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ULTRAVIOLET CALIBRATION PROCEDURES FOR GEMINI EXPERIMENT M-407

By Roy C. Stokes and John E. Novotny
Manned Spacecraft Center
Houston, Texas

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ABSTRACT

Ultraviolet radiometric calibration and data analysis techniques were developed for Gemini in-flight experiment M-407. The object of the experiment was to measure the spectral albedo of the moon between 2000 and 3200 Å using an objective grating spectrograph. Because of unfavorable phase angles of the moon during Gemini flights X, XI, and XII, the experiment could not be conducted. However, considerable effort was devoted to the project in the areas of technique development related to performance and evaluation of the in-flight measurements. A brief summary of the experiment with a description of the hardware, the ultraviolet calibration techniques, and the data reduction techniques developed for the experiment are given in this report.

ULTRAVIOLET CALIBRATION PROCEDURES

FOR GEMINI EXPERIMENT M-407

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SUMMARY

Ultraviolet radiometric calibration and data analysis techniques were developed for measurements with an objective grating spectrograph of the spectral albedo of the moon between 2000 and 3200 Å. The experiment, scheduled for Gemini flights X, XI, and XII, could not be conducted because of unfavorable phase angles of the moon during each flight.

The spectral irradiance of the moon was to be measured by relating microdensitometer traces of lunar spectrograms to calibration spectrograms. This required the construction and calibration of a standard ultraviolet source to simulate the moon. A 1-meter concave-grating monochromator was used to calibrate the ultraviolet source directly against a thermocouple and relative to a National Bureau of Standards radiance lamp and a carbon arc.

The direct method requires measurements (1) of the efficiency of the monochromator, (2) of the sensitivity of the photomultipliers, (3) of the effects of air absorption, and (4) of the reflectivity of the mirrors. Results of these measurements are given. The estimated possible error in the calibration is ±15 percent over the spectral range of 2500 to 4000 Å and ±25 percent from 2000 to 2500 Å. An equation is derived to give the spectral albedo from the lunar spectral irradiance at any phase angle.

INTRODUCTION

An in-flight experiment, designated M-407, was scheduled for the last three Gemini flights (Gemini X, XI, and XII) to determine the ultraviolet spectral reflectivity of the lunar surface between 2000 and 3200 Å. However, the experiment could not be conducted because the moon was too close to the sun during each of the flights. During the Gemini XII flight, there was a total solar eclipse.

Even though the experiment was not conducted, considerable effort was devoted to the project in the areas of hardware development, experimental procedures, ultraviolet calibration techniques, and data reduction techniques. A brief summary of the experiment and hardware with a description of the hardware, the ultraviolet calibration techniques, and the data reduction techniques developed for the experiment are given in this report.

The ultraviolet reflectivity of the lunar surface must be known to insure adequate protection of astronauts on the lunar surface. The Crew Systems Division of the Manned Spacecraft Center has specified that the total ultraviolet radiation dose between 2000 and 3200 Å for a 4-hour exposure must not exceed $1 \times 10^4\ \mu J/cm^2$ to prevent sunburn of the skin and photo-opthalmia of the eyes. The incident solar energy is about 2000 times greater than this for a 4-hour period.

Since a lunar astronaut will devote considerable time to observing the lunar surface, it will be essential to know the reflectivity of the lunar surface in order to calculate the total ultraviolet radiation dose between 2000 and 3200 Å incident on the astronaut's face. The absorption of ultraviolet radiation by the earth's atmosphere makes it impossible to determine the reflectivity of the lunar surface at wavelengths shorter than 3200 Å from ground-based measurements.

SYMBOLS

A_{EN} area of monochromator entrance slit, cm^2

A_i area of moon image at any phase angle, cm^2

A_{io} area of image of full moon, cm^2

A_M area of mirror, cm^2

A_m cross-sectional area of moon, cm^2

A_o illuminated area of full moon normal to the direction of the earth, cm^2

A_s surface area of a sphere whose radius is equal to the distance between the earth and the moon, cm^2

A_{sp} area of entrance aperture of flight spectrograph, cm^2

A_{TC} area of thermocouple sensing element, cm^2

A_x illuminated area of the surface of the moon at any phase angle normal to the direction of the earth, cm^2

a lunar albedo

a_λ lunar albedo at a wavelength λ

(BP) bandpass of monochromator and flight spectrograph, Å

D dispersion of monochromator and flight spectrograph, Å/cm

$D(\lambda)_c$ density of calibration spectrograms at a wavelength λ

$D(\lambda)_m$ density of lunar spectrograms at a wavelength λ

d distance between grating rulings, cm

d_1 distance between standard source and mirror, cm

d_2 distance between mirror and monochromator, cm

$\left(E_xSW\right)$ exit-slit width, cm

E_λ efficiency of monochromator or flight spectrograph at a wavelength λ

(FI) fraction of the lunar disk illuminated

$\left(fl_C\right)$ focal length of collimator, cm

$\left(fl_L\right)$ focal length of flight spectrograph, cm

$\left(fl_M\right)$ focal length of mirror, cm

H radiant flux per unit area or irradiance, $\mu W/cm^2$

H_F radiant flux per unit area incident on the spectrograph film, $\mu W/cm^2$

H_L radiant flux per unit area from National Bureau of Standards (NBS), standard irradiance lamp, $\mu W/cm^2$

H_m irradiance of the moon, $\mu W/cm^2$

H_{se}	irradiance of the sun, $\mu W/cm^2$
$H(\lambda)$	spectral irradiance (flux per unit area per unit wavelength interval), $\mu W/cm^2$-Å
$H(\lambda)_c$	spectral irradiance of standard ultraviolet source, $\mu W/cm^2$-Å
$H(\lambda)_m$	spectral irradiance of the moon, $\mu W/cm^2$-Å
$H_o(\lambda)_m$	spectral irradiance of the full moon, $\mu W/cm^2$-Å
$H(\lambda)_{se}$	spectral irradiance of the sun, $\mu W/cm^2$-Å
h_i	height of collimator entrance-aperture image, cm
h_o	height of collimator entrance aperture, cm
I_{pm}	output current of photomultiplier, μA
i	angle of incidence for flight spectrograph, deg
$J(\lambda)_c$	exposure of calibration spectrogram at a wavelength λ, $\mu J/cm^2$
$J(\lambda)_m$	exposure of lunar spectrogram at a wavelength λ, $\mu J/cm^2$
K	constant, defined in equation (24)
L	length of an arc from the lunar limb to the terminator in the plane of θ, cm
L_x	angular subtense as measured from the earth of the arc normal to the direction of the earth, deg
$N(\lambda)$	spectral radiance of a standard source, $\mu W/cm^2$-Å-sr
$N(\lambda)_{NBS}$	spectral radiance of NBS standard lamp, $\mu W/cm^2$-Å-sr
n	order number of grating
P	flux, μW

P_A	flux transmitted at atmospheric pressure, μW
P_{EN}	flux through monochromator entrance slit, μW
P_{EX}	flux through monochromator exit slit, μW
P_m	flux reflected by the moon in all directions, μW
P_{sm}	solar flux incident on the moon, μW
P_V	flux transmitted at a pressure of 10^{-6} mm Hg, μW
$P(\lambda)$	spectral flux (flux per unit wavelength interval), $\mu W/Å$
$P(\lambda)_m$	spectral flux of the moon, $\mu W/Å$
$P(\lambda)_{EN}$	spectral flux through monochromator entrance slit, $\mu W/Å$
$P_i(\lambda)_{EN}$	spectral flux incident on monochromator entrance slit, $\mu W/Å$
$P(\lambda)_{sp}$	spectral flux through entrance aperture of flight spectrograph, $\mu W/Å$
p	geometric albedo
q	phase integral
R	angular subtense of the radius of the moon (as measured from earth), deg
R_{me}	distance from the earth to the moon, cm
R_λ	reflectance of mirror at a wavelength λ
S_{TC}	sensitivity of thermocouple, $\mu V/\mu W$
$S(\lambda)_{pm}$	sensitivity of photomultiplier at a wavelength λ, $\mu A/\mu W$
T	transmission
t_c	exposure time for calibration spectrograms, sec
t_m	exposure time for lunar spectrograms, sec

V_{TC}	output voltage of thermocouple, μV
W_{mi}	width of a monochromatic lunar image, cm
w_i	width of collimator entrance-aperture image, cm
w_o	width of collimator entrance aperture, cm
X	length of absorbing air path, m
α_λ	absorption coefficient at a wavelength λ, m^{-1}
γ	film gamma or slope of the linear portion of the density-log exposure curve
ΔY	difference between the selenographic longitudes of the earth and the sun, deg
ΔZ	difference between the selenographic latitudes of the earth and the sun, deg
θ, ϕ	angular relationship between the earth, moon, and sun where θ is the phase angle (with the moon as the apex for θ and ϕ), deg
λ	wavelength, Å
Φ_θ	ratio of the spectral irradiance of the moon at any phase angle to the spectral irradiance of the full moon
Ω_λ	angle of diffraction for a wavelength λ, deg

Superscripts:

'	used in equation (26) to denote parameters that apply to the standard ultraviolet source (unprimed terms in eq. (26) apply to the standard radiance sources)

DISCUSSION

Experimental Approach

Experimental procedures. - The lunar reflectivity or albedo is defined as the ratio of total solar flux reflected by the moon in all directions to the incident solar flux (ref. 1). The solar flux per unit area incident on the moon is assumed to be the same as the solar flux per unit area incident on the earth, because the distance between the earth and sun is approximately equal to the distance between the moon and sun. Thus, the solar flux incident on the moon P_{sm} is

$$P_{sm} = H_{se} A_m \tag{1}$$

where H_{se} is the solar flux per unit area incident on the earth (solar irradiance) and A_m is the cross-sectional area of the moon.

The solar flux reflected by the moon in all directions P_m is

$$P_m = \int_{\text{sphere}} H_m \, dA_s \tag{2}$$

where H_m is the flux per unit area incident on the earth that is reflected by the moon (lunar irradiance) and is a function of θ and ϕ which define the angular relationship between the moon, earth, and sun. Also in this equation dA_s is the differential area on the surface of a sphere with a radius equal to the distance between the earth and moon with H_m measured at dA_s. Then by the definition of the lunar albedo and equations (1) and (2), the lunar albedo a is

$$a = \frac{\int_{\text{sphere}} H_m \, dA_s}{H_{se} A_m} \tag{3}$$

Equation (3) is used to calculate the albedo over a wavelength interval $\Delta\lambda$ by measuring the total flux per unit area for H_{se} and H_m over $\Delta\lambda$. However, it is more convenient to use the concept of spectral flux $P(\lambda)$ (flux per unit wavelength interval) at a specific wavelength λ, where, in general,

$$P(\lambda) \equiv \frac{\partial P}{\partial \lambda} \tag{4}$$

Likewise, for spectral flux per unit area (spectral irradiance)

$$H(\lambda) \equiv \frac{\partial H}{\partial \lambda} \tag{5}$$

Equation (3) is now expressed as

$$a_\lambda = \frac{\int_{\text{sphere}} H(\lambda)_m \, dA_s}{H(\lambda)_{se} A_m} \tag{6}$$

where a_λ is the spectral albedo at a wavelength λ, $H(\lambda)_{se}$ is the solar spectral irradiance, and $H(\lambda)_m$ is the lunar spectral irradiance. The integral is evaluated in the section on spectral albedo.

If $H(\lambda)_m$ is measured from above the earth's atmosphere, then the spectral albedo for wavelengths between 2000 and 3200 Å can be determined using equation (6), because $H(\lambda)_{se}$ between 2000 and 3200 Å has been determined using measurements made from rockets (ref. 2). Originally, for this experiment, the lunar spectral albedo was to be determined for wavelengths between 2000 to 4000 Å to provide an overlap with ground-based data.

Ultraviolet spectrograms of the moon are made with an objective grating spectrograph; then $H(\lambda)_m$ is measured by relating the microdensitometer traces of the lunar spectrograms to calibration spectrograms. The calibration spectrograms are made from an ultraviolet source of known spectral irradiance.

Figure 1. - Ultraviolet spectrograph for Gemini experiments S-013 and M-407.

Experimental hardware. - The ultraviolet spectrograph that was to be used for this experiment consisted of a 70-mm general-purpose experimental camera with an objective grating attachment. Figure 1 is a photograph of the spectrograph. The spectrograph had an f/3. 3, ultraviolet achromatic lens with quartz/lithium fluoride elements and a focal length of 7. 3 cm. The lens produced 50-micron images of point sources over the spectral range of 2200 to 3200 Å. The grating was a 6000-line/cm replica grating blazed for

2000 Å. It was mounted at an angle of 50° between the optical axis of the lens and the plane of the grating. This combination of lens and grating gave a dispersion of 1800 Å/cm.

The spectrograph was flown on Gemini X, XI, and XII for experiment S-013 to obtain ultraviolet stellar spectra. The results from experiment S-013 were very good, and there is no reason to believe that experiment M-407 would not have been just as successful if the phase of the moon had been favorable during any of the flights.

Calibration Approach

Calibration hardware. - The laboratory equipment used to construct and calibrate the ultraviolet source of the calibration spectra consisted of the following: (1) a cesium telluride (solar-blind) photomultiplier and an S-11 sodium-salicylate-coated photomultiplier, (2) a hydrogen lamp with direct-current power supply, (3) two monochromators, one of which is a 1-meter concave-grating monochromator, (4) a collimator, (5) a thermocouple, (6) a carbon arc, and (7) a high-voltage power supply for the photomultipliers. Details on the ultraviolet source and a description of the use of the laboratory equipment to calibrate the ultraviolet source are given in the sections that follow. The hydrogen lamp and its power supply were chosen from several tested to give optimum correspondence with the requirements of the experiment.

The standard ultraviolet source. - The ultraviolet source to be used as a standard to calibrate the flight spectrograph must have characteristcs similar to the ultraviolet radiation reflected by the moon. This requires a source:

1. That has a continuous spectrum over the range of 2000 to 4000 Å

2. That is at infinity with respect to the flight spectrograph in order to simulate the moon

3. That has a spectral irradiance of the same magnitude as the expected spectral irradiance of the moon

4. That has a constant output, rather than one that varies periodically at 60 or 120 cps

5. That is stable and repeatable

A molecular hydrogen arc lamp satisfies the first requirement. The second and third requirements are met by illuminating the entrance aperture of a reflecting collimator and varying the distance between the lamp and entrance aperture. With this arrangement, the entrance aperture becomes a source at infinity with a spectral irradiance equal to the spectral flux per unit area at the exit aperture of the collimator. A ground-quartz diffusion disk is placed over the entrance aperture to insure even illumination.

The hydrogen lamp and direct-current power supply used satisfied the fourth and fifth requirements. The output of the lamp was checked at 2100 Å, 2500 Å, and 3200 Å over a period of 3 days. The tests confirmed that the lamp was stable to within 2 or 3 percent over a period of at least 4 hours and was repeatable to within about 5 percent.

As stated previously, $H(\lambda)_m$ is measured by relating microdensitometer traces from spectrograms of an ultraviolet source of known spectral irradiance to the lunar spectrograms. The ultraviolet calibration source must have flux characteristics similar to the flux reflected by the moon, and the spectral irradiance of the source must be calibrated over the spectral range from 2000 to 4000 Å.

Calibration of the standard source. - A 1-meter concave-grating monochromator is the primary instrument used to calibrate the standard source. The flux from the standard source is focused on the entrance slit of the monochromator, and the flux through the exit slit is measured with a photomultiplier. The sensitivity of the photomultiplier must be calibrated over the spectral range from 2000 to 4000 Å in order to measure the flux through the exit slit, and a relationship between the flux through the exit slit and the spectral irradiance of the source must be derived.

Calibration of the photomultiplier. - The monochromator is equipped with a double-beam attachment used to measure simultaneously the output of two detectors, as in figure 2. The oscillating mirror between the detectors and the exit slit of the

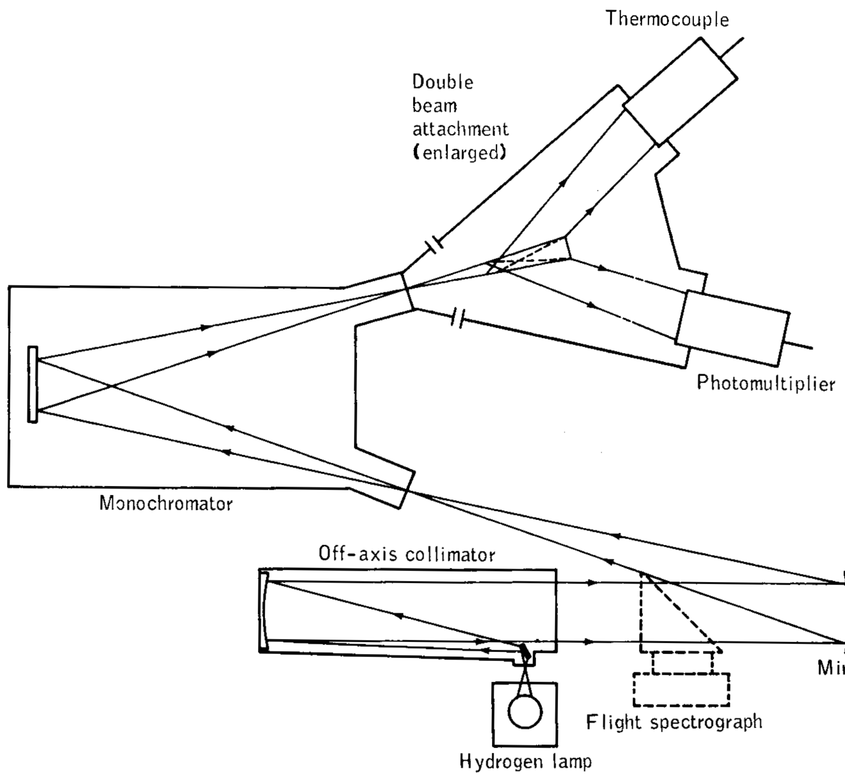


Figure 2. - Monochromator with double-beam attachment used in calibration procedure for Gemini experiment M-407.

monochromator deflects the beam of flux from the exit slit to the photomultiplier and then to the thermocouple at a rate of 7 cps. This double-beam attachment is used to calibrate a photomultiplier against a thermocouple by the following procedure.

The thermocouple is removed from the double-beam attachment and illuminated with a National Bureau of Standards (NBS) irradiance lamp. A chopper in front of the thermocouple chops the illumination at the same frequency as that at which the mirror oscillates. The output voltage of the thermocouple is measured with the same amplifiers that are used with the monochromator. The sensitivity of the thermocouple is given by

$$S_{TC} = \frac{V_{TC}}{H_L A_{TC}} \tag{7}$$

where S_{TC} is the sensitivity of the thermocouple, V_{TC} is the output voltage of the thermocouple, H_L is the irradiance of the NBS lamp, and A_{TC} is the area of the sensing element of the thermocouple.

The measured sensitivity of the thermocouple is 8.3 $\mu V/\mu W$. The thermocouple is reconnected to the double-beam attachment and an aperture of the same size as the sensing element of the thermocouple is placed in front of the photomultiplier. This aperture must be located at the same distance from the exit slit of the monochromator as the sensing element of the thermocouple, because the sensing element of the thermocouple is much smaller than the sensing element of a photomultiplier. The photomultiplier is located several centimeters behind the aperture. The flux from the exit slit of the monochromator is in a diverging beam; hence, the flux through the aperture is distributed over, but not beyond, the sensing area of the photomultiplier.

A strong ultraviolet source is placed at the entrance slit of the monochromator, and the outputs of the photomultiplier and thermocouple are recorded as a function of wavelength. The flux incident on the photomultiplier is equal to the flux incident on the thermocouple at any wavelength. Thus, the sensitivity of the photomultiplier at a wavelength λ is

$$S(\lambda)_{pm} = \frac{I_{pm} S_{TC}}{V_{TC}} \tag{8}$$

where $S(\lambda)_{pm}$ is the sensitivity of the photomultiplier at a wavelength λ, I_{pm} is the output current of the photomultiplier at a wavelength λ, and V_{TC} is the output voltage of the thermocouple. The sensitivity of a thermocouple is independent of wavelength (ref. 3). The sensitivities of the cesium telluride (solar-blind) photomultiplier and the

S-11 sodium-salicylate-coated photomultiplier are plotted in figures 3 and 4 as a function of wavelength. The S-11 photomultiplier is coated with sodium salicylate to extend its sensitivity into the ultraviolet (ref. 4).

A strong source is required to calibrate a photomultiplier against a thermocouple because the sensitivity of a thermocouple is very low. After the photomultiplier is calibrated, it can be used to measure flux that cannot be detected by a thermocouple, if care is taken to insure that the photomultiplier is operating within its linear range. The slit in front of the photomultiplier is removed so that all the flux through the exit slit is incident on the photomultiplier. However, when the slit is removed, the photomultiplier must be moved closer to the exit slit of the monochromator to prevent overfilling of the sensing area of the photomultiplier.

The flux through the exit slit of the monochromator is related to the spectral flux through the entrance slit by

$$P_{EX} = P(\lambda)_{EN} E_{\lambda}(BP) \tag{9}$$

where P_{EX} is the flux through the exit slit, $P(\lambda)_{EN}$ is the spectral flux at a wavelength λ through the entrance slit, E_{λ} is the efficiency of the monochromator at a wavelength λ, and (BP) is the bandpass of the monochromator.

The bandpass of a grating monochromator is the product of the dispersion of the monochromator and the exit-slit width, provided that the entrance-slit width is equal to or less than the exit-slit width. With this condition,

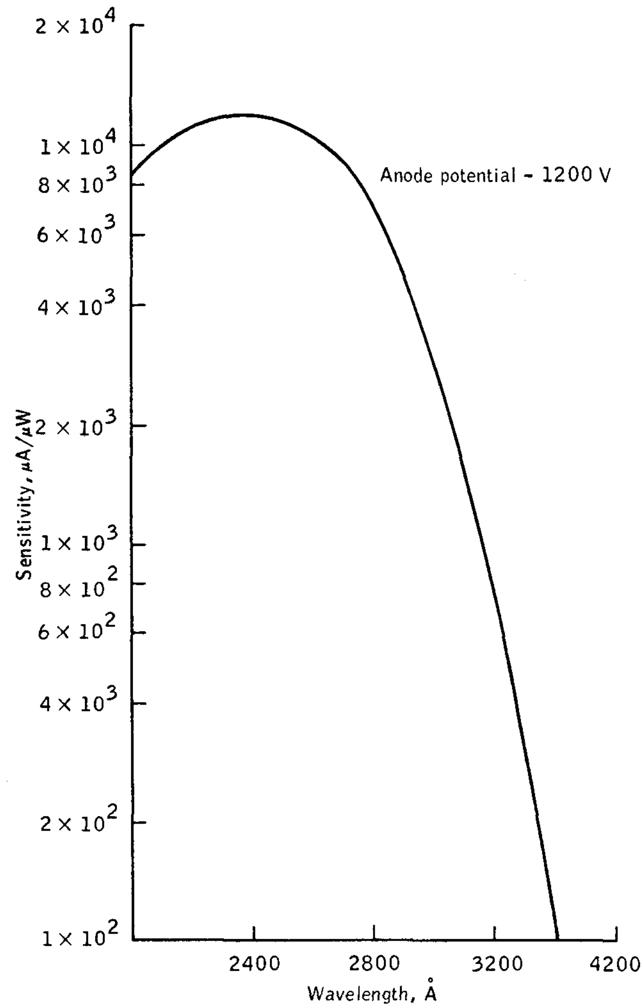


Figure 3. - Sensitivity of a cesium telluride (solar-blind) photomultiplier.

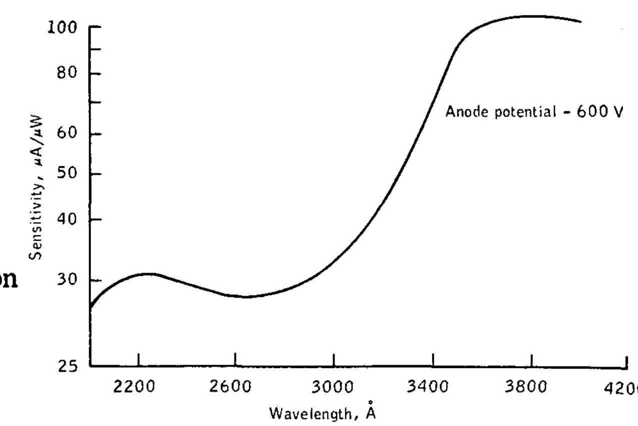


Figure 4. - Sensitivity of an S-11 sodium-salicylate-coated photomultiplier.

equation (9) is expressed as

$$P_{EX} = P(\lambda)_{EN}E_{\lambda}D\left(E_xSW\right) \tag{10}$$

where D is the dispersion of the monochromator and $\left(E_xSW\right)$ is the exit-slit width. The dispersion of the 1-meter concave-grating monochromator is 166 Å/cm.

Efficiency of the monochromator. - In order to use equation (10), the efficiency of the 1-meter concave-grating monochromator must be measured over the spectral range of 2000 to 4000 Å. The efficiency is measured by focusing an image of the exit slit of a second monochromator on the entrance slit of the 1-meter concave-grating monochromator and measuring the flux through the entrance and exit slits of the primary monochromator. The bandpass of the primary monochromator must be greater than the bandwidth of the monochromatic flux from the secondary monochromator. The divergent angle of the flux forming the image on the entrance slit of the primary monochromator must be less than the acceptance angle of the primary monochromator to prevent overfilling of the grating. The efficiency is

$$E_{\lambda} = \frac{P_{EX}}{P_{EN}} \tag{11}$$

where E_{λ} is the efficiency of the 1-meter concave-grating monochromator at a wavelength λ, P_{EX} is the flux through the exit slit at a wavelength λ, and P_{EN} is the flux through the entrance slit at a wavelength λ. The measured efficiency of the 1-meter concave-grating monochromator is plotted as a function of wavelength in figure 5.

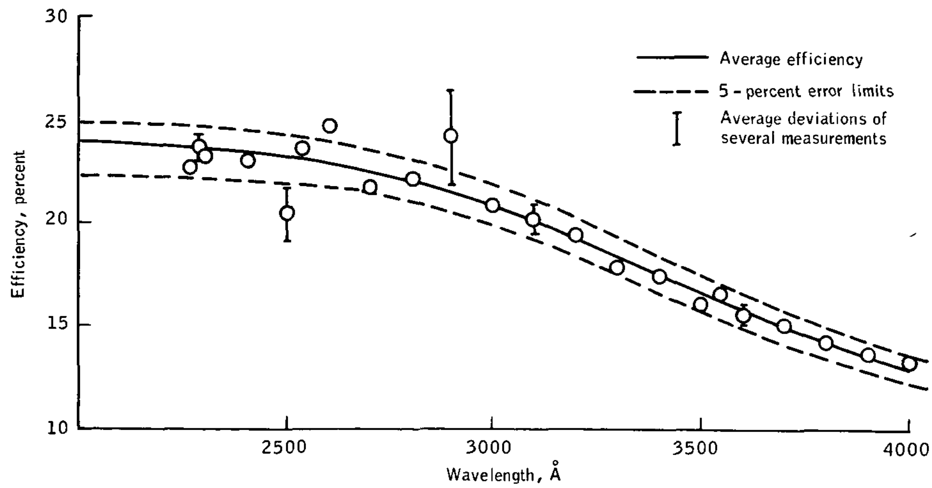


Figure 5. - Efficiency of the 1-meter concave-grating monochromator.

Spectral irradiance of the standard source related to the spectral flux through the entrance slit of the monochromator. - The entrance aperture of the collimator is a source at infinity with a spectral irradiance $H(\lambda)_c$ equal to the spectral flux per unit area at the exit aperture of the collimator. If the collimated beam of flux from the collimator is focused by a mirror on the entrance slit of the monochromator, as shown in figure 2, the spectral flux through the entrance slit of the monochromator is related to $H(\lambda)_c$ by

$$H(\lambda)_c = \frac{P(\lambda)_{EN}}{R_\lambda e^{-\alpha_\lambda(d_1+d_2)} A_M} \tag{12}$$

where R_λ is the reflectivity of the mirror at wavelength λ, α is the absorption coefficient of air at wavelength λ, d_1 is the distance from the collimator to the mirror, d_2 is the distance from the mirror to the entrance slit, and A_M is the area of the mirror. Equation (12) is valid provided the diameter of the mirror is less than the diameter of the exit aperture of the collimator. Also, the entrance slit of the monochromator must be larger than the image of the entrance aperture of the collimator focused at the entrance slit of the monochromator. Furthermore, the angle between the axis of the collimator and the mirror should be less than 10° to prevent distortion of the image. The distance d_1 must be chosen so that the unvignetted central portion of the collimated beam overfills the mirror, and all the flux through the entrance slit of the monochromator must be incident on the monochromator grating.

Absorption coefficient of air. - The absorption coefficient of air is measured with the 1-meter concave-grating monochromator. The flux through the exit slit is measured when the chamber of the monochromator is at ambient pressure and again when it is under a vacuum of about 10^{-6} mm Hg. Hence, the transmission through the airpath of the monochromator is

$$T = \frac{P_A}{P_V} \tag{13}$$

where T is the transmission through the airpath of the monochromator, P_A is the flux at ambient pressure, and P_V is the flux at 10^{-6} mm Hg.

The absorption coefficient α is defined by

$$e^{-\alpha X} = T \tag{14}$$

where X is the length of the absorbing path and e is the base of natural logarithms. The length of the absorbing path X is equal to 2 meters for the grating monochromator. This is the distance between entrance slit and exit slit. The transmission of 2 meters of air is plotted as a function of wavelength in figure 6.

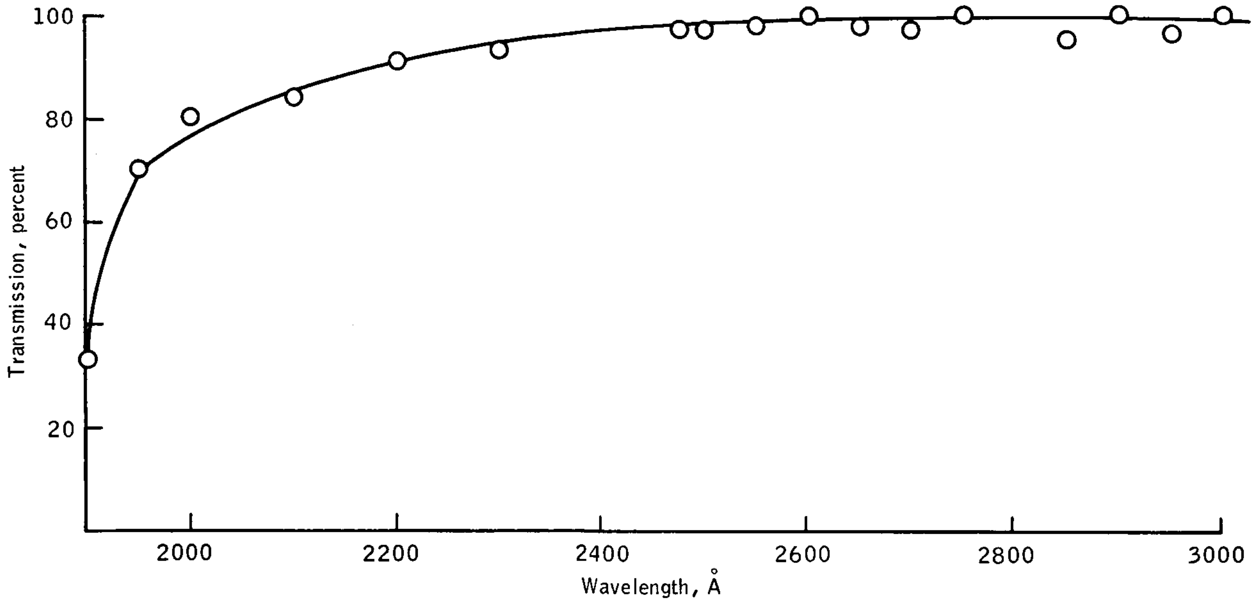


Figure 6. - Transmission of 2 meters of air.

The remaining parameter required by equation (12) is the reflectivity of the mirror. The reflectivity of the mirror is essentially constant over the spectral range of 2000 to 4000 Å with an average value of 89 percent.

Spectral irradiance of the standard source related to the output current of the photomultiplier. - The flux through the exit slit of the monochromator P_{EX} is related to the output current I_{pm} of the photomultiplier by

$$P_{EX} = \frac{I_{pm}}{S(\lambda)_{pm}} \qquad (15)$$

where $S(\lambda)_{pm}$ is the sensitivity of the photomultiplier at a wavelength λ. Combining equations (10), (12), and (15) gives

$$H(\lambda)_c = \frac{I_{pm}}{S(\lambda)_{pm} R_\lambda E_\lambda e^{-\alpha_\lambda (d_1+d_2)} A_M D \left(E_x SW\right)} \qquad (16)$$

Thus, the spectral irradiance of the standard source is calculated with equation (16) by measuring the photomultiplier current as a function of wavelength as the monochromator scans the spectral range from 2000 to 4000 Å. The validity of this technique for measuring the spectral irradiance of the standard ultraviolet source is confirmed by using the same techniques to measure the spectral radiance of a tungsten lamp as calibrated by NBS over the spectral range of 2500 to 4000 Å. The tungsten lamp is placed in front of the spherical mirror at a distance equal to the radius of curvature of the spherical mirror. An image of the lamp filament is focused on the entrance slit of the monochromator. The same mirror that was used to focus the flux from the collimator on the entrance slit of the monochromator is used to focus the image of the filament on the entrance slit of the monochromator. It is very important that this lamp be at a distance from the mirror equal to the radius of curvature of the mirror so that the image of the filament will be the same size as the filament. However, the image of the filament must be larger than the entrance slit of the monochromator. References 5 and 6 cover in detail the use of this lamp. The following equation is given in reference 6 for the spectral flux through the entrance slit of a monochromator when the lamp is used in the manner described

$$P(\lambda)_{EN} = \frac{R_\lambda N(\lambda)_{NBS} A_{EN} A_M}{d_2^{\,2}} \tag{17}$$

where $P(\lambda)_{EN}$ is the spectral flux through the entrance slit, R_λ is the reflectivity of the mirror at a wavelength λ, $N(\lambda)_{NBS}$ is the spectral radiance of the tungsten lamp as calibrated by the NBS, A_{EN} is the area of the entrance slit, A_M is the area of the mirror, and d_2 is the distance between the mirror and the entrance slit. When equations (10) and (15) are combined, the spectral flux through the entrance slit of the monochromator as a function of the output current of the photomultiplier is given by

$$P(\lambda)_{EN} = \frac{I_{pm}}{S(\lambda)_{pm} E_\lambda D\left(E_x SW\right)} \tag{18}$$

The spectral radiance of the tungsten lamp is calculated by combining equations (17) and (18) and measuring the output current of the photomultiplier such that

$$N(\lambda)_{NBS} = \frac{I_{pm} d_2^{\,2}}{R_\lambda A_{EN} A_M S(\lambda)_{pm} E_\lambda D\left(E_x SW\right)} \tag{19}$$

Figure 7 compares the spectral radiance of the lamp, as given by the NBS, to those values for spectral radiance determined using equation (19). In general, the agreement is good. The high values around 2500 Å are attributed to scattered light at longer wavelengths because the measurements were made only with the S-11 photomultiplier. The reason for the low values around 4000 Å is probably a combination of errors: (1) in photomultiplier sensitivity, (2) in the efficiency of the monochromator, and (3) in the NBS calibration of the NBS standard lamp.

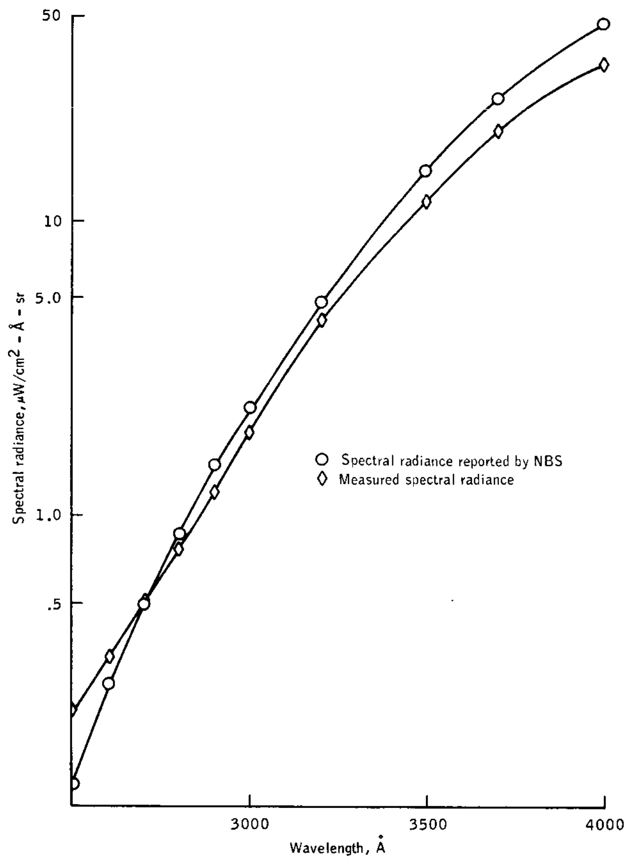


Figure 7. - Spectral radiance of tungsten lamp as calibrated by NBS compared with measured values.

Calibration of the standard ultraviolet source with other standards. - Although the technique just described is satisfactory for calibrating the standard ultraviolet source, it is not practical to use this technique for a day-to-day check on the calibration. The efficiency of the monochromator and especially the sensitivity of the photomultiplier are subject to change over a period of time, and it is time consuming to measure these parameters each time the calibration is to be checked. Therefore, a technique was developed to check the calibration of the standard ultraviolet source against other standards.

An NBS spectral radiance lamp and a carbon arc are used as standards. The spectral radiance of the lamp as calibrated by NBS is used as a standard over the spectral range from 2500 to 4000 Å. A carbon arc has proved to be a good spectral radiance standard in the ultraviolet (ref. 7) and is used as a standard for wavelengths shorter than 2500 Å.

An image of the collimator entrance aperture, the standard ultraviolet source to be calibrated, is focused on the entrance slit of the monochromator by a spherical mirror as shown in figure 2. The distance between the exit aperture of the collimator and the mirror is adjusted to be three times the focal length of the mirror. The distance between the mirror and entrance slit is equal to the focal length of the mirror; thus, the optical path between the collimator and the entrance slit is four times the focal length of the mirror. Since the diameter of the mirror is less than the exit aperture of the collimator, the spectral flux incident on the entrance slit of the monochromator is

$$P_i(\lambda)_{EN} = H(\lambda)_c A_M R_\lambda e^{-4\alpha_\lambda \left(fl_M\right)} \tag{20}$$

where $P_i(\lambda)_{EN}$ is the spectral flux incident on the entrance slit of the monochromator and fl_M is the focal length of the mirror. Other terms are the same as defined previously. The image is larger than the entrance slit; therefore, the spectral flux through the entrance slit is

$$P(\lambda)_{EN} = P_i(\lambda)_{EN}\frac{A_{EN}}{A_i} \tag{21}$$

and

$$A_i = \frac{h_o w_o\left(fl_M\right)^2}{\left(fl_C\right)^2} \tag{22}$$

where A_{EN} is the area of the entrance slit of the monochromator, A_i is the area of the collimator entrance aperture image, w_o is the width of the collimator entrance aperture, h_o is the height of the collimator entrance aperture, and $\left(fl_C\right)$ is the focal length of the collimator. From equations (18), (20), (21), and (22),

$$H(\lambda)_c = \frac{I_{pm}h_o w_o\left(fl_M\right)^2}{A_{EN}A_M R_\lambda e^K\left(fl_C\right)^2 S(\lambda)_{pm}E_\lambda D\left(E_x SW\right)} \tag{23}$$

where

$$K = -4\alpha_\lambda\left(fl_M\right) \tag{24}$$

Equation (23) is identical to equation (16) except that it applies for different conditions.

The carbon arc and then the NBS lamp is focused by the mirror on the entrance slit of the monochromator (as shown in fig. 8). The distance between these sources and the mirror is adjusted to equal the radius of curvature of the mirror. Thus, the total distance between the sources and the entrance slit of the monochromator is twice the radius of curvature of the mirror or four times the focal length of the mirror.

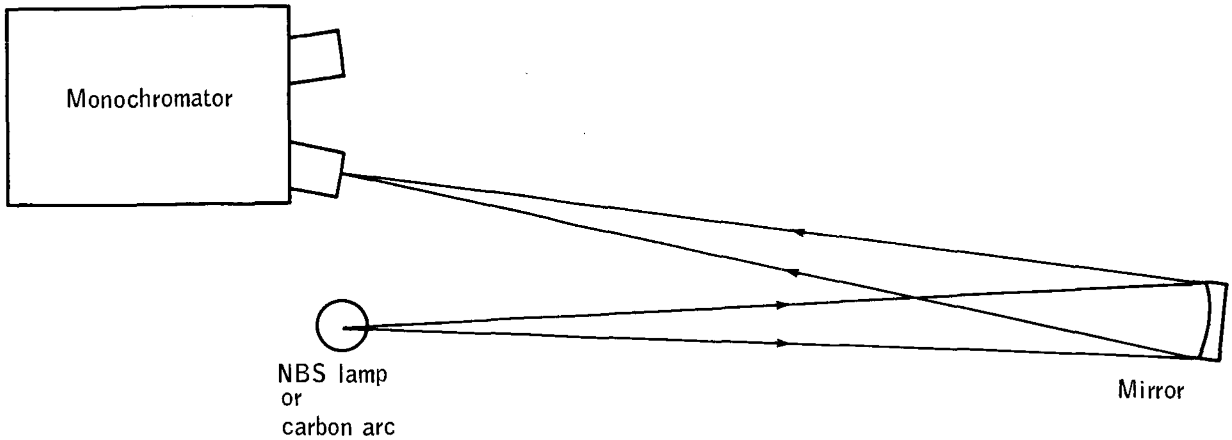


Figure 8. - Optical arrangement for using NBS lamp and carbon arc as standards.

Equation (19) gives the spectral radiance $N(\lambda)$ of a source as a function of photomultiplier current. However, air absorption is neglected because equation (19) applies for wavelengths where air absorption is negligible. Rewriting equation (19) to include air absorption for a path equal to four times the focal length of the mirror gives

$$N(\lambda) = \frac{4I_{pm}\left(fl_M\right)^2}{A_{EN}A_M R_\lambda E_\lambda e^{K_D}\left(E_x SW\right)S(\lambda)_{pm}} \tag{25}$$

Note that $d_2^{\ 2}$ in equation (19) is equivalent to $4\left(fl_M\right)^2$ in equation (25).

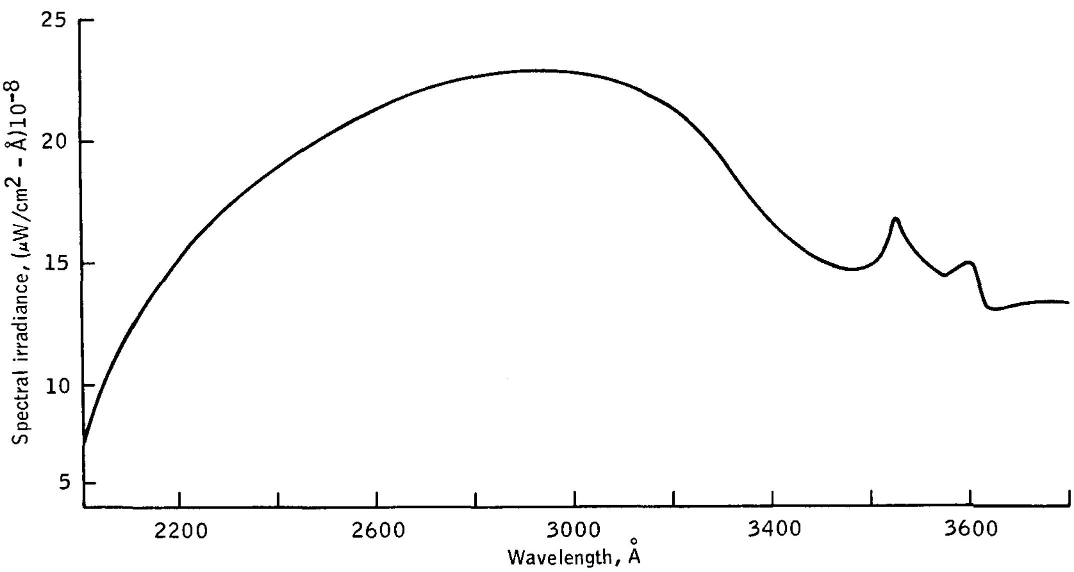
Since the monochromator, mirror, photomultiplier, and airpath are the same for each measurement, equations (23) and (25) are combined to give

$$H(\lambda)_c = \frac{N(\lambda)I'_{pm}h_o w_o A_{EN}A_M\left(E_x SW\right)}{4I_{pm}A'_{EN}A'_M\left(fl_C\right)^2\left(E_x SW\right)'} \tag{26}$$

where primed terms denote parameters that apply to the standard ultraviolet source and unprimed terms apply to the standard radiance sources. The exit slit width and the entrance slit area can be the same for each source to simplify equation (26).

Since the convergent angle of the flux forming the image of the collimator entrance aperture on the monochromator entrance slit will be twice the convergent angle of the flux forming the images of the carbon arc or the NBS lamp, different areas of the monochromator grating are illuminated in each case. In order to illuminate the same area of the grating with each source, the aperture of the mirror is stopped down by about a factor of 2 for measurements of the standard ultraviolet source. This is very important because the efficiency of the grating is dependent on the area illuminated. The angle between a line from the source to the mirror and a line from the mirror to the entrance slit of the monochromator must be less than 10° to prevent distortion of the image. The cesium telluride (solar-blind) photomultiplier is used with the carbon arc and the NBS lamp for measurements below 3200 Å to eliminate errors resulting from scattered light of longer wavelengths. The S-11 photomultiplier is used for measurements above 3200 Å. The cesium telluride photomultiplier is attached to one channel of the double-beam attachment, (fig. 2), and the S-11 photomultiplier to the other channel.

With this technique, the spectral range from 2000 to 4000 Å is scanned in one operation and the spectral irradiance of the standard ultraviolet source can be calibrated against the carbon arc and the NBS lamp is less than an hour. The spectral irradiance of the standard ultraviolet source as determined with the carbon arc and the NBS lamp is plotted in figure 9. The estimated possible error is ±25 percent from 2000 to 2500 Å and ±15 percent from 2500 to 4000 Å. The basis for these estimated errors is discussed in the concluding remarks section.



Parameters

Entrance slit width of monochromator for collimator and NBS lamp	0.100 cm
Entrance slit width of monochromator for carbon arc	2.00×10^{-4} cm
Entrance slit height	0.120 cm
Diameter of mirror for collimator	6.46 cm
Diameter of mirror for carbon arc and NBS lamp	4.34 cm
Entrance slit width of collimator	0.100 cm
Entrance slit height of collimator	0.400 cm

Figure 9. - Spectral irradiance of the standard ultraviolet source as determined with the NBS spectral radiance lamp and with the carbon arc.

Calibration of the flight spectrograph. - After the spectral irradiance of the standard ultraviolet source has been determined, the flight spectrograph is calibrated by placing it in front of the exit aperture of the collimator and making a series of calibration spectrograms at various exposure times. The spectral irradiance of the standard ultraviolet source at any wavelength λ is a function of the density of the spectrogram at λ. Thus, an equation is required to relate the spectral irradiance of the standard ultraviolet source to the density of the spectrogram.

The exit aperture of the collimator is larger than the entrance aperture of the spectrograph; therefore, the spectral flux through the spectrograph (the flux after reflection, dispersion by the grating, and transmission by the lens) is

$$P(\lambda)_{sp} = H(\lambda)_c A_{sp} E_\lambda \tag{27}$$

where $P(\lambda)_{sp}$ is the spectral flux through the spectrograph, A_{sp} is the area of the entrance aperture of the spectrograph, and E_λ is the efficiency of the spectrograph. The efficiency of the spectrograph is the product of the efficiency of the objective grating and the transmission of the lens.

The flux through the spectrograph at any wavelength forms a monochromatic image of the collimator's entrance aperture and is recorded on film in the spectrograph. This image is in effect the exit slit of the spectrograph. The height and width of the image are

$$h_i = h_o \frac{(fl_L)}{(fl_C)} \tag{28}$$

$$w_i = w_o \frac{(fl_L)}{(fl_C)} \tag{29}$$

where h_i is the height of the image, w_i is the width of the image, and (fl_L) is the focal length of the lens. The bandpass of the spectrograph is

$$(BP) = Dw_o \frac{(fl_L)}{(fl_C)} \tag{30}$$

where D is the dispersion of the spectrograph. The flux per unit area incident on the film H_F is

$$H_F = \frac{H(\lambda)_c A_{sp} E_\lambda D\left(fl_C\right)}{h_o\left(fl_L\right)} \tag{31}$$

Exposure is the product of the flux per unit area incident on the film and exposure time. The exposure at any wavelength is related to the spectral irradiance of the standard ultraviolet source at this wavelength by

$$J(\lambda)_c = \frac{H(\lambda)_c A_{sp} E_\lambda D t_c\left(fl_C\right)}{h_o\left(fl_L\right)} \tag{32}$$

where $J(\lambda)_c$ is the exposure of the calibration spectrograms at a wavelength λ and t_c is the exposure time for the calibration spectrograms. Exposure times are usually varied by a factor of 2 for each exposure over an exposure range of several hundred for values of $J(\lambda)_c$. Density is a linear function of the logarithm of exposure over a range of 10 to 100 for values of $J(\lambda)_c$, depending on type of film. For the linear portion of the curve

$$\gamma = \frac{D(\lambda)_c}{\log J(\lambda)_c} \tag{33}$$

where γ is the slope of the linear portion of the density-log exposure curve and $D(\lambda)_c$ is the density of the calibration spectrogram at a wavelength λ.

The calibration and the lunar spectrograms are made on the same roll of film and developed at the same time so that γ is the same for both sets of spectrograms. Thus

$$\frac{D(\lambda)_c}{D(\lambda)_m} = \frac{\log J(\lambda)_c}{\log J(\lambda)_m} \tag{34}$$

where $D(\lambda)_m$ is the density of lunar spectra at a wavelength λ, and $J(\lambda)_m$ is the exposure for the lunar spectra at a wavelength λ. Exposure times for the lunar and the calibration spectrograms must be of the same order of magnitude to eliminate errors resulting from film reciprocity effects.

Spectral irradiance of the moon equated to exposure. - Equal exposures for the calibration and the lunar spectra do not imply equal spectral irradiance for the moon and the standard ultraviolet source, because the bandpass of the spectrograph is a function of the size and shape of the moon. The size and shape of the moon is a function of phase angle, defined as the angle between the centers of the earth and the sun with the center of the moon as the apex. The phase angle is zero for the full moon.

From the geometry of the earth-moon-sun relationship shown in figure 10, the length of the arc L from the lunar limb to the terminator in the plane of θ is

$$L = R(\pi - \theta) \tag{35}$$

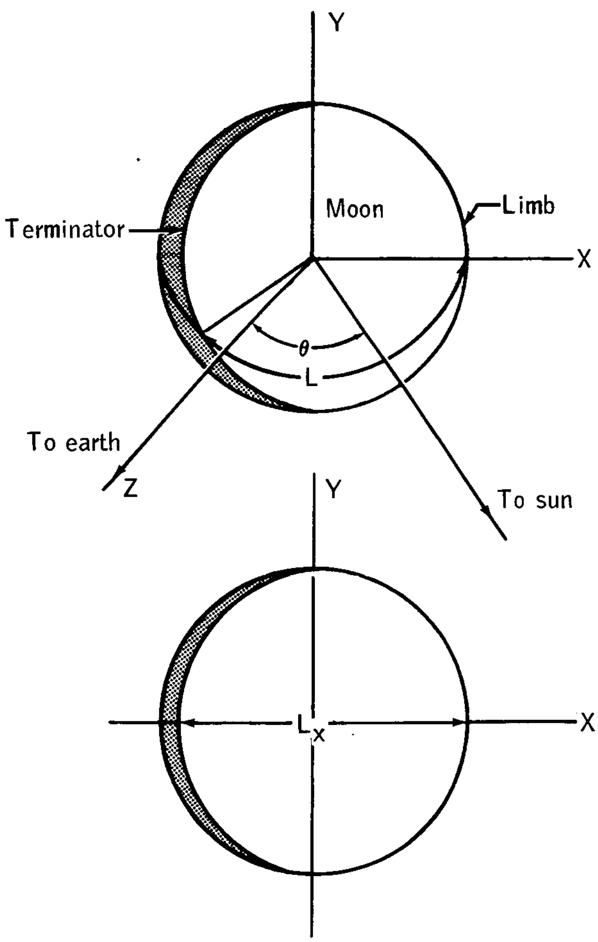


Figure 10. - Geometry of the earth-moon-sun relationship.

where R is the radius of the moon, θ is the phase angle, and $(\pi - \theta)$ is the angle subtended by the arc L. By equation (35),

$$dL = -Rd\theta \tag{36}$$

and the differential length of the arc parallel to the X-axis, which is normal to the direction of the earth, is

$$dL_X = -R \sin \theta d\theta \tag{37}$$

For any phase angle

$$L_X = -R\int_{\pi}^{\theta} \sin \theta d\theta$$

$$= R(1 + \cos \theta) \tag{38}$$

L_X and R are expressed in terms of the angles subtended by L_X and R as measured from the earth rather than being expressed in terms of length. For example, if the radius of the moon is 16 minutes of arc and the phase angle is 60°, then the angle subtended by the limb and the terminator along L is 24 minutes of arc. Integrating over the surface of the moon, the illuminated area A_x of the moon normal to the direction of the earth is

$$A_x = \frac{\pi R^2}{2}(1 + \cos\theta) \tag{39}$$

The area of a monochromatic image of the full moon A_{io} is

$$A_{io} = \pi\left(fl_L\right)^2\tan^2 R \tag{40}$$

and

$$\frac{A_i}{A_{io}} = \frac{A_x}{A_o} \tag{41}$$

where A_o is the illuminated area of the surface of the full moon normal to the direction of the earth. Thus, A_i, the area of a monochromatic image of the moon at any phase angle, is

$$A_i = \frac{\pi\left(fl_L\right)^2\tan^2 R(1 + \cos\theta)}{2} \tag{42}$$

The flux per unit area incident on the spectrograph film H_F is

$$\begin{aligned} H_F &= \frac{H(\lambda)_m A_{sp} E_\lambda (BP)}{A_i} \\ &= \frac{2H(\lambda)_m A_{sp} E_\lambda (BP)}{\pi\left(fl_L\right)^2\tan^2 R(1 + \cos\theta)} \end{aligned} \tag{43}$$

The spectrograph is oriented such that the dispersion is parallel to L_x; thus the width of a monochromatic lunar image W_{mi} along L_x is

$$W_{mi} = \left(fl_L\right) \tan L_x \tag{44}$$

and the bandpass is

$$(BP) = D\left(fl_L\right) \tan L_x \tag{45}$$

Hence, the exposure of the lunar spectrogram at any wavelength for any phase angle is

$$J(\lambda)_m = \frac{2H(\lambda)_m A_{sp} E_\lambda t_m D \tan L_x}{\pi\left(fl_L\right)\tan^2 R(1 + \cos \theta)} \tag{46}$$

where t_m is the exposure time for the lunar spectrogram.

For equal densities of the lunar and calibration spectrograms, equations (32), (34), and (46) are combined to give

$$H(\lambda)_m = \frac{\pi H(\lambda)_c \left(fl_C\right) t_c \tan^2 R(1 + \cos \theta)}{2h_o t_m \tan L_x} \tag{47}$$

It must be emphasized that for equation (47) to be valid, the exposure times for the calibration and lunar spectra must be of the same order of magnitude, $D(\lambda)_c$ must equal $D(\lambda)_m$, and the dispersion of the spectrograph must be parallel to L_x.

The radius of the moon for any time is given in The American Ephemeris and Nautical Almanac (ref. 8). The phase angle is calculated from either

$$\theta = \sqrt{(\Delta Y)^2 + (\Delta Z)^2} \tag{48}$$

or

$$\cos \theta = 2(FI) - 1 \tag{49}$$

where ΔY is the difference between the selenographic longitudes of the earth and the sun, ΔZ is the difference between the selenographic latitudes of the earth and the sun, and (FI) is the fraction of the lunar disk illuminated. The value of these parameters is also tabulated in reference 8. The selenographic longitudes and latitudes of the earth and the sun are tabulated to the nearest 0.01°. Equation (48) is used for an accurate determination of the phase angle. Equation (49) is much simpler, but the fraction of the lunar disk illuminated is tabulated to only two significant figures.

Wavelength calibration. - The calibration and lunar spectra do not have the spectral lines needed to establish a wavelength scale for their spectrograms. Therefore, a wavelength calibration is required in addition to the spectroradiometric calibration already discussed.

For the wavelength calibration, an ultraviolet line source, such as a low-pressure mercury or cadmium lamp, is substituted for the hydrogen lamp at the entrance aperture of the collimator and a spectrogram of the line source is made with the flight spectrograph. The spectrograph is attached to the collimator, so that the orientation between the two is the same for both wavelength and radiometric spectrograms. Hence, the wavelength scale for the radiometric calibration spectrograms is the same as the wavelength scale for the wavelength calibration spectrogram. Both the zero-order image and the center of the spectrograms are used as common points to tie the scales together. Since the zero-order image is grossly overexposed for the longer exposure times, it is very difficult to determine its exact location. In these cases, only the centers of the spectrograms can be used as common points.

A wavelength scale for the lunar spectrograms is not necessarily the same as the scale for the calibration spectrograms, since the dispersion of the spectrograph is a function of the angle between the direction of the incident flux and the grating. The grating equation gives $\sin\Omega_\lambda$ as

$$\sin \Omega_\lambda = \frac{n\lambda}{d} + \sin i \tag{50}$$

where Ω_λ is the angle of diffraction for a wavelength λ, i is the angle of incidence, n is the order number, and d is the distance between rulings on the grating.

Figure 11 is an optical diagram of the flight spectrograph. From the geometry of this diagram and from the grating equation the following relationships are apparent.

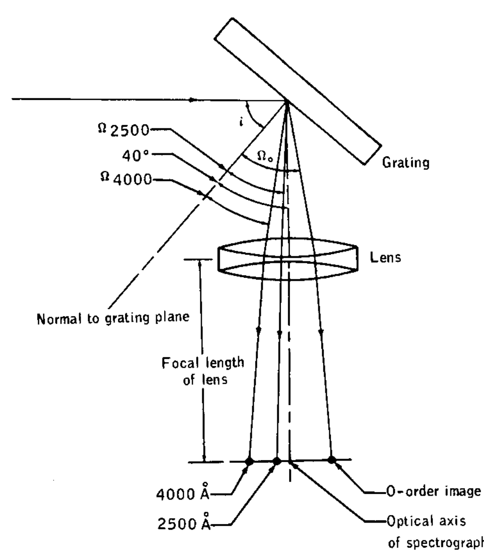


Figure 11. - Optical diagram of the flight spectrograph.

1. The angle between the optical axis of the spectrograph and the zero-order image is given by $i - 40^\circ$.

2. The distance, as measured on the spectrogram, between the zero-order image and the center of the spectrogram is given by $\left(fl_L\right)\tan(i - 40^\circ)$. (The optical axis of the spectrograph corresponds to the center of the spectrogram.)

3. The angle between the zero-order image and the flux at a wavelength λ diffracted by the grating is given by $i - \Omega_\lambda$.

4. The angle between the optical axis of the spectrograph and the flux at a wavelength λ diffracted by the grating is given by $40^\circ - \Omega_\lambda$.

The first two relationships are used to determine the angle of incidence by measuring the distance on the spectrogram between the zero-order image and the center of the spectrogram. After determining the angle of incidence, the grating equation is used to solve for the angles in the third and fourth relationships. The focal length of the lens multiplied by the tangent of the angles in relationships 3 and 4 gives the distance between the zero-order image (or the center of the spectrogram) and any wavelength. This method of establishing a wavelength scale for the lunar spectrograms was checked with a cadmium spectrogram. It proved satisfactory for angles of incidence between 48° and 52°. Typical microdensitometer traces of a standard ultraviolet source spectrogram, a lunar spectrogram, and a cadmium lamp spectrogram are shown in figures 12, 13, and 14, respectively.

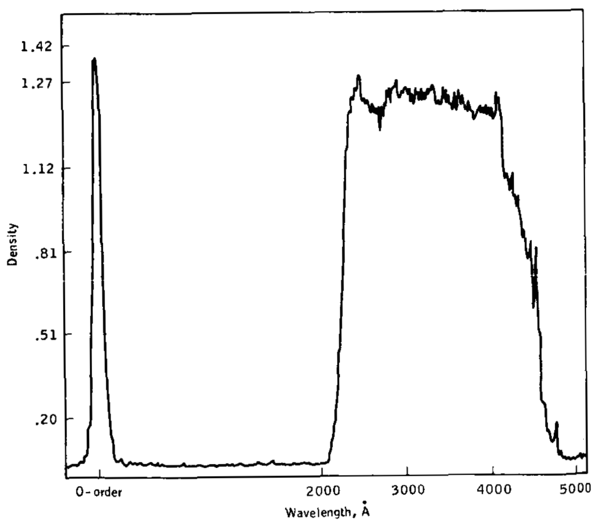


Figure 12. - Microdensitometer trace of standard ultraviolet source spectrogram.

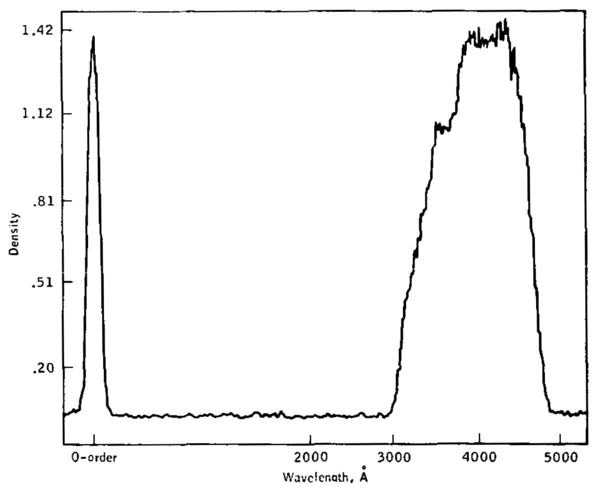


Figure 13. - Microdensitometer trace of lunar spectrogram made from the ground.

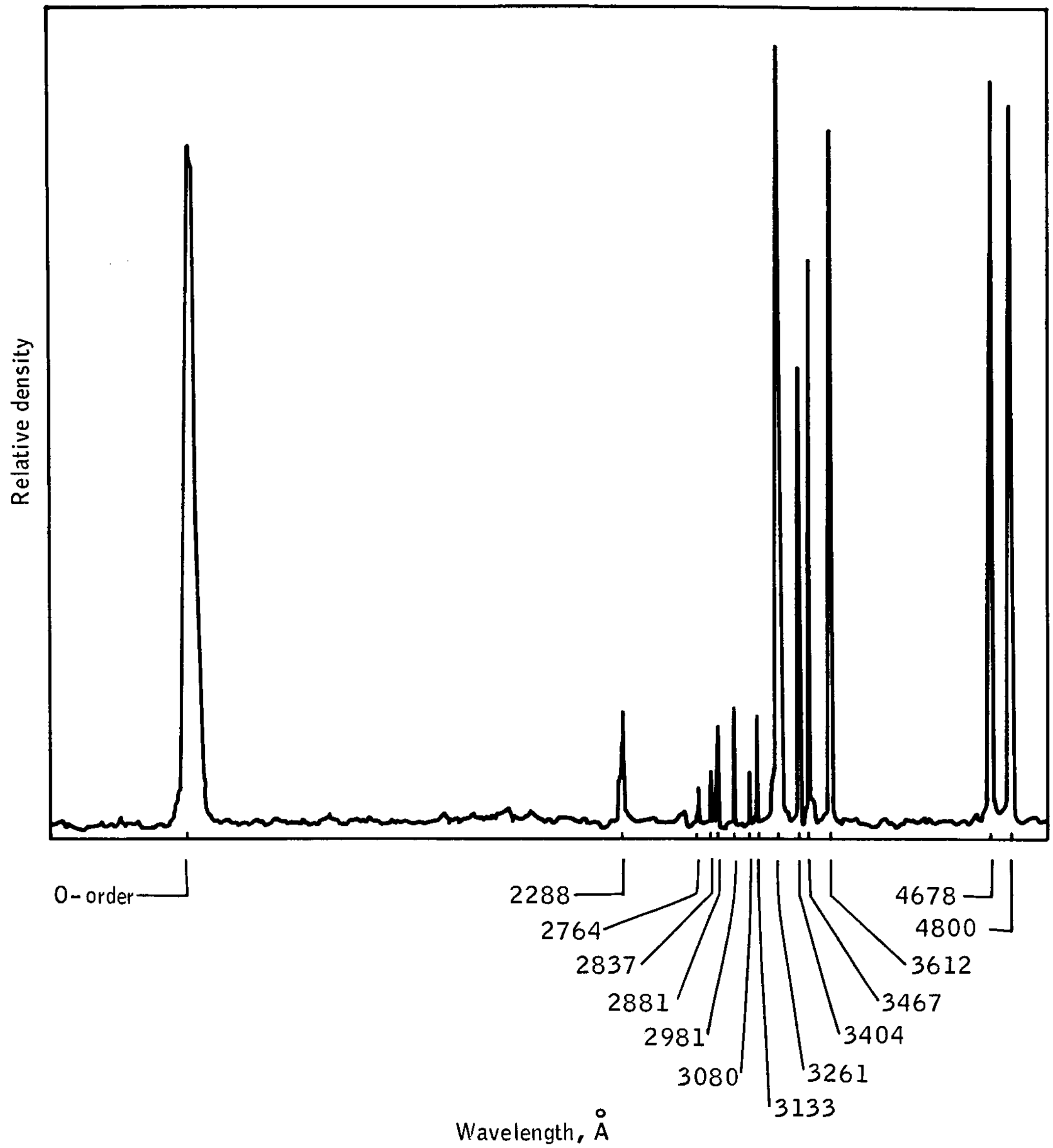


Figure 14. - Microdensitometer trace of a cadmium lamp spectrogram.

Spectral albedo. - After measuring the spectral irradiance of the moon at a phase angle θ by the methods covered in the preceding sections of the report, the spectral albedo or reflectivity is calculated by equation (6). The integral in equation (6) is evaluated in essentially the same way as given in reference 1, except that the albedo is calculated in terms of spectral irradiance for the full moon and of the sun rather than in terms of stellar magnitudes.

Consider a sphere with a radius equal to the distance between the earth and the moon R_{me} with the center of the sphere taken to be at the center of the moon

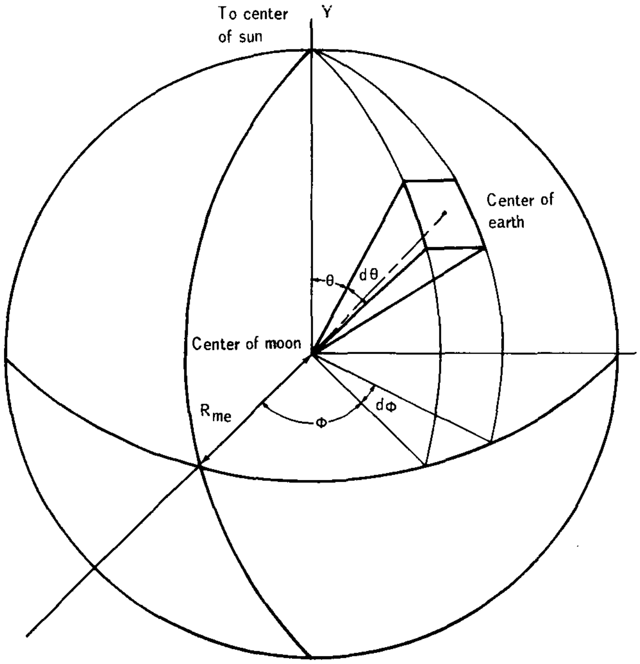


Figure 15. - Geometry for calculating albedo.

(as shown in fig. 15). The axes of the sphere are chosen such that the Y-axis corresponds to a line from the center of the moon to the center of the sun. The position of the earth with respect to the moon is expressed in terms of θ and ϕ where θ is the phase angle. $H(\lambda)_m$ is measured at the earth over an infinitesimal area dA_s. Thus, the infinitesimal spectral flux reflected by the moon in the direction of dA_s is

$$dP(\lambda)_m = H(\lambda)_m dA_s \tag{51}$$

and the total flux reflected by the moon in all directions is

$$P(\lambda)_m = R_{me}^2 \int_0^{\pi} \int_0^{2\pi} H(\lambda)_m \sin\theta \, d\phi d\theta \tag{52}$$

Assuming $H(\lambda)_m$ is not a function of ϕ (ref. 1)

$$P(\lambda)_m = 2\pi R_{me}^2 \int_0^{\pi} H(\lambda)_m \sin\theta d\theta \tag{53}$$

Let

$$\Phi_\theta = \frac{H(\lambda)_m}{H_o(\lambda)_m} \tag{54}$$

where $H_o(\lambda)_m$ is the spectral irradiance at full moon. Thus

$$P(\lambda)_m = 2\pi R_{me}^2 H_o(\lambda)_m \int_0^{\pi} \Phi_\theta \sin\theta d\theta \tag{55}$$

Substituting equation (53) into equation (6) gives

$$a_\lambda = \frac{2\pi R_{me}{}^2 H_o(\lambda)_m \int_0^\pi \Phi_\theta \sin\theta d\theta}{H(\lambda)_{se} A_m} = pq \tag{56}$$

where the geometric albedo p is given by

$$p = \frac{\pi R_{me}{}^2 H_o(\lambda)_m}{H(\lambda)_{se} A_m} \tag{57}$$

and the phase integral q is given by

$$q = 2\int_0^\pi \Phi_\theta \sin\theta d\theta \tag{58}$$

The ratio of the spectral irradiance of the moon at any phase angle to the spectral irradiance of the full moon (symbolized Φ_θ) has been determined by several investigators. The values reported by Rougier, as tabulated on page 214 of reference 1, are generally accepted. From Rougier's data based on a mean wavelength of 4450 Å, the spectral irradiance of the full moon can be determined from its spectral irradiance at any phase angle, and the phase integral can be evaluated. The ratio Φ_θ is plotted as a function of phase angle in figure 16. The phase integral q is equal to 0.585 (ref. 1). For the mean distance between the moon and the earth

$$a_\lambda = 2.86 \times 10^4 \frac{H_o(\lambda)_m}{H(\lambda)_{se}} \tag{59}$$

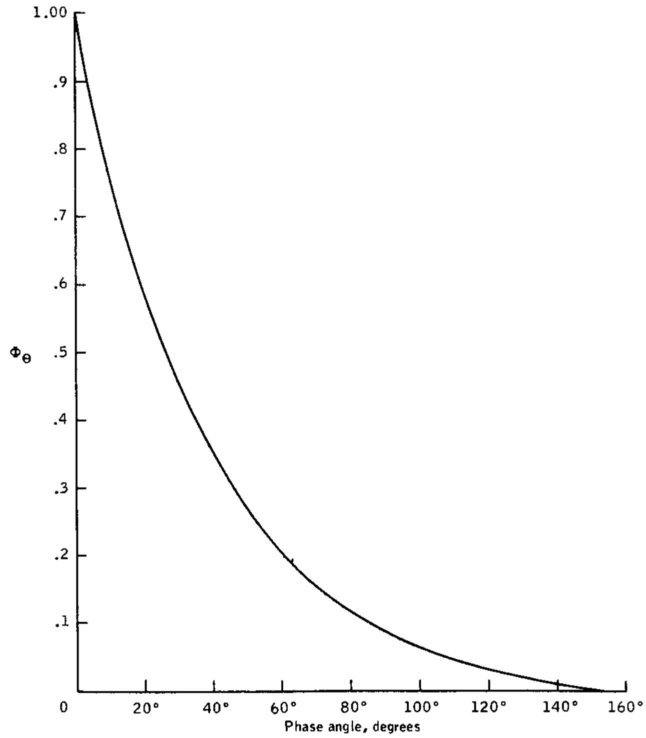


Figure 16. - Ratio of the irradiance of the moon at any phase angle to the irradiance of the full moon.

MSC 290-68

It must be assumed that the value of Φ_θ is the same for ultraviolet wavelengths as it is for visible wavelengths. If the experiment had been conducted on all three flights, it is certain that sufficient data would have been obtained on spectral irradiance of the moon as a function of phase angle to verify the validity of this assumption.

The spectral irradiance of the moon for wavelengths greater than 3200 Å is given in reference 9. It is of interest to note the results of two groups who recently reported on measurements of the spectral albedo of the moon at wavelengths shorter than 3200 Å. The flux values tabulated in reference 10 were used with equation (59) to calculate the albedoes given in table I. Table I also includes values for spectral albedo from Gemini experiment D-4-7.

CONCLUDING REMARKS

The calibration of the standard ultraviolet source against the NBS lamp and the carbon arc is believed to be more accurate than measuring the flux at the exit slit of the monochromator and then relating this flux to the spectral irradiance of the standard ultraviolet source with equation (16). However, schedules under which the calibration techniques were developed permitted neither a detailed comparison of the two techniques nor an analysis of probable error.

Estimates of possible errors for calibrations against the NBS lamp and the carbon arc were made from the repeatability of the measurements and the accuracy of the calibration of the NBS lamp and the carbon arc. The NBS estimated the accuracy of the calibration of their lamp at about 8 percent for the shorter wavelengths (ref. 5). The repeatability of calibration measurements with the NBS lamp averaged about 5 percent. This indicates a possible error in the calibration of the standard ultraviolet source of ±10 to ±15 percent from 2500 to 4000 Å. The possible error increased to ±25 percent for wavelengths shorter than 2500 Å, using the carbon arc. Johnson (ref. 7) estimated that his calibration of the carbon arc could have been in error by as much as ±20 percent. The repeatability of calibration measurements with the carbon arc averaged about 5 percent. This agreed with the 3 to 4 percent reported by Johnson (ref. 7).

Photographic radiometry is useful for measurements with about 20-percent accuracy; therefore, the total possible error in measuring the spectral irradiance of the moon should be on the order of 30 to 50 percent. The spectral irradiance of the moon at wavelengths shorter than 3200 Å can be determined relative to measurements between 3200 and 4000 Å using ground-based measurements to establish an absolute scale. Ideally, this could reduce the possible error by a factor of 2.

Manned Spacecraft Center
National Aeronautics and Space Administration
Houston, Texas, July 11, 1967
923-50-10-06-72

TABLE I. - SUMMARY OF RECENT ULTRAVIOLET LUNAR ALBEDO MEASUREMENTS

[From ref. 10 and Gemini experiment D-4-7]

Wavelength, Å	Albedo	Source
2200	$\left(5.8 {+7.1 \atop -1.5}\right) \times 10^{-3}$	Ref. 10
2260	8.7×10^{-3}	D-4-7
2300	7.8×10^{-3}	D-4-7
2400	9.5×10^{-3}	D-4-7
2400	$(1.1 \pm 0.4) \times 10^{-2}$	Ref. 10
2500	1.6×10^{-2}	D-4-7
2600	1.8×10^{-2}	D-4-7
2700	1.6×10^{-2}	D-4-7
2740	$(8.6 \pm 3.5) \times 10^{-3}$	Ref. 10
2800	1.7×10^{-2}	D-4-7
2900	1.8×10^{-2}	D-4-7
2910	$(9.5 \pm 3.7) \times 10^{-3}$	Ref. 10
3000	1.6×10^{-2}	D-4-7
3050	1.7×10^{-2}	D-4-7

REFERENCES

1. Kuiper, G. P.; and Middlehurst, B. M., eds.: Planets and Satellites. Vol. III. University of Chicago Press (Chicago), 1961, pp. 214 and 306-309.

2. Johnson, Francis S., ed.: Satellite Environment Handbook. Second ed., Stanford University Press (Stanford, Calif.), 1965.

3. Johnston, R. G.; and Madden, R. P.: On the Use of Thermopiles for Absolute Radiometery in the Far Ultraviolet. Appl. Optics., vol. 4, no. 12, Dec. 1965, pp. 1574-1580.

4. Johnson, F. S.; Watanabe, K.; and Tousey, R.: Flourescent Sensitized Photomultipliers for Heterochromatic Photometery in the Ultraviolet. J. Opt. Soc. Am., vol. 41, no. 10, Oct. 1951, pp. 702-708.

5. Stair, Ralph; Johnston, Russell G.; and Hallbach, E. W.: Standard of Spectral Radiance for the Region of 0.25 to 2.6 Microns. J. Res. Natl. Bur. Std., vol. 64A, no. 4, July-August 1960, pp. 291-296.

6. Instructions for Using the NBS Standards of Spectral Radiance. Revised February 21, 1961. Available from Natl. Bur. Std.

7. Johnson, F. S.: Spectral Radiance of the Carbon Arc from 1900 to 2500 Ångströms. J. Opt. Soc. Am., vol. 46, no. 2, Feb. 1956, pp. 101-103.

8. Staff of the Nautical Almanac Office: American Ephemeris and Nautical Almanac. G.P.O. (Washington, D.C.), 1967.

9. Stair, Ralph; and Johnston, Russell: Ultraviolet Spectral Radiant Energy Reflected from the Moon. J. Res. Natl. Bur. Std., vol. 51, no. 2, Aug. 1953, pp. 81-84.

10. Carver, J. H.; Horton, B. H.; and Burger, F. G.: Rocket Determination of the Night Ozone Distribution and the Lunar Ultraviolet Flux. Weapons Res. Est., Dept. of Physics, University of Adelaide (Australia), 1965.