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DESIGN AND CALIBRATION OF FAR-UV PHOTOMETERS FOR ROCKET USE

by

C. B. Opal

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Preface

This laboratory has been concerned with the calibration and associated circuitry for photomultipliers used in scientific rocket instrumentation. This report describes some of the techniques used for far ultraviolet (1050-1900 A) photomultipliers. The methods described here were used and partially developed by C. B. Opal as part of his research. This report is based on part of his Ph.D. thesis.

H. W. Moos

1. Introduction

Many of the sounding-rocket experiments performed by this laboratory involve measurements of far-ultraviolet emissions from planets, stars, and the upper atmosphere. Spectral resolution has been achieved through the use of filterwheels,[1] grating spectrometers,[2] and prism spectrometers.[3] The detectors used with these instruments have been photometers with Types 541G, 542G, and 641G photomultipliers (manufactured by Electro-Mechanical Research). Methods of processing the photomultiplier outputs and of calibrating the photometers are the subject of this report

2. General description of G-tubes

Types 541G, 542G, and 641G are rugged, compact photomultipliers designed specifically for rocket and satellite applications.[4] All have lithium fluoride windows, cesium iodide photocathodes, and electron multipliers with 18 venetian-blind dynodes. The window and cathode materials are chosen to maximize sensitivity between 1050 and 1800 A. Because of the high work function of CsI, thermal emission from the cathode is extremely low (on the order of one electron per sec), and the sensitivity of the cathode drops sharply above 1800 A, which is important when discrimination against long-wavelength scattered light is desired. High-work function dynodes of silver-magnesium are used to preserve the low-dark current and long-wavelength insensitivity characteristics of the cathode. The secondary-emission efficiency of these dynodes is rather low, so more multiplier stages and higher dynode voltages than commonly used with visible-sensitive tubes are required. Current gains of 10^6 can usually be obtained with 3000 v across the dynode string. Large-value dynode dropping resistors (4 mΩ) are used for low power consumption; this limits the maximum usable anode current to a few microamperes.

The three types of photomultipliers differ primarily in their arrangements of windows and cathodes. Types 541 and 542 are end-on tubes with semi-transparent photocathodes deposited on the insides of the windows; the diameter of the cathode is 1 cm on the 541 and 2.8 cm on the 542. Type 641 is a side-window tube, with an opaque cathode deposited on the inner wall of the tube opposite a window 1 cm in diameter. The opaque cathode gives a sensitivity typically three times higher than the semi-transparent type. The choice of tube is generally dictated by practical considerations, such as the required cathode area and convenience of mounting.

3. Processing the anode signal

The photomultiplier output must be processed in a way which is compatible with rocket telemetry restrictions and which provides the highest possible signal-to-noise ratio. Two basically different methods can be used. The first is to meter the anode current with an electrometer and to telemeter a voltage proportional to the current (or, perhaps, the logarithm of the current). The second is to count individual electron cascades and to telemeter an analog or digital representation of the counting rate. The relative merits of the two methods are discussed below. To a large extent the following discussion applies to any photomultiplier with characteristics similar to those of G-tubes.

The signal-to-noise ratio achieved by any detection system is ultimately limited by shot noise, which results from the discrete nature of the photon detection process. For mathematical convenience in the following discussion, signal-to-noise ratios will be expressed in units of energy, rather than in more conventional units of voltage. The best possible ratio of signal energy to noise energy obtainable at the output of a photomultiplier is given by quantum statistics as QN, where N is the total number of photons incident on the photomultiplier window during the measurement and Q is the quantum efficiency (the mean fraction of incident photons which initiate electron cascades). The dark current of G-tubes is so low that it seldom affects the signal-to-noise ratio; consequently, it will be ignored in the following discussion. In order to calculate the efficiency of a given system, it is necessary to know the amplitude distribution of the electron cascades. The distribution for G-tubes, as measured by Rome[5] and as confirmed in this laboratory, is

$$P(\alpha) = \frac{1}{\bar{g}} e^{-\alpha/\bar{g}} \qquad (3.1)$$

where $P(\alpha)$ is the probability of a pulse containing α electrons and $\bar{g}$ is the mean number of electrons in a pulse. This relation was found to hold to an accuracy of a few per cent over the range $0.1\,\bar{g} < \alpha < 10\,\bar{g}$. At lower levels, noise in the pulse-height analyzer obscured the photomultiplier pulses, and at higher levels accuracy was limited by the possibility that several pulses might occur within the resolution time of the analyzer. For purposes of the following computations, it will be assumed that Equation 3.1 holds for all pulse heights.

The anode current for this pulse-height distribution will be

$$\bar{I} = QNq \int_0^\infty \alpha P(\alpha) d\alpha$$

(3.2)

$$= QNq \int_0^\infty \frac{\alpha}{\bar{g}} e^{-\alpha/\bar{g}} d\alpha = QN\bar{g}$$

where q is the electron charge.

For a current pulse of α electrons and normalized shape i(t), the energy spectrum will be given by[6]

(3.3) $$E(f,\alpha) = \int_{-\infty}^{\infty} e^{-2\pi ift} \int_{-\infty}^{\infty} \alpha q i(t') \alpha q i(t-t') dt' dt$$

$$= q^2 \alpha^2 I(f)$$

where I(f) is the energy spectrum of the normalized shape. The spectrum of the anode current can be found by averaging over pulse heights:

(3.4) $$\bar{E}(f) = QN \int_0^\infty q^2 \alpha^2 I(f) P(\alpha) d\alpha$$

$$= QNI(f) \int_0^\infty q^2 \frac{\alpha^2}{\bar{g}} e^{-\alpha/\bar{g}} d\alpha = 2 q^2 \bar{g}^2 QNI(f)$$

The least noise would result if all pulses had the same height, $\bar{g}$, in which case the noise spectrum would be given by

(3.5) $$\bar{E}(f) = QND(f,\bar{g}) = q^2 \bar{g}^2 QNI(f)$$

The efficiency of the current measuring technique is thus

(3.6) $$\eta = \frac{q^2\bar{g}^2 QNI(f)}{2q^2\bar{g}^2 QNI(f)} = 0.5$$

The full 100% efficiency could be realized by counting all electron cascades. In practice, because of noise limitations, it is possible to count only cascades that contain more than α_o electrons. The expected number of counts in this case is

(3.7) $$N' = QN\int_{\alpha_o}^{\infty} P(\alpha)d\alpha$$

$$= QN\int_{\alpha_o}^{\infty} \frac{1}{\bar{g}} e^{-\alpha/\bar{g}} d\alpha = QNe^{-\alpha_o/\bar{g}}$$

and the efficiency of the system is

(3.8) $$\eta = \frac{N'}{QN} = e^{-\alpha_o/\bar{g}}$$

Typical values of α_o and $\bar{g}$ are 10^5 and 10^6, so that efficiencies of 90% or more can be obtained with practical pulse counting circuitry.

In addition to an improvement in signal-to-noise ratio, the photon counting method has several practical advantages over the current measuring method. The gain of a typical G-tube is approximately proportional to the 9th power of the volage, V, across the dynode string. Taking the derivative of Equation 3.2

(3.9) $$\frac{d\bar{I}}{\bar{I}} = 9\,\frac{dV}{V}$$

whereas in the photon counting method, taking the derivative of Equation 3.7

(3.10) $$\frac{dN'}{N'} = \left(\frac{\alpha_0}{\bar{g}} \right) 9 \frac{dV}{V}$$

An additional source of instability has been introduced through possible variations in the setting of the parameter α_0, but again from Equation 3.7

(3.11) $$\frac{dN'}{N'} = \left(\frac{\alpha_0}{\bar{g}}\right) \frac{d\alpha_0}{\alpha_0}$$

Thus a reduction in sensitivity to gain changes by the factor $\alpha_0/\bar{g}$ is achieved through the use of the photon counting method. Another important practical advantage of this method is that the anode can be A.C. coupled to the measuring circuits, which not only eliminates problems of zero drift but also allows the tube to be operated with the cathode at ground potential. On some tubes it has been found that when the cathode is at the full negative high voltage, field distortions or static-charge buildups occur; these modify the collection efficiency of the electron multiplier, resulting in a non-linear response and as much as a two-fold reduction in sensitivity. On newer tubes, a thin, conducting nickel film is deposited over the cathode and nearby walls in an attempt to overcome this effect; nevertheless, better performance has always resulted when the tube is operated with the cathode grounded. A second problem is corona discharge through the window, which can occur at ambient pressures in the 0.1 Torr range when the cathode is at high voltage. Although the discharge does not destroy the tube, it deposits contaminants on the window, reducing the sensitivity, and causes a large increase in dark current which persists much longer than the duration of a rocket flight.

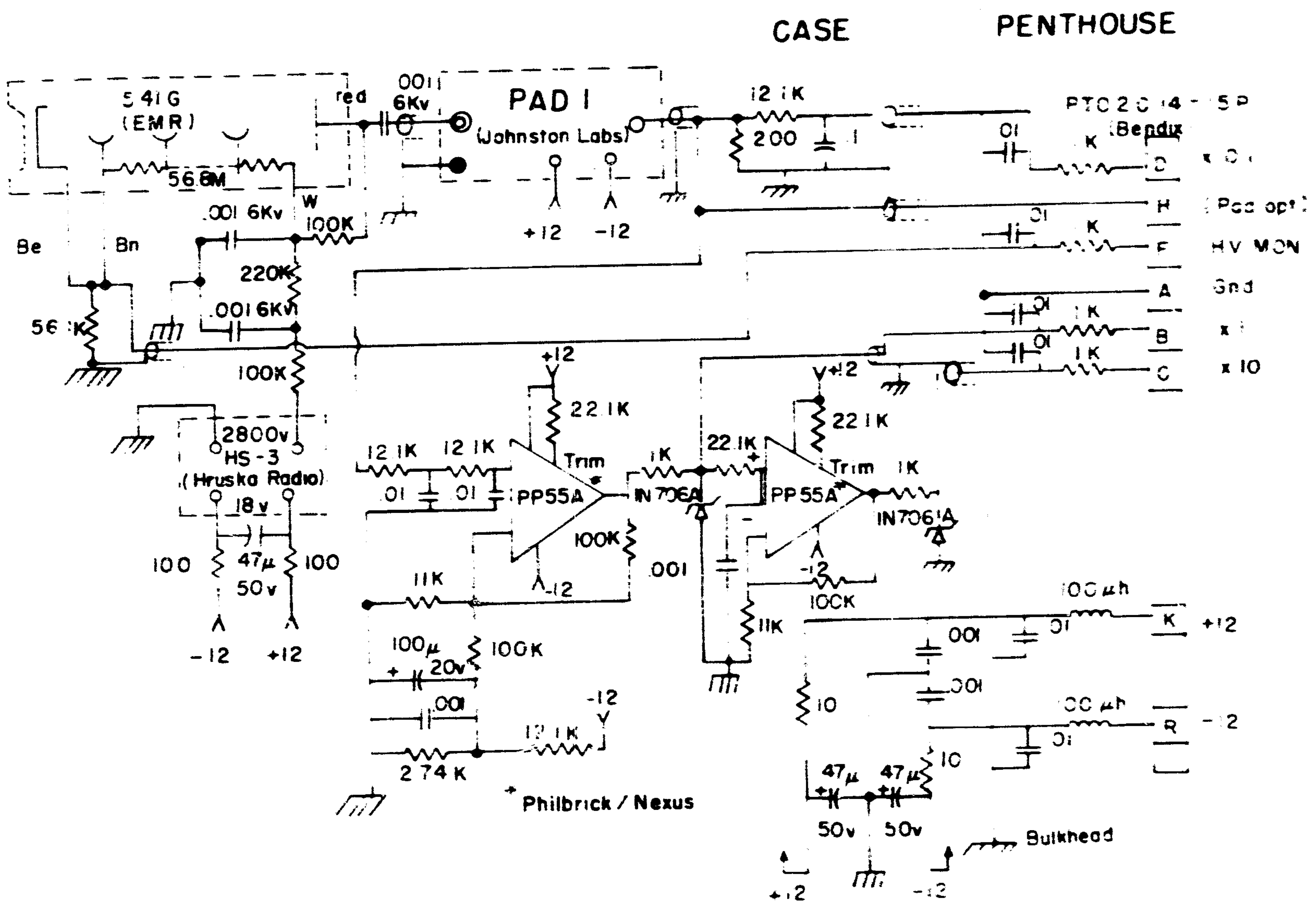

Figure 1. Schematic diagram of pulse-counting photometer. Resistances are in ohms, capacitances in microfarads.

Electrometer-amplifier detection systems have been used at this laboratory for many years.[2] With high-gain amplifiers, it is possible to count individual photoelectron bursts on the telemetry records, but because of the slow response of electrometers this counting technique is applicable only at flux levels corresponding to a few tens of photoelectrons per sec. Many small pulses are lost in noise, so that the efficiency achieved by this method is rather low. The use of an electrometer requires that the anode be at ground potential, and the problems associated with having the cathode at high voltage remain. Cathode arcing can be avoided by turning the high voltage on only after outgassing of the payload is complete, but this introduces additional complications in requiring a timer and corrections for drifts of gain and dark current, which persist for half a minute after the high voltage is turned on.

The schematic diagram of a photometer system specifically designed for photon counting is shown in Figure 1. This photometer, which was successfully flown as the detector on an Aerobee rocket astronomical experiment,[3,4] uses a 541G. A similar dual photometer with 641G-tubes has been flown twice, also successfully. The cathode of the photomultiplier is grounded, and the photoelectron bursts are coupled through a D.C. blocking capacitor into the low-impedance input of a pulse amplifier and discriminator (PAD) manufactured by Johnston Labs. Inside the PAD, an incoming photoelectron burst charges up a 10 pf capacitor in the feedback path of a high-speed (500 Mc) amplifier. The capacitor is quickly discharged through a 1000 Ω resistor;

the result, for an input burst of 10^6 electrons, is a pulse about 10 ns long and 10 mv high. The pulse is amplified and compared with an adjustable reference voltage. If the amplitude of the pulse exceeds the reference level, it passes through another amplifier and triggers a one-shot multivibrator, which delivers a standard pulse about 5 v high and 1 μsec long to the output load. The discriminator reference level is normally set to trigger for input bursts of more than 10^5 electrons. Under these conditions noise in the preamplifier will not trigger the discriminator, but some care is necessary to make sure that spurious counts are not generated by transients or r.f. in nearby wiring. A short (5 cm or less) lead from the anode to the PAD input is mandatory. The photomultiplier, high-voltage supply, and PAD are mounted in a tightly shielded housing. All leads from the housing are decoupled, with resistor-capacitor networks on high-impedance signal leads and inductor-capacitor networks on low-impedance power wiring. A network consisting of a 68 Ω resistor and a 0.001 μf bypass capacitor is installed inside the PAD case in series with its output lead.

The PAD output pulses are directly compatible with digital-counting circuitry, but must be processed for transmission on a telemetry channel. The largest bandwidths available on analog telemetry channels are about 1 kc, so that the 5 v·μsec PAD-output pulse would be stretched to a 5 mv·msec pulse after transmission and would be lost in noise. The schematic of a pulse stretcher and amplifier which shapes the pulses suitably for transmission on IRIG FM/FM telemetry subcarrier channels higher than 10 kc is included in Figure 1. The PAD output pulses are stretched in a double R-C filter with a 120 μsec time constant and fed through two amplifiers, each with a gain of ten (a double-pole filter is necessary to prevent overshoot introduced by the high-frequency response of the amplifiers). A small D.C. offset of -0.18 v, determined by a precision resistor divider, is present at the output of every PAD unit; this is balanced out by a voltage divider at one of the inputs of the first amplifier. Zener diodes limit the maximum amplifier output voltages to 5.6 v, and additional decoupling capacitors prevent self-oscillation of the amplifiers (which can occur if long input leads are used). Only the high-gain (X 10) output is used for photon counting and, on a 70 kc subcarrier, it produces pulses that are 1 v high and less than 1 msec long. As many as 1000 pulses per sec can be counted on 40 inch per sec telemetry records. At higher counting rates the mean PAD output voltage, which has been calibrated against counting rate, is measured on the low-gain (X 1 and X 0.1) channels.

A disadvantage of the amplifier-discriminator method of photon counting is dead time in the discriminator. The true counting rate, n, can be obtained from the dead-time formula

$$n \approx n'/(1 - n'\tau) \qquad (3.12)$$

where n' is the observed counting rate and τ is the dead time, which is about 1.25 μsec for the PAD unit described above. This formula does not apply exactly to the D.C. output of the PAD, because the main output pulse is followed by a 1 μsec tail containing about 20% of the area of the main pulse; the discriminator can be re-triggered during the tail and part of the pulse area thereby lost. In order to achieve high accuracy, it is necessary to calibrate the system against a linear detector. The required corrections to Equation 3.12 are negligible at counting rates below 10^5 per sec.

The use of extremely high photomultiplier gains with the photon counting system can lead to problems. For example, at an operating voltage of 3300 v, individual amplified output pulses from one channel of the dual 641G photometer were found to be non-uniform in height. The particular tube used had an abnormally high gain (10^7) at 3300 v; approximately 10% of the current pulses from this tube produced double triggering of the discriminator and a larger-than-normal pulse. It was not determined whether this was caused by overload in the PAD unit or by afterpulsing in the photomultiplier because of regenerative effects.

It is desirable to use as low a photomultiplier high voltage as possible in order to avoid the possibility of multiple counting, as well as for practical reasons such as reduced insulation requirements and power consumption. Similarly, the highest possible discriminator level should be used because triggering of the PAD by external interference or by dark-current pulses originating from the dynodes increases rapidly as the discriminator level is lowered. A proper compromise setting for these variables can be found in the following manner. An arbitrary discriminator level is chosen and the counting rate is measured at several values of the high voltage. As is evident after taking the logarithm of Equation 3.7

(3.13) $$\ell n\ N' = \ell n\ QN - \alpha_0/\bar{g}$$

the ultimate counting rate can be found by plotting the logarithm of N′ against the reciprocal of the current gain $\bar{g}$ and extrapolating to infinite gain. The ultimate combination of high voltage and discriminator level should be chosen so that at least 80% of the ultimate counting rate is achieved.

4. Calibrating the photometer

Most applications require a calibration of the sensitivity of the photomultiplier detector system as a function of wavelength. Methods for determining the far-ultraviolet flux on the face of the photomultiplier and physical factors which influence the final calibration are the subjects of this section.

Standard far-ultraviolet intensity sources suitable for laboratory use are not available; consequently, it is necessary to calibrate the photometer system against a detector of known sensitivity. Thermopiles calibrated in the visible against a standard lamp cannot be used, because the photon fluxes required for a usable output signal from a thermopile are greater than 10^7 per sec,[7] well beyond the range of most photomultiplier detection systems. The calibration procedure used at this laboratory is first to determine the absolute sensitivity of the photometer at 1216 A by comparison with an ion chamber of known yield, and second to determine the relative sensitivity at other wavelengths from a comparison with the yield of a fluorescent film having a nearly constant ultraviolet-to-visible photon conversion efficiency.

The 1216 A reference detectors used are sealed nitric oxide cells of the type described by Stober et al.[8] and manufactured by Melpar. These are particularly convenient for comparisons with standards at other laboratories. After an aging period the cells are quite stable, barring sudden undetected changes in sensitivity resulting from window contamination. The window problem also applies to photomultipliers, and will be discussed in greater detail below. In order to have an independent and reproducible standard a flowing-gas ionization chamber, similar to that described by Samson[9] but with the addition of a removable window, has been constructed. The photoelectric yield (ratio of ions produced to photons absorbed) of NO at 1216 A has been determined by Watanabe et al.[10] to be 0.81, and NO is the filling used by most workers. The yields of methyl iodide and carbon disulfide have not been determined as accurately, but may be close to 1.0, and in any case these gases are less corrosive than NO. With a filling of CH_3I, agreement with standards at other laboratories has been achieved by assuming an efficiency of 0.90 for our chamber, but possible errors introduced by impurities in the filling gas, window adsorption, and incomplete capture of ions have not yet been thoroughly investigated. The accuracy of the absolute calibrations at present is, at best, ± 25%, but this is adequate for many purposes.

Relative sensitivity calibrations are made by comparisons with the fluorescence yield of sodium salicylate films. Various workers have found, from comparisons with thermopiles, that the ultraviolet-to-visible photon conversion efficiency of salicylate is nearly independent of wavelength between 1000 and 2500 A, although there are some indications that there is a 20% rise in yield above 1300 A. Loss in sensitivity of the film after extended exposure to vacuum or intense illumination has been reported. The results of these experiments have been reviewed by Samson[11] and Shreider.[12] No differences greater than 20% in relative or absolute yield between fresh films and those over a year old have been observed in this laboratory when the films are prepared as described below.

To prepare the sodium salicylate films, a piece of microscope slide is cleaned in potassium dichromate-sulfuric acid solution, in distilled water, and finally in anhydrous methanol; it is then clamped under the warm-air exhaust of a portable hair dryer. A freshly prepared solution (50% saturated) of sodium salicylate is deposited on the slide with a chromatograph spray. The density of the spray is kept low so that the droplets will dry immediately on contact with the slide; spraying is continued until a uniform, translucent film of about 3 mg of salicylate per cm^2 is produced. The slide is mounted in a holder which is attached near the face of a 541N photomultiplier manufactured by EMR. The sensitivity of this combination is only about 10% of that of a good G-tube, but the signal-to-noise ratio is high enough to permit accurate measurements.

The accuracy of the relative quantum efficiency measurements is essentially determined by uncertainty in the flatness of the sodium salicylate response, which may increase as much as 25% over the 1050 to 2500 A range.

Calibrations are performed with a McPherson one-meter normal-incidence monochromator or a laboratory version of the half-meter Ebert monochromator designed by Fastie[2] for rocket use. Some care with the baffling of these instruments is required to eliminate long-wavelength scattered light, to which the sodium salicylate is sensitive. Stable lamps with a continuous output are necessary for comparing detectors and determining linearity. The lamp most used is a D.C. capillary discharge in flowing hydrogen gas. This lamp produces the many-lined H_2 spectrum, which is useful for relative sensitivity calibrations. The lamp is operated at pressures near 1 Torr at a current of 50 ma. After a warm-up period of about an hour, the lamp output is stable to 5% per hour at all wavelengths in the far ultraviolet. High-intensity microwave-excited lamps of the type described by Wilkinson and Byram[13] are also used. These are sealed lamps filled with noble gases at pressures near 400 Torr and, depending on the gas filling, produce continua in various parts of the 1100 to 1900 A range. A small Raytheon diathermy machine running at 50 w output is used as the power source. A particularly useful version of this lamp is unsealed and runs on flowing commercial grade helium; though not particularly stable, the lamp produces intense, well-isolated resonance lines of carbon, nitrogen, oxygen, and hydrogen, which are convenient for making scattered light measurements and for determining residual transmissions of filters.

Several factors influence the reliability of the final photometer calibration. As discussed earlier, the electrostatic field geometry in the vicinity of the cathode can have a strong influence on the sensitivity, and it is best to perform calibrations in the final flight housing. The extent of irregularities in cathode sensitivity can be determined with the use of the isolated Ly α line from the helium lamp described above. The vertical exit slit of the monochromator is opened wide and masked down parallel to the horizontal plane. The resulting small Ly α spot can be scanned across the tube window with the wavelength drive. Irregularities of 25% in the space of a few millimeters were observed on one 541G with this technique. In situations involving critical geometries or small illuminated areas, only tubes with uniform cathode response should be used. In any case, the geometry of the calibrating illumination should be similar to that expected in flight.

Anomalous behavior at long wavelengths (2537 A) has been experienced, particularly with tubes having abnormally high long-wavelength responses. Under illumination sufficiently intense to produce a meaningful signal at these wavelengths, the photomultiplier output decays in amplitude with a time constant of several seconds. Whether this is due to thermal effects or to photochemical processes involving impurities in the cathode material has not been determined; in any case, calibrations of G-tubes at wavelengths above 2000 A are usually unreliable.

The factor that introduces the greatest uncertainty in the final calibration of the photometer is the possibility of window contamination on the photomultiplier. The effect of contamination is more pronounced at 1216 A, where the sensitivity can drop by a factor of two, than at 1600 A, where changes are usually less than 25%. As suggested by Mr. Gilbert Fritz of the Naval Research Laboratory, the short-wavelength sensitivity can be restored by lightly polishing the window with fine sapphire powder, but the sensitivity often deteriorates again within a few days.

Tests were performed on an old tube to determine whether laboratory hazards were the cause of the deterioration. Cigarette smoke blown at the window had no short-term effect; neither did soldering flux from a hot iron. A drop of Convalex 10 diffusion pump oil produced the expected deterioration, which persisted even after the window was cleaned with Freon. The original sensitivity was restored after repolishing. Drops in sensitivity are not correlated with length of exposure to the vacuum systems used in this laboratory, which run on this oil. However, other oils deposited on the window, perhaps from fingerprints or residual machine oil on the housing, could have similar effects. Longer-term degradations, such as those which would result from corrosion of the window by chemicals dissolved in adsorbed water, have not been investigated. The best procedure for maintaining window transmission at a constant level appears to be the following: polish the windows of new tubes to remove contaminants deposited during the manufacturing process, and then allow the window transmission to stabilize by maintaining the tube for several weeks in an environment similar to payload storage conditions.

5. Summary and conclusions

The relative merits of anode-signal processing by photon counting and current measuring techniques have been discussed. The advantages of photon counting, as applied to G-tubes, are 1) nearly two-fold improvement in signal-to-noise ratio, 2) more convenient processing of low-level signals on analog telemetry channels and direct compatibility with digital telemetry systems, 3) greatly reduced sensitivity to changes in tube operating conditions, 4) elimination of zero drift, and 5) compatibility with operation of the cathode at ground potential, thereby improving linearity and sensitivity and eliminating problems of window arcing. The advantages of current measuring are 1) less sensitivity to electrical interference and 2) better capability for handling large signals. In nearly all applications the photon counting method is preferable. A rocket photometer system implementing the photon counting method has been described.

The far-ultraviolet calibration procedure used in this laboratory has been described. The procedure is reproducible and yields absolute accuracies of about ± 35%. Several factors can introduce errors in the calibration. The photomultiplier sensitivity depends on shielding conditions near the cathode area, the cathode response is not always uniform, and large temporal changes in window transmission can occur. With proper care, however, most problems associated with the use of G-tubes can be avoided, and a reliable, reasonably well-calibrated far-ultraviolet photometer system can be constructed with the use of these photomultipliers.

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