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INFRARED DETECTORS AND FOCAL PLANE ARRAYS

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Temperature limitations to infrared detectors[1]

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ABSTRACT

Carrier generation within a photodetector is reviewed to determine the shot noise of generation-recombination, arising from thermal radiation from within the detector itself. Since this is a noise that exists in all detectors at a finite temperature, it sets the absolute limit of detectivity that no detector of whatever type or design can exceed. The author's intent is to preclude managers from believing that higher detector temperature operation can be permitted. The equations are given and exemplar graphs are displayed for two interesting cutoff wavelengths, using coordinates that may readily be related to system performance needs. Several particular types of detectors are compared with the absolute limit curve.

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DISCUSSION

Summary and conclusions:

In the frequent case of an infrared camera imaging a terrestrial scene with about a 300K background it is well recognized that background limited infrared performance (BLIP) refers to the terrestrial background. It is the shot noise of the radiation of this background which is the dominant noise. However, when the camera is used to image a scene against a much colder background, e.g. deep space, the shot noise of that background, being very small, may not be the dominant noise. However, the detector array is still immersed in the radiation of the cryogenic dewar and cold finger. Indeed, parts of each element of the detector array are irradiating the remainder of the element. The detector is immersed in its own self-radiation. The shot noise of this self-radiation may be the dominant noise. Several authors have addressed this problem[2, 3, 4, 5, 6, 7] for particular types of detectors.

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1. This research was supported by Contract SDIO84-88-C-0042 with the Strategic Defense Initiative Organization, The Pentagon, Washington, DC. It was encouraged by LTC Richard J. Yesensky, USA.

2. D. Long et al, "Detectivity vs Temperature in IR Photon Detectors", Proc, IRIS Specialty Group on IR Detectors and Imaging, Vol. 1, pp387 to 400, August 1978.

3. A.S. Jensen, "Sensitivity Limitations of IR Detector Temperature", Proc. NAECON80, pp799 to 802, May 1980.

4. M.A. Kinch, "Fundamental Limits of IR Detectors", Opt. Soc. Amer. Conf. on Lasers & Electro-Optics, CLEO/QELS '89, 1989 Technical Digest Series, Vol. 11, Session MA, 24 April 1989; to be published elsewhere.

5. Richard L. Petritz, "The Relation between Lifetime, Limit of Sensitivity, and Information Rate in Photoconductors," Photoconductivity Conference, pp49 to 77, John Wiley & Sons, New York (1956). This mostly is concerned with photoconductors as used for communication, with more interest in lower signal to noise ratios than are practical for imaging, and more interest in narrow resonant signal bandwidths than the low pass video required by imaging. He also uses the equations from van Roosbroeck and Shockley[10].

6. Donald Long, "Generation-Recombination Noise Limited Detectivities of Impurity and Intrinsic Photoconductive 8-13um Infrared Detectors," Infrared Physics, Vol. 7, pp121 to 128, 1967. His equations 11 and 12 are closely related to equations 10 and 3 respectively of this paper. See also Donald Long, "On Generation-Recombination Noise in Infrared Materials," Infrared Physics, Vol. 7, pp169 to 170, 1967. .

7. M.M. Blouke, C.B. Burgett and R.L. Williams, "Sensitivity Limits for Extrinsic and Intrinsic Infrared Detectors," Infrared Physics, Vol. 13, pp61 to 77, 1973. His equation 24 is the same as equation 10 here.

This paper follows the general procedure of Long[2] and Jensen[3] to determine an absolute lower limit on the noise of a quantum detector, a goal which can never be reached much less exceeded, for any and all types of detectors. There is established a detection level beyond which no one will ever expect to attain. This level is expressed as an equivalent BLIP flux density. This limit is set by the self-radiation of the detector itself, simply because it is at a finite temperature. This is often referred to as the thermal generation-recombination noise limit. It is set by a shot noise and not a resistive Johnson-Nyquist noise. This level is then compared with the results of Long and of Jensen and of Kinch[4].

This BLIP flux density is then related to a Noise Equivalent Flux Density, which is a further function of the product of the detector area and the exposure time (or ratio of the detector area to the circuit bandwidth). For subaperture targets (those that are not resolved by the sensor system) the relation is made to the Noise Equivalent Number of photons per pixel. It is possible then to use these scales for comparison with the system parameters and target flux at the focal plane to determine how to apply a detector in a desired sensor system.

For comparison to other detector candidates we use Kinch[4] equations for extrinsic silicon (XSi), and Forrester et al[8] equations for a superconductor (SC). For the SC, however, since quasi-particles (qp) generated farther than a coherence length from a weak link or a Josephson junction (JJ) do not produce a signal, the coherence length is used instead of the absorption length. One must be aware, however, that the ratio of these two lengths may also be a factor in the effective carrier lifetime so that the overall operation of the detector may be a weak function of this ratio.

A second part of this paper examines the lower limit on the noise of an ideal bolometer. The bolometer is ideal in that it is radiatively coupled only. It is shown that this noise, though often considered to be a thermal noise, is really a shot noise of the detector self-radiation. This result is also compared with the noise of a quantum detector of Kinch and the absolute lower limit of Jensen. Bolometers may have a niche where long wavelength detection is required while the detector must operate at as high a temperature as is permitted by the target signal which must be detected.

Radiative generation of carriers in quantum detector:

Assume:

1. quantum detector, absorption of photon generates a charge carrier
2. sharp spectral cutoff appropriate to band gap
3. signal is integral of carriers generated during an exposure time; all generated carriers contribute to the signal
4. Planck density of quanta, function of temperature and wavelength
5. mean free path of quantum is equal to the reciprocal of the absorption coefficient (though equation (5) below makes a better substantiated approximation than this)
6. no other noise sources (Johnson-Nyquist thermal noise from dissipative sources, preamplifier noises, etc. are assumed to be zero to obtain an ideal situation focussed on the detector alone)

Assumption #5 means that the product of the thickness, b, of the material and the absorption coefficient, α, is unity. To err on the side of the ideal the quantum efficiency, η, is also taken as unity.

8. M.G. Forrester and J. Talvacchio, "Photon Detection by High-Temperature Superconducting Films: Fundamental Limits", Proc. Intnat. Conf. M^2-HTSC, Materials and Mechanisms of Superconductivity, High-Temperature Superconductors II at Stanford University, pp391 to 392, North-Holland, July 1989. Also Physica C, pp162 to 164 (1989), North-Holland

In the event that the lifetime of the carrier is shorter than the exposure time, assumption #3 requires that some means be provided to integrate all the short term effects, within the lifetime of the carriers, over the period of the exposure time. This may be an engineering challenge. When this is done, the output signal is the product of any carrier gain that occurs within the detector, the signal radiation induced carrier generation rate per unit area, the illuminated area, and the exposure time:

$$S = G * g * A * t \qquad \text{[carriers]} \tag{1}$$

Similarly, since every photon in this radiation is independent, the carriers they generate have a Poisson distribution and the noise is its shot noise. This noise is the product of the carrier gain within the detector and the square root of the product of the carrier generation rate per unit area, the illuminated area, and the exposure time:

$$N = G * \sqrt{g * A * t} \qquad \text{[carriers]} \tag{2}$$

Consequently, for maximum signal-to-noise ratio the carrier generation rate is the quantity of interest. The area and the exposure time are system design parameters.

There are two approaches that lead to the calculation of the carrier generation rate:

(1) Thermodynamic: The first starts with the Fermi-Dirac statistics for the carrier, which are fermions, and from thermodynamics. This results in an expression for the carrier density of the detector material[9]. If, then, the carrier lifetime can be calculated, the ratio of the density of states to the carrier lifetime can be taken as the carrier generation rate simply because the average carrier density must remain constant at thermal equilibrium.

We follow this approach, using the equations of Kinch[4] and Forrester et al, to obtain curves for particular types of detectors for comparison to the absolute limiting curve.

The problem with this approach is that of determining the maximum carrier lifetime based only upon fundamental principles. In general, there are too many practical considerations involved, such as impurity states, defect states, etc. The detector material and its configuration may be important determining factors. It is difficult to establish a carrier lifetime that absolutely cannot be improved. A determined manager can always order the materials engineer to go back to the lab and make it better.

Since the purpose of this paper is to establish an absolute physical limit, which may not even be attainable, and certainly not exceeded, by any arbitrary type of detector, we take a second approach:

(2) Radiation: Generally this follows Long[2] which in turn follows van Roosbroeck and Shockley[10] and is detailed in R.A. Smith[11]. The carrier generation rate is derived assuming that they are excited above their ground state at zero kelvin only by radiation and lattice photons from the lattice of the detector itself because it is at a finite temperature. All of this radiation is within the material of the detector, not in free space. Hence in Planck's Radiation Law the speed of light is that within the material. If c is taken as the speed of light in free space, that within the material must be c/n_{opt}, where n_{opt} is the optical index of refraction. This results in a higher value of flux density within the material than it emits from its surface. This author interprets this to result from the

9. R.A. Smith, "Semiconductors", esp. pp74 to 79 and equation 18 p78, Cambridge Un. Press, 1968.

10. W. van Roosbroeck & W. Shockley, Phys. Rev., Vol. 94, p1558 et ff, 1954.

11. R.A. Smith, "Semiconductors", esp. pp288 to 290, Cambridge Un. Press, 1968. Note that on p289 in equation 205 there is a typographical error, the factor c^3 should be in the denominator.

reflectance of the surface, few photons getting out of the surface, more remaining inside, much as a laser operates, but in this case the radiation is non-coherent.

Thus the radiative generation rate[12, 13, 14] [carrier/sec*cm^2] is:

$$g = \frac{8 \cdot \pi \cdot n_{opt}^2}{c^2} \cdot \left[\frac{k \cdot T}{h}\right]^3 \int_{u_c}^{\infty} \frac{u^2}{-1 + \epsilon^u}\, du; \quad \text{where } u = \frac{\left[\frac{h \cdot c}{k}\right]}{\lambda \cdot T}; \quad u_c = \frac{\left[\frac{h \cdot c}{k}\right]}{\lambda_c \cdot T} \tag{3}$$

where it can readily be seen that the square of the speed of light in the medium is in the denominator so that the square of the refractive index (n_{opt}) must be a factor in the calculations. One might also note from the factor in the denominator within the integral that this approach involves Bose-Einstein statistics since the photons are bosons. Expressed in terms of the radiation constants the equation becomes:

$$g = \left[\frac{4 \cdot \left[2 \cdot \pi \cdot c^2 \cdot h\right] \cdot n_{opt}^2}{h \cdot c}\right] \cdot \left[\frac{k \cdot T}{h \cdot c}\right]^3 \cdot \int_{u_c}^{\infty} \left[\frac{u^2}{-1 + \epsilon^u}\right] du \quad \text{[carrier/sec*cm}^2\text{]} \tag{3a}$$

Long[2] approximates the integral to be $u_c^2 * e^{-u_c}$ arguing that for practical cases $u_c >> 1$. Actually, the integral has very significant contributions for values of $0.1 < u < 6$, and the approximation is not valid except for $u_c >> 3$, that is $\lambda_c T << (hc/k)/3 = 14388\ \mu m{*}K/3 = 4796\ \mu m{*}K$. Now since the peak of the Planck function of photon flux density vs temperature[15] occurs at $\lambda_m T = 3669.84\ \mu m{*}K$, the condition is equivalent to $\lambda_c << (4/3){*}\lambda_m(T)$. A better approximation has to be used for situations with long wavelengths and higher detector temperatures.

Intrinsic photovoltaic detector:

Kinch[4] takes the first (thermodynamic) approach, expressing the thermal generation rate (per unit area) of minority carriers as the ratio of the carrier density to the product of the carrier lifetime and the absorption coefficient. He assumes Auger limited lifetime in HgCdTe and the generation rate becomes:

$$g = \left[\frac{n_{opt} \cdot \left[\frac{k \cdot T}{e}\right]^{1.5}}{\left[1.66 \cdot 10^{12} \cdot V \cdot sec\right] \cdot \alpha \cdot E_g^{0.5} \cdot \epsilon^u}\right] \text{[carrier/sec * cm}^2\text{]}; \quad \text{where } u = \frac{e \cdot E_g}{k \cdot T} \tag{4}$$

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12. Some algebra exchanges the absorption index, k, in equation 205 on p289 of Smith[11], for the absorption coefficient, α, according to the equation given by Smith[11] on p288 above his equation 200.

13. For a pure quantum detector we assume zero absorption coefficient for wavelengths longer than the cutoff wavelength, i.e. we ignore the bolometric response that results from absorption of radiation by the lattice. This changes the lower integration limit from zero to u_c (following many other authors we use u instead of x for the argument in the integral)

14. This author also prefers to express the fundamental constants in these equations thus:
$2{*}\pi{*}c^2{*}h = 37418.4\ um^4{*}W/cm^2$, first radiation constant
$hc/k = 14388.3\ um{*}K$, second radiation constant
$hc = 1.98648{*}10^{-19}\ um{*}J$

15. Note well that this is the peak of the curve of photon flux in units [photon/sec*cm^2*um]. It occurs for $u_m = 4{*}[1-\exp(-u_m)]$. Wein's Law is usually written for the peak of the curve of power flux in units [W/cm^2*um] which occurs for $u_m = 5{*}(1-\exp(-u_m))$ for which (15.1) $\lambda_m{*}T = 2897.88um{*}K$

Long et al[2] take the second (radiation) approach following van Roosbroeck and Schockley[10] and obtain in their equation (A1) p395 the same result as equation (3) above. They continue to obtain an expression for D*, along the way discussing optimizing the thickness, b, of the absorbing region and the resultant quantum efficiency. For maximum signal to noise ratio $[1-\exp(-b^*\alpha)\}/(b^*\alpha)^{0.5}$ must be maximized. They obtain a minimum multiplying factor:

$$\left[\frac{b\cdot\alpha}{\eta}\right]_{min} = \frac{1.2564}{0.7153} = 1.756 \text{ [photon/carrier]}; \qquad \eta = 0.7153 \text{ carriers/photon} \qquad (5)$$

which must be applied to the *minimum* BLIP flux density which may be derived from these generation rates.

Equivalent BLIP flux density upon detector surface:

The current noise spectral density of a detector is the sum of that from the self radiation and the scene radiation:

$$\frac{d}{df}i_n^2 = 2\cdot e^2\cdot b\cdot\alpha\cdot A\cdot g + 2\cdot e^2\cdot A\cdot\eta\cdot\Phi_B \qquad [A^2/Hz] \qquad (6)$$

Equating the two noises for the –3 dB equivalent BLIP flux density:

$$\Phi_B = g\cdot\left[\frac{b\cdot\alpha}{\eta}\right] \qquad [\text{photon/sec*cm}^2] \qquad (7)$$

Thus the carrier generation rate is proportionately related by equation (7) to the equivalent, background limiting, photon flux density from the scene which is incident upon the detector. This equivalent BLIP flux density is one possible figure of merit of a detector, and has been used by both Jensen[2] and Kinch[3] as one coordinate for a graphical representation of detector performance as a function of detector temperature. It will be used for detector comparisons in this paper also.

This assumes that all the photon generated carriers are simply swept out to become signal charge. In practice, extracting the signal from a detector may introduce its own associated noise, which will add in quadrature with this radiation noise.

Detectivity:

Detectivity, commonly represented by D*, is a common figure of merit, inversely proportional to the root of the BLIP flux density:

$$D^* = \left[\frac{\lambda}{hc}\right]\cdot\sqrt{\frac{\eta}{\Phi_B}} \qquad [\text{cm*root Hz/W}] \qquad (8)$$

Noise Equivalent Flux Density:

To be detectable the target signal does not have to exceed the equivalent BLIP flux density. Rather, it need only exceed the shot noise of this radiation, by an amount which depends on the system design. The noise equivalent flux density (NEΦ) is the flux density of a target signal which is just equal in amplitude to the rms noise of the radiation. From equation (2) the NEΦ:

$$NE\Phi = \Phi_n = \sqrt{\frac{\Phi_B}{\eta \cdot A \cdot t}} \qquad [\text{photon/sec*cm}^2] \qquad (9)$$

For a given detector, with its BLIP flux density, design choice of the product of detector size and exposure time, based on system considerations, determines the smallest target flux density which can be detected. This is appropriate for targets which are resolved by the system, that is, for targets that subtend many pixels.

Noise equivalent number of photons/pixel:

Many systems applications involve targets which are too small to be resolved by the system. These are called subaperture targets, and a majority of their radiation impinges upon one pixel only. The noise equivalent signal of such a subaperture target is the noise of the total radiation incident upon one pixel during an exposure time:

$$NEN = N_n = \sqrt{\frac{\Phi_B \cdot A \cdot t}{\eta}} \qquad [\text{photon/pixel}] \qquad (10)$$

Extrinsic silicon detector:

The blocked impurity band (BIB) detector is selected since it has the lowest dc leakage current, hence lowest noise and dissipated Joule heating power of this type. Kinch[4] equations and his parameters are used directly, but adjusted for the chosen cutoff wavelength, despite this perhaps not being attainable in reality.

Superconductor nonequilibrium (quantum) detector:

Forrester et al[8] equations and parameters are used directly except that the coherence length is used instead of either detector thickness or the reciprocal of the absorption coefficient. This assumes a weak link or other JJ type detector where quasi-particles (qp) generated farther than a coherence length from the JJ do not appear in the output. We still assume that the detector is so configured that signal photons still generate qp within a coherence length of a JJ so that the quantum efficiency is still unity. We assume a gain of 2 qp/photon since qp are generated in pairs. A superconductor detector that utilizes other mechanisms may have to be computed differently. For proper comparison with the other detectors the bandgap is assumed to be that appropriate for the chosen cutoff wavelength, regardless of reality.

Bolometric detector:

Taking the second (radiation) approach and applying the equation (3) above, we must take the integral over all u from zero to infinity. The argument of the integral is finite over the entire range, and the integral is also finite but difficult. It is given by Gradshteyn et al[16] as:

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16. I.S./ Gradshteyn and I.M. Ryzhik, "Table of Integrals, Series, and Products", esp. p325, section 3.411, equation 1, Academic Press, 1980

$$\int_0^{\infty} \left[\frac{u^2}{-1 + \epsilon^u} \right] du = \Gamma\ (3) \cdot \text{Zeta}(3) \tag{11}$$

Gamma(n) = (n–1) ! so that Gamma(3) = 2.

Riemann's zeta function is given in Tuma[17] as:

Zeta(3) = 1.202 056 903 159 594

so that:

$$I_b = \int_0^{\infty} \left[\frac{u^2}{-1 + \epsilon^2} \right] du = 2.404113806 \tag{11a}$$

hence the generation rate for a bolometer[18] is:

$$g = \left[\frac{4 \cdot \left[2 \cdot \pi \cdot c^2 \cdot h\right] \cdot n_{opt}^2}{h \cdot c} \right] \cdot \left[\frac{T}{\left[\frac{h \cdot c}{k}\right]} \right]^3 \cdot I_b \qquad [\text{carrier/sec*cm}^2] \tag{12}$$

This generation rate is the minimum BLIP flux density, obtainable if the entire charge generated by incident scene flux can be gotten out of the bolometer without additional noise (another engineering challenge). Furthermore, this is for a bolometer of infinite electrical resistance so that no Johnson thermal noise is present. Note also that any thermal conductive coupling, for example through a support to a substrate, will also produce a Johnson thermal noise. For a real bolometer with finite resistance the thermal noise contributes an additional effective generation rate:

$g_{total} = g + g_R$ where the resistive contribution (13)

$g_R = 2{*}k{*}T/(e^2{*}R{*}A)$ (13a)

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17. Jan J. Tuma, "Engineering Mathematics Handbook", 2nd, enlarged and revised edition, esp. p99, section 8.08(1)(b), McGraw-Hill Book Company, 1970.

18. It is interesting at this point to apply the integral of equation (11) to the Planck radiation equation. When applied to the radiation equation for power flux, the integral becomes:

$$\int_0^{\infty} \left[\frac{u^3}{-1 + \epsilon^u} \right] du = \Gamma(4) \cdot \text{Zeta}(4) = \frac{\pi^4}{15} \tag{18.1}$$

and the familiar Stefan-Boltzmann equation results:

$$H(T) = \sigma T^4 \qquad [\text{W/cm}^2] \tag{18.2}$$

where sigma = 5.669 623 456*10^{-12} W/cm^2*K^4, the Stefan-Boltzmann constant. On the other hand for photon flux the radiation (3) equation applies. The result is:

$$\Phi(T) = \sigma_j T^3 \left[\text{photon/sec*cm}^2\right] \qquad \text{note: temperature is cubed!} \tag{18.3}$$

where σ_j = 1.520 288 574*10^{11} photon/sec*cm^2*K^3

Comparison of detector types:

Figure 1 is a plot of log (BLIP flux density/[photon /sec*cm^2]) as a function of detector temperature.

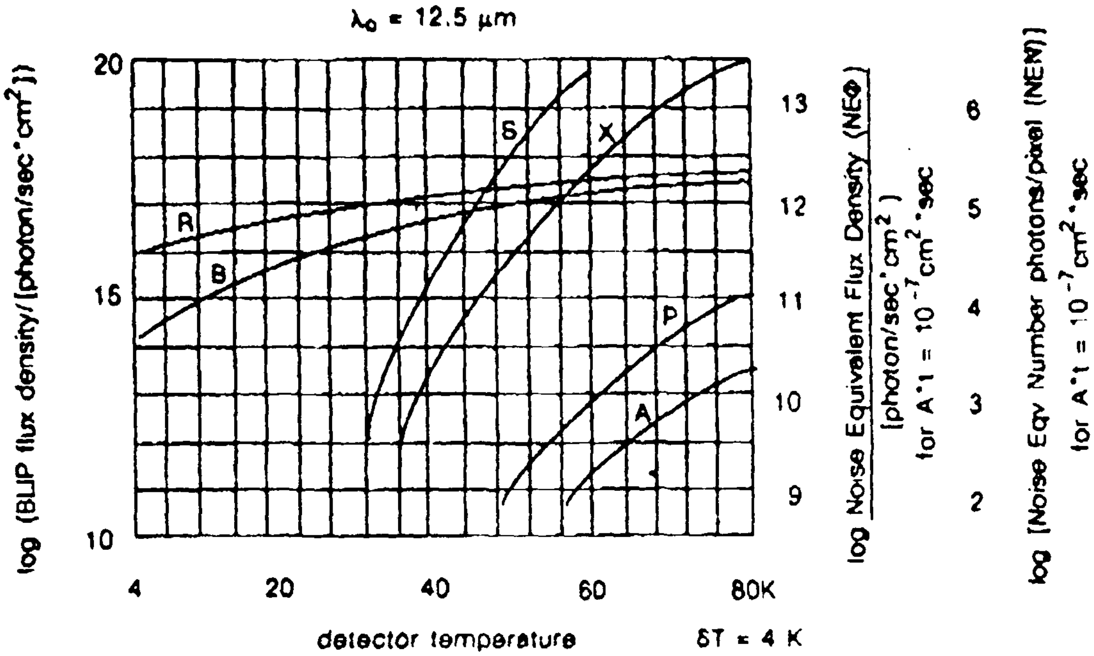

Figure 1.
log (BLIP flux density) vs Detector Temperature
12.5 μm cutoff wavelength

A = absolute minimum by equation (3)
P = HgCdTe photovoltaic detector by equation (4)
X = extrinsic silicon detector
S = superconducting detector
B = bolometric detector by equation (11)
R = bolometric detector with R = 1330 Ohm (12)

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Using equation (8) one could readily put an auxiliary scale on the ordinate for D* for the particular cutoff wavelength.

Since Jensen[3] uses the equations from Long[2], his curves are identical with the absolute minimum curve A given in these figures.

In the figure the first auxiliary scale on the right is the log (Noise Equivalent Flux Density/[photon/sec*cm^2]) for an area * exposure time product of 10^{-7} cm^2 sec (e.g. a pixel 100um square and an exposure time of 1ms), which corresponds to the BLIP flux density on the left. It is against this ordinate that target flux densities should be compared. The second right hand scale is the log (Noise Equivalent Number of photons/pixel) for the same parameter. It is against this ordinate that subaperture targets (that is, small targets unresolved by the optical system and the focal plane pixel size) are to be compared.

Note that the photovoltaic detector is better for the shorter cutoff wavelengths, for reasonable cryogenic temperatures. However, there is a niche for bolometric detectors where it is necessary and possible for the detector to be operated at a higher temperature. This is particularly true where the cutoff wavelength must be large. Also, despite the advent of high temperature superconductors, any quantum detector that depends upon superconductive effects will have to be operated at a low temperature. The possible choice of cutoff wavelength and detector temperature must be made by systems analysis, considering the target, its temperature and range, data rate requirements, practical optics and cryogenic equipment.

It must be emphasized that curve A is an absolute ideal. No amount of engineering can be ever expected to develop a detector of any type whose performance will come close to this curve and certainly not below it.

Acknowledgement:

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