Abstract. Any image acquired by optical, electro-optical, or electronic means is likely to be degraded by the environment. The resolution of the acquired image depends on the total modulation transfer function (MTF) of the system and the additive noise. Image restoration techniques can improve image resolution significantly; however, as the noise increases, improvements via image processing become more limited because image restoration increases the noise level in the image. We characterize the influence of the MTF and noise level on human target acquisition probability to ascertain the advantages, if any, of image restoration. Conditions when restoration would be advisable are determined. © 1998 Society of Photo-Optical Instrumentation Engineers. [S0091-3286(98)01007-1]

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1 Introduction

Image restoration techniques have been developed to improve the quality of images degraded by distortion and noise. The measure for comparing the improved image to the original degraded one is dependent on the task to be performed. We consider whether image restoration is worthwhile for human subjects performing target acquisition (in particular, target recognition) in real-world scenarios, using electro-optical equipment.

Two types of limits to the recognition capability of a human observer can be considered: limits caused by degraded contrast and limits caused by noise. In contrast-limited imaging, the maximum usable spatial frequency \( f_{r \text{ max}} \) is determined from the model shown in Fig. 1. Contrast deriving from the overall system modulation transfer function (MTF) is limited by the threshold contrast of the observer at the output.\(^1\) An object or target can be resolved if contrast between it and the background is greater than the threshold contrast required at the output.

A second limitation is due to noise. Noise-limited images are usually characterized by random “snow” over the display, against which the object or target is to be resolved. Target resolution is thus limited by noise. As the signal-to-noise ratio (SNR) increases, the snow gradually is less evident and smaller detail is resolved.\(^2\) The intersection of the display SNR with the required SNR determines \( f_{r \text{ max}} \) for noise-limited imaging (Fig. 2).

In reality, since both noise and distortion are present in a system, we can be limited by each effect, although one will normally be dominant. Low brightness signals in IR images with considerable noise will be noise limited. This occurs when \( f_{r \text{ max}} \) in Fig. 1 is larger than \( f_{r \text{ max}} \) in Fig. 2. If we imagine the target signal rising, the noise will be less significant. At some point, contrast-limited imaging will have been achieved. This corresponds to a situation in which \( f_{r \text{ max}} \) in Fig. 1 is smaller than \( f_{r \text{ max}} \) in Fig. 2.

The purpose of this paper is to determine when image restoration can improve the probabilities of target acquisition. Image restoration improves the sharpness of an image from any distortion present, however, since image restoration increases noise, it is possible for a restored image to be poorer than its original, particularly for noise-limited imaging. Thus, the use of restoration may be, but does not have to be, beneficial. We performed two experiments. Our first experiment was to ask observers to compare restored and nonrestored images. Experimental results showed that no observer felt that restoration harmed resolution, no matter how poor the SNR was; on the other hand, restoration did not help with regard to noise-limited images, which had very little distortion, but did help with regard to contrast-limited images, which had significant blur. Since the first
turbulence parameters image depending on the isoplanatic patch, according to the frequencies and to produce wavefront tilt, which causes time exposures is to produce image blur at high spatial frequencies.

Atmospheric blur derives from both turbulence and aerosol plumes. The improvement due to restoration was accomplished by comparing the number of correct answers in both restored and unrestored scenarios.

2 Atmospheric MTF

Atmospheric blur derives from both turbulence and aerosol phenomena. The effect of the turbulent medium over long-time exposures is to produce image blur at high spatial frequencies and to produce wavefront tilt, which causes image shifts, either of the whole image or of parts of the image depending on the isoplanatic patch, according to the turbulence parameters (turbulence strength and inner and outer scales). The image distortions caused by the wavefront tilt (typically of the order of tens or hundreds of microradians) can be partially compensated for either by adaptive techniques or by using a sufficiently short exposure time, less than the characteristic fluctuation time (usually a few milliseconds). A wavefront sensor to construct the atmospheric phase transfer function in addition to image intensity can be used with adaptive optics techniques to sense an undistorted image. However, simple digital image restoration can be used with an atmospheric Wiener filter to reduce and even remove effects of turbulence by enhancing the image at high spatial frequencies selectively; this enhances primarily the high-spatial-frequency content of the image least affected by turbulence, thus restoring the image. This technique corrects simultaneously for aerosol blur as well.

The MTF of atmospheric turbulence for long exposures of spherical waves is given by

$$\text{MTF}_T = \left(-57.53 \Omega_r^{5/3}\lambda\right) \lambda^{-1/3} \int_0^\infty C_n(z) \left(\frac{z}{L}\right)^{5/3} \mathrm{d}z,$$

where $\Omega_r$ is angular spatial frequency, $\lambda$ is wavelength, $L$ is the length of the atmospheric path, and $C_n^2$ is refractive-index structure coefficient.

Aerosols cause light scatter, including that at small angles such as hundreds of microradians. This resulting image blur is described by the MTF:

$$\text{MTF}_a = \begin{cases} \exp\left[-\int_0^L (A_a+S_a) \left(\Omega_r / \Omega_c\right)^2 \mathrm{d}z\right], & \Omega_r \leq \Omega_c \\ \exp\left[-\int_0^L (A_a+S_a) \mathrm{d}z\right], & \Omega_r > \Omega_c \end{cases},$$

where $A_a$ and $S_a$ are absorption and scattering coefficients, respectively, and $\Omega_c$ is the cutoff angular spatial frequency, determined by system and/or aerosol parameters.

3 Image Restoration Techniques

Restoration of distorted images has long been a difficult challenge. The majority of image restoration algorithms require some knowledge about the degradation process and associated parameters. These include the classical Wiener filter restoration techniques and the more recent iterative restoration algorithms. Such information is not always available and the restoration results are found to be highly dependent on the optical transfer function (OTF) and on the accuracy with which its parameters are identified from the degraded image. (The OTF is the frequency response, in terms of spatial frequency, of an optical system to sinusoidal distributions of light intensity in the object plane; the OTF is the amplitude and phase in the image relative to the amplitude and phase in the object as a function of frequency, when the system is assumed to respond linearly and to be space invariant.)

3.1 Mathematical Model of Image Blurring

We assume that the blurring process can be modeled as a spatially invariant linear system. The blurred image $g(x,y)$ is equal to the convolution of the object intensity function $f(x,y)$ and the point spread function (PSF) $h(x,y)$ of the blurring system. Since the critical effect is the atmospheric degradation, the PSF is the result of the atmosphere only. The noise $n(x,y)$ is modeled as additive. The degraded image can be written as

$$g(x,y) = \int \int h(x-x', y-y') f(x',y') \mathrm{d}x' \mathrm{d}y' + n(x,y).$$
The most important stage for the restoration is modeling the PSF according to the real nature of the blur. When information is available about the forms of the degradation present in an image, restoration techniques can be employed for correction. It is important that a good model of the degradation be available.

The method for restoration that was used here is based on the conventional Wiener filter. For the quantitative analysis of target acquisition, the approximate form of the Wiener filter was used, i.e.,

\[ M(u,v) = \frac{H^*(u,v)}{H(u,v)H(u,v) + 1/\text{SNR}}, \]

where \( H(u,v) \) is the atmospheric MTF as a function of spatial frequencies \( u \) and \( v \), and SNR was used as the investigated parameter. Although the atmospheric Wiener filter developed in Ref. 5 yields better restoration results, the use of a simpler conventional Wiener filter was justified here since we are interested in whether restoration is worthwhile at all. The specific restoration algorithm can be refined in further research.

## 4 Experiment Description

The preceding formulation successfully restores degraded images to which noise has been added. These MTFs are actual atmospheric modulation transfer functions, where we have taken into account the distortion caused by aerosol particles as well as the distortion caused by long exposure to the turbulence. The aerosol MTF parameters used for light aerosol loading are as follows: a scattering coefficient equal to 0.1 km\(^{-1}\), an absorption coefficient equal to 0.01 km\(^{-1}\), and a cutoff frequency equal to 10 cycles/mrad. The line-of-sight was assumed to be a 6.5-km horizontal path.

Additive Gaussian noise was added and the restorations were performed with a standard Wiener filter. We conducted two experiments involving observers: a qualitative experiment comparing restored and nonrestored images and a quantitative experiment measuring target recognition.

### 4.1 First Experiment: Image Restoration Quality

The method used to check the extent of improvement achieved by restoration was similar to that presented recently by Copeland et al. Each pair of pictures (of a parking lot, taken by a regular camera and scanned by the computer, as seen in Fig. 3), one before restoration and one after, was presented to observers. Observers were asked to indicate in which image they believed a chosen target was easier to detect. In this way, the improvement or lack of it by restoration became apparent. Images were presented on a computer screen to the subjects. Figure 3 show one of the sample images. Figure 3(a) shows a scene under the conditions of light aerosol loading with moderate turbulence; (MTF1 in the first experiment). Figure 3(b) is the restored image.

The first experiment included the MTF that represented situations where \( \sigma_n = 4 \times 10^{-15} \), \( \sigma_n = 4 \times 10^{-16} \), \( \sigma_n = 4 \times 10^{-17} \), and \( \sigma_n = 1.3 \times 10^{-17} \) m\(^{-2}\) (\( \sigma_n \) characterizes the turbulence strength; larger \( \sigma_n \) implies heavier turbulence and greater distortion).

### 4.2 Second Experiment: Checking Image Restoration Quantitatively

The second experiment included MTFs that represented situations where \( \sigma_1 = 5 \times 10^{-15} \), \( \sigma_2 = 1 \times 10^{-15} \), \( \sigma_3 = 5 \times 10^{-16} \), \( \sigma_4 = 1 \times 10^{-16} \), \( \sigma_5 = 5 \times 10^{-16.5} \), and \( \sigma_6 = 5 \times 10^{-17} \) m\(^{-2}\) were labeled MTF6, MTF5, MTF4, MTF3, MTF2, and MTF1, respectively. To each image, a different amount of Gaussian noise (randomly generated by the computer) was added. The method used to check the extent of improvement achieved by restoration was by asking viewers to recognize Latin letters in different sizes from a synthetic image of letters arranged in a square matrix (shown in Fig. 4), from both distorted and restored images. The letters represent a quantitative means of considering recognition of targets at different distances. We recorded the number of right answers in each case, both for all matrix letters and for each letter size (each row). To achieve maximum reliability, we changed the letters in each trial.

It is known that detection/recognition can be limited in two ways: either by limited resolution or by excessive noise. When restoring images, one generally increases the noise while sharpening the image. If an image was initially limited by the noise, restoration will not help (and may well hurt) target acquisition capability. On the other hand, if an image is contrast-or blur-limited, then the restoration should help.

## 5 Results

Analysis of the data confirmed many of our theories about the effects of noise on target acquisition. Restoration did not play as large a part in target acquisition when noise was at its highest levels; however, it did help substantially when noise was minimal and distortion levels were high.

For our analysis, we looked separately at large and small targets (fonts 8 to 12 were classified as “small” and fonts 14 to 20 were classified as “large”). The justification for this grouping of the data lies in the inherent ability of people to recognize large targets more easily than small ones. Hence, comparing the performance levels of acquisition of large targets to those of small targets could not be supposed to be informative. A \( t \) test confirmed this supposition with mean score yield for rows with large targets being 3.6 and the mean for small targets being 2.6 [\( t(2878) = 7.53; p < 0.01 \)]. We averaged the performance scores per subject in each target condition (i.e., noise level, distortion level, and restoration condition), for the small and large targets, yielding an average score for each type of target. We used this average score for our analysis of the data.

A three-way analysis of variance (ANOVA) was run [restoration(2)×noise(5)×distortion(6), with the dependent variable treated as a repeated measure] to determine the effects of the various target conditions on acquisition performance. For the small targets (fonts), restoration alone did not have an appreciable effect on target acquisition performance [\( F(1,5) = 0.05; p = 0.83 \)]. In contrast, restoration alone did have a significant impact on target acquisition scores for large targets [\( F(1,5) = 9.9; p = 0.03 \)].

Since restoration adds noise, we were interested to see at what point, if any, the addition of noise by the restoration process would denigrate performance. The interaction be-
tween noise and restoration for both small and large targets was significant \[ F(4,20) = 22.4; \ p < 0.01 \] and \[ F(4,20) = 11.9; \ p < 0.01 \], respectively. Interestingly, the effect of restoration on target performance was not consistently negative or positive. As seen in Figs. 5 and 6, at the lower noise levels, restoration had a positive effect on score; at higher levels of noise, restoration had a negative effect. This was most noticeable with the small targets.

What looked like a negative effect of restoration, however, was not really related to actual large performance score differences. At the higher noise levels, the actual difference in the means of the scores before restoration compared with after restoration (0.1 at noise level 5 and 0.2 at noise level 4) were values of much less than 1. Since scoring was in whole numbers, this means that the subjects did not discriminate substantially more targets before restoration than after restoration. Essentially, at high noise levels, it was so noisy that hardly any targets were discriminated at all. Out of a perfect score of 8, the mean scores for all target sizes were, respectively, for noise levels 1 to 5 as follows: 6.6, 6.0, 1.8, 0.8, and 0.4.

Since the higher levels of noise so drastically impaired acquisition performance, for our study of how restoration affected target acquisition performance at different distortion levels, we confined the data for our analysis to the three lower levels of noise. A three-way ANOVA

**Fig. 3** Some first-experiment images: (a) an atmospheric MTF used, (b) original image, (c) degraded image, and (d) restored image.
Fig. 4 Some second-experiment images: (a) original image, (b) degraded image, (c) restored image, and (d) an atmospheric MTF used.

Fig. 5 Restoration effects at different noise levels for small targets.

Restoration effects at different noise levels for small targets
2-way interaction
F(4,20)=22.36; p<.0000

Fig. 5 Restoration effects at different noise levels for small targets.
[restoration(2)×noise(3)×distortion(6)] was performed with performance score treated as a repeated measure.

For small targets, distortion alone had a significant effect on target acquisition performance \(F(5,25) = 953.5; p < 0.01\). The interaction between restoration and distortion was also significant \(F(5,25) = 11.1; p < 0.01\). This means that restoration effects on acquisition performance were different depending on distortion level. As seen with noise, at some distortion levels, restoration was significantly helpful with target acquisition performance, while at others, there was a negative effect (see Fig. 7).

For large targets as well, distortion had a significant effect on target acquisition performance \(F(5,25) = 702.2; p < 0.01\). Here, too, restoration, when interacting with distortion, was significant \(F(5,25) = 9.3; p < 0.01\). Acquisition of large targets, however, was facilitated to some degree by restoration at all distortion levels (see Fig. 8).

We were interested to see that at lower levels of distortion, restoration had less of a positive (for small targets even a slightly negative) effect on performance, while at higher levels of distortion, restoration was a plus. Juxtaposed to this, in interaction between restoration and noise, restoration had a positive effect at the lower levels of noise and was problematic at the higher levels. We were, thus, interested to see the interaction between noise and distortion in their effect on performance. Figures 9 and 10 illustrate the interaction between noise and distortion for small and large targets, respectively. Notice that distortion has almost no effect on performance at the lowest levels when there is little noise present. This is especially true for the large targets, which apparently are easily discriminable even through the fourth level of distortion at the lowest level of noise. Noise is most effective at lowering performance, even for large targets (as noted earlier when we
discussed removing the two highest levels of noise for some of the analysis. Distortion approaches the level of noise’s debilitating effect on performance only at its highest level (6) for large targets.

Interaction of all three factors at all levels [restoration(2)×noise(5)×distortion(6)] in their effects on target acquisition performance was found to be significant for both small and large targets. The three-way interaction of restoration, noise, and distortion is graphically illustrated in Fig. 11 for small targets and in Fig. 12 for large targets.

6 Discussion and Conclusions

In our experiments, we expected that for high levels of atmospheric degradation and low levels of noise (contrast-limited imaging), the restoration would be beneficial. For low levels of turbulence and high levels of noise (noise-limited imaging), we suspected the restoration might not help and might even hinder target acquisition because of increased noise. Our experiments were performed to check these predictions and to yield quantitative information as to the parameters where observer performance changes from being noise-limited to contrast- or distortion-limited.

This can be explained through the nature of the Wiener filter: the Wiener filter is MTF dependent (according to spatial frequency dependence) and as such, for high and moderate distortion levels and all noises, its influence is high. Therefore the restored image is better than the degraded one (see MTF4, MTF5, and MTF6 in Figs. 7 and 8). But when decreasing the distortion, for low SNRs, the Wiener filter becomes less dominant [i.e., the Wiener filter both restores the image (signal) and increases the noise]. Thus, its correction is minor and the restored image is worse than the degraded one (note especially MTF2 in the noise 4 graph of Fig. 11). This phenomenon is present for
Effects of distortion and noise on performance - large targets

Fig. 10 Effects of noise and distortion on performance for large targets.

Restoration effects, given noise and distortion levels - small targets

Fig. 11 Restoration effects for given noise and distortion levels for small targets.

Restoration effects, given noise and distortion levels - large targets

Fig. 12 Restoration effects for given noise and distortion levels for large targets.
weak MTFs and heavy noise (small SNRs). For high SNRs, restoration improves recognition probabilities. Being spatial frequency dependent, the Wiener filter restorations affected letters that contained high spatial frequencies, i.e., small letters, making their restoration less beneficial when the SNRs are low and distortion is weak as opposed to the same cases for larger letters.

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References


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