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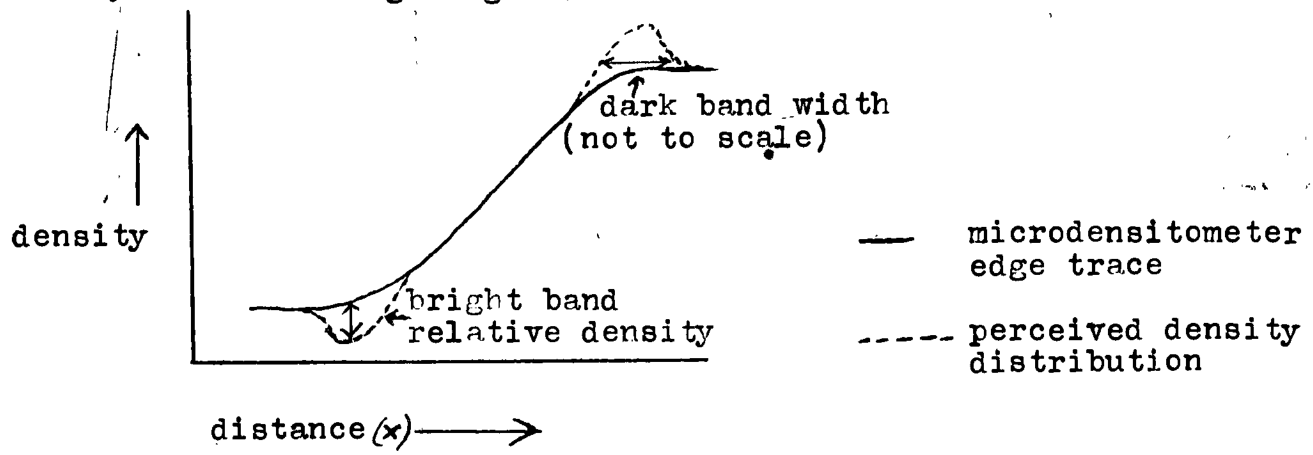
-Abstract-

The Mach Phenomenon*(as perceived on photographic film) is herein investigated as a function of edge acutance, contrast and illumination level for the purpose of determining its probable effect in the area of visual image evaluation. The results indicate that dark Mach band widths increase as acutance decreases and dark band width is independent of contrast and illumination level while light band widths remain constant, over the ranges investigated. Using these findings as a basis, a dark band width predictor equation was found, taking the form; dark band width (in microns) = K/acutance, when average edge gradient is the measure of acutance. The probable effects (which increase in importance as acutance decreases) of the Mach bands on visual image evaluation is then discussed.

* a visual sensation of density bands near edges

-Introduction-

About 100 years ago Ernst Mach[1], a scientist-philosopher, investigated the purely visual phenomenon apparent near some edges, now signified by his name. This "Mach Phenomenon" can be most aptly described by the following diagram:



It is now believed (with some exceptions[2]) that this visual phenomenon is due to the inhibition of cone photoreceptors within the retina. A highly stimulated (by light) photoreceptor, which sends impulses to the brain in the form of electrical potential energy, may inhibit the response of a nearby, less stimulated photoreceptor, which can result in a visual dark band along the darker side of a perceived (object) edge. A similar inhibitory mechanism produces a light band on the light side of an edge.[3,4]

The numerous investigations to date on the Mach Phenomenon[1-8] are mainly concerned with discovering the complete visual process which produces this effect and the variables which govern its appearance. Past research into this area usually investigated it as a function of edge sharpness, contrast, and illumination level but with little regard to the placement of absolute values on these variables, although attempts have been made at formulating Mach band predictor equations.[2,3,4,9,12]

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In the area of image evaluation, it has been found that Mach bands appearing on the edges of microscope images can effect their perceived size and shape and thus their measurement and may also enhance edge sharpness under certain conditions. It would not be unreasonable to assume, therefore, that this phenomenon may have an effect upon detection and recognition in aerial and other informational photographs. Since this research involves the relevancy of the Mach Phenomenon to photographic images, a new area in regard to this phenomenon is here being investigated.

-Objectives-

I) To investigate the probable effects of the Mach Phenomenon in the area of photographic image evaluation and to measure the Mach band attributes of width, location, and relative density, in light of the experimental results obtained from the following:

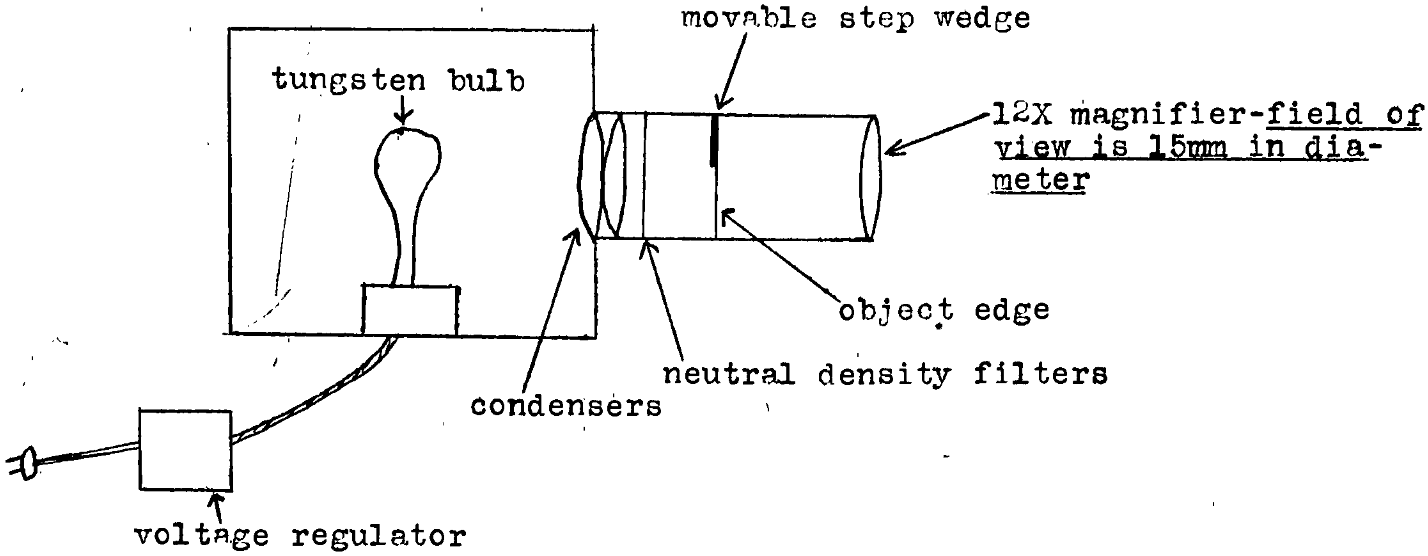
a) An investigation of the relationship between the above Mach band attributes near edges and the three variables which are thought to have the greatest effect upon these attributes; namely, acutance, contrast and illumination across the edge.

b) With the data obtained from "a" as a basis, to explore the formulation of an accurate Mach band predictor equation.

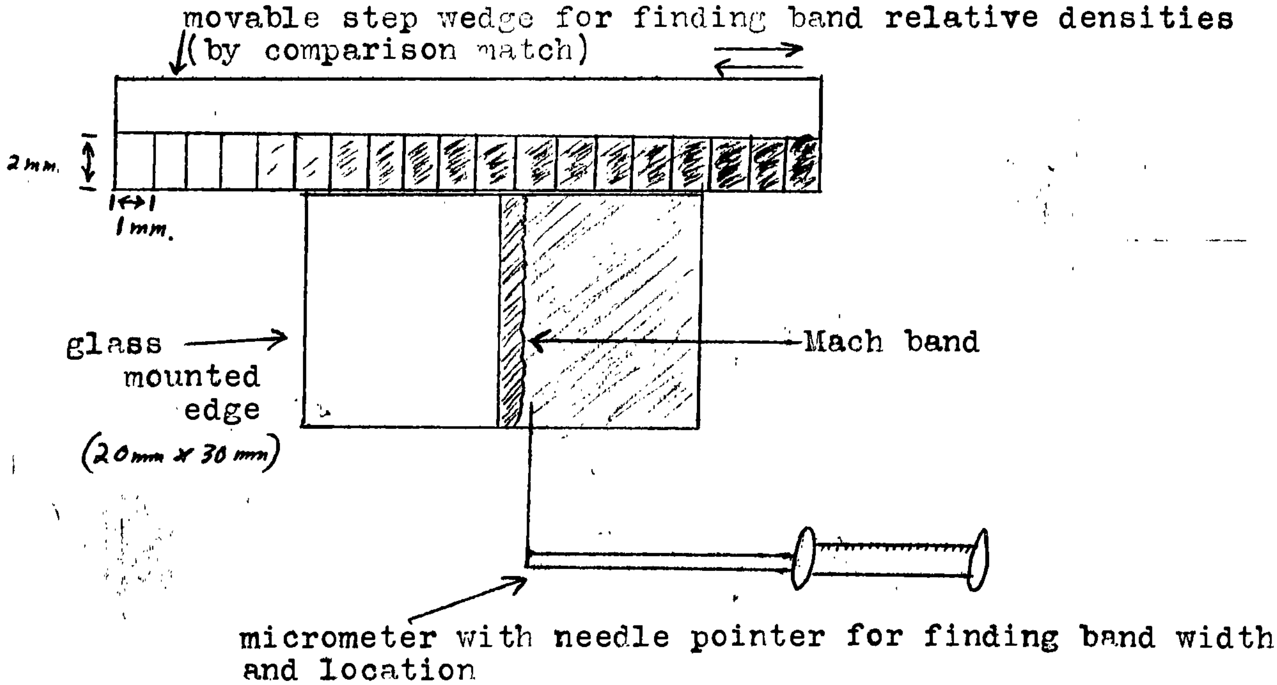
-Experimental Program-

Twenty-five edges, i.e., five acutance values (varied by defocusing the camera lens) and five different contrast edges for each acutance value, were photographed on SO-243,35mm,fine-grain aerial film and microdensitometer traces were then made of the edges. The darker side of each edge on the film was held to a constant density and density scales (i.e., contrast, in this paper) ranged from 0.2-0.8. The edges were then viewed in the following apparatus:

Side view:



Front view:



Observers (four were used, two of which had normal vision) were given a set of instructions to read beforehand which suggested to them what they may see when looking through the 12X magnifier at the edges and the measurement procedure to be used if a Mach band(s) was seen. Each Mach band width was measured three to four times by each observer, although two observers measured bands on only twelve edges apiece instead of the total number of twenty-five edges. The three illuminance levels used in the apparatus were approximately 45 candles/sq.ft. ("f.c."), 18 f.c. and 4.5 f.c. while the average room illuminance was held to 0.4-0.8 f.c. Observers were seated comfortably for minimum strain and no observing period lasted for more then 45 minutes. In addition, it was attempted to measure the relative density of Mach bands by having the observers slide the step wedge(visible in the field of view of the magnifier) until a particular step was found that "matched" the density of a Mach band immediately below it.

The microdensitometer edge traces previously mentioned were used to calculate the acutance of each edge using both the formula of Higgins and Jones,* with variations, and the average edge gradient. A subjective ranking experiment was also conducted and the formula for acutance finally chosen was that which best agreed with the subjective sharpness values obtained for the edges.

After the data was collected, it was tested for a normal distribution by use of the χ^2 test[14] and an analysis of variance table was set up to find those factors under investigation which had

* see ref. #13 , see also appendix.

a significant effect upon Mach bands. Using the results of the ANOVA, an appropriate graph was drawn and the equation of the curve lying on it was found.

-Results-

First of all, the microdensitometer traces showed no evidence of chemical adjacency effects on the edges, signifying that the following results are due to the Mach Phenomenon alone.

The apparatus and step wedge together were not constructed with small enough tolerances to accurately measure Mach band relative densities and subsequently only qualitative results can be given for this particular Mach band attribute. Relative densities of dark Mach bands ranged from about 0.1-0.5 and seemed to increase as edge acutance decreased. Although the light Mach bands were too thin to judge their relative densities, it was noted by two observers (for some edges) that the light band relative densities pulsated - without change in their apparent widths. It was also noted by three observers that most dark Mach bands decreased in relative density across their widths, being of a lower relative density on the side of the band adjacent to the edge then on the side furthest from the edge.

The acutance value finally used (that which correlated best with the sharpness ranking experiment) was that of average edge gradient (as measured with a straight edge and "eyeball"), although values for some edges using the somewhat "standard" acutance formula (see Appendix) are here given for a frame of reference.

acutance of sharpest edge = 1,550 (density/mm^2)
• = 400 "
• = 190 "
• = 86 "
acutance of dullest edge = 65 "

Since the data was found to be normally distributed, a two factor (acutance, contrast) ANOVA table was analysed using the combined observations (at the 45 f.c. illumination level) of all four observers. After the ANOVA was calculated, results of which follow, it was clearly evident by a simple comparison of data that illumination level had no significant effect upon band width.

ANOVA: (at 95% confidence)

1) Acutance has a significant effect upon dark Mach band width while contrast and acutance-contrast interaction do not.

2) variance $= \sqrt{M.S.\mathcal{E}} = 1.06$

After rather futilely attempting to fit a second degree polynomial to the data points, the equation, dark band width = K/acutance was found (through trial and error) to fit best and, as shown on the accompanying graph, dark Mach band widths increase as acutance decreases.

In all observations the dark and light Mach bands were located adjacent to, and on opposite sides of, the visual edge location. In addition, it was soon apparent that the light Mach bands did not vary in width under any change in the levels of acutance, contrast and/or illumination, the average width being 94 microns with a standard deviation of 16 microns. In a few cases it was also noted by observers that an edge seemed to have two light bands of different relative densities (an observation also made by Charman and Watraciewicz[10]), time being limited however, this was not investigated further. Also, in a limited experiment of the effect of field size on Mach band width, the field of view was reduced to 7mm by 8mm, which showed no apparent change in dark band widths although the bands appeared to become fainter.

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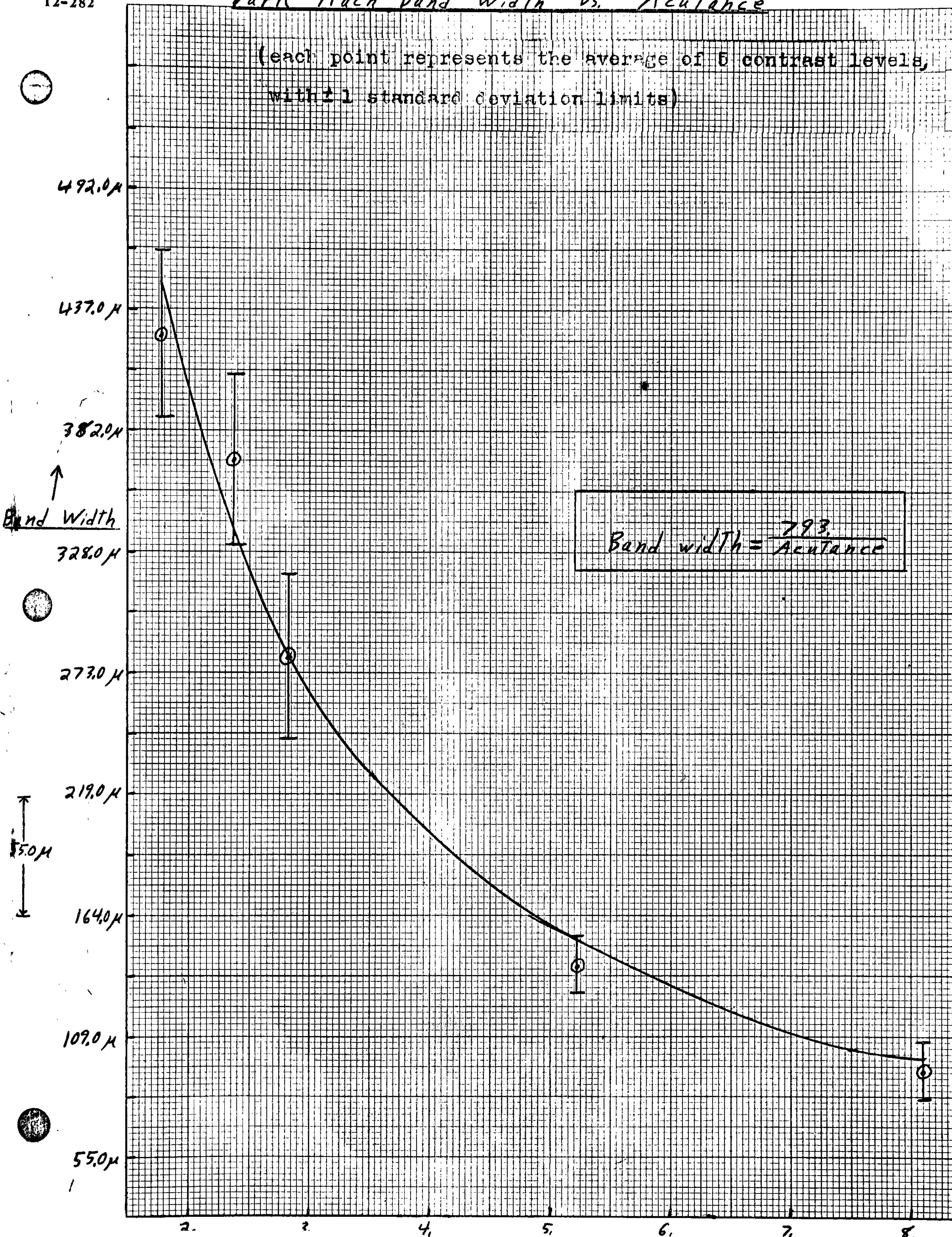
Dark Mach Band Width vs. Acutance



-Discussion of Results-

Given the acutance value (i.e., average gradient) of an edge, the Mach band width could be predicted from the equation; dark band width (in microns) = 793/acutance. This equation, in effect, is a constant divided by the average derivative of density with respect to distance across the edge, in the above equation acutance = average gradient (slope) = $\overline{\frac{dD}{dx}}$. Original Ludvigh[17] predicted that a band width formula would take the form:

$$\text{band width} = K/\frac{d^4 I}{dx^4}$$

where: I = illuminance on retina
x = distance, on retina, across the edge

As can be seen, the two equations are similar and band width in both cases is dependent on quantities that are interrelatable through geometrical optics. Since illuminance and contrast were not found to have a significant effect upon band width, the prediction of band width by use of a log luminance vs. brightness curve (as discussed in ref. # 15) would be inappropriate, although this method may predict band relative density.

Based on the results of this experiment it is apparent that the Mach Phenomenon assumes increasing importance in the visual evaluation of informational photographs as specific edges within the picture <u>decrease</u> in acutance. At low acutance values the recognition and measurement of objects within a photograph would be very much complicated by the Mach bands present, although detection may be enhanced since apparent contrast across an edge is increased by the presence of these bands. It is seen from the data obtained then, that Mach bands can occur in sufficient widths and relative densities to merit their consideration when visually evaluating photographic images. More conclusive statements on this subject however, can only be made when the effect of different spatial frequencies (a subject partially investigated by Lowry and DePalma[16]) and noise (i.e. graininess) on Mach bands is investigated.

-Appendix-

Acutance is generally defined as any objective, quantitative measure which correlates well with sharpness - a subjective factor. Higgins and Jones[13] found the formula,

$$\frac{\sum \left(\frac{\Delta D_i}{\Delta x}\right)^2}{(N)(D.S.)}$$

N= number of Δx increments
D.S.= density scale

to correlate well with sharpness. In this research the above formula has not correlated well with the edges used, even with changes in it such as multiplying by density scale or taking it out altogether.

The density scale limits used for all acutance determinations were 97.5% of D max. and D min. + 2.5% D min., although it was found that for the edge traces used, these two points were not too critical.

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