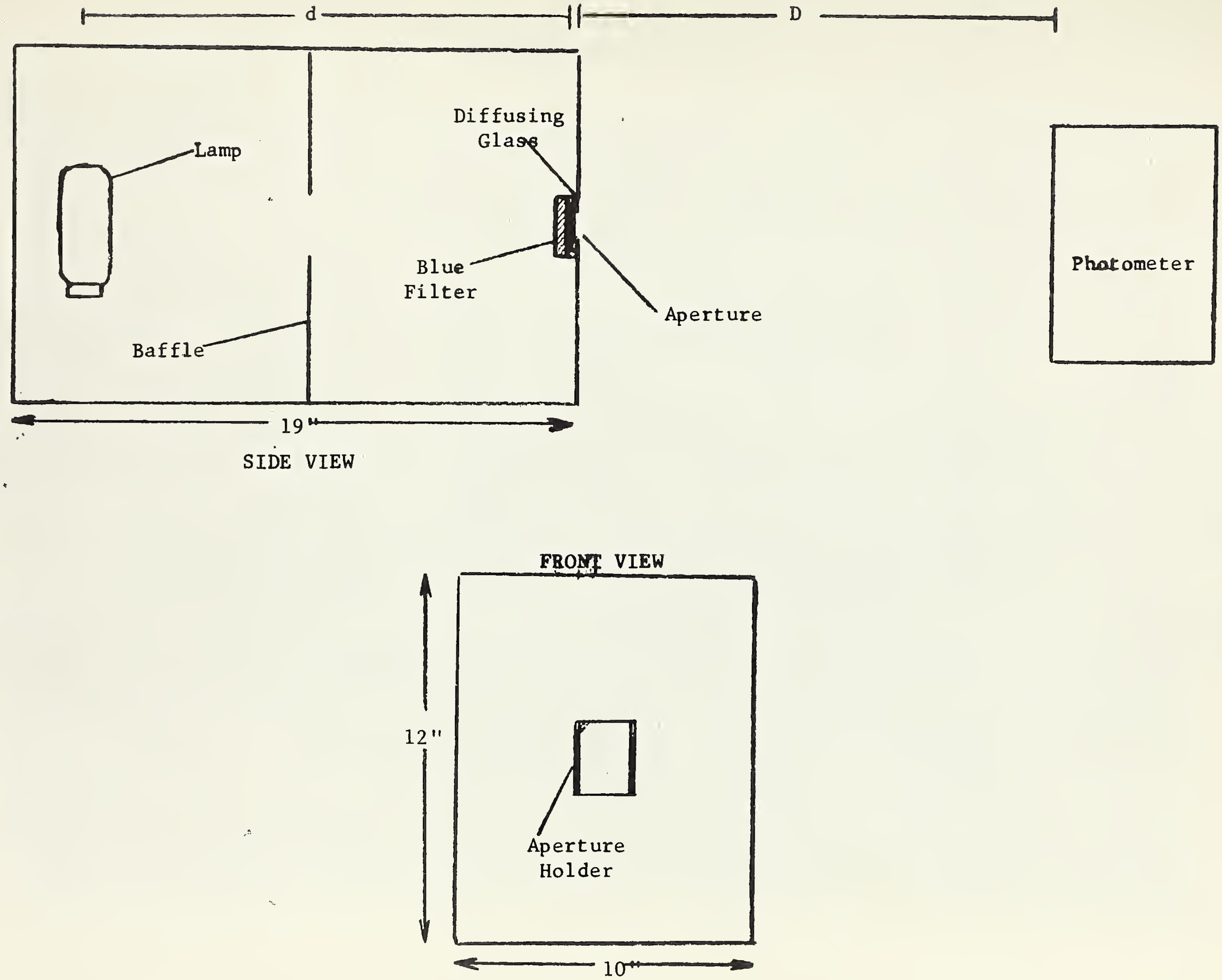
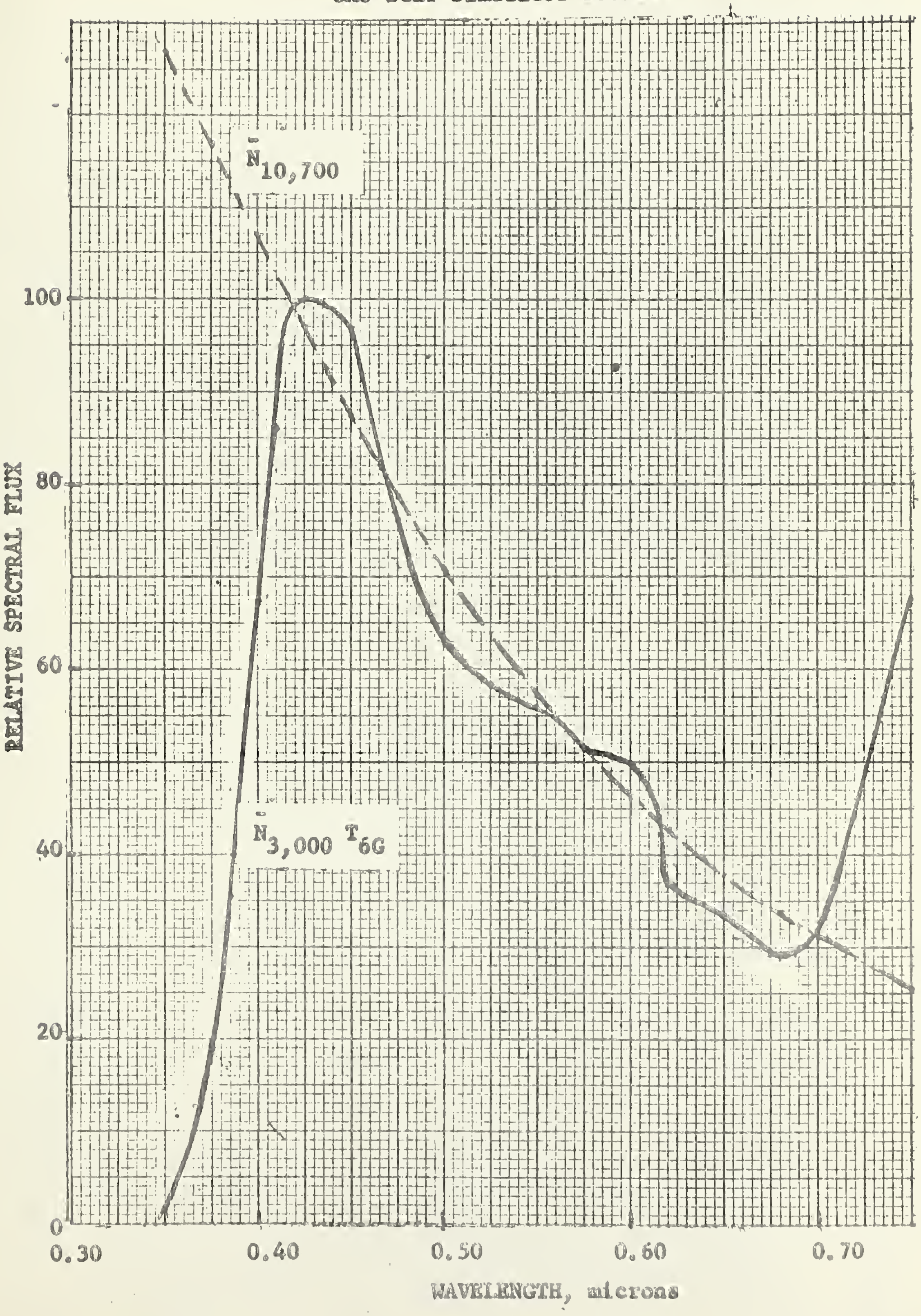

d
D
Lamp
Baffle
Diffusing
Glass
Blue
Filter
Aperture
Photometer
19"
SIDE VIEW
FRONT VIEW
12"
Aperture
Holder
10"

Figure 1

Relative Spectral Flux Distribution
of a
Type AO (10,700°K) Star
and of the
OAO Star-Simulator Source



Predicted Relative Spectral Output
of a
Receiving System Containing an Average S-4 Surface
With a Type A0 (10,700°K) Star
and
With the Designed OAO Star-Simulator Source

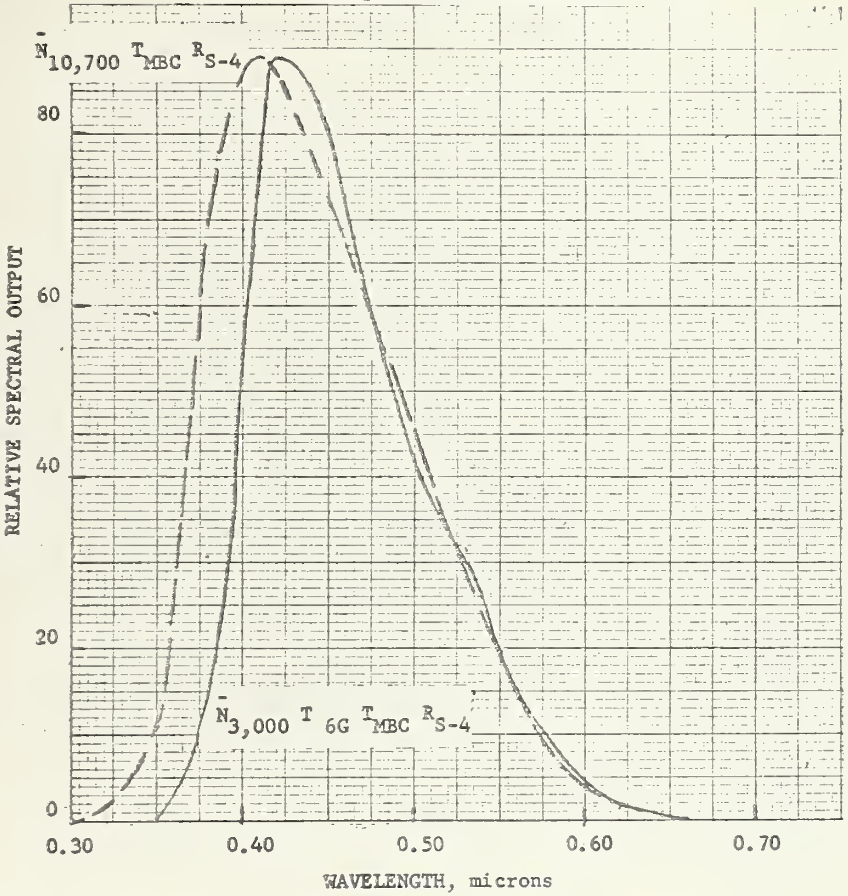


Figure 3a

Predicted Relative Spectral Output
of a
Receiving System Containing an Average S-20 Surface
With a Type A0 (10,700°K) Star
and
With the Designed OAO Star-Simulator Source

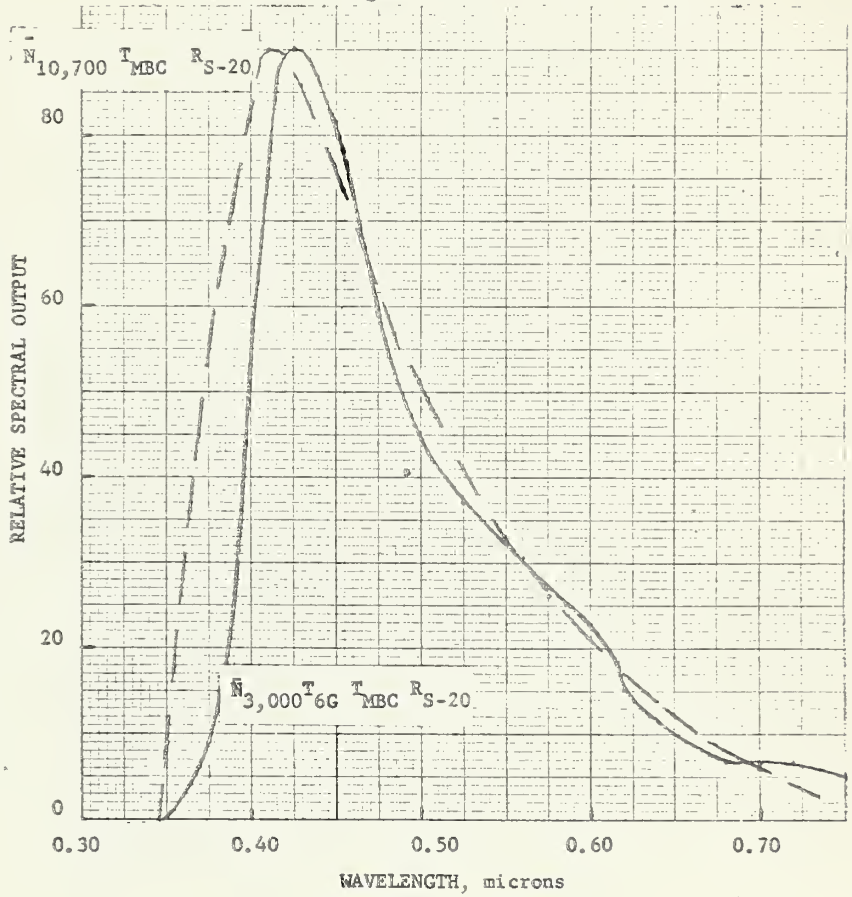


Figure 3b

Predicted Relative Spectral Output
of a
Receiving System Containing
an Extreme Red-Shifted S-4 Surface
With a Type AO (10,700°K) Star
and
With the Designed OAO Star-Simulator Source

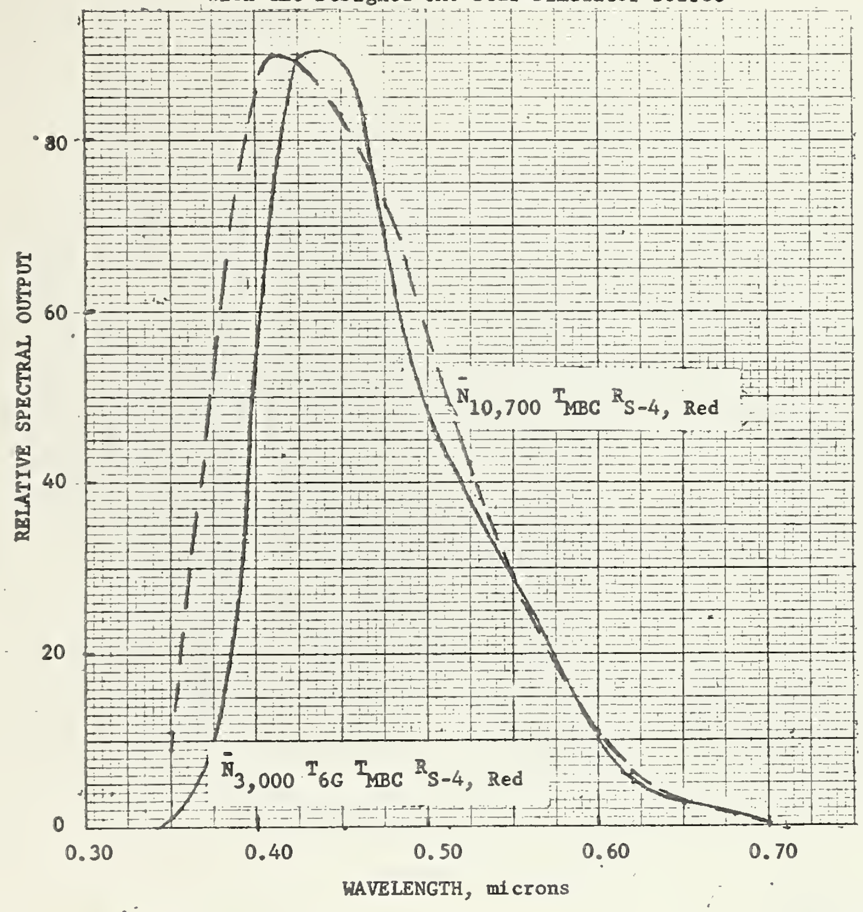


Figure 4a

Predicted Relative Spectral Output
of a
Receiving System Containing
an Extreme Blue-Shifted S-4 Surface
With a Type AO (10,700°K) Star
and
With the Designed OAO Star-Simulator Source

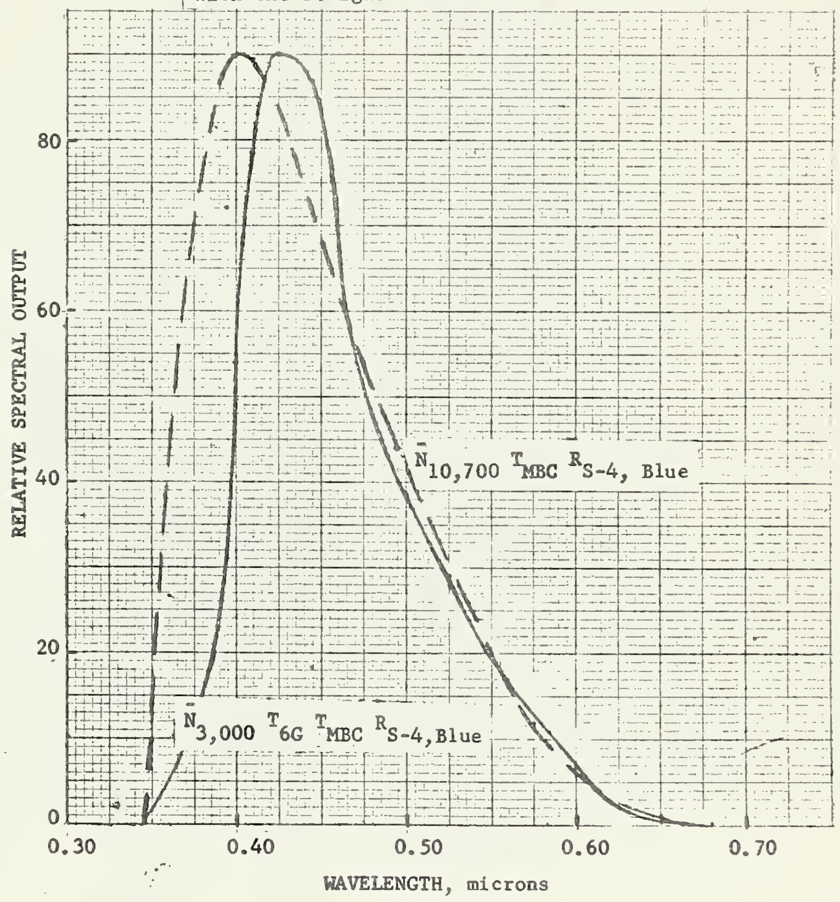


Figure 4b

Predicted Relative Spectral Output
of a
Receiving System Containing an Average S-4 Surface
With a Type AO (10,7000°K) Star
and
With a Xenon-Lamp, 6G-Filter Combination

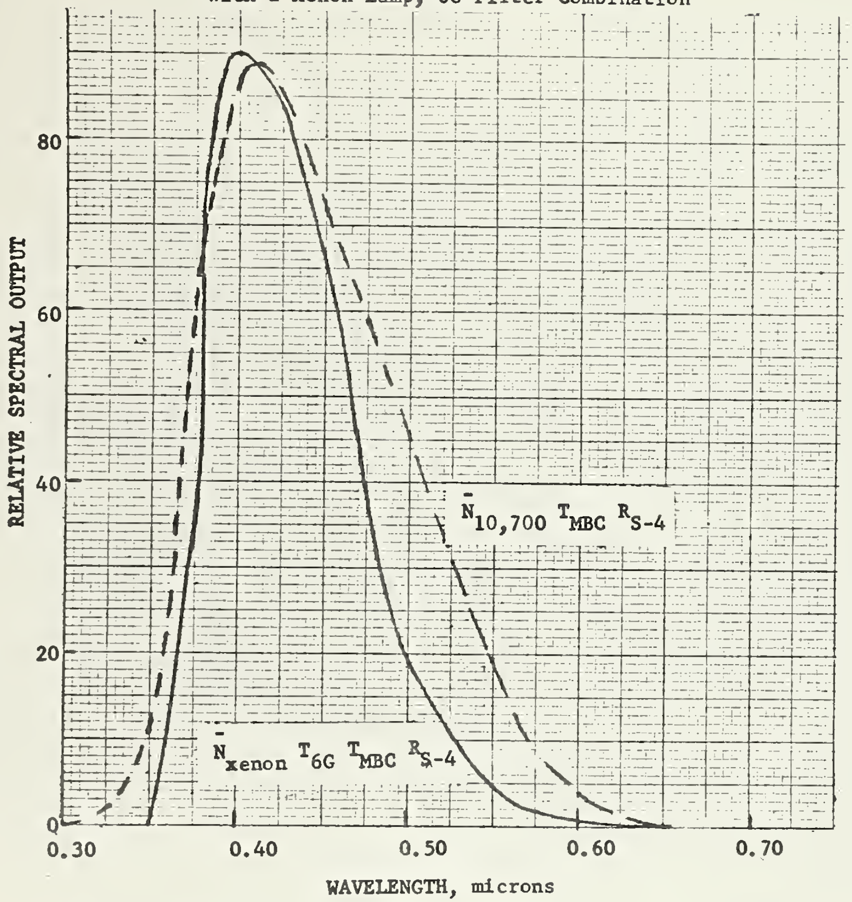


Figure 5a

Predicted Relative Spectral Output
of a
Receiving System Containing an Average S-20 Surface
With a Type AO (10,700°K) Star
and
With a Xenon-Lamp, 6G-Filter Combination

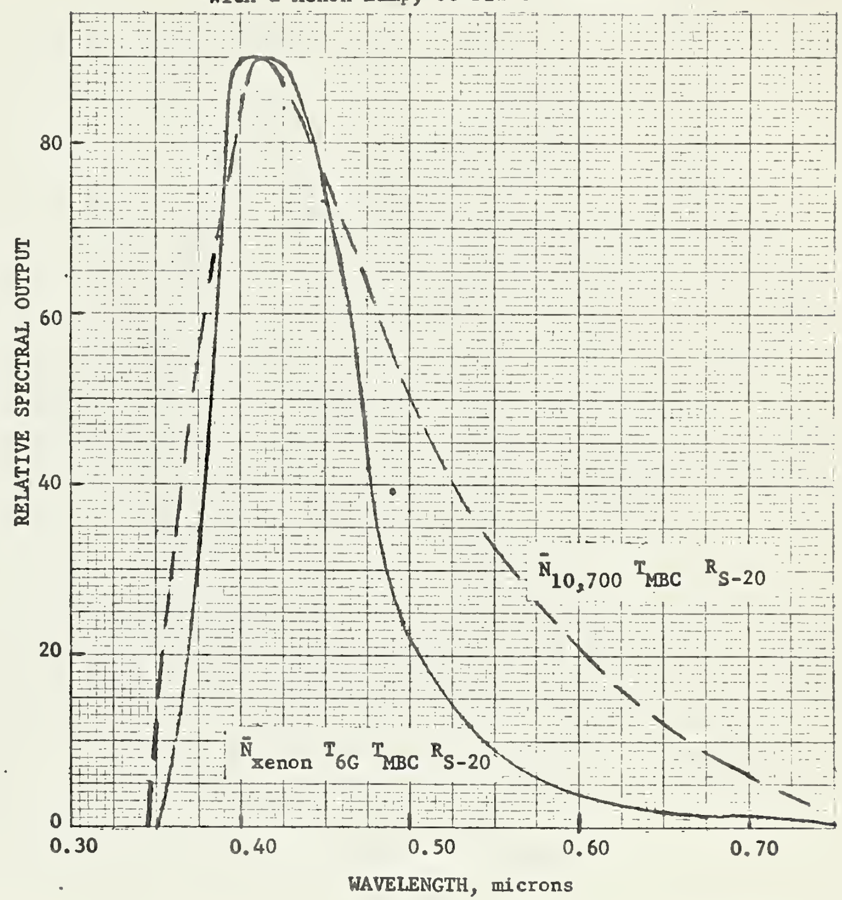


Figure 5b

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