THE LIMITATIONS IN RESOLUTION AND DISCRIMINATION IN BRIGHTNESS DIFFERENCES FOR LIGHT AMPLIFIER SYSTEMS USING CONTRAST ENHANCEMENT

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INTRODUCTION

A requirement exists for light amplification in the military and scientific fields to observe phenomena that the human eye, even at its best cannot sense, or for photographing objects at light levels for which present photographic systems are not sufficiently sensitive. Furthermore, there exist many situations in which the intensification of the light is not as essential as the necessity to increase the contrast between the objects in the field of view as they are presented in the intensified image to the human eye or recording device. An effective light amplifying device, in addition to being able to detect the lowest light levels that are of interest to be presented on the reproducer, must permit an arbitrary increase in contrast. The limitations of the device should be governed only by the randomness of light itself and the randomness of the conversion of the energy of the light. At the present state-of-the-art, the only system capable of fulfilling both requirements, light intensification and contrast enhancement, is the closed circuit television light amplifier. It is possible with this kind of light amplifier to increase the contrast of the reproduced picture on the cathode-ray tube screen arbitrarily to such an extent that only a fraction of the value of the fluctuations (irregular statistical variations) in the emission from the photocathode dark current of the pick-up tube corresponds to the total brightness range of the cathode-ray tube screen. Hence, brightness differences too small to be sensed or easily overlooked by the unaided human eye may be readily perceived visually from the cathode-ray tube screen of such a light amplifier. The necessary change in contrast can easily be achieved with proper circuitry in the video amplifier of the closed circuit television system. The video amplifier circuitry can also be built in such a manner that arbitrary threshold and amplitude limiting of the signal permits any amount of the signal to be supressed, and only that portion of the signal containing pertinent information is amplified. Such an arrangement makes possible the reproduction on the cathode-ray tube screen of celestial bodies during the daytime hours without reproduction of the brightness of the daytime sky. This unique property of the closed circuit television light amplifier system permits effective daytime tracking and photographic recording of artificial satellites which otherwise, by employing conventional methods, could not be done (Gebel, 1958).

I started research work on this type of light amplifier at the Aeronautical Research Laboratory in 1952, and the first system was flight-tested in 1953 on several moonlit nights. Although the results were favorable and most observers on the flights were more than impressed, the system at that time could not provide pictures of the ground under star light alone. The objective of obtaining pictures at light levels that cannot be sensed by the unaided human eye was finally solved by developing, under contract, the intensifier image orthicon. This tube uses one or more intensifier stages in the same envelope before the storage and scanning sections of an ordinary image orthicon (Morton, Ruedy, Kelley, and Ward, 1960). The research task also investigated the use of special target plates for this type of system (Lempert, 1960). Further, special pick-up tubes producing a video signal from moving objects only have been conceived and successfully developed under contract by the Aeronautical Research Laboratory (Gebel, 1960). The extraordinary importance of the latter pick-up tube for use in the military field and the superiority of such a light amplifier over the single or multi-stage image converter tube type light intensifier is evident and needs no further explanations.

THE LIMITATIONS IN LIGHT AMPLIFICATION

Light amplification, because of the quantum nature of light, is faced with certain limitations. The act of vision or of measuring or recording light may be considered as a counting of quanta of light for a selected exposure time and for selected areas of resolution. Due to the quantum nature of light, different elements of resolution at the focal plane, receiving their illumination from the same light source with an equal average intensity, will deviate from each other in the true count of quanta which has fallen upon them during the selected time of exposure. It is usually assumed that the probability of the deviation in the number of quanta to which the different resolution elements have been exposed corresponds to a Poisson distribution. Therefore, the standard deviation from the average is approximately the square root of the average number of the collected quanta of light during the selected exposure time and for the selected resolution area (Rose, 1948). The detector for the light, which may be, for example, a photocathode transducing the energy of the light into electrons or a photographic emulsion transducing the energy into photographic grains, may have a quantum efficiency which is small compared to unity. Then the deviation from the average number of electrons or photographic grains obtained is the limiting factor in detection, because of the randomness of the conversion of the energy and of the smaller numbers involved. The statistical distribution considered valid here is also a Poisson distribution. The fluctuation in the light focused onto the resolution element is usually neglected and the standard deviation then is determined only by using the square root of the average number of produced electrons or grains. This fundamental deviation in the number of produced electrons or photographic grains which exists between the different resolution elements for a homogeneously exposed detector is the theoretical limiting factor for detecting brightness differences between different resolution areas. If the difference in brightness between resolution elements becomes so small that the standard deviation in the number of electrons or photographic grains produced during the selected exposure time for each resolution element becomes equal to the average difference in brightness between resolution elements, then obviously the probability to detect with certainty which resolution elements belong to the brighter or the darker object is too small for practical purposes (Rose, 1948).

THEORETICAL SIGNAL TO NOISE RATIO FOR DETECTION OF LIGHT AS A FUNCTION OF RESOLUTION AND EXPOSURE TIME

In analogy to certain practices in electronics, we may consider the standard deviation from the average number of quanta of light, or the average number of produced electrons or photographic grains, as the noise and the average count as the signal. For further clarification of this terminology I shall first analyze the situation involving a detector which is divided into a large number of resolution elements of equal area. All the resolution elements have been exposed to a uniform illumination at the same time and for the same selected time duration. Then the standard deviation from the average number of electrons or grains will be the measure of the amount of deivation that has to be considered as existing between the number of electrons or grains occuring at the different resolution elements. This case applies to photographic emulsions, etc., if used as an image detector. The other situation would involve a detector whose whole area is used as one single resolution element. This single resolution element is repeatedly exposed to the same flux of light, the exposures being of equal time duration. Here, the standard deviation will be the measure of the amount of deviation that has to be considered to exist between the counts of electrons during the different exposures. This case applies to photo cells, etc. Both cases are basically identical, as they are the result of the randomness of the conversion of the energy of light. In the following calculations the purpose for assuming the most optimistic values is to prevent unrealistic speculations, and also to provide a goal in the field of light amplification. Under these assumptions, for electronic image conversion, all noise sources are neglected except the fundamental fluctuation (irregular statistical variations) of the photoemission, expressed by the standard deviation in the average number of electrons emitted by the photocathode. For the photographic case an ideal emulsion having no inherent background is assumed.

I shall derive equations for an image detector which has a large number of resolution elements, where the resolution elements are arbitrarily selected but of equal size. In these derivations I shall deal with the electronic case, but the equations may also be applied analogously to the photographic case; then, the parameters such as "electrons", "television lines", etc., would have to be changed to the proper terminology.

I shall designate as e_p the average number of electrons produced during the selected exposure time by a selected area of resolution. As previously stated I shall ignore the fluctuation of light itself and consider only the randomness of the energy conversion process. Then I may write for the theoretical optimum signal to noise ratio, δ_e,

$$\delta_e = \frac{e_p}{e_p^{1/2}} = e_p^{1/2}. \tag{1}$$

Using the standard radiation curves for the Sun (Moon, 1940), the average number of quanta, Q_D, per mm^2 sec counted for a spectral region from $\lambda = 415$ mμ to 680 mμ and with a spectral composition similar to daylight, which corresponds to the illumination E_D in foot-candles, is found to be

$$Q_D \approx 10^{11} \cdot E_D. \tag{2}$$

Using this relationship and denoting with l_s the side length in mm of one square resolution element necessary to collect a sufficient number of quanta for obtaining a chosen signal to noise ratio, the exposure time as t_e in seconds, and the photocathode quantum efficiency as η_p, we may write for the number of electrons e_p occuring for one element of resolution during the selected exposure time

$$e_p = Q_D \cdot t_e \cdot \eta_p \cdot l_s^2, \tag{3}$$

and using Eq. (2) for Q_D for the spectral region as previously defined,

$$e_p \approx 10^{11} \cdot E_D \cdot t_e \cdot \eta_p \cdot l_s^2 \tag{4}$$

Eq. (4) used in Eq. (1) yields for δ_e

$$\delta_e \approx 3.2 \cdot 10^5 (E_D \cdot t_e \cdot \eta_p)^{1/2} \cdot l_s. \tag{5}$$

Rewriting Eq. (5) we find the value for l_s in mm

$$l_s \approx \frac{3.2 \cdot 10^{-6}}{E_D^{1/2}} \cdot K_1 \tag{6}$$

where

$$K_1 = \delta_e \left(\frac{1}{t_e \cdot \eta_p} \right)^{1/2}. \tag{7}$$

Figure 1 is a graphic illustration of Eq. (6) using l_s as a function of E_D with $K_1(\delta_e, t_e,$ and $\eta_p)$ as parameters. Figure 2 compares the theoretical limit in detection of the lowest possible light level in accordance with the previous equations with the best double stage intensifier image orthicon pick-up tube. These tubes were built by Dr. G. A. Morton and Dr. J. E. Ruedy of RCA under contracts AF33(616)-2631 and AF 33(616)-3946, initiated by the Aeronautical Research Laboratory.

For practical purposes, it is not only of interest to know the photocathode illumination, but also the lowest permissible brightness B_L in foot-lambert in the field of view as a function of l_s which can be achieved with the different possible optical systems. The relationship between the illumination E_D in the focal plane and the brightness B_L is given by the well known equation

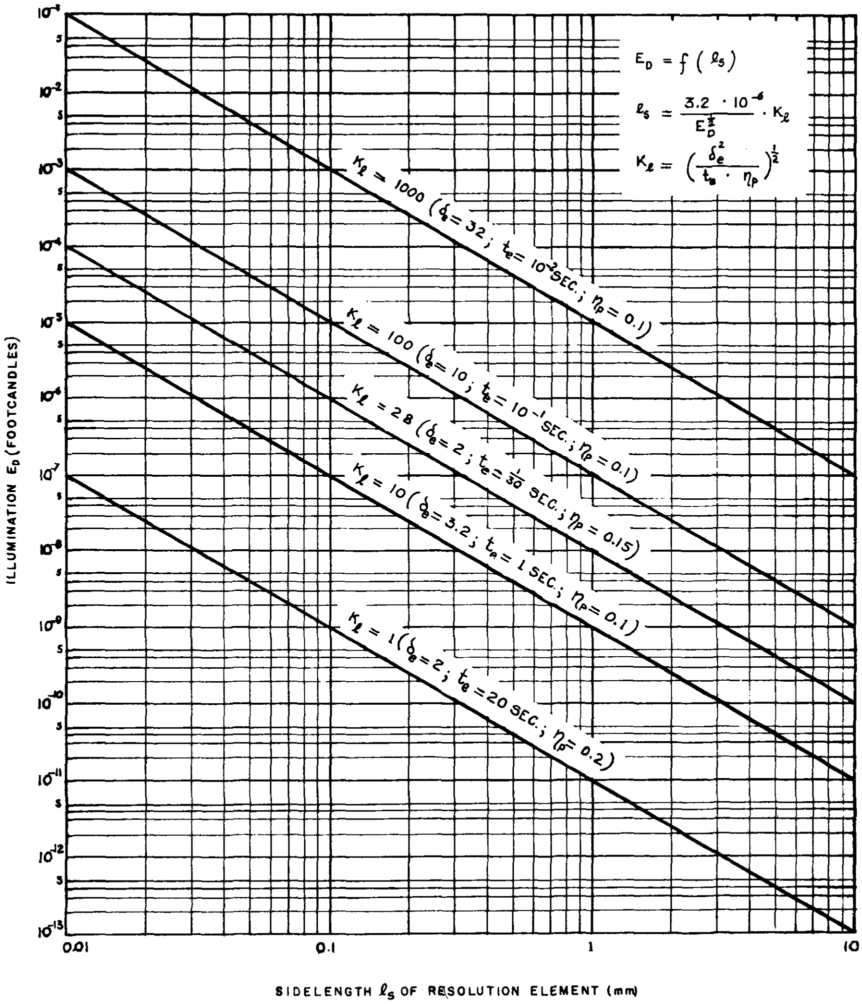

FIGURE 1. Minimum illumination of a photosensor necessary for detection as a function of the sidelength of resolution element with the indicated design parameters.

$$E_D = \frac{1}{4} \cdot \frac{B_L}{F^2} \cdot \eta_T. \tag{8}$$

where η_T is the transmission factor of the lens and F is the aperture number of the lens ($F = \frac{f_T}{D}$, where f_T and D are the focal length and diameter of the lens system, respectively). If E_D is known as assumed in fig. 1, then the factor K_B by which E_D must be multiplied to obtain the necessary brightness of the observed area for the lens system employed may be calculated by rewriting Eq. (8)

$$K_B = \frac{B_L}{E_D} = \frac{4 \cdot F^2}{\eta_T}. \tag{9}$$

For the present state-of-the-art the efficiency η_T of the lenses may be assumed to be approximately 0.6 to 0.8, depending on the number of lens elements used and other design factors. If E_D in figure 1 is multiplied by a factor 5 F^2 the graph can be used for obtaining the lowest possible light levels as a function of resolution at the focal plane.

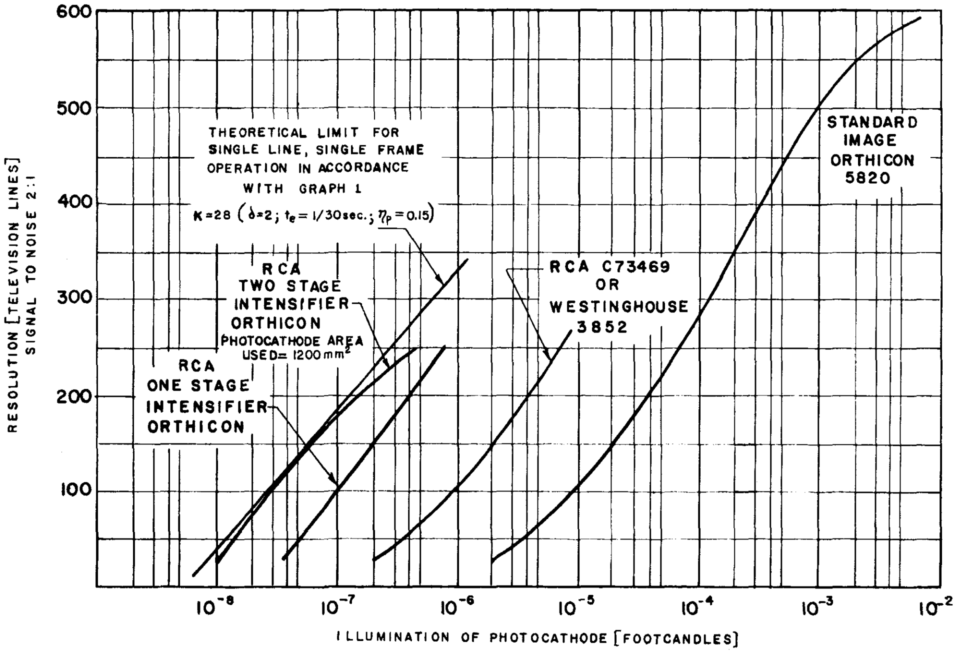

FIGURE 2. Pick-up tube performance compared to the theoretical limit of detectability.

THE PROBLEM OF CONTRAST DISCRIMINATION

In the previous section I treated some of the fundamental problems in detecting light, and I was concerned about the smallest possible area that can be detected as a function of light level, signal to noise ratio and other parameters involved. In practice, however, the problem does not consist in the detection of the lowest possible light level only, but also in detecting different objects in the field of view which requires the capability of discriminating between different brightness levels. It is of utmost importance in this field of endeavor to determine the smallest brightness difference which can be detected as a function of light level and the other design parameters involved. If I have to discriminate between an area having a brightness level of B_O in foot-lambert and another area or the background with the lesser brightness of B_B in foot-lambert, I may define as contrast C between the two areas

$$C=\frac{B_O-B_B}{B_B}=\frac{B_\Delta}{B_B}. \tag{10}$$

As stated previously, because of the quantum nature of light the instantaneous values of B_O and B_B are not constant but fluctuating, and it is usually assumed that the deviations from their average value corresponds to a Poisson distribution. It is logical to consider, as it is usually done, the probability, p, to be for practicle purposes, zero for discriminating between B_O and B_B if the difference B_Δ between the average values of B_O and B_B becomes smaller than the standard deviation of the background radiation. Furthermore, since I am dealing with detectors having a quantum efficiency of a small fraction of unity, I may neglect the deviation from the average photon number of B_O and B_B and must consider the standard deviations in the number of produced electrons. I shall designate with e_O the average number of electrons caused by B_O during the selected time at one resolution element and with e_B the average number of electrons that are caused by B_B during the selected time at one resolution element; the difference between e_O and e_B we shall call e_Δ. Then in consideration of the previous statements I will arbitrarily assume here that the limit in contrast discrimination is reached when e_Δ becomes equal to the standard deviation of e_B. I may write now in accordance with our definitions

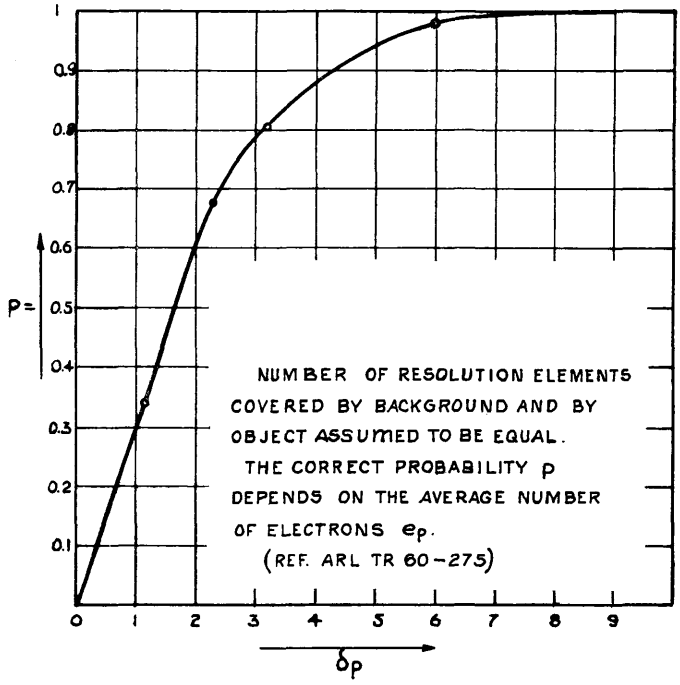

FIGURE 3. Approximate probability for discrimination between an object and surrounding background, using a photosensor.

$$C=\frac{e_O-e_B}{e_B}=\frac{e_\Delta}{e_B} \tag{11}$$

and minimum contrast c_{lim} occurs when

$$e_\Delta=e_B^{1/2}. \tag{12}$$

A certain probability p of detection is assured when

$$e_\Delta = \delta_p \cdot e_B^{1/2} \tag{13}$$

where the relations between p and δ_p is shown in figure 3, which has been calculated by using a graph showing the deviation from the average number n of a Poisson distribution, which was treated in another paper of mine (Gebel and Devol, 1961).

It follows from Eqs. (4), (10), and (12) that the contrast c_{lim} which assures a certain probability of detection p is given by

$$c_{lim} \approx \frac{3.2 \times 10^{-6}}{(E_B)^{1/2}} \cdot K_D \tag{14}$$

where

$$K_D = \frac{\delta_p}{l_s} \left(\frac{1}{t_e \cdot \eta_p} \right)^{1/2}. \tag{15}$$

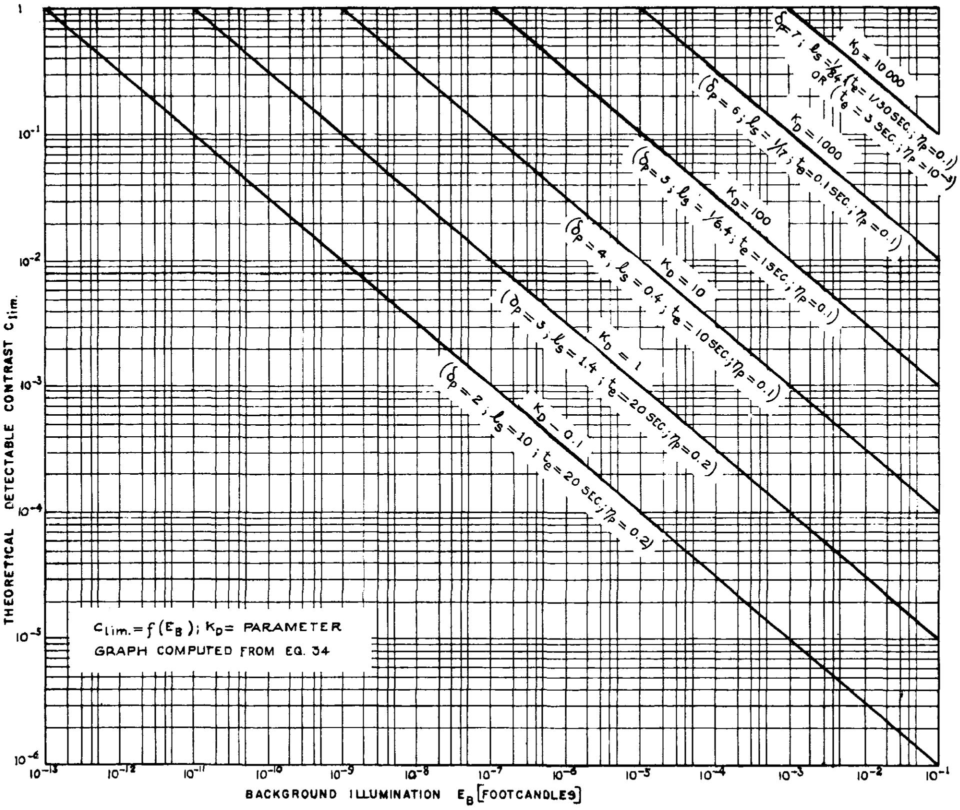

FIGURE 4. Contrast theoretically detectable by a photosensor as a function of background illumination.

To assure the proper intended use of Eq. (14), according to the assumptions used here, the selected background illumination E_B must be sufficiently high for the chosen K_D to produce, for each resolution element, an average of more than one electron, using the parameters t_e, η_p, and $\frac{1}{l}$. This situation is satisfied when

$$10^{11} \cdot E_B \cdot t_e \cdot \eta_p \cdot \frac{1}{l_s} > 1. \tag{16}$$

For practical applications, levels of background illumination producing for each resolution element during the selected exposure time only a few electrons, are not of too much concern as the limiting factor for contrast detection. The practical limitation here is usually the photocathode dark current emission (for the photographic case, fogging of the emulsion).

In Figure 4, by using Eq. (14), the limiting contrast is shown as a function of the background illumination E_B with K_D as parameter. Using Eq. (9) the neces-

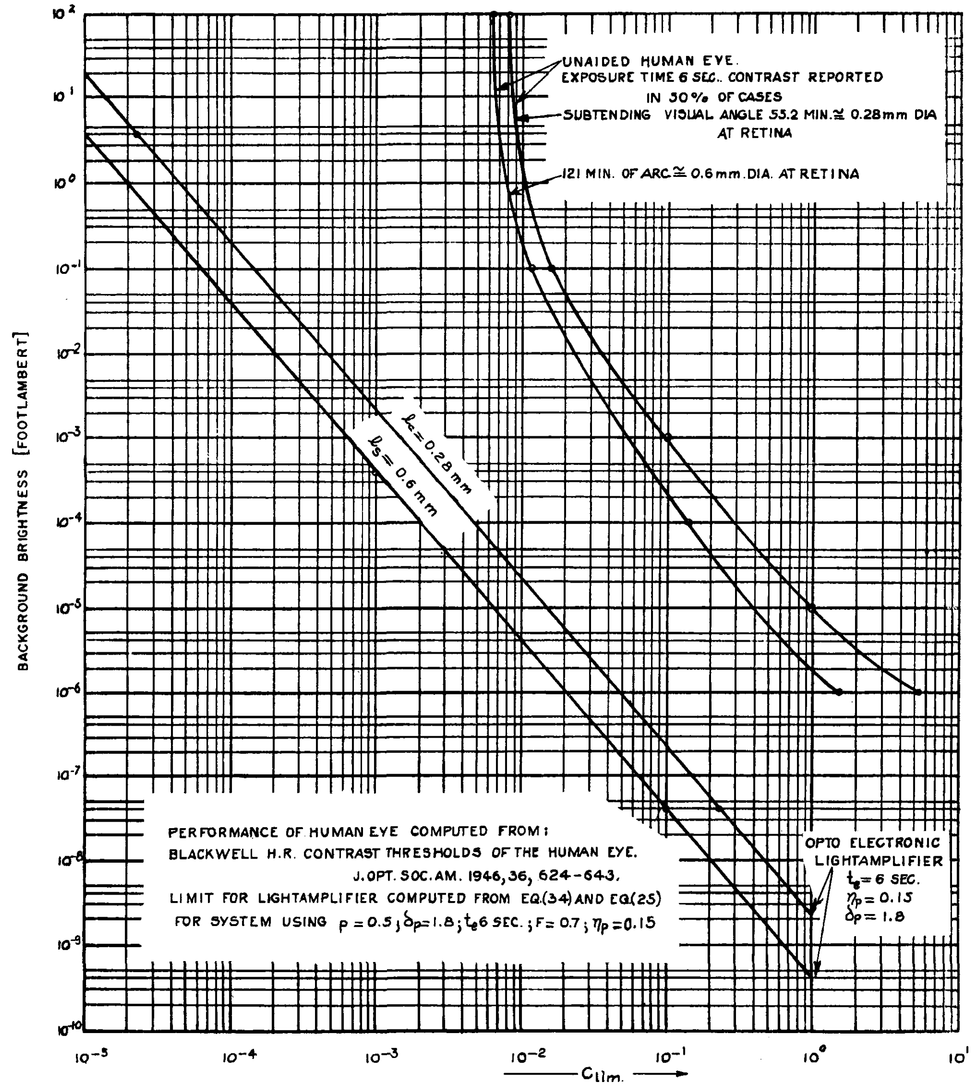

FIGURE 5. Practical threshold for contrast discrimination of the unaided human eye in comparison to the theoretical limit of closed circuit television light amplifier using contrast enhancement.

sary brightness for the object in the field of view for the lens system used may be calculated. Figure 5 compares the unaided human eye with the present state-of-the-art of a closed circuit television light amplifier, using a fast optical system and a cooled double-stage intensifier image orthicon. By cooling the primary photocathode of the intensifier image orthicon pick-up tube, the fluctuations in the photo emission process become practically the only limitations in performance which have to be considered.

CONCLUSION

As shown by figure 5 the theoretical limitations in contrast discrimination approachable with the present state-of-the-art of light amplifier systems employing contrast enhancement, suitable pick-up tubes, and lenses with high light gathering power is considerably superior to that of the unaided human eye. Factors which will determine how far the superiority can be realized in practice are: (1) sufficient quantum efficiency and homogeneity of the photocathode in the pick-up tube; (2) proper cooling of the front end of the tube to avoid the practical limitation of the photocathode dark current; (3) enough preamplification to overcome the scanning beam noise; and (4) adequate storage capability of the target plate.

ACKNOWLEDGMENTS

This technical report was accomplished under Project 7072, "Research on the Quantum Nature of Light", Task 70827, "Light Amplification", of the Aeronautical Research Laboratory, Air Force Research Division, with Mr. R. K. H. Gebel as task scientist. I wish to express my sincere thanks to Mr. Roy Hayslett for helpful suggestions and for his assistance in preparing this paper.

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