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THE ANALYSIS AND ENGINEERING DESIGN OF A PINHOLE TV CAMERA

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Task 7883-17

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ABSTRACT

Pinholes used in place of glass lenses in combination with modern high gain low noise level TV camera tubes may solve some television visual display problems. Both increased depth of field and field of view are logically anticipated results. The high f-number of a pinhole might be compensated for by the high signal gain of currently available TV camera tubes. Analytical results indicate that a 100° wide included field of view can be attained with moderate lighting levels and available hardware. The design requirements are defined for a TV pinhole camera system.

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Pinholes used in place of glass lenses in combination with modern high gain low noise level TV camera tubes may solve some television visual display problems. Both increased depth of field and field of view are logically anticipated results. The high f-number of a pinhole might be compensated for by the high signal gain of currently available TV camera tubes. Analytical results indicate that a 100° wide included field of view can be attained with moderate lighting levels and available hardware. It is recommended that a TV pinhole camera system be constructed of stated design requirements for further testing and evaluation.

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FOREWORD

Television mediated visual displays in visual simulation can benefit considerably from both wider fields of view and increased depth of field. Both of these characteristics are attainable with a pinhole (lens). The scope of this project is to determine the feasibility of, and explore both subjective and objective advantages of replacing the glass lens with a pinhole in the TV camera. Ship docking and aircraft landing approach visual displays, mentioning two training areas, require wide visual fields of large in-focus depths. This report shows it is possible to build a camera of this type with acceptable limitations in signal-to-noise ratio. Further work in a TV pinhole camera system is justified.

The report covers a period of almost four years and is the combined results of two sequential project engineers. The logical action following this analytical report is construction of a TV camera to recommended specifications followed by laboratory objective and subjective tests. Side benefits of this study have been an in depth study of diffraction limited lenses and a review of currently available low light level TV cameras and TV camera tubes.

John McKechnie

J. C. McKechnie
Project Engineer

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LIST OF SYMBOLS

a	distance - object to aperature
B	object illumination (reflected light)
d	pinhole diameter
Eo	on axis image plane illumination
Ep	inclined ray illumination on image plane
F	focal length
f	f/number
G(u,v)	pupil function
i	intensity
λ	wavelength of light
Ne	equivalent passband
Neh	equivalent horizontal passband
Nev	equivalent vertical passband
w	frequency; radians per millimeter
P	diameter of object
R	resolution in TV lines
r	aperature radius (d/2)
s	radius of TV camera tube photosensitive surface
S(x,y)	point spread function
τ (w)	optical contrast function
θ	field of view
u,v	rectangular coordinates in the pupil plane
Vx,Vy	spatial frequency, lines per millimeter
x	TV raster width
y	TV raster height
z	minimum image spot size

SECTION I

INTRODUCTION

The need exists in visual simulation for a TV camera combined with an optical probe having the following characteristics:

- a very small entrance pupil
- a nearly infinite depth of field
- a large field of view

These attributes should be combined with moderate lighting requirements. Such a camera would be used with 2D and 3D model scenes for image generation of TV displays.

The pinhole combined with a high gain TV camera tube appears to be an attractive solution to many of the problems associated with existing wide angle optical probes. The pinhole has a large depth of field, is free of distortion and is very simple to make.

Historically, analysis of the pinhole began with Lord Rayleigh in 1891(1). Stationary time exposure images could be formed on film plates and examined. In 1964, pinhole optics were combined with a TV camera in the expectation of achieving operational advantages over the conventional glass lens and TV camera system.(15) Since that time improvements in TV camera sensitivity and higher resolution units appear to have overcome the earlier system limitations and thus a new examination of the combination was warranted.

SECTION II

STATEMENT OF THE PROBLEM

The depth of field, linearity and off axis imagery of a pinhole is unique. In addition, the scaled entrance pupil of the pinhole when using model scenes closely represents the perspective of human eyesight. The pinhole image plane brightness decreases as both the resolution and included field of view is increased. A question is raised "Can an improved visual simulation image pick up unit be achieved by matching a high gain TV camera tube to a suitable diffraction limited pinhole?" What are the system parameters and what system performance could be reasonably expected?"

SECTION III

METHOD

This analytical task consisted of two parts. The first part was concerned with the effect of the pinhole on the frequency response of the overall television system and the necessary light levels. The second part, was an engineering system design and the establishment of a firm performance specification.

PART I

Theoretical Analysis of the Pinhole Performance - The great depth of field of lenses having large f numbers leads to the simplicity of a pinhole when far field diffraction no longer applies, i.e., when the image plane is less than $\frac{d^2}{\lambda}$ from the aperture, where d is the aperture diameter. Furthermore, the image formed by a pinhole is distortion-free and the effects of astigmatism and curvature are largely unnoticed. The response of the system drops, however, since the wave error at the aperture is much higher than for a Fraunhofer-diffraction limited lens.

The Optimum Pinhole

The optimum diameter and focal length of a pinhole lens may be found by experiment; that is, the diffraction pattern formed by the pinhole is photographed at various focal positions, and the photographs are examined by a scanning microdensitometer. The film axial distance resulting in the smallest "spot" establishes the optimum focal length. It was found that experiment confirmed the predictions of diffraction theory, i.e., in the near or Fresnel field, the optimum pinhole occurs when the focal length for objects at near infinity is approximately:

$$F = r^2/\lambda \quad (1)$$

The radius of the pinhole is given by r, and the wavelength of light by λ. The optimization of a pinhole was fully covered by Rayleigh[1] in 1890. In addition to arriving at Equation (1), Rayleigh computed the intensity distribution in the focal plane and obtained the limit of resolution of the optimum pinhole. A simple method of determining the optimum pinhole is to calculate the intensity on axis when the pinhole is equivalent to the first Fresnel zone. It was found that the intensity is a maximum for this condition; from energy considerations it can be deduced that the spot diameter is a minimum. This method cannot predict the limiting resolution or spot size, but an expression equivalent to Equation (1) was found.

Once the spot size is determined, we know the limiting resolution i.e., the highest spatial frequency that the system will pass. Often, this information is not enough since it may occur that the optical system will not pass lower spatial frequencies. The frequency response of a pinhole may be easily determined experimentally and checked (with more difficulty) by theoretical means. Thus, the accuracy of the experimental technique can be monitored by the theoretical predictions.

The Frequency Response of an Optimum Pinhole

An edge gradient technique of measuring frequency response is particularly suited to a pinhole lens for two reasons. First, the recording film and the analyzing microdensitometer have a much higher frequency pass-band than the pinhole, thereby minimizing corrections. Second, the edge gradient of a pinhole is a relatively shallow slope, therefore graphical differentiation is less hazardous than the equivalent process for a good quality glass lens.

A pinhole of 0.31mm (0.012 inch) diameter was selected for experiment. According to Equation (1), the optimum "focal length" is 46mm (1.81 inches) for green light ($\lambda = 5.5 \times 10^{-4}$mm) or 2.16×10^{-5} inches. The pinhole was mounted in the back of a single lens reflex camera, and placed 46mm (1.81 inches) from the film plane (Figure 1). A selected razor blade edge, backed by opal glass and illuminated from behind with a high pressure mercury arc, served as the object. The straight edge was situated 460mm (18.11 inches) in front of the pinhole, so that the image formed by the pinhole was a 10:1 reduction in lineal size of the object.

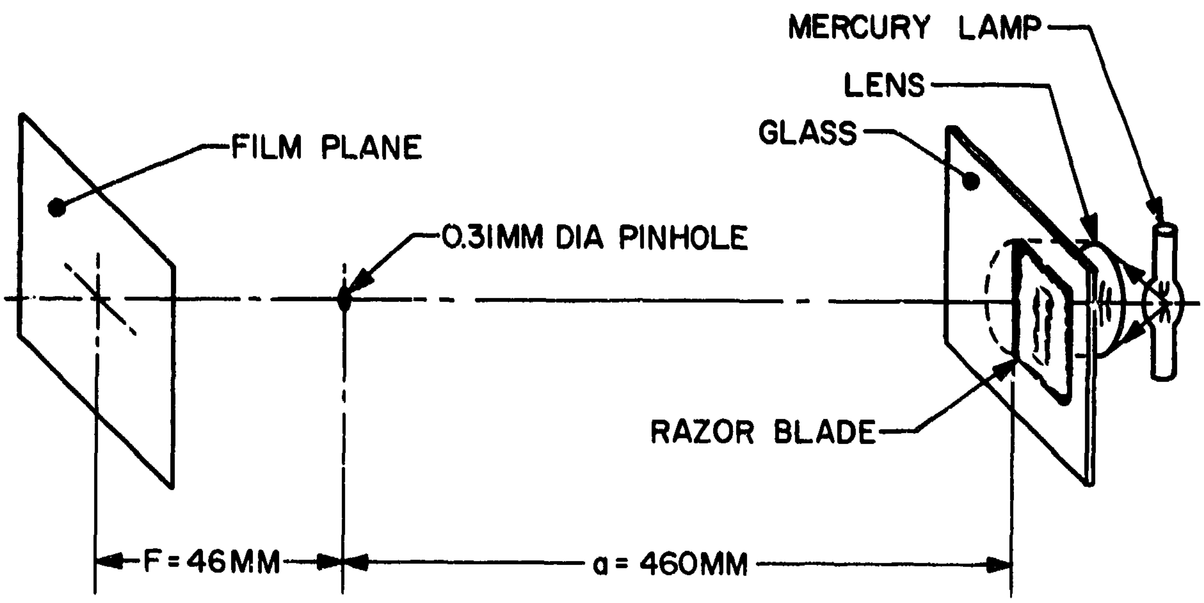


Figure 1. Experimental Arrangement for Pinhole MTF

The observed image was a Fresnel diffraction phenomenon. In a setup of this kind, care must be taken to insure that the light reaching the pinhole was not spatially and temporally coherent, since for practical reasons, we are interested only in the response of an incoherent system. The illuminated region of the object had a maximum dimension of 2.2cm (0.866 inch) so the diameter of the region at the pinhole in complete incoherence* was

$$P_1P_2 = \frac{0.61\, a\lambda}{p} = \frac{0.61(460)(5.5\times10^{-4})}{11} = .014\text{mm (0.00055 inch)}$$

*Reference 2, p 509.

where 'a' was the distance of the pinhole from the illuminated razor blade, P_1P_2 was the distance between two points in the plane of the pinhole and p was the radius of the illuminant. Since p was much smaller than the pinhole diameter the entire pinhole was illuminated by spatially incoherent light. Note that the mean wavelength of the light was 5.5×10^{-4} mm (2.165×10^{-5} inch); this is the mercury green line, isolated by a wide band interference filter.

Panatomic X photographic film was used as the recording medium; the object luminance was 630 f-L so that the exposure time calculates to 4 sec including correction for failure of reciprocity. After exposure, the film was developed in D-76, 1:1 dilution, for six minutes. The response of the film for this development is shown in figure 3. A number of microdensitometric traces were made of the photographically recorded razor edge object. An Ansco Model 4 Recording Microdensitometer using a 75 micron (0.00295 inch) long, one micron wide scanning aperture was the analyzing device. The response of this device is 100% and flat to 100 lines/mm. The smoothed edge gradient response of the pinhole is shown in figure 4.

Now, we must consider the implications of figure 4. If we had taken an infinitely narrow section of the illuminated object and imaged this luminous line with the pinhole, the resulting image would appear as in figure 2.

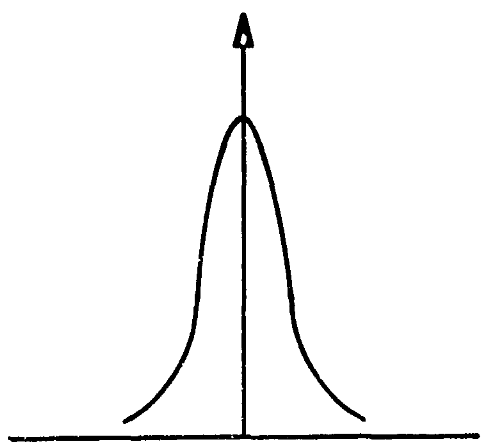


Figure 2. Line Spread Function of Pinhole (General)

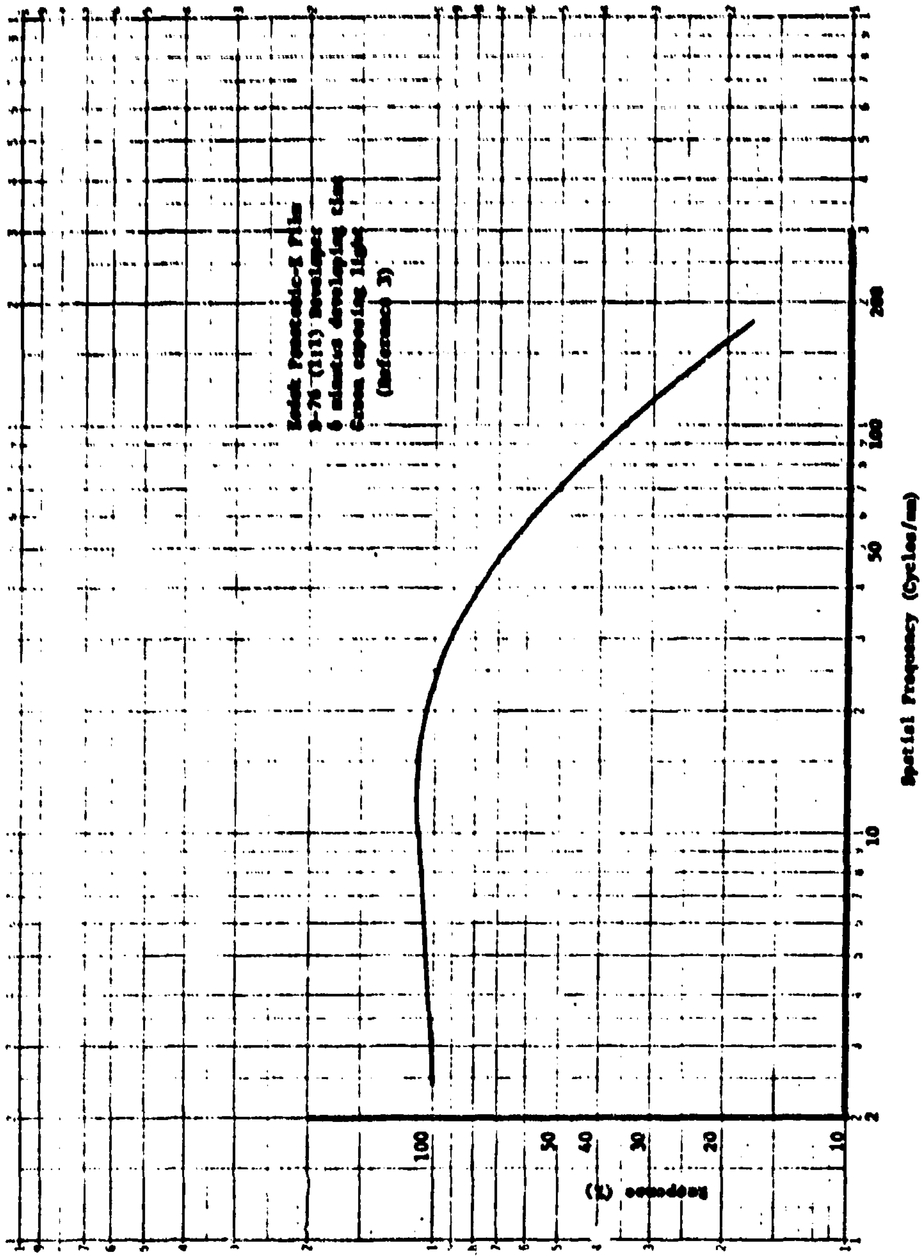


Figure 3. Response of Kodak Panatomic X

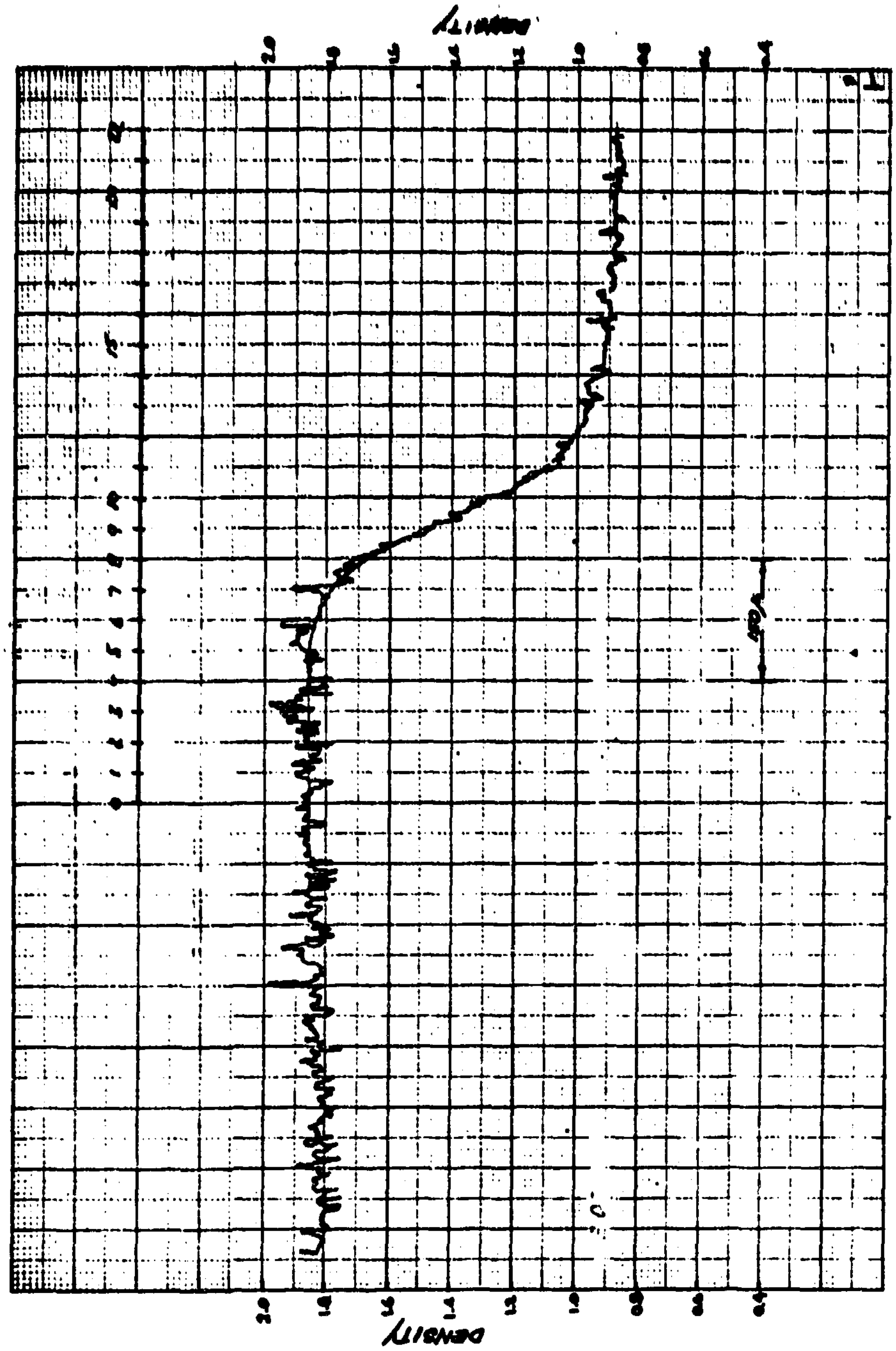


Figure 4. Edge Gradient Formed by .31mm (0.0122 inch) Diameter Pinhole at 46mm (1.811 inches)

This is called the line spread function of the system, and it gives information about how the lens or pinhole modifies the geometrical image. The edge trace of figure 4 can be thought of as the sum of an infinite number of these spread functions. Since the summing process is equivalent to an integration, it follows that, the spread function of the pinhole can be extracted from the edge gradient of figure 4 by differentiation. Clearly we must be able to calculate, or otherwise determine, the spread function of the pinhole $S(x-e, y-n)$ before the image $i(w_x, w_y)$ may be calculated theoretically. This is a sizable task. It turns out, however, to be relatively simple to do experimentally and this is effectively where the art stands at present.

The density values were first converted to transmittance values since the transmission is proportional to the image illuminance. There are a number of methods[4,5] that are used to avoid graphical differentiation of data typified by figure 4. Graphical differentiation normally is very inaccurate because the slope of any point on the edge gradient is difficult to judge, especially if the gradient is rapidly varying. This is serious for high quality lenses where the edge gradient is abrupt, but for a pinhole graphical differentiation is much less hazardous. Accordingly, the line spread function of the test pinhole is shown in figure 5. The tabulated graphical differentiation data used to produce the line spread function (figure 5) from the edge gradient-microdensitometer trace (figure 4) is listed in appendix B.

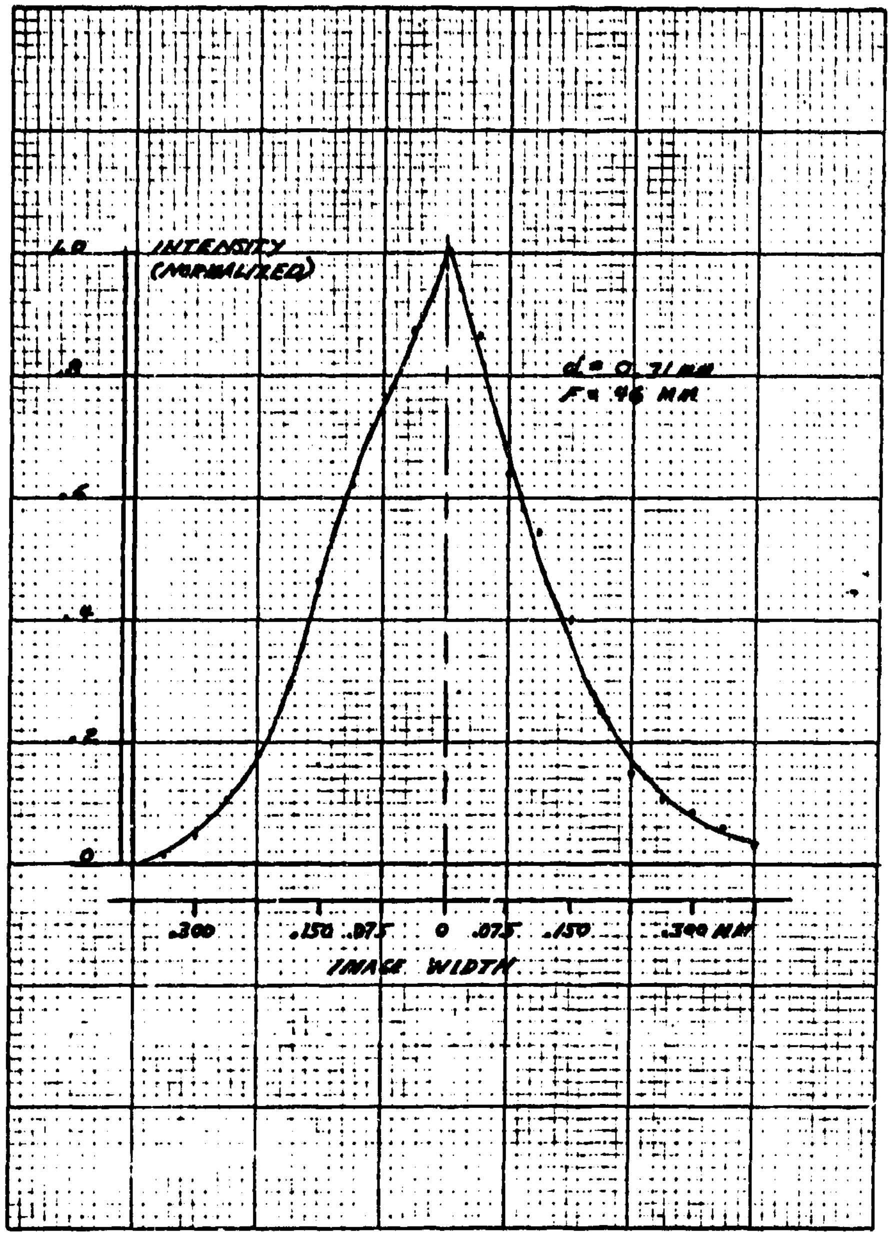


Figure 5. Line Spread Function of Pinhole

This is the image that would be formed by the pinhole of a one-dimensional uniform intensity impulse. The intensity distribution in the line image is given by,

$$I_i\ (X_i) = \int_{-\infty}^{\infty} I_o(X_o)\ S\ (X_i - X_o)\ d\ X_o, \tag{2}$$

where $I_o(X_o)$ is the intensity distribution in the object and $S(x_i - x_o)$ is the transmission function or spread function of the lens or pinhole. The terms of Equation (2) may be represented in terms of their spatial spectra by Fourier inversion;

$$i_i(w) = \int_{-\infty}^{\infty} I_i(x_i)e^{-iwxi}\ dx_i \qquad \text{(a)}$$

$$i_o(w) = \int_{-\infty}^{\infty} I_o(x_o)e^{-iwx_o}\ dx_o \qquad \text{(b)} \qquad (3)$$

$$(W) = \int_{-\infty}^{\infty} S(x)e^{-iwx}\ dx \qquad \text{(c)}$$

The optical transfer function* or frequency response of the system is given by $\Upsilon(w)$.

By direct substitution of (3) into (2) or by invoking the convolution theorem, we find that,

$$i_i(w) = i_o(w)\ \Upsilon(w).$$

Thus, the optical system is a linear filter of spatial frequencies.

The line spread function is usually fairly simple to measure. A more fundamental quantity is the point spread function which is related to the line spread function by,

$$S(x) = \int_{-\infty}^{\infty} S(x,y)dy. \tag{4}$$

If the optical system is rotationally symmetric, it is possible to obtain the point spread function from the line spread function, although the actual derivation is rather complicated.[6] Assuming that we obtained the point spread function by the inversion of equation (4), we now have the intensity distribution in the image, due to a point source. Alternatively, the amplitude disturbance may be expressed by the well known Kirchoff-Fresnel diffraction integral of the form,

$$u(x,y) = \int_{-\infty}^{\infty} \int_{\infty}^{\infty} G(u,v)e^{\frac{-ik}{R}}\ (ux + vy)\ dudv$$

*This is but one of many names given to the response function.

where u and v are rectangular coordinates in the exit pupil, F is axial distance from pupil to image, and G(u,v) is the pupil function. G(u,v) describes the manner in which the incoming wave is modified by the pupil; its phase determines the aberrations of the optical system. The point spread function is therefore,

$$S(x,y) = u(x,y)\ u^*(x,y) \tag{5}$$

Substituting S(x,y) into the analogous two-dimensional form of equation 3(c),

$$(w) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} u(x,y)\ u^*(x,y) e^{-i(w_x\ x\ w_y)}\ d\,x\,dy, \tag{6}$$

and invoking the convolution theorem for the transform of a product

$$\tau\ (w) = C\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} G(u,v)\ G^*\ (u-u',\ v-v')\ dudv \tag{7}$$

From the form of equation (7) it can be seen that G(u,v) is related to a frequency function. That is, if u (x,y) is represented in terms of a Fourier integral, it will be seen that the pupil function is identical to a frequency response function when

$$\frac{u}{\lambda F} = Vx \qquad \frac{v}{\lambda F} = Vy, \tag{8}$$

where vx and vy are spatial frequencies.

Now, an optimum pinhole is equivalent to the first Fresnel zone, so that a phase error of $\frac{\lambda}{2}$ exists between the axis and the hole edge. If the amplitude is constant over the pinhole, then the pupil function is

$$G\ (u,v) = Ce^{ik\frac{\lambda}{2}\frac{(u^2+v^2)}{a^2}} \tag{9}$$

The factor $\frac{u^2 + v^2}{a^2}$ denotes the portion of the maximum wave error at any point (u,v) in an aperture of radius r. It is interesting to note that the intensity pattern in the image plane of an optimum pinhole is described by Fresnel diffraction. It is equivalent to the pattern formed by an out of focus, diffraction limited lens with the same wave error. The optical transfer function of an optimum pinhole is found from the normalized autocorrelation function,

$$\frac{\tau(ux,vy)}{\tau(o,o)} = \frac{1}{4a^2}\int_{u'-a}^{a}\int_{v'-a}^{a} e^{\frac{ik}{2}\left(2\,uu'-\frac{u^{-2}}{2} + 2vv'-\frac{v^{-2}}{2}\right)}\ dudv.$$

Shifting coordinate axes by $\xi = u - \frac{u}{2}$, ξ = v-v/2 gives,

$$\frac{\tau(Vx,Vy)}{\tau(o,o)} = \frac{1}{a^2}\int_o^{\frac{a-u'}{2}}\int_o^{\frac{a-v'}{2}} \cos^2 \pi(u'\xi + v'u)\, d\xi dn. \qquad (10)$$

This function was plotted in figure 6 for Vy = 0, and for an optimum pinhole .31mm in diameter. Also plotted, was the response calculated from equation 3(c), using the experimentally determined line spread function shown in figure 5.

This agreement is excellent. From the curves it is seen that,

$$\tau(ux) = 0.04 \quad \text{when } \lambda\left(\frac{f}{r}\right) V = 1.75$$

This means that two spots are just being visually resolved when they are separated by

$$\frac{1}{V} = \frac{r}{1.75} = 0.57\ r. \qquad (11)$$

Using Rayleigh's criterion, the threshold of resolution occurs when two spots are separated by a distance equal to twice that at which the intensity drops to half maximum. For an optimum pinhole this distance is

$$\frac{1.7\ \lambda b}{\pi\ r} = 0.54\ r$$

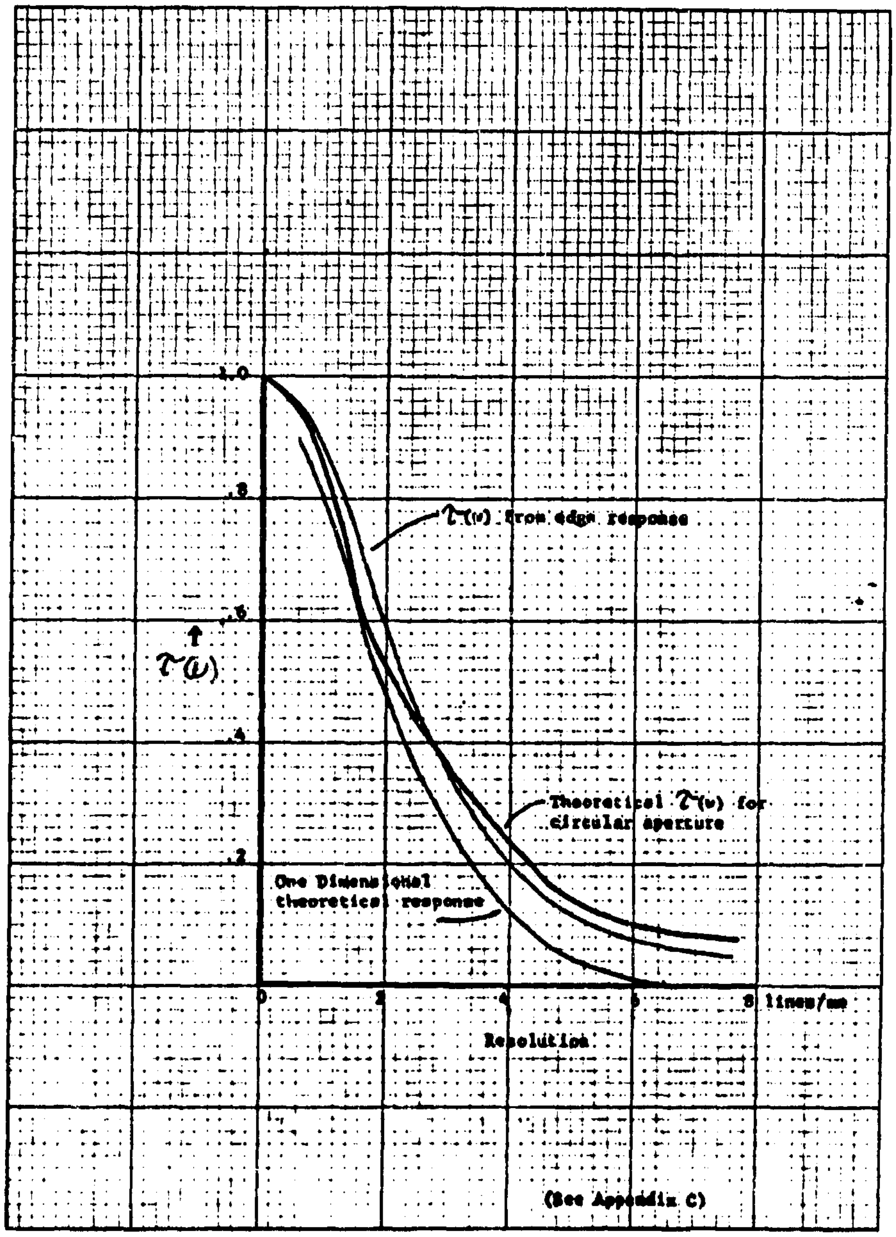


Figure 6. Theoretical and Experimental Response of a Pinhole

In good agreement with equation (11). The curve of figure 6 is superficially related to the conventional concept of "resolving power", only through equation (3). That is, the object spectrum determines the image spectrum, so that the image of, say, a square wave intensity pattern has a different spectral response than the image of sine wave intensity pattern. Since the spectral components of a sine wave are altered only in amplitude by a linear filter, it follows that the response $\tau(V)$ may be experimentally determined by imaging a sine wave intensity pattern and measuring the reduced amplitude vs frequency. For this reason, $\tau(V)$ is often called the sine wave response. It also follows that the determination of threshold response by use of square wave patterns such as the 1951 USAF resolving power target, reveals hardly any information about the filtering properties of a lens system. This is because the threshold response is a single number that depends greatly on the target contrast; the response to other frequencies and object distributions is not known. For instance, a lens out of focus by an amount

$$z = \frac{3.6}{\pi} \lambda \frac{(F)^2}{(r)},$$

will pass a sine wave pattern of maximum spatial frequency

$$Vm = \frac{1.8r}{F\lambda}.$$

A high contrast, square wave resolution target with frequency of the order of Vm, will appear to be just resolved by the system. This number, Vm, might then be used as a quality index without the knowledge that a sine wave frequency $\frac{Vm}{2}$, is not passed. Resolution targets do have value as a production line check on quantities of similar lenses, where a departure from normal, limiting resolving power, can be traced to a mechanical or optical fault. However, even in photographic systems, resolving power has been found[11] to be a less desirable method of measuring performance. Furthermore, the information passing capacity of a aberration-less system is not necessarily limited by diffraction.[11]

Pinhole Optics in Visual Displays

The prime advantages of a pinhole lens are the large depth of field and distortion-less imaging. The chief disadvantages are low spatial frequency response and high f/number. For many applications, the advantages outweigh the disadvantages; sometimes a wide angle camera with extremely large depth of field, is needed.

Depth of Field

The depth of field of a conventional lens is defined as the range of object distances for which an acceptable image is formed in a given plane of the lens image space. What constitutes an acceptable image may be largely a matter of subjective opinion. In photography the image is just acceptable when a point object is imaged as a blur circle $\frac{F}{1728}$ in diameter[7], where F is the focal length of the lens. In any case, if the blur circle is large enough, geometrical optics is sufficient to calculate the depth of field. For diffraction limited optics, the depth of focus is first determined from the allowable wavefront error at the exit pupil, then the depth of field is computed. Consider the depth of field of an optimum pinhole, if the wave error is arbitrarily allowed to increase from $\frac{\lambda}{2}$ to $\frac{3\lambda}{4}$. The expression,

$$r = \sqrt{\frac{2\,\Delta aF}{a + F}} \qquad (12)$$

gives the relationship between the pinhole radius r, focal length F, and object distance a, for a wave error of Δ wavelengths. For an optimum pinhole, $r^2 = \Delta F$ so that an object distance $a = 2F$ is required for a wave error of $\frac{3\lambda}{4}$. For a diffraction limited lens, an increase in wave error of $\frac{\lambda}{4}$ is equivalent to the image plane shifting by[8]; $z = 2f^2\lambda$, (13)

where f is the f/number. (See Appendix A.)

It was easily calculated from geometrical optics, that for an f/10 cone in the image plane and white light of effective wavelength 5×10^{-4}mm (1.97×10^{-5} inches) the closest object distance for the image shift given by (13) is approximately $a = 10F^2$. Thus, the lens has a handicap of 5F:1 over the pinhole for the closest object distance, given an equal increase in wave error. For a fixed effective f/number, this handicap does not change with object distance. Thus, a pinhole lens, of focal length 15mm (0.592 inch) will image objects from a distance of 30mm (1.18 inch) to infinity with an increase of the wave error of $\frac{\lambda}{4}$. An f/10 spherical glass lens of the same focal length, images object from 2250mm (8.87 inches) to infinity with the same clarity as the pinhole, if the same wave errors occur.

The degradation in response of the pinhole when the wave error increases from $\frac{\lambda}{2}$ to $\frac{3\lambda}{4}$ is shown in figure 7*.

*Reference 8, p 92.

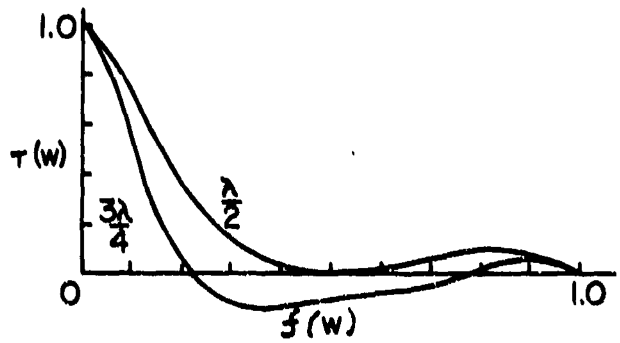


Figure 7. Response of Pinhole for Two Different Wave Errors

The highest spatial frequency passed by the system ranges from about $\frac{1.75}{r}$ to $\frac{0.6}{r}$ as the object moves from infinity to a distance 2F from the pinhole.

The response of the pinhole also changes as we move away from the optical axis, in the focal plane. The pinhole begins to appear as an ellipse, with increasing eccentricity as the angle increases between the optical axis and the line of observation. The diffraction pattern spreads, in the plane of the optical axis and the minor axis of the apparently elliptical pinhole. The frequency response falls as the angle increases; the highest spatial frequency passed at an angle of 50° is about one-half of the axial value. If the focal surface is a plane, the maximum response is further reduced to about one-third the axial value, for a viewing angle of 50°. This rate of falloff is not significantly different for a glass lens; it can be reduced at the risk of image distortion, by curving the focal surface concave toward the pinhole.

Photometry

The illumination also falls as we move away from the axis, in the focal plane. The falloff is

$$Ep = Eo \cos^4\theta \qquad (14)$$

where Eo is the axial illumination and θ is, again, the angle subtended at the pinhole between the axial focal point and some other point in the focal plane. Although the $\cos^4\theta$ dropoff is also encountered in lens systems, it is a less serious problem because of the relatively narrow field angles of ordinary lenses.

By a trivial derivation, assuming an object small compared with the object to pinhole distance

$$E_o = \frac{B}{4f^2}, \qquad (15)$$

where B is the object luminance in foot-lamberts, f is the f/number of the pinhole, and E_o is the axial image point illumination in foot-candles. Essentially, equations (14) and (15) completely define the photometry of a pinhole system.

A Pinhole-Television System

Let us see how a pinhole lens might be used in a television system. Deciding arbitrarily on a 100° horizontal field and recognizing beforehand the necessity of a sensitive detector, such as an image orthicon, the geometry may be quickly determined. Assuming a photocathode scanning format 36 x 24mm in size, the required pinhole focal length is F = 18 cot 50° = 15mm. (0.59 inch). The diameter of the pinhole is found from (1), i. e.,

$$d = 2\sqrt{\lambda F}$$

$$\approx 2\sqrt{5 \times 10^{-4} \times 15} = .17\text{mm } (0.0067 \text{ inch})$$

Now, the scene highlight luminance depends on the luminance factor of the object (in the direction of the pinhole) and the amount of incident illumination. A survey of commercially available illuminants shows that without going to extremes in lighting, an incident illumination of 350 lumens per square foot is easily accomplished* over a model scene ten feet square. Assuming the object model to be diffusing with a maximum reflection factor of 0.8, then the object highlight luminance is,

$$B = 350 \times 0.8 = 280 \text{ ft-L.}$$

Using equation (14), the photocathode illumination is,

$$Ep = \frac{280}{4} \left(\frac{.17}{15}\right)^2 \cos^4\theta$$

$$\simeq .01 \cos^4 \theta \text{ f.c.}$$

Along the diagonal of the photocathode format, the maximum field semi-angle is 55° so that the minimum highlight illumination on the photocathode is

$$Ep = .01 \cos^4 55^\circ = .001 \text{ foot-candles}$$

The central illumination level and the 10:1 falloff at the field edges may be adequately handled by a 7629A image orthicon. Because of the non-linear light transfer characteristic of this tube, a 10:1 illumination falloff

*Using two 1000 watt quartz iodine lamps at a distance of 8 feet (2.44 meters) results in only a 5:1 drop in output current. The 5:1 falloff may be compensated by automatic gain circuitry which boosts the output signal in the required fashion. The 7629A image orthicon has no definite operating point like more conventional tubes. Generally, the highlight illumination of the 7629A photocathode would be about 4×10^{-3} foot-candles. For this level, and a f/88 pinhole, the object illumination would not have to be higher than 150 foot-candles although the signal to noise ratio at the edges of the field would be low.

A mechanical problem arises if the pinhole and image orthicon are to view a model scene, as is often the case in real world visual simulation. The pinhole is the entrance pupil of the system, and the center of perspective, so that the distance between the pinhole and model terrain effectively sets the model scale. In aircraft simulation the model scale is required to be as large as physically possible, to keep overall model sizes within reason. For instance, a model area 20 feet square could represent a real world area of 10 miles square at a scale of 2,500:1. To "land" on this terrain the pilot's eye would be at a simulated distance of .005" above ground. The model size is reasonable, but the detector distance is far too small for practical use. Assuming that .125" is a practical approach distance for the pinhole, we still must contend with the size of the image orthicon tube and its focusing coil assembly. There are a number of ways that this problem may be overcome, but the simplest solution is to use an optically flat first surface mirror, external to the pinhole, as in figure 8.

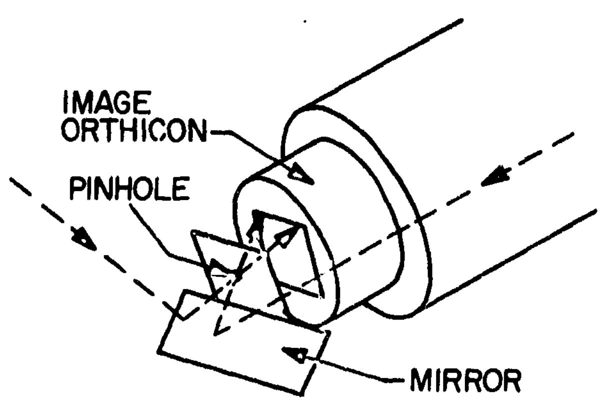


Figure 8. Light Deflection Arrangement

This solution is useful only if the vertical field component is less than 90°. A side view of this arrangement, showing a 76° vertical field, is illustrated in figure 9.

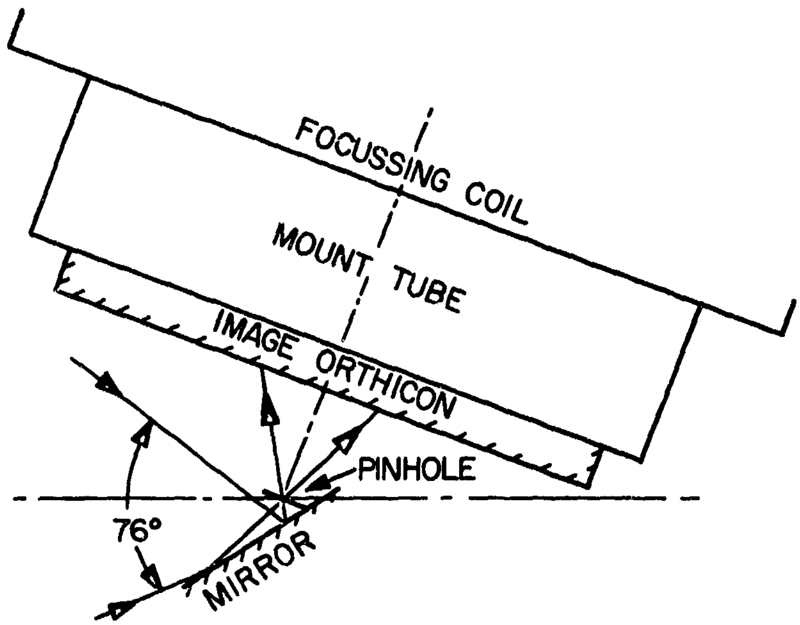


Figure 9. Folding Arrangement for Pinhole-Orthicon Imaging

It is obvious that for a view extending above the local horizontal, the minimum inclination (θ) of the image orthicon is equal to half the vertical angular field. For a 100° horizontal field (76° vertical field), and with the image orthicon inclined 90° from the horizontal, the angular view extends 38° below the local horizontal to 38° above. The mirror need not be very large, limited only by obstruction of the marginal rays by the image orthicon or the pinhole plate. In the example cited above, the limiting obstruction is not the orthicon, but the pinhole plate; nevertheless, a mirror only 6mm (0.236 inch) long would be sufficient to clear all obstructions and to give the required field. In the horizontal direction the mirror would be about 10mm (0.394 inch) with ample margin.

Display

A display CRT may be used directly to view the image formed by the pinhole. Usually, this is not done because the advantages of the wide angle pickup cannot be realized with existing monitor sizes and the required viewing distance. If the viewed image is to appear not only in its proper perspective but at the correct distance, then the eye must be fooled into believing that the image is much more than just a few feet ahead.

Sometimes a positive lens is placed in front of the display CRT in such a way that the image appears at infinity and the correct perspective is achieved. In this case, if the viewer's head is not fixed, a large lens, generally of plastic, is needed. If the eye is the aperture stop of the virtual image viewing system, the position of the entrance pupil moves as the head moves, with accompanying changes in the angular field of view, figure 10a. This is minimized by a large display to lens distance. In virtual image viewing of display CRT's, this distance is likely to be short; unless the head is fixed, the image perspective will be continually varying. In addition, a single, large simple lens introduces objectionable aberrations; a 100° viewing field would cause serious image distortion.

Another method of virtual imaging is to use a combination of two concave mirrors or a lens-mirror combination, figure 10b. A symmetrical system will minimize image distortion, a factor to be considered with large angular fields. A system of this kind has an exit pupil, at which the eye must be placed. The pupil may be made fairly large, but generally will allow lateral head movements of only a few inches. Furthermore, the eye must be placed in close proximity to the pupil position if the angular field is large.

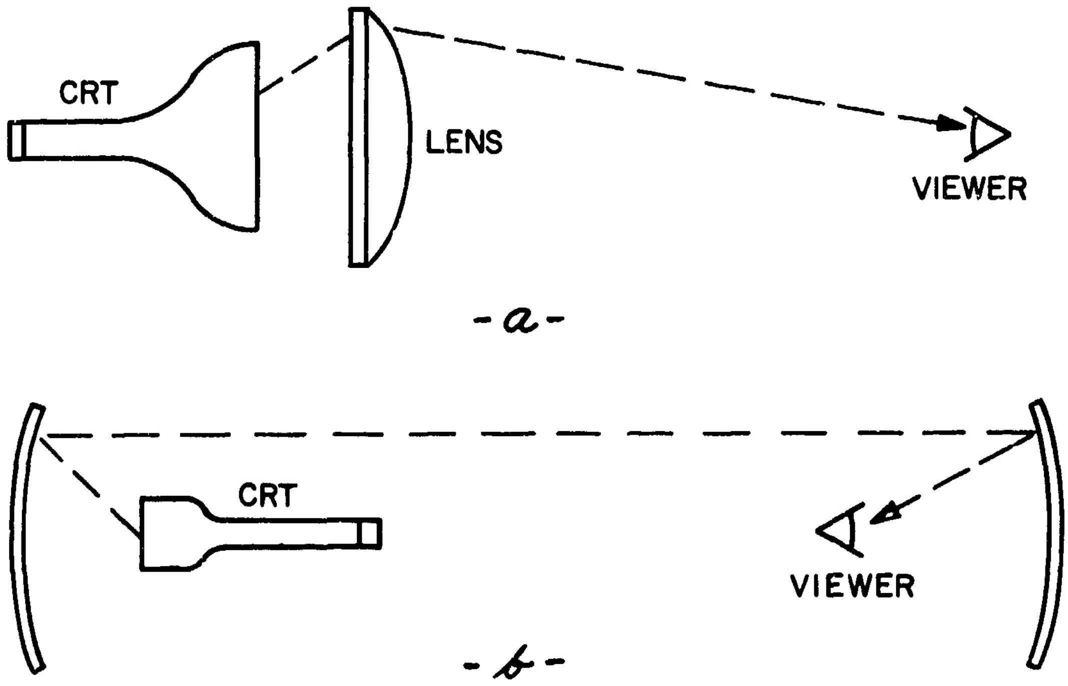


Figure 10. Virtual Image Viewing Systems

An alternative to a virtual imaging system is a projection display which is often chosen, in spite of the low image luminance. Suppose the viewing point is fixed ten feet from the projection screen; regardless of the projection geometry, the luminance of the screen for a given viewing angle ϕ (in radians) is approximately

$$B_s = B_{CRT}\, TG \left(\frac{D}{2400f}\right)^2 \text{ foot-lamberts} \qquad (16)$$

assuming a spherical front projection screen with center point at the eye position. In this equation, D is the horizontal dimension (inches) of the display CRT raster, T is the transmittance of the projection lens, G is the screen gain, and f is the f number of the projection lens. If a minimum screen luminance of 2 f-L is acceptable, and the lateral eye position is maintained within a few inches so that a screen gain of 5 is feasible, then the required CRT luminance for a 100° field is

$$B_{CRT} = \frac{B_s}{TG} \left(\frac{2400f}{D}\right)^2$$

$$= \frac{2}{(0.85)(5)} \left(\frac{240 \cdot 1.75 \cdot 8}{5}\right)$$

$$= 21{,}000 \text{ f-L},$$

assuming an f/8 lens with 85% transmission, and a horizontal raster dimension of 5". The CRT luminance calculated above is difficult to achieve with a conventional projection CRT. Screen and lens requirements can be considerably relaxed if a high luminance display device is used, similar to the Eidophor or GE Light Valve. However, there is a problem in the match of a wide angle projection lens to the distortionless characteristic of the pinhole. A wide angle lens of the Dagor type may be used for low distortion imaging over a 100° field, provided the lens aperture ratio is not less than about f/16.

System Response

Since a television system images in two dimensions only, it is possible to obtain the system response by multiplication of the response factors of the individual cascaded components. The two dimensional response of a .17mm (.0067 inch) diameter pinhole (100° horizontal field), typical image orthicon and projection CRT (525 line raster) are shown in figure 11. The responses assume a large object distance and circular scanning apertures in the orthicon and display CRT. The equivalent system response is denoted by the dashed line. The response of the system is very nearly Gaussian in shape, an expected result. Since the area under the curve $[\tau(w)]^2$ is a measure of the total sine wave energy passed by the system and therefore a measure of the information capacity, it may be useful to employ Schade's[9] definition of N_e, the equivalent response as shown in figure 11. Since the system response is Gaussian, it follows, that to a good approximation*, the

*Note: $N_e = \int \tau(v)^2 dn$

$$= \int_0^{\infty} \left[e^{-N^2(K_1+K_2+K_3)}\right]^2 dn$$

$$= 1/2\sqrt{2} \left[\frac{\pi}{K_1+K_2+K_3}\right]^{1/2}$$

$$\frac{1}{N_e^2} = \frac{K_1+K_2+K_3}{8\pi} = \frac{1}{N_1^2} + \frac{1}{N_2^2} + \frac{1}{N_3^2}$$

The individual responses only approach a Gaussian shape, but the inaccuracy of equation (17) is very small.

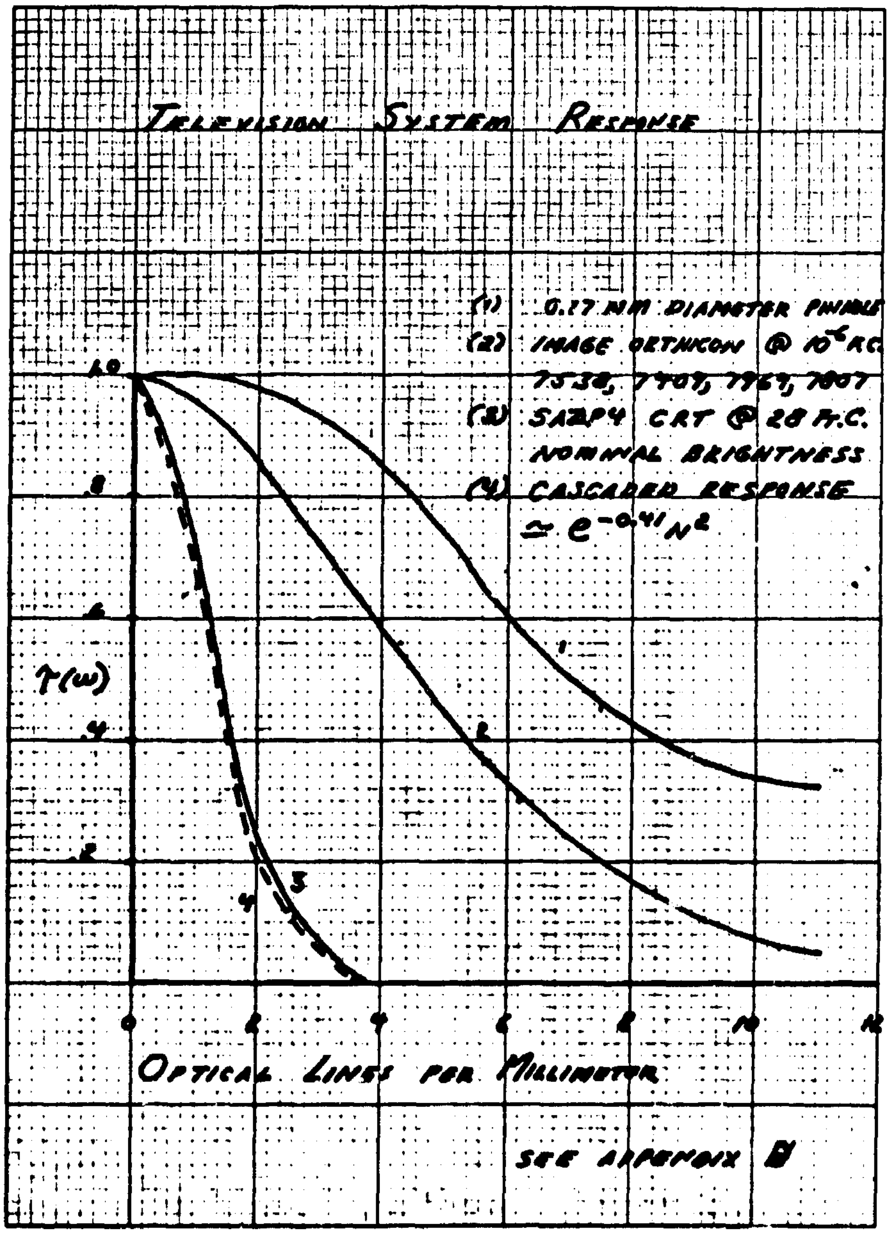


Figure 11. Television System Response

equivalent response, N_e, may be found from

$$\frac{1}{N_e^2} = \frac{1}{N^2_{pinhole}} + \frac{1}{N^2_{orthicon}} + \frac{1}{N^2_{CRT}} \qquad (17)$$

This formula is given liberal use in the field of optics to determine system resolution. In these cases N is replaced by R, the resolving power limit of each component. Many times, the use is overextended, particularly when three dimensional imaging is involved, and where the component responses are not Gaussian.

Still to be considered, is the projection or viewing optics that may follow the display CRT. If the display is projected, then the system is further cascaded by the addition of projection optics, screen and the observer's eye. These three components will not degrade the system any further since their responses will be much higher than the television especially when the effects of enlargement are considered. That is, assuming no further degradation, the cascaded response will be as shown in figure 11 except the absicssa scale is divided by 60. The factor, 60, is roughly the enlargement that takes place when a 100° projection angle is used with a screen ten feet distant. Thus, a television system having a circular scanning aperture is response limited by the raster line number, particularly if a 50% line overlap is used to secure a uniformly illuminated field. The images formed by a wide angle television system will not be sharp because the system response is well below the response of the eye. At present, a pinhole does not significantly degrade the system response over that of a perfect lens of much lower aperture ratio.

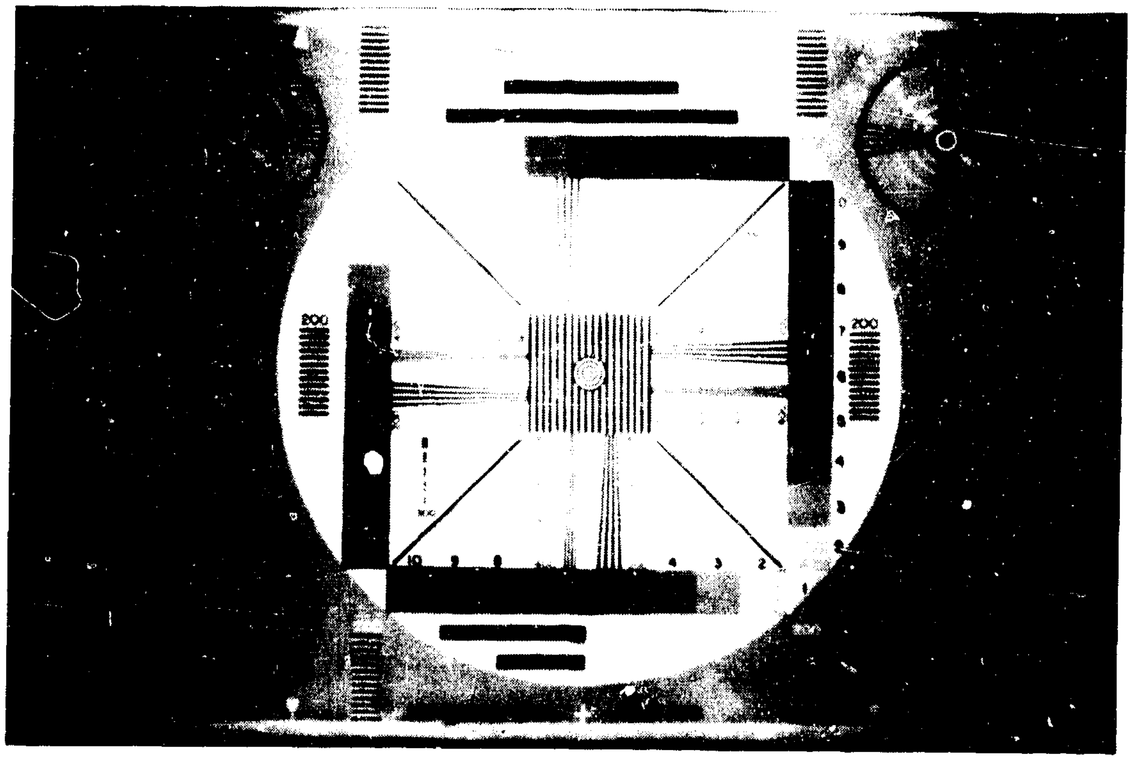
If the scanning aperture is elliptical, with the semi-minor axis horizontal, then the horizontal response of the television system can be made much higher than the vertical response, with a resulting increase in image sharpness. According to Schade's definition of equivalent passband, N_e, the resulting overall response of the television system is,

$$N_{eT} = (N_{eh} N_{ev})^{1/2} \qquad (18)$$

where N_{eh} is the equivalent horizontal passband and N_{ev} is the equivalent vertical passband. Considering the maximum performance possible at this date, it is doubtful that N_{eT} can be made much higher than 150 lines/picture height. A .17mm (0.0067 inch) diameter pinhole of 100° horizontal angular field has Ne = 300 lines/picture height. Even in this system, the pinhole would not seriously degrade system performance.

Demonstrated System

The feasibility of a pinhole-television system was demonstrated using a 0.1mm (0.0039 inch) diameter pinhole with a 10mm (0.39 inch) focal length. The photocathode of an 8057 image orthicon was placed at the focal plane. The image was viewed by observing a 7" display CRT, via a catadioptric image viewing system with an apparent field of about 90°. A number of small automobile models were used as objects, and sufficient illumination was provided to give a highlight luminance of 400 f-L. This image was not sharp in spite of the relatively high scanning line number (1029) because the display CRT degraded the system resolution. (The eye response is much higher than any of the components of this system.) A mild zooming effect was accomplished by moving the orthicon further away from the pinhole. No noticeable image degradation occurred when the focal length was doubled.



Pinhole:	**.006 inches (0.153mm) diameter**
Test Pattern:	**18 by 22 inches (0.48m by 0.56m)**
Focal length:	**0.58 inches (14.7mm)**
Image size:	**1.12 by .84 inches (28.4mm by 21.4mm)**

Figure 12. Pinhole Photograph of EIA Test Pattern

The system used for this demonstration normally employed an optical probe made up of many glass lenses. Even a low f/number, diffraction limited lens could not improve this system, if the observer is forced to view a low response display CRT over a wide angle.

PART II

ENGINEERING DESIGN

In designing an ideal TV pinhole camera system the starting point is analysis of the pinhole followed by selection of the TV camera tube and last, selecting the geometry of the optical path.

Pinhole Selection

The selection of an optimum pinhole is based upon several factors:

f/number (limited by reasonable object scene light levels and maximum TV camera tube gain)

resolution (limited by minimum acceptable valves)

focal length (field of view attainable)

The pinhole diameter chosen to produce the best resolution is limited by two parameters: geometry of the TV camera tube with its enclosure, and the TV tube photosensitivity.

First, a survey disclosed a variety of additional equations for determining a suitable pinhole diameter in terms of focal length.[12-21] These formulas were converted to inches and an assumed light wavelength of λ = 5500A° (green light).

From optical bench tests taken with .006 and .012 inch (0.153 and 0.306mm) diameter pinholes (Figure 12) S. Franke's formula was chosen as similar to Equation 13. It is interesting to note from Franke's equations that the spot resolution is approximately 1/3 of the pinhole diameter.

The TV raster is a 4:3 aspect ratio rectangle within the TV camera tube's circular photosensitive disc of fixed maximum diameter. Therefore, the focal length of the pinhole is fixed by the desired field of view. Other parameters such as lens f/number and image plane resolution are fixed once these terms are established.

Design Equations

There are four relationships which must be satisfied to produce the most effective design. These relationships can be described in equation form.

The first equation relates the field of view to the pinhole focal length and the TV camera tube raster size:

$$F = s \cot \left(\frac{\theta}{2}\right) \qquad (19)$$

The value s is the radius of the TV camera tube photo sensitive surface. Using a rectangular aspect ratio of 4:3, the horizontal and vertical fields of view are actually less than Θ. (Figure 13.)

Table 1. Pinhole Diameter, Focal Length and Resolution

Source	Reference Number	Optimum Pinhole Diameter	Smallest Image (radius)
Franke	(12)	$d = 38\times10^{-3}\sqrt{F}$ millimeters	$z = 11.4\times10^{-3}\sqrt{F}$ millimeters
Hardy & Perrin	(13)	$d = 21\times10^{-3}\sqrt{F}$	$z = d$
Reynolds & Ward	(14)	-	$z = 1.22\ nd$
Gallas, Gilbert & Hitterdal	(15)	$d = 4.45\times10^{-3}\sqrt{F}$	minimum
McNeil, G. T.	(16)	$d = 35.2\times10^{-3}\sqrt{F}$	(approximately equal to eye when viewed at 250mm)
Mack & Martin	(17)	$d = 44.5\times10^{-3}\sqrt{F}$	minimum
Petzval	(13)	$d = 33.1\times10^{-3}\sqrt{F}$	$z = 55.2\times10^{-5}\ (\frac{F}{d})$
Henney & Dudley	(18)	$d = 7\times10^{-5}\ F$	minimum

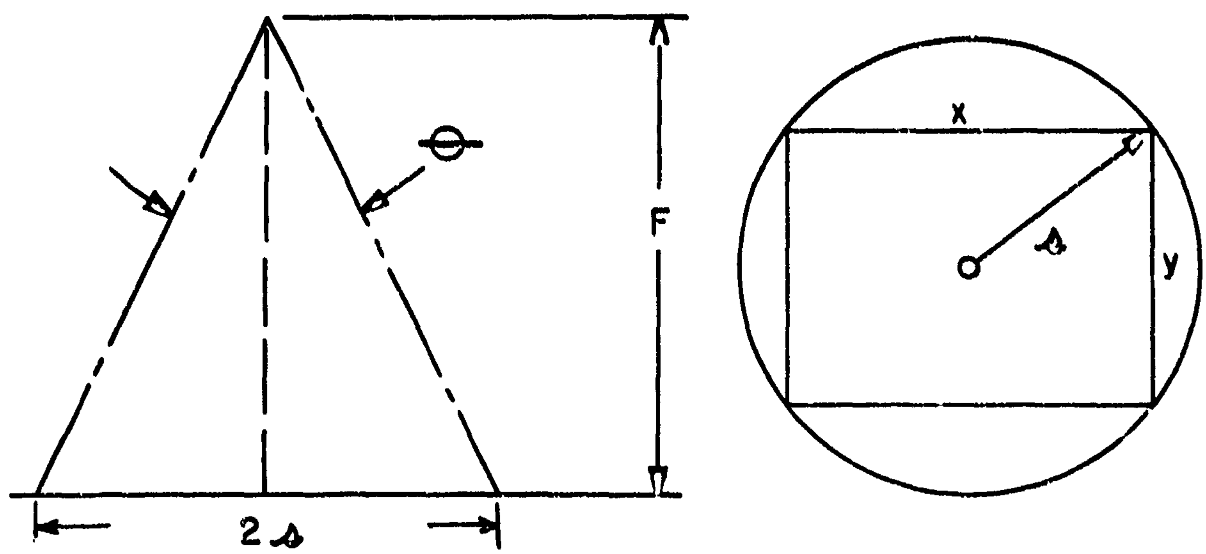


Figure 13. Field of View and Raster Configuration

Determining the horizontal and vertical field of view:

$$\tan \frac{\theta_x}{2} = \frac{4}{5} \tan \frac{\theta}{2} \qquad (20)$$

$$\tan \frac{\theta_y}{2} = \frac{3}{5} \tan \frac{\theta}{2} \qquad (21)$$

The second equation relates the axial pinhole image ray light level to the reflected light from the scene being viewed. (Figure 14.)

$$f = \frac{F}{d}$$

$$E_o = \frac{B}{4f^2} \qquad (22)$$

The third equation represents the image light level reduction caused by off axis projection of light through the pinhole onto the image plane (Figure 15).

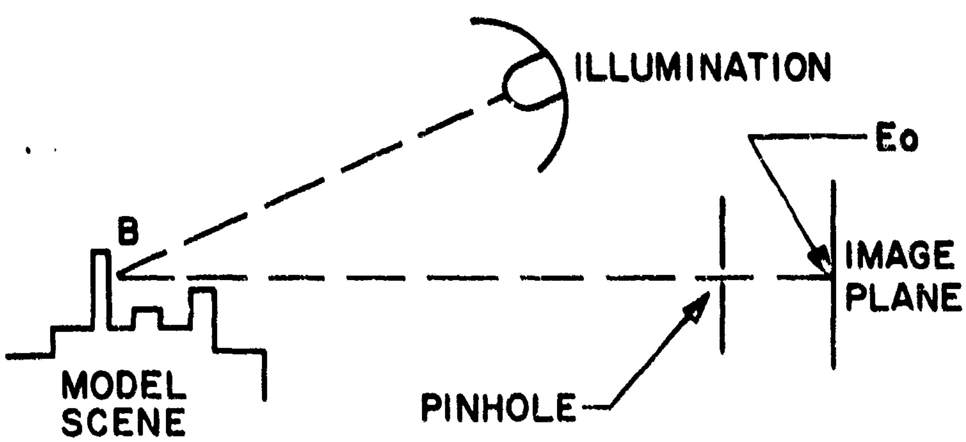
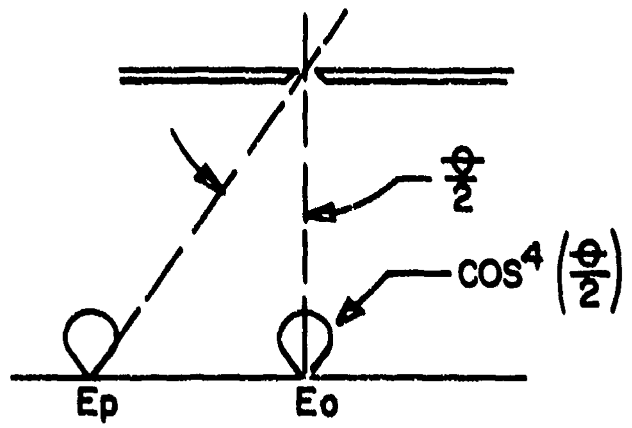


Figure 14. Direct Image Plane Pinhole Illumination



(Equation 23)

Figure 15. Off Axis Pinhole Image Plane Illumination

This image light level reduction from off axis projection is a major problem and a limiting constraint. For example, at 60 degrees off axis, the light level is reduced to 6% of the axial light level on the image plane.

The fourth equation is the relationship between the pinhole diameter and its effective focal length for the best image plane resolution. A considerable number of different equations exist for this relationship (Table 1). Petzval's derivation described in Hardy & Perrin(13) illustrates the parameters involved. Franke's empirical equation best describes the existing relationship between pinhole diameter and optimum focal length(12). These results agreed with laboratory tests.

The resolution of a pinhole is the result of wavefront cancellation and of parallel rays projected through the pinhole. Franke's equations are:

$$d = 38 \times 10^{-3}\sqrt{F}\ \text{mm}$$

$$= 7.55 \times 10^{-3}\sqrt{F}\ \text{inches} \qquad (24)$$

$$z = 11.4 \times 10^{-3}\sqrt{F}\ \text{mm} \qquad (25)$$

$$= 2.24 \times 10^{-3}\sqrt{F}\ \text{inches}$$

With normal contrast ranges attainable, laboratory tests show a line can be imaged in the width z of Franke's equation. The term λ = 5500A° (the wavelength of green light) is included in the coefficient of equation (24).

These first four equations can be combined to determine (F', θ, d). The terms (Ep, B, s, λ) are held constant (see Appendix E).

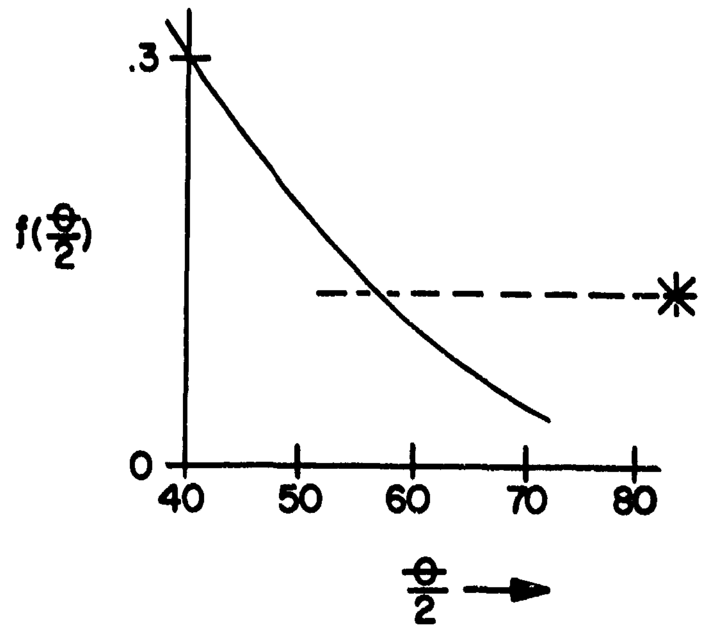


Figure 16. Combined f(θ/2) Overall Equation

$$7 \times 10^4 \left(\frac{Eps}{B}\right) \geq \tan\frac{\theta}{2} \cos^4\frac{\theta}{2} \qquad (26)$$

Ep and s are chosen from the considered TV camera tube specifications. B is based on the practicable reflected light levels.

The critical design parameters (F', θ, d) are then determined from equations 19, 22, 23, and 24. The pinhole image resolution in terms of TV lines can be determined from equation 25 (and Appendix G).

$$R = 88 \frac{(y)}{\sqrt{F}} \text{ TV lines} \qquad (27)$$

(Note y and F in millimeters)

TV Camera Tubes Available

The light level of the pinhole generated image is low due to the [illegible] f/number of the pinhole. A limiting factor exists in that, for a pinhole lens, the resolution increases as the pinhole is reduced in size. Since a smaller size pinhole means less light, it is desirable to use the smallest pinhole which will provide adequate image lighting.

By the principle of trading lower light level for higher resolution, present day TV camera tubes with their high gains and greater signal to noise ratios can produce adequate TV resolution with moderate lighting requirements. A possibility is the 7967 Image Orthicon.

Table 2. TV Camera Tube Performance

	Image Orthicon 7967
Target Size	50mm
Sensitivity, maximum	10^{-5} FC
Resolution at 10^{-4} FC	700
2.2×10^{-4}	700
1.8×10^{-3}	700
Signal to noise ratio	
at 10^{-4} FC	White 8
2.2×10^{-4}	10
1.8×10^{-3}	13.5

<u>Combined Pinhole and TV Camera Tube</u>

The maximum off-axis pinhole look angle can be determined from equation (26) and:

$$E_p = 2.2 \times 10^{-4} \text{ Lamberts}$$

$$s = 25.0 \text{ mm } (.984 \text{ inches})$$

$$B = 100 \text{ Candles}$$

From figure 16 and Table 3:

$$.1515 = f\ (56^\circ)$$

diagonal (max)

Table 3. Off Axis Capability

Equation $7 \times 10^4 \left(\frac{Eps}{B}\right) \geq \tan\left(\frac{\theta}{2}\right) \cos^4\left(\frac{\theta}{2}\right)$

θ	$\theta/2$	$f(\theta/2)$
80°	40°	.2890
85	42.5	.2708
90	45	.2500
95	47.5	.2273
100	50	.2034
105	52.5	.1790
110	55	.1546
115	57.5	.1308
120	60	.1083
125	62.5	.0873
130	65	.0684
135	67.5	.0518
140	70	.0376
145	72.5	.0259
150	75	.0167

The total rectangular view possible using a 4:3 aspect ratio from equation 20 and 21 is:

$$\theta_H = 2\ (50^\circ)$$

$$= \underline{100^\circ}$$

and

$$\theta_V = \underline{83\text{-}1/2^\circ}$$ (Ref: Appendix F)

The necessary focal length and pinhole diameter for this camera is determined as follows:

$$F = \frac{4}{5} (.25) \cot 56^\circ$$

$$= 16.7 \text{ mm } (.66 \text{ inches})$$

The optimum pinhole diameter for F = 16.7mm can be calculated using equation (24).

$$d = .159\text{mm diameter } (.0061 \text{ inches})$$

The expected system resolution is then calculated from equation (27).

$$\text{for } \theta_y = (50^\circ)2$$

Pinhole resolution in TV lines = 592 TV lines (vertical). A 1029 line TV raster has approximately 800 visible TV lines. Therefore, the combined pinhole and camera tube resolution would be:

$$R_t = \sqrt{\frac{R_1^2 \times R_2^2}{R_1^2 + R_2^2}} \qquad (29)$$

= 476 TV lines (vertical)
and 635 TV lines (horizontal)

<u>Geometry Considerations</u>

It is desirable to minimize the scaled distance between the pinhole line of sight and the ground. The TV camera line of sight clearance combined with any reasona' le scale factor requires a probe for right angled viewing by the camera. A front surfaced mirror can be used for the probe. The small image format and short focal length necessary to produce a wide field of view cause the vertical view to be limited by the TV tube's outer focus yoke. The ground clearance for simulated level flight can be held to 7.1 centimeters (1.8 inches) as shown in figure 17a. The vertical included angle however is limited. Ray tracing by means of a layout indicates the vertical included field of view will be 76° if the focusing yoke interference is overcome. An alternate optical probe interference solution would be use of a rigid fiber optic, right angle image bundle as shown in figure 17b. (See Appendix H & I also).

Monochromatic blue-green light will add somewhat to the pinhole resolution. The image resolution can be further enhanced by painting the 3-D object model scene a single color corresponding to the monochromatic lighting with proportionate gray shades. A further refinement on this optical probe can be made by replacing the mirror with a flexible fiber optic bundle as shown in figure 18.

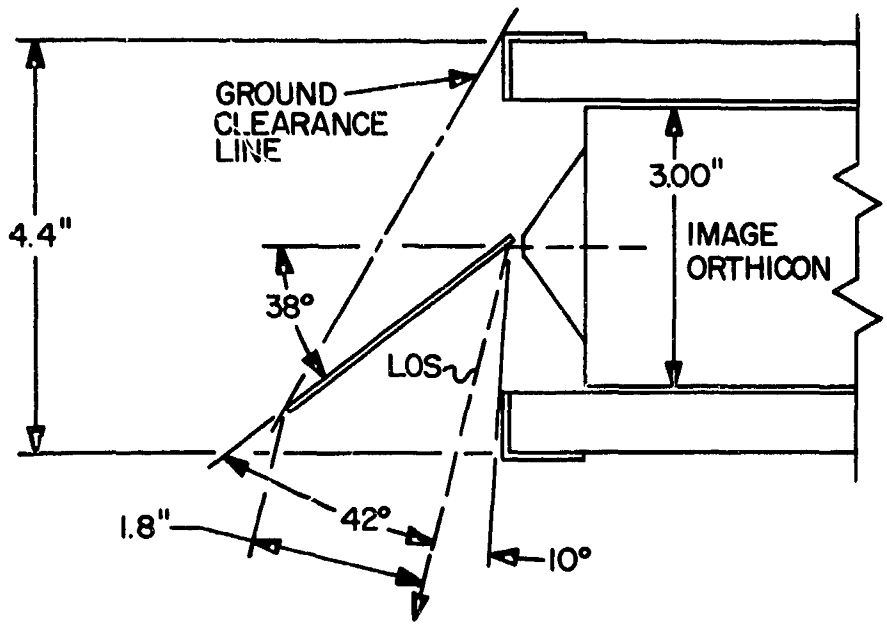


Figure 17a. Mirror Ray Trace Clearance

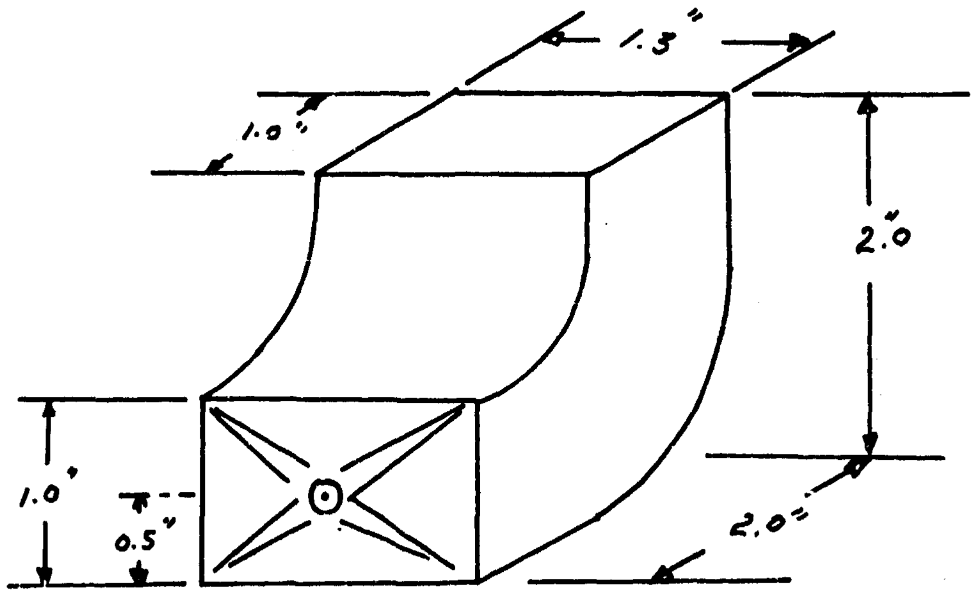


Figure 17b. Rigid Fiber Optic Probe

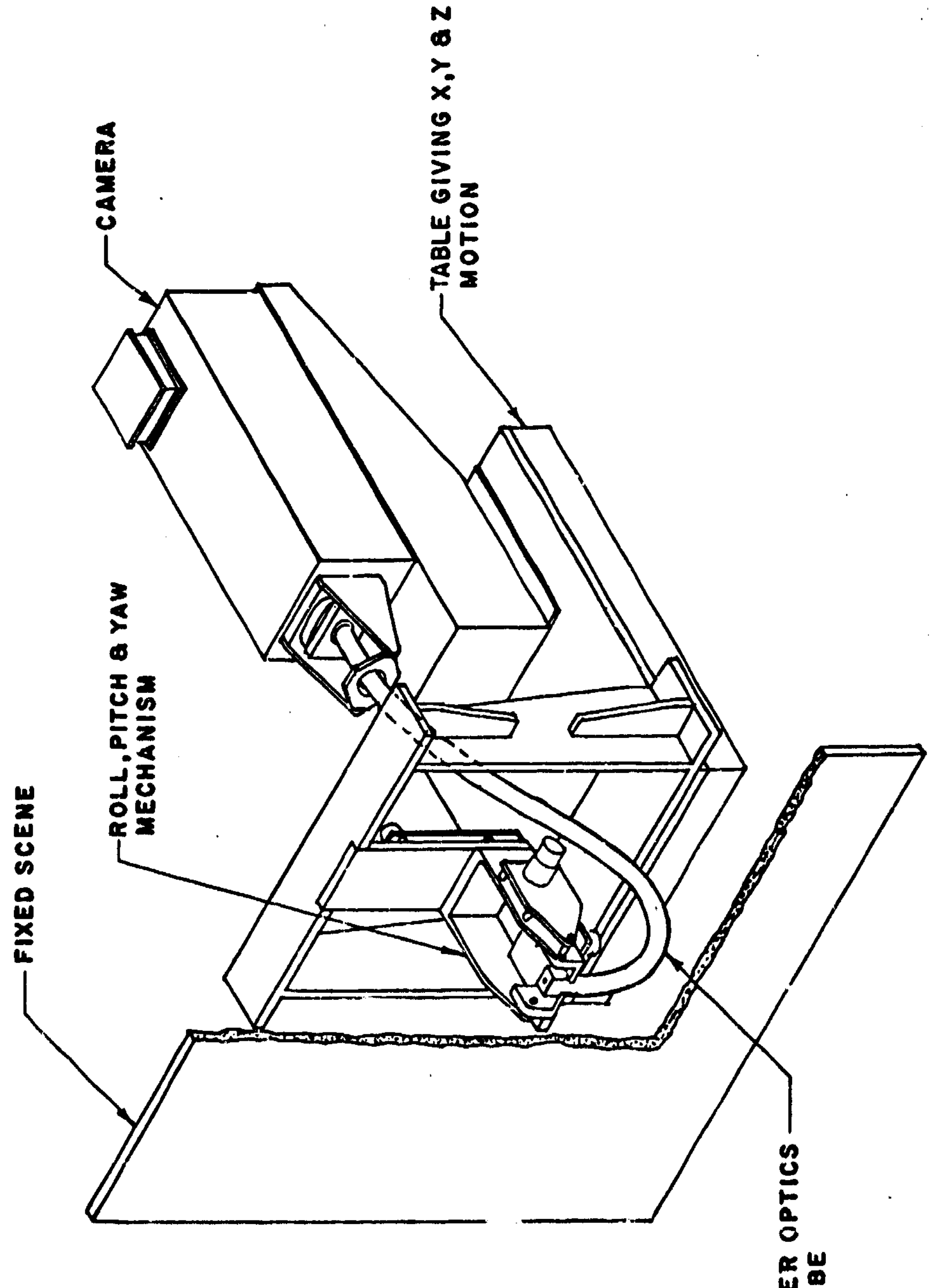


Figure 18. Fiber Optic Image Probe and Mechanism

The floxible probe would be capable of pitch, roll and yaw about the pinhole entrance pupil. This technique will also provide a low inertia optical probe. (Figure 18).

TV Camera System

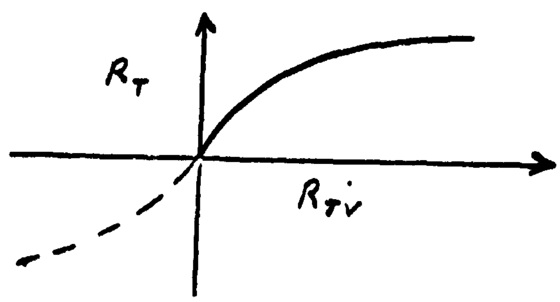
The TV camera itself should be a reasonably high resolution near-conventional camera with a high light gain camera tube. A justified approach would have the TV system resolution capability somewhat better than the pinhole itself. This can be shown from the overall resolution formula:

given $$\frac{1}{R_T^2} = \frac{1}{R_p^2} + \frac{1}{R_{TV}^2}$$

then $$\frac{\partial \frac{1}{R_T^2}}{\partial R_{TV}} = -2\, R_{TV}$$

therefore $$\Delta R_T : \frac{1}{\sqrt{2}R_{TV}} \qquad (30)$$

graphically



A conventional 1029 line TV camera having 800 active scan lines, modified for off axis gain compensation and a high gain camera tube would be suitable.

SECTION IV

CONCLUSIONS

It has been shown that the optical transfer function of a pinhole-image orthicon television system would be degraded primarily by a projection CRT. The TV pinhole camera would provide a virtually infinite depth of field and can produce a field of view up to 130 degrees. New camera tubes of high photometric gain make it possible to produce adequate gray scales at reasonable light levels. The pinhole provides nearly absolute linearity of the transmitted scene with no optically generated distortion. Resolution of the pinhole however, does not match that of good glass lenses. Moreover, the signal to noise ratio of a closed circuit television system using a pinhole lens will be "just adequate" with present day TV camera tubes and normal lighting levels.

SECTION V

RECOMMENDATIONS

The analysis and engineering design presented here demonstrated that a TV pinhole camera can be built. The design specifications in Table 4 are recommended as reasonable nominal requirements.

Improvements in resolution for both the pinhole and the optical pickup can be made by using monochromatic lighting. It remains for more sensitive higher gain, TV camera tubes to improve the signal to noise levels. The TV pinhole camera has definite applications in specific visual simulation training areas requiring great depths of field, near perfect linearity and uninterrupted wide fields of view. Three examples of this are: aircraft landing, terrain vehicle, and ship docking visual simulation. Continued work involving pinhole optics in visual simulation should provide solutions to many of the limiting conditions of presently used optical probes.

Table 4. System Specifications

Pinhole

- diameter - .00512 inches (0.130mm)
- metal surround thickness; less than .0025 inches (0.0635mm)
- focal length - optimum for FOV 16.7mm (.66 inches)
- field of view - 100° by 84°
- with front surfaced mirror - 76° vertical minimum
- image format - 4:3 aspect ratio
- image size - 50mm diagonal
- camera tilt - 14° permissible
- prism ground clearance - 1-3/8 inches
- depth of field - 2 inches to 20 feet minimum

TV Camera

- field/frame rate - 60/30 Hz, 2:1 interlace
- line rate - 30,870 Hz
- lines per frame - 1029
- pulse widths

horizontal blanking	7 μs
horizontal drive	4.5 μs
vertical blanking	21 horizontal lines
vertical drive	15 horizontal lines

Synchronization signals - negative going
Sweep linearity (effective) - ±1% H & V; ±2% position error
Sweep failure protection - required
Camera sensitivity - full output with 5×10^{-5} ft candles
Camera tube - EIA type 7967 Image Orthicon

Off axis compensation - for the required width field of view the camera head gain shall be capable of compensation, at the camera, for off axis degeneration of irradiance on the face of the camera tube; $i = f(\cos^4 \frac{\theta}{2})$

- bandwidth - 20 Mhz ± 1dB, 30 Mhz - 3dB
- gray scale - 10 steps EIA logarithmic gray
- video amplifier - 1 V pp output, 2 V pp before overload
- resolution (with glass lens) - 800 TV lines at center, 600 TV lines at corners, at 10^{-4} ft candles
- resolution (with pinhole) - 600 TV lines at center, 450 lines at corners at 100 ft candles scene brightness

Video SNR

- at 1×10^{-4} ft candles at photocathode
- SNR (whites) 8
- at 1.8×10^{-3} ft candles at photocathode
- SNR 13.5

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SECTION VI

APPENDIX A

The edge response of any image forming system depends on the location of the object and image planes. However, with a lens system, the spread function may be significantly different at different object distances because the effective focal ratio changes more rapidly. With a pinhole, the frequency response will be almost constant from a very short object distance to infinity because the diffraction pattern is not significantly altered. For instance, if $a = 10b$, then

$$(2\zeta + \Delta 2\zeta) = \sqrt{\frac{a + b}{a}} = \sqrt{\frac{11b}{10b}} = 1.05$$

Hence, the resolved spots are only 5% further apart than when $a \rightarrow \infty$.

(See Page 14.)

APPENDIX B

Table of Graphical Differentiation of MTF (Figure 4)

No.	Δ Density / mm Slope	Trans-mittance Slope	s	Normalized Transmissivity Slope	Normalized Transmissivity Slope X5
1	0		0		
2	.35	.0112	.0375	.0156	.078
3	.895	.0301	.0750	.043	.215
4	1.87	.072	.1125	.103	.515
5	2.93	.123	.150	.176	.880
6	4.18	.205	.1875	.292	1.460
7	5.33	.324	.225	.463	2.315
8	5.60	.438	.2625	.625	3.125
9	5.47	.538	.300	.768	3.840
10	4.96	.612	.3375	.875	4.375
11	4.50	.700	.375	1.00	5.000
12	3.30	.605	.4125	.864	4.320
13	2.20	.452	.450	.645	3.225
14	1.70	.384	.4875	.548	2.740
15	1.13	.287	.525	.410	2.050
16	.64	.176	.5625	.252	1.260
17	.373	.106	.600	.151	.755
18	.255	.074	.6375	.106	.530
19	.20	.059	.675	.0843	.421
20	.135	.041	.7125	.0585	.293
21	.066	.020	.750	.0285	1.43
22	0	0	.7875		

Note: Graphical differentiation of edge trace data (figure 4) to obtain line spread function (figure 5). Film MTF constant over range of consideration.

APPENDIX C

From edge response measured

lines/mm	τ (w)
0	1
1.6	.72
3.2	.31
7	.05

lines/mm	τ(w) (2D) Theoretical
.75	.91
1.5	.65
2.3	.46
3	.35
4.6	.165
6.2	.09
7.6	.08

lines/mm	τ(w) (1D) Theoretical
.8	.86
1.6	.63
3.2	.235
5.2	.03
6.5	0

Reference figure 7.

APPENDIX D

MTF
.17mm dia
Pinhole

lines/mm	τ(w)
2.8	.91
5.6	.65
8.5	.45
11.4	.34

MTF 3" dia
Image Orthicon
@ 10^{-6} F C
(IO 7538,7409,7969,7807)

lines/mm	τ(w)
2.1	.84
4.1	.56
6.3	.30
8.4	.14
10.4	.07

MTF 5" Projection
CRT (525 lines 5AZP4)

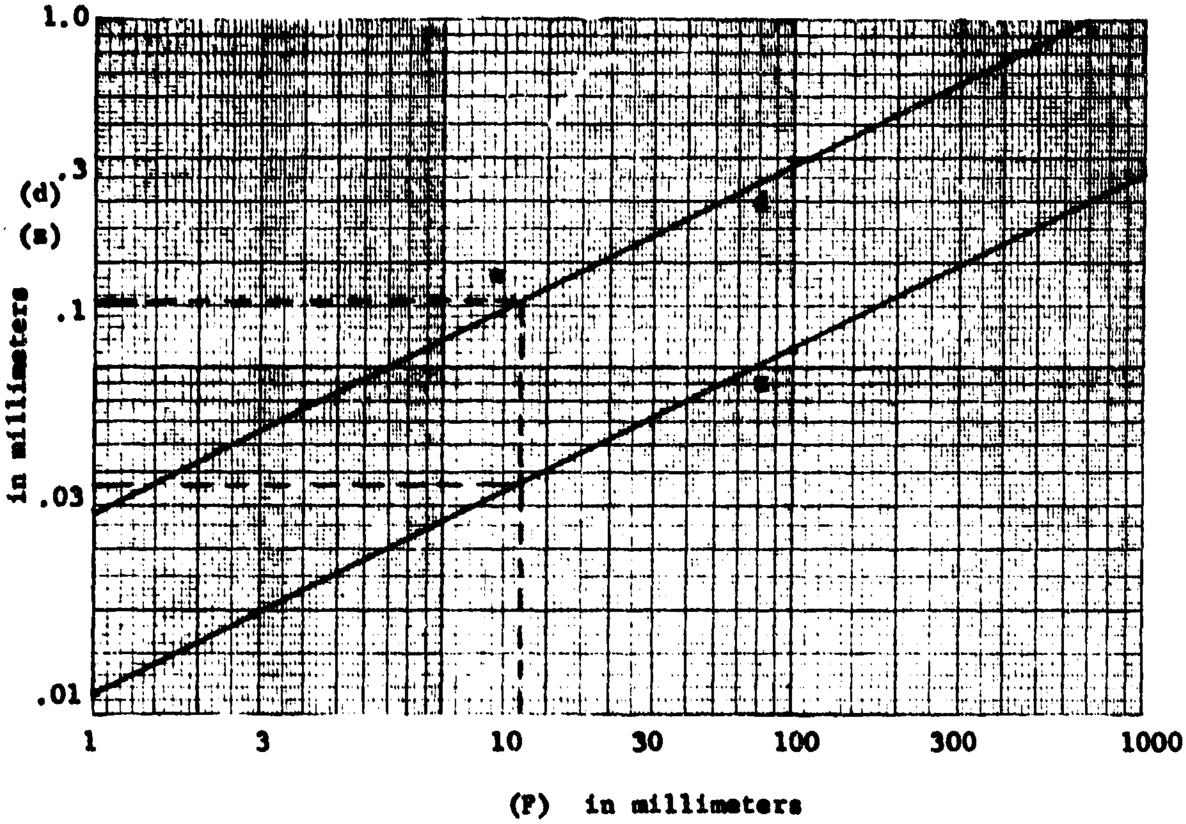
lines/mm	τ(w)
.85	.76
1.7	.32
2.55	.12
3.4	.02

MTF Cascaded Response

lines/mm	τ(w)
1	.645
1.5	.37
2	.19
3	.04

Reference Figure 11

APPENDIX E



Note: These values are based upon G. Franke's equations.

$d = 38 \times 10^{-3} \sqrt{F}$

$z = 11.4 \times 10^{-3} \sqrt{F}$

* Design Point

(d) = .159 millimeters (0.0061 inch)
(z) = .046 millimeters (0.0018 inch)
F = 16.7 millimeters (0.66 inch)

Figure 19. Optimum Focal Length (F) vs Resolution (z) and Pinhole Diameter (d)

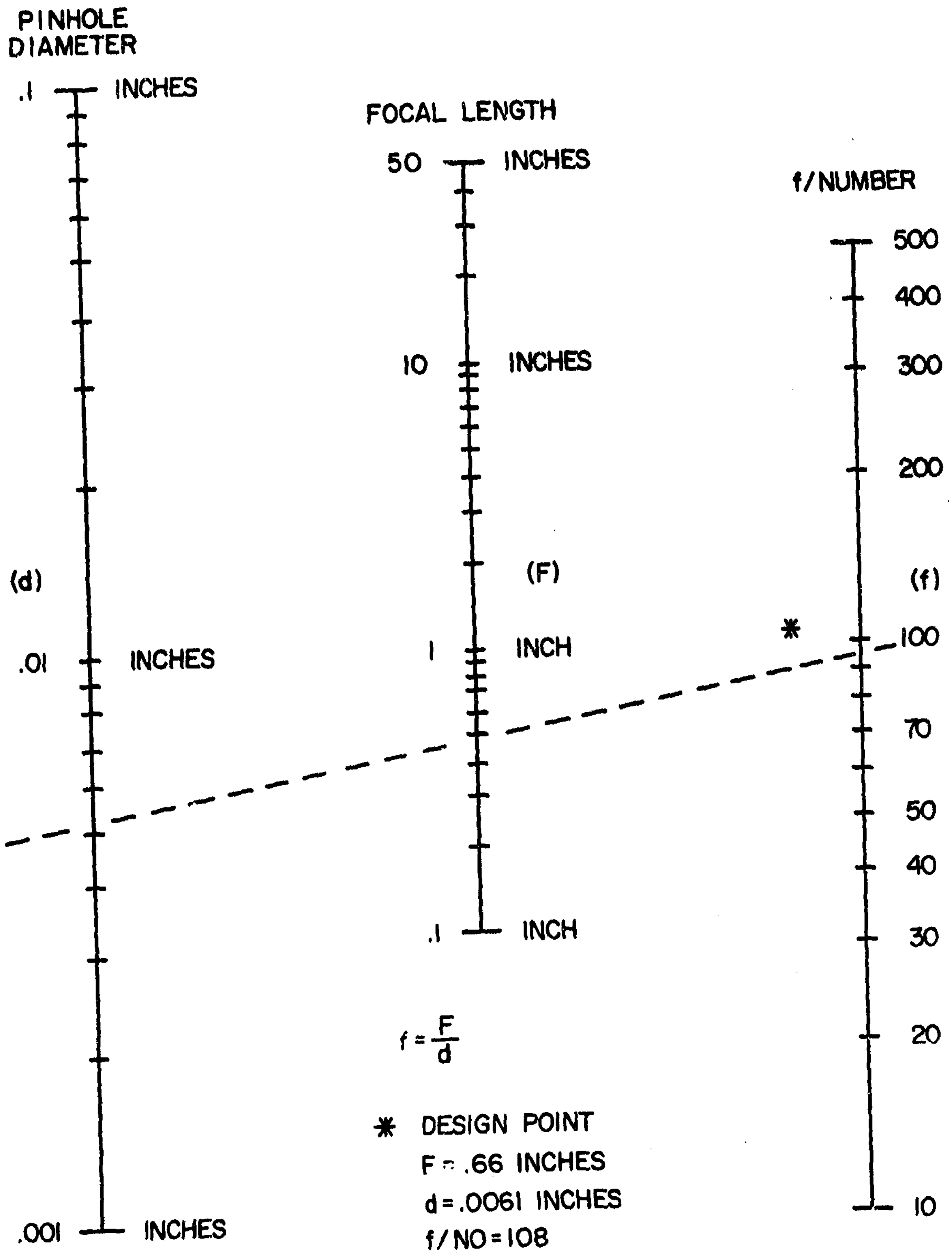


Figure 20. Pinhole (Lens) F/Number

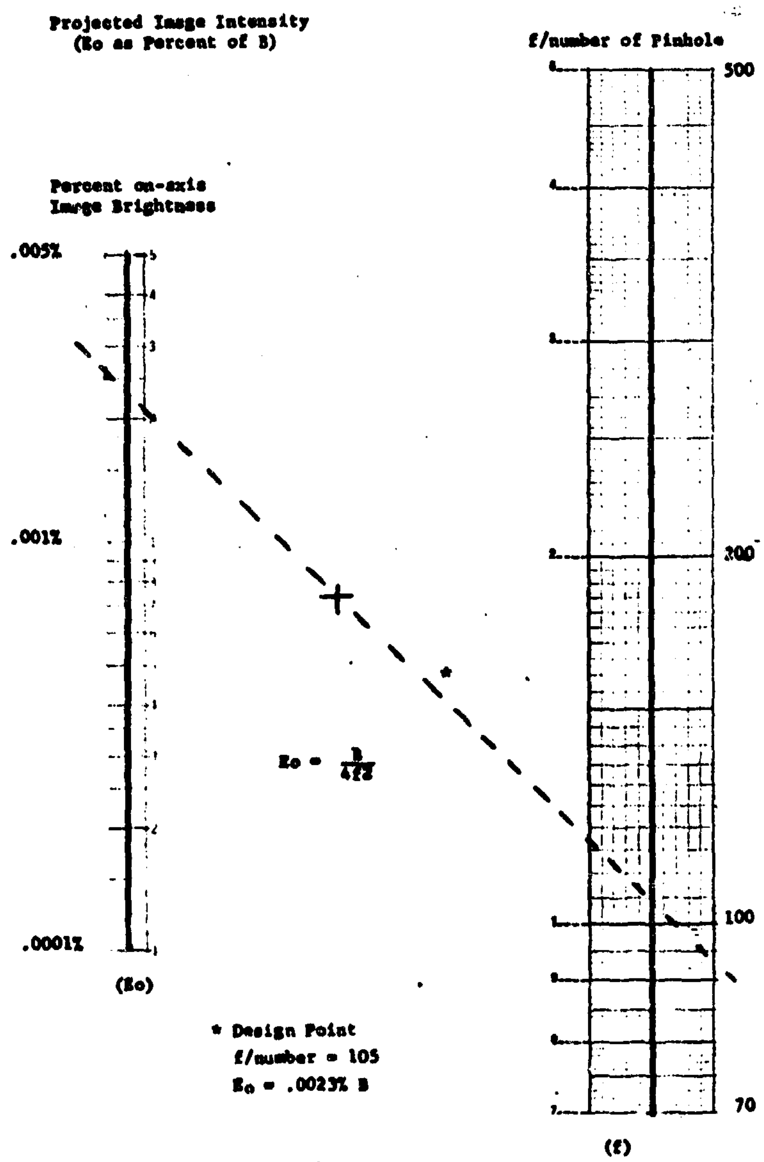


Figure 21. Projected Image Intensity (Eo as percent of B)

The combined $f\left(\frac{\theta}{2}\right)$ Overall equation relating the pinhole to the TV camera tubes photosensitivity can be determined:

$$Ep = Eo \cos^4 \left(\frac{\theta}{2}\right) \qquad (1)$$

$$Eo = \frac{B}{4f^2} \qquad (2)$$

where $f = F/d$

$$F = s \cot \left(\frac{\theta}{2}\right) \qquad (3)$$

$$d = 7.55 \times 10^{-3} \sqrt{F} \qquad (4)$$

Combining equation (1) and (2)

$$Ep = \frac{Bd^2}{4F^2} \cos^4 \left(\frac{\theta}{2}\right)$$

substituting equation (3) and (4)

$$Ep = \frac{B\ (7.55 \times 10^{-3})^2}{4s} \tan \frac{\theta}{2} \cos^4 \left(\frac{\theta}{2}\right)$$

or

$$(7 \times 10^4)\ \frac{sEp}{B} = \tan \left(\frac{\theta}{2}\right) \cos^4 \left(\frac{\theta}{2}\right)$$

APPENDIX F

Given: 4/3 Aspect ratio 100° horizontal FOV

Required: raster size, effective pinhole height, maximum image ray angle, vertical FOV

Solution: $2a = \frac{3}{5}\ (.984)(2)$

$2a = \underline{\underline{1.18''}}$ (Fig. 1)

$2b = \frac{4}{5}\ (.984)(2)$

$2b = \underline{\underline{1.57''}}$ (Fig. 2)

$h = .79 \cot 50^\circ$

$= (.79)(.83910)$

$= \underline{\underline{.6629}}$ (Fig. 2)

If we let $\phi_H = 100^\circ$ horizontal FOV, AR = 4/3

$$\frac{a}{b} = \frac{\tan \phi_V/2}{\tan \phi_H/2}$$

$\phi_V/2 = 2 \text{ Arc tan } \frac{(a)}{(b)} \tan (\phi_H/2)$

$= 2 \tan^{-1} \frac{(3)}{(4)} \tan 50^\circ)$

$= 2 \tan^{-1} \left(\frac{3}{4}\right) (1.1916)$

$= 2\ (41^\circ\ 48')$

$\phi_V = \underline{\underline{83\text{-}1/2^\circ}}$ (Fig. 2)

Result: (1) The necessary raster size to fit within the 1.97" diameter image orthicon photosensitive surface area with a 4/3 aspect ratio is:

width = 1.57" or 100°
height = 1.18 or 83-1/2°

(2) The effective pinhole height above the tube photosensitive surface is:

h = 0.66 inches

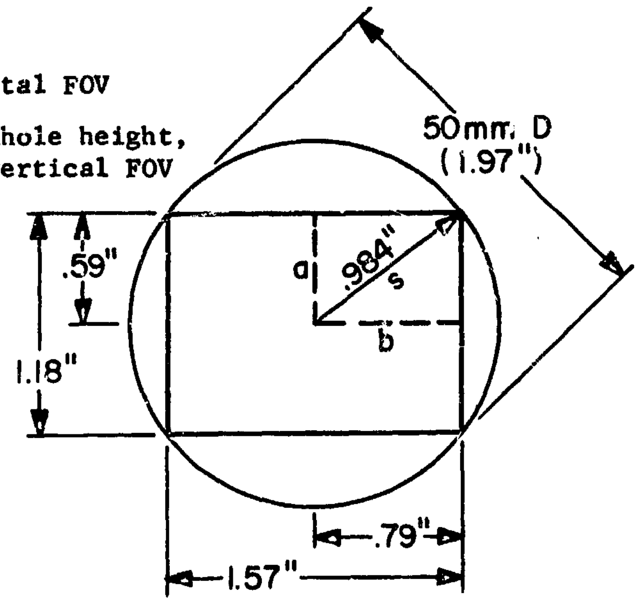
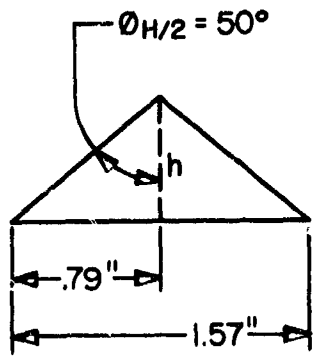
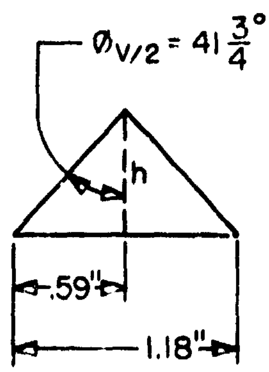


FIGURE 1



HORIZONTAL

FIGURE 2



VERTICAL

FIGURE 3

Figure 22. Definition of Field of View and Effective Pinhole Height (1,2,3)

APPENDIX F

Given: 4/3 Aspect ratio 100° horizontal FOV

Required: raster size, effective pinhole height, maximum image ray angle, vertical FOV

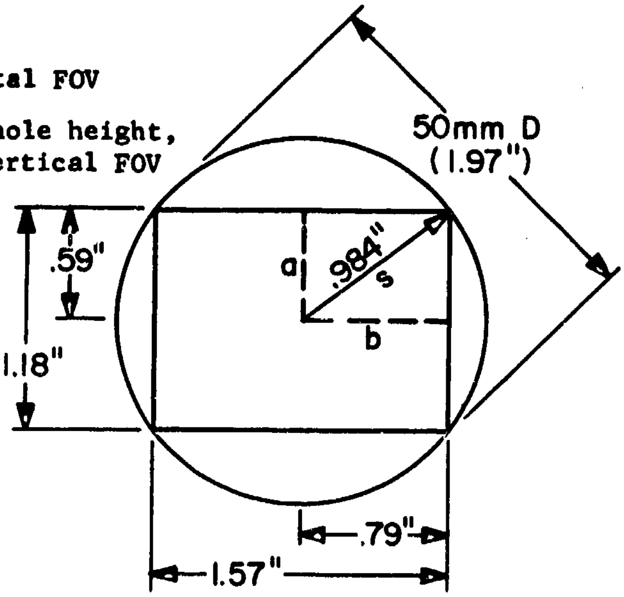


FIGURE 1

Solution: $2a = \frac{3}{5}\ (.984)(2)$

$2a = 1.18"$ (Fig. 1)

$2b = \frac{4}{5}\ (.984)(2)$

$2b = 1.57"$ (Fig. 2)

$h = .79 \cot 50°$

$= (.79)(.83910)$

$= .6629$ (Fig. 2)

If we let $\emptyset_H = 100°$ horizontal FOV, AR = 4/3

$$\frac{a}{b} = \frac{\tan \emptyset_V/2}{\tan \emptyset_H/2}$$

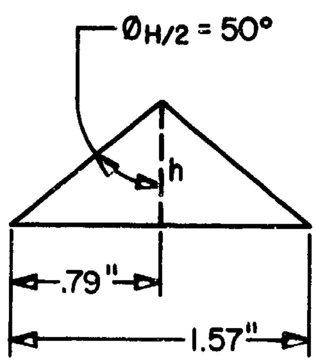
$$\emptyset_V/2 = 2 \text{ Arc tan } \frac{(a)}{(b)} \tan (\emptyset_H/2)$$

$$= 2 \tan^{-1} \frac{(3)}{(4)} \tan 50°)$$

$$= 2 \tan^{-1} \left(\frac{3}{4} \right) (1.1916)$$

$$= 2\ (41° 48')$$

$$\emptyset_V = 83\text{-}1/2° \quad \text{(Fig. 2)}$$



HORIZONTAL

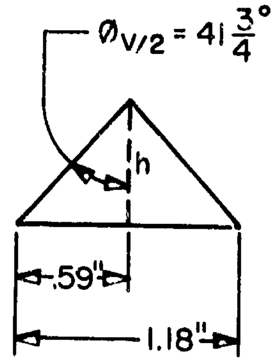
FIGURE 2

Result: (1) The necessary raster size to fit within the 1.97" diameter image orthicon photosensitive surface area with a 4/3 aspect ratio is:

width = 1.57" or 100°
height = 1.18 or 83-1/2°

(2) The effective pinhole height above the tube photosensitive surface is:

h = 0.66 inches



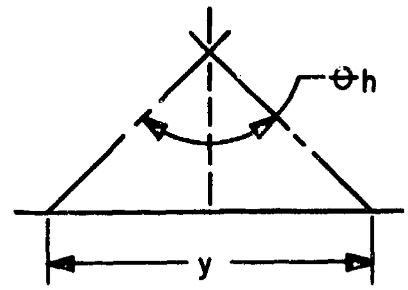
VERTICAL

FIGURE 3

Figure 22. Definition of Field of View and Effective Pinhole Height (1,2,3)

Next we can determine the field of view θ in terms of a fixed raster height and pinhole distance F (Figure 1):

$$F = \frac{y}{2 \tan \theta/2} \qquad (7)$$



combining equations (6) and (7):

$$\text{line pair per raster height}^* = \frac{y}{120 \lambda} \sqrt{\frac{2 \tan \theta/2}{y}}$$

$$= \frac{(\sqrt{y})}{85 \lambda} \sqrt{\tan \theta/2} \qquad (8)$$

Now:

for green light = .5461 microns

$$= .215 \times 10^{-4} \text{ inches}$$

and y = 1.18 inches height (for 50mm format)

substituting in equation (8)

$$\text{line pairs/raster width}^* = \frac{\sqrt{1.18}}{(85)\ 0.215 \times 10^{-4}} \sqrt{\tan \theta/2}$$

$$= 540 \sqrt{\tan \theta/2} \qquad (9)$$

Figure 23. Field of View vs Pinhole Distance and Raster Width

*Note: Equation 4 more closely represents TV line width rather than optical line pair distance. This is attributed to the overall MTF and SNR. In addition pinhole image plane resolution decreases as the off-axis viewing angle increases. In fact, the limiting pinhole image angle occurs where the pinhole surround metal thickness does not allow a direct ray through the pinhole

APPENDIX G

Problem: Determine the TV Camera tube image plane resolution vs the field of view for a pinhole lens.

Assumptions:

(1) TV Camera tube raster height fixed at y = 1.18" (30mm)

(2) Pinhole diameter (d) and focal length (F) chosen for optimum resolution.

(3) Predominant light, green, at 5461 A°

Solution:

f = f number

F = focal length (image plane distance)

d = pinhole diameter

y = raster height

λ = light wavelength

θ = camera field of view in width

$$f = F/d \quad (1)$$

$$d^2 = 7 \times 10^{-5} F \ (*) \quad (2)$$

therefore from equation (1) and (2)

$$f = \sqrt{\frac{F}{7 \times 10^{-5}}}$$

$$f = 120\sqrt{F} \quad (3)$$

From reference 1:

line pair distance = λf (4)

line pairs per raster height = $\frac{y}{\lambda f}$ (5)

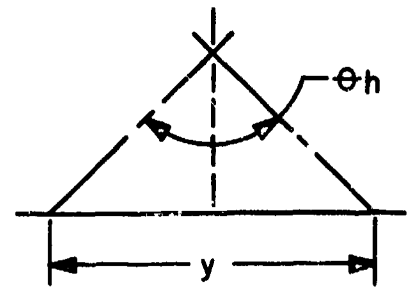
Combining equations (3) and (5)

line pairs per raster height = $\frac{y}{120 \ \lambda \sqrt{F}}$ (6)

*Reference: Henney & Dudley, Handbook of Photography pp 25-26.

Next we can determine the field of view θ in terms of a fixed raster height and pinhole distance F (Figure 1):

$$F = \frac{y}{2 \tan \theta/2} \qquad (7)$$



combining equations (6) and (7):

$$\text{line pair per raster height*} = \frac{y}{120\,\lambda} \sqrt{\frac{2 \tan \theta/2}{y}}$$

$$= \frac{(\sqrt{y})}{85\,\lambda} \sqrt{\tan \theta/2} \qquad (8)$$

Now:

for green light = .5461 microns

$= .215 \times 10^{-4}$ inches

and y = 1.18 inches height (for 50mm format)

substituting in equation (8)

$$\text{line pairs/raster width*} = \frac{\sqrt{1.18}}{(85)\ 0.215 \times 10^{-4}} \sqrt{\tan \theta/2}$$

$$= \underline{\underline{540 \sqrt{\tan \theta/2}}} \qquad (9)$$

Figure 23. Field of View vs Pinhole Distance and Raster Width

*Note: Equation 4 more closely represents TV line width rather than optical line pair distance. This is attributed to the overall MTF and SNR. In addition pinhole image plane resolution decreases as the off-axis viewing angle increases. In fact, the limiting pinhole image angle occurs where the pinhole surround metal thickness does not allow a direct ray through the pinhole

A table relating resolution to included angular field of view (θ_h) can be made:

θ_h	$\theta/2$	$\tan \theta/2$	$\sqrt{\tan \theta/2}$	$540\sqrt{\tan \theta/2}$	Angular res per line pair
20°	10°	.176	.42	227	1.27 mr.
40°	20	.364	.60	324	2.14
60°	30	.577	.76	410	2.54
80°	40	.839	.92	497	2.79
100°	50	1.19	1.09	592	2.94
120°	60	1.73	1.32	713	2.92

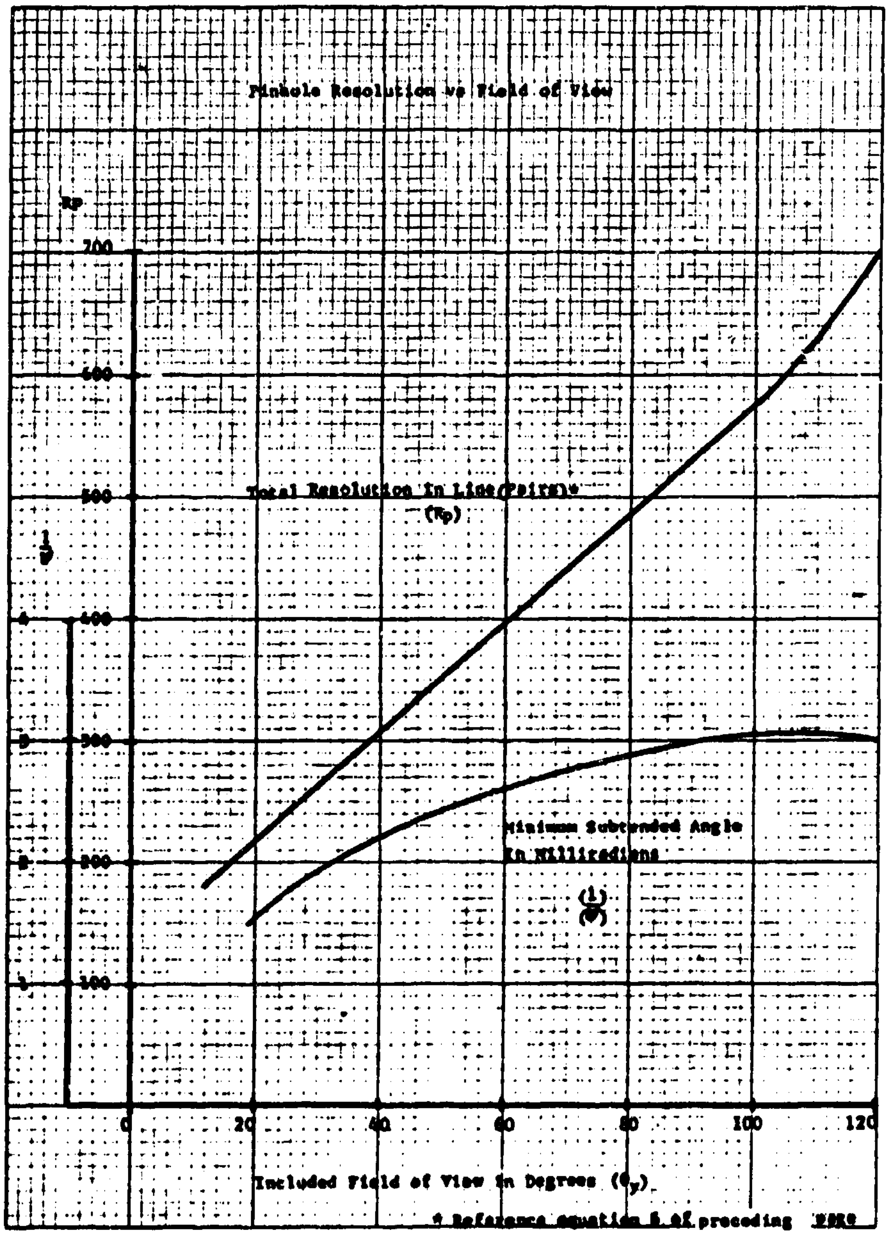
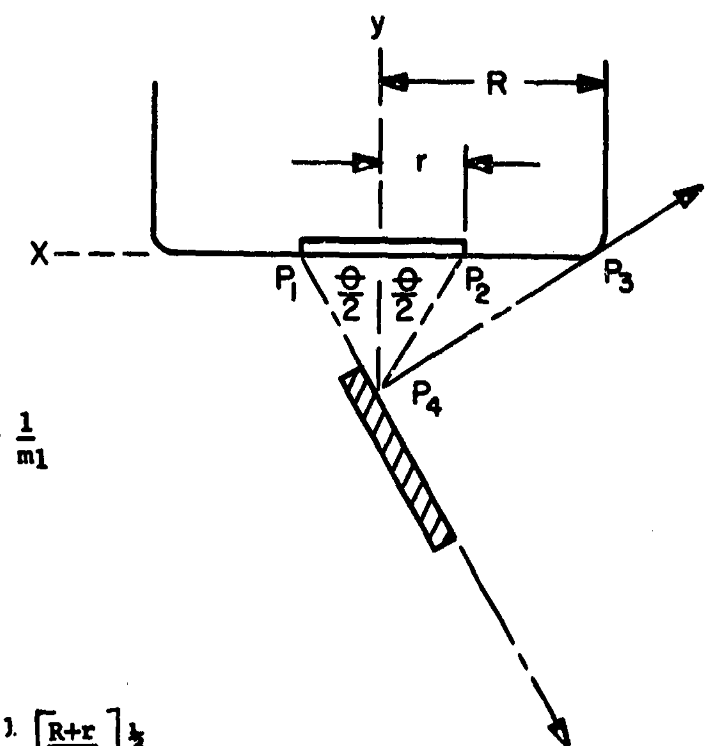


Figure 24. Pinhole Resolution vs Field of View

APPENDIX H

The maximum vertical look angle can be computed for a TV camera tube with a non-interfering deflection and focus yoke.



Let: $m_1 = \frac{-y4}{r}$, $m_3 = \frac{y4}{R}$

$m_2 = \frac{y4}{r}$, $\frac{m_2 + m_3}{2} = -\frac{1}{m_1}$

then $\frac{2r}{y} = \frac{y}{r} + \frac{y}{R}$

or $y = r\left(\frac{2R}{(R+r)}\right)^{\frac{1}{2}}$

From Figure 1 $\theta = 2\tan^{-1}\left[\frac{R+r}{2R}\right]^{\frac{1}{2}}$

$K = r/R$

$r = k \cdot R \qquad K \leq 1$

$\theta = 2\tan^{-1}\left[\frac{(1+K)}{2}\right]^{\frac{1}{2}}$

let $K = 1$

$\theta = 2\tan^{-1} 1$

$\theta = 90^{\circ}$ max

Figure 25. Analytical Vertical FOV Limit

For a TV camera tube having a fully photosensitive image plane and a 3:4 aspect ratio, the limiting clearance for viewing is at the upper center for field.

$$K = \frac{v}{r}$$

$$K = \frac{3}{5}$$

$$\theta = 2 \tan^{-1} \sqrt{.8}$$

$$= 2 \tan^{-1} (.894)$$

$$2 (41.8^{\circ})$$

$$= 83.6 \text{ maximum}$$

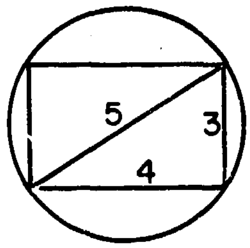
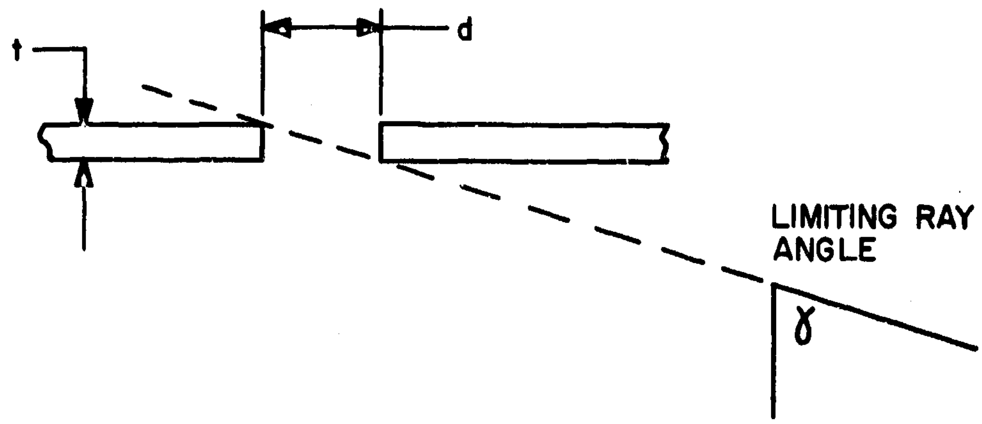


Figure 26. Minimum Peripheral Clearance

APPENDIX I

A FOV limitation verified by laboratory experiment is the pinhole metal surround thickness:



$$\gamma = \tan^{-1} \frac{(d)}{(t)}$$

Example:

t = 0.003 inch

d = 0.006 inch

$\gamma = 62\frac{1}{2}°$

Figure 27. FOV Limit Due to Pinhole Material Surround