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Technical Note

1972-3

J. O. Dimmock
T. M. Quist

Range Capability
of an Infrared Vidicon Sensor
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LINCOLN LABORATORY

(6) RANGE CAPABILITY OF AN INFRARED VIDICON SENSOR (U). (8)

(Title UNCLASSIFIED)

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Group 52

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ABSTRACT

(U) The range capability of an infrared photoconductive vidicon is calculated as a function of background photon flux density. Range is maximized by adjusting a quantity which involves the target photoconductive gain, the quantum efficiency and the spectral bandwidth. The optimum value of the product of these three factors is obtained as a function of background flux. A limiting factor is the amount of charge that can be stored on the vidicon retina for the frame time. This is determined by the maximum breakdown field of retina material and the retina capacitance or dielectric constant. The resultant equations are evaluated for several practical situations. In the case of high backgrounds, range capability can be increased by enhancing the capacitance of the vidicon retina or alternatively by employing frame-to-frame signal integration.

Accepted for the Air Force
Joseph R. Waterman, Lt. Col., USAF
Chief, Lincoln Laboratory Project Office

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RANGE CAPABILITY OF AN INFRARED VIDICON SENSOR (U)

I. INTRODUCTION

(U) In this note we calculate the range capability of an infrared photoconductive vidicon as a function of background photon flux density. It is assumed that the vidicon is operating in the return beam mode and that the dominant noise is beam shot noise. Range is maximized by adjusting a quantity which involves the target photoconductive gain, the quantum efficiency, and the spectral bandwidth. The optimum value of the product of these three factors is obtained as a function of background flux. A limiting factor is the amount of charge that can be stored on the vidicon retina for the frame time. This is determined by the maximum breakdown field of the retina material and the retina capacitance or dielectric constant.

II. ANALYSIS

(U) The electron beam current required to replace the charge lost during the discharge or frame time, t_f , is given by

$$i_b = \frac{Q}{t_d} = \frac{C_e (V_o - V_c)}{t_d} \quad , \quad (1)$$

where t_d is the dwell time of the electron beam on an elemental area A_e of capacitance C_e , and

$$V_o - V_c = V_o (1 - e^{-t_f/RC}) \quad , \quad (2)$$

where V_o is the initial and V_c the final voltage across the retina. The

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discharge RC time constant is given by

$$RC = \rho \epsilon = \epsilon / \sigma \quad (3)$$

where ρ , ϵ , and σ are the resistivity, dielectric constant, and conductivity, respectively, of the retina target material. The conductivity is assumed to be determined by the background photon flux density at the retina and is given by the current density j divided by the applied electric field E :

$$\sigma = j/E \quad (4)$$

The current density in the photoconductor is given by

$$j = \frac{q}{h\nu} H'_b \eta G \quad (5)$$

where q is the electronic charge, $h\nu$ is the photon energy, H'_b is the background flux density at the retina, η is the quantum efficiency, and G is the photoconductive gain given by

$$G = \frac{\mu\tau E}{d} \quad (6)$$

where μ is the carrier mobility, τ is the carrier lifetime, and d is the target thickness. The conductivity is thus given by

$$\sigma = \frac{q}{h\nu} H'_b \eta \frac{\mu\tau}{d} \quad (7)$$

and is a constant throughout the discharge time, although E is changing.

The RC discharge time is given by

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$$KC = \frac{hv}{q} \frac{\epsilon d}{H'_b n \mu \tau} = \frac{hv}{q} \frac{\epsilon E}{H'_b n G} \quad (8)$$

(U) The electron beam current required is then given by

$$i_b = \frac{C V}{t_d} \frac{e o}{t_d} (1 - e^{-K t_f H'_b}) \quad (9)$$

$$= \frac{\epsilon A V}{d t_d} \frac{e o}{t_d} (1 - e^{-K t_f H'_b}) \quad (10)$$

$$= \frac{\epsilon A E o}{t_d} (1 - e^{-K t_f H'_b}) \quad (11)$$

where E_o is the initial field across the retina and K is a factor given by

$$K = \frac{q}{hv} \frac{n \mu \tau}{\epsilon d} = \frac{q}{hv} \frac{n G}{\epsilon E} \quad (12)$$

(U) We can consider that the signal current is the change in i_b brought about by a small change in H'_b . Thus,

$$i_s = \Delta i_b = \frac{\epsilon A E o K t_f}{t_d} e^{-K t_f H'_b} \Delta H'_b \quad (13)$$

where $\Delta H'_b$ like H'_b is in watts/cm². If we assume that this is focussed on a single element of area A_e , then $\Delta H'_b = h_s / A_e$ where h_s is the signal flux on the retina in watts.

(U) The shot noise in a return beam vidicon is given by¹

$$\overline{i_n} = (2q i_b B/m)^{1/2} \quad (14)$$

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where $B = 1/2t_d$ is the bandwidth and

$$m = i_b/I_b \quad (15)$$

is the ratio of target discharge current to total read beam current I_b . For optimum sensitivity, m will typically take on values between 0.15 and 0.2.¹ For the present, we will assume a value of 0.2. Substituting Eq. (11) in Eq. (14) and solving for the signal-to-noise ratio using Eq. (13), we obtain after rearranging terms

$$\frac{S}{N} = \frac{i_s}{I_n} = \frac{h_s}{H'_b} \left(\frac{m\epsilon E_o}{qA_e} \right)^{1/2} \frac{xe^{-x}}{(1 - e^{-x})^{1/2}} \quad , \quad (16)$$

where

$$x = Kt_f H'_b = \frac{t_f}{RC} \quad (17)$$

$$= \frac{q}{hv} \frac{\eta \mu \tau}{\epsilon d} t_f H'_b = \frac{q}{hv} \frac{\eta G}{\epsilon E} t_f H'_b \quad . \quad (18)$$

(U) The signal flux h_s and background flux H'_b at the retina can be referred back to the target signal and background flux density incident on the optical system

$$h_s = \frac{H_s A_s A_o}{\pi R^2} T_o \quad , \quad (19)$$

where H_s is the source radiance in watts/cm², A_s is the source area, A_o is the optics area, R is the range, and T_o is the total transmission efficiency of the optical system.

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$$H'_b = \frac{H_b}{4F^2} T_o \quad , \quad (20)$$

where H_b is the background flux density at the entrance aperture, and F is the f -number of the optical system. Substituting in Eq. (16) using $A_o = \pi D^2/4$ where D is the optics diameter we obtain

$$\frac{S}{N} = \frac{H_s A_s F^2 D^2 \eta_s}{R^2 H_b} \left(\frac{m\epsilon E_o}{q A_e} \right)^{1/2} \frac{x e^{-x}}{(1 - e^{-x})^{1/2}} \quad , \quad (21)$$

where η_s is the fraction of the signal flux falling on the elemental area A_e . Using $f = FD$ where f is the focal length, $A_e = A_r/n$ where A_r is the active area of the retina, n is the number of resolution elements, and $\Omega_{FOV} = A_r/f^2$ where Ω_{FOV} is the total angular field of view, Eq. (21) becomes

$$\frac{S}{N} = \frac{H_s A_s \eta_s}{H_b R^2 \Omega_{FOV}} \left(\frac{m\epsilon E_o}{q} n A_r \right)^{1/2} \frac{x e^{-x}}{(1 - e^{-x})^{1/2}} \quad . \quad (22)$$

(U) The signal-to-noise ratio or alternatively, the range given by Eq. (22) can be maximized with respect to the parameter x . For example, we can write H_s and H_b in terms of the spectral radiance in watts/cm² micron, $H_s = W_s \Delta\lambda$, and $H_b = W_b \Delta\lambda$, where $\Delta\lambda$ is the spectral bandwidth of the sensor. Equation (18) then becomes

$$x = \frac{q}{h\nu} W_b \frac{\eta G \Delta\lambda}{\epsilon E} t_f \cdot \frac{T_o}{4F^2} \quad (23)$$

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so that Eq. (22) can be optimized by adjusting the product $\eta G A \Delta t_f$ or alternatively $\eta \Delta t_f$. Taking the derivative of Eq. (22) with respect to x or effectively with respect to these parameters (since $H_s/H_b = W_s/W_b$ is assumed independent of Δ), we obtain a maximum at $x = x_0 = 0.6438$, for which

$$Y_0 = \frac{x_0 e^{-x_0}}{(1 - e^{-x_0})^{1/2}} = 0.4908 \quad .$$

The maximum range obtainable through adjustment is given, from Eq. (22), by

$$R^2 = \frac{W_s A_s \eta Y_0}{W_b \Omega_{FOV} S/N} \left(\frac{mcE_0}{q} n A_r \right)^{1/2} \quad (24)$$

under the condition that x given by Eq. (23) equals x_0 .

(U) There is an additional condition which must be considered. The minimum amount of target beam current which can be supplied by an oxide-coated thermionic cathode is approximately 10^{-6} A,² although this might be increased to 10^{-5} A by using a higher-power electron gun.³ Under high background operating conditions, this is given by i_b , where

$$i_b = \frac{\epsilon A_e E_0}{t_d} (1 - e^{-x_0}) \quad . \quad (25)$$

However, $A_e/t_d = A_r/t_f$ so that this becomes

$$i_b = \frac{\epsilon A_r E_0}{t_f} (1 - e^{-x_0}) \quad . \quad (26)$$

(U) In the case where the minimum elemental area A_e is limited by the diffraction of the optics, A_e is given by

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$$A_e = (2.44F\lambda)^2, \quad (27)$$

where λ is the wavelength of the signal radiation. Therefore, the effective number of resolution elements is

$$n = \frac{A_r}{(2.44F\lambda)^2}. \quad (28)$$

Substituting this into Eq. (24), we obtain

$$R^2 = \frac{W_s A_r n Y_o}{W_b \Omega_{FOV} S/N} \frac{A_r}{(2.44F\lambda)} \left(\frac{m\epsilon E_o}{q} \right)^{1/2}. \quad (29)$$

However, using $\Omega_{FOV} = A_r/f^2$ and $f = FD$, this can be rewritten as

$$R^2 = \frac{W_s A_r n Y_o}{W_b S/N} \frac{fD}{(2.44\lambda)} \left(\frac{m\epsilon E_o}{q} \right)^{1/2}. \quad (30)$$

This can be rewritten in one additional useful form using Eq. (26) as

$$R^2 = \frac{W_s A_r n Y_o}{W_b S/N} \frac{D}{(2.44\lambda)} \left\{ \frac{m t_f i_b}{q \Omega_{FOV} (1 - e^{-x_o})} \right\}^{1/2} \quad (31)$$

Since the electron beam current is effectively limited to between 10^{-5} and 10^{-6} A, this indicates that one cannot gain indefinitely by increasing ϵ and E_o without increasing t_f as is also shown by Eq. (26).

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III. EVALUATION

(S) We can evaluate these range equations for various values of the relevant parameters. For a 1-m^2 , 300°K unit emissivity standard target in the $7.5\ \mu\text{m}$ region, $W_s A_s = 26\ \text{W}/\mu\text{m}$. We assume a minimum signal-to-noise ratio of $S/N = 6.5$ and a fraction of the signal power in a minimum resolution element $\eta_s = 0.84$. For the optical system, we assume

$$D = 25.4\ \text{cm}$$

$$F = 1.5$$

$$f = 38.1\ \text{cm}$$

$$A_r = 2.7 \times 2.7\ \text{cm} = 7.29\ \text{cm}^2$$

$$\Omega_{\text{FOV}} = 0.071 \times 0.071\ \text{rad} = 5 \times 10^{-3}\ \text{sr} (4^\circ \times 4^\circ)$$

For a $7.5\ \mu\text{m}$ system, this gives for A_e from Eq. (27)

$$A_e = 27.5 \times 27.5\ \mu\text{m} = 7.56 \times 10^{-6}\ \text{cm}^2$$

$$n = 984 \times 984 = 9.68 \times 10^5$$

(S) For an Al-doped Si retina, we estimate a maximum bias field of $E_0 = 1000\ \text{V}/\text{cm}$ and the dielectric constant is $\epsilon = 11.5\ \epsilon_0 = 1.02 \times 10^{-12}\ \text{F}/\text{cm}$. Using these parameter values, the range obtained vs background flux density is plotted in Fig. 1 (curve labeled $\epsilon = 11.5\ \epsilon_0$). We have also plotted in Fig. 1 a curve corresponding to a retina with a hundredfold enhanced capacitance (curve labeled $\epsilon = 1150\ \epsilon_0$). For the parameters assumed above, ($\epsilon = 11.5\ \epsilon_0$, $A_r = 7.29\ \text{cm}^2$, $E_0 = 1000\ \text{V}/\text{cm}$), and a $1/30\ \text{sec}$ frame time, Eq. (26) gives a beam current of $10^{-7}\ \text{A}$, well within the present

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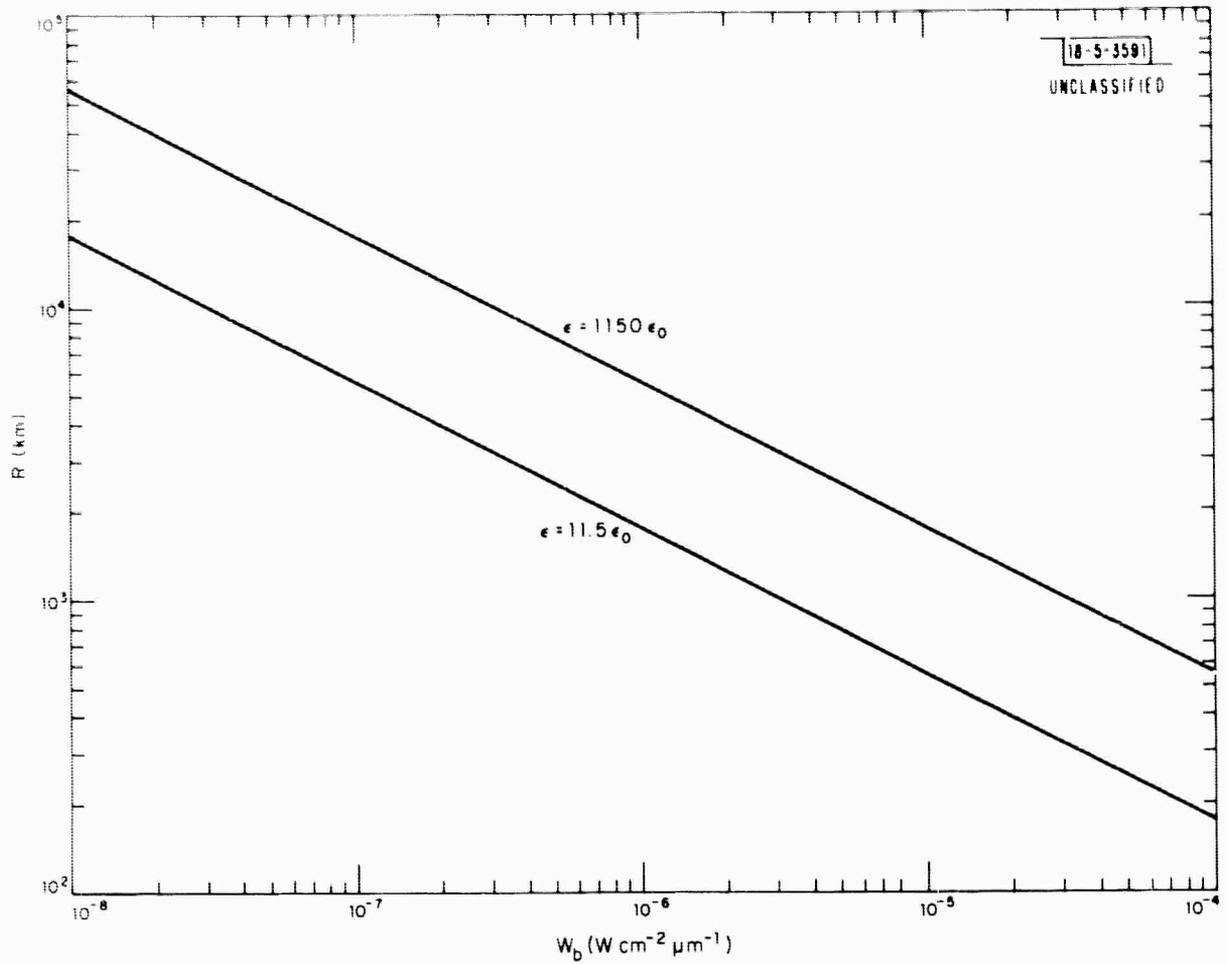


Fig. 1. Range vs background radiation density for an infrared vidicon sensor with and without capacitive enhancement. (U)

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electron gun capabilities. It has been suggested by H. Sippach and R. Reddington of General Electric that it may be possible to enhance the capacitance of the retina by as much as a factor of 100 by employing special structures. The present electron gun could handle a factor of 10 increase in capacitance at the same 1/30 sec frame time. A factor of 100 could only be accommodated through the incorporation of the higher-power electron gun, which is a major modification, or through an increase in frame time to 1/3 sec.

(S) In Fig. 2 we plot the optimum values of ηG , $\Delta\lambda$, and t_f as a function of W_b from Eq. (23) setting $x = x_0$. As Eq. (23) only establishes the product of these quantities, their values can be traded off against each other. In Fig. 2 we have assumed a maximum value for ηG of 0.05, $0.1 \mu\text{m} \leq \Delta\lambda \leq 2 \mu\text{m}$ and a minimum value for t_f of 1/30 sec. For a specific system, different values for t_f , ηG , and $\Delta\lambda$ than those shown in Fig. 2 may be desirable, but it appears that an optimum condition can be reached for the background shown provided one is willing to use long frame times in low backgrounds. This is not a serious problem as the system is very sensitive in these backgrounds and a departure from optimization will not seriously degrade the range capability. A similar plot for the capacitively enhanced system is given in Fig. 3. This indicates that the capacitively enhanced system cannot be optimized much below $W_b = 10^{-6} \text{ W/cm}^2 \mu\text{m}$. Again, this is not much of a problem as the system is very sensitive and one would probably prefer to employ a nonenhanced system with a faster frame rate in these backgrounds.

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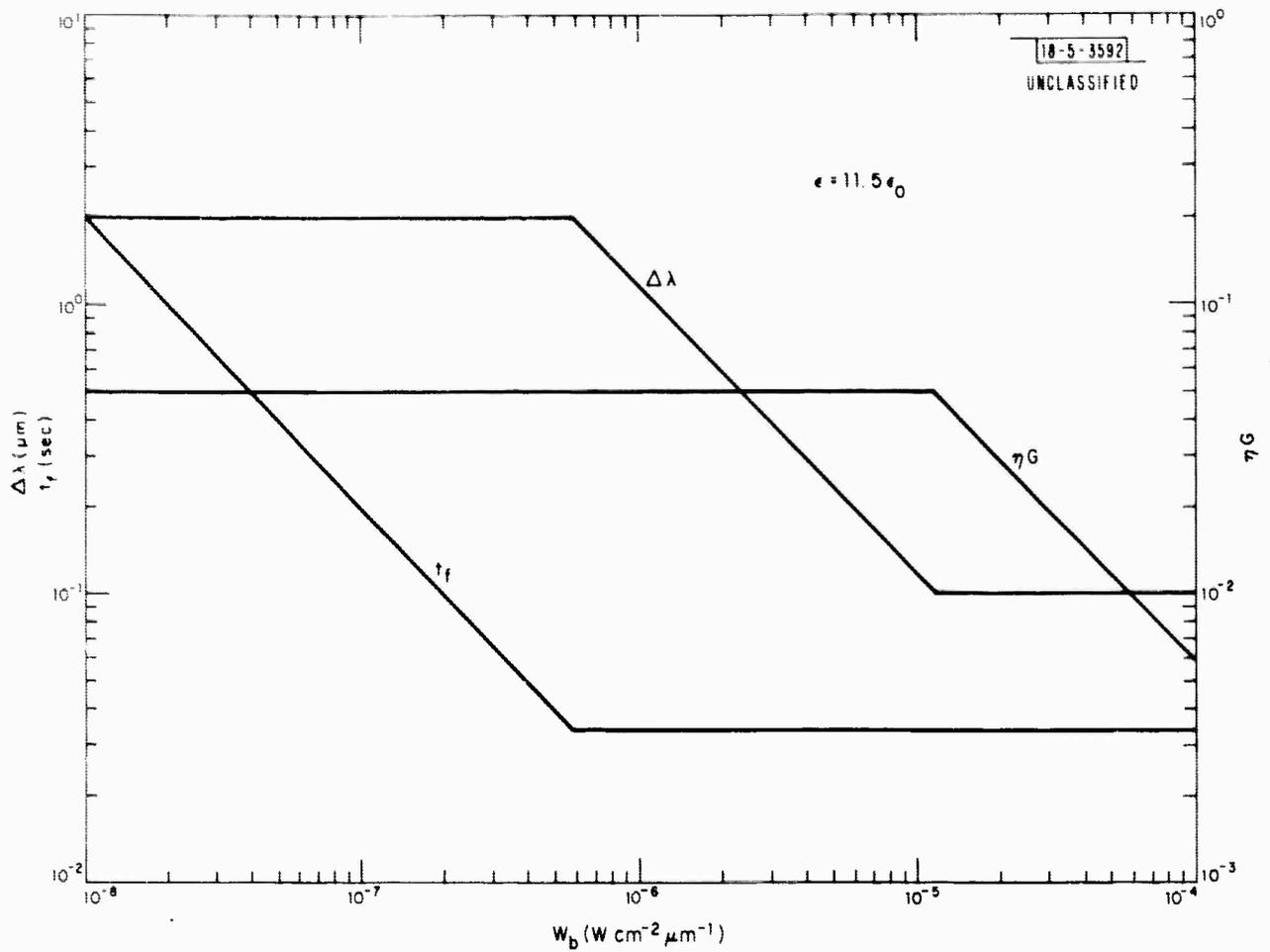


Fig. 2. Optimum values of frame time, spectral bandwidth and gain-efficiency product as a function of background radiation density for the vidicon sensor without capacitive enhancement. (U)

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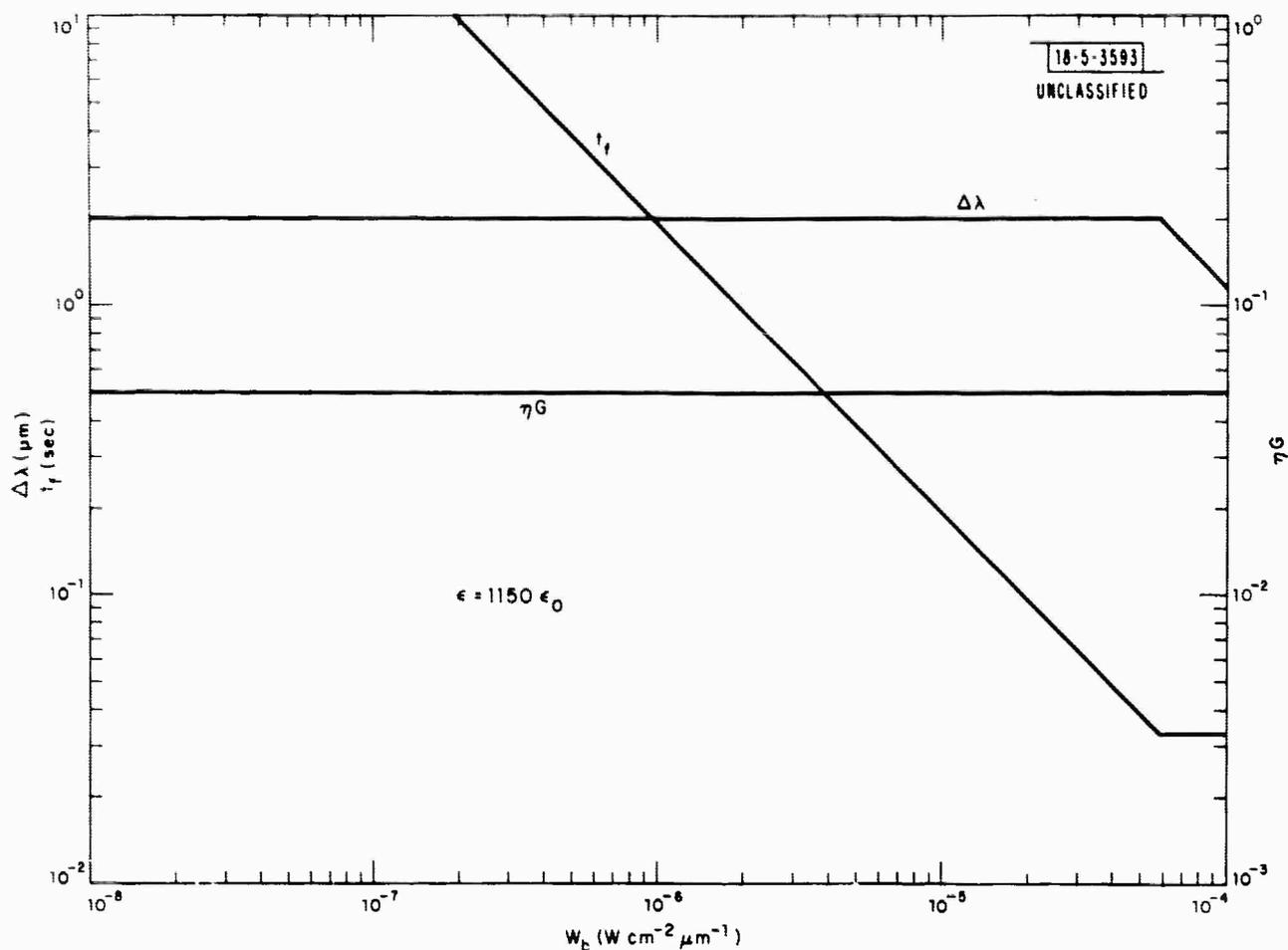


Fig. 3. Optimum values of frame time, spectral bandwidth and gain-efficiency product as a function of background radiation density for the vidicon sensor with capacitive enhancement. (U)

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IV. CALCULATION FOR AN AIRCRAFT SYSTEM

(S) The background encountered by an aircraft-borne sensor system arises principally from two sources: the atmospheric background radiance at the altitude and look angle of the aircraft, and the radiance from any warm elements in the optical system. The ambient temperature outside an aircraft at altitudes between 40 and 100 kft is approximately 220°K so that optical elements at ambient should attain this temperature. The present refractive telescope is designed to operate with a 1-1/4" thick Ge objective, which will be at or near ambient temperature. The possibility of reducing the thickness of this by a factor of 2 is under study. The expected radiance of these two Ge objectives at 220°K is plotted in Fig. 4. Also plotted is the spectral radiance for a 220°K grey body with an emissivity of 1.5 percent, which is about the best one can hope to do using a reflective optical system, and that of a 300°K black body. Also shown in the figure is the atmospheric background radiance obtained from balloon measurements at 40 and 65 kft,⁴ adjusted for a look angle of 15° above the horizon. The optimum operating wavelength for each situation is that at which $W_s(300^\circ\text{K})/W_b\lambda$ is a maximum. This is given in Table I, along with the background flux density W_b , the signal flux density W_s , the optimum spectral bandwidth $\Delta\lambda$, and the expected system range. The values of ηG assumed are those given in Fig. 2 and $t_f = 1/30$ sec. The rest of the parameters are those assumed above for the noncapacitively enhanced retina.

(S) The results for a hundredfold capacitively enhanced system are given in Table II, where ηG is assumed fixed at 0.05 and $\Delta\lambda$ at 1.0 μm and the

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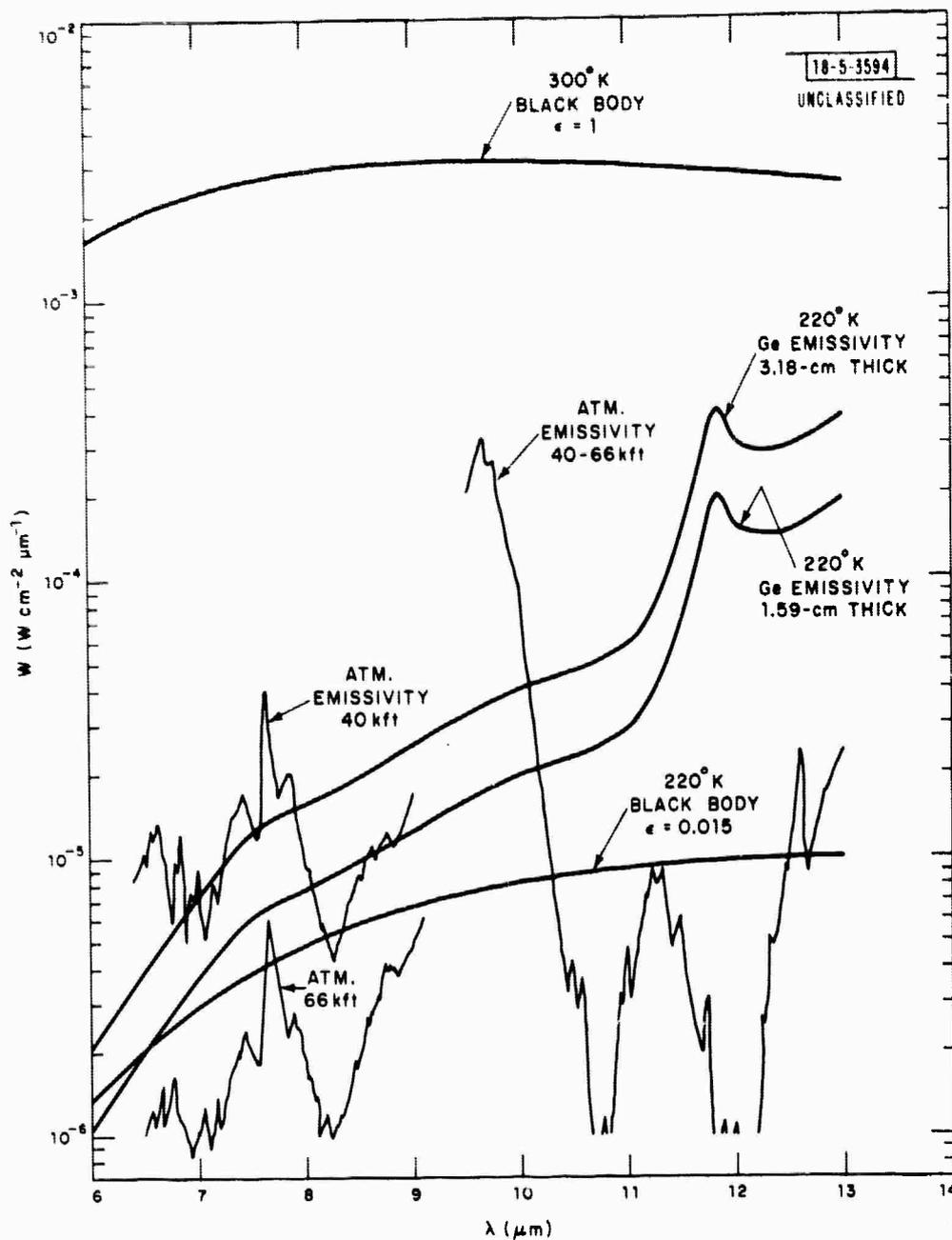


Fig. 4. Background and signal radiation density vs wavelength for a 300°K black body and various background conditions corresponding to aircraft altitudes of 40 and 66 kft and various optical systems. (U)

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TABLE I (S)

ALTITUDE	TELESCOPE	$\lambda_o (\mu m)$	$W_b (W cm^{-2} \mu^{-1})$	$W_s (W cm^{-2} \mu^{-1})$	$\Delta \lambda (\mu m)$	$t_f (sec)$	Range (Km)
40 Kft	Ge Refractor Ambient ele- ment 3.18cm thick	7.0	1.5×10^{-5}	2.4×10^{-3}	0.1	$\frac{1}{30}$	450
	Ge Refractor Ambient ele- ment 1.59cm thick	8.3	1.4×10^{-5}	3×10^{-3}	0.1	↓	500
	Reflective $\epsilon = 1.5\%$	8.3	9×10^{-6}	3×10^{-3}	0.1		600
66 Kft	Ge Refractor Ambient ele- ment 3.18cm thick	6.5	5×10^{-6}	2×10^{-3}	0.27	$\frac{1}{30}$	750
	Ge Refractor Ambient ele- ment 1.59cm thick	6.5	3×10^{-6}	↓	0.45	↓	950
	Reflective $\epsilon = 1.5\%$	6.5	3×10^{-6}		0.45		950

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TABLE II (S)

<u>ALTITUDE</u>	<u>TELESCOPE</u>	$\lambda_o (\mu m)$	$W_b (W cm^{-2} \mu^{-1})$	$W_s (W cm^{-2} \mu^{-1})$	$\Delta \lambda (\mu m)$	$t_f (sec)$	Range(Km)
40 Kf.	Ge refractor Ambient ele- ment 3.18cm thick	7	1.8×10^{-5}	2.4×10^{-3}	1	0.23	1300
	Ge refractor Ambient ele- ment 1.59cm thick		1.4×10^{-5}			0.3	1500
	Reflective $\epsilon = 1.5\%$		1.3×10^{-5}			0.32	1550
66 Kf.	Ge refractor Ambient ele- ment 3.18cm thick		1.0×10^{-5}			.42	1750
	Ge refractor Ambient ele- ment 1.59cm thick		5×10^{-6}			.84	2500
	Reflective $\epsilon = 1.5\%$		4.5×10^{-6}			.93	2600

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optimum values of t_f are given in the table. As indicated, the frame times get rather long for the lower backgrounds. Some departure from the optimum condition, along with a reduction in range, may be necessary if long frame times are not tolerable.

V. CONCLUSIONS

(S) An LWIR photoconductive vidicon's, in principle, a very sensitive device when operated under low background conditions. For optimum operating conditions the background at the retina should be less than approximately 10^{-7} W/cm² for a standard vidicon. If the charge storage capability of the retina can be increased by increasing its effective capacitance then the vidicon can be operated at higher background levels. For example, a 100 fold increase in capacitance would allow a 10 fold increase in background power without loss of sensitivity. However, a 100 fold increased retina capacitance and the higher background power requires a larger electron beam current than the presently available 10^{-6} A or an increase in frame time. A comparison of Table I and Table II shows that on the average a 100 fold increase in capacitance gives a factor of about 2.7 increase in range.

(S) All range calculations have been done for S/N = 6.5 which is considered necessary for a tracking instrument. However, if the sensor is required only to view and obtain radiometric data on the target then the S/N can be reduced by about a factor of 3. A 3 to 1 reduction in the S/N requirement gives a $3^{1/2}$ increase in range. This means that for the nonenhanced vidicon sensor the range would become 1650 km. In addition it may be possible to employ frame-to-frame integration to increase the S/N at a given range, or

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alternatively to increase the range. If this integration can be accomplished over p frames then the S/N at a given range can be increased by $p^{1/2}$ or the range at a given S/N can be increased by $p^{1/4}$. For example a 16 frame integration gives a 2 fold increase in range for the same S/N, or a range of 1900 km = 1000 nmi for the 66 kft, 1.59 cm Ge refractor or $\epsilon = 1.5\%$ reflective telescopes. At this range the target can be expected to remain within a single resolution element for about 0.6 sec so that a 30 frame/sec system could integrate for 18 frames and a 100 frame/sec system could integrate for 60 frames giving almost 2650 km = 1400 nmi range. In practice these numbers will probably be somewhat less but it does appear that a range of 1000 nmi could be achieved at 66 kft using frame-to-frame integration and 100 frames/sec. Note that at 100 frames/sec the optimum spectral bandwidth for these systems is increased to about 1.5 μm and the performance is quite comparable to that of a capacitively enhanced system. Note also that the information rate is about the same since the frame time is increased for the capacitively enhanced system.

(S) However, the frame-to-frame integration scheme has the potential advantage of a larger dynamic range since the minimum single frame S/N can be close to unity in the integration mode at long range whereas at short range where the signal is larger the integration can be reduced or eliminated and information can be obtained from each frame. A reduction in the frame-to-frame integration will in fact be necessary at shorter ranges as the target moves more rapidly through the field-of-view.

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(S) There are, of course, a number of questions which need answers such as:

1. Can a vidicon with the specified resolution and sensitivity performance be obtained?
2. Can the telescope be constructed maintaining diffraction limited optics?
3. Can the frame-to-frame integration be accomplished without loss in signal-to-noise ratio?
4. Can all of this be incorporated into an aircraft capable of flying at 66 kft?
5. Can the telescope pointing be maintained to 70 μ rad over 1/2 sec?
6. Etc.

We intend to obtain answers to as many of these questions as possible over the next 6 months. If these answers are affirmative then a range of 1000 nmi for a 1 m^2 , 300°K target appears feasible from an aircraft at 66 kft. The situation at 40 kft appears quite marginal unless the vidicon instantaneous field of view is reduced to allow the frame rate to be increased to at least 200 frames/sec, since a factor of $(100)^{1/4}$ at least is required in range. If this could be accomplished then the vidicon could be scanned to recover the full field of view in 1 to 2 sec. However we are clearly significantly better off at the higher altitude.

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