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AN IMAGE RESTORATION EXPERIMENT ON TURBULENCE-DEGRADED IMAGES

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TABLE OF CONTENTS

Page

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INTRODUCTION

The transmission of an image through turbulent media degrades the quality of the final image formed by an optical system. This degradation causes a loss of the information contained in the image (in the context of information theory) and an increased difficulty of extraction of the remaining information by the human observer. The information-content loss is irretrievable. However, the image can be processed so that the remaining information is more easily interpreted by the human visual system. The Visibility Laboratory of the University of California is engaged in a research program to find suitable methods of processing images degraded by turbulent media. This research is sponsored by the Advanced Research Projects Agency through contract NObs-92058 between the University of California and the Bureau of Ships.

The work described here is a continuation of that reported by Harris.[1] Specifically this report deals with the processing of turbulence degraded images formed in the laboratory for the case in which

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[1] J. L. Harris, Restoration of Atmospherically Distorted Images, Progress Report (Scripps Institution of Oceanography, San Diego, SIO Ref. 63-10.)

the modulation transfer function is well known. Two types of image degradations will be treated: time-invariant and time-variant. Time-invariant images are those in which each image has been recorded over a long period of time so that consecutively recorded images appear identical. Time-variant images are those in which each image is recorded in a short period of time so that consecutively recorded images have undergone different degradations. The basic theory of the method of restoration will now be discussed.

The method of processing is based on theory given by Harris[2]. The following terminology is used. The ideal image is represented by $H(x, y)$. It is the irradiance map formed in the image plane of the optical system when no turbulence is present. The degrading effect of the turbulence is characterized by $S_I(x, y)$, the input point spread function. $S_I(x, y)$ is the image plane irradiance map formed when the object is a point source and when the turbulence is present. The Fourier transform of $S_I(x, y)$ is the modulation transfer function. For the time-invariant case $S_I(x, y)$ does not change from one recording to the next; for the time-variant case it does. The effect of the turbulence is to degrade the ideal image, resulting in $H_I(x, y)$, the input image.

Let $F\left[f(x, y)\right]$ denote the Fourier transform of $f(x, y)$. F is, in general, a complex quantity carrying both amplitude and phase information. If the optical system is linear and homogeneous, a simple relationship exists between the Fourier transforms of $H(x, y)$, $S_I(x, y)$ and $H_I(x, y)$:

$$F\left[H(x, y)\right] = \frac{F\left[H_I(x, y)\right]}{F\left[S_I(x, y)\right]} . \qquad (1)$$

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[2] J. L. Harris, Image Evaluation and Restoration, J. Opt. Soc. Amer. 56, (1966).

H(x, y) can then be found by taking the inverse transform.

$$H(x, y) = F^{-1}\left\{ F\left[H(x, y)\right] \right\} = F^{-1}\left\{ \frac{F\left[H_I(x, y)\right]}{F\left[S_I(x, y)\right]} \right\} . \qquad (2)$$

Equation (2) represents one of the most direct methods of image processing. It requires a knowledge of the input point spread function (or, equivalently, the modulation transfer function) of the degrading parameter at the time the image is recorded. The limitations of this method are imposed by the ability to know the point spread function with sufficient precision and by the presence of noise in the recorded image.

The point spread function may be known from previous knowledge (in the time-invariant case) or it may be obtained by including in the field of view of the optical system an object whose ideal image is known. The input image of this known object is recorded at the same time as the input image of the unknown object. Let the subscript K denote the known object and the subscript U denote the unknown object. The input image of the known object, for example, is then $\left[H_I(x, y)\right]_K$. From Eq. (1) $S_I(x, y)$ can be found by use of the known object.

$$F\left[S_I(x, y)\right] = \frac{F\left[H_I(x, y)\right]_K}{F\left[H(x, y)\right]_K} \qquad (3)$$

The $F\left[S_I(x, y)\right]$ found from the known object can now be applied to the unknown object. From Eq. (2):

$$\left[H(x, y)\right]_U = F^{-1}\left\{\frac{F\left[H_I(x, y)\right]_U}{F\left[S_I(x, y)\right]}\right\}$$

$$= F^{-1}\left\{\frac{F\left[H_I(x, y)\right]_U \qquad F\left[H(x, y)\right]_K}{F\left[H_I(x, y)\right]_K}\right\} \tag{4}$$

This is the equation which describes the processing used on the turbulence degraded objects to be shown later in the report. In the actual processing the Fourier series, rather than the transform, was used. Equation (4) is an operation applied separately to each frequency term of the Fourier series.

EXPERIMENTAL PROCEDURE

Figure 1 is a block diagram of the entire process from generation of the turbulence-degraded pictures to the processed image.

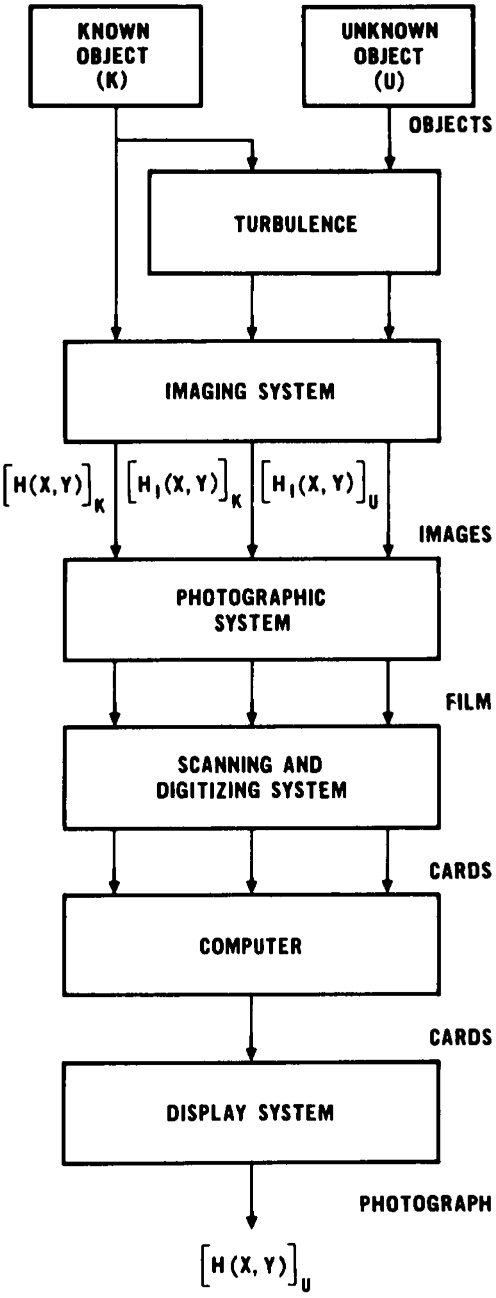


Figure 1

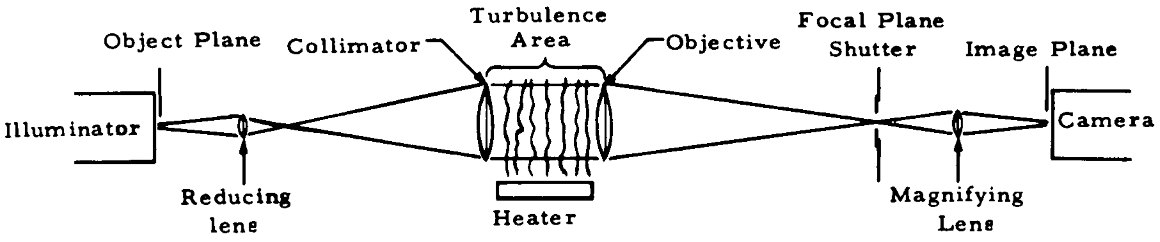


Fig. 2. Optical System for Generating Turbulence Distorted Images.

The optical system is shown in detail in Fig. 2. A reduced image of the objects to be degraded was formed, and the image was effectively put at infinity by a collimating lens. The "unknown" image was a numeral 5, and the "known" image was a small pinhole. The angular height of the numeral 5, as measured after collimation, was 40 seconds of arc. The pinhole was 4 seconds of arc in diameter, and the separation of the numeral and pinhole was 200 seconds of arc. The turbulence area was between the collimator and objective lens and was 20 inches long. Both lenses were of 90 inches focal length, and the objective was stopped to a diameter of 4 inches. As can be seen from Fig. 3, flux from both objects passed through the same tube of turbulence within .02 inches out of a total diameter of 4 inches. Thus the point spread function was, for practical purposes, constant over the objects.

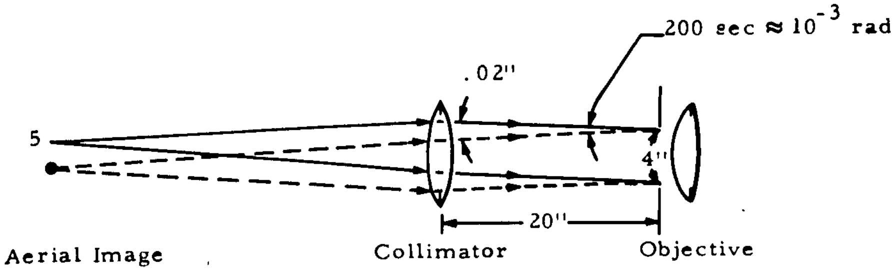


Fig. 3. Representation of the paths of flux through the turbulence area from the outermost points on the objects.

The objective lens formed the degraded images in its focal plane from which they were imaged with a magnification of four onto the film plane of a 35 mm camera. The time-invariant images were recorded on Plus-X film at one-minute exposure times. The time-variant images were recorded on TRI-X film at 5 milliseconds. Flux levels were adjusted for optimum exposures in both cases. In addition, gray scales were printed onto the film for determination of the film H and D curve.

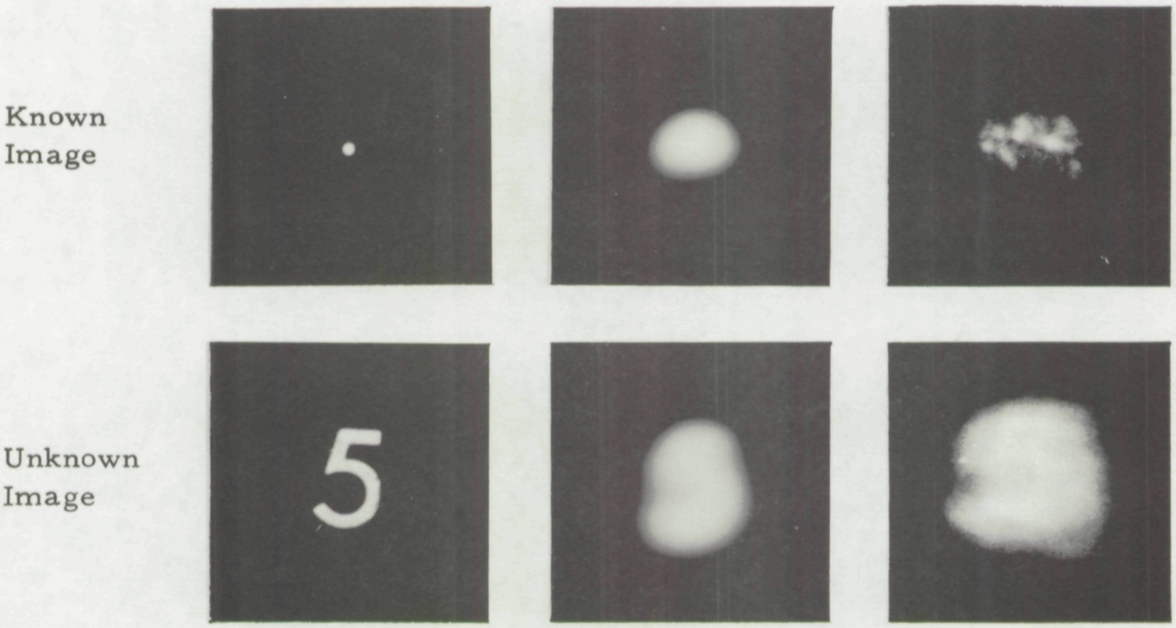
Following photographic processing, the transparencies were scanned by a system which recorded the two-dimensional transmission characteristics on punched cards. The transmission values were measured at intervals .1 mm apart. The recorded unknown object in the absence of degradation was about 2.0 mm high on the transparency. Thus there were about 20 resolution elements across the image. The H and D curve was also obtained by scanning the gray scale transparency.

The card decks were processed on a CDC 3600 computer. The first step was to transform the data via the H and D curve into data representing positive images. A two-dimensional Fourier analysis was then performed on the three positive images, representing: the known ideal image, the known degraded or input image, and the unknown degraded or input image. The modulation transfer function was found from the first two and applied as correction factors to the unknown degraded image. An inverse Fourier transformation was then made, and a deck of cards representing the luminance values of the restored unknown image was punched out. These cards were read by a system which produced a photographic print of the restored images. The scanning and reconstruction systems are described in more detail in references [1] and [2].

In making the restorations the number of terms of the Fourier series used in the reconstruction process was varied to produce pictures whose maximum spatial frequencies were 2, 3, and 5 cycles per millimeter. This was done for the following reason. The potential ability to distinguish fine detail increases as higher spatial frequencies are used in the restored image. However, in the degraded images the attenuation and phase shift of spatial frequencies due to turbulence tends to increase with increasing spatial frequency, resulting in higher correction factors for the higher frequencies. Noise, which is present in some degree in the original input images, is more greatly amplified at the higher spatial frequencies in the restored image. In this system the noise is due to film graininess and fluctuations in the scanner system. Therefore, the gain in resolving power obtained by adding higher spatial frequencies is gradually offset by the increase of spurious components (noise) in the final picture. By reconstructing the picture for various maximum values of spatial frequency a compromise between resolving capability and noise can be subjectively chosen.

EXPERIMENTAL RESULTS

Figure 4 shows the undistorted objects and the time-invariant and time-variant turbulence-degraded images. The processed images are shown in Fig. 5 for the various maximum spatial frequencies. Figure 6 shows the time-variant restoration at 3 cycles per millimeter with the background clipped so as to provide a high contrast picture.

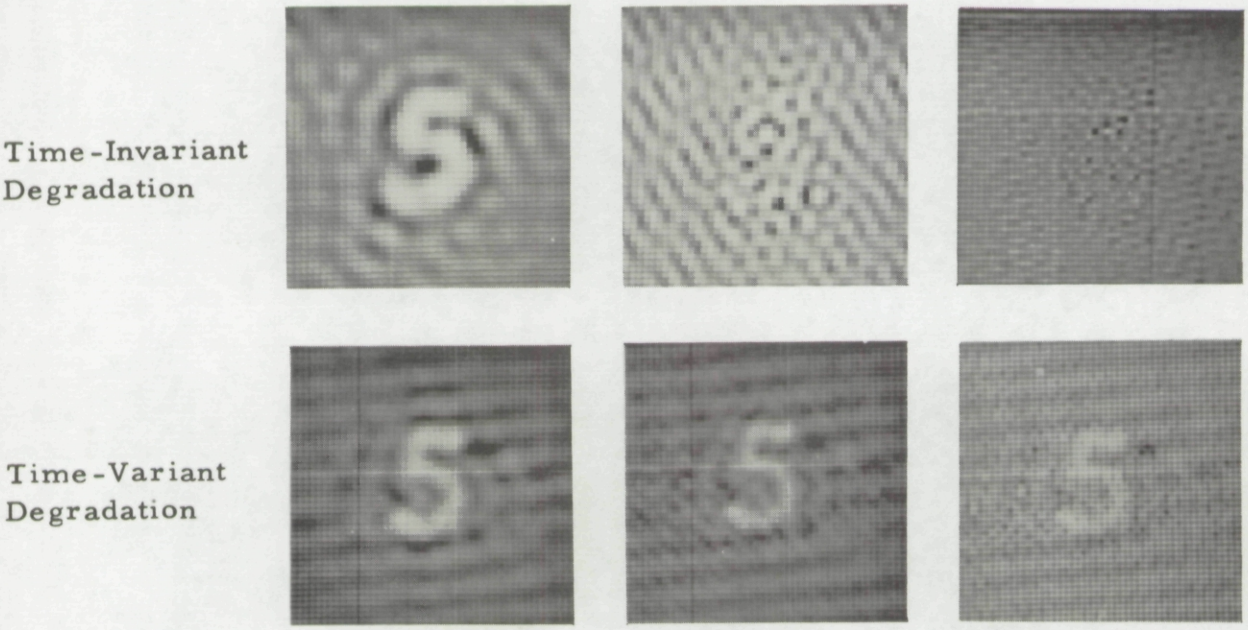


a) Undegraded Images

b) Time-invariant Degraded Images

c) Time-variant Degraded Images

Figure 4. The undegraded and turbulence-degraded images.



a) 2 cycles per millimeter

b) 3 cycles per millimeter

c) 5 cycles per millimeter

Figure 5. The time-invariant and time-variant turbulence-distorted images restored with maximum spatial frequencies of 2, 3, and 5 cycles per millimeter.

Figure 6. The time-variant turbulence-degraded image restored with a maximum spatial frequency of 3 cycles per millimeter and with the background removed.

DISCUSSION OF RESULTS

Comparison of Fig. 4 and Fig. 5 show that the processing resulted in a significant improvement of the quality of the unknown image. For the restorations having a maximum frequency of 2 cycles per millimeter the results for the time-variant and time-invariant cases are approximately equivalent. At 3 cycles per millimeter the time-variant restoration is obviously superior. At 5 cycles per millimeter, which is the maximum reproducible frequency due to the scanning process, the time-invariant restoration is completely obscured while the time-variant restoration is quite clear. The reason for these differences can be understood by considering the amplitude and phase corrections applied to the spectra of the distorted images. These are shown in Fig. 7 and Fig. 8.

Figure 7 shows the amplitude restoration factors applied to the horizontal frequencies of the degraded unknown images. These factors are the reciprocal of the amplitude of the modulation transfer function.* Comparison of the two curves shows that for increasing spatial frequencies the time-invariant case required much higher restoration factors than did the time-variant case. For the restorations at 5 cycles per millimeter the time-invariant case had factors up to 2600, while the time-variant case factors were up to only 110. Thus the time-invariant restorations were

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*A non-linearity, probably in the correction for the film H and D characteristics, caused the fundamental frequency of the modulation transfer function for the time-variant case to have a value greater than unity. A partial correction was made by normalizing this frequency to unity. Therefore, the restoration factors for the time-variant case shown in Fig. 7 should be considered to be approximate values.

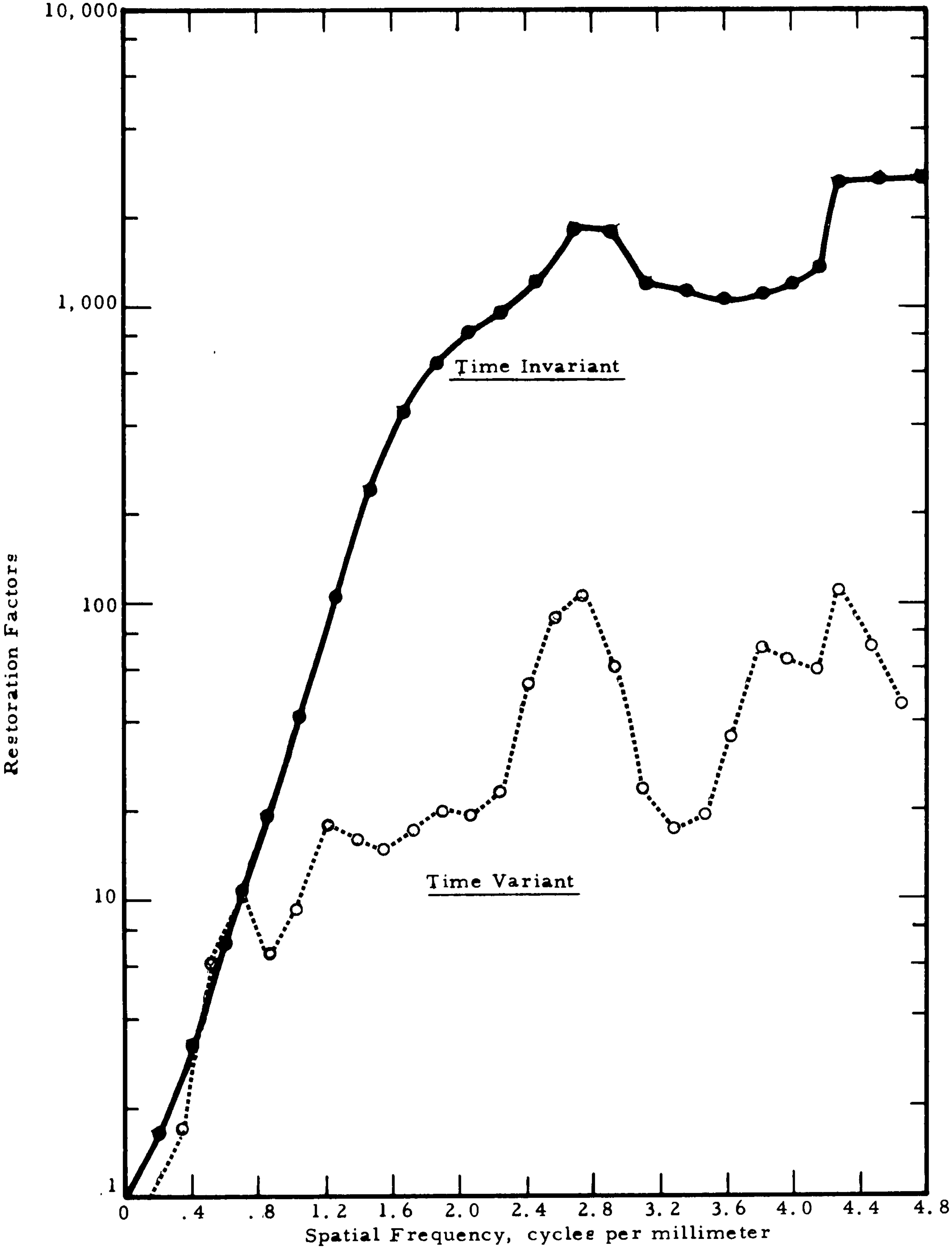

Fig. 7. Comparison of restoration factors for the time-invariant and time-variant images.

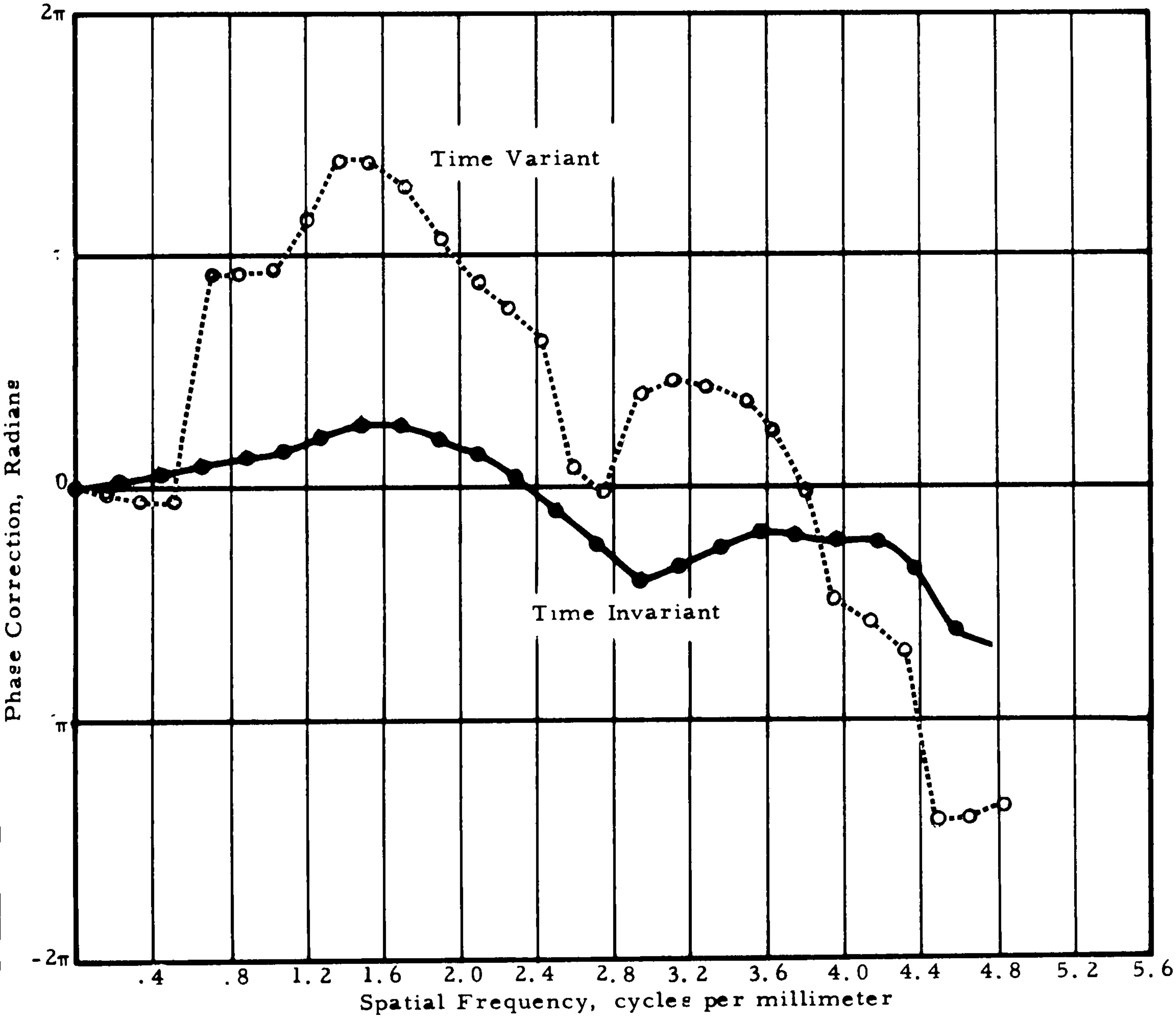

Fig. 8. Comparison of Phase Corrections for the Time-Invariant and Time-Variant Image.

much more susceptible to the effects of noise.

Figure 8 shows the corrections applied to the phases of the horizontal frequencies. These are the negatives of the phases of the modulation transfer function. In general, the time-invariant case had phase shifts much smaller than that of the time-variant case.

Figures 7 and 8 point out an important change in the type of image degradation due to turbulence when exposure time is varied. Specifically, the effect of the turbulence for short exposures can be to cause moderate amplitude attenuations and large phase shifts while for long exposures the effect is to cause high amplitude attenuations and relatively low phase shifts. This result can be explained by considering a single frequency of the modulation transfer function for the time-variant case. The amplitude and phase of this frequency can be represented by a vector. If the behavior of this vector as a function of time could be observed, its amplitude and phase would be found to fluctuate. If many of these vectors were added together, corresponding to recording an image over a longer period of time, and if the vector sum were divided by the number of vectors added together, then the resultant vector would have a length shorter than the mean length of the individual vectors. The division by the number of individual vectors corresponds to maintaining a constant exposure. Thus the effect of increasing the exposure time is to cause a reduction in the amplitude of the modulation transfer function. If the exposure time is increased sufficiently to approach the time-invariant case, then the phase of the resultant vector will approach the mean of the individual vectors.

In terms of signal-to-noise ratio a small amplitude attenuation and a large phase shift is more favorable than a large amplitude attenuation and a small phase shift. Thus for a given optical system with a fixed entrance pupil, the exposure time should be as short as possible, consistent with flux requirements for good recording. In the case where the entrance pupil diameter and the exposure time are both variable and a limited amount of flux is available, then the choice of the optimum pupil-diameter-time combination becomes more complex, since there is a spatial integration effect over the entrance pupil which also affects the modulation transfer function.

CONCLUSIONS

The results of this experiment show that a dramatic improvement of the quality, as assessed by the human visual system, of a turbulence-degraded image can be obtained by processing the image after its initial recording. The experiment also shows that greater improvements are possible when, for a fixed optical system, the exposure time used in the initial recording is kept as short as possible consistent with flux requirements. These conclusions are based upon processing involving detailed knowledge of the m. t. f. of the system for each recording.

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13 ABSTRACT

This report describes an experiment in which processing techniques were applied to turbulence-degraded images to improve their visual image quality. The initial objects were photographed through laboratory-generated turbulence. The resulting transparencies of the degraded images were digitized by a photoelectric scanner, recorded on punched cards, and processed on a digital computer. The processing consisted of applying corrections to the amplitude and phase coefficients of the two-dimensional Fourier series representing the degraded images. The correction factors were obtained from the point spread function of the turbulence measured at the time the images were photographed. The processed data was used to generate photographs of the restored images. The experiment was done for 5-millisecond and 1-minute exposure times. The restored images were found to have significantly more visual detail than the original degraded images, with the 5-millisecond exposure restorations being superior to the 1-minute exposure restorations. (U)

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