AMP 334

ON OPTICAL IMAGING THROUGH AIRCRAFT TURBULENT BOUNDARY LAYERS*

by

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NOMENCLATURE

c_p	=	specific heat of air
C	=	normalization constant for spectrum
D	=	aperture diameter
$E_{\epsilon\epsilon}(k)$	=	spectrum of fluctuations, Eq. (1)
I	=	light intensity, w/cm^2
k	=	wavenumber of light, cm^{-1}
ℓ	=	scale size of turbulence
n	=	exponent in spectrum
o	=	initial
r	=	separation distance
T	=	temperature
u	=	velocity in x direction
W	=	wall
y	=	distance normal to boundary layer
α	=	extinction coefficient, cm^{-1}
β	=	constant Eq. (12)
δ	=	boundary-layer thickness, cm
Δ	=	rms value
ϵ	=	dielectric constant, air
Θ	=	angle from optical axis
ρ	=	mass density
ϕ	=	azimuthal angle
σ	=	volume scattering
Ω	=	solid angle
∞	=	free stream

ABSTRACT

An analysis is presented of optical resolution quality as affected by aircraft turbulent boundary layers. The wind-tunnel data of Stine and Winovich[1], was analyzed to obtain the variation of boundary layer turbulence scale length and mass density rms fluctuations with Mach number. The data gave good agreement with a mass density fluctuation turbulence spectrum that is either isotropic or orthogonally anisotropic. The data did not match an isotropic turbulence velocity spectrum which causes an anisotropic non-orthogonal mass density fluctuation spectrum. The results indicate that the average mass density rms fluctuation is about 10% of the maximum mass density across the boundary layer and that the transverse turbulence scale size is about 10% of the boundary layer thickness. The results indicate that the effect of the turbulent boundary layer is large angle scattering which decreases contrast but not resolution. Using extinction as a criteria the range of acceptable aircraft operating conditions are given.

INTRODUCTION

The question of the quality of optical imaging through aircraft windows with turbulent boundary layers is important for both reconnaissance and earth resources technology. In general an optical image recorded through such a window may be degraded by both the variation of the mean properties of the boundary layer in the direction parallel to the window and the fluctuations of mass density in the boundary layer on the window, since the index of refraction varies proportionally to the mass density. In this note we consider only the latter, and use the wind tunnel data of Stine and Winovich[1] to determine bounds for the degradation for flight cases. We will compare the differences between this analysis and previous analyses.[2]

The degradation of the image quality depends on two quantities, the extinction number $\alpha\delta$ which represents the scattering of light out of the diffraction pattern, and the ratio of the turbulence scale size to the diameter of the imaging optics.[3] If the turbulent scale size is much smaller than the aperture diameter, the effective resolution is insensitive to $\alpha\delta$, but the image intensity at the image plane is decreased[3] by $\exp(-\alpha\delta)$. The light scattered by the turbulent boundary layer raises the apparent background intensity.

Analysis of Wind-Tunnel Data

The differential cross section for scattering from a unit volume of a random medium is given by[1,4]

$$d\sigma/d\Theta = (1/4)\,\pi(\Delta\epsilon)^2\,\epsilon^{-2}\,(1+\cos^2\Theta)\,k^4\,E_{\epsilon\epsilon}\left[(2\,k\,\sin\Theta/2)\right] \qquad (1)$$

where $E_{\epsilon\epsilon}$ is the three dimensional spectrum of fluctuations of the dielectric constant such that

$$\int_{-\infty}^{\infty} E_{\epsilon\epsilon}(k)\, d\underset{\sim}{k} = 1 \tag{2}$$

The cross section for light intensity scattered out of a cone of half angle Θ is then given by

$$\sigma(\Theta) = 2\pi \int (d\sigma/d\Omega)\, \Theta\, d\Theta \tag{3}$$

and the light energy remaining in the cone is determined from

$$dI(\Theta)/dy = - I(\Theta)\, \sigma(\Theta) \tag{4}$$

Using a general three-dimensional spectrum

$$E_{\epsilon\epsilon} = C\, \ell^3 (1 + k^2 \ell^2)^{-n} \tag{5}$$

Eq. (3) and (4) may be integrated. Since $k \gg 1$, Θ is always small hence $2 \sin \Theta/2 \cong \Theta$, $\cos \Theta \sim 1$. The result for the light intensity through a small aperture at the focal plane after traversing a boundary layer is:

$$\ell n \left[I(\Theta)/I_o \right] = - \frac{C \pi^2 k^2 \epsilon^{-2}}{2(n-1)} \int_0^{\delta} \frac{\ell (\Delta\epsilon)^2\, dy}{(1 + k^2 \ell^2 \Theta^2)^{n-1}} \tag{6}$$

If ℓ and $(\Delta\epsilon)^2$ do not vary greatly through the major portion of the boundary layer, we may take them as constant, equal to their average value. Then Eq. (6) becomes:

$$\ell n \left[I(\Theta)/I_o \right] = - \frac{C \pi^2 k^2 \epsilon^{-2}}{2(n-1)} \frac{\ell (\Delta\epsilon)^2\, \delta}{(1 + k^2 \ell^2 \Theta^2)^{n-1}} \tag{7}$$

The intensity "on axis", which corresponds to the image intensity is obtained from Eq. (7) by setting $k\ell\Theta \ll 1$, yielding:

$$\ell n \left[I(0)/I_o \right] = -C\,\pi^2 k^2 \ell (\Delta\epsilon)^2 \epsilon^{-2}\,\delta/2(n-1) \equiv -a\,\delta \qquad (8)$$

which gives the formula for the extinction number. Eq. (7) can then be rewritten as

$$k^2 \ell^2 \Theta^2 = \left\{ \ell n \left[I(0)/I_o \right] / \ell n \left[I(\Theta)/I_o \right] \right\}^{1/(n-1)} - 1 \qquad (9)$$

There exists three unknowns in Eq. (9): ℓ, $I(0)/I_o$, and n, which are found from the experimental data. In the experiment of Ref. 1, collimated light of wavelength 0.52 μm was passed through a wind tunnel with turbulent boundary layers, and refocused. Various aperture stops were used and the total light intensity which passed through the aperture was measured giving $I(\Theta)/I_o$. The radius of the aperture defined Θ.

If the correct value of n is chosen, a plot of $\left\{ \left[\ell n\, (I(\Theta)/I_o) \right]^{1/(n-1)} \right\}^{-1}$ vs Θ^2 should be a straight line. For the high Mach number, high density experiments it was found that the best fit of the data to a straight line occurred when n = 2,* (see Fig. 1) which corresponds to an exponential correlation function of the index of refraction fluctuations, with an integral scale equal to ℓ, and $C = \pi^{-2}$. The intersection of the straight line with the abscissa then gives ℓ (since k is known), and the intersection

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* The analysis of Ref. 1 assumed that n = 2.

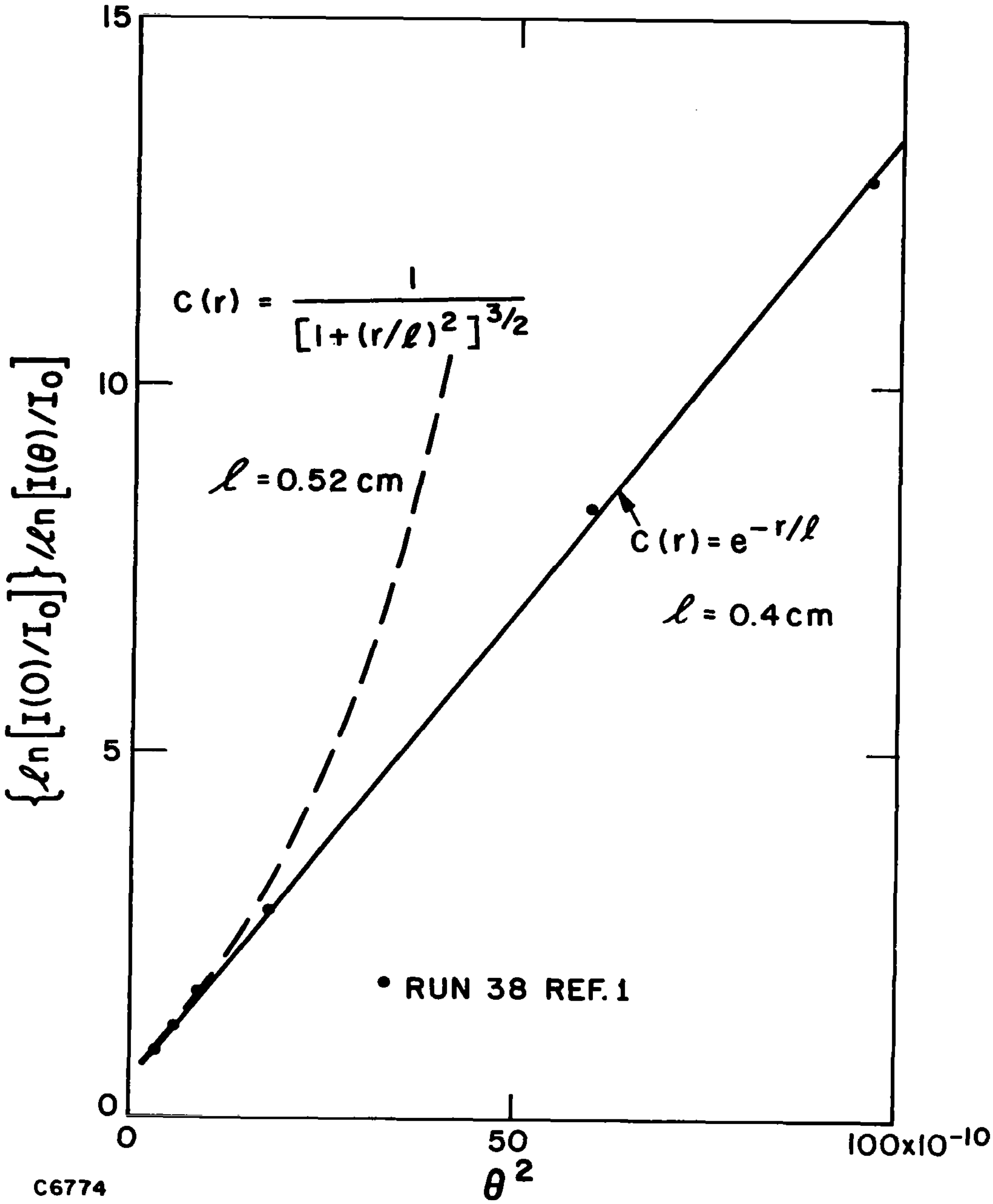

Fig. 1 Theoretical and experimental[1] dependence of light intensity with aperture half angle, for two theoretical correlation functions for dielectric constant fluctuations.

of the line with the ordinate gives $\ell n \left[I(0)/I_o \right]$ which, from Eq. (8) gives $(\Delta\epsilon^2)$. For the wavelength used (0. 52μm),

$$(\Delta\epsilon)^2/\epsilon^2 = 4\,(2.76 \times 10^{-4})2(\Delta\rho^2)/\rho_s{}^2 \tag{10}$$

so that the rms mass density fluctuations can be obtained.

In Ref. 1, the Mach number was varied from 0. 4 to 2. 5 and the free stream density from about 1 atmosphere to 0. 1 atmosphere. In analyzing the data according to the above scheme, the greatest optical effects and hence smallest spread in the data occurred for the higher Mach numbers. We have analyzed only the data for the turbulent boundary layers with natural transition.

RESULTS

Figure 2 shows the resulting ratio of integral turbulence scale to boundary-layer thickness for 38 cases in Ref. 1. Each case is represented by a dot. The triangles represent arithmetic averages for each Mach number range. As explained previously, the largest scatter occurs for the lowest Mach number. However, it is clear for Mach numbers greater than unity that $\ell/\delta \approx 0.1$, and may be somewhat larger for subsonic Mach numbers. These small values are initially surprising since the integral scale ℓ should be about half the longitudinal velocity integral scale (if the turbulence is isotropic). Since it is generally believed that the ratio of the latter to the boundary-layer thickness is about 0. 4, we would expect ℓ/δ to be 0. 2. However, the scale size of the turbulence is smaller near wall,

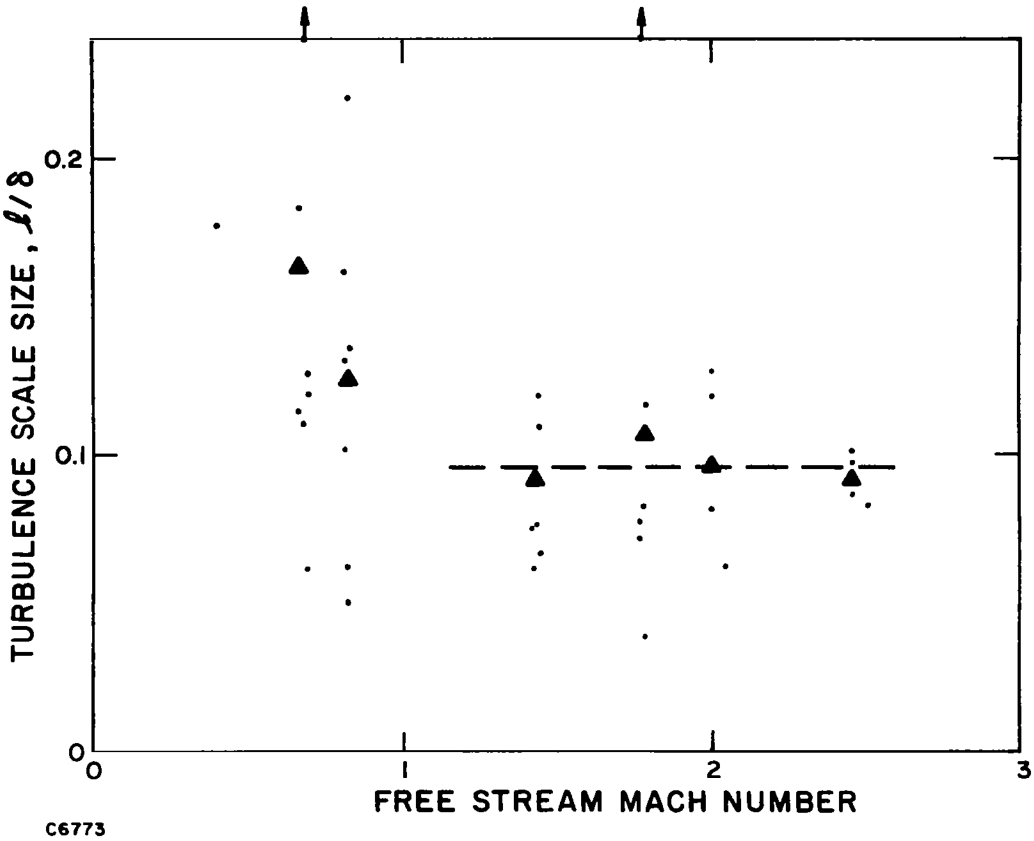

Fig. 2 Ratio of mass density turbulence scale size to boundary-layer thickness, deduced the data of Stine and Winovich.[1]

the method of interpretation only yields the average value in the boundary layer, weighted by the fluctuations. Thus, the average value of ℓ/δ is not inconsistent with our knowledge of boundary layers.

The deduced mass density fluctuations are shown in Fig. 3, where we have compared the deduced mass density fluctuations to two quantities: the mass density difference across the boundary layer $\rho_W - \rho_\infty$, and the temperature ratio across the boundary layer $T_W/T_\infty - 1$. It was assumed that the wall temperature of the experiment was adiabatic, with a recovery factor of unity. Again there is a large amount of scatter particularly at the lower Mach numbers. The large circles and triangles represent averages for each Mach number range; the former for mass density differences, and the latter for temperature ratio. Except for low Mach numbers, the ratio of ratio of $\Delta\rho$ to $\rho_\infty - \rho_W$ appears to be constant, equal to about 0.1, while the values based on temperature ratio decrease monotonically with Mach number.

The constancy of the mass density fluctuation ratio with Mach number can be demonstrated approximately, as follows: assuming that pressure fluctuations can be neglected, then locally $\Delta\rho/\rho \sim \Delta T/T$. Thus the average value through the boundary layer is

$$\frac{\Delta\rho}{\rho_\infty - \rho_W} = \left(1 - \frac{\rho_W}{\rho_\infty}\right)^{-1} \int_0^1 \frac{\Delta T}{T} \frac{\rho}{\rho_\infty} d(y/\delta) \qquad (11)$$

From Ref. 5, $\Delta T/T$ through the boundary layer is approximately constant, given by

$$\frac{\Delta T}{T} \sim \frac{(T_W/T_\infty - 1)}{1/2\,(T_W/T_\infty + 1)} \beta \qquad (12)$$

where β is a constant. We approximate the integral of ρ/ρ_∞ by the arithmetic average at the end points, viz:

$$\int_0^1 \frac{\rho}{\rho_\infty} \, d(y/\delta) = 1/2 \left(\frac{\rho_w}{\rho_\infty} + 1 \right) = 1/2 \, \frac{T_\infty}{T_w} \left(1 + \frac{T_w}{T_\infty} \right) \tag{13}$$

Combining Eqs. (11, 12, and 13),

$$\frac{\Delta\rho}{\rho_\infty - \rho_w} = \text{constant} = \beta \tag{14}$$

Thus, the average mass density fluctuation ratios should be insensitive to Mach number. The average value of β from Ref. 5 is about 0.07; from Fig. 3 we deduce that the average value of β is about 0.1. This difference is not significant in view of the approximations made in evaluating Eq. (11); the main point is the constancy of $\Delta\rho/(\rho_\infty - \rho_w)$ with Mach number is consistent with measurements of temperature fluctuations in boundary layers.

To compare with previous results we note that Hufnagel[2] used $\ell/\delta = 0.1$ which is consistent with this analysis, however, his results correspond to a correlation function of the form

$$c(r) = (1 + r^2/\ell^2)^{-3/2} \tag{15}$$

Using Eq. (15), with Eqs. (1) and (4), the calculated dependence of $I(\Theta)$ diverges greatly from the data, see Fig. 1. In addition, the density fluctuations were taken to vary as

$$\Delta\rho = 0.2\,(T_w - T_\infty)/1/2\,(T_w + T_\infty) \tag{16}$$

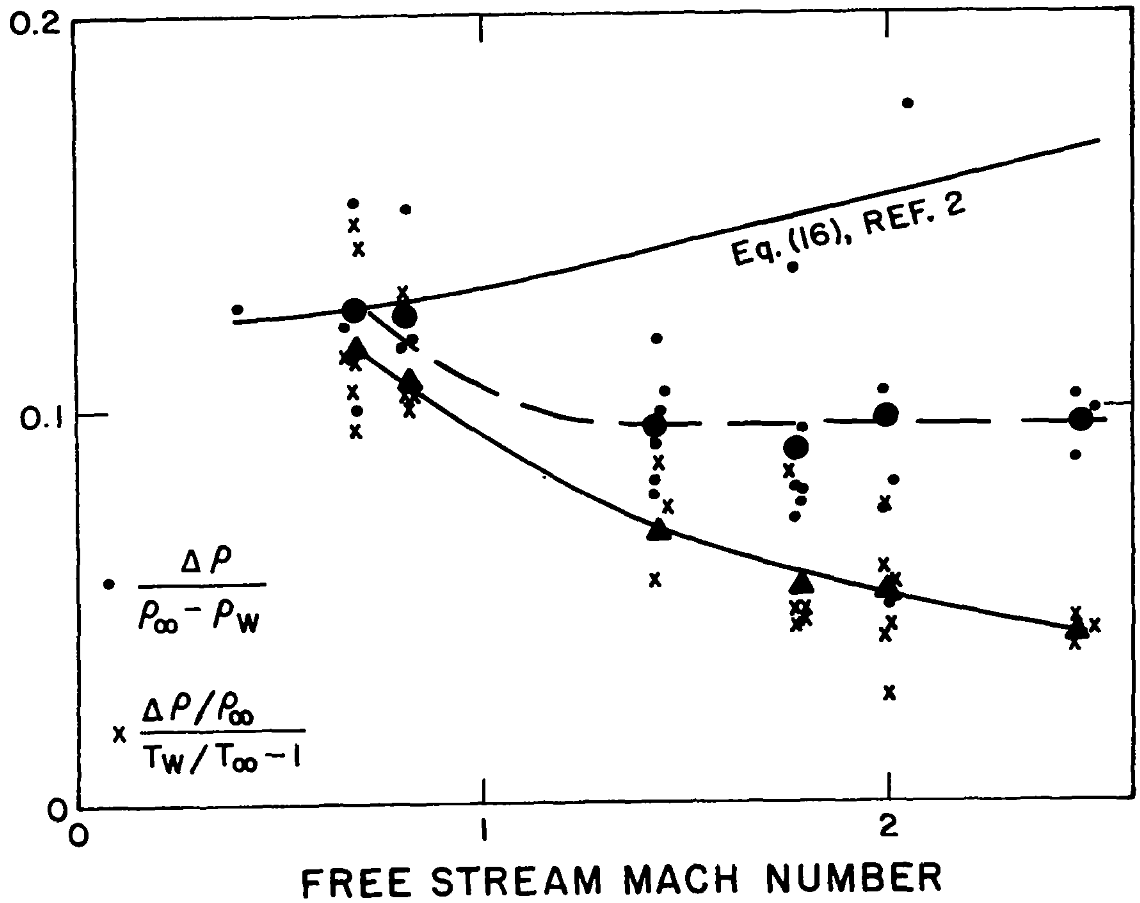

Fig. 3 Mass density fluctuations, deduced from the data of Stine and Winovich.[1]

While this expression passes through the vicinity of the subsonic data points of $\Delta\rho/(\rho_\infty - \rho_w)$, the trend with Mach number disagrees with the values deduced from the experimental data; as we indicated previously $\Delta\rho/(\rho_\infty - \rho_w)$ is approximately constant and does not vary with Mach number.

EFFECT OF ANISOTROPIC TURBULENCE

There is no reason to believe that the spectrum is isotropic, hence we have also investigated several anisotropic spectra; the only assumption being that one principle axis of the spectrum coincides with the direction of propagation. In an actual boundary layer the angle between principle axes of the spectrum and the spatial coordinates is of the order of 20°, hence the latter assumption should be quite good.

For an anisotropic orthogonal density fluctuation spectrum, Eq. (5) becomes:

$$E_{\epsilon\epsilon} = C\,\ell_1\ell_2\ell_3\left[1 + \sum_i k_i^2\,\ell_i^2\right]^{-n} \tag{17}$$

where, for propagation in the y direction,

$$\begin{aligned} k_x &= - k \sin\Theta \cos\phi \approx k\Theta \cos\phi \\ k_y &= k(1 - \cos\Theta) \approx k\Theta^2/2 \\ k_z &= - k \sin\Theta \sin\phi \approx k\Theta \sin\phi \end{aligned} \tag{18}$$

and $d\Omega = d\phi \sin\Theta\, d\Theta$. For $\ell_z = \ell_x \neq \ell_y$, then for $n = 2$, Eq. (7) becomes:

$$\ell n \left[I(\Theta)/I_o \right] = 1/2 \, (\Delta\epsilon)^2 \, \ell_y \, k^2 \, \delta \left[1 + k^2 \, \ell_x^2 \, \Theta^2 \right]^{-1} \qquad (19)$$

Thus the turbulence scattering angle depends on the scale size in the plane normal to the path (ℓ_x) but the extinction depends on the scale size in the direction of propagation (ℓ_y). In this case it is not possible to isolate separately the effects of scale size ℓ_y and density fluctuations since they appear as a product.

Another example of an anisotropic spectrum corresponds to an isoenthalpy flow in the x direction. Then $c_p \, \Delta T = U \Delta u$, and the spectrum for temperature (or density) fluctuations is the same as for Δu, e. g. $E_{\epsilon\epsilon} = E_{11}$. For isotropic velocity fluctuations, we can also use an exponential velocity fluctuation correlation function, for which[6]

$$E_{\epsilon\epsilon} = E_{11} = 2 \, \pi^{-2} \ell^5 \, (k^2 - k_1^2) \, (1 + k^2 \, \ell^2)^{-1} \qquad (20)$$

The dependence on aperture angle Θ of light intensity is again obtained by integration of Eq. (1) and (4):

$$\ell n \left[I(\Theta)/I_o \right] = -1/2 \left(\frac{\Delta\epsilon}{\epsilon} \right)^2 k^2 \, \ell \delta \, (1 + k^2 \Theta^2 \ell^2)^{-1} \left[1 - (2 + 2 k^2 \ell^2 \Theta^2) \right]^{-1} \qquad (21)$$

This form is similar to Eq. (1), except that there is some curvature in the plot of $1/\ell n \left[I(\Theta)/I_o \right]$ vs Θ^2 for $k \Theta \ell < 5$. This curvature is not evident in the data; hence the assumption of isoenthalpy and isotropic velocity turbulence which leads to Eq. (21) is rejected.

A third possible anisotropic form for $E_{\epsilon\epsilon}$ corresponds to isoenthalpy flow, but with different scale sizes in the 3 orthogonal directions. A form of the velocity spectrum which satisfies incompressible continuity is:

$$E_{ij} = A \left[\ell_i \ell_j \delta_{ij} \sum_{\ell} k_{\ell}^2 \ell_{\ell}^2 - k_i k_j \ell_i^2 \ell_j^2 \right] f(k_i \ell_i) \qquad (22)$$

For example, if the velocity correlation function is exponential, in the three orthogonal directions, then

$$E_{\epsilon\epsilon} = E_{11} = 2\pi^{-2} \ell_1 \ell_2 \ell_3 \left[(k_2 \ell_2)^2 + (k_3 \ell_3)^2 \right] \left[1 + \sum k_{\ell}^2 \ell_{\ell}^2 \right]^{-3} \qquad (23)$$

for which Eqs. (1) and (4) may be approximately integrated to obtain

$$\ell n \left[I(\Theta)/I_o \right] = -1/2 (\Delta\epsilon^2) k^2 \ell_1 \ell_2^3 \ell_3 \delta \ell^{-4} \left[1 + k^2 \Theta^2 \ell^2 \right]^{-1} \left[1 - (2 + 2k^2 \ell^2 \Theta^2) \right] \qquad (24)$$

where

$$\ell^2 = 3/4\, \ell_2^2 + 1/4\, \ell_1^2 \qquad (25)$$

Again, Eq. (24) exhibits curvature near the origin, which is not present in the data. Thus we conclude that either Eq. (7) with $n = 2$, or its anisotropic form Eq. (19) are most consistent with the data; and that the scattered light is not consistent with isoenthalpy flow with either an isotropic or anisotropic velocity spectrum.

APPLICATIONS TO FLIGHT

For the usual cases that the aperture of the imaging device is much larger than the turbulence scale size, the primary effect on the diffraction pattern from a distant point source will be attenuation of the light by turbulence scattering, but the resolution will not be changed appreciably[2]. Typical diffraction patterns are shown in Fig. 4. For example the case $\alpha\ \delta = 0.50$ corresponds to a boundary layer 11 cm thick, a Mach number of 0.8, and an altitude of 9 km. While the theoretical resolution is insensitive to the extinction, excessive extinction causes loss of contrast, since the scattered light enters adjacent resolution cells. Thus, we may define some approximate criteria: if $\alpha\delta > 2$, then the ability to image will be poor, but if $\alpha\ \delta < 0.4$, the ability to image should be quite good. Figure 5 shows these approximate boundaries, for three boundary layer thicknesses, 1, 3, and 10 cm.

From Fig. 5, it can be seen that the seeing effects are very sensitive to Mach number in the vicinity of Mach one, but insensitive to Mach number at high Mach numbers. This latter effect is caused by the fact that $1 - \rho_W/\rho_\infty$ goes asymptotically to unity with increasing Mach number. For all Mach numbers, the "seeing" is sensitive to the boundary-layer thickness, hence there is always a gain in keeping the boundary layer over the window of imaging device as thin as possible. Other techniques may also be useful for improving the imaging, such as cooling the window to reduce the temperature excess, and hence mass density fluctuations. One note of caution: these results are based on a smooth window flush with the aircraft skin. Window moldings, recesses, etc. could degrade the imaging quality by increasing either the optical path through the turbulence layer or the scale size of the turbulence.

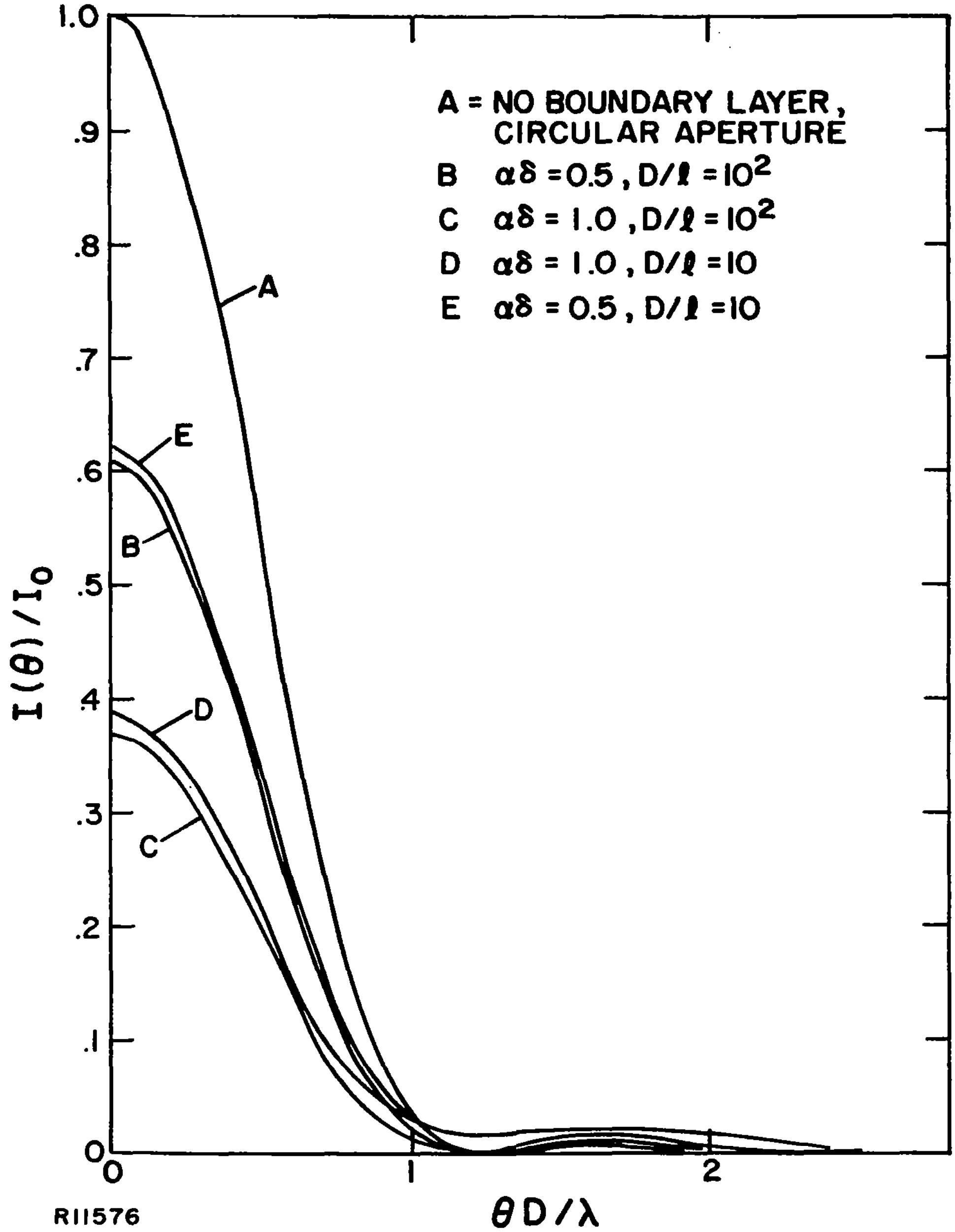

Fig. 4 Diffraction patterns.

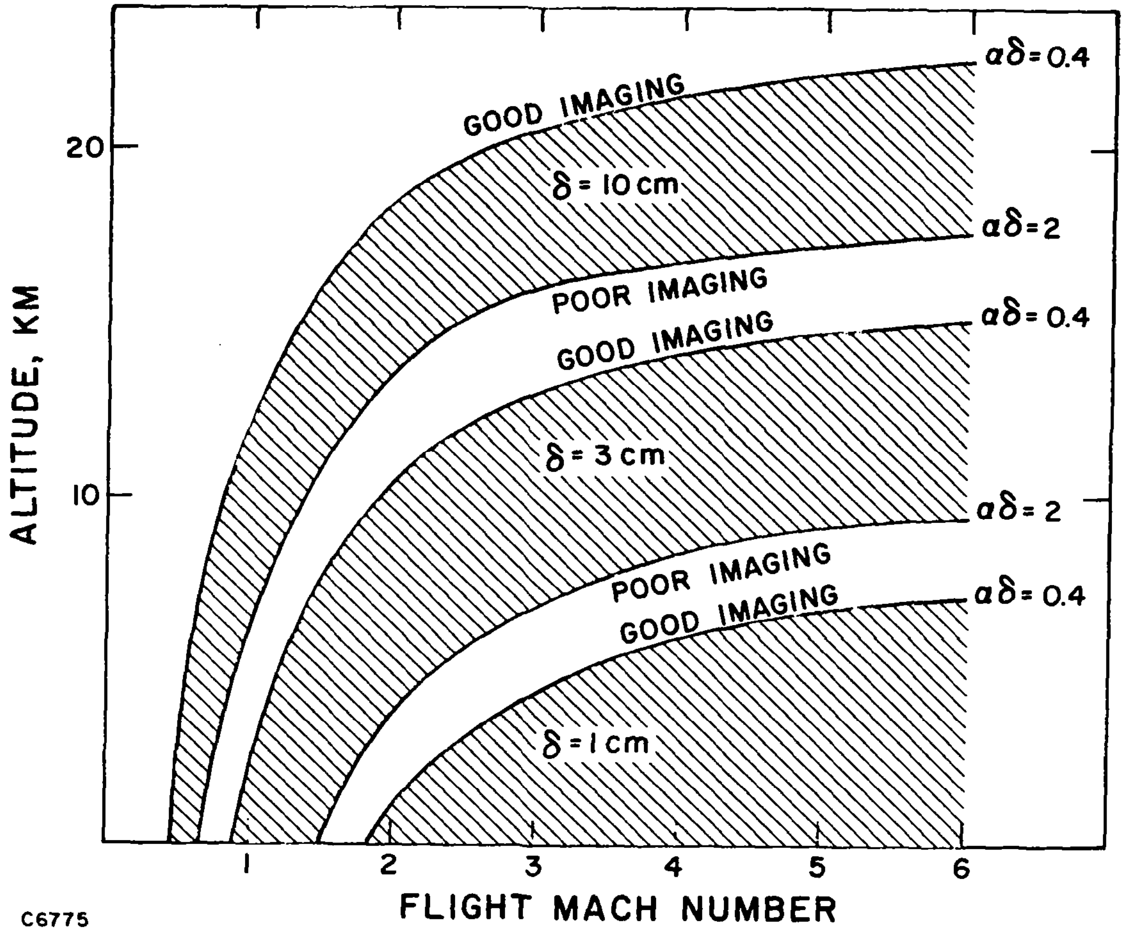

Fig. 5 Imaging quality boundaries for various boundary-layer thicknesses, flight Mach numbers, and altitudes.

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