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NOISE IN MULTIPLIER PHOTOTUBES

E. H. Eberhardt

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ABSTRACT

Various types of noise encountered in multiplier phototubes are discussed, with emphasis on the non-dark noise generated by the internal photoemission and secondary emission processes. Suitable measurement techniques are described, with test results given in terms of the effective loss of cathode sensitivity and quantum efficiency, for a series of ITTIL tubes, including S-1, S-11 and S-20 varieties. The test results tend to confirm the Shockley-Pierce multiplier noise theory, but substantial deviations are observed.

INTRODUCTION

Depending on the specific tube, its selected mode of operation and the detection application involved, the ability of a multiplier phototube to detect input radiation during a given time interval may be determined by any one of the following noise sources:

a. Monitoring circuit dark noise.

b. Tube dark noise.

c. In single quantum-electron counting operation, the probability of having no output signal quantum event count during the observation time interval.

d. Environmentally determined intensity fluctuations of any background flux present, and of the signal flux itself to be detected.

e. The inherent random quantum fluctuations of any background flux present, and of the signal flux to be detected, combined with the internal noise generating properties of the subsequent tube conversion and multiplication processes.

Failure of a prospective multiplier phototube user to fully consider each of these several possible detection-interfering factors in any given application may lead to entirely erroneous conclusions regarding the expected detection capability.

Monitoring circuit dark noise for most multiplier phototube applications can be made entirely negligible. The high internal charge amplification available in properly operated electron multipliers and their ability to deliver the resultant amplified output charge to a suitable choice of load impedance, leads to a situation in which the minimum possible signal level, a single emitted photoelectron from the photocathode, produces a large, readily detected output signal, of the order of 10^5 to 10^7 electrons in the load impedance, normally exceeding monitoring circuit dark noise charge fluctuations. This advantageous characteristic is in marked contrast to radiation detectors without high internal charge amplification for which the single electronic charges, or group of a few charges carrying the signal information can never hope to be fully distinguishable experimentally from the dark noise fluctuations of the load impedance electrons (Johnson noise) and other monitoring circuit dark noise.

Residual, dark noise fluctuation of the output power from the detector proper with no incident radiation present is found, of course, in multiplier phototubes as in all radiation detectors. Following IEEE recommendations[1] the dark noise limited performance is conveniently specified in terms of the peak-to-peak value of a square-wave-modulated input flux yielding an rms signal output power just equal to the output dark noise power in a specified noise bandwidth, usually 1 cps, a parameter called the equivalent noise input or ENI. Alternatively, in single electron counting applications the performance may be specified[2] in terms of the input flux yielding an output signal count in a given time interval, usually 1 second, just equal to the statistical uncertainty in the dark count. A commonly encountered, and yet apt-to-be-misleading evaluation of the detection properties of multiplier phototubes, is based on the measured magnitude of the d-c dark current output, or more properly on the input d-c flux level equivalent to this d-c dark current. Although this "equivalent anode dark current input", per se, may be of some significance in certain detection applications, the fluctuation, of this dark current, which constitutes the ENI measured at appropriately low test frequencies, instead of the d-c level, is more likely to be the significant factor in the majority of applications.

When operated in the single quantum-electron counting mode of operation described elsewhere by the author[2] and by others[3], multiplier phototubes are restricted in their ability to detect input flux by the necessity of having at least one output quantum event count during any given observation time interval, entirely independent of all other signal-interfering factors. Even if all other noise sources were totally eliminated, this restriction would establish the lowest radiation detection level possible. Restrictions of this type are, of course, common to all single quantum event counters, such as Geiger tubes, spark chambers, cloud chambers, multiplier phototube-scintillator crystal nuclear counters, solid-state nuclear particle detectors, as well as multiplier phototubes in the single quantum-electron counting mode. The ability of multiplier phototubes in this latter mode to count single quantum events at energies as low as the 1 to 3 electron volt region characteristic of photocathode sensitivities is particularly noteworthy.

In certain detector applications a multiplier phototube may be subjected to a background flux incident on the photocathode simultaneously with the signal flux to be detected, with intensity fluctuations of this background flux present as a result of uncontrolled environmentally-determined parameters, such that the correspondingly non-constant output current interferes with the detection of the input signal flux. Similarly, if some property of the signal input flux itself, such as intensity, time-of-arrival, etc. is to be measured, any non-constant properties of the signal flux may interfere with the desired measurement. By considering the signal flux property-measuring problem as being equivalent to the detection of a small increment of radiation, within some given intensity level or time-of-arrival, in the presence of a residual signal flux, it can be seen that both types of interfering fluctuations are conceptually identical. Environmentally-determined fluctuations of this type may occur experimentally entirely independently of the inherent quantum character of the input radiation, well known experimental examples being the night sky radiation fluctuations and familiar twinkling of atmosphere-transmitted stellar radiation, noted by Baum[4], and the fluctuating atmospheric refraction effects observed in laser beam transmission systems.

Even though the above environmentally determined intensity fluctuations were to be totally eliminated, the inherent quantum fluctuations of both the background flux and of the signal flux itself will remain. These fluctuations, combined with the associated noise-generating conversion and charge multiplication processes within the multiplier phototube, may establish the detection ability in many practical applications. Again following IEEE terminology[1] the resultant output current fluctuations for any constant, unmodulated input flux, either background or signal-generated, will be called "noise-in-signal". Noise-in-signal can be readily distinguished from monitoring circuit noise and tube dark noise by the fact that it is not present when no flux, within the spectral wavelength region exciting photoemission from the photocathode, is allowed to fall onto the photocathode. Unlike detectors sensitive to ambient temperature radiation, this test condition can be readily established in multiplier phototubes by the use of an optically opaque mask. For tubes with S-1 type photocathodes, which may be slightly sensitive to the 300 degrees K ambient temperature radiation of the mask, this excitation noise is normally included in the tube dark noise.

A number of important examples of multiplier phototube applications detection-limited by noise-in-signal may be noted. These include: (1) the detection of the flux output from flying spot scanner illumination, where the quantum statistical fluctuations of the instantaneous illumination signal level and subsequent tube-generated noise interferes with the ability to detect image illumination changes, (2) image scanning with deflectable multiplier phototubes, i. e. electronic image dissectors,[5] where a similar statistical fluctuation situation occurs, (3) tracking or acquisition of stars and other flux-radiating objects against a non-dark background, (4) demodulation of optical communications information in the presence of stray light and of the quantum fluctuations of the information-transmitting beam itself, and (5) optical radar systems in the presence of stray background illumination. In each of these applications, the fluctuations from the background flux present or from the signal flux itself to be detected can be expected to establish the limiting capability to detect or measure the radiation, if suitable low dark noise tubes and circuits are selected.

The fact that such non-dark-noise-related parameters as noise-in-signal, or the lack of generating a single quantum event count during a given observation time can establish the limiting ability of multiplier phototubes follows from the low absolute dark noise levels which have been achieved, with ENI values as low as 100 quanta/second (approximately 10^{-17} watts) of 4500 Å radiation, equivalent to approximately 10^{-13} lumens of 2870 degrees K radiation onto an S-20 type photocathode, having been reported.[2] For such detectors, unlike the majority of solid-state varieties, dark noise may not be the detection or measurement limiting parameter in certain applications, particularly those for which the signal information must be extracted in a short interval of time (typically a few milliseconds or less in the examples noted above).

When a detector is, in fact, noise-in-signal or event-generation limited, no noise-in-signal-based ENI specification or related detectivity[6] rating can be assigned and no direct comparison with detectivity-rated solid-state detectors can be made until a particular input flux level, generating the noise-in-signal, has been determined by the user.

NOISE-IN-SIGNAL PRINCIPLES

When estimating the over-all noise-in-signal generating properties of multiplier phototubes, the generally accepted procedure has been to assume that the photocathode generates noise current according to:

$$I = F S \tag{1}$$

and

$$i^2 = 2 e I \Delta f \tag{2}$$

where F = input flux

S = photocathode sensitivity ratio, defined in Fquation 1

I = average photoemission current corresponding to F

e = electronic charge

i = rms noise-in-signal component of I

Δf = noise measurement bandwidth

and that the multiplier generates excess noise according to the noise ratio, k, derived by Shockley and Pierce[7] and discussed by Spangenberg,[8] where:

$$k = \frac{Mm - 1}{M(m - 1)} \cong \frac{m}{m - 1} \quad \text{for } M \gg m \tag{3}$$

and M = signal current gain of the multiplier

m = average gain per stage

and $(k)^{1/2}$ is the ratio by which the output noise-in-signal current exceeds the product of the noise-in-signal current at the input to the multiplier and the current gain, M, of the multiplier.

While these relationships, Equations 1 - 3, according to Jones[9] have been reasonably well established as being characteristic of the ultimate limiting performance of multiplier phototubes, they do not include any excess noise-in-signal generating properties. Predictions of possible sources of excess noise-in-signal may be conveniently based on the statistical quantum event characteristics of the multiplier phototube, or, more specifically, on the following two possibilities (1) that the output charge delivered to the anode circuit for each interacting input quantum fluctuates more widely in magnitude than the Poisson-derived Shockley-Pierce theory predicts, or (2) that delayed bursts of charge of similar magnitude maybe internally triggered in addition to those directly generated by the input quanta. Among the most readily predictable of these excess noise-in-signal generating sources would be:

a. A non-uniform gain/stage distribution of the dynodes of the electron multiplier.

b. Uncontrolled insulator surface charging leading to changes in the electron trajectories, and subsequent gain changes in the electron multiplier.

c. Delayed or "secondary" photoemission from the photocathode or other tube components produced by fluorescent radiation, visible, ultraviolet or soft X-ray, generated by electrons bombarding various internal tube surfaces.

d. Loss of photoelectrons between the photocathode and the first stage of the electron multiplier.

e. Gas ionization, producing added input charge to the electron multiplier, or added electron emission from the photocathode by positive ion bombardment.

f. Indeterminant numbers of "stages" of multiplication as in continuous electron multipliers[10, 11] or bypassing of individual dynode stages.

g. Non-Poissonian statistical behavior[12] of the basic secondary emission process in the electron multiplier.

h. Time-delayed "secondary" electron emission, or, what might be described as non-self-sustained Malter[13] emission.

i. Multi-electron emission at the photocathode, one input quantum generating more than one electron, or a time-coincident group of quanta, as from scintillators and phosphors, generating a corresponding time-coincident group of electrons.

In view of the possible, almost probable occurrence of one or more of these noise-in-signal-modifying processes within practical multiplier phototubes, a direct measurement of over-all noise-in-signal as opposed to a computed value based on indirect measurements is clearly desirable.

MEASUREMENT TECHNIQUES

Direct measurements of noise-in-signal have been reported by Engstrom, Stoudenheimer, and Glover[14] on RCA type 5819 multiplier phototubes, using a measurement technique later adopted[1] by the IEEE. All excess noise was expressed in terms of an effective collection efficiency for electrons leaving the photosurface and entering the electron multiplier. An empirically determined multiplier noise ratio of

$$k = 1 + \frac{1.54}{m - 1} \cong 1.51.$$

possibly applicable only to the 5819 tubes, was assumed, and the modifications necessary to convert their final relationships to other tubes or other experimental equipment are not entirely clear.

In our laboratories we have adopted a similar test procedure, but have chosen instead to express the results in terms of an effective value, k_{eff}, of the noise ratio, k, avoiding any assumptions as to the expected multiplier noise behavior. According to the basic definition of the noise ratio already noted above an effective value may be defined as:

$$k_{eff} \equiv \frac{(\text{max. signal to noise-in signal ratio available from the photocathode})^2}{(\text{measured output signal to noise-in-signal ratio})^2}$$

$$= \frac{(I/i)^2}{(I_o/i_o)^2} \tag{4}$$

where I_o is the output signal current corresponding to the photocathode photoemission current I, and i_o is the rms output noise current component of I_o corresponding to the rms cathode noise current, i, measured at the same noise bandwidth. Assuming no experimental measurement errors, the magnitude of k_{eff}, according to this definition would always be equal to or greater than unity. The noise ratio, k_{eff}, as used here is similar to, but should not be confused with the familiar noise figure or noise factor of a two-port electron device[15] based on the minimum no-signal, i.e. "dark" noise power generated by the equivalent input resistance. The noise ratio, k_{eff}, is based instead on the magnitude of the minimum noise-in-signal current (i.e. the maximum signal to noise-in-signal current ratio) generated by the photoemission process at the photocathode, a parameter whose absolute magnitude depends on the arbitrary choice of an absolute input test flux level.

Assuming that a suitable test flux level and noise bandwidth have been chosen, the two output currents, I_o and i_o, are directly and readily measureable parameters in most high gain multiplier phototubes. The corresponding maximum current ratio, I/i, available from the photocathode however, cannot, in general, be measured directly, the electron multiplication process itself usually representing the lowest noise method available for measuring this ratio. Instead, a maximum value is derived from independent cathode sensitivity measurements using average rate-of-flow methods[1] at much higher flux levels, where precautions are taken to avoid anomalous current generation during the measurement. The resultant value of the effective noise ratio, k_{eff}, will then include excess noise generation by multi-electron photoemission, as well as delayed electron emission, (if generated in the tube as a multiplier phototube but not as a diode), collection efficiency, multiplier noise, etc.

Assuming that a separate cathode sensitivity measurement has indeed been made, the maximum current ratio, I/i, may be predicted from the following combination of Equations 1 and 2:

$$(I/i)^2 = F S/2 e \Delta f \tag{5}$$

where F is the particular test flux level and Δf is the noise bandwidth at which the output current ratio, I_o/i_o, is evaluated. The effective noise ratio, k_{eff}, of the multiplier phototube is then given by:

$$k_{eff} = \frac{F S i_o^2}{2 e I_o^2 \Delta f} \tag{6}$$

where all determining parameters are either known or directly measurable.

The physical significance of the effective noise ratio, k_{eff}, can be clarified by noting, from Equations 4 - 6, that a high vacuum diode phototube with a cathode sensitivity, S/k_{eff}, would theoretically generate an output signal to noise-in-signal ratio just equal to that of the actual multiplier phototube with cathode sensitivity, S, and effective noise ratio, k_{eff}. Thus S/k_{eff} can be considered as the effective cathode sensitivity, S_{eff}, of the multiplier phototube as far as noise-in-signal generating properties are concerned, i. e.:

$$S_{eff} = S/k_{eff} \tag{7}$$

Similarly, if the response of the photocathode had originally been expressed in Equation 1 in terms of the quantum efficiency, Q, in electrons/quantum for the particular test flux, F, in quanta/second, such that:

$$I = F Q e \tag{8}$$

then an effective quantum efficiency, Q_{eff}, for the multiplier phototube would be given by:

$$Q_{eff} = Q/k_{eff} \tag{9}$$

k_{eff} is therefore a direct measure of the effective loss of quantum efficiency of the photocathode in a multiplier phototube when operated under noise-in-signal limited conditions. The effective quantum efficiency parameter Q_{eff} for multiplier phototubes corresponds to the "quantum efficiency" defined and used by Rose[16] to describe camera tubes, and to the "detective quantum efficiency" defined and discussed in detail by Jones,[9] which may be used to describe all noise-in-signal limited detectors. The equally significant roles of cathode quantum efficiency and effective noise ratio are evident from Fquation 9.

TEST EQUIPMENT

The cathode sensitivity ratio, S, in amperes/lumen, was measured with a standard 2870 degrees K tungsten lamp source at a known flux output, monitored in lumens, following IEEE recommended[1] procedures, operating the cathode of the multiplier phototube with respect to all other electrodes as a diode. The usual precautions were taken to minimize gas ionization, non-saturated photoemission, cathode fatigue, and other possible sources of measurement error. A source of this type is not expected to produce multi-electron photoemission.

Alternatively, the average emitted photocurrent, I, could have been measured directly, bypassing the need for a cathode sensitivity measurement, but this was not feasible at the test flux levels necessary to avoid space charge saturation in the anode output circuit, because of leakage currents in the cathode circuit.

The remaining measurements of output current, I_o, and rms output noise current, i_o, were made on the test equipment shown by the block diagram in Figure 1. The 10^{-7} lumen test source was also a standard 2870 degrees K tungsten lamp in order for the results to correspond directly, without the use of conversion factors, to the cathode sensitivity measurements, but any other test source could have been used provided that the product, FS, in Equation 6 were to be replaced by the emitted photocathode current. This flux was actually chopped with a simple non-synchronous rotating shutter at about 10-100 cps and the resulting square wave output voltage signal generated by the output current across an equivalent 100K ohm load resistance was observed with a calibrated d-c oscilloscope, the peak-to-peak voltage corresponding to the desired output current, I_o. Although this current could also have been observed directly with a d-c ammeter and no chopping, the technique adopted permitted a simultaneous visual check on anomalous noise behavior, both dark and noise-in-signal, as well as possible response frequency anomalies, added causes for production line tube rejection. The applied high voltage was then adjusted to give the desired anode sensitivity as evidenced directly by the observed oscilloscope peak-to-peak deflection in combination with the known load impedance and input flux level. At each test sensitivity, the chopper was stopped at an open position and the output rms noise-in-signal voltage across the same load resistance, and thus the rms output current, i_o, was measured with a calibrated rms voltmeter between the two frequencies, 5 and 1005 cps, i.e. at a noise bandwidth of 10^3 cps, established by a capacitance, C, of about 2200 pf, in combination with the 100K ohm load resistance, the stray capacitance of the test circuit, and the rms voltmeter characteristics. Noise bandwidth frequencies for simple "RC" roll-off circuits of this type occur at $\pi/2$ times the more usual "3 db" bandwidth frequencies.[17] The test flux area for the noise measurements was nominally 0.014 inch in diameter, but not too sharply defined or uniformly distributed. Tube position during test was mechanically adjusted to have this incident flux area axially centered on the effective photocathode area. For tubes with effective cathode areas less than 0.014 inch in diameter, a proportional area correction factor was applied, introducing possible error. Test area for the cathode sensitivity measurements was larger than the noise test area and ranged up to about 0.5 inch in diameter, nominally including the noise test area, so that inhomogeneities in cathode response would be expected to cause errors.

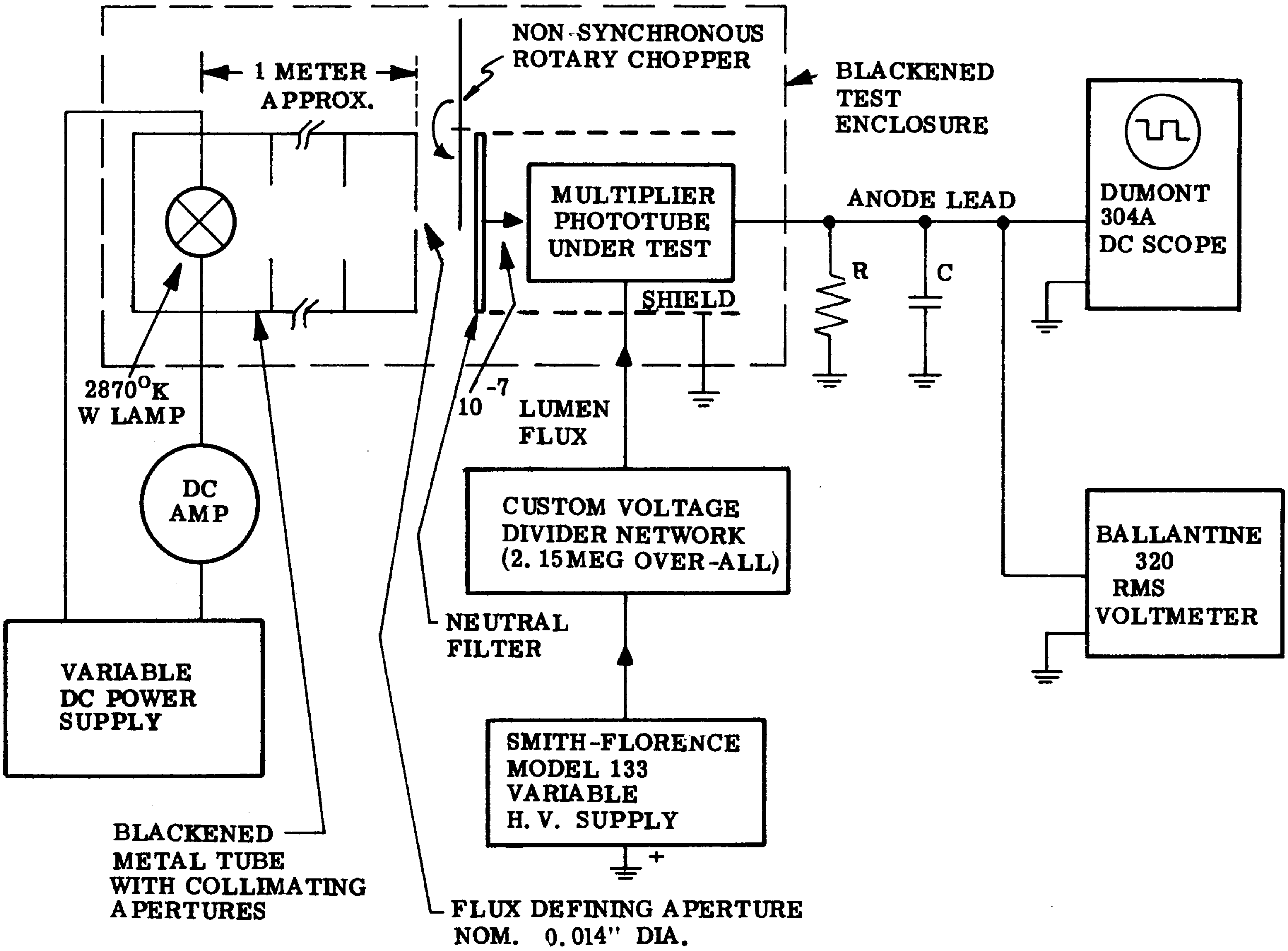

Figure 1 Block diagram of the test equipment used to monitor multiplier phototube characteristics

TEST RESULTS

Noise ratio versus anode sensitivity measurements on a production line series of ITT Industrial Laboratories' (ITTIL) multiplier phototubes of the types described elsewhere by the author,[2] including FW-118 and FW-142 types with S-1 photocathodes, FW-129 and FW-136 types with S-11 photocathodes, and FW-130 and FW-143 types with S-20 photocathodes, some of which were later rejected for not meeting ITTIL commercial tube specifications, including cathode sensitivity, are shown in Figure 2. The noise ratio tends to be approximately independent of the anode sensitivity (current out per unit flux in) and thus of the multiplier current gain over the test range, exceeding two orders of magnitude, with perhaps a tendency to decrease at the higher anode sensitivities as predicted by the Shockley-Pierce theory (dashed lines). It also tends to exceed the theoretical value, as expected, for the majority of tubes tested. However, the presence of two tubes in this sample with a measured noise ratio somewhat less than predicted by the Shockley Pierce theory indicates possible errors in our test procedures or in the calibration of our test equipment.

Effective quantum efficiency, Q_{eff}, versus cathode quantum efficiency, Q, at peak cathode response is shown in Figure 3 for a larger sampling of ITTIL multiplier phototubes, each point representing the test results on a single tube at 10^3 amperes/lumen anode sensitivity. As expected, the points do tend to lie below the $k_{eff} = 1$ line, also somewhat below the dashed $k_{eff} = 1.52$ line corresponding to the predicted noise behavior based on the Shockley-Pierce theory with $k = m/(m - 1) \cong 2.9/(2.9 - 1) = 1.52$, approximately corresponding in turn to the 10^3 amperes/lumen anode test sensitivity for these 16-stage multiplier phototubes. A low cathode sensitivity tube is actually tested at a slightly higher average gain/stage, m, than a high cathode sensitivity tube, as can be seen from the dashed lines in Figure 2, and should therefore have a slightly lower k_{eff} value at a given anode sensitivity.

Numerical factors of 0.016, 0.233, and 0.13, based on registered[18] S-response information, were used to convert the measured cathode sensitivities in microamperes per lumen of 2870 degrees K tungsten lamp radiation to approximate values of the corresponding peak quantum efficiencies in percent, for S-1, S-11, and S-20 photocathodes respectively, in plotting Figure 3. Resultant errors in the magnitude of the peak quantum efficiency due to departure of individual cathodes from the registered spectral response may cause a shift of the points in this figure parallel to the 45 degree, $Q = Q_{eff}$, lines but not in their displacement from these lines, the factor of primary significance.

Higher noise ratios and lower effective quantum efficiencies would be expected if the test source used for the noise measurements produced multi-electron emission. The magnitude of these parameters may also be expected to depend on the specific choice of the upper and lower noise bandwidth test frequencies, and possibly on the test flux magnitude. An investigation of these possibilities is now in progress in our laboratories.

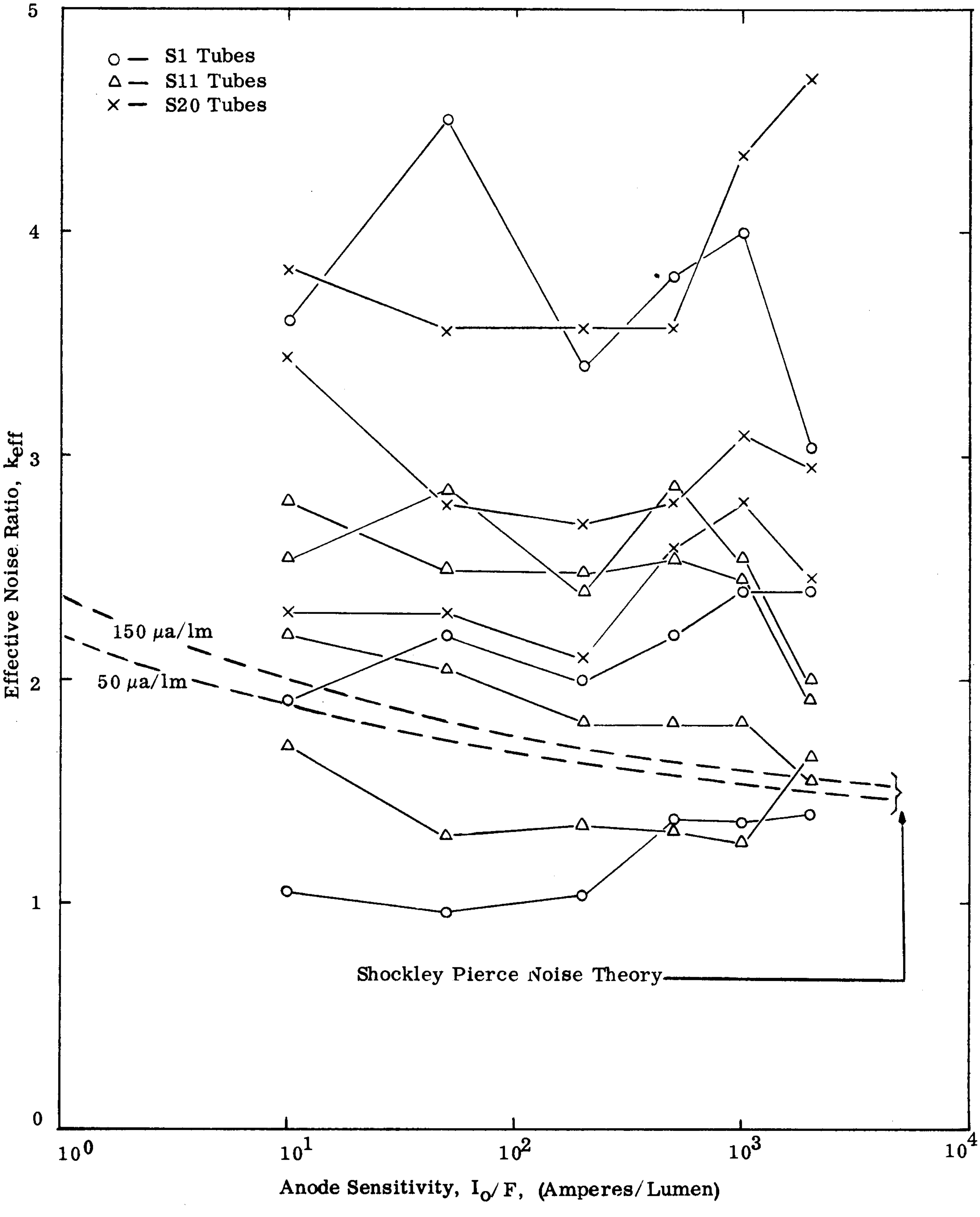

Figure 2 Effective noise ratio versus anode sensitivity for a production line sample of ITTIL multiplier phototubes

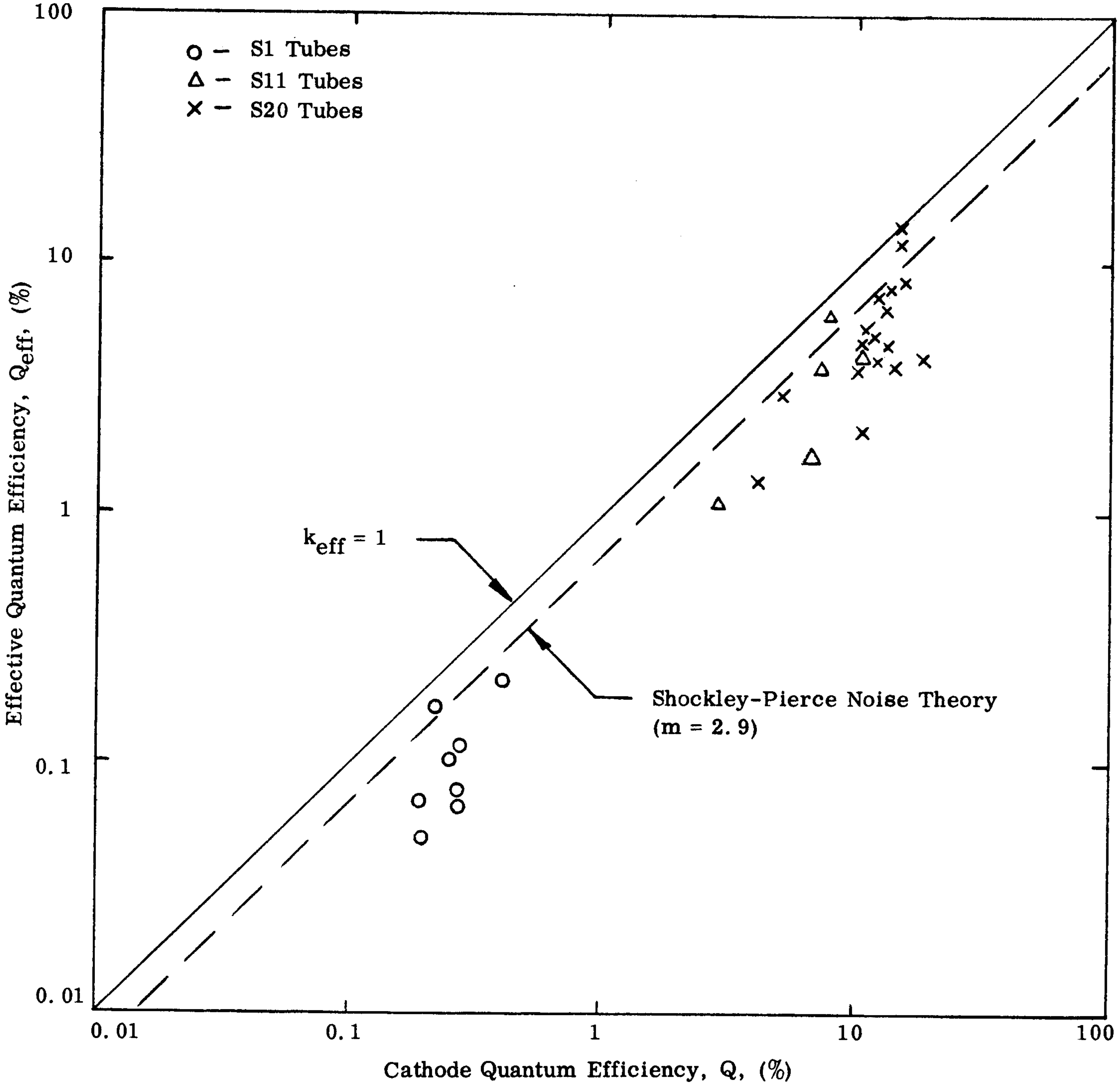

Figure 3 Effective quantum efficiency at 1000 amperes/lumen anode sensitivity and peak response wavelength versus the corresponding cathode quantum efficiency for a production line sample of ITTIL multiplier phototubes.

DARK CURRENT MEASUREMENTS

D-c output dark current, I_{od}, and rms output dark current, i_{od}, may be conveniently monitored for the multiplier phototube under test on the same equipment shown in Figure 1, but with the test flux, F, masked off. An electrometer may be required on some tubes for the d-c dark current measurements. The equivalent anode-dark-current input, F_d, i. e. the input flux level required to give a d-c output current just equal to the observed d-c dark current, I_{od}, may be computed from the proportionality:[1]

$$F_d/I_{od} = F/I_o \tag{10}$$

and the equivalent noise input or ENI may be computed from the similar proportionality:[1]

$$(2/\pi)^{1/2} (1000)^{1/2} \text{ENI}/i_{od} = F/I_o$$

where the factor $(2/\pi)^{1/2}$ converts the peak-to-peak ENI flux to an equivalent rms value in a 1 cps bandwidth, and the factor $(1000)^{1/2}$ converts the measured rms current, i_{od}, in a 1000 cps bandwidth to an equivalent current for a 1 cps bandwidth. The measured magnitudes of I_{od} and i_{od}, even for the S-1 type multiplier phototubes tested were negligible compared to the corresponding I_o and i_o magnitudes.

REFERENCES

1. "IRE Standards on Electron Tubes Methods of Testing 1962", Part 5, Section 7, IEEE Publication Number 62 IRE 7. S1 (1962)

2. Eberhardt, IEEE Tr. on Nuc. Sc., NS-11, No. 3, 48 (1964)

3. Morton and Mitchell, Nucleonics 4, No. 1, 16 (1949)

4. Baum, Chapt. I, Paragraphs 3-4, "Astronomical Techniques" Univ. of Chicago Press, 1962, edited by W. A. Hiltner

5. "Reference Data for Radio Engineers", 4th Ed., 410-411, International Telephone and Telegraph Co. (1956)

6. Jones, J. Opt. Soc. Amer. 50, 1058 (1960)

7. Shockley and Pierce, Proc. I. R. E. 26, 321-32 (1938)

8. Spangenberg, "Vacuum Tubes", Sections 12.14 & 19.10, McGraw-Hill Book Co. (1948)

9. Jones, "Advances in Electronics and Electron Physics", Vol XI, Academic Press, 87 (1959)

10. Heroux and Hinteregger, Rev. of Sc. Instr., 31, 280 (1960)

11. Grant, Proc of the Image Intensifier Symposium, Ft. Belvoir, Va., Oct. 24-26, 1961, 63-71 (unclassified)

12. Bay and Papp, IEEE Tr. on Nuc. Sc., Vol NS-11, 160 (1964)

13. Malter, Phys. Rev., 50, 48, 1936

14. Engstrom, Stoudenheimer and Glover, Nucleonics 10, No. 4, 58-62 (1952)

15. IRE Standards on Electron Tubes, Proc. IRE 45, 1000 (1957)

16. Rose, "Advances in Electronics", Vol. I, 131, Academic Press (1948)

17. Valley and Wallman, "Vacuum Tube Amplifiers", Footnote 1 page 169 Vol. 18 Rad. Lab. Series, McGraw Hill Book Co. (1948)

18. "Relative Spectral Response Data for Photosensitive Devices" JEDEC Publication No. 50, Published by the Electronic Industries Association, N. Y., N. Y. (1964)