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Materiel Test Procedure 5-2-510
White Sands Missile Range

U. S. ARMY TEST AND EVALUATION COMMAND
COMMON ENGINEERING TEST PROCEDURE

NOISE TESTS OF GUIDANCE COMPONENTS

1.0 OBJECTIVE

This Materiel Test Procedure (MTP) presents a basic discussion of the methods used to determine noise effects on guidance component performance.

2.0 BACKGROUND

The accuracy of the guidance and control systems of missiles is limited, in part, by the quality of the signals employed. This signal quality is a function of the noise that is superimposed upon the signal. A guidance and control signal is the portion of detectable energy in guidance and control channels which contains guidance and control information. Noise is the additional portion of detectable energy which interferes with the extraction of this information.

3.0 REQUIRED EQUIPMENT

3.1 Special Facilities

Test personnel should use specified test facilities and equipment insofar as these have been proven effective through previous use. It is recommended that test instruments be accurate to the magnitude of ten greater than the function being measured.

A sled test run may be used to determine noise, in case of infrared and optical system, which may be produced when the radiated energy must pass through rocket motor exhaust or tubulent missile wakes.

3.2 Instrumentation:

a. Vacuum tube voltmeter (VTVM), differential voltmeter or digital voltmerer, db meter.
b. Standard types of noise generators.
c. An appropriate desk calculator for calculating noise power and voltage levels and comparisons thereto.
d. Tungsten filament lamps, xenon flash tubes, and other suitable IR and optical sources.
e. Indexing heads for testing accelerometers, and gyroscopes.

4.0 REFERENCES

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5.0 SCOPE

5.1 SUMMARY

The noise test considerations, are summarized as follows:

a. Electronic Noise---Theoretical estimation and physical investigation of noise type, source, and level in resistors, vacuum tubes, and transistors.

b. RF and Radar Control Systems Noise---Theoretical estimation and physical investigation of antenna thermal noise level and mixer noise level, where mixing is accomplished with vacuum tubes.

c. Infrared and Optical Systems Noise---Theoretical estimation and physical investigation of pre-detection and post-detection noises in IR and optical devices.

d. Inertial Guidance Systems Noise---Theoretical estimation and physical investigation of noise generated in accelerometers and gyroscopes.

5.2 LIMITATIONS

Due to the variety of noises that may be found, a detailed coverage of the entire field can not be included. This MTP is therefore limited in scope to those noises which are the most common and frequently are found in electronic, RF and radar control, and infrared and optical systems. The various types of noise, sources of noise, and noise test considerations presented in this MTP are representative of the general field. However, this MTP does not cover vibrational noises such as those generated in rocket engine systems. The procedures outlined were intentionally made general to provide coverage for measuring, theoretically estimating, and calculating noise levels in various missile systems.

6.0 PROCEDURES

6.1 PREPARATION FOR TEST

The personnel performing these tests should be fully qualified engineers and/or technicians. All documentation pertaining to the unit under test should be available.

The test conductors should exercise caution so that the design limitations of the item under test are not exceeded, and to insure that all personnel observe standard safety practices.

6.2 TEST CONDITIONS

The test conditions that may be required for noise evaluation are classified in three categories:

a. Tests conducted at room ambient conditions

b. Tests conducted in a specified environment then compared to the results of similar tests previously conducted at room ambient conditions

c. Tests conducted in a specified environment then repeated at room ambient conditions

6.3 TEST CONDUCT

Personnel conducting the tests, making theoretical estimations, or mathematical calculations should be thoroughly familiar with the instrumentation, equipment, and test configurations. The following considerations should be used throughout the test.

a. Follow standard laboratory and manufacturer's safety practices to avoid injury to personnel and damage to equipment.

b. Consult all pertinent paragraph and figure references, prior to commencing a particular test or performing a particular noise investigation.

c. Visually examine components to ensure that there is no evidence of corrosion or physical damage. Ensure that components conform to design specifications. Identify terminals and input and output circuit requirements of the electrical components.

Refer to an electrical schematic if necessary.

6.3.1 Electronic Noise

The measurement of electronic noise usually consists of connecting a noise or signal source, such as a noise diode, and an input measuring device such as a variable attenuator or a milliammeter to the input of the device under test, and a power measuring device, such as a bolometer, db meter, or VTVM to the output. The equipment is usually connected as in figure 1.

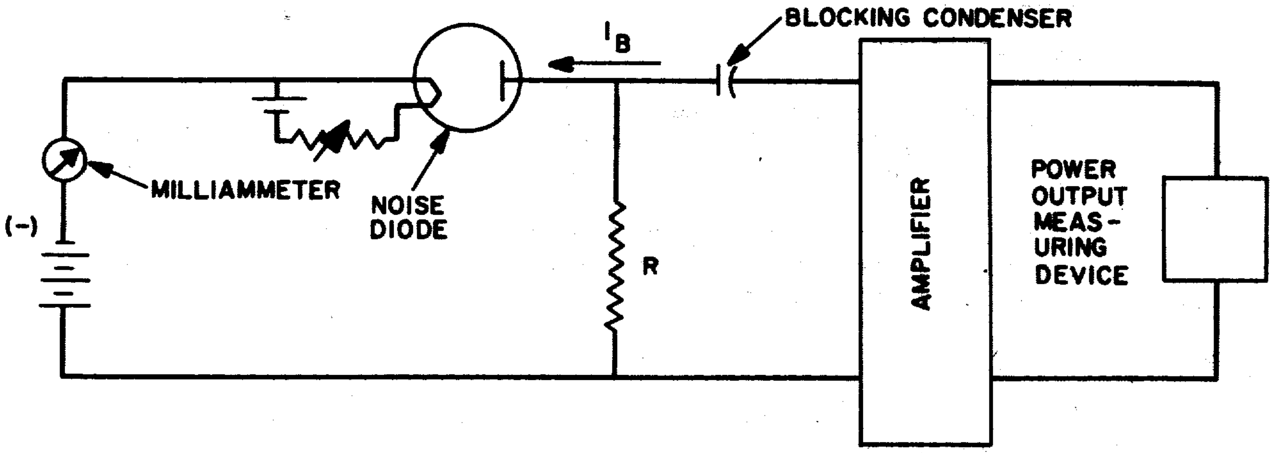


Figure 1. Electronic Noise Test

1) To run a noise test with this configuration the power output of the amplifier is measured with the noise diode off and the amplifier turned on. The diode current I_b should be zero.
2) Apply power to the noise diode and increase the power until the power output is twice the previous reading.
3) Note the diode current level I_b.

6.3.2 RF and Radar Control Systems Noise

RF noise measurements are generally the same as those for other electronic devices, except for the special techniques that are used at higher frequencies.

a. Gas Tube Generator Method

1) Take an ordinary argon gas tube and insert it in a specially constructed waveguide as shown in Figure 2.

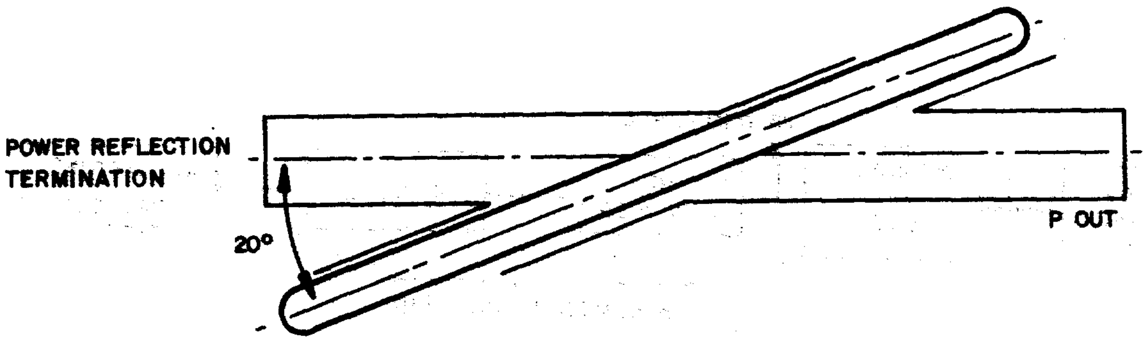


Figure 2. Gas Tube Generator

2) The tube is mounted at 20° to the horizontal to eliminate shot noise, and is terminated to give maximum power output, and is in turn connected to a variable attenuator, and the whole connected to a power meter.
3) A graph of Noise Figure versus the attenuator setting is then obtained by comparing the output of the generator with the tube off to that with the tube fired.
4) The generator is then connected as in Figure 3 and the test proceeds as follows:

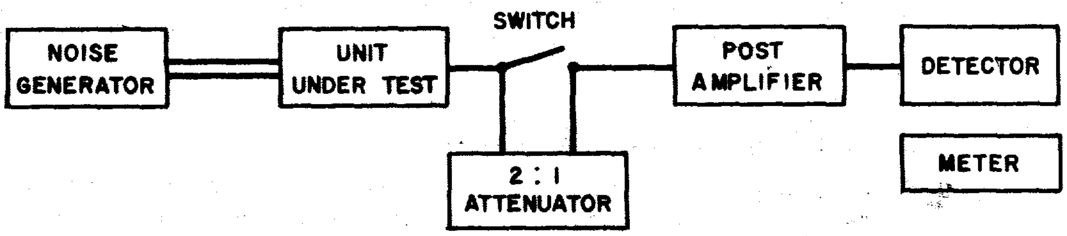


Figure 3. Attenuator Post Amplifier Method

5) With the attenuator switch closed and the noise generator off observe the output meter.
6) Open the switch, start the generator and increase the generator output until the meter indication is the same as it was with the switch open and the generator off.
7) Note the current supplied to the generator.

b. Bolometer Method

1) The equipment is connected as in Figure 4. The preamplifier bandwidth is greater than that of the unit under test and the amplifier flat over the range of operation of the unit under test.

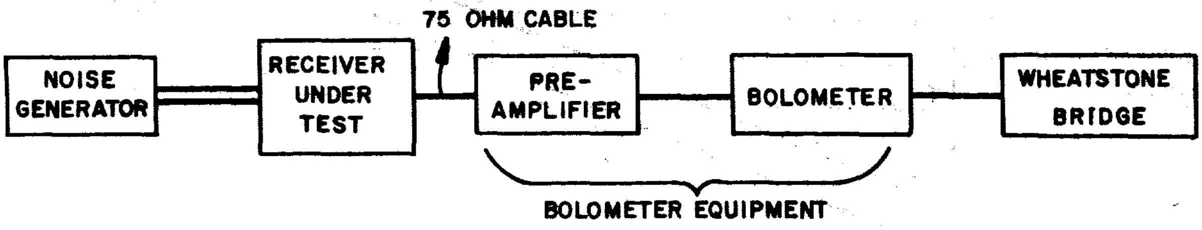


Figure 4. Bolometer Method of Noise Figure Measurement

2) Balance the Wheatstone Bridge with the receiver inoperative.
3) Start the receiver, but leave the noise generator off. This will unbalance the bridge.
4) Rebalance the bridge and note the change in the bolometer resistance caused by the receiver noise power.
5) Unbalance the bridge by twice the value of the resistance previously noted.
6) Turn on the noise generator and increase its power until the bridge is again balanced.
7) The noise generator power is now equal to the receiver noise power and the sum of the two powers are twice the receiver power noted.

6.3.2 Infrared and Optical Systems Noise

To test IR and Optical Devices for noise considerations the output of the system is first measured under zero input conditions and then supplied with a suitable input until the output level is twice its previous value. The procedure could be conducted as follows:

a. Connect a power meter to the output of the system under test, cover the radiation pickup device thoroughly and measure the output level.

b. Excite the device under test with a "black body" source increasing the intensity level (temperature) until the output reading is twice the one with no input.

c. Record this value plus the power supplied to the source.

d. If, as in some types of optical and IR devices the radiation input to the system under test is modulated then the modulating frequency should be recorded also.

6.3.4 Inertial Guidance System Noise

This test is used largely to determine the mechanical noise introduced into an inertial system by aberations in the sensing components and windforces.

6.3.4.1 Accelerometer Noise

a. To measure null offset or the output of accelerometer at conditions of zero acceleration mount the accelerometer on a index head with its sensitive axis perpendicular to the axis of rotation of the index head.

b. Rotate the index head until the sensitive axis of the accelerometer is perpendicular to the earth's center of gravity. This should give zero acceleration conditions. Record output of the accelerometer and the angle of the head.

c. Rotate index head 180°, record accelerometer output and angle.

6.3.4.2 Gyroscope Noise

a. Random Drift is the principal cause of gyroscopic noise and can be measured by a process known as a cogging test. Mount the gyroscope on a turntable with the gyro's input axis and the turntable axis vertical and with the gyro's signal generator driving the turntable.

b. The component of earth rate along the gyro's input axis is used to drive the turntable at a slow rate. Let the turntable drift at least two degrees, measure the time interval required for this drift.

c. Repeat this process at least 15 times.

6.4 Test Data

6.4.1 Electronic Noise

Record the power output in db with the noise diode off and on. Record the diode current in milliamperes.

6.4.2 RF and Radar Control Systems Noise

Record both the input power levels in db and the output levels in db.

Record Bridge Resistance readings in ohms.

6.4.3 IR and Optical Systems Noise

Record the power supplied to the IR or light source in db. Record the power output in db. Record frequency in Hz. Record Temperature of source in degrees Kelvin.

6.4.4 Inertial Guidance System Noise

6.4.4.1 Accelerometer Noise

Record Accelerometer output in volts and index head angle in degrees.

6.4.4.2 Gyroscope Noise

Record angle in degrees, and the time in seconds.

7.0 Data Reduction and Presentation

7.1 Electronic Noise

The relative effect of noise upon any electronic device is usually expressed by a numerical ratio known as the noise figure which is expressed as:

$$\text{Noise Figure} = F = \frac{\text{signal-to-noise power ratio of the ideal system}}{\text{actual signal-to-noise power ratio of output}}$$

The noise Figure can be calculated using this formula or by using the formulas given in appendix "A" and "B" and data taken from the devices under test; however it is standard practice to use formulas developed specifically for the test method used. For example the formula for the method given in this procedure is:

$$F = 20\ I_b R$$

where:

I_b = noise diode current

R = the value of the input resistor R

This relationship is valid for room temperature ($T = 290°K$).

7.2 RF and Radar Control Systems Noise

For tests employing a gas tube generator the noise figure is read directly from a graph which is determined by taking the ratio of the output of the generator off (N_1) and the generator on (N_2) and plotting noise figure versus attenuator setting with noise figure calculated as $F_{db} = 15.2 - 10 \log (N_2/N_1 - 1)$. When a CW signal generator is to be used as a noise source then the noise figure is calculated by:

$$F = \frac{250\ E_{in}^{2}}{BR_o}$$

where:

E_{in} = generator output in microvolts (uv)

B = the bandwidth of the device under test

R_o = the characteristic impedance of the signal generator

To convert noise figure to a db equivalent the expression db = 1 OlogF may be employed.

7.3 IR and Optical Systems Test

The calculations for noise figure for these systems are similiar to those previously given. The temperature of the source needed to make the output of the unit twice what is was under zero input conditions, is recorded and the noise figure is computed from:

$$F = \frac{Po}{KT_1\ G\Delta f}$$

where:

Po = output power of the detector system
G = power gain of the system
Δf = the bandwidth of the system
T_1 = the absolute temperature of the source
K = Stephen-Boltzman constant

7.4 Inertial Guidance System Noise

7.4.1 Accelerometer Noise

The expression for null offset in terms of voltage output of the accelerometer is:

$$(NO)_{volts} = \frac{E(\phi_o) + E(\phi_1)}{2}$$

The null offset in multiples of gravity is:

$$(NO)_{\S} = \frac{E(\phi_o) + E(\phi_1)}{2\ (SF)}$$

where:

ϕ_o = The angle of the index head at the start of the test

ϕ_1 = ϕ_o + 180°

(SF) = scale factor used to convert g's of acceleration into volts

$E(\phi_o)$ and $E(\phi_1)$ = The voltage readings at ϕ_o and ϕ_1 respectively

7.4.2 Gyroscope Noise

The expression for the drift rate for any one test is:

$$\omega_L \text{ (drift) } \frac{\text{Degrees}}{\text{Hour}} = \frac{2°}{(\text{elapsed time in hours})_i}$$

The random drift rate is the standard deviation of all of the calculated drift rates. Standard deviation is defined as the square root of the sum of the squares of the difference between each point and their numerical average divided by the number of tests minus one:

$$\text{Random drift} = \left[\frac{\sum_{i=1}^{n} \left(\omega_i - \sum_{j=1}^{n} \frac{\omega j}{n} \right)^2}{(n - 1)} \right]^{\frac{1}{2}}$$

where:

n = the number of tests

7.5.0 TEST RESULTS

Prepare a log book for each system tested and record the results of the noise tests and investigations. Enter all pertinent data in this log, including theoretical estimations, mathematical calculations, and measured noise levels that are obtained during the tests or investigations. Record all predetermined conditions and indications at which the tests or investigations were conducted.

APPENDIX "A"

Causes of Noise in Guidance Systems

Noise levels that are due to random electron motion are determined by the basic physical considerations involved and are calculable from theoretical formulas. Noise levels associated with microstructure characteristics depend upon manufacturing techniques and are not as easily calculable, although there are formulas available which can be used to assist in a evaluation.

Noise in resistors is random and depends upon the resistance, absolute temperature, and frequency bandwidth over which noise is observed. Resistor noise is independent of the resistor material.

The principal sources of noise within vacuum tubes are shot effect, reduced shot effect, partition noise, and those sources associated with the construction features of the vaccum tube, such as cathode flicker, collision ionization, and microphonics. Collision ionization in a vacuum tube is due to residual tube gas. Shot effect and reduced shot effect random noise arises in vaccum tubes because of the discreteness of the electronic charge. Partition noise is due to the random division of current between electrodes in a multielectrode device.

Transistor noise is due to components having a uniform frequency spectrum and noise power that are inversely proportional to the frequency. The uniform spectrum components are generated by thermal agitation in the extrinsic base resistance and by three random intrinsic mechanisms which are generally assumed to be independent. These random intrinsic mechanisms are, shot noise of generation, shot noise of collection, and recombination noise.

Hum is an audio engineering term which refers to a-c signals that couple into signal channels from local power frequency voltages, currents, and fields. Chief sources of a-c voltages of this type in missile electronic systems are power supply ripple and choppers that are used in chopper-stabilized d-c amplifiers.

Microphonics are a-c signals induced by mechanical vibrations of vaccum tube elements and circuit elements, especially in the first stage of high gain amplifier systems.

Ground clutter noise in RF and radar control systems is due to the reflections of radar signals from surrounding terrain. Ground clutter of considerable magnitude may occur at any point along the transmitting or receiving path for systems used at low elevation angles, following the transmission of radar pulse.

Noise in inertial guidance systems usually occurs in accelerometers and gyroscopes. Noise in accelerometers is generated in the pickoff device that transforms the mechanical motion of the accelerometer into an electrical signal and by the random wandering of the null offset. Noise in gyroscopes is produced by the signal generator or pickoff device which transforms the gyro's rotational output into an electrical signal and by the random drift due to unknown random torques acting upon the gyro's output axis.

Post-antenna noise may be caused by the mixer and/or RF amplifier. Crystal diodes are used as mixers for frequencies over 500 megacycles. The intermediate frequency noise developed by the output circuit of a crystal mixer is greater than the thermal noise of the crystal output resistance. This may be taken into account by assuming that the crystal acts as though its output resistance has an absolute temperature 1.5 to 3.0 times higher than the absolute room temperature. For those cases where mixing is accomplished using vacuum tubes, mixer noise is obtained by considering the tube to be an amplifier operating at the output (intermediate) frequency, and averaging the intermediate frequency noise power over the plate current variations occurring during one local oscillator cycle. Noise in RF amplifiers is significant, in most cases, because noise generated in this stage is amplified at full gain. Noise generated in subsequent stages is amplified at less than full gain.

The most important noise sources which occur before infrared or optical signals are detected, are photon shot noise and background radiation. Photon shot noise arises in a received signal because it is composed of individual photons in the frequency range of the emitter. Within a given sampling period, there can be statistical fluctuations in the number of photons arriving at the detectors surface. In active systems, background radiation is discriminated against by narrow band modulation of the transmitted beam and by selecting favorable spectral regions. However, in passive systems, only spectral filtering can be employed. Typical sources of background radiation are clouds, the horizon, terrain variations, and sunlit terrain.

Atmospheric turbulence effects on the received signal are important in active infrared and optical systems. This turbulence or shimmer effect may modulate background radiation so that some portion of the background radiation will appear modulated at the frequency of the active signal and will be introduced into the signal channel as noise. Normally, background frequencies are relatively low and their effect can be reduced by appropriate selection of transmitter frequencies.

In most well designed infrared and optical systems, the important source of post-detection noise is detector noise. Typical photoconductive detectors are lead sulfide film and boron-doped silicon. In these devices, the main source of noise is produced by the current passing through the cell. It is due to contact noise, similar to that generated between carbon grains in a microphone, and other characteristics of the microstructure of the material. The power spectrum of this noise generally is inversely proportional to the frequency and directly proportional to the square of the steady state current. Photoemissive devices have two sources of noise. These are shot noise of the emitted electrons from the photocathode and dark current noise due to emission from the photocathode in the absence of incident radiation.

Engineering convention for expressing noise levels in various equipment requires that several calculations be made. These calculations are presented briefly. More detailed and thorough presentations may be found in the references or in any standard electronics text.

Electronic Noise

Resistor Noise -- Resistor noise energy is uniformly distributed over the RF spectrum. Theory dictates the following expression for the rms noise voltage:

$$e_{rms} = 7.4 \sqrt{RBT} \ \mu\mu\text{volts}$$

where:

e_{rms} = rms noise voltage

R = resistance in ohms

B = bandwidth in cps

T = temperature in °K

This formula applies to noise from wirewound and carbon deposit resistors. Carbon resistors typically have greater noise due to microstructure effects and, consequently, are not often used in noise-sensitive portions of systems.

Vacuum Tube Noise

The expression for determining the reduced shot effect in diode vacuum tubes with space-charge limited emission is:

$$i_{rms} = 7.4 \sqrt{\frac{T_C B}{R}} \ \mu\mu\text{amp}$$

where:

i_{rms} = the rms noise current
T_C = absolute cathode temperature °K
B = bandwidth
R = the a-c diode resistance

The expression for determining the reduced shot effect in triode vacuum tubes with space-charge limited operation is:

$$R_{eq} = \frac{2.5}{G_m} \frac{I_p}{I_p + I_2} \left(1 + 8 \frac{I_2}{G_m}\right)$$

where:

I_p = plate current

I_2 = screen-grid current

Transistor Noise -- Transistor noise is believed to arise from collector leakage (l) and fluctuating surface recombination velocity (f). The $\frac{1}{f}$ component may be accounted for approximately by connecting a noise generator across the collector to the internal-base terminals of a transistor equivalent circuit. The expression is:

$$\overline{i_f^2} = \frac{K_1}{f} + \frac{K_2 I_e^2}{f} \text{ amp}^2/\text{cycle}$$

where:

$\overline{i_f^2}$ = mean square noise current

f = frequency

I_e = average d-c emitter current

K_1 and K_2 = empirically determined parameters

The parameter (K_1) is a function of collector-to-base d-c voltage (V_c) and temperature, and can change by a factor of three for a one-volt change in (V_c). K_2 is an empirically determined factor strongly dependent on emitter current. The approximate formula for determining thermal noise in a transistor is:

$$e_{rms} = 7.4 \sqrt{T \; r_b \; B} \quad \mu\mu \text{ volts}$$

where:

T = temperature in °K

r_b = TEE model base resistance

B = effective bandwidth

The approximate formula for determining shot noise of generation in a transistor is:

$$\bar{i}_b = 560 \sqrt{\frac{I_e B}{\beta}} \quad \mu\mu \text{ amp}$$

where:

$\bar{i}_b$ = mean noise current of generation

I_e = average d-c emitter current

B = effective bandwidth

β = current amplification factor

The expression for approximating shot noise of collection in a transistor is:

$$\bar{i}_c = 560 \sqrt{I_c B} \quad \mu\mu \text{ amp}$$

where:

$\bar{i}_c$ = mean noise current of collection

I_c = average d-c collector current

The expression for approximating recombination noise in a transistor is:

$$\bar{i}_{co} = 560 \sqrt{I_{co} B} \quad \mu\mu \text{ amp}$$

where:

$\bar{i}_{co}$ = mean noise current of recombination

I_{co} = cutoff current of transistor

In the frequency region where $\frac{1}{f}$ noise is not important and high frequency dropoff has not become significant, a better approximation to the total noise current at the transistor output terminal is:

$$\bar{i}_N^2 = B\left[\bar{i}_c^2 + \left(\frac{\beta\,(r_b + R_s)}{r_b + R_s + \beta\, r_e}\right)\left(\bar{i}_b^2 + \bar{i}_{co}^2 + \bar{i}_T^2\right)\right] \quad \text{amp}^2$$

where:

R_s = the external signal source resistance

r_e = TEE model emitter resistance

$\bar{i}_T^2$ = mean square thermal noise current given by $\bar{i}_T^2 = 55\,\frac{T\ B}{R_s + r_b}$

Electronic Noise Useful Relationships -- A Signal-to-noise ratio is often increased by using narrow band filters to limit the response of a system to the frequency range in which the desired information is confined. This eliminates noise power from the frequency region outside this range without affecting signal power. To relate the ratio of output noise to input noise for a filter with transfer characteristics (Y (f)), the following expression may be used:

$$P_o(f) = |Y(f)|\ 2p_i(f)$$

where:

$P_o(f)$ = power spectrum of the output

$P_i(f)$ = power spectrum of the input

"White" noise occurs when the power is uniformly distributed throughout the frequency domain. An approximate expression developed from this relationship is:

$$P_o = K\, P_i\, B$$

where:

B = bandwidth of the filter

K = a constant

This formula is particularly useful in estimating the effects of increasing or reducing the bandwidth of the signal channel. In most systems, noise is contributed by several sources. The expression for approximating the total noise voltage contributed to any one point in the signal channel is:

$$e_{rms_T} = \left(\Sigma e^2 \ rms_i \right) \frac{1}{2}$$

where:

e_{rms_T} = the root mean square amplitude of the total noise voltage

e_{rms_i} = the root mean square amplitude of the voltage from i^{th} noise source

From this formula, it is clear that rms noise voltages do not add linearly. Actually, if the rms noise from one source is more than twice that from a second source which is added to it, the first contributes 90 percent, or more, of the total rms noise.

RF and Radar Control Systems Noise

In conducting studies of the noise in RF and radar control systems, the same general techniques are used as are used in other electronic systems. Since the lower limit of noise in these systems is the thermal noise of the antenna, this noise level is calculated first. Thermal noise and RF amplifier noise may be approximated by using the expression given for resistor noise, as described in paragraph 7.1.1. Vacuum tube noise formulas are given in paragraph.

Although noise power measurements can be made at microwave frequencies, these normally require special techniques and are not usually accomplished in test and evaluation programs. Noise measurements are made at those points in the electronic signal processing system where the frequencies have been converted to ranges below 50 mega Hz. Refer to Appendix B for a typical example of a radar noise calculation.

Antenna Thermal Noise -- Antenna noise is in equilibrium with its surroundings and represents a lower limit of noise level for the entire RF and radar control system. The value taken for the resistance of the antenna and the temperature to be applied is the temperature of that portion of the surroundings with which the antenna is in equilibrium. For example, if the antenna is pointed toward the sky, temperatures of about 20° K may be obtained, but when pointed toward landscape backgrounds, temperatures may be in the range of 290°K. Kelvin is an absolute thermometric scale. 0° K is equal to absolute zero (-273° c).

Mixer Noise -- The results of mixer noise, where mixing is accomplished with vacuum tubes, as described on Page A-3, are conveniently expressed in terms of an equivalent input resistance (R_{eq}). For each particular mixer tube type, this equivalent resistance is calculated from the following expressions:

a. Triode vacuum tube mixers:

$$R_{eq} = \frac{4}{g_c}$$

b. Pentode vaccum tube mixers:

$$R_{eq} = \frac{I_b}{I_b + I_c^2} \quad \frac{4}{g_c} + \frac{20\ I_c 2}{g_c^2}$$

c. Pentagrid converters - pentagrid mixers:

$$R_{eq} = \frac{20\ I_b}{g_c^2\ I_{sp}} (I_{sp} - I_b)$$

In these expressions g_c is the conversion transconductance, and I_{sp}, I_b, and I_c are the total space current, plate current, and screen current, respectively, measured and averaged over one local oscillator cycle.

Infrared and Optical Systems Noise

IR and optical frequencies represent electromagnetic radiation of extremely short wavelength as compared with microwave frequencies. The regions of the electromagnetic spectrum occupied by these frequencies are shown in Figure 1. The techniques and theory of the use of these two spectral regions are quite similar. Both may be reflected from metallic mirrors or refracted by suitable materials such as glass (optical) or silicon and germanimum (IR) to form images of the emitting sources. Refer to Appendix "B" for a typical example of an infrared noise calculation.

This system is appropriate to passive detection. The chopper near the image plane serves two purposes:

a. It locates the image in the field of view. This is accomplished by using a chopper reticle pattern which provides an output signal with modulation characteristics dependent upon image radial and angular position.

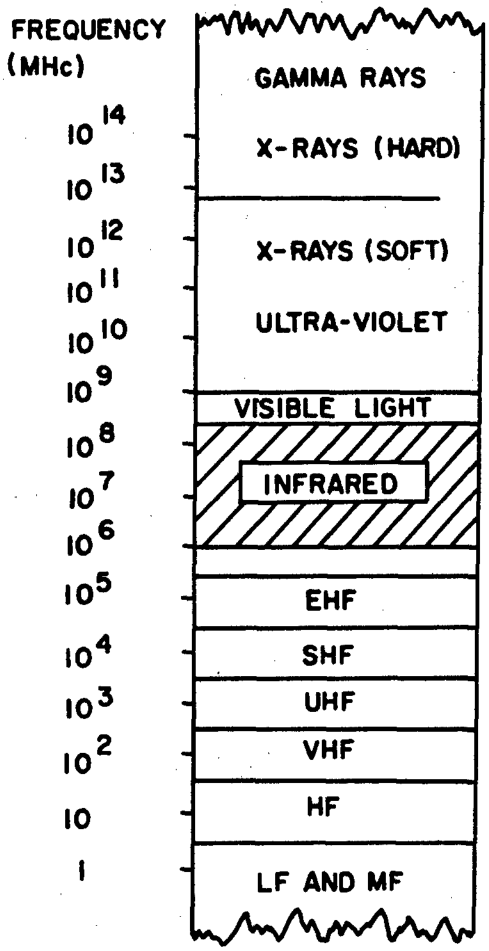


Figure A-1. Electromagnetic Spectrum

Typical Signal Detection Systems -- A typical image forming system with a detector is shown in Figure 2.

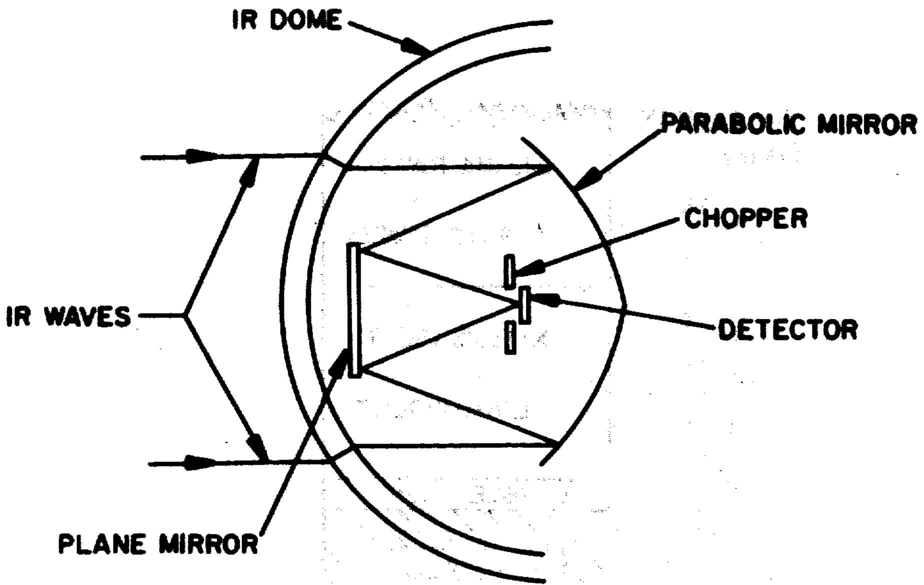


Figure A-2. Typical IR Detection Optical System

b. It provides an a-c signal for subsequent electronic detection and amplification.

In an active system, the detection equipment is similar to that shown in Figure 2, except that the infrared or optical frequency is already modulated at the source. Scanning of the image plane to locate the target in the field of view is accomplished by rotating reticles, image-scanning prisms, or similar devices. Typical detector systems use photoconductive solid state devices or vacuum tubes containing photocathodes. Photoconductive devices are most sensitive in the infrared and decrease in sensitivity considerably in the ultraviolet. Photocathode devices generally are most sensitive in the ultraviolet and visible regions. Their sensitivity drops rapidly in the near infrared regions. In specifying the detector sensitivity, it is useful to use a quantity known as Noise Equivalent Power (NEP). This quantity is the minimum radiation input power necessary to produce an output signal equal to the rms of electrical power output of the detector.

Blackbody Radiation Relationships -- In many systems which use passive or active infrared in optical frequencies, the sources of radiation are "blackbody" sources. The radiation characteristics of blackbodies are related to the temperature of the source. Blackbody radiation theory states that, as the temperature of an emitting object increases, the electromagnetic radiation emitted from the surface will change in two ways:

a. The radiation peak shifts toward the shorter wavelengths.

b. The total radiated energy increases as the fourth power of the object's absolute temperature. This relationship is expressed as follows:

$$R = 5.67 \times 10^{-12} e T^4$$

where:

R = the total radiation emitted from the surface in watts/cm^2

T = the temperature in °K

e = an emissivity factor

The emissivity factor (e) depends upon the material and its surface finish. The e factor for a silver mirror, for example, is 0.02, while the e factor for a lamp black surface is 0.95. Typical spectral characteristics for blackbody radiation at various absolute temperatures are shown in Figure 3.

In calculating received infrared radiation at a detector, consideration must be given to the transmission characteristics of the atmosphere. Moisture and carbon dioxide in the air attenuate and/or scatter infrared energy sharply in some parts of the spectrum, and less heavily, or not at all, in others. In this respect, the atmosphere acts somewhat like an electrical filter by passing certain frequencies and rejecting others, except that the amount of attenuation will vary with the amount of moisture in the air.

Pre-detection and Post-detection Noises -- Pre-detection noise may be due to photon shot noise. Within a given sampling period there may be statistical fluctuations in the number of photons arriving at the detector's surface. A convenient expression for the variation in pulse height of the arriving pulses or signal-to-noise ratio (S/N) is:

$$S/N = (n \tau)^{-\frac{1}{2}}$$

where:

n = the average number of photons arriving per sec

τ = the pulse length

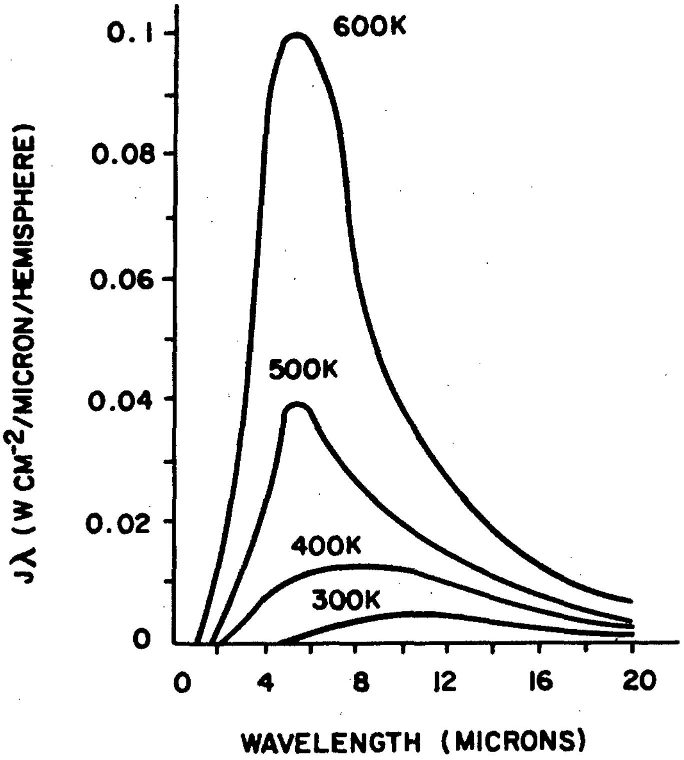


Figure A-3. Blackbody Spectra

A more convenient relationship for those cases where CW noise is of interest is as follows:

$$S/N = 0.7\sqrt{\frac{n}{B}}$$

where:

B = bandwidth of the receiving system

Post-detection noise is generally detector noise in photoconductive devices, photoemissive devices, and electronic noise. The optimum sensitivity of a photoconductive cell depends primarily upon the chopping frequency, cell temperature, and cell current. To characterize the sensitivity of cells, the following expression may be used:

$$S = \frac{NEP}{A^{\frac{1}{2}}} \left(\frac{f}{\Delta f}\right)^{\frac{1}{2}}$$

where:

NEP = as defined previously

f = the chopper frequency

Δf = the system bandwidth

A = the cell area

This expression assumes that the photoconductive cells are current noise limited and that the noise power per unit bandwidth varies inversely with the frequency. The NEP for a particular frequency, bandwidth, and cell area is readily calculable using this equation. The noise calculation for a photoemissive device is accomplished by inserting the sum of the current due to emission from the photocathode in the absence of incident radiation into the following expression and then solving the expression:

$$I_{rms} = 5.6 \times 10^{-10} \sqrt{IB}$$

where:

B = the bandwidth of the detection system

I = the sum of the two currents

I_{rms} = the rms noise associated with these currents

Electronic post-detection noise in infrared and optical systems is calculated by using the techniques and expressions described in paragraph 7.1. through 7.3.

APPENDIX "B"

Effects of Noise in Guidance and Control Signal Channels

Simplified analysis is accomplished to indicate the effects of noise in signal channels. This is further accomplished to determine the need for computer investigations, however, complete analysis for this purpose usually are not conducted during test and evaluation programs. The most convenient instrument for an analysis of noise effects in guidance and control signal channels is the analog computer. Using appropriate noise generators, typical noise levels may be simulated during runs on the computer. Successive runs with, or without, noise will clearly indicate the effects of noise on various parameters of the system. Studies of this type generally are better than analytic studies where mathematical methods are practical in only a few cases. A signal-to-noise ratio usually varies from point-to-point in the signal processing channels. Variations are introduced by filters, signal shaping networks, and limiters.

1.1 Noise filtering -- In most missile systems, overall system response does not exceed 10 cps. If noise is generated above this frequency region, it can be effectively eliminated by filters without affecting the control intelligence. Since missile systems generally do not respond beyond 10 cps. it may appear that electronic filtering is not necessary. Caution must be exercised since high frequency noise may still degrade and destroy control intelligence due to the action of limiter circuits. Noise filtering is introduced into system design as early as possible following the introduction of noise into the signal channels. Two common types of noise which may be effectively eliminated with filters are:

a. Chopper noise, typically at frequencies around 400 cps

b. Vibration noise such as microphonics and contact chatter which may occur at any audio or sub-audio frequency, but is usually stronger at frequencies above 10 cps. In those cases where frequencies are in the same frequency region as control intelligence, less than 10 cps, filters cannot reduce noise without also adversely affecting the useful signal.

1.2 Noise in Signal Shaping Networks -- Both signal and noise are transformed by signal shaping networks. Consider a shaping network represented by a transfer function as follows:

$$K_T \left(\frac{1 + \tau_1 S}{1 + \tau_2 S} \right) \qquad \tau_1 \gg \tau_2$$

where: K_T = the d-c gain

τ_1 and τ_2 = the time constants of the signal shaping network

Consider the input signal to be:

$$K_S \tau$$

where: K_s = a constant

τ = time

This input signal may represent, for example, a missile departure from a desired flight path. A noise signal, taken at a single frequency for simplicity, is added to this signal to give a combined signal plus noise expression as follows:

$$K_s \tau + A_n \sin \omega_n \tau$$

where: A_n = the amplitude of the noise

ω_n = the noise frequency in radians per second

Noise of this type may be due to vibration, pickup, tracker jitter, or other similar causes. The signal-to-noise ratio for this input is:

$$S/N = \frac{K_s \tau}{A_n}$$

To generate the output signal of the shaping network, the transform of the input is multiplied by the transfer function as follows:

$$\left[\frac{K_s}{S^2} + \frac{A_n \omega_n}{S^2 + \omega_n^2}\right] \left[K_T \left(\frac{1 + \tau_1 S}{1 + \tau_2 S}\right)\right]$$

Taking the inverse of this expression and dropping transient terms, the signal shaping network output is:

$$K_T K_s (\tau_1 - \tau_2) + K_T K_s \tau + A_n K_T \left[\frac{1 + (\tau_1 \omega_n)^2}{1 + (\tau_2 \omega_n)^2}\right]^{\frac{1}{2}} \sin (\omega \tau)$$

This output results in the following expression for signal-to-noise ratio:

$$\frac{K_s \tau + K_s (\tau_1 - \tau_2)}{A_n \left[\frac{1 + (\tau_1 \omega_n)^2}{1 + (\tau_2 \omega_n)^2}\right]^{\frac{1}{2}}}$$

After shaping, the signal-to-noise ratio depends on the noise frequency. In a typical case where $\tau_1 >> \tau_2$, signal-to-noise decreases as the noise frequency increases. As ω_n approaches large values the expression asymptotically approaches:

$$\frac{S}{N} \longrightarrow \frac{K_s (t + \tau_1) \tau_2}{A_n \tau_1}$$

This action is typical of differentiating networks. The effects of noise are emphasized as the noise frequency increases and as the constant associated with the differentiating term, τ_1, is increased.

1.3 High Level Noise and Noise Clipping -- A major consideration in analyzing the effects of noise in guidance and control channels is the clipping of high level noise peaks by limiting circuitry. This results in the general effect of distortion the signal and reducing the signal level. Figure B-1 illustrates how noise clipping produces these two general effects.

In Figure B-1,(a) illustrates a d-c medium level control signal which is not limited. In Figure B-1,(b) illustrates a high frequency having a high level noise added. Peaks of this noise are clipped. In Figure B-1,(c) illustrates subsequent filtering of the combined signal and clipped noise. The high frequency components introduced by the noise and noise clippings are filtered out, leaving an output signal with the following characteristics:

a. Ripple distortion added to the d-c signal due to filtered noise
b. Reduced average level due to noise clipping followed by filtering

In cases of extremely high noise levels, noise clipping followed by filtering can reduce the output signal to an average level of zero.

1.4 Electronic Noise Calculation

The following is an example of a typical electronic noise calculation:

In a high gain signal amplifier used for 1 kc/sec infrared signals, the first stage employs a 12AX7 high gain triode. The grid input uses a grid resistor of 2.2 k ohms and a 100 cps filter. An estimation of the amplifier input noise is required. The input noise is the sum of the noise of the grid resistor and the tube noise of the 12AX7. First, calculate the tube noise of the 12AX7. Taking the G_m of the 12AX7 as 1250 µ mhos, the noise formula yields the following result:

$$R_{eq} = \frac{2.5}{G_m} = \frac{2.5}{1250} = 2 \text{ k ohms}$$

The noise corresponding to this equivalent input resistance is:

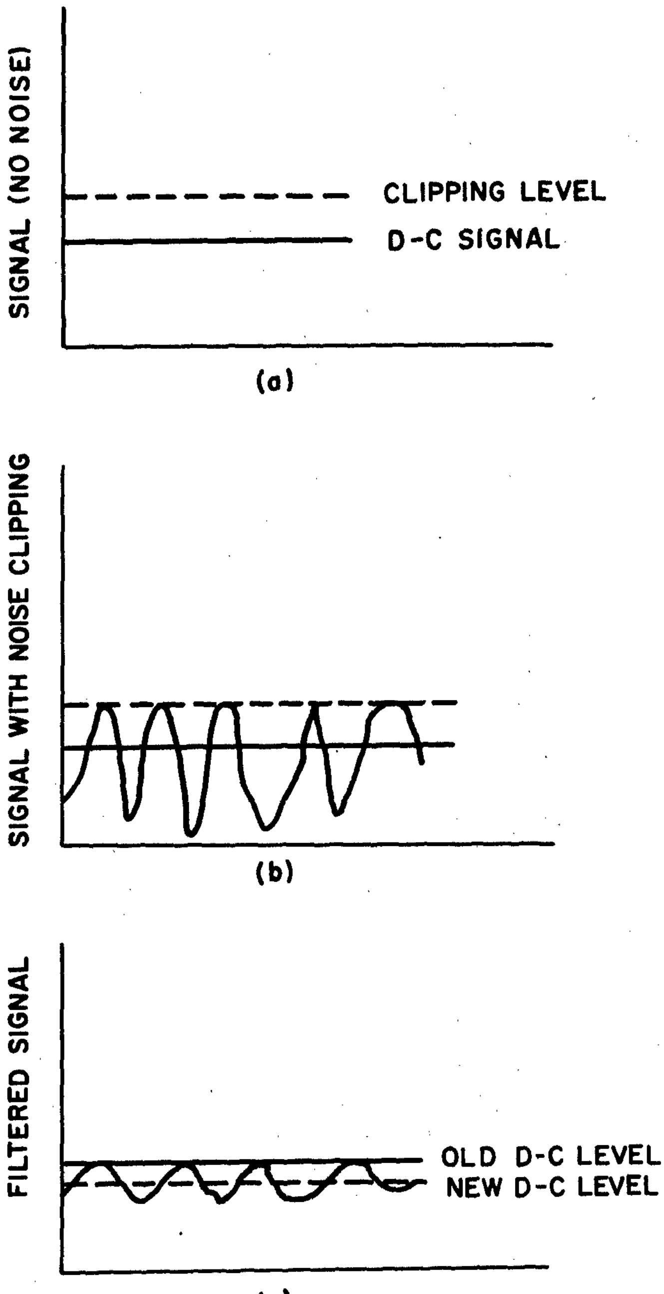
$$e_{rms} = 7.4 \sqrt{RBT} \ \mu\mu \text{ volts}$$

Taking the temperature as 290° K:

$$e_{rms} = 0.057 \ \mu\text{volts}$$

The same formula is used to calculate the noise contributed by the input grid resistance:

$$e_{rms} = 0.060 \ \mu \text{ volts}$$


SIGNAL (NO NOISE)
CLIPPING LEVEL
D-C SIGNAL
SIGNAL WITH NOISE CLIPPING
FILTERED SIGNAL
OLD D-C LEVEL
NEW D-C LEVEL

(a)

(b)

(c)

The total input noise of the amplifier is then found by adding the tube noise and the grid resistor noise. This yield:

$$e_{rms} = \sqrt{(.057)^2 + (.060)^2}\ \mu \text{ volts} = .083 \text{ volts}$$

1.5 Radar Noise Calculation

The following is an example of a typical radar noise calculation:

Assume that a calculation of the theoretical maximum free space range of a radar system is required and that the system has the following characteristics:

Peak pulse power (P_p) = 20 kilowatts (kw)
System bandwidth (B) = 25 megacycles per second (mc/sec)
Transmitting antenna gain (G) = 10^3
Effective receiving antenna area (A_r) = 20 square feet
Effective target reflecting area (σ) = 500 square feet

The theoretical power (P_r) returned to the antenna from the target for a single pulse when the target is at a range (R) is shown to be as follows:

$$P_r = \frac{P_p \quad G\sigma}{(4\pi R^2)^2} \quad A_r = \frac{20 \times 10^3 \times 10^3 \times 500 \times 20}{16 \quad \pi^2 \ R^4} = \frac{1.3 \times 10^9}{R^4} \text{ watts/ft}^2$$

Assuming the apparent antenna temperature to be 300° K, the thermal noise power input (P_n) to the antenna is given as:

$$P_n = KTB = 1.4 \times 10^{-23} \times 300 \times 25 \times 10^6 = 1.1 \times 10^{-13} \text{ watts}$$

$$K = \text{Boltzmann's constant} = 1.38 \times 10^{-23} \text{ Joules/°K}$$

Then by taking a signal-to-noise ratio of 2 for the minimum target detection, the following is obtained:

$$S/N = 2 = \frac{1.3 \times 10^9}{R^4} / 1.1 \times 10^{-13}$$

This gives a maximum range formula as follows:

$$R = (60 \times 10^{20})^{\frac{1}{4}} = 2.8 \times 10^5 \text{ ft or 52 miles}$$

This represents a maximum range as determined by the theoretical lower limit of thermal noise of the antenna. This range will reduce as additional noise is added at the RF amplifier, mixer, and other signal processing stages.

1.6 Infrared Noise Calculation

The following is an example of a typical missile optical tracking beacon and detector system calculation:

For purposes of tracking a missile at ranges of 10 kilometers or less, a flashing xenon lamp is mounted on the missile body. This lamp radiates a peak power of 10 watts at a repetition frequency of 100 cps and a duty factor of 0.5. The receiver uses a photoconductive dector and collection optics with an aperture of 10 square centimeters. The bandwidth of the electronic system is 100 Hz. The photoconductive dector has a photocathode efficiency of 10 percent, that is, one in ten received photons produces a photoelectron at the surface of the cathode. The received power (P_r) for range (R) in centimeters at the aperture is given as follows:

$$P_r = \frac{10 \text{ watts} \times 10 \text{ cm}^2}{4\pi R^2}$$

Assuming that the average wavelength of the xenon lamp is 4500 angstrom units (photon energy of 4×10^{-19} Joules/photon), this may be expressed as:

$$P_r = \frac{2 \times 10^{19} \text{ photons/sec}}{R^2}$$

Taking the photocathode efficiency as 10 percent yields a photocathode current of:

$$I = \frac{0.33}{R^2} \text{ amperes}$$

Calculate the noise associated with this current as:

$$I_{rms} = \frac{32 \times 10^{-10}}{R} \text{ amperes}$$

and S/N ratio given by:

$$\frac{I}{I_{rms}} = \frac{10^8}{R}$$

Thus, the formula gives the signal-to-noise ratio for any range in centimeters (cm). At 10 km, for example, it is 100.