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Quantification of the unsharp masking technique of image enhancement

Larry A. Scarff

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QUANTIFICATION OF THE UNSHARP MASKING TECHNIQUE OF IMAGE ENHANCEMENT

by

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TECHNIQUE OF IMAGE ENHANCEMENT

by

Larry A. Scarff
B.S. Rochester Institute of Technology
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A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in the School of
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College of Graphic Arts and Photography
of the Rochester Institute of Technology

June, 1981

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QUANTIFICATION OF THE UNSHARP MASKING TECHNIQUE OF IMAGE ENHANCEMENT

by

Larry A. Scarff

Submitted to the Photographic Science and Instrumentation Division in partial fulfillment of the requirements for the Master of Science degree at the Rochester Institute of Technology

ABSTRACT

The technique of unsharp masking is described and its use as an image enhancement technique discussed. A mathematical model for the masking process is developed; experimental testing and MTF measurements of the masked and sharpened images are made to test the validity of the mathematical model as a predictor of the mask and final image characteristics. The effect of contrast, mask unsharpness, and source spread function size on the resulting MTF are presented. Subjective evaluations are used to determine the visually optimum image. It is shown that the visually "best" image is not necessarily the one with the largest MTF value or area; suggestions are made for adjusting existing image quality specifications to incorporate the results of unsharp masking techniques.
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INTRODUCTION

The desired result of the photographic process is a "perfect" recreation or reconstruction of an original scene, complete in every detail. Because of the limitations inherent in any imaging system, this ideal result cannot be achieved, and some compromise must be made in the quality of the final image. All photo-optical systems suffer some degree of image degradation; the severity of this degradation being dependent on the type of equipment used and the care taken to insure optimum results.

Once the image has been recorded on the photographic material, however, it would seem that little (if anything) could be done to restore or reconstruct image information that was lost due to the inefficiencies in the photographic process. This statement is strictly true; information about a scene cannot be retrieved from an image if the detail was not recorded when the photograph was made. However, by using proper techniques, faint or barely recognizable detail can be enhanced or improved; in essence it becomes visually easier to extract information from the image, thus improving the overall quality of the photographic record.

Common methods for image enhancement today center around digital image processing by computer. These techniques provide the computer with a digital record of the
gray levels in the image and perform mathematical operations on the image data which produce an "enhanced" image when the signal is converted back into tones of gray. Computer picture processing is currently being studied by numerous researchers and will not be addressed directly in this paper. Other methods for image enhancement - what might be termed the optical analog of digital image enhancement - are the photographic methods of image sharpening or edge enhancement.

It is possible to improve the visual appearance of an image by sharpening the edges, or boundary, between distinct objects in the image by exaggerating the density difference across the edge. With increased edge definition (up to a point) the visual appearance of the image is improved and it is judged to be of a higher quality than an identical image without the edge sharpening. One form of accentuating the edge gradient, known as adjacency effects,\textsuperscript{1-3} is produced by processing the film using a high solvent/low activity developer that produces a greater development effect (larger density differences) at the boundary of different exposure regions than the density difference obtained in the region surrounding the boundary. This procedure requires that the enhancement be done in the development stage and allows for no additional sharpening after the image has been chemically developed. Thus, any requirement for enhancement must be specified beforehand.
and cannot be adjusted at a later time. Also, the amount and degree of sharpening is difficult to control with this procedure.

Another photographic method for image enhancement is known as unsharp masking. It is analogous to the adjacency effect in the results obtained; the method of producing these results is completely dissimilar, however. Once a photographic image of a scene has been obtained, another image can be produced on film from the original image. This duplicate image of opposite sign (e.g., a positive if the original image was a negative) is made slightly "blurry" or unsharp, either by defocusing (if a projection imaging system is used) or by physically separating the original image and duplicating film (if a contact printing system is used.) The contrast and amount of unsharpness of this duplicate are two critical factors that determine the final image quality, and will be discussed in detail later in this paper. The original and unsharp duplicate are now placed in contact and a final image produced from the combination of the two images. Paradoxically perhaps, the image resulting from the unsharp mask and original image combination will be visually sharper than an image produced from the original record alone. The image enhancement is due to the edge sharpening that occurs when an unsharp mask is used; this result is depicted graphically in Figure 1.
**Figure 1**

A graphical analysis of the edge enhancement produced by the unsharp masking technique.
Figure 1

(a) "Sharp" edge image on a photographic material.

(b) Blurred, unsharp, reversed image of edge, processed to a lower contrast.

(c) Sum of densities of original edge and unsharp edge.

(d) Transfer curve.

(e) The combination is printed onto another photographic material with appropriate contrast to recover the original edge contrast.

(f) Final edge image showing enhanced density gradient at edge boundaries.
can be controlled by the amount of unsharpness and contrast of the mask image, this process has the advantage of allowing the selection of the amount of sharpening to be produced and the spatial frequency (object size) region in which the sharpening will have the greatest effect. Also, since it is not necessary to produce this form of sharpening during the image development process, it can be altered or added when required, based on the individual requirements for the final image.

We note that an optimum degree of unsharpness must exist that will produce the "best" visual image. It is suggested that this optimum will be dependent on many factors; image magnification, image and object contrast, and the sharpness of the original image. It is the purpose of this research to determine a theoretical model for the unsharp masking process, predict the theoretically optimum mask parameters for a specific image, and to test the theoretical predictions through experimentation. Subjective evaluations of picture sharpness will then be correlated with objective measurements of the experimental images to determine the validity of the theoretical predictions for the masking process.
BACKGROUND

The technique of unsharp masking was originally described by Spiegler and Juris\textsuperscript{4} and by Yule\textsuperscript{5}. Yule proposed a method for increasing the visual sharpness of a photographic image by printing together a photographic image and an unsharp or blurred reversed duplicate of the image, called a mask. The results obtained from printing this combination gave an increase in the apparent sharpness of edges in the image, when the contrast of the print film was adjusted so as to produce a normal density range on the final output image. The mask in combination with the original image significantly reduces the low frequency contrast, but does not affect the high frequency contrast; since it is the high frequency contrast that affects the apparent sharpness, the masked image appears sharper than an image produced without the masking process.

Yule outlines a procedure that might be used to produce unsharp masks: A transparent or diffusion sheet is used as a spacer between the original image and the masking film, and the original-spacer-masking film combination is rotated below an off-axis point light source to obtain annular illumination. This system produces a blurred image on the masking film that is then registered with the original image and the combination exposed on a higher contrast film.
to produce the final enhanced image. This method of producing the mask produces an annular spread function; other shapes of point spread functions are also obtainable by altering the method used to produce the unsharp mask$^6$.

The technique of unsharp masking proposed by Yule has been modified by several other researchers to incorporate other methods to produce edge enhanced images. Johnson$^7$ and Kelly$^8$ have proposed methods for producing enhanced images using the Herschel effect. Kelly suggests that exposures be made on photographic film exhibiting the Herschel effect; a sharp exposure is made with short wavelength light, and an out of focus exposure is made with long wavelength light. The exposure made at the longer wavelengths will effectively erase part of the original exposure at short wavelengths, (due to the Herschel effect$^9$) and produce an enhanced "unsharp masked" image. This technique can also be applied by using a lens with significant chromatic aberration, focused at short wavelengths, or by inserting into the light path appropriately colored spatial filters which will weight the spread function as desired.

Phosphor quenching$^{10}$ is a similar application except that it uses a phosphor screen that is excited by ultraviolet radiation and quenched by infrared radiation. If both sources are used, the ultraviolet to fog the screen and the infrared to quench the screen selectively through a blurred image, film exposed to an image illuminated by the
phosphor screen will produce a masked, edge enhanced image. Armitage and Lohmann\textsuperscript{11} have shown that an absolute increase in high frequency modulation can be achieved by making a mask that is defocused or blurred to such an extent that spurious resolution for a band of frequencies is achieved. In this region, when the mask is combined with the original image an absolute enhancement will be achieved. This result is shown graphically in Figure 2. These and other methods of photographic image enhancement techniques have been reviewed by Levi\textsuperscript{12} in a very good survey of current enhancement techniques. Digital image enhancement using a method of derivative subtraction techniques have been studied\textsuperscript{13, 14} and the suggestion is made that these techniques correlate with unsharp masking.

Rosenfeld suggests the intuitively simple analogy that if an image can be blurred or smoothed by an averaging or integration process, then an image might be sharpened or edge enhanced by a differentiation process. A number of differential operators have been used as edge enhancing functions, most notably the Laplacian, which is proportional to the difference between the gray level at a point and the average gray level in an annulus centered at the point. In Figure 3, the second derivative of an edge function is subtracted from the edge itself; note the similarity to the results obtained by unsharp masking.
"Usual" unsharp masking technique giving relative enhancement in the high frequencies.

Phase reversal on mask in high frequencies gives "absolute" enhancement.

**Figure 2**

Graphical representation of unsharp masking, showing the effects of defocus on two frequency regions. Note the absolute enhancement in (b) in the frequency region where spurious resolution occurs. (From Armitage and Lohmann, reference 11.)
Figure 3

Diagram showing the type of edge enhancement produced by the subtraction of first and second derivatives from a one-dimensional representation of a degraded edge.
Figure 3
Additional investigation has been made to determine a mathematical model for the prediction of the resulting density distribution when film is processed in a developer exhibiting adjacency effects. The results obtained with adjacency effects are similar to those produced by unsharp masking, though the mechanisms for the two processes differ significantly. Thus, the model describing adjacency characteristics is not directly applicable to describe masking effects. The reader is referred to references 1 and 2 for additional information concerning adjacency effects and the experimentally derived mathematical model.

Most of the practical application of the unsharp masking technique is found in the graphic arts industry for improving the sharpness of reproductions, and in radiography for improving detail and image quality in radiographs. Currently, masking techniques used by workers in these fields have been developed through trial and error; no method for predicting the optimum degree of mask unsharpness or contrast to use for a specific set of image characteristics has been investigated.
MATHEMATICAL DEVELOPMENT

The explanation of the edge enhancement resulting from unsharp masking is found by noting some fundamental concepts of Fourier analysis and their applications to the photographic process. For a brief summary and review of these principles, refer to the discussion in Appendix A. We can apply the concepts of MTF analysis to form a simple, elementary model for the masking process. Masking has been used primarily as a method for dynamic range (contrast) compression, as shown in Figure 4. A superposition of the negative and positive images will produce an image having a transmittance equal to $T_n \times T_p$ at all points; thus, the densities of the two images are additive. In the process known as sharp masking, the transmittances of the positive are inversely proportional to those of the negative at all points, altered only by the contrast of the masking film. When an unsharp, or blurred positive image is made from a sharp negative, the fine detail (high frequency information) is degraded by the larger point spread function caused by the blurring process. This "smearing" of the exposure in high frequency regions decreases the contrast significantly in those areas as compared to the low frequencies (large areas) in the scene. When the film is processed, the contrast (and hence the modulation) of the high frequencies
Figure 4

The use of a mask to lower the contrast and decrease the output density range of a negative.
is less than that of the low frequencies. When the two images are superimposed, a subtraction of negative and mask density range effectively occurs (since the images are of opposite sign; one positive and one negative,) and contrast (modulation) is more significantly reduced in the low frequency region. When the combination is printed onto a higher contrast film to restore the low frequency modulation, an effective increase in the high frequency modulation occurs, producing "enhanced" high frequency detail.

We note that if the MTF characteristics of the mask could be selectively adjusted, various degrees of enhancement could be produced at each level of frequency. For example, Schade\textsuperscript{17} has suggested that an optimum mask would produce a flat output MTF curve over a wide range of frequencies. Thus, we would theoretically produce a mask with an MTF which, when used in combination with the negative MTF will yield the greatest region of level response. Such an MTF can be obtained by adjusting the point spread function used in the production of the unsharp mask and the image contrast of the mask. For increased enhancement (greater than the original scene modulation) other point spread functions and/or mask contrast values may be used, depending on the desired result.

The effects of masking revolve around a frequency-wise change in contrast, associated with the spread function size and shape used when producing the mask. Also contributing

to the final result are factors involving the original negative contrast and point spread function, and the mask and print material contrast. The effect of this "frequency selective" contrast control can be observed mathematically by the following arguments:

We note that the photographic process can be regarded as log-linear in a finite region of the D-Log H response curve. The requirement of linearity exists if the principle of superposition holds; i.e.,

\[ f(x + y) = f(x) + f(y) \]  \hspace{1cm} (1)

For a photographic system this is true provided the system transformation is the linear approximation of the D-Log H curve, or more commonly referred to as gamma (\( \gamma \)). Thus, for this case superposition holds, since the density resulting from the sum of two log exposure values is equivalent to the sum of the densities produced by each exposure individually.

With this assumption of log-linearity, we can begin an analytical examination of the effects of masking on the final image characteristics. We start with an original target of modulation \( M_0 \). By definition, modulation is given by the equation

\[ M_0 = \frac{(T_{\text{max}}/T_{\text{min}}) - 1}{(T_{\text{max}}/T_{\text{min}}) + 1} \]  \hspace{1cm} (2)
where $T_{\text{max}}$ and $T_{\text{min}}$ are the maximum and minimum transmittances of the target. We can solve equation (2) for the ratio of maximum to minimum transmittance:

$$\frac{T_{\text{max}}}{T_{\text{min}}} = \frac{(1 + M_0)}{(1 - M_0)} \quad (3)$$

Exposure of this target on film will produce an incident exposure ratio equal to the target transmission ratio. The log exposure difference ($\Delta \log H$) can thus be expressed by:

$$\Delta \log H = \log \left( \frac{T_{\text{max}}}{T_{\text{min}}} \right) = \log(1 + M_0) - \log(1 - M_0) \quad (4)$$

If the negative material has an MTF significantly less than unity for some frequencies of interest, then $\Delta \log H$ becomes frequency dependent, and the effective log exposure range on the negative is given by the expression

$$\Delta \log H_n(\nu) = \log \left[ 1 + M_0 M_n(\nu) \right] - \log \left[ 1 - M_0 M_n(\nu) \right] \quad (5)$$

where the subscript "n" refers to the negative, and $M_n(\nu)$ is the MTF value for the negative material at frequency $\nu$.

When the film is developed to a contrast $\gamma_n$, the log exposure difference will produce a density range on the negative given by

$$\Delta D_n = \gamma_n \left[ \Delta \log H_n(\nu) \right] \quad (6)$$

This negative may now be (i) exposed onto a material to produce a print directly without masking, or (ii) an unsharp
mask produced and the combination printed in register to obtain the final image. We now examine the results obtained using both methods. (Note: In the following discussion, the subscript "n" will indicate a quantity that refers to the negative; the subscript "m" indicates a value for the mask; "p" refers to the unmasked print material, and "p'" refers to the masked print material.)

Case i: **Normal Printing**

To restore the modulation to the value of $M_o$, the print material must have a contrast $\gamma_p$ such that $\gamma_n \times \gamma_p = 1.0$; thus, the required gamma for the print is the reciprocal of the negative gamma. The log exposure difference for the print material will be equal to the density range of the negative, given in equation (6). Thus, we see:

\[
\Delta \log H_p = \gamma_n \Delta \log H_n(\nu) \quad (7)
\]

\[
\Delta D_p = \gamma_p \gamma_n \Delta \log H_n(\nu) = \Delta \log H_n(\nu) \quad (8)
\]

We have assumed here that the MTF of the print material will be essentially unity over the frequency region of interest.

Since the density range on the final print ($\Delta D_p$) is logarithmically related to the output transmittance ratio, we see:
Therefore, the output modulation on the print as a function of frequency is given by

\[ M_p(\nu) = \frac{\phi - 1}{\phi + 1} \]  

and the effective system MTF is simply \( M_p(\nu)/M_0 \).

Case ii: Unsharp Masking

When an unsharp mask is made from the negative using a mask contrast \( \gamma_m \) and an MTF for the mask of \( M_m(\nu) \), we note that the output modulation for the masked image will be the product of the negative output modulation \( M_{out}(\nu) \) and \( M_m(\nu) \). To determine \( M_{out}(\nu) \) we begin from equation (6):

\[ \left( \frac{T_{\text{max}}}{T_{\text{min}}} \right)_n = 10^{(\Delta D_n)} \]  

\[ M_{out}(\nu) = \frac{1 - \left( \frac{T_{\text{max}}}{T_{\text{min}}} \right)_n}{1 + \left( \frac{T_{\text{max}}}{T_{\text{min}}} \right)_n} \]  

Now, using the same principles as were used for the calculations of original negative exposure range, we can determine the effective log exposure range for the mask image:
\[
\frac{H_{\text{max}}}{H_{\text{min}}} = \frac{1 + M_{\text{out}}(\nu) M_{\text{m}}(\nu)}{1 - M_{\text{out}}(\nu) M_{\text{m}}(\nu)} \quad (13)
\]

\[
\Delta \log H_{\text{m}} = \log \left[ 1 + M_{\text{out}}(\nu) M_{\text{m}}(\nu) \right] - \log \left[ 1 - M_{\text{out}}(\nu) M_{\text{m}}(\nu) \right] \quad (14)
\]

The density range of the mask, \( \Delta D_{\text{m}} \), is then simply

\[
\Delta D_{\text{m}} = \gamma_{\text{m}} \Delta \log H_{\text{m}} \quad (15)
\]

When the original negative and the unsharp mask are placed in register with each other, the resulting combination density range \( \Delta D_{\text{comb}} \) will be the difference of each density range:

\[
\Delta D_{\text{comb}} = \Delta D_{\text{n}} - \Delta D_{\text{m}} \quad (16)
\]

When the combined mask and negative are exposed onto a print material with contrast \( \gamma_{\text{p}} \), (and again assuming that the print material MTF is essentially unity over the range of frequencies of interest) the resulting density range on the print \( \Delta D_{\text{p}} \) will be given by:

\[
\Delta D_{\text{p}} = \gamma_{\text{p}} \Delta D_{\text{comb}} \quad (17)
\]
Again, the logarithmic relationship between density range and transmittance ratio gives

\[
\frac{T_{\text{max}}}{T_{\text{min}}} = 10^{\left(\Delta D_{p}\right)} = \omega
\]  

(18)

Thus, the output modulation as a function of frequency for the masked image is given by

\[
M_{p}(\nu) = \frac{\omega - 1}{\omega + 1}
\]  

(19)

The system MTF for the masked case is thus \(M_{p}(\nu)/M_{0}\).

If we now consider the proper print contrast for the mask + negative combination print, we note that the final density range on both the masked and unmasked prints will be equal for some chosen frequency; hence, we can equate equation (8) and equation (17) and obtain after substitution:

\[
\gamma_{p} = \frac{1}{\gamma_{n} - \gamma_{m}\left(\frac{\Delta \log H_{m}(\nu)}{\Delta \log H_{n}(\nu)}\right)}
\]  

(20)

\(\gamma_{p}\), will, in most cases, be chosen such that the print density range (and hence the print MTF) will be equal for both masked and unmasked prints at a low frequency (\(\nu \approx 0\)).
This specification will produce equal macro-density levels for both images. If it is assumed that the values of the negative and mask transfer functions are unity at zero frequency, then the calculation of the required print gamma for the masked image can be simplified. Through substitution it can be shown that equation (20) will reduce to:

\[ \gamma' = \frac{1}{(\gamma_n - \gamma_m \gamma_n)} \]  \hspace{1cm} (21)

since for unity MTF values, \( \Delta \log H_m = \Delta D_n = \gamma_n \Delta \log H_n \).

A relatively simple computer program was developed for an Apple computer that will solve equation (10) and equation (19) and determine the resulting MTF values for both the masked and unmasked prints, for various values of mask contrast and negative and mask MTF shapes. For a listing of the computer program, consult Appendix B.

Discussing now some specific results obtained from the computer analysis, we will begin by examining the affects due to the unsharp masking process on a "perfect" negative having MTF values of 1.0 for all frequencies of interest. The affect on the final system MTF by masking with a mask MTF proportional to \( \sin(x)/(x) \) and scaled to provide various levels of "unsharpness" is shown in Figure 5. Shown in Figure 6 are the results when
different levels of mask contrast (and hence, final print material contrast) are used. Note that the region of enhancement becomes greater as the mask is made increasingly unsharp (poor MTF,) and that the degree of enhancement (system MTF values above 1.0) is increased with increased mask contrast. There is, however, a practical limit to the unsharpness in the mask that will produce acceptable results; this is due to the flare and scattering problems when exposing the mask image and will be discussed further in the next section. Figure 7 shows comparisons of the effect when various types of MTF shapes are used in the mask making process. It can be seen that by changing the shape of the mask MTF, a slight degree of control over the range of frequencies to be enhanced is possible.

When actual photographs are made of a target or scene, some amount of blur, defocus, or other source of image degradation may cause the negative image to have modulations significantly less than 1.0 in the frequency range of interest. Three levels of degraded negative MTF values have also been used to examine the effects of masking on more realistic, optically-degraded images. The optically degraded MTF values were obtained from the work of Levi and Austing who calculated MTF values at various levels of defocus for a perfect lens. The levels of defocus used in the following analysis represent "sharp," "just blurry," and "very blurry" subjective amounts of degradation, and
Figure 5

Graph showing the theoretically determined enhanced modulation transfer functions produced using various levels of mask blur.
Figure 6
Effect of changes in mask contrast on the resulting theoretical MTF for a "Perfect" original MTF of 1.0. Mask contrast: (a) 0.2; (b) 0.4; (c) 0.6.
Figure 7
Various mask MTF shapes and the associated enhancement produced by each mask MTF. --- = Cosine function; ---- = "Sinc" function; ---- = Sinc² function.
are shown in Figure 8. Figure 9 illustrates the amount of enhancement available with the aid of unsharp masking techniques applied to these defocused originals.

In the preceding examples we have assumed that the input modulation ($M_0$) was constant at a value of 0.70. Because of the non-linearities introduced when determining the final modulation from log values (density) the resulting output modulation and hence the final MTF values will be dependent on the original input modulation. Figure 10 shows the calculated values of MTF for different levels of input modulation, with all other factors held constant. As can be seen, the MTF values increase as smaller input modulation values are used. This result is consistent with that shown by Kriss, Nelson, and Eisen who derived a model to predict the results obtained with films processed to produce a large amount of adjacency effects. Since the results produced by adjacency effects and unsharp masking techniques are similar, correlations with Kriss' work would be expected. Figure 11 shows the MTF values obtained by Kriss for various input modulation values. It should be remembered that when an actual scene is used, an entire spectrum of modulation levels will be present, and hence, a family of MTF values will result, one for each input modulation and frequency combination present in the scene. Since the following experimental work was performed with only one scene, the resulting optimum mask MTF and contrast
Figure 8
Three original MTF shapes representing various degrees of original scene blur.
Possible enhancement scheme for a "sharp" original MTF.
Figure 9b
Possible enhancement scheme for a "just blurry" original MTF.
Possible enhancement scheme for a "very blurry" original MTF.

- Optimum Response
- Enhanced Image
- Original
- Unsharp Mask

Frequency (cycles/mm.)

MTF

1.75 1.50 1.25 1.00 0.75 0.50 0.25

Figure 9c
Figure 10
Effect of the original input modulation \( M_0 \) on the predicted enhanced MTF. 
(a) \( M_0 = 0.2 \); (b) \( M_0 = 0.4 \); (c) \( M_0 = 0.6 \); (d) \( M_0 = 0.8 \).
Figure 11

The effective modulation transfer function as a function of input modulation ($M_i$) for films with adjacency effects. Input modulation values are (a), 0.2; (b), 0.4; (c), 0.6; (d), 0.8. (From Kriss, Nelson, and Eisen - reference 20.)
values will be strictly valid only for this scene. Further study would include an analysis of various scenes with different Weiner (power) spectra to determine if the optimum values presented here differ significantly for various scene power distributions.

Summarizing, by knowing the range of frequencies that are to be enhanced and also the degree of enhancement required, a selection of proper MTF shape and scaling, mask contrast, and final print contrast may be made to provide an increase in image sharpness not possible through normal printing processes. It has been suggested by several researchers¹⁹-²¹ that a reasonable objective measure of image sharpness and quality is a comparison of the areas under portions of the system MTF curves for various images. With the aid of unsharp masking it now becomes theoretically possible to increase the modulation level of a range of frequencies much higher than 1.0, thus increasing the area contained under the MTF curve and hence increasing its measured "quality factor." However, images produced with an extraordinary amount of enhancement become visually displeasing due to an exaggerated edge sharpness beyond the level that is visually acceptable. Thus, a visual optimum must exist and the definition of quality through area measurements alone might be modified somewhat to incorporate these masking effects. Through experimentation and subjective analysis this question of a visual optimum will now be examined.
EXPERIMENTAL

In order to correlate the theoretical models for unsharp masking effects with subjective judgements concerning image sharpness, unsharp masks and enhanced images were produced under a variety of conditions and subsequently examined by a panel of judges to determine the degree of improvement in sharpness for each image. The two major objectives of this experimentation were as follows:

i. Determine whether the proposed mathematical model adequately predicts the effects observed when image enhancement is performed using the unsharp masking technique.

ii. By varying some of the parameters associated with the original negative image, mask production, and film sensitometry, determine the optimum conditions to provide the best degree of improvement in image sharpness for negatives of different quality.

To obtain a solution to the first objective, a sinusoidal test target was used as the original negative and enhanced using this technique. Objective measurements of mask and system MTF could then be compared with the values predicted by the mathematical model. The second objective requires that actual scenes be photographed under different
conditions and that a matrix of differently enhanced images be produced and each image subjectively judged for improvement. The techniques used to produce these "scene" images (as well as the enhanced sinusoidal target images) will now be discussed.

Two basic parameters were varied to produce original negatives with varying sharpness levels; image blur due to errors in focus position, and the signal-to-noise ratio of the original negative image (adjusted by selecting films that differ in granularity.)

It was decided that the scene to be photographed should contain a variety of objects varying in texture and size in order to provide the viewer with a broad range of subjects with which to judge sharpness improvement. A scene containing text material, as well as a variety of objects with different spatial frequency information were used in the scene. A person was not included in the scene, as it was decided that edge sharpening would not be appropriate on portrait-type images, and the subjective impression of "optimum" might be altered. Thus, the subjects for all of the tests were inanimate objects and the results obtained are based on the subjective impressions of only these objects. However, since most scientific applications for image sharpening do not include photographs of people, the results presented here will be valid for most scenes.
A gray scale was also included in the scene in order to monitor the final image contrast, but it was located in an area of the object field that could easily be excluded from the final area to be viewed. The absence of a gray scale in the final scene required judges to base their decision upon picture sharpness and scene contrast, rather than on gray scale reproduction. For a complete description of the scene, refer to Appendix C.

In order to vary the signal-to-noise ratio on the negative images, two film types having significantly different granularity values were used; Kodak Professional Copy Film, type 4125, and Kodak Recording Film, type 2475 provided high and low signal-to-noise ratios, respectively.

It can be seen from equation 21 that a relatively high negative contrast is desirable if mask contrast values around 0.5 are to be used and the final print contrast is not to exceed 3.0. The value of 3.0 was considered to be the maximum contrast that could be obtained from an emulsion whose contrast could be easily altered through processing. Emulsions having infectious development characteristics such as "Lith-type" films were considered undesirable for this experiment as contrast is not easily adjustable for these films through development.

A film format for the final images of 4" x 5" was chosen for ease in handling, processing, and mask making. Since the 2475 film is only available in 35 mm. format,
inter-positives were produced on Fine Grain Release Positive Film, type 7302, and then 4" x 5" negatives made from the inter-positives by contact printing onto Professional Copy Film. This procedure also served to enlarge the grain structure on the final negative, thus providing a lower signal-to-noise ratio for the tests.

Three focus positions were used for both film images. The original negatives made with the 4125 film were photographed using a Plaubel view camera and a 235 mm. focal length Schneider lens, visually focused on the subject. One image was made with the subject in focus, and then two levels of defocus were used to produce images that represented "just blurry" and "very blurry" reproductions of the scene. An identical procedure was followed for the 2475 film, except that the camera used was a Nikon F-2 with a Nikkor 55 mm. macro-lens. For a more complete discussion of the calculations involved in selecting the defocus positions, refer to Appendix C.

The design of the apparatus used to produce the unsharp masks from the original 4" x 5" negatives was based on the following requirements:

a. It was desired to adjust the degree of blur introduced into the mask image through an adjustable physical separation between the negative and mask film. The geometric effects of this alteration on the mask-image point spread function (and hence the mask MTF)
can be seen in figure 12. The equation relating the image point spread function, "a," to the source point spread function, "A," is given by:

\[
\frac{A}{L} = \frac{a \times n}{d}
\]  \hspace{1cm} (22)

where "L" is the separation between the exposing source and the negative, "d" is the separation between the negative and the mask, and "n" is the index of refraction of the medium between the negative and the mask film.

b. The source point spread function was to be altered by inserting a variable density filter between the diffuse light source and the film. This filter could be adjusted to provide different source point spread functions, thus controlling the shape of the mask MTF. Adjustments in the scale of the MTF could thus be made not only by the size of the filter but also by adjusting the distance between the filter and the negative.

c. The registration between negative and mask must be accurately controlled to allow for their re-registration when making the enhanced image. Thus, a system that allowed longitudinal movement between the mask and negative but maintained the lateral registration of the system was essential.
Figure 12

The image formed on the masking film from a point on the negative. The exposure distribution on the mask film is the mask image point spread function.
Figure 13 shows a diagram of the completed apparatus. Negative-mask separation was adjusted through the use of 5" x 7" glass plates which varied in thickness, while lateral registration was preserved by the three-point registration system. A larger negative-mask separation was possible with this system by using a metal spacer that provided an air gap of approximately 10 mm. between the negative and mask film. A 4" x 5" Omega condenser enlarger was used as the exposing unit; with the lens removed from the enlarger, a piece of opal glass located at the negative gate provided a uniform diffuse source. Variable size and density filters could also be located at the negative gate to adjust the spread function size and shape. Figure 14 shows the entire exposing system ready for operation. Some important design considerations for producing an acceptable mask exposing system that were investigated during this research are discussed further in Appendix D.

Another consideration for the exposing system is that the geometries of the mask making and print making light paths be complementary to each other. Because of the separation of the mask film and negative, and the divergence of the light from the exposing source, the mask image will be slightly magnified. Upon printing, the position of the negative and mask are reversed; the negative is placed in contact with the print film and the mask is
Figure 13
Apparatus used for producing unsharp masks and enhanced final images. Top photograph shows the individual elements of the system; bottom photograph illustrates the use of the three-point registration system.
Figure 13
Figure 14

Equipment required for enhancement system: Diffuse light source (enlarger), non-contact registration apparatus, and vacuum pump (to insure firm contact and proper registration.)
separated from this negative-print film sandwich. The diffuse exposing source is now focused on the film by a lens and the mask-to-negative separation adjusted so that the cone angle of the exposing source is identical with the angle of light when the mask was exposed. This adjustment accounts for the slight difference in magnification and provides exact mask-to-negative registration. These principles are outlined in Figure 15.

In order to strictly control processing variability and accurately determine the necessary development time to obtain the desired contrast, a deep-tank nitrogen-burst development system was used. A complete description of the sensitometric tests conducted with this system to determine processing characteristics can be found in Appendix E. The masking film used for the initial tests was 5" x 7" Kodak Pan Masking Film, type 4570 developed in Kodak DK-50 developer, diluted 1:1 with water. For all enhanced images, the print film used was Kodak Contrast Process Ortho Film, 4154 (4" x 5" sheets) developed in Kodak developer HC-110, dilution A.

As previously mentioned, the mask MTF shape and scale were adjusted via the aperture filter. To obtain a \((\sin x)/(x)\) or "sinc" function shaped MTF for the mask, square aperture filters were used, varying in width to provide different scaling values. Scaling was adjusted by noting the width of the aperture on the mask film will
Figure 15

Detail of final enhanced image production. Original negative and print film are placed in contact; mask image is again separated a distance "d" from the negative, with lens aperture and s' distance adjusted to produce a similar cone angle $\theta$ as was used when making the mask.
be equal to the first zero value for the MTF (see Figure 16.) Circular and annular aperture masks were also used, providing Bessel- and Cosine-type MTF shapes.

Originally, the desired cutoff values for the mask MTF were selected for their relationship to the SQF band proposed by Granger\textsuperscript{19} when the final print was viewed at a distance of 30 cm. (see Appendix F.) The values chosen for the mask cutoff frequency were 2, 4, 8, and 16 cycles/mm. It was also decided that the separation between negative and mask film would be held constant at a 3/8 inch air gap, and scaling adjusted by aperture size alone. Using equation 22, one can select a value for L that is convenient and will allow convenient aperture widths to be used.

After some initial tests it was discovered that the scattering effects caused by the silver grains in the negative and mask caused a noticeably degraded final image to be produced. This result required that smaller values for the width "d" be used and the values of L and A re-adjusted to provide the same geometric angles. New values for "d" of 2 mm. and 6 mm. were selected using glass plates to provide the separation, and it was found that the 2 mm. separation provided the best results, allowing geometric scaling through changes in L and A, but limiting the degree of scattering caused by the Callier-Q factor associated with the silver images used in this system. During these tests the use of color materials was considered in order
Figure 16

Relationship between spread function width and zero modulation values for various spread function shapes:
(A) Square aperture, $\frac{\sin(x)}{x}$ frequency spectrum;
(B) Circular aperture, Bessel function frequency spectrum;
(C) Annular aperture, dampened cosine frequency spectrum.
to provide the system with an inherently lower Q-factor because the dye clouds that replaced the silver grains in the color images would cause significantly less scattering to occur. However, this option was discarded since the goal of this research was to optimize a practical method for unsharp masking; since most of the current applications of this technique rely on silver materials, the decision was made to continue the tests with black-and-white silver photographic materials.

Using the 2 mm. separation and adjusting "L" to 638 mm., aperture sizes of 2" and 1" were used to expose the sinusoidal targets to produce masks with scaled MTF shapes. Also exposed was the focused, high signal-to-noise ratio scene, and the masks processed to a gamma of 0.6. From these images, enhanced positives were produced and examined. It was found that although there was a slight difference in the mask MTF values for the two aperture sizes, it was not significant enough to produce a visual difference between the scene images made with differently shaped apertures. For this reason, the use of variable density aperture masks for MTF shaping became unnecessary since both the mathematical model and experimental evidence indicated that there was no observable difference between images produced with different aperture shapes (see Figure 7.) An annular aperture mask was used to expose a sinusoidal target, however, to examine the enhancement
effects of this radically different source spread function.

A much greater effect is noticed when mask contrast is altered. Contrast levels of 0.4 and 0.6 were used for masks made from each high signal-to-noise ratio negative. From these, the proper print contrast was selected to restore the low frequency contrast to 1.0. A series of images were made varying the contrast of the mask for the cases shown in Table 1. These were then examined by judges to obtain a ranking of their sharpness. The gray scale contrasts for all images were maintained as uniform as possible; Figure 17 shows the small deviations in gray scale reproduction inherent between the prints produced.

In addition to the scenes indicated above, sinusoidal target exposures were made for the cases shown in Table 1 in order to provide objective information about the enhancement produced at each level. In the next section, the objective results obtained through analysis of the resulting enhanced MTF values and the subjective results determined through observations of the scene images will be correlated and compared with the mathematical model results presented earlier.

When the low signal-to-noise ratio negatives were enhanced using the system described, a significant decrease in overall image quality was obtained. This degradation was caused by an enhancement of the image noise (grain
Table 1

Exposures produced and analyzed for the scenes and sinusoidal target images. Sinusoidal target images were produced at two contrast levels for each indicated blur value; mask contrasts of 0.4 and 0.6 and the corresponding print contrasts of 1.67 and 2.5. (PM = Pan Masking Film; FP-4 = Ilford FP-4 Film. All enhanced images were produced on Contrast Process Ortho Film.)
Table 1

a) ORIGINAL SCENE EXPOSURES:

<table>
<thead>
<tr>
<th>Original</th>
<th>Contact Print - no mask</th>
<th>Contact Mask</th>
<th>Blurred mask: (a = 0.10 \text{ (d = 2 mm.)} \gamma_m = 0.4)</th>
<th>(\gamma_m = 0.6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sharp</td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>D</td>
</tr>
<tr>
<td>Just Blurry</td>
<td>E</td>
<td>F</td>
<td>G</td>
<td>H</td>
</tr>
<tr>
<td>Very Blurry</td>
<td>J</td>
<td>K</td>
<td>L</td>
<td>M</td>
</tr>
</tbody>
</table>

b) SINUSOIDAL EXPOSURES:

<table>
<thead>
<tr>
<th>Width &quot;a&quot;</th>
<th>Separation &quot;d&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 mm.</td>
</tr>
<tr>
<td>0.05</td>
<td>PM FP-4</td>
</tr>
<tr>
<td>0.10</td>
<td>-</td>
</tr>
<tr>
<td>0.20</td>
<td>-</td>
</tr>
<tr>
<td>0.40</td>
<td>-</td>
</tr>
</tbody>
</table>

PM: Present, -: Absent
Figure 17a

Gray scale reproduction for enhanced "sharp" images;

- sharp mask, \( \gamma = 0.4 \);
- unsharp mask, \( \gamma = 0.4 \);
- unsharp mask, \( \gamma = 0.6 \);
- positive, un-masked image.
Figure 17b

Gray scale reproduction for enhanced "just blurry" images:

- sharp mask, $\gamma = 0.4$;
- unsharp mask, $\gamma = 0.4$;
- unsharp mask, $\gamma = 0.6$;
- positive, un-masked image.
Figure 17c
Gray scale reproduction for enhanced "very blurry" images:

- sharp mask, $\gamma = 0.4$; 
- unsharp mask, $\gamma = 0.4$;
- unsharp mask, $\gamma = 0.6$; 
- positive, un-masked image.
structure) by the masking process. So severe was the noise amplification that further tests with the low signal-to-noise ratio images were discontinued in order that a more detailed analysis of the high signal-to-noise ratio images could be performed.
OBJECTIVE RESULTS

Measurements of the sinusoidal target images produced on the masking film and the enhanced image values were obtained using a Joyce-Loebl microdensitometer. From this data the MTF values for both the mask and enhanced images were determined. The microdensitometric procedure used to determine the MTF data is discussed in Appendix G. It was noted after calculation of the mask MTF values that the values never reached 1.0 at low spatial frequencies; in fact the maximum value obtained with the 4570 film was 0.65. This low value was attributed to three factors:

1. Light scattering within the emulsion of the negative and between the negative and mask film;

2. Lack of an adequate anti-haliation backing on the masking film to inhibit back-scatter of the light in the masking film;

3. Flare in the exposing system.

Of the three factors, (1) could not easily be reduced, but (2) and (3) were adjusted by selecting a camera-type film with properties of fine grain and an anti-haliation coating. Ilford FP-4 film was selected, and the exposing source baffled as much as possible to limit flare. With
these modifications, low frequency MTF values of 0.80 were achieved; slightly better but still not reaching 1.0 at low frequency levels. It is felt that the inherent flare caused by the exposing conditions has had the most significant affect on the low MTF values. As will be seen, however, this alteration of the MTF can be taken into account in the mathematical model and in some cases may even be desirable. By adding a scaling factor to the mask MTF value we are able to adjust the model to include flare in the mask making process. Using a value for the scaling factor equal to the experimental MTF value at low frequencies, Figure 18 shows the correlation between the calculated MTF shape and the one produced by experimentation. Figure 19 gives a comparison between the theoretically calculated enhanced MTF values and those produced through experimentation.

Objectively, then, it can be concluded that the most significant factor in adjusting the amount of apparent enhancement produced in the final image is the contrast of the mask. Very small changes result for differently shaped source spread functions, although a slight degree of modification is possible. Also of interest is to note the affect of the lower MTF values for the mask at low frequencies on the resulting enhanced image. Even with the use of a "sharp" mask (one produced through direct contact printing with the negative) a slight enhancement
Figure 18

Experimental and computer predicted values of the mask MTF for two different masking films; Kodak Pan Masking Film (——) and Ilford FP-4 film (-----).
Figure 19

Experimental and computer simulated enhanced MTF values for two levels of mask contrast:

(a) $a = 0.05$, $\gamma_m = 0.6$;  
(b) $a = 0.10$, $\gamma_m = 0.6$;  
(c) contact mask, $\gamma_m = 0.4$;  
(d) $a = 0.10$, $\gamma_m = 0.4$;  
(e) un-masked MTF (Kodak Commercial film.)

* - Computer predicted MTF, $a = 0.10$, $\gamma_m = 0.6$;  
+ - Computer predicted MTF, $a = 0.10$, $\gamma_m = 0.4$. 
(MTF values above 1.0) is achieved caused by the system flare, inherent Q-factor, and back-scatter producing a slight blurring of the mask image.

These problems of scatter caused a lower limit to be placed on the experimental production of very sharp masks. Hence, it is not possible to reach any definite conclusions regarding the smallest degree of degradation that will provide a noticeable enhancement. As will be seen, however, this problem will not be extremely significant when specifying an optimum after subjective examination of the images.

It was determined that because of the exposure system used and the Q-factor scattering, enhanced images produced using a separation of 6 mm. or greater showed a marked degradation rather than an increase in apparent image sharpness. Thus we can state that for optimum results using silver negatives and a diverging/converging type exposing system, separations less than approximately 4 mm. are essential. The 2 mm. separation used for this experimentation proved quite acceptable. Also, within a very wide range, the source intensity distribution will have an insignificant affect on the results produced. Much more significant is the geometric scaling (size) of this spread function on the mask image (which determines the degree of mask unsharpness.) Again, however, within a range of acceptable limits (depending somewhat upon the magnification and viewing conditions of the final image) scaling changes
of the mask MTF will not produce significantly different results. For the tests conducted in this research, mask MTF values with zero response between 6 and 12 cycles/mm produce enhanced images of equal quality, while a mask MTF with a cutoff frequency of 4 cycles/mm produced an unacceptably blurry final image.

Of most importance in providing a significant change in the final MTF then, is the mask contrast. As will be noted in the following subjective evaluations, some judges indicated a limit on the amount of MTF improvement above a value of 1.0 that is acceptable before a displeasing image has resulted. However, objective enhancement (sharpening) of the image MTF can continue to increase until limited by the constraints of the print-material contrast.
SUBJECTIVE ANALYSIS

Visual evaluations of the twelve images outlined in Table 1 were performed by sixteen judges. They were asked to rank and then to scale the images according to their image sharpness. The testing was designed to statistically determine the following:

1. What relative increase in perceived sharpness can be achieved with images that initially were "sharp," "just noticeably blurry," and "very blurry?"

2. Through this enhancement technique, is it possible to improve an image of a blurry original above the level of sharpness of a higher quality original image produced without masking?

3. Is there an optimum level of masking that will produce the most visually pleasing image?

To maintain consistency in the observations, the judges were chosen from faculty and students of the Photographic Science and Instrumentation program at the Rochester Institute of Technology. It was felt that this group of individuals would have similar definitions for sharpness, and would examine the images for similar characteristics.
In order to address the above questions, it was necessary to assign a numerical, rank order to the twelve images. It was impractical to present the judges with all images simultaneously and ask them to rank each on a specific scale, so an abbreviated ranking system was devised:

First, each judge was asked to rank (not scale) the four images produced from the same original negative in order of sharpness. They were then asked to rank the same images in order of their "pleasantness" with respect to sharpness. These two questions provided a measure of the "pleasing" quality of the image sharpness compared to the perceived sharpness of the image.

Next, each judge was presented with six images to rank in order of sharpness. These consisted of the unmasked images made from each negative original, along with the "sharpest" masked image that the judge had selected from each group in the previous ranking. Finally, each judge was presented with a pair of images (chosen from the rank order that the judge indicated above) and a third image that the judge had indicated was between the other two with respect to sharpness. The judge was then asked to scale the third image between the two initial images on a scale from one to nine, with nine as the sharpest image. This sequence was continued, selecting different triads of images until all possible cases had been ranked— all rankings being made between one and nine. Through a simple
algebraic solution to these scaling values, all twelve images could then be scaled relative to each other on the same scale, with a maximum sharpness value of nine. The differences between the scaled values could then be used to measure relative changes in the degree of enhancement for the different images.

Figure 20 shows the average scaling of all images provided by eleven of the sixteen judges giving consistent responses. Also shown are one-sigma regions for each average rank value. As can be seen, judges were not consistent in their ranking values to allow for any significant rank numbers to be extracted from the data if analyzed by simple rank order values.

However, although judges may differ in the rank number assigned to each image, they may agree on the relative position with one image to another with respect to rank. That is, the differences in the scaled values will indicate if there is agreement among judges about the degree of sharpness improvement. For this analysis, a non-parametric statistical test (sign test\textsuperscript{23}) was used to determine if there was a significant difference between the sharpness improvement for the sharp, just blurry, and very blurry images. The results indicate that the degree of improvement in sharpness was about equal for the just blurry and sharp images, but significantly less for the very blurry images, as can be seen in Figure 20.
Figure 20

Subjective ranking of the twelve images outlined in Table 1. The range indicated for each ranked value is ± one standard deviation, based on the ranks assigned by 11 consistent observers from a total sample of 16 judges.
By examining the differences between the sharp, unmasked image and the just blurry, best masked image, it would be possible to determine if the slightly defocused image could be made to equal or surpass the sharpness of a sharp but unmasked image through masking techniques. Statistically, it was shown that there was no difference between the two images, and hence, approximately equal sharpness quality was obtained for both images. By comparison, there was a unanimous decision from the judges that the unmasked, slightly blurry image was significantly less sharp than the sharp image. Hence, significant improvement in slightly blurry originals is possible through masking procedures. Very blurry images, however, show only small improvements in image sharpness with masking, and the judges significantly disagree on the amount of masking that provides the sharpest image. This result indicates that little, if any, real enhancement is possible with extremely defocused images.

It was felt at the outset of this experimentation that it would be possible to "over enhance" an image; that is, if the mask level were increased too much it was hypothesized that an image with an outlining effect would be produced that might be displeasingly sharp. To test this hypothesis, a total of eighteen judges were asked to observe the four images produced from the sharp negative using different amounts of masking. They were then asked
to choose the "sharpest" image of the group and also the "most pleasing with respect to sharpness." Table 2 shows the responses from the judges to these two questions. As can be seen, although there is significant agreement on the "sharpest" image, the judges are divided with respect to the most pleasing image. Statistically, the statement that "people prefer images produced with a mask contrast of 0.4 above those produced with a mask contrast of 0.6" can be made with only 75% confidence. Note also that this applies only to sharp original images. If slightly blurred or very blurred originals are used, the disagreement among judges regarding an optimum becomes even greater, and a statistically significant optimum cannot be determined.

Summarizing the results of the preceding analysis, it can be stated that a significant improvement in image sharpness can be achieved with sharp or slightly blurry originals. The degree of improvement in the sharpness was judged to be equal for both sharp and slightly blurry images. This result is slightly different than originally thought, as it was predicted that there would be a greater increase in the perceived sharpness of the blurry images than the sharp images. Essentially, it has been shown that there was as much improvement in the sharpness of the "sharp" original as there was in the "just blurry" original.

Improvements through masking showed no significant difference between sharp, unmasked originals and well-
Table 2

Response of eighteen judges when asked about the sharpness of an originally "sharp" image with various amounts of image enhancement from unsharp masking. (See Table 1 for an explanation of the degrees of enhancement used.)

QUESTION: "Which image is the sharpest?"

<table>
<thead>
<tr>
<th>Least enhanced</th>
<th>Most enhanced</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>Response</td>
<td>0</td>
</tr>
</tbody>
</table>

QUESTION: "Which image is the most pleasing with respect to sharpness?"

<table>
<thead>
<tr>
<th>Least enhanced</th>
<th>Most enhanced</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>Response</td>
<td>0</td>
</tr>
</tbody>
</table>
masked, slightly blurry originals. Finally, with 75% confidence it can be stated that mask contrasts of 0.40 (which produce a final MTF value of 1.3 for an original object modulation of 0.70) gave more pleasing results than mask contrasts of 0.60 (producing MTF values of 1.5 with 0.70 original object modulation.) Therefore, it seems that a maximum MTF value for the final image of approximately 1.3 for "average" contrast objects is an optimum sharpness level above which images begin to look "outlined." Again, this result is true only for sharp original images. It should also be noted here that the modulation level of 0.70 for the original scene corresponds to a difference in object contrast of approximately 2.5 stops. For other modulation levels, the optimum enhanced MTF level may differ from the value indicated here.
CONCLUSIONS AND RECOMMENDATIONS

It has been shown that improvements can be made at all levels of focused and defocused original images with respect to apparent sharpness if the signal-to-noise ratio of the image is reasonably high (as in most normal photographs with low to moderate graininess.) The theoretical degree of enhancement can be calculated through the use of equations (3) through (19) and has been shown to be in reasonable agreement with experimental data.

A visual optimum for the degree of enhancement of the MTF above 1.0 can be specified for sharp original scenes, and has been found through subjective analysis to be 1.3 (at a 75% confidence level) for scenes with original modulation of 0.70. The optimum blur level of the mask is somewhat dependent on the apparent magnification of the final print, though under normal viewing distances and magnifications, a range of blur levels were found to give similar degrees of enhancement. That is, observations of the enhanced images at different viewing locations produced no significant alteration in the results determined through the statistical analysis of the images viewed at 30 cm.

The unsharpness of the mask is limited by the scattering within the photographic material; images that are excessively unsharp will produce degraded results. Thus, as long as
the mask is not excessively unsharp, the degree of mask blur has a surprisingly minor affect on the final degree of enhancement.

Mask contrast is the most important factor affecting the final image sharpness. For sharp images, contrasts of approximately 0.4 or 0.5 were found to be optimum for the best visual appearance; when blurry images are used, contrast values for the mask of 0.6 or higher would be recommended. However, contrast values above 0.6 require very excessive print material contrast (above 2.5) and processing technique and accurate exposure determination become extremely important.

Finally, it was seen that when relatively low signal-to-noise ratio images (produced using a coarse grained film) were enhanced using this technique, the grain structure was enhanced as well as image detail, producing little improvement and possibly a slight degradation of the total image quality. For improvement of sharpness for grainy images, then, an aperture mask shaped to provide a sharper image of the grain on the mask while blurring frequencies lower than the grain frequency is required. Also required for experimental realization of improved sharpness is a better system for producing the mask and print images than was used in this research, as the frequencies of significance are very high and could not be reproduced in this system. The relationship between viewing magnification
and mask unsharpness, and improved sharpness in low signal-to-noise images could use further examination. Also of interest would be the alteration of these results through the use of non-scattering photo-sensitive materials for producing the negative and mask images.

Based on the results of this research, the following recommendations can be made for the simplified use of the unsharp masking technique to produce an enhanced image:

For an average, sharp negative, processed to a gamma of 1.0, the optimum conditions for enhancement of frequencies between 1 and 12 cycles/mm. are:

Simple circular diffuse source; the geometry of the light source should be aligned such that the angle subtended by the image of the source on the masking film as seen from a point on the negative is approximately 3° - 5°. This angle must be preserved between the mask and negative when printing for exact registration of the image.

The optimum mask and print contrast for a system providing MTF values of 1.0 for the mask at low frequencies would be 0.5 for the mask and 2.0 for the print material. This combination would restore the low frequency contrast to an acceptable level and optimize the visual impression of the final scene.
LIST OF REFERENCES


IMAGE ANALYSIS PRINCIPLES

Film Characteristic Response Function

The output of the photographic process resulting from various levels of input can be determined from the response function (or characteristic curve) of the film. This function is usually described by the relationship between developed density (D) and the incident log exposure (log H.).

The region of linearity of the D - log H curve is described by the slope, gamma (\( \gamma \)) within the linear region. This linear portion can be modeled by the function:

\[
D = \gamma (\log H - \log H_0)
\]

(23)

where \( H_0 \) is the extrapolated amount of exposure that will produce zero density. The transmittance (T) of an attenuator is a more fundamental quantity than density, and hence density can be defined in terms of the transmittance:

\[
D = \log \left( \frac{1}{T} \right)
\]

(24)

The transmittance is defined as the ratio of the amount of energy transmitted by the sample to that incident on the sample. Transmittances are multiplicative; i.e., for two attenuators, their combined transmittance is the product of their individual transmittances:

\[
T_{1+2} = T_1 \cdot T_2
\]
**Point Spread Function**

The scattering, or distribution of exposure within an emulsion, due to an exposure to an ideal, point source of radiation is characterized by the point spread function, \( p(x,y) \). The shape of \( p(x,y) \) is affected by the scattering properties of the emulsion. System point spread functions are also affected by optical scattering caused by the image-forming elements of the photographic system.

**Line Spread Function**

For a symmetric point spread function, the line spread function, \( s(x) \), can be obtained by a one-dimensional integration of the point spread function:

\[
 s(x) = \int_{-\infty}^{\infty} p(x,y) \, dx \quad (25)
\]

Experimentally, the line spread function may be obtained by numerically differentiating an edge exposure as a function of position.

**Modulation**

Modulation, \( M \), is a measure of the effective exposure variation produced by a sinusoidal input. Mathematically, modulation can be expressed as:

\[
 M = \frac{H_{\text{max}} - H_{\text{min}}}{H_{\text{max}} + H_{\text{min}}} \quad (26)
\]
In this equation, $H_{\text{max}}$ refers to the maximum value of exposure from the sinusoidal input, and $H_{\text{min}}$ is the minimum exposure. An exposure distribution of the form:

$$H(x) = H_0 \left[ 1 + M \cos(2\pi f x) \right]$$

(27)

has a frequency $f$, modulation $M$, and an average exposure $H_0$.

**Fourier Transform**

A function $g(x)$ has a one-dimensional Fourier Transform given by:

$$\mathcal{F} \left[ g(x) \right] = G(f) = \int_{-\infty}^{+\infty} g(x) e^{-i2\pi f x} \, dx$$

(28)

**Modulation Transfer Function**

The modulation transfer function (MTF) provides information about the frequency response of the system, or the ability of the system to reproduce signals of various frequencies. The MTF of a system is defined as

$$\text{MTF} = \frac{\text{Output System Modulation (M')}}{\text{Input System Modulation (M)}}$$

(29)

Values of MTF that are greater than unity thus indicate an enhancement or increase in the modulation of the object signal. MTF is also defined by the Fourier Transform of the line spread function for the system or element being tested.
Convolution

As it applies to image formation, convolution may be thought of as an operation that expresses the total exposure at an image point, produced by all the contributions of the exposure at that point from the spreading of light within the system. For an object exposure distribution \( h(x,y) \), the image exposure distribution, \( g(\xi,\eta) \) can be obtained:

\[
g(\xi,\eta) = h(x,y) * p(x,y) \quad (30)
\]

where * denotes the convolution operation. Mathematically,

\[
h(x,y) * p(x,y) = \int_{-\infty}^{+\infty} h(x,y) p(\xi-x,\eta-y) \, dx \, dy \quad (31)
\]

A convenient property of the Fourier Transform is shown below:

\[
\mathcal{F} \left[ h(x,y) * p(x,y) \right] = H(\xi,\eta) \cdot P(\xi,\eta) \quad (32)
\]

where the capitals indicate a Fourier Transform operation.
APPENDIX B

COMPUTER PROGRAM FOR MTF PREDICTION
HOME : VTAB 3
10 DS = "" : ROM DS IS CNTL-D
20 PRINT "INPUT "NAME OF FREQUENCY? ";N$
30 PRINT DS;"OPEN ";N$
40 PRINT DS;"READ ";N$
50 INPUT N
60 DIM FQ(N)
70 FOR J = 1 TO N
80 INPUT FQ(J)
90 NEXT J
100 PRINT DS;"CLOSE ";N$
110 PRINT : INPUT "NAME OF ORIGINAL MTF FILE? ";MTF$
120 PRINT DS;"OPEN ";MTF$
130 PRINT DS;"READ ";MTF$
140 INPUT C : IF C = N GOTO 42
150 PRINT "FREQ. DATA DOES NOT MATCH MTF DATA - PRESS SPACE BAR TO START OVER ": GET Q$
160 GOTO 21
170 IF NEG$ = "YES" GOTO 44
180 DIM OGILMOD(C)
190 FOR J = 1 TO C
200 INPUT OGILMOD(J)
210 NEXT J
220 PRINT DS;"CLOSE ";MTF$
230 IF KEEP$ = "YES" GOTO 100
240 HOME : HTAB 4 : PRINT TAB( 3 )"WHAT WAS THE GAMMA OF ": PRINT TAB( 3 )"THE NEGATIVE? == > ";
250 INPUT G
260 HTAB 8 : PRINT TAB( 3 )"WHAT WAS THE MODULATION?": PRINT TAB( 3 )"OF THE ORIGINAL TARGET? == > "; INPUT O
270 DIM BN(N) : DIM NRMOD(N) : DIM MODMASK(N)
280 TEXT : HOME : VTAB 3 : PRINT TAB( 3 )"SELECT MASK SHAPE FROM": PRINT "": PRINT TAB( 3 )"THE FOLLOWING?": PRINT "": PRINT 
190 PRINT TAB( 3 )"1" : TAB( 10 )"SQUARE": PRINT TAB( 3 )"2" : TAB( 10 )"ANNULUS": PRINT TAB( 3 )"3" : TAB( 10 )"HEIGHT": PRINT TAB( 3 )"4" : TAB( 10 )"Diameter": PRINT TAB( 3 )"1" : TAB( 10 )"WIDTH OF RING": PRINT TAB( 3 )"2" : TAB( 10 )"ALL DISTANCES IN MILLIMETERS": PRINT "": PRINT "": PRINT 
300 PRINT TAB( 3 )"SELECT 1, 2, OR 3 ":; V : GOTO 414
310 INPUT " ": V
320 TEXT : HOME : VTAB 1 : INPUT " SELECT MASK SHAPE 1, 2, OR 3 ":; V : PRINT "": GOTO 414
330 HOME
340 IF V = 3 THEN INPUT "WIDTH OF RING": W
350 VTAB 6 : PRINT TAB( 3 )"WHAT IS THE MASK CONTRAST THAT": PRINT TAB( 3 )"YOU WOULD LIKE TO USE? == > "; INPUT MG
360 VTAB 12 : PRINT TAB( 3 )"WHAT IS THE CUT-OFF FREQ?": PRINT TAB( 3 )"FOR THE MASK? == > "; INPUT A
370 PI = 3.14159
380 KG = 1.0294482
390 INPUT "WHAT IS MAXIMUM MTF FOR MASK?": MAX
530 INC = FQ(2) - FQ(1)
545 FOR J = 1 TO N
550 IF J = 1 THEN BU(J) = ZMAX: GOTO 560
551 IF V = 1 THEN GOTO 555
552 IF V = 2 THEN GOTO 554
553 BU(J) = COS (2 * PI * FQ(J) / A) * ZMAX * SIN (PI * FQ(J) * W) / (PI * FQ(J) * W): GOTO 560
554 BU(J) = ( SIN (PI * FQ(J) / A) / (PI * FQ(J) / A)) * ZMAX: GOTO 560
555 BU(J) = ( SIN ((PI * FQ(J) / A)) / (PI * FQ(J) / A)) * ZMAX
560 NSEGMOD = 0 * OGIOMOD(J)
562 HNEG = K * ( LOG (1 + NSEGMOD) - LOG (1 - NSEGMOD))
564 DNEG = NG * HNEG
566 TNEG = 10 * DNEG
568 OITMOD = (TNEG - 1) / (TNEG + 1)
570 MSKMOD = OITMOD * BU(J)
572 HMASK = K * ( LOG (1 + MSKMOD) - LOG (1 - MSKMOD))
574 DMASK = NG * HMASK
578 DCOMB = DNEG - DMASK
580 IF J = 1 THEN GOSUB 2000
582 DPRINT = FQ * DCOMB
584 TPRINT = 10 * DPRINT
586 MODMASK(J) = (((PRINT - 1) / (PRINT + 1)) / 0
588 NRMDEN = DNEG / NG
590 PRNIT = 10 * NRMDEN
593 NRMNOD(J) = (((PRINTT - 1) / (PRINTT + 1)) / 0
596 NEXT J
599 IF FS = "YES" GOTO 610
600 HCR = HCOLOR = 7
610 HPLT 270, 155 TO 10, 155 TO 10, 5 TO 270, 5 TO 270, 155
620 FOR I = 0 TO 8
630 HPLT 10, 18.75 * I + 5 TO 13, 18.75 * I + 5
635 NEXT I
640 FOR I = 0 TO FQ(N) STEP 2
650 HPLT 10 + (260 / FQ(N)) * I, 155 TO 10 + (260 / FQ(N)) * I, 152
655 NEXT I
660 FOR I = 1 TO N
670 Y = 155 - OGIOMOD(I) * 75
680 X = 10 + (260 / FQ(N)) * FQ(I)
690 IF I = 1 GOTO 710
700 HPLT(X, Y)
705 NEXT I
710 HPLT(X, Y)
715 NEXT I
720 FOR I = 1 TO N
730  Y = 155 - BNU(I) * 75
740  X = 10 + (260 / FQ(N)) * FQ(I)
750  IF Y > 155 THEN Y = 155
755  IF Y < 0 THEN Y = 0
760  HPlot X,Y
765  NEXT I
770  GET T$
775  HOME
780  FOR I = 1 TO N
790  Y = 155 - NRMOD(I) * 75
800  Z = 155 - MODMASK(I) * 75
810  X = 10 + (260 / FQ(N)) * FQ(I)
820  IF Z > 155 THEN Z = 155
830  IF Z < 0 THEN Z = 0
840  HPlot X,Y; HPlot X,Z
850  NEXT I
860  HOME : VTAB 23
870  PRINT "PRINT GAMMA WAS "; F$
880  PRINT "ANOTHER?": INPUT F$
890  IF F$ = "YES" GOTO 1000
900  PRINT "WANT TO SAVE THIS? ": INPUT SVE$
910  IF SVE$ = "YES" GOTO 940
920  GOTO 2050
930  HOME : VTAB 24: END
940  INPUT "NM,NG,0,2MAX,AND A"; NG, NM, 0, 2MAX, A
950  GOTO 545
960  PG = 1 / (NG * (1 - MG))
970  RETURN
980  TEXT : HOME
990  FOR I = 1 TO N
1000  NQ = INT (NRMOD(I) * 100) / 100
1010  M = INT (MODMASK(I) * 100) / 100
1020  B = INT (BNU(I) * 100) / 100
1030  PRINT TAB(3) NQ; TAB(12) M; TAB(18) B
1040  NEXT I
1050  IF I > 20 THEN GET F$
1060  NEXT I
1070  END
APPENDIX C

SCENE CONTENT AND CALCULATIONS OF DEFOCUS

Constructing the scene that was to be used as the subjective test for image enhancement required initial consideration of several factors. First, the types of objects to be used in the scene must be chosen. Many objects with varying degrees of fine detail were selected to provide the viewer with visual information about sharpness at many frequencies. For low frequency information, a loosely folded white handkerchief provided a large highlight area; the folds in a black cloth used for the backdrop gave a large shadow area, and plain covered books gave a midtone region for examination. Mid-frequency information in the scene was provided by subjects such as a clarinet, printed text material, paper money, and a wood-grain texture. Very fine twigs and branches from a dried plant were used to give the highest frequency information in the scene. Suspended above the objects was a log periodic resolution target and a large gray scale to be used for objective measurements of the image. These targets were positioned so that they could be masked out of the final image that would be examined by judges so as not to influence decisions about sharpness through objective targets. Figure 21 shows the completed scene.
Figure 21a

"Sharp" scene used for subjective analysis of image sharpness improvement through unsharp masking.
Figure 21b

"Just Blurry" scene used for subjective analysis of image sharpness improvement.
Figure 21c

"Very Blurry" scene used for subjective analysis of image sharpness improvement.
The magnification and depth of field existing in the original negative were also important to produce acceptable test scenes. The magnification needed to be large enough for the gray scale image to be measured using a densitometer with a 2 mm. aperture, and the still-life must fill the short dimension of the film format. These requirements fixed the magnification at a value of 0.17. Of greater importance was the selection of an f/number that would provide the necessary depth-of-field to keep all objects acceptably sharp in the initial photograph, and then provide a reasonably uniform amount of blur over the entire scene when the defocused images were produced. The calculation of the depth-of-field using a 235 mm. focal length lens set at f/45 using geometrical optics principles is shown below:

1. To determine the required object distance (s):

\[
s = f \left( 1 + \frac{1}{M} \right) = 1.65 \text{ meters} \quad (33)
\]

where M is the value of magnification, 0.17.

2. The hyperfocal distance for the lens set at f/45 can be determined (using the angular resolution of the eye as the acceptable angular blur:)

\[
S_h = \frac{\text{lens diameter}}{\text{angular blur}}
\]

\[
= 5.22 \text{ mm.} / 0.0005 \text{ radians}
\]

\[
= 10.4 \text{ meters} \quad (34)
\]
Calculating the near and far distances that will be in acceptable focus at \( f/45 \):

\[
S_n = \frac{s \cdot S_h}{S_h + s} = 1.4 \text{ meters} \quad (35)
\]

\[
S_f = \frac{s \cdot S_h}{S_h - s} = 1.9 \text{ meters} \quad (36)
\]

Thus, a total depth-of-field of less than two feet exists at \( f/45 \) under the specified conditions. The still-life was adjusted to keep the distance between the front and back objects less than two feet.

Degrees of defocus were decided upon based on the Optical Transfer Function value provided by the lens at the maximum frequency of Granger's SQF band (see Appendix F.). The "just blurry" image was chosen to have a 50% OTF value at 40 cycles/mm., and "very blurry" a 10% OTF at 40 cycles/mm. as measured at the retina when viewing the final image. If the photographs were to be viewed at a distance of 30 cm. \((M = 0.07)\) the corresponding image frequency will be 3 cycles/mm. Consulting published data for the OTF values of a perfect lens\(^{18}\) at various levels of defocus, the following expression can be used to determine the degree of movement from exact focus position needed to provide the desired level of OTF at the selected frequency:

\[
\delta = 2\Delta N^2\lambda \quad (37)
\]

where the symbols are defined as follows:
\[ \delta = \text{required degree of focus shift} \]
\[ \Delta = \text{number of Rayleigh units of defocus desired} \]
\[ N = f/\text{number of lens} \]
\[ \lambda = \text{wavelength of light (555 nm. used for calculation)} \]

Solving equation (37) using the proper value for \( \Delta \) obtained from the tables published by Levi\textsuperscript{18} we obtain focus shift values of approximately 8 mm. for a 50% OTF value at 4 cycles/mm., and approximately 13 mm. for a 10% OTF value.

A means for verification of these values is to use the geometrical approximation for resolution that would imply the OTF value would approach zero at the desired frequency (4 cycles/mm. would indicate a blur circle diameter of 0.25 mm.) Using the same conditions as above, we can obtain the focus shift required, based on the geometric analysis shown in Figure 22. Using the equation

\[ \delta \approx \frac{0.25 \, s'}{D} \]  \hspace{1cm} (38)

where \( D \) is the lens diameter and \( s' \) the image distance, a value of approximately 13 mm. is obtained, which is in good agreement with the prediction using the OTF tables.

Thus, these two focus shifts were used when producing the original 4 x 5 inch negatives. An error in measurement of the exact degree of focus shift on the view camera
Figure 22

Diagram showing the relationship between object plane, plane of sharp focus, and a defocused image plane with a blur circle diameter of a'.
caused one of the defocused images to vary somewhat from the calculated level of blur. Examination of the "very blurry" image indicates that the 10% modulation level occurs at approximately 1 cycle/mm. rather than 4 cycles/mm. as calculated. The exact degree of blur, however, was not considered to be a critical factor in the analysis to follow, and hence, the "very blurry" defocused image was not re-photographed.

When producing low signal/noise ratio images, a 35 mm. camera was used, and defocus was adjusted visually in order to provide an amount approximately equal to that produced on the 4 x 5 inch film. The camera position was adjusted to maintain a similar field of view to that of the 4 x 5 image. The 35 mm. negatives were then magnified to 4 x 5 inches in an enlarger to provide the same total magnification on the final negative as the high signal/noise ratio negatives.
APPENDIX D

METHODS OF PRODUCING AN UNSHARP MASK

Various exposing methods can be used to produce the unsharp mask image. Some methods, however, have inherent deficiencies which make them unsuitable when a systematic analysis of the masking process is to be performed. Several of these methods were investigated before one that would provide the necessary control using available equipment was found. These systems are discussed here in order that the problems existing with each system might be mentioned.

**Collimated Light System**

It was suggested by Yule\(^5\) that the increased magnification associated with the separation of the negative and mask film could be eliminated if a collimated source was used. This method would allow the mask and negative to be contact-printed to produce the final enhanced image; a more convenient method than using a mask-print separation and converging light when making the enhanced image. A large collimating lens could be used to provide parallel light rays over a sufficiently large area. However, an area five inches in diameter was required for exposing 4 x 5 inch film, and hence a 5-inch diameter (or larger)
lens was required. As existing optical equipment was limited, a point source was used at a distance great enough to provide acceptably "parallel" light. The method used for varying the separation between negative and mask was to mount the masking film on a vertically moveable stage and position the negative on a fixed platform above the film, as shown in Figure 23. Separation could then be adjusted by varying the height of the stage above the masking film.

When unsharp mask images were produced using this system, it was noted that a "ringing" effect occurred in the image, caused by the partial coherence of the light source. Unsharpness was also difficult to vary through separations of the negative and mask using this system. At this time, a log-periodic target was also thought to provide reasonable objective measurements of mask blur and MTF. However, closer investigation of the proper use of this target shows that a lens must be present in the system in order to filter the high-frequency information from the square-wave target and produce an effective "log-periodic" sine-wave target. Since this unsharp masking system does not use a lens to cause defocus, the square wave target was inappropriate for use. Thus, the sinusoidal target was adopted for all objective MTF measurements.
Collimated Light Source

Figure 23
Method proposed for controlling the negative-to-film separation using collimated light to maintain unit magnification between the negative and mask.
**Projection System**

Another possible system for producing the unsharp mask is to project the original image through a lens and position the masking film at different heights above the plane of exact focus to produce various degrees of image blur. When producing the enhanced image, the mask would be positioned in the same location relative to the plane of exact focus as it was when exposed. The original negative image would be focused on the print film; the unsharp mask would alter the defocused image beam and produce an enhanced final image.

The major problem inherent with this system is the scattering properties of the mask film. As mentioned in the text, scattering caused by the silver grains will alter the geometric model proposed for the defocus blur and cause severe image degradation rather than enhancement if this scattering occurs to a significant degree. It is felt that with the method mentioned here, the scattering would not be affecting merely a diverging or converging cone of diffuse illumination, but instead causing scattering to occur in an image-forming beam. It is therefore suggested that the affect on the resulting image would be a severe loss of image detail rather than an enhancement, unless non-scattering emulsions were used for the masking film. As suggested in the body of this paper, one possible course for further investigation would be to test the results of unsharp masking systems when low Q-factor emulsions were used for the mask and original negative.
Because of the inherent problems just mentioned, it was decided that the best approach would be to limit the separation between the negative and mask film to minimize the scattering effects, and use a large diffuse source rather than a point source to eliminate the coherence-type effects. The use of a large, diffusing source causes a magnification change in the mask image which must be offset by non-contact printing with the original when producing the final enhanced image. These requirements were satisfied by the masking procedure outlined in this report and as was shown in Figure 13.
APPENDIX E

SENSITOMETRIC TESTING

Processing repeatability is very important for these tests, and hence a means of accurately controlling the amount of agitation, processing solution temperature, and developer characteristics must be used. For these tests a nitrogen-burst apparatus was used to provide repeatable agitation. Stainless steel deep tanks (6" x 8" x 8") were used to hold both developer and fixer solutions. The developing tank was equipped with a "Y-type" gaseous burst pipe fitting on the inside bottom surface of the tank. This fitting has holes uniformly spaced across the pipe to allow nitrogen to be bubbled through the developer to serve as the agitation method. The holes are positioned on the underside of the pipe (which is elevated slightly from the bottom surface of the tank) to produce a more uniform agitation throughout the tank.

For this experiment a Kodak gaseous burst timer and solenoid valve were used and a burst rate of one second every ten seconds used for all tests. The nitrogen pressure was adjusted at three pounds/sq. inch; these conditions were found to give results that simulated the results obtained through continuous agitation of the film in a tray.
It is also very important that the developing tank is level in order for the agitation to be uniform throughout the tank. A change in solution depth across the tank will alter the pressure at the bottom of the tank and produce a non-uniform distribution of the nitrogen bubbles across the tank. Careful levelling was accomplished using shims under the tank and adjustments were made while observing the bubble distribution until uniformity was obtained.

Temperature control was maintained at $68^\circ$ F by using a standpipe in the sink to provide about a six inch depth of water in which the processing tanks were immersed. The water bath was adjusted and maintained at $68^\circ$ using a Kodak temperature control valve. This system gave a developer temperature control of $68^\circ \pm 0.5^\circ$ F, even though the ambient temperature was often less than $55^\circ$ F.

Since it was required to be able to adjust mask and print film contrast over a wide range, extensive development time tests were made using different developers until an appropriate combination was determined. It was found that Kodak developer DK-50, diluted 1:1 with water provided excellent control for mask contrast, while Kodak developer HC-110, dilution A was used with the Contrast Process Ortho film. The experimental data for the film/developer combinations used for these experimental tests are shown in Figures 24 and 25.
Figure 24

Characteristic curve for Kodak Contrast Process Ortho Film, Kodak HC-110 developer, dilution A, 68° F., nitrogen burst agitation; 1 sec. burst every 10 sec.
Figure 24
Figure 25

Characteristic curves for Kodak Pan Masking Film, DK-50 developer, 68° F, nitrogen-burst agitation; 1 second burst every 10 seconds.
APPENDIX F

SUBJECTIVE QUALITY FACTOR

There have been numerous attempts to specify an objective measure of image quality that accurately correlates with subjective evaluations of images. Several methods suggested specify an objective quality ranking based on the area under all or part of the system Modulation Transfer Function. One such quality factor proposed by Granger and Cupery suggests that the region of frequencies to which the eye is most sensitive be used as the bandwidth over which the area under the system MTF is evaluated; image quality is then directly related to this area value and is termed the "subjective quality factor." The spatial frequency region or bandwidth used to determine the SQF value is specified to be between 10 and 40 cycles/mm. as measured at the retina. These values were chosen since they are the region of most significant visual response, as shown in Figure 26. Viewing distance, of course, will significantly alter the spatial frequency region as measured on the image that will produce the desired values at the retina. Hence, the frequency axis in the figure has been scaled in terms of frequencies in cycles/degree as well; this type of scaling is independent of viewing distance.
Figure 26

MTF for the visual system showing Granger's SQF passband. The three scales shown give the frequency scale in terms of:

(a) Cycles/mm. on the retina;
(b) Cycles/degree;
(c) Cycles/mm. on a print viewed at 30 cm.
Also shown is a scale for approximate frequencies on the image if viewed from a distance of about 30 cm., the viewing distance used for the subjective testing discussed in this paper.

Through proper scaling using a log-frequency axis, the frequencies used to determine the subjective quality factor can be easily adjusted to incorporate changes in system magnification. Because of the log-frequency scaling, the frequency region over which the MTF is evaluated remains constant, and is adjusted for magnification changes by a simple sliding of the SQF bandwidth along the log frequency axis. This process provides a simple evaluation of images produced at any level of magnification.

Granger has shown that for grain-free images there is a linear correlation between the area under the system MTF between the specified frequency band and the subjective quality ranking by judges for a wide range of magnifications and MTF shapes. As a result of the work presented in this paper, however, it is noted that it is possible to increase the area under the system MTF to such a degree that the judged estimate of image quality will decrease, although the SQF value continues to increase. Thus, this predictor of image quality must be applied carefully when analyzing images that have been produced with an excessive degree of adjacency effects, or enhanced using techniques of unsharp masking or other means of edge enhancement.
APPENDIX G

MICRODENSITOMETRY

The modulation transfer function (MTF) for both the mask and enhanced images was determined using sinusoidal transmission distributions of varying frequencies as the test objects. The target consisted of 19 frequencies and seven different neutral density areas; this target has been manufactured by the Eastman Kodak Company and is discussed in detail in a paper by Lamberts. Figure 27 shows the target configuration and the values determined for the frequency and density of each target area. Experimentally determined values are shown for selected patches in parentheses, in addition to the values assigned to the patch by the manufacturer. Experimental measurements of the frequency and sinusoidal nature of the target patches were made by scanning the target using a Joyce-Loebl microdensitometer to obtain density vs. position information. After conversion into transmittance values, the sinusoidal fluctuation was verified by graphical comparison of the microdensitometer data and a mathematical sinusoidal model. The results for one frequency value are shown in Figure 28. The frequency values determined experimentally agree with the published data. The modulation of the
Figure 27

Scheme of test object used for the objective MTF analysis. The figures for the sinusoidal targets indicate the specified and (experimentally determined) frequency values in cycles/mm. Values for the gray scale patches indicate nominal net density above base + fog.
Figure 28

Experimental (○) and calculated (----) values for sinusoidal transmittance vs. distance distribution. Modulation = 0.7, average transmittance = 18.5%.
sinusoidal targets was determined through measurement to be 0.70; the published value is stated as "about 65% for all but the very highest spatial frequencies." Again, there is satisfactory agreement between these values.

After exposure and processing of the mask, enhanced target images, and normally exposed (non-masked) target images, the MTF was determined through the following procedure:

1. Selected frequency values were measured using the Joyce-Loebl microdensitometer adjusted with the following conditions:

   For .75 and 1.5 cycles/mm.
   50:1 magnification arm
   20 x Bausch and Lomb 0.40 N.A. efflux objective

   For 3 and 6 cycles/mm.
   200:1 magnification arm
   20 x Bausch and Lomb 0.40 N.A. efflux objective

   For 12, 18, and 24 cycles/mm.
   500:1 magnification arm
   50 x Bausch and Lomb 0.85 N.A. efflux objective

   Wedge Gradient
   0.043 density units/cm. for all mask images
   0.131 density units/cm. for enhanced and non-masked images.
Scanning Slit

All measurements were made using actual slit dimensions of 0.5 mm. x 17 mm. The effective slit dimensions will vary with image magnification.

2. Step tablet exposures were produced at the same time as the sinusoidal exposures and these were scanned to determine machine density vs. macro-density information; a typical graph is shown if Figure 29. From this data, a machine q-factor value was determined for each film and efflux objective used.

3. Maximum and minimum density values were determined through measurements made on the microdensitometer traces, and these values checked to insure that both exposure levels were produced on the straight-line portion of the film response curve.

4. Output modulation and MTF were then derived for each sample using the following procedure:

   a. Measure the distance between maximum and minimum on the microdensitometer trace, $\Delta H$.

   b. Convert to machine density difference, $\Delta D_{\text{machine}}$:

      $$\Delta D_{\text{machine}} = (\Delta H) \times \text{(wedge gradient)}$$

   c. Convert to diffuse density, $\Delta D_{\text{diffuse}}$:

      $$\Delta D_{\text{diffuse}} = (\Delta D_{\text{machine}}) \times \text{(q-factor)}$$
Figure 29

Calibration curve for conversion of the Joyce-Loebl microdensitometer density values into diffuse density values. Curve shown is for Contrast Process Ortho film; an "F-wedge" was used in the microdensitometer.
d. Convert to a log-exposure difference, $\Delta \text{Log-H}$:

$$\Delta \text{Log-H} = \frac{(\Delta D_{\text{diffuse}})}{(\gamma_{\text{macro}})}$$

e. Determine output exposure modulation, $M_{\text{out}}$:

$$M_{\text{out}} = \frac{10^{(\Delta \text{Log-H})} - 1}{10^{(\Delta \text{Log-H})} + 1}$$

f. Determine the system MTF:

$$\text{MTF} = \frac{M_{\text{out}}}{M_{\text{in}}}$$

where $M_{\text{in}} = 0.70$.

Following are the machine q-factor values for the films used in this experiment:

<table>
<thead>
<tr>
<th>Film</th>
<th>Machine q-Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kodak Pan Masking Film</td>
<td>1.08</td>
</tr>
<tr>
<td>Kodak Contrast Process Ortho Film</td>
<td>1.23</td>
</tr>
<tr>
<td>Kodak Commercial Film</td>
<td>1.18</td>
</tr>
<tr>
<td>Ilford FP-4 Film</td>
<td>1.10</td>
</tr>
</tbody>
</table>

Consult Appendix E for information pertaining to the characteristic curves for the films used in these tests.
Larry Scarff received his undergraduate and graduate education in Photographic Science at the Rochester Institute of Technology from 1974 to 1977. Prior to attending R.I.T. he attended Moorpark College in Moorpark, California from 1972 to 1974 as a Physics major.

After completion of his coursework at R.I.T. he became an instructor in the Photographic Science Division of R.I.T. and held the rank of Lecturer until his departure in June, 1981 after completion of his M.S. thesis. During this time, he taught courses in introductory photographic optics; sensitometry; tone reproduction; radiometry and photometry; and color photographic systems. His current position is Photographic Scientist/Engineer with the Itek Corporation, Optical Systems division, in Lexington, Massachusetts.

Born in North Hollywood California on May 18, 1954, Larry and his wife Deborah were married in 1979 and are both United States citizens.