Quantum noise limits the pinspeck camera to simple objects

M. Young

Optical Electronic Metrology Group, Electromagnetic Technology Division, National Bureau of Standards, Boulder, Colorado 80303

Received October 4, 1981

The pinspeck camera projects a low-contrast image with a great deal of veiling glare. Quantum noise determines that the camera can image only simple objects that contain no more than a few hundred picture elements.

The pinspeck camera is the complement of the pinhole camera: It uses an opaque dot located in the center of a large, clear aperture. Each point on the object casts a shadow of the dot onto the image plane. The image is therefore a weak, negative image surrounded by the veiling glare caused by the other object points.¹ If there are m equally bright object points, the image contrast is m/(m-1).

The resolution of the pinhole camera is best when the pinhole occupies a single Fresnel zone and is, in effect, a zone plate with one clear zone^{2,3}; at first glance, the same argument may seem appropriate to the pinspeck camera as well. However, Babinet's principle is difficult to apply to the pinspeck, essentially because the viewing screen is located in the near field of the clear aperture and there are no useful regions where the intensity is zero. Indeed, we expect to see not a dark shadow but rather the Fresnel bright spot at the center of the pinspeck image of a single point. This suggests that the pinspeck must occupy many Fresnel zones so that it casts, more or less, a geometrical-optics shadow; therefore the pinspeck will have to be large compared with a typical pinhole. The resolution limit is then about equal to the pinspeck radius; we call the corresponding circle of confusion a picture element.

The contrast of the pinspeck camera is small if m is large. How many object points may be present before the image is lost in the veiling glare?

To answer this question, assume first that one threshold detector covers each picture element; the detector will register a count if the number of photoelectrons exceeds some number T. During the exposure time, the average number of photoelectrons collected by a detector is N_i if the detector is located at an image point and N_o if it is not. The presence of quantum noise dictates that the image will be detectable, roughly speaking, provided that N_i is less than T by at least one standard deviation and that N_o is greater than T by at least one standard deviation; that is,

$$N_i + N_i^{1/2} \le T \le N_o - N_o^{1/2},\tag{1}$$

where the terms involving the square roots are the standard deviations associated with the averages N_o and N_i (quantum or photon noise).⁴

If there are p detectors per picture element, the numbers of counts registered by individual detectors are statistically independent variables with mean N (equal to either N_i or N_o) and standard deviation $N^{1/2}$. The average number of counts registered by the ensemble is pN_i because of the assumption of statistical independence, the standard deviation is the rms value $(pN)^{1/2}$ of the individual-detector standard deviations. Therefore, including also some additional, signal-independent noise n, we may generalize formula (1) to

$$pN_i + (pN_i)^{1/2} + n \le T \le pN_o - (pN_o)^{1/2} - n.$$
 (2)

Formula (2) may be solved exactly, but an approximate solution

$$C \le 1 - 2[(pT)^{-1/2} + n/(pT)]$$
(3)

for large pT is more useful. Here, $C = N_i/N_o$ is contrast of the image. (If the image is positive, the minus sign must be replaced by a plus sign and the inequality reversed.)

Formulas (1)-(3) have general validity; when we apply formula (3) to the pinspeck camera, we find that

$$m < (pT)^{1/2}/2,$$
 (4)

when n = 0. By way of example, let us choose the relatively large pinspeck radius of 1 mm and a rectangular array of detectors with resolving power of 50 lines/mm ($p \sim 8000$). If we set T equal to 5, formula (4) shows that m must be less than 100. Even so, some of the image points will be lost in the veiling glare; if we adopt a more stringent requirement of two or three standard deviations in formula (1), m is reduced to 30 or 50. Finally, had we chosen p = 1, T would have had to be unacceptably large; we required the detector array to ensure a high effective threshold pT.

Film will often be the preferred detector. For argument's sake, we take T to be 5, on average, for each grain.⁵ If the grains are randomly distributed, the standard deviation of film-grain noise is approximately $l^{1/2}$, where l is the number of developed grains in a given area.⁶ Because l cannot exceed p, we conclude that the signal-independent noise term in formula (3) will always be at least a factor $T^{1/2}$ smaller than the quantum-noise term, and the estimates of the preceding paragraph will have to be reduced somewhat. At best, the pinspeck camera can record only simple objects. This novel invention may be useful in limited applications (such as x-ray imaging) in which there are ample intensity and few resolvable object points and where some form of high-threshold detection is available.

Note added in proof: I have just learned that the pinspeck camera is not new but was invented several years ago and patented by the University of Texas (A. Zermeno, L. M. Marsh, and J. Hevizi, "Imaging by point absorption of ra-

0030-3941/82/030402-02\$01.00

© 1982 Optical Society of America

JOSA Letters

diation," U.S. Patent 4,085,324, April 18, 1978). Use of the pinspeck camera for examining x-ray tubes was the subject of a thesis [R. Cowart, "An investigation of the inverse pinhole camera," M.S. thesis (University of Texas, Austin, Texas, June, 1976)]. Texas Medical Instruments of San Antonio owns the commercial rights to the pinspeck camera, which it uses in more than one application.

REFERENCES

1. A. L. Cohen, "Anti-pinhole imaging," Opt. Acta (to be published).

- 2. M. Young, Optics and Lasers (Springer-Verlag, New York, 1977), pp. 90-96; "Pinhole optics," Appl. Opt. 10, 2763-2767 (1971); "Pinhole imagery," Am. J. Phys. 40, 715-720 (1972); "Zone plates and their aberrations," J. Opt. Soc. Am. 62, 972-976 (1972).
- 3. J. Walker, "The pleasures of the pinhole camera and its relative
- J. Walker, The predsures of the philote camera and its reactive the pinspeck camera," Sci. Am. 245(11), 192-200 (1981).
 See, e.g., W. B. Wetherell, "The calculation of image quality," in Applied Optics and Optical Engineering, R. R. Shannon and J. C. Wyant, eds. (Academic, New York, 1980), Vol. VIII.
- 5. R. Shaw, "Photographic detectors," in Applied Optics and Optical Engineering, R. R. Shannon and J. C. Wyant, eds. (Academic, New York, 1980), Vol. VIII.
- 6. J. F. Hamilton, "The photographic grain," Appl. Opt. 11, 13-21 (1972).

1