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**RESTORATION OF ATMOSPHERICALLY
DEGRADED IMAGES**

VOLUME 1

WOODS HOLE SUMMER STUDY

JULY 1966

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Advisory Committee to the
Air Force Systems Command

**NATIONAL ACADEMY OF SCIENCES
NATIONAL RESEARCH COUNCIL**

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9 Report on

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11 1966

12 93 p.

15 AF 18(600)-2891

For content. See: Proc. Conf.

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If the Theory of making Telescopes could at length be fully brought into Practice, yet there would be certain Bounds beyond which Telescopes could not perform. For the Air through which we look upon the Stars, is in a perpetual Tremor; as may be seen by the tremulous Motion of Shadows cast from high Towers, and by the twinkling of the fix'd Stars. But these Stars do not twinkle when viewed through Telescopes which have large apertures. For the Rays of Light which pass through divers parts of the aperture, tremble each of them apart, and by means of their various and sometimes contrary Tremors, fall at one and the same time upon different points in the bottom of the Eye, and their trembling Motions are too quick and confused to be perceived severally. And all these illuminated Points constitute one broad lucid Point, composed of those many trembling Points confusedly and insensibly mixed with one another by very short and swift Tremors, and thereby cause the Star to appear broader than it is, and without any trembling of the whole. Long Telescopes may cause Objects to appear brighter and larger than short ones can do, but they cannot be so formed as to take away that confusion of the Rays which arises from the Tremors of the Atmosphere. The only Remedy is a most serene and quiet Air, such as may perhaps be found on the tops of the highest Mountains above the grosser Clouds.

Sir Isaac Newton, *Opticks*, 4th edition, 1730
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PREFACE

The Woods Hole Summer Study on Restoration of Atmospherically Degraded Images was held at the National Academy of Sciences - National Research Council Summer Studies Center at Woods Hole, Massachusetts, during the period 27 June through 23 July 1966. The Study was initiated by the Optical Maser Panel of the Advisory Committee to the Air Force Systems Command of the National Academy of Sciences - National Research Council, and the work was supported by the Air Force Systems Command under Contract AF18(600)-2891. — *New*

During the course of a survey of Air Force laser projects in the winter of 1965-1966, the Optical Maser Panel visited the Air Force Avionics Laboratory's Electro-Optical Surveillance Research Facility at Cloudcroft, New Mexico, read reports on the Project AMOS (ARPA Midcourse Optical Surveillance) observatory on Mt. Haleakala in Hawaii, and discussed the problems of satellite surveillance with people knowledgeable in the field. The survey emphasized the importance of image reconstruction in a variety of contexts, and indicated the possible contribution of laser technology to this problem. The Panel concluded that major improvements in the quality of photographic images will not be obtained merely by technical refinements of optical systems and recording media, since in many cases, the controlling limitation is atmospheric turbulence.

Classical methods of image restoration depend, by and large, on nothing more complicated than some form of contrast amplification to make the image more interpretable. However, much more information is thought to be extractable from atmospherically degraded images than is found by presently used techniques. New methods are within reach which involve study of the nature of the "noise" that degrades the image and the use of signal processing techniques to achieve best possible representation of the original object. Feasibility of such sophisticated techniques depends (1) on the fact that atmospheric turbulence and other degrading

influences have identifiable characteristics which, together with known characteristics of the original object, can be utilized to optimize image rendition, (2) on the exploitation of electro-optical image sensor techniques which are fast enough to "freeze" image motion due to atmospheric turbulence, and (3) on the availability, for image processing, of high-speed digital computers with large memories.

That there is promise in such an approach is indicated by a limited amount of research at several institutions, and, in particular, by work at the Visibility Laboratory of the University of California, San Diego, in which significant restoration of atmospherically degraded images has been achieved on an experimental basis by digital processing. However, the Optical Maser Panel was not aware of any groups other than the Visibility Laboratory which are actively pursuing these objectives, and it was felt that the potential importance of the techniques is great enough to warrant attention by a wider variety of competent people.

To this end, the Academy agreed to sponsor and the Air Force Systems Command to support a four-week study by a group of research scientists from universities, industrial laboratories, and government, representing skills in a variety of fields such as information theory, atmospheric physics, optical design, electromagnetic theory, laser physics, digital computation, image evaluation, and photography.

Interest in the subject of the study proved so great that initial plans for a group of 10 or 12 full-time participants and perhaps 20 part-time consultants had repeatedly to be revised upward. Ultimately the working group amounted to about 20, with a total of 51 people on hand at one time or another. As a consequence, a number of last-minute requests for invitations from well-qualified persons had to be turned down because of lack of facilities at the Summer Studies Center.

In order to accomplish anything definite in the short span of four weeks, the attention of the Summer Study was focused almost entirely on a quite restricted problem, namely, the use of sophisticated image-processing techniques to undo the effects of atmospheric turbulence on images of objects of small angular subtense, photographed from the ground looking up. This is the problem which arises in satellite surveillance, and the size of the following report indicates how much the participants found to say about it. We are aware, of course, that atmospheric turbulence is not the only factor that degrades images, that images of large angular subtense are also of interest, and that optical imaging is not the only tool available to an information-gathering system. Some of the results of the Summer Study are applicable in a broader context, and, in any case, it is our hope that participants will undertake on their own whatever extensions seem most interesting to them.

It is perhaps worth noting that although the Summer Study was set up to permit classified discussions up through Secret, with two minor exceptions all the

work reported was unclassified; and to the best of our knowledge, there are no gaps owing to military classification in the present report.

The following report and appendixes represent what was written at the Summer Study, with a few minor changes but no essential additions. Some of the authors were asked to assist in editing what they wrote, but the final form was in all cases the responsibility of the Director. In a few instances, participants contributed first-class papers which were judged to be outside the scope of the study. These have been collected in Volume 3, "Miscellaneous Papers," and it is expected that most of them will be published in appropriate technical journals. In doubtful cases, the decision where to put a particular piece of work was made by the Director.

Extraordinary enthusiasm and willingness to work were exhibited by all participants in this study. It would be difficult to single out participants for individual praise, but special mention must be made of James L. Harris, Sr., and Joseph W. Goodman for leadership of the work in passive and active reconstruction schemes, respectively, and for writing large sections of the final report.

A major portion of the success of the study was due to the technical cooperation and support of the Air Force Avionics Laboratory, as represented at Woods Hole by Col. Telford S. Byington, Chief, Reconnaissance Division, Air Force Avionics Laboratory, Research and Technology Division, Wright-Patterson Air Force Base, Dayton, Ohio, and by Edmund T. Tyson, Technical Manager, Electro-Optical Surveillance Research Facility, Cloudcroft, New Mexico. Smooth and effective liaison between the Summer Study and the Air Force was provided by Lt. Col. John A. Fiorillo, AFSC Headquarters Project Officer, Research and Technology Division, Bolling Air Force Base, Washington, D. C.

Particular credit is owed to Kenneth S. McAlpine, Executive Secretary of the Advisory Committee to the Air Force Systems Command, for his energetic and enthusiastic handling of the multitude of administrative details connected with setting up and running the Summer Study. In addition, our thanks are due to the staff of the NAS-NRC Summer Studies Center at Woods Hole, and to Hazel Bandler, Joy Catanzaro, and Barbara Stusse, the hardworking secretaries who produced the original typescript; to Barbara Stusse who also produced the entire final document for printing; and to Jacqueline Boraks of the Academy's Printing and Publishing Office for her design and production editing. To them and to everyone who supported the Summer Study, we express our gratitude.

December 1966

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I INTRODUCTION

SCOPE AND LIMITATIONS OF STUDY

At present, the quality of telescopic images of objects in space is limited not by optical quality, tracking precision, or available flux, but rather by the image degradation produced by atmospheric turbulence. For example, the diffraction limit of a 48-in. telescope is 0.1 sec of arc, but seeing effects limit the actual resolution to several tenths of a second. It is natural then to inquire whether image processing techniques can be employed to gain resolution for large optical systems. The purpose of the present study is to investigate this question.

In this study, the term "image restoration" will not refer to classical techniques which depend only on contrast amplification to make the image more interpretable. It implies, rather, that we perform a more sophisticated mathematical operation on a recorded pattern of light intensity, using either digital or analog techniques, for the purpose of undoing the effects of whatever degradations may be present and restoring, as nearly as possible, the image which would have been recorded in the absence of degradations.

The problem of restoring images of space objects is dramatically simpler than some image restoration problems (e. g. , aerial reconnaissance photographs) because space objects are viewed against a dark uncluttered background and because

the objects can be adequately defined by a small number of picture elements. For example, a 5-sec-of-arc object, viewed with a 0.1-sec-of-arc diffraction-limited system, to a first approximation can be adequately defined by a 50 x 50 matrix of numerical values. While it is obvious that the same principles of image processing which apply to the case of looking up also apply to looking sidewise or down, it is also obvious that the different cases involve large differences in the amount of data to be processed and are therefore quite likely to require different techniques. In the present study, we have limited ourselves almost entirely to the problem of viewing small angular subtense objects in space, using ground-based optical telescopes typified by the Cloudcroft installation. This is perhaps the simplest real problem faced by image restoration, but it has the merit of being both intrinsically important and also a stepping-stone to more difficult problems.

It cannot be emphasized too strongly that the function of image processing is to display the information content of an image so as to make it intelligible to the human visual system. No amount of image processing can increase the information content of an image; it can only make the information that is already there more usable. The only meaningful way to evaluate an image is to find out whether it conveys to a human observer the information for which it was recorded.

In any particular context, of course, it is possible to say something about what information is wanted from an image. For example, in the context of satellite surveillance, one might wish to determine any or all of the following things: size of the satellite to the diffraction limit (e. g., ± 0.25 ft at 200 miles for a 0.1-sec-of-arc system); shape (conical, spherical, etc.); and surface features, such as windows or apertures, antennas, solar panels or paddles, painting for temperature control, surface texture, photometric characteristics, and radiometric characteristics. Since, however, images may be recorded for any of a great variety of purposes, we did not feel that it was within the scope of the study to specify criteria for image evaluation, except to note that at some point a human observer is an essential link in the chain.

A number of other limitations were intentionally imposed on the present study. The general restriction to objects of small angular subtense, with a limited number of resolution elements, has already been mentioned. Furthermore, we did not consider sources of image degradation other than atmospheric turbulence, such as imperfect optical systems or motion blur due to tracking errors, even though it is well known that many of the same restoration techniques which are discussed in the present report can correct for these factors too. Finally, we did not discuss other means of collecting information electromagnetically, for example, by microwave or laser radar, although it is obvious that such alternative means would have to be considered in any military systems study. In return for this

narrowing of our view, it is believed that we have succeeded in getting a reasonably thorough coverage of the original subject of the study, namely, the restoration of atmospherically degraded images.

GENERAL TOPICS CONSIDERED

Volume I of the present report contains a connected account of the results of the Summer Study, with a minimum of mathematics. As indicated by the index, the approaches to image processing which we have considered are described in three parts (Chapters III, IV, and V) of rather disparate length.

Postdetection Passive Image Processing

Chapter III is devoted to a discussion of the techniques, status, and problems of digital and analog processing techniques. These refer to a variety of kinds of operations which can be performed on a degraded image in order to make the image more interpretable. Since the effect of atmospheric turbulence is, in general, to reduce the amplitude of the higher spatial frequency components of an image, the objective is to restore these components to their proper values. During very short exposures, the high spatial frequencies are not attenuated so much as during long exposures, but they are provided with instantaneous phase shifts which must be corrected for. The long-exposure transfer function of the atmosphere is fairly well known, but a major problem in the short-exposure case is to obtain either exact or statistical knowledge of the instantaneous transfer function so as to correct for it.

Once the transfer function is known or guessed, one may restore the image either digitally, by Fourier transform or convolution techniques, or by optical analog processing, using the Fourier-transforming properties of a lens together with suitable filters. Digital techniques are very flexible and are fast enough for pictures with a relatively small number of resolution elements; they have been developed at the Visibility Laboratory and the Jet Propulsion Laboratory, in particular. Optical techniques can potentially handle very large quantities of data; they are under development at, among other places, Technical Operations, Inc., the Conduccion Corporation, and the University of Michigan.

Wavefront-Reconstruction Techniques

Chapter IV describes an active method of image reconstruction, whereby the interference fringes between a laser-illuminated object and a coherent reference source are photographed and used in a holographic technique to reconstruct the image of the desired object, even though the intervening medium may have been randomly inhomogeneous. In essence, the coherent reference, which may be a specular reflection point on the object itself, provides a record of the atmospheric inhomogeneities at the instant the picture was taken. The method works best when the inhomogeneous layer is near the camera, as is usually the case with a ground-based telescope looking up. The method was invented a few months ago by J. W. Goodman and co-workers at Stanford. Laboratory tests to date and theoretical analyses are very encouraging; field tests are recommended.

Predetection Image Processing

In Chapter V, two systems are described which depend on electronics to improve imagery. The first, due to R. L. Gregory, decides automatically "when the seeing is good" and builds up an exposure through a sequence of very short partial exposures. The second is a system built at the Itek Corporation which automatically stabilizes the image of a small object on the retina of an electronic image tube, in spite of motion of the object, the medium, and the image tube. Either or both of these systems may be useful partial solutions to the problem of getting a good picture through a time-varying medium.

Volume 2 of the report includes 37 appendixes, which are more or less independent technical papers arranged to correspond to the order of presentation in Volume 1 and referenced for the benefit of the reader who wants additional detail. Among the appendixes are several descriptions of proposals which were not evaluated at the Summer Study, but which are put on record for possible future investigation.

Finally, a few papers and notes were written at Woods Hole which were judged to be outside the scope of the Summer Study. For archival purposes, these miscellaneous papers have been collected in Volume 3, but with no attempt to correlate them with the contents of Volumes 1 and 2.

II CONCLUSIONS AND RECOMMENDATIONS

Recent general advances in image processing, together with specific accomplishments in processing of images degraded by laboratory generated turbulence, indicate that image restoration is ready to make the step from experimental procedure to useful operational tool. It is also clear that additional work is needed in a number of areas to increase our understanding and to develop more effective techniques and equipment.

We make the following conclusions and recommendations.

IMMEDIATE PROCESSING OF REAL TELESCOPIC IMAGES

The gap between the quality of images processable in the laboratory and the quality of images obtainable from telescope systems such as may be found at the Air Force observatory at Cloudcroft, New Mexico, is almost vanishingly small. This gap should be bridged as quickly as possible. As a first step, observatories which can do so should furnish satellite images to organizations which have image-processing facilities. It appears that limited experimental processing of real telescope images can be started almost immediately.

As soon as successful processing of satellite photographs has been achieved, a small image-restoration facility should be set up at or near an active observatory so that the observatory can process its own pictures. Digital computers are plentiful, film scanning equipments are not complex or expensive, and in the beginning the observatory could draw heavily on the experience and techniques developed by the Visibility Laboratory of the Scripps Institution of Oceanography of the University of California, San Diego. Such an operation would provide invaluable practical experience in image restoration with a relatively small financial outlay.

EXPANSION OF PROCESSING RESEARCH AND DEVELOPMENT

As image restoration moves from research toward exploratory development, it would be highly desirable to broaden the base of the research and development effort by bringing a number of organizations into the field. It is not being suggested that contracts be let at once to design equipments for large high-volume image-processing centers; in our opinion, this would be premature at a time when we have not yet accomplished our first restoration of a real telescope image. What is needed is further development and evaluation of techniques; one way to encourage this would be to distribute pictures taken at Cloudcroft to anyone who wants to try processing them. As experience leads to the routine use of specific methods of image restoration, equipment systems can be designed to perform the operations rapidly and economically.

One specific project, which was discussed but not evaluated by the Summer Study, would be the construction of a flexible real-time picture-processing unit to be coupled with a human observer. The input to the processor might be one or more recorded images from a telescope, either in the form of photographs or magnetic tape. The output would be a picture on a cathode-ray tube. The operator might be provided with a large number of controls and programs to permit nearly continuous alteration of the parameters of the picture restoration process, so that he could use step-by-step deductions and a priori knowledge to zero in on the most informative picture. Features which might be provided include linear filtering with various weighting functions, together with nonlinear operations such as changes in contrast, brightness contour maps, stretchings and warpings to make obvious edges straight and to superimpose separate pictures, and addition of shifted differentiated pictures to eliminate blur caused by motion and tracking error. A further study is recommended to sharpen the objectives of such a project, provide cost estimates, and produce a firm proposal.

ATMOSPHERIC MEASUREMENTS RELATED TO IMAGE PROCESSING

Two specific types of information about the effects of atmospheric turbulence relate directly to image restoration questions. The first of these is the nature of the point-spread function (or its Fourier transform, the optical transfer function), and the second is the size of the isoplanatic patch, i. e. , the region over which the point-spread function is essentially constant. As discussed later in the report, it is possible to get some a posteriori information about these questions merely by analyzing a series of degraded images, but direct experimental measurement is perfectly feasible and should be done.

Statistics of the long- and short-exposure point-spread functions should be obtained from large numbers of photographs of bright stars or of laser sources at very high altitudes, under various seeing conditions and at various angular elevations. Analyses of the results should be performed using the techniques now being employed at the Visibility Laboratory for the statistics of point-spread functions due to heat-generated turbulence.

Similarly, experiments should be made with double stars of various separations or with pairs of high-altitude sources to determine the sizes of the isoplanatic regions (i. e. , the regions in which both sources seem to vary in the same way). If done with sources at different altitudes, such experiments would settle the old argument as to whether most of the turbulence which affects seeing is near the ground or at the tropopause.

Finally, various interferometric techniques have been proposed for measuring the mutual coherence function (which is equivalent to the effective long-exposure transfer function) of light directly across the aperture of a large telescope; these also should be considered.

CONTINUED DEVELOPMENT OF SENSOR PACKAGES

Development of film and electro-optical sensors looking toward further improvements in signal-to-noise (S/N) ratio and dynamic range is of continuing importance. The extent to which image processing can be successfully employed is directly linked to the precision with which the irradiance map which produced the image can be defined. The precision limitations imposed by a real sensor can be divided into two major categories, assuming sufficient illumination so that sensitivity is not a problem.

The first category is lack of precision due to sensor noise. The ideal detector would be limited only by noise associated with the statistics of photon arrival. Film falls short of this goal because of the noise introduced by its granularity.¹ Photosensitive electronic components are a considerable improvement over film in this respect. Their fundamental S/N ratio under suitable circumstances almost meets the goal set above. An illustration in the report shows that an array of photosensitive elements of reasonable quantum efficiency could achieve 10 to 1 improvement in S/N ratio with respect to film. However, in a typical use of the image orthicon for this application, the system collects photons from the object only about 6 percent of the time. An additional inefficiency is that in some cases the images of interest occupy as little as 5 percent of the image orthicon format, while the beam noise is determined by the bandwidth associated with requiring that the entire format be scanned. These examples indicate that there are potentially order-of-magnitude improvements in S/N ratio obtainable with the use of current photosensitive elements designed for this specific task. Since order-of-magnitude improvements in S/N ratio translate into very significant improvements of the potential for image processing, it is recommended that serious consideration be given to the question of sensor packages specifically designed for image-processing applications.

The second category is the lack of precision in determining the irradiance map in the image plane, due to sensor dynamic-range limitations and uncalibrated sensor nonlinearity. Experience at Cloudcroft has indicated that an object of interest may have highlights and lowlights which cover a dynamic range of 10^5 or more. Existing sensor packages at Cloudcroft can only cover 10^3 or less, and this is true of all currently available photosensitive elements. Certain special films have a dynamic range as high as 10^5 , but they lack the desired S/N performance as mentioned above. Outside its dynamic range, the sensor saturates and clips the signal, which adversely affects the extent to which the image can be subsequently processed. Sensor nonlinearity (exclusive of saturation or clipping) is not a fundamental limitation, provided that adequate procedures for calibrating the nonlinearity are used. The problem of extending the dynamic range of sensors, however, is a serious problem which merits further study.

¹R. Clark Jones, J. Opt. Soc. Am. 52, 1193 (1962).

DIGITAL VERSUS ANALOG PROCESSING

There is little doubt that at the present stage of image processing, the general-purpose digital computer is unparalleled for flexibility, accuracy, fast turn-around time, and ability to handle any desired nonlinear operation. We believe that it will continue to be the preferred tool for research in image restoration, where the emphasis is on development, evaluation, and comparison of alternative techniques.

On the other hand, the potential advantages of optical analog processing in handling very large pictures, and in carrying out similar linear operations (e. g., Fourier transformations and filtering) on large numbers of pictures, are considerable, and therefore the development of analog processing should also be supported. The ultimate processing center, as envisioned somewhat later in this report, may well involve both digital and analog operations in an on-line facility.

PREDETECTION SCHEMES

Inasmuch as the Gregory scheme for automatic real-time sampling is essentially operational, and since it would not be difficult to adapt the equipment to the 48-in. telescope at Cloudcroft, we recommend that it be tried there. As a first step, Gregory has proposed to test the scheme at Cambridge, using existing equipment and a series of short-exposure motion pictures, perhaps of satellites, taken with the Cloudcroft telescope. If results are encouraging, he would then try lunar and planetary pictures through the telescope itself. This would settle the important question whether the technique is as advantageous for large telescopes as it is for small ones. If so, he would propose to investigate a series of ideas for applying the method to satellite photography. It is our understanding that none of these experiments will involve a great deal of money or observatory time.

Finally, if any pictures are obtained which show improvement as assessed visually, they should be further subjected to postdetection processing and the doubly processed pictures compared with pictures processed by each method separately.

CONTINUED RESEARCH ON COHERENT WAVEFRONT-RECONSTRUCTION TECHNIQUES

The most promising of the coherent imaging techniques which we have seen is the Goodman wavefront-reconstruction scheme. It must be recognized that this technique was invented only a few months ago, and so it is in a much earlier stage of research than some of the passive image-restoration techniques. Nevertheless, the scheme seems quite promising, and we strongly recommend that further research and development be supported looking toward the development of a capability for imaging space objects through a turbulent atmosphere. In particular, tests need to be carried out as soon as possible under real atmospheric conditions. A reasonable set of tests, as equipment becomes available, would be:

1. Imaging over a horizontal path (not the satellite surveillance problem but easy to do);
2. Imaging an airplane with a corner-cube array;
3. Imaging a satellite with a corner-cube array;
4. Imaging a satellite with a specular reflection point.

Of course additional laboratory work and further theoretical analyses of wavefront-reconstruction techniques should proceed concurrently.

THEORETICAL STUDIES OF IMAGE PROCESSING

In the development of image-restoration techniques, numerous specific analytical problems are sure to arise and to be handled on an ad hoc basis. It would be well, however, if some broader theoretical studies could be undertaken. These might include:

1. Theoretical limitations to processing, owing to such effects as quantum limitations, sensor noise, uncorrectable nonlinearity, incorrect transfer function, or errors in a priori information. Error analyses (for example, in connection with film scanners) will be important in order to answer practical questions like, "How much precision do we really need? "
2. Studies of optimal processing techniques. What are the trade-offs between motion, noise, and precision of reconstruction? As the number of sample images increases, do different processing schemes approach the same limit, and if so, how fast?

In any study of optimal processing, however, we must be very careful not to confuse a mathematically tractable criterion of optimality with the as yet unknown

criteria employed by a human being. Before drawing ultimate conclusions on system requirements, we need a better understanding of the way in which the human mind evaluates an image and recognizes details in it. These extensive and difficult questions were entirely outside the scope of this study.

Finally, we would like to emphasize that in image restoration, as in other fields, the door must always be left open for new inventions. This is particularly true at present of coherent imaging techniques. In this study we have concentrated on methods that seem most promising at the moment. The fact that we have not mentioned a particular scheme, or have dismissed it as unevaluated, does not mean that we wish to downgrade new ideas. Should another study of the same type be held in five years, we would expect many new ideas to have developed; in fact, we will regard the development of such ideas as one measure of the success of the present study.

III PASSIVE IMAGE PROCESSING FOR INCOHERENTLY ILLUMINATED OBJECTS

GENERAL DESCRIPTION OF PROCESSING

For the case of objects which are incoherently illuminated, the image-forming operation performed by an optical system is linear in electromagnetic power. That is, each point on the object produces a distribution of power in the image plane (point-spread function), and the composite image is the linear superposition of the power distributions from each of the points which make up the object. The imaging operation is therefore described by the integral,

$$H_I(x, y) = \iint H(x', y') S(x', y'; x, y) dx' dy' , \quad (1)$$

where $H(x', y')$ is the irradiance (watts \cdot meters⁻²) map associated with the geometric projection of the object into the image plane (the ideal image), $S(x', y'; x, y)$ is the point-spread function defined in x and y for every object point x', y' , and $H_I(x, y)$ is the composite image, which is an irradiance map defined for all image points x, y .

By far the largest existing program of research on the subject of this section is that of the Visibility Laboratory of the University of California, San Diego. A brief account of the Visibility Laboratory program is given in Appendix 1.

Image processing consists of obtaining solutions to Eq. (1) for $H(x', y')$, based on knowledge of the recorded image $H_I(x, y)$, various levels of a priori knowledge of $S(x', y'; x, y)$, and in some cases limited a priori knowledge of some characteristics of $H(x', y')$.

The most favorable case for processing, and the one which has received primary attention, is the case in which the point-spread function is invariant over some small region (the isoplanatic region) of interest in the image plane. The integral (1) then becomes a convolution,

$$H_I(x, y) = \iint H(x', y') S(x' - x, y' - y) dx' dy' , \quad (2)$$

or in shorthand notation,

$$H_I = H * S. \quad (3)$$

Fourier Transform Solutions

Equation (2), being a convolution, can be conveniently solved with the use of Fourier transformation. A restatement of Eq. (3) in the Fourier domain reduces the equation to a simple product of the form,

$$F[H_I] = F[H] F[S] . \quad (4)$$

The terms $F[H_I]$ and $F[H]$ are the spatial frequency spectra of the recorded image and ideal image, respectively, and $F[S]$ is by definition the optical transfer function. Solving for $F[H]$ and taking the inverse Fourier transformation, we readily obtain the formal solution,

$$F[H] = \frac{F[H_I]}{F[S]} = F[H_I] F[T] \quad (5)$$

and

$$H = F^{-1} \left\{ \frac{F[H_I]}{F[S]} \right\} = F^{-1} \left\{ F[H_I] F[T] \right\} , \quad (6)$$

where

$$F[T] = 1/F[S] . \quad (7)$$

In practice we do not attempt to obtain exact solutions of the kind described by Eq. (6). The presence of noise in the image tends to make such solutions meaningless because, in frequency regions where $F[H_I]$ is less than the noise, the operation described in the equation simply implies large amplifications of noise. We have therefore to be satisfied with an approximately restored image H_O , obtained by convolving H_I with a processing optical transfer function T_P ; thus

$$F[H_O] = F[H_I]F[T_P] , \quad (8)$$

and

$$H_O = F^{-1} \left\{ F[H_I]F[T_P] \right\} \quad (9)$$

In principle $F[T_P]$ should be equal to $F[T]$ in frequency regions where $F[H_I]$ is large compared to the noise and small in frequency regions where $F[H_I]$ is small compared to the noise. An important part of image processing is the careful selection of T_P in an attempt to maximize the interpretability of the output image.

Convolution Integral Solutions

It is clear from Eq. (8) that the restoration operation is describable by the convolution integral

$$H_O = H_I * T_P . \quad (10)$$

Whether processing is accomplished by Fourier transformation or by convolution is a practical rather than a theoretical decision, since the operations are mathematically equivalent. The decision would depend on the comparative time and cost of accomplishing the numerical operations (see Numerical Techniques, page 36). Since the determination of T_P from data on S may be most easily obtained from Fourier operations, it may be that at least this part of the problem will use Fourier transformations, while the actual processing operations may be either Fourier or convolution.

Long- and Short-Exposure Point-Spread Functions

To carry out image processing as described above, we have to know or to estimate the point-spread function (or its Fourier transform, the optical transfer function), and we have to convince ourselves that the isoplanatic region is big enough so that the image is really a convolution of the object with an invariant point-spread function. This section describes long- and short-exposure point-spread functions in general terms, and the next section discusses isoplanatic regions in the same way. Appendixes 2 through 8 of Volume 2 are concerned with various theoretical and experimental aspects of these questions, and Appendix 9 describes a more or less pragmatic approach to the determination of atmospheric properties from the point of view of image processing.

Consider the graphs shown in Figures 1(a), 1(b), and 1(c). These graphs are hypothetical (one-dimensional) examples of "instantaneous" point-spread functions, as observed by an optical system with a reasonably small aperture compared to the scale of the atmospheric turbulence. In each case, the center of gravity of the image is shifted from its mean value. For lack of a standard term, we call the shift displacement; it should be distinguished from the spreading of the images about their centers of gravity. The spreading we shall call short-term blur.

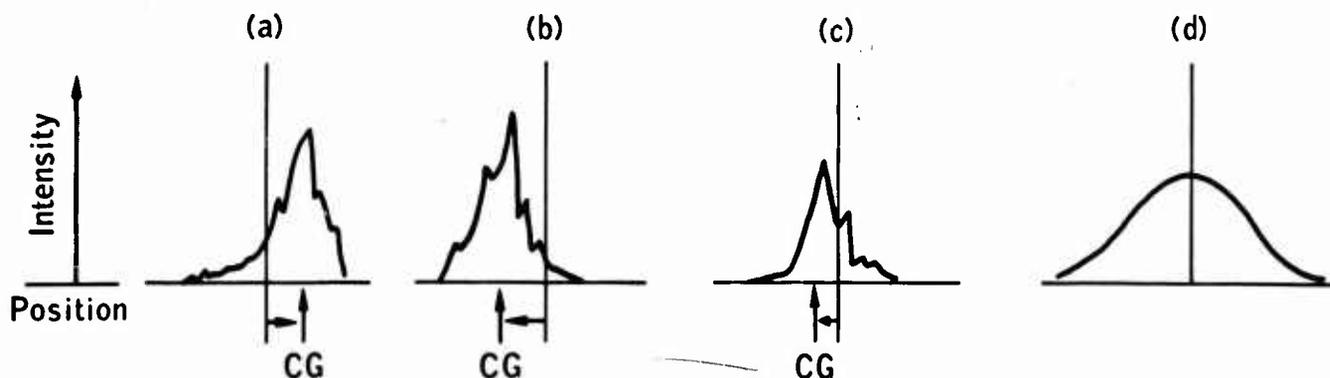


FIGURE 1 (a) - (c) Examples of instantaneous point-spread functions; (d) long-term blur.

If one averaged these instantaneous point-spread functions through a photographic time exposure (or equivalent operation), the result would look as shown in Figure 1(d). Note that the image motion (i. e., time-changing displacement) and the short-term blurs have combined to give a smooth long-term blur. Because of the image motion, the long-term blur is greater (more spread) than the average short-term blur (Figure 2), which would be obtained by shifting the instantaneous

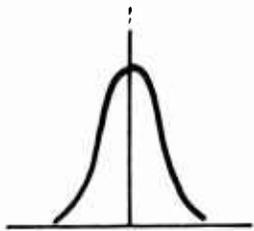


FIGURE 2 Average of shifted point-spread functions; short-term blur.

point-spread functions back to a common center of gravity and then averaging. Indeed, often the displacement is much greater than the short-term blur, and, as a result, the long-term blur is caused mostly by the displacement. One therefore prefers to use as short an exposure time as possible in order to minimize the effect of turbulence-induced blur.

The qualitative differences between long- and short-exposure point-spread functions (psf's) are reflected in qualitative differences between the corresponding optical transfer functions (OTF's). For example, since the short-exposure psf is more peaked than the long-exposure psf, the short-exposure OTF is wider (i. e., it falls off more slowly at higher spatial frequencies) than the long-exposure OTF. On the other hand, since the long-exposure psf is symmetric about the geometric image point, the long-exposure OTF is real, whereas the short-exposure OTF has phase shifts corresponding to the spatial displacement of the short-exposure psf.

An additional complication appears if the telescope aperture is large compared to the scale of the atmospheric turbulence. Then the image of a point source, instead of being a dancing or quivering point, may consist of several more or less clearly defined but fluctuating bright points on a diffuse or filamentary background. The instantaneous peaks in the short-exposure psf correspond to refraction through several different atmospheric turbulons. Occasionally one of these peaks will dominate all the others for an instant, and during that time the image of the point source is very nearly diffraction limited. The probability that such an instant of good seeing will occur during any given interval of time is considered briefly in Appendix 2.

One is clearly interested in determining theoretical and experimental relationships between the statistics of the atmosphere and the statistics of psf's and OTF's, although it is outside the scope of this report to give more than a couple of references. Hufnagel and Stanley² have determined the average long-exposure OTF in terms of certain statistical structure constants of the refractive index (cf. Appendix 3); and Tatarski³ has given an approximate but simple expression for the variance of the displacement, or, equivalently, the mean-square fluctuation

²R. E. Hufnagel and N. R. Stanley, *J. Opt. Soc. Am.* 54, 52 (1964).

³V. I. Tatarski, *Wave Propagation in a Turbulent Medium* (McGraw-Hill Book Company, Inc., New York, 1961), pp. 224-227.

of the angle of arrival of starlight. Experimental results are in moderately good agreement with theory, insofar as the statistics of the atmosphere can be independently determined. A quick approximate calculation of the mean short-exposure OTF is given in Appendix 4.

Although additional theoretical analysis is possible and desirable, for image-processing purposes the most immediate practical need is the collection and analysis of a considerable amount of experimental data on short-exposure psf's (see Appendixes 6 and 9). Other experiments which may be relevant include the interferometric measurement of the mutual coherence function, which is equivalent to the long-exposure transfer function of the atmosphere, across the aperture of the telescope (Appendix 7), as well as the direct measurement of the shape of the incoming wavefront using the Hartmann test (Appendix 8).

Isoplanatic Regions

In image processing, it is of obvious importance to know if the turbulence-induced degradation is identical in all parts of the field of view of interest. An isoplanatic region is that part of the field of view over which the degradation is effectively constant, i. e., the field of view over which the point-spread function is invariant.

To illustrate the effect of interest, consider the situations shown in Figures 3(a) and 3(b). In the first case, the "turbulent eddies" are near the receiving telescope. The light from both stars in the field of view undergoes nearly identical perturbations, and thus their images will look nearly identical. In the second case, however, the "eddies" are smaller and far from the receiver. In this case, the light from the two stars undergoes different perturbations and we may expect their images to look different. In the first case the stars are within an isoplanatic region and in the second case they are not.

In the real world, there is turbulence "close" to the receiving telescope, "far" from the telescope, and at intermediate distances. From visual examinations of telescopic images of extended objects — such as the moon — one sees that some disturbances affect large areas (several minutes of arc in diameter) similarly, while other disturbances have only local effects (less than 5 sec of arc in diameter). It is clear that "isoplanatic region" is not a sharply defined concept; rather, there is a continuously decreasing correlation between two point-spread functions as they are moved apart in the field of view.

Strictly speaking, therefore, the concept of isoplanatic region should be replaced by the concept of a complex cross-correlation function between the optical

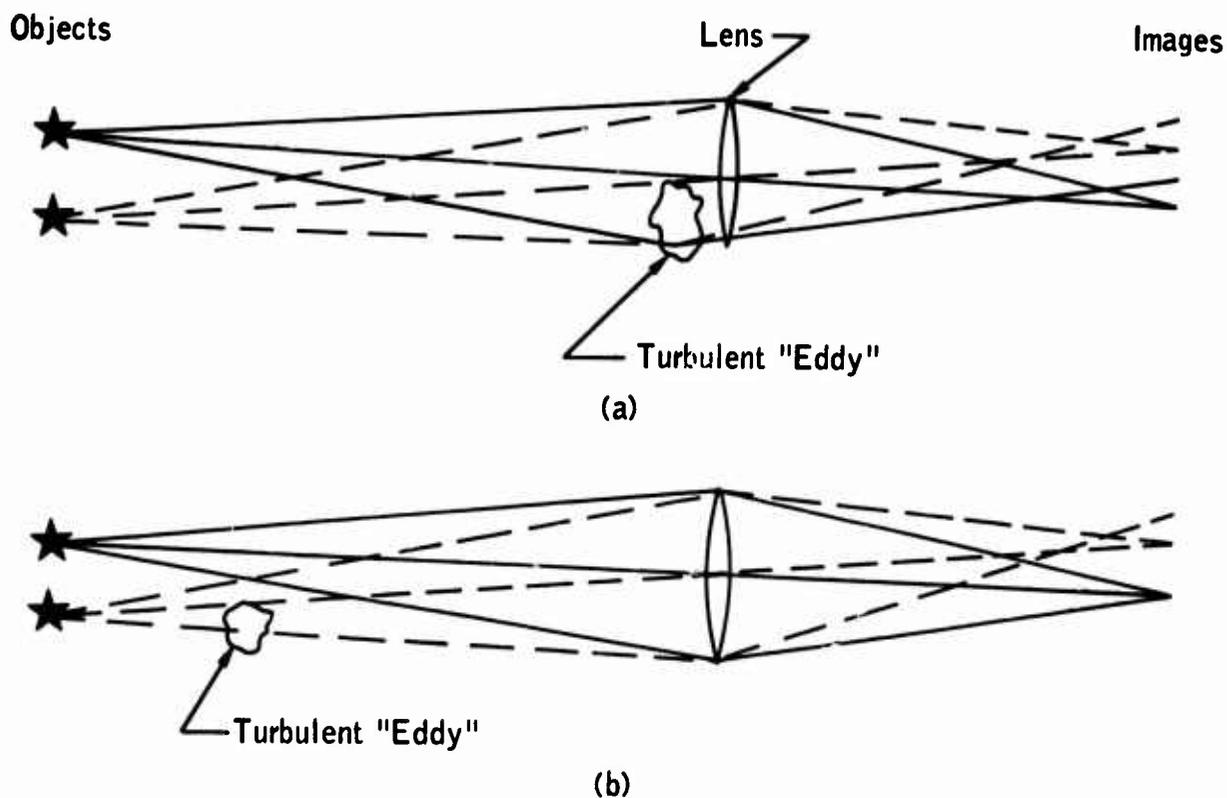


FIGURE 3 Illustrations showing how location of turbulence affects the size of the isoplanatic region.

transfer functions for two positions in the field of view. Such a correlation function would also be a function of spatial frequency, but this added complexity could yield desirable extra information.

This concept is explored further in Appendix 5. An empirical approach to isoplanatism, from the viewpoint of image processing, is discussed in Appendix 9.

Some Examples of Telescopic Images of Space Objects

As a matter of general interest and to indicate what image-processing techniques will have to cope with in the real world, we now show a number of pictures taken with the 48-in. telescope at Cloudcroft at a focal length of 900 in. Figures 4 to 8 and the accompanying descriptions were provided by E. T. Tyson.

Two more Cloudcroft photographs are contained in Appendix 16, and show the effect of specular reflections from satellites exceeding the dynamic range of photographic film. In addition, Appendix 10 describes visual observations of several satellites through the telescope at Cloudcroft and illustrates something that astronomers have known for a long time, namely, that under certain conditions the eye can see a great deal more through a telescope than photographs appear to record.



Slant Range: 432 statute miles
Exposure Time: 1/125 sec

Film: Eastman Kodak 4X (35 mm)
Camera: Leica IIc

Remarks: Seeing on this night was relatively poor. The width of the meteorite detection panel is 13 ft and subtends 1 sec of arc by calculation. Seeing has spread the apparent width to 3 sec of arc.

FIGURE 4 Satellite Pegasus A.



Slant Range: 521 statute miles
Exposure Time: 1/125 sec

Film: Eastman Kodak 4X (35 mm)
Camera: Leica IIc

Remarks: Most of the apparent difference in size between Figures 4 and 5 is due to a difference in enlargement. Seeing for Figure 5 was about 1 sec of arc. Note the shadow of the rocket body on the meteorite detection panel.

FIGURE 5 Satellite Pegasus C.

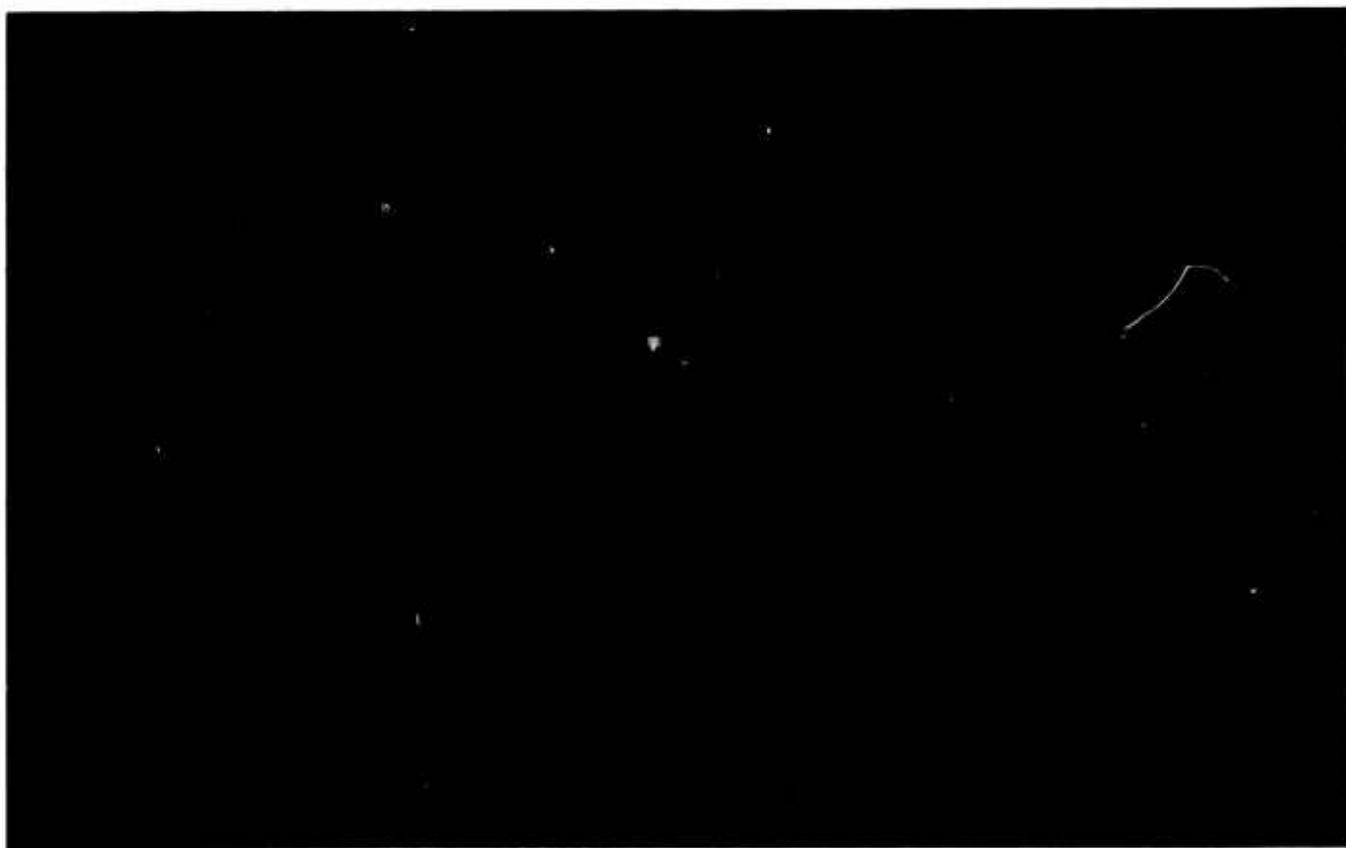


Slant Range: 57,340 ft
Exposure Time: 1/125 sec

Film: Eastman Kodak 4X (35 mm)
Camera: Leica IIC

Remarks: The exposure was made 2 hr after sunrise. The bar pattern size ratio is approximately $\sqrt{2}$. The smallest pattern resolved (fourth smallest visible) corresponds to 0.6 sec of arc on the wing with USAF lettering. Note the poorer resolution on the opposite wing, due to differential seeing effects in the atmosphere.

FIGURE 6 U-2 aircraft.



Separation: 2 sec of arc
Exposure Time: 1/60 sec

Film: Eastman Kodak 4X (35 mm)
Camera: Leica IIc

Remarks: Seeing on this night was average. Note that at 1/60 sec, some structure is left in the point-spread functions. To casual observation the point-spread functions are similar; i. e., the two stars are qualitatively in the same isoplanatic patch.

FIGURE 7 Double star Xi Ursae Majoris.



Slant Range: Varying, approximately 450 statute miles
Film: Eastman Kodak Plus-X (16 mm) Exposure Time: 1/60 sec
Frame Rate: 24 frames/sec Camera: Auricon

Remarks: This sequence of pictures shows the "boiling" motion caused by relatively poor seeing. Examination of the images shows several relatively sharp images with adjacent frames relatively fuzzy.

FIGURE 8 Successive frames of satellite Pegasus A.

MATHEMATICAL TECHNIQUES FOR PROCESSING TURBULENCE-DEGRADED IMAGES

The mathematical processing technique required for restoration of a turbulence-degraded image depends on whether the exposure time is long or short, on the extent of the a priori knowledge of the statistics of the degradation process, on the extent of the a priori knowledge of the nature of the object, on whether or not the entire image lies in a single isoplanatic region, and on whether the object illumination is coherent or incoherent. This section will describe operationally (no equations) the kinds of mathematics required for each of the various cases described above. We will then discuss briefly the image recording requirements which are necessary for successful processing, and conclude with a few remarks on the possible application of statistical estimation techniques.

Long Time Exposures

When the exposure time associated with the image recording is long enough to obtain a good statistical sample of the stochastic degradation process, then the point-spread function (psf) will be a smooth monotonic function along any radius. If, for this psf, any line drawn through the center of gravity (CG) traces out an even function of irradiance as a function of position along the line (mirror symmetry about the CG), then the optical transfer function will be real, i. e., no phase shift, and the modulus will be a smooth function which may fall rapidly with frequency.

Image restoration for long time exposure image degradations can be accomplished using frequency compensation in the Fourier domain or equivalent convolution integrals in the spatial domain. Experiments have shown that successful image processing can be achieved with little or no a priori knowledge of the optical transfer function (OTF), although it is obvious that best results can be obtained if it is known exactly.

If the actual transfer function is not known, restoration is achieved by "guessing" a processing modulation transfer function which is a smooth monotonic function of frequency, and adjusting the scale factor of the function by trial and error until satisfactory results are obtained. Experiments have shown that a first-order correction for point-spread function asymmetry can be made by giving the processing modulation transfer function an elliptic character in the two-dimensional Fourier domain, and adjusting the constants governing orientation of the major axis and ratio of the major-minor dimensions by trial and error.

Star images recorded with similar exposure times just before or just after the object image recordings may be useful in defining the approximate conditions during the observation.

The primary difficulty with the long-exposure case is that the high spatial frequencies of the image may be so badly attenuated that they are lost in the sensor noise. Multiple long-exposure images can be integrated to improve the signal-to-noise (S/N) ratio.

Short Time Exposures - Isoplanatic

The short time exposure ($\lesssim 10$ msec) image will be termed isoplanatic if, over the dimensions of the image, the psf is invariant, i. e., the isoplanatic patch is larger than the dimensions of the image. In the short time exposure with a large aperture telescope the psf will generally have no significant symmetry. This means that the OTF will have sizable phase shifts. The attenuation of the high spatial frequencies can be expected to be significantly less than that associated with the long time exposure. It is in fact the large phase shifts of the short exposure which, by complex addition of many short exposures, produce the high attenuation of the long-exposure case.

The short-exposure isoplanatic case must be further subdivided by specifying the extent to which the OTF is known a priori.

TRANSFER FUNCTION KNOWN EXACTLY

The simplest case is the one in which the OTF can be known exactly, as for example by simultaneously recording a star image or other point-source image located close enough to the object to be within the same isoplanatic patch. Under these ideal conditions, the point-source image can be used to obtain the OTF characterizing the degradation, and processing by Fourier or convolution integral operations can be used to restore the image.

This case is a very favorable one from the point of view of processing potential. We will not, however, usually be so fortunate as to have a convenient point source nearby. During this study, the question was raised as to the possible use of points of high specular reflection on the object itself to obtain psf information. This interesting suggestion merits further exploration.

TRANSFER FUNCTION KNOWN STATISTICALLY

In this case, we assume that by means of a large number of star images recorded before and/or after the object observations, we can obtain information about the

statistics of the OTF, i. e. , a two-dimensional frequency function for amplitude and phase of each spatial frequency component. If a series of images of the unknown object are collected and Fourier transformed, standard statistical techniques can be used to make a best fit of the recorded data to the statistical distributions, thereby generating a best estimate of the correct amplitude and phase for each spatial frequency component. Finally, we inverse transform this "best estimate" spectrum to obtain a "best estimate" restored image. Experiments of this type are just now beginning at the Visibility Laboratory of the University of California, San Diego. It is significant to note that the mathematical operations associated with this statistical approach are in general not linear operations and therefore cannot be performed by simple Fourier domain frequency compensation or convolution integral processes.

A possibly practical though nonoptimum technique for handling a series of short exposures would consist of adding the series of images to obtain the equivalent of a long time exposure. If the addition is accomplished with precision, as for example on a digital computer, then the resulting image will have some of the advantages of ease of processing associated with the long-time-exposure case, and an S/N ratio superior to the single long-time-exposure image.

A rapidly tumbling object considerably increases the difficulties of image processing. This case has received insufficient study to allow firm conclusions. Certain obvious possibilities exist, such as photoelectric recording to determine tumbling rates, with the photoelectric device used to trigger image recording at one or more specified tumbling angles.

TRANSFER FUNCTION UNKNOWN

If the psf is completely unknown even in a statistical sense, then the most likely processing technique is to acquire a series of short exposures, add them together with precision to obtain the equivalent of a long time exposure and process as suggested above under Long Time Exposures (page 25).

On a more speculative basis, however, one might believe that the degradation process of atmospheric turbulence may be characterized by specifying a relatively small number of parameters of the statistics of the OTF, and that observation of the statistics of the spectrum derived from a series of short-exposure images of an unknown object might allow reasonable characterization of the turbulence, followed by statistical treatment of the type described in the preceding section. This is a type of speculation which only experience can verify. Experiments relevant to these ideas will soon be under way at the Visibility Laboratory.

Short Time Exposures - Nonisoplanatic

When the psf changes shape over the image dimensions, then the integral which relates the object and image becomes a type which cannot be solved directly by Fourier or convolution integral techniques. Formal mathematical solutions, although straightforward in principle, would appear to be computationally difficult and would require either knowledge of the psf or of its statistics at every point in the field. Further study of this case is required to determine whether there may be practical solutions, for example, possibly breaking the image into a number of approximately isoplanatic regions.

We can, however, resort to the precise addition of a series of such images to obtain a long-time-exposure image, in which isoplanatism will exist over the image if the psf is statistically invariant over the image. Processing can then be performed as previously described for the long-time-exposure case.

Use of A Priori Information

All image processing is based on the use of a priori information in one form or another. It is a rather obvious, but sometimes overlooked, fact that if we truly had no a priori information we would have no reason to suspect that the object is not an exact replica of the image which we have recorded. Under these conditions we might conclude that the object consists of a massive number of small grains and that the object changes shape with time, even breaking into pieces once in a while.

We do not in practice reach any such conclusions because we know that the granularity is in our film, that our optical system has finite resolution, that we are observing the object through the atmosphere about which we have some knowledge, and that the object is perhaps a man-made device which may be tumbling but is generally not expected to change physical configuration.

Each of these statements of a priori knowledge has important bearing on the process of information extraction. It is sometimes quite difficult to translate intuitive knowledge into the analytic statements which must be made in order to utilize the knowledge in the processing operation.

A priori knowledge of the OTF of the atmosphere has been discussed elsewhere in this report. However, little has been said about a priori knowledge of the nature of the object.

Let us assume that we take a photograph of a satellite and subject it to an image-processing operation. We then view the processed image and immediately

note that there are "things wrong with it." A first observation might be that the background around the object is not uniform, but rather consists of some complex mixture of sinusoidal patterns. Since we know a priori that the background is not of this character, we could attempt to adjust our processing operation to produce an image which conforms with this knowledge. We could perform similar operations using other pieces of information such as gross dimensions of the object, straight edges of the object, points of specular reflection, or, in some cases, fairly detailed knowledge of some region of the object.

This type of use of a priori knowledge with respect to the object has not been extensively explored. In view of the possibility that effective handling of a priori information could produce important improvement in processing capability, further study is certainly warranted.

Processing of Conventionally Formed Images Using Artificial Illumination

The case in which the image is conventionally formed but the object is artificially illuminated, presumably by laser, is sufficiently distinct to warrant special mention. If the object is coherently illuminated, the relation between object and image is still given by a convolution integral, except that now the linear operation is on the complex electromagnetic field strength, rather than on the real intensity. To solve such a convolution requires that the image field and the complex point-spread function be known as complex quantities.

The problem becomes even more complicated when the object illumination is partially coherent. An example would be the case in which a pulsed laser of relatively short coherence time is used. Here the coherence distance (parallel to the direction of propagation) is small compared with the depth of the object, and the spatial coherence (perpendicular to the direction of propagation) may be comparable with the dimensions of the object.

It was suggested in the course of this study that it might be possible to generate information about the amplitude and phase of the image by simultaneously recording both the image irradiance and the modulus of the Fourier transform of the amplitude and phase of the image. (These Fourier transforms appear at the front and back focal planes of the optical system.) However, a quick look at the mathematical problem of determining the phase of a complex-valued function of two variables from a knowledge of the modulus of the function and that of its Fourier transform was not encouraging. Fortunately, it does not appear that we really need to solve this problem.

In the first place, at the present time a special effort would have to be made in order to record an image in which coherence was significant, even if we wished to do so. The exposure time would have to be so short that two points on the object had maintained the same path difference to a fraction of a wavelength. What is even more important, with the present 4-J Q-switched laser, or the planned 200-J long-pulse laser at Cloudcroft, the coherence length of the transmitted radiation is undoubtedly so short (probably less than 1 cm) that for all practical purposes, the radiation may be regarded as incoherent. Thus incoherent processing techniques may be applied directly to such pictures.

Finally, if we had at hand a system which really provided coherent illumination (but without a means of measuring complex field strengths), we would still have the options of artificially degrading the coherence, or of averaging over a set of several images in the computer, in order to use incoherent processing. Since perfect processing is expected to reach the diffraction limit no matter whether the initial image is coherent or incoherent, it appears at this stage that the easiest way out is to make the image incoherent and proceed from there.

Image Recording Requirements

If we visualize image processing as an attempt to solve a convolution integral, it is apparent that any error or uncertainty in knowledge of either the image or the point-spread function will increase the error or uncertainty in determination of the object. Errors or uncertainties in knowledge of the image would include sensor noise (or photon statistics in the case of the ideal sensor) and uncorrected or improperly corrected nonlinearities in the sensor (H-D curve in the case of film). In the case of Fourier domain processing, it is quite clear that in spatial frequency regions where the spectrum of the image has amplitudes lower than the sensor noise level, correct estimation of the amplitude and phase of the image spectrum cannot be made. This means that, in general, the lower the noise level of the sensor, the further out in the spatial frequency spectrum we can expect to recover information successfully. Noise then is the primary limitation in image processing, and great care should be taken in the recording of images to maximize the S/N ratio.

PRECISE IRRADIANCE MEASUREMENTS

The basic requirements on image recording where image processing is contemplated can best be described by invoking a new concept. Let us regard our

telescope systems not simply as big cameras designed to take pictures, but rather as scientific measuring apparatus whose function is to perform radiometry. All image processing begins with an irradiance map measured in the image plane. The success of the processing will depend on the precision with which our irradiance measurements have been performed. With this new outlook on the function of the telescope, we can bring to bear the techniques and experience associated with the fields of photometry and radiometry.

CALIBRATION PROCEDURES

With the concept stated above, it becomes clear that, as with any scientific measurement, we must carefully calibrate our measuring apparatus. If we are using film, for example, we can call on quite substantial technical knowledge which has evolved in the field of photographic photometry, including, for example, the technique associated with the use of gray scales. With other sensors, such as the image orthicon, no such body of experience exists; however, the functional task associated with calibration is still quite clear so long as we maintain that the purpose of the device is to record irradiance maps.

EFFICIENT USE OF SENSORS

When image processing is to be performed, both the selection of a sensor and the manner in which it is used may differ from what would be done if the primary function were production of images for direct viewing without processing. For example, in the case of photographic film the compromise of speed, granularity, focal length, and exposure might be resolved in a quite different fashion for the two cases. These questions need further exploration. Some considerations relating to optimum image size and density are given in Appendix 11.

One thing which is clear is that we must attempt to make full use of the observation time by recording as many images as possible. An example occurs in the case of the image orthicon. The image recording techniques which have hitherto been used with the image orthicon at Cloudcroft have two prominent inefficiencies.⁴ The first of these is that the photocathode is gated on for 1 msec and read out in 1/60 sec. Therefore, flux from the object is collected only 1/16th of the time available. A second consideration is that the typical image may occupy only approximately 5 percent of the total image orthicon format, yet beam noise is determined by the bandwidth required to scan the entire format in the frame time. Techniques need to be investigated for overcoming these inefficiencies.

⁴E. T. Tyson, private communication.

Since S/N ratio plays the dominant role in image processing, it is extremely important to make the original image recording with the greatest possible precision. For this reason photosensitive arrays have great appeal, and, for the case of object dimensions which translate into a relatively modest number of picture elements, may soon become practicable. Using sensors of high quantum efficiency, and perhaps sequential sampling techniques, it would be possible to obtain the equivalent of continuous recording of the output of each element in the array. Obviously, the goal is to come as close as possible to photon counting, the statistics of which constitute the fundamental limitation. It is interesting that, with such an array, "exposure time" can be chosen after the fact by integrating the continuous records over the selected time period.

Statistical Estimation Techniques Related to Image Processing

The application of statistical estimation theory to the restoration of images degraded by the atmosphere is a subject which has not, to the best of our knowledge, been much studied. Some beginnings along this line are reported in Appendixes 12 through 14 of the present study.

In these appendixes, R. S. Kennedy concludes that statistical techniques may be quite relevant and valuable when the task is either to restore images of many different objects or to obtain a single image from many degraded images of the same object. D. Slepian derives the processing filter which minimizes the mean-squared error for a photograph distorted by a stochastic point-spread function in the presence of additive noise. Finally, T. S. Huang shows that, in the case of satellite pictures, the film grain noise is approximately multiplicative.

Analyses such as the foregoing cannot be made or interpreted "off the top of the head," since they require both mathematical sophistication and also very careful attention to the relevance of the model being analyzed. Nevertheless, we strongly encourage such theoretical investigations, in the expectation that they will ultimately lead to valuable insights into the over-all problem of image restoration.

OPERATIONAL PROCEDURES FOR IMAGE PROCESSING

The linear mathematical operations associated with image processing can be mechanized by either digital or analog techniques. Digital processing can be done on a general purpose computer, and analog processing generally employs a

coherent optical system for performing the Fourier transform and filtering operations. Digital and analog techniques are discussed below, followed by a brief description of a scheme currently under development, in which corrective convolution is included in the film scanner itself.

Finally, the reader's attention is called to Appendix 15, in which an example is given of the kind of image analysis that can currently be done by a skilled photointerpreter using a specialized instrument called the Isodensitracer. The Isodensitracer does not "process" an image in the sense of the present study, but it does make the image more interpretable by displaying very subtle gradations in the density of the photographic transparency.

Digital Processing

Digital processing offers the advantage of great flexibility in the choice of processing procedures, together with extremely high precision. The operations can be either linear or nonlinear, and the "filters" can be quickly and easily changed without the necessity of any physical fabrication. For all these reasons, the high-speed general-purpose digital computer is ideally suited to exploration of processing techniques.

We shall now discuss some questions relating to the successive stages of a digital processing operation, including linearity and dynamic range of sensors, methods of data input, numerical techniques, data output, and finally a few examples of current results obtained by digital image processing.

LINEARITY AND DYNAMIC RANGE OF SENSORS

One of the major problems of satellite image recording is the large dynamic range of surface brightness exhibited by satellites. For example, a specular spherical satellite will show a mirror-like reflection of a solar image, having the surface brightness of the sun itself, from a small portion of its surface. The rest of the surface may be diffusely reflecting, and it is shown in Appendix 16 that the brightness ratio can easily be greater than 50,000:1.

Typical sensors that have been used for recording include film and image orthicons. The dynamic range of faster films tends to be greater than that of slower films. Fine-grain slow-speed emulsions have a dynamic range of 2 decades. A fast film such as Royal-X has a range in excess of 3 decades with normal processing. In Appendix 17, J.H. Altman discusses various films, such as XR (extended-range) film, which have ranges in excess of 5 decades. These ranges are obtained by other than normal processing. The useful dynamic range of a film is, of course, the range over which the film is linear or at least nonzero gamma correctable.

Image orthicons typically have a dynamic range of 2.5 decades and vidicons about 3 decades, with some prospects of extension to as much as 4 decades.

Magnetic tape recording systems such as video (TV) tape recorders or instrumentation recorders typically have a dynamic range of 40 dB. This range is set by the electronics, mechanical components, or the tape itself. The instrumentation recorder in use at the Cloudcroft facility is limited by flutter and wow. The video recorder is limited by the tape and electronics. Tapes have been demonstrated that are capable of 50 dB; however, the electronics of the recorder require very careful calibration to make use of this range.

DATA INPUT TO PROCESSOR

Film Scanners

As has been noted, the digital computer performs processing operations with great precision. The precision limitations of the image restoration are due, therefore, to the limitations in precision of the input data. If we are working with degraded images on film, then the fundamental limitation of the operation is the film granularity. The function of the film scanner is to extract the information from the film and transfer it to the computer without loss of precision. This means that the scanner must have a noise level somewhat lower than the film noise level.

A considerable quantity of appendix material (Appendixes 18 through 20, by J. L. Harris, R. V. Shack, and H. L. Kasnitz, respectively) has been written on film scanners and will not be repeated here. There are many design choices available. Light sources can be tungsten lamps, lasers, or cathode-ray tubes; photodetectors can be multiplier phototubes, image dissectors, or television camera tubes; scanning can result from moving the film, moving a physical aperture positioning a cathode-ray tube spot, or electromagnetic deflection in image dissectors or TV camera tubes.

For each specific scanning application, the design must be carefully considered with respect to optical resolution, problems of flare or stray light, adverse effects of coherent film illumination, and system stability and noise level, in order that the scanner can perform its mission of extraction of information from the film without contamination.

There are no fundamental reasons why we cannot achieve film scanners of adequate precision and sufficient speed to meet any reasonable requirements for processing of film images of satellites, although at the present writing such scanners cannot generally be regarded as "off-the-shelf" items.

Magnetic Tape Systems

Orthicons, vidicons, and other similar devices produce an electrical output which may be directly recorded on magnetic tape or other suitable medium. The recording may be either analog or digital.

Analog Recorders are characterized by their bandwidth and their dynamic range. Frequency modulation is usually employed to provide for the necessary low-frequency response. Presently available recorders offer a bandwidth of about 5.5 to 6.0 Mcps, with an S/N ratio of 43 to 46 dB peak signal to root-mean-square (rms) noise.

The dynamic range of the recorder should match the dynamic range of the sensor used. The resolution of a tape recorder is usually set equal to its S/N ratio. Thus a 40-dB dynamic range means that one could recover 20 voltage levels from the instrument and each level would have a "one-sigma" probability of being correct due to the added white noise of the recorder.

Several possibilities for reducing the dynamic range of the signal to a level compatible with the recorder are available. Radar systems often use logarithmic intermediate-frequency amplifiers to compress the dynamic range of the signal, and recovery of data extending over 60 to 80 dB in dynamic range may be accomplished to an accuracy of between ± 1 and ± 0.5 dB. Similar accuracies may be expected from specially designed video logarithmic amplifiers.

When the dynamic range and the accuracy available with analog recording are sufficient to handle the dynamic range of the sensor or the expected dynamic range at the picture, there is no a priori reason to digitize the data at the sensor. Digitization of the data tape can be accomplished at the computer, and the input data can be slowed down if necessary to digitize and enter the data in one continuous operation.

Digital Recording must be used at the sensor whenever the dynamic range and/or the accuracy required exceeds the capability of the analog recorder. It is necessary, of course, to have a voltage-to-binary converter than can digitize the analog signal to the required accuracy in the required sampling time. A 30-cycle framing rate over a 500 by 500 element field produces data at a rate of 7.5×10^6 samples per second. Analog-to-digital (A/D) converters exist that can digitize to at least 9 bits (512 parts) at a 10-Mcps sample rate, and digitization to 10 or 11 bits should be possible. The capabilities of the A/D converter will limit the maximum framing rate that can be used.

Once the data are digitized, any reasonable bit rate may be continuously recorded. Modern computer-type digital recorders can handle data at rates of the order of 10^5 8-bit words per second. Such recorders are thus not efficient for very high bit rate applications. However, techniques are available to record digital information at high bit rates on conventional analog tape recorders. Lincoln

Laboratory has recently recorded data on 14-channel 1.5-Mcps bandwidth instrumentation recorders at the rate of 10^6 bits per second per channel, and there is reason to expect that still higher bit rates may be possible with low error rates. Thus, for example, 11 bits at a 7.5-Mcps rate, or 82.5 megabits per second, could be recorded on six standard instrumentation recorders.

Photoelectric Arrays

The sensor elements which are convenient to use in image recording, such as film and TV camera systems, fall considerably short of attaining the precision of measurement set by the photon limit. It is therefore tempting to consider the eventual use of photoelectric sensors which can achieve substantially higher S/N ratio. The obvious bottleneck is the number of units in an array which would be necessary to record a significant number of image resolution elements. Some speculations along this line may be found in Appendix 21.

NUMERICAL TECHNIQUES

Digital Fourier transformation by the conventional direct method can be quite time consuming if a large number of points are to be considered. The computing time is proportional to N^2 , where N is the total number of sample points, or to M^4 , if the points are arranged in an $M \times M$ array as would be common for image processing.

An ingenious combinational algorithm, originally suggested by Good and developed by Cooley and Tukey, makes the computing time proportional to $N \log_2 N$, and simultaneously reduces the storage requirements and roundoff errors. The Cooley-Tukey method is described in detail in Appendix 22. Here we shall merely give an idea of the time reductions which it permits. The following data are based on the use of an IBM 7094 with certain additional assumptions.

<u>N</u>	<u>Direct</u>	<u>Cooley-Tukey</u>
64 x 64	8 min	3 sec
256 x 256	30 hr	1 min
512 x 512	20 days	5 min
1024 x 1024	1 year	20 min

One should not read too much into the particular time estimates given above, inasmuch as computer speeds are still on the increase. Also, the estimates were based on the assumption that the computer memory is large enough to store all the input samples, which would be true only for the first line in the case of a 7094. (The problem of insufficient storage is discussed in Appendix 22.) However, the tremendous relative advantage of the Cooley-Tukey method is obvious.

Similar improvements can be had in the computation of convolution integrals. Here the most efficient procedure is to take Fourier transforms by the Cooley-Tukey method, multiply the transforms, and then take the inverse transform of the product, again using the Cooley-Tukey method. More details are given in Appendix 22.

Finally, Appendix 23 indicates that the computation time for a two-dimensional convolution can be greatly reduced when the kernel is separable (i. e. , a product of functions of one variable). This may well occur in the problem of restoring long-exposure atmospherically degraded images.

DATA OUTPUT; DISPLAY REQUIREMENTS

The output from digital processing is a set of numerical values which define the restored image. These data must be transformed into image form. In view of the modest number of picture elements associated with satellite photography, the display requirements for such images can be easily met. For example, we might picture a CRT display of this information, developing persistence either by rapid repetitive scan or by using storage-tube techniques. Such a display can be readily photographed for permanent record and detailed observation. The limited dynamic range of the CRT phosphor is of no consequence if the system is sufficiently stable or repeatable, since any given point on the picture may be repeated as often as necessary to realize the full dynamic range of the recording material.

Since the image display system becomes a tool for the image interpreter, it would be well to include in the system extensive manual control of display characteristics. These might include variable clipping levels, conventional contrast enhancement, and, perhaps more generally stated, the ability to present the image with any desired characteristic curve for the display. Another possibility for aiding the interpretation function might be the ability to superimpose isoluminance contours on the displayed image.

EXAMPLES OF CURRENT RESULTS

Various examples of long- and short-exposure images degraded by heat-generated turbulence and restored by digital Fourier transformation techniques are shown in Appendix 1. This work was done at the Visibility Laboratory of the University of California, San Diego. Figure 9 of the present section shows a typical short-exposure point-spread function and a degraded numeral 5 taken at the same instant, together with the restored numeral 5. Additional details of the restoration procedure are given in Appendix 1.

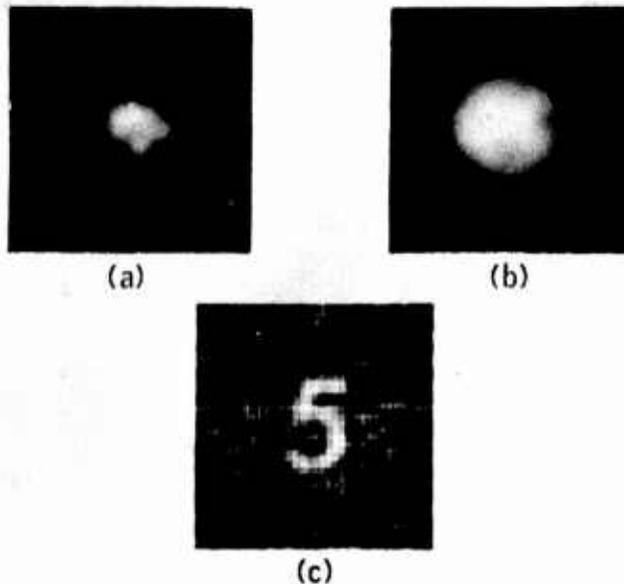


FIGURE 9 (a) Turbulence-degraded point-spread function; (b) turbulence-degraded numeral 5; (c) restoration of numeral 5.

An example of a photograph re - stored at the Jet Propulsion Laboratory using digital convolution⁵ is shown in Figure 10. This is a picture of a footpad of the Surveyor spacecraft and the adjacent lunar surface. The enhancement which was applied to the photograph⁶ consisted of a correction for the modulation transfer function (MTF) of the television camera system as measured before the flight, out to the 20 percent point on the MTF curve; in other words, the maximum amplification applied to a spatial frequency amounted to 5:1.

Optical Analog Processing

PRINCIPLES OF OPTICAL PROCESSING

Digital processing of imagery is an extremely valuable research tool. Versatile and nearly noise-free, it is well adapted to the investigation of basic phenomena in the laboratory. Digital techniques, however, deal with an essentially one-dimensional stream of information. Thus two-dimensional images must be scanned, digitized, and the information stored in the computer. The computer must, in general, perform two-dimensional transform or convolution operations; and finally, the data must be reconstructed into an image. The time required for all these operations depends critically on the number of resolution elements in the image to be processed.

While time delay and equipment complexity are justified in the research laboratory, some practical image-processing problems, such as in aerial reconnaissance work, may require very rapid processing rates. If spatial frequency filtering is the required operation, an optical analog computing system can accommodate these large rates.

⁵R. Nathan, "Digital Video-Data Handling," Tech. Rept. No. 32-877, Jet Propulsion Laboratory, California Institute of Technology, January 5, 1966.

⁶D. R. Montgomery and F. J. Wolf, *IEEE Spectrum* 3, 8, 54 (Aug. 1966).

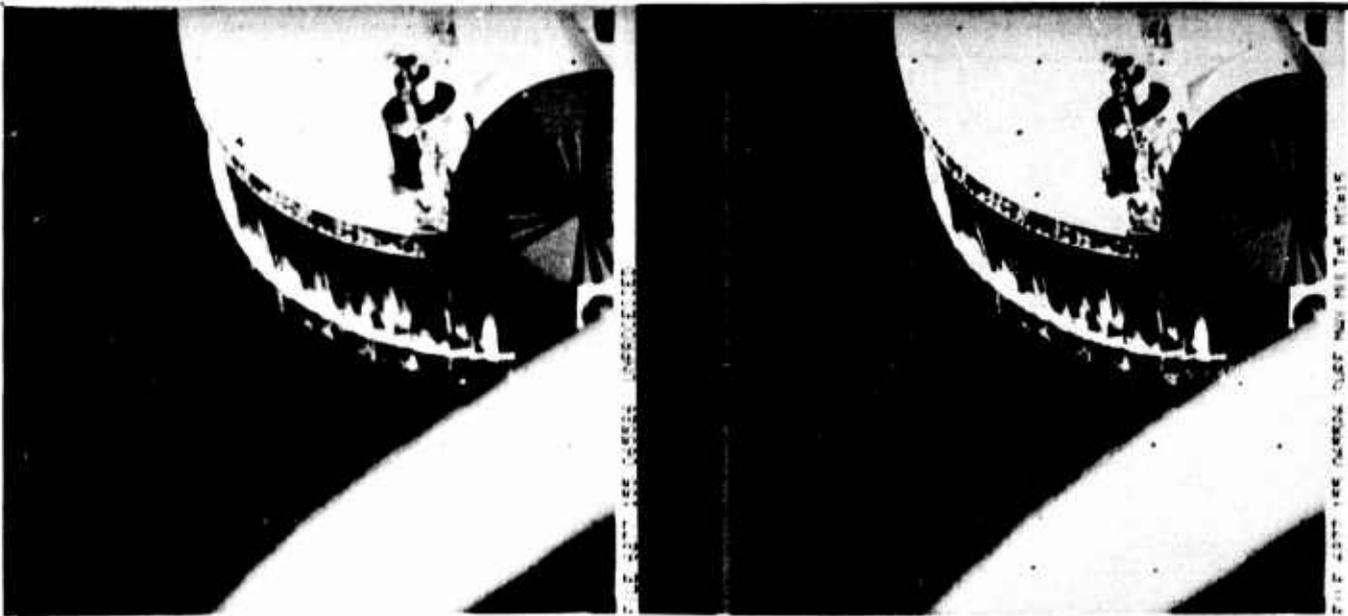


FIGURE 10 Surveyor Mission A, spacecraft footpad. Left, before enhancement; right, after enhancement.

Although both coherent and incoherent techniques have been employed for analog computations, the former are by far the most versatile and useful. The basic principle on which an optical analog system works is the following: If a lens is placed a focal distance away from a transparency, the light at the focal distance away from the lens on its output side is distributed according to the two-dimensional spectral analysis of the object. In coherent systems it is the amplitude, and in incoherent systems it is the intensity, which is thus transformed. A spatial frequency filter can be provided by placing at the output focus a transparency whose transmittance varies in any desired manner, and the inverse transform of the filtered image may then be produced by a second lens another focal distance away. More generally, all the well-known tools of Fourier transformations and linear systems analyses are realizable in optical analog systems.

ADVANTAGES OF OPTICAL PROCESSING

The primary advantages of optical analog techniques for large-volume image processing are speed and simplicity. The utility of the optical analog computer for image enhancement results from a good match of problem and solution: Imagery is basically two dimensional, and optical systems process in two dimensions. The optical computer has no scanners or other moving parts. The usable object format size is limited only by the physical size of the lens. The data processing rate is set by the time required to expose the output (filtered) image. Typically, an entire 9 in. x 9 in. aerial reconnaissance photograph can be processed in tens of seconds.

In its simplest form, a coherent optical analog filter is merely a transparency which varies the light amplitude in the Fourier transform plane. The transmittance of the filter can be arbitrarily modified by density modulation of fine-grain silver halide film. If the desired filter function is complex, i. e., if phase as well as amplitude variations are needed, then it is possible to use an interferometric technique which has been developed by Vander Lugt for producing arbitrary complex optical filters (Appendix 24).

In some applications, the form of the filter may be known, but the absolute scale may vary from one picture to the next. A simple optical system (see Appendix 25) allows one to arbitrarily change the scale of the filter function. The operator can continuously vary this scale and simultaneously observe the filtered output until an optimum image is obtained.

LIMITATIONS OF OPTICAL PROCESSING

Noise in Coherent Optical Systems

Noise is probably the biggest factor against using the cw laser directly in a coherent optical system. Due to the large spatial coherence of the laser, dust, lens scratches, bubbles, and other imperfections generate individual diffraction rings. If low-quality lenses are used in a system, the final output picture may contain considerable diffraction noise. Lenses which perform well in incoherent light often prove useless in coherent light due to bad "cosmetic" quality.

In developing coherent optical systems for performing analog computations, several techniques have been developed to reduce the noise to a tolerable level.

Reduction of Spatial Coherence. Many applications do not require the extreme spatial coherence of the laser. Destroying some coherence merely enlarges the resolution element in the Fourier transform plane, since the transform plane image is convolved with the image of the source. One has the option of destroying the spatial coherence of the laser or of using a high-intensity arc source, a pinhole to give some spatial coherence, and an interference filter to give some temporal coherence. A relatively large arc source and pinhole may be satisfactory for restoring long-exposure turbulence-degraded images, where all that is required is a real smoothly varying transfer function to accentuate high spatial frequencies.

Improvement of Lens Quality. Since each lens adds its own diffraction noise, one major advantage of the image enhancement system is its simplicity (compared with coherent optical radar processors, for example). The image

enhancement processor has only two lenses after the entrance pinhole. Over the past several years, several optical component manufacturers have become familiar with lens cosmetic quality requirements for coherent optical processors. Much higher-quality lenses have become available within the past year. Thus the source of much of the noise has been removed.

Time Averaging of Noise. If the preceding techniques fail to reduce the noise level sufficiently, time averaging techniques have been proposed. For example, the input film could be translated linearly through the system in synchronism with the output recording film. Since the noise is stationary in space, it would average out on the moving recording film. Alternatively, the lenses could be rotated about the optical axis. The image theoretically remains stationary, but now the noise contributed by the rotating components averages out. Although these techniques have not yet been tried experimentally for the image-restoration problem, the optical system is simple enough to make it very likely that noise can be successfully controlled.

Photographic Linearity

The silver halide photographic process is very nonlinear. A coherent optical analog system responds to the amplitude transmission of film. On the straight-line portion of the conventional photographic curve of density versus log exposure (Hurter-Driffield curve), we can write

$$T_A = KE^{-\gamma/2}$$

where T_A is the amplitude transmission, E is the exposure (product of light intensity and time, neglecting reciprocity failure), and γ is a constant. Positive transparencies correspond to negative γ and vice versa. In the context of coherent optical processing, the photographic emulsion is said to be linear if $\gamma = -2$, so that

$$T_A = KE .$$

Linearity, in the sense just defined, is essential to a coherent optical analog system. Nonlinearity generates harmonics of the spatial frequencies; and if the amplitude of the n th harmonic of a spatial frequency f is comparable to the amplitude of the frequency component nf in the original object, the latter component may be completely masked by the nonlinearity. This is particularly critical in turbulence restorations, where we are attempting to accentuate the higher spatial frequencies by several orders of magnitude over the lower frequencies. Harmonic distortion may not be detectable on the degraded photograph, but may be revealed by the restoration process.

A technique which has been used (Appendix 26) to obtain linearity for coherent optical processing is to contact print a low-gamma negative onto a high-gamma positive, so that the resulting gamma product is equal to 2. With reasonably careful manual developing procedures, this contact print can be made linear within 1 percent over 12 to 15 dB of dynamic range. A simpler method has been demonstrated in which Kodak Minicard Film is reversed by a procedure which gives the required gamma with a dynamic range of at least 12 dB (Appendix 27).

Photographic film is linear only over a portion of the H-D curve. In general, for analog processing the film must be pre-exposed by a uniform light level to bias it above the toe of the H-D curve. Digital processing can take advantage of a larger useful dynamic range, because in principle the computer can measure the H-D curve and compensate the input data over the entire curve.

Some idea of whether a photographic emulsion is sufficiently linear to be useful in a given analog processing situation may be obtained as follows. The major distortion introduced by nonlinearity will be generation of the second harmonic of each spatial frequency component. If the second harmonic distortion is 1 percent, then the required differential processing gain per spatial frequency octave would have to be 100 to 1 before the second harmonic distortion would be equal to the desired spatial frequency amplitude in the same band. As indicated in Appendix 26, harmonic distortions of less than 1 percent have been obtained routinely, using the contact print technique. It appears that this will be good enough for some useful restoration applications. Experimental verification is required.

Dynamic Range

The total dynamic range of coherent optical filters may be inadequate for some applications. For example, in some of the digital reconstructions reported in Appendix 1, the intensity of the highest spatial frequency was multiplied by a factor of 1,000. In a coherent system, this would correspond to 60 dB in intensity, a range which nobody has yet been able to achieve in an analog system except by paying a big price in resolution. One might possibly achieve the desired result by filtering twice.

Filter Generation Time Delay

To generate new filters, a separate photographic process is required. The time to make a filter varies from several minutes to several hours, depending on the application. If a processing impulse response function is available on film, a

complex spatial filter (interferometric type) can be exposed and processed in less than 5 min. If an amplitude transfer function is specified analytically, it may take several hours to draw the function on paper and photographically reduce it onto film.

In an operational situation, one would hope to maintain a library of filters, which can be interchanged in a few seconds. This is definitely feasible in the linear motion and out-of-focus correction problems, where the processing transfer function is known in advance. It is to be hoped that the digital research programs will yield a set of optimum filters for the atmospheric turbulence case.

DEMONSTRATION OF IMAGE ENHANCEMENT USING ANALOG TECHNIQUES

We now describe an experiment to demonstrate the restoration of long-exposure turbulence-degraded images by analog spatial filtering.⁷ As is well known,^{8,9} the effect of a turbulent atmosphere on a long-time-exposure image is simply to multiply the free-space transfer function of the lens by a transfer function which depends on the statistics of the atmosphere. There is some experimental evidence (e.g., time exposures of stellar images) which indicates that the average point-spread function of the atmosphere is symmetric about its center of gravity, so that the corresponding transfer function is real. In principle, it is then straightforward to record the point-spread function photographically and to fabricate the inverse filter.

For use in a coherent optical processor, we need to record the image intensity, $I(\vec{x})$, on a positive transparency whose amplitude transmittance, $T_A(\vec{x})$, is proportional to the image intensity; i. e.,

$$T_A(\vec{x}) = KI(\vec{x}).$$

As discussed above, this means we require $\gamma = -2$; and the image contrast must not exceed the film's input dynamic range. Whenever this condition is not satisfied by the existing aerial image, a modified exposure can always be obtained by adding a uniform exposure before, during, or after the aerial image exposure. In the experiments to be discussed here, this type of linear storage was actually accomplished by initially recording the aerial image on Kodak Panatomic-X film, processing for $\gamma = 1/2$, and then contact printing onto Kodak High Resolution plate and processing for $\gamma = 4$.

⁷P. F. Mueller and G. O. Reynolds, to be published.

⁸R. E. Hufnagel and N. R. Stanley, J. Opt. Soc. Am. 54, 52 (1964).

⁹G. O. Reynolds and T. J. Skinner, J. Opt. Soc. Am. 54, 1302 (1964).

The same basic procedure was applied in each experiment. A degraded image $I_i(\vec{x})$ was obtained by incoherently imaging an object transparency $I_o(\vec{x})$ through an aberrating medium, and the long-exposure image was linearly stored. In addition, the long-exposure point-spread function $I_p(\vec{x})$ was obtained separately by letting the object be an effective point source. After being stored linearly, this long-exposure point-spread function was Fourier transformed to yield the system transfer function $\tau(\vec{k})$, from which the inverse was produced photographically. In the experiments described here, the transfer function of the medium purposely degrades the image much more than the transfer function of the lens-film combination, $\tau_o(\vec{k})$. In fact, the object bandwidth is sufficiently limited so that $\tau_o(\vec{k})$ is essentially unity over the region of interest. Next, the degraded image transparency was placed in the object plane of the system shown in Figure 11. Upon Fourier transformation, the product of the object spectrum times the system transfer function, namely $\tilde{I}_o(\vec{k})\tau(\vec{k})$, appears in the transform plane. When an inverse filter $1/\tau(\vec{k})$ (i. e., the inverse transfer function of the average atmospheric variations) is properly inserted in the transform plane and the resulting amplitude distribution retransformed, the enhanced image $I_o(\vec{y})$ appears in the image plane.

Before showing the results, we will point out some practical difficulties in fabricating an inverse filter. We want a filter that characterizes the inverse of the random medium transfer function. As already noted, we expect the long-exposure transfer function to be real. However, this is not enough to insure that we can make the inverse filter. The transfer function must also be positive and have finite contrast — contain no zeros — to make the inverse filter photographically. We then require the photographic storage to be such that the amplitude transmittance is inversely proportional to the square root of the exposure. This requirement is met when $\gamma = 1$, so that

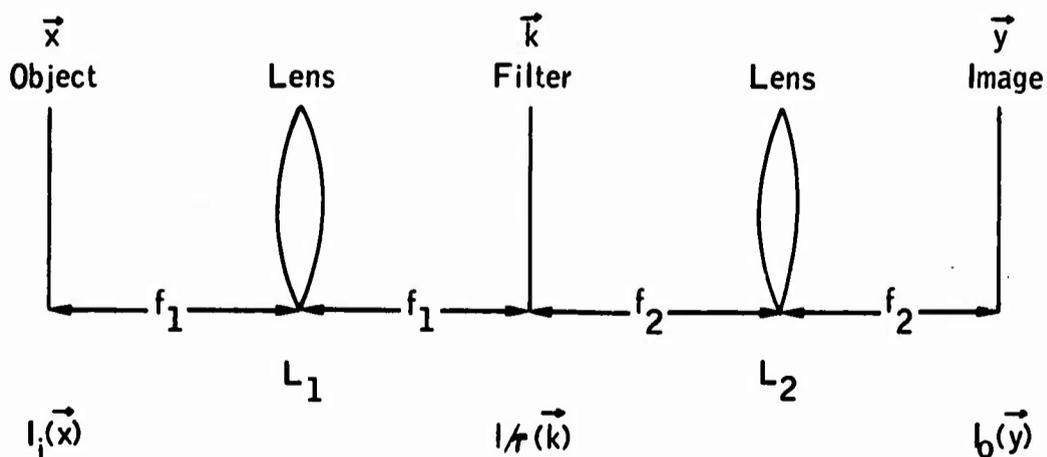


FIGURE 11 Experimental filtering setup.

$$T_A(\vec{x}) = \frac{K}{\sqrt{E(\vec{x})}} = \frac{K}{A(\vec{x})}$$

where $A(\vec{x})$ is the amplitude modulus. For the last equation to be generally valid, the contrast of $E(\vec{x})$ must not exceed the useful dynamic range of the recording film. Unlike the linear process with $\gamma = -2$, the exposure for inverse storage cannot be modified to satisfy the dynamic range condition by adding a uniform exposure.

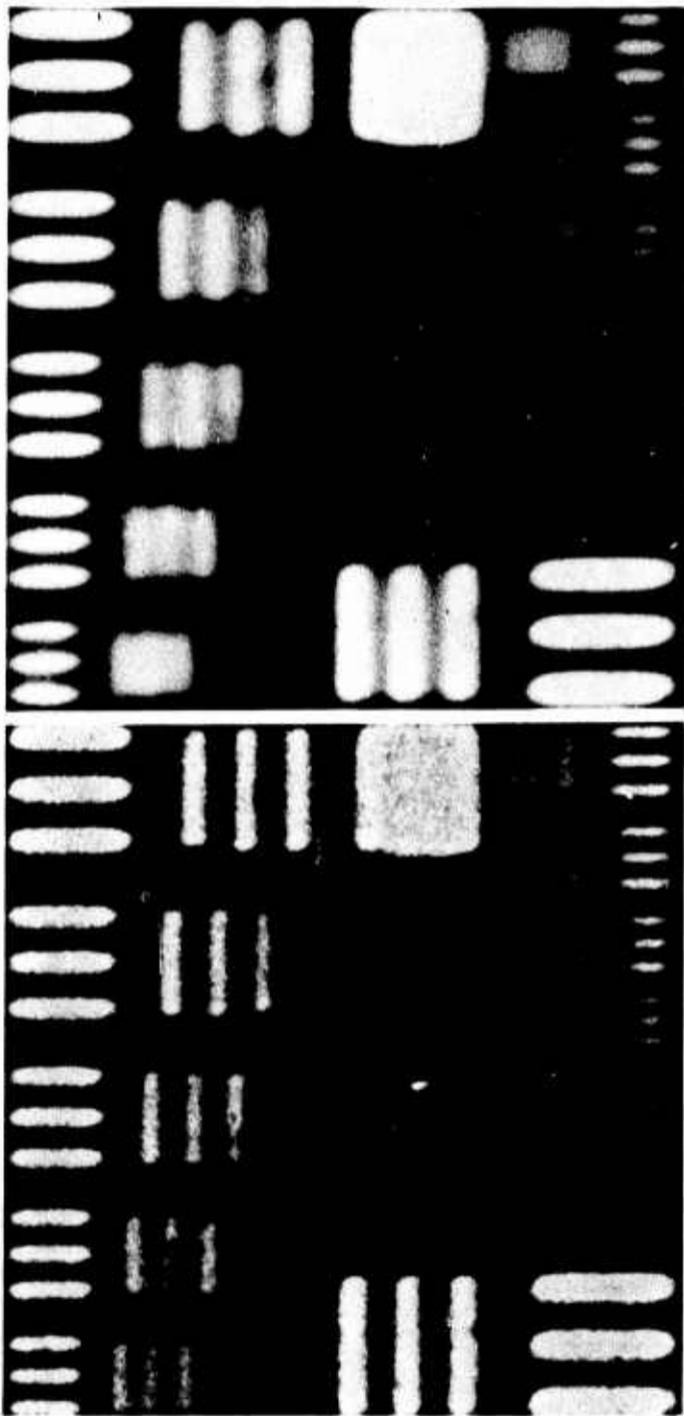


FIGURE 12 (a) Bar target degraded by strong heat-generated turbulence; (b) restoration by coherent analog filtering.

In the actual experiments, we prepared the two targets for the imaging system. In each target, a point source was placed in the center of the target. This was done to insure that the point-spread function and the degraded image were subjected to the same averaging procedures. A hot plate with a variable thermostat produced the random medium. Figure 12(a) shows a bar target photographed through a severe heat, and Figure 13(a) shows a printed target photographed through a moderate heat. In both cases, the exposure times were on the order of 30 sec, so that appreciable averaging occurred during the exposure. The enhanced photographs resulting from coherent filtering of these aberrated images are shown in Figures 12(b) and 13(b).

COMBINED DIGITAL AND ANALOG SYSTEMS

It will be apparent from what has gone before that in several ways digital and analog image-processing techniques are complementary to each other. One might therefore imagine the ultimate image-processing facility as combining the best features of both in an on-line operation. Some

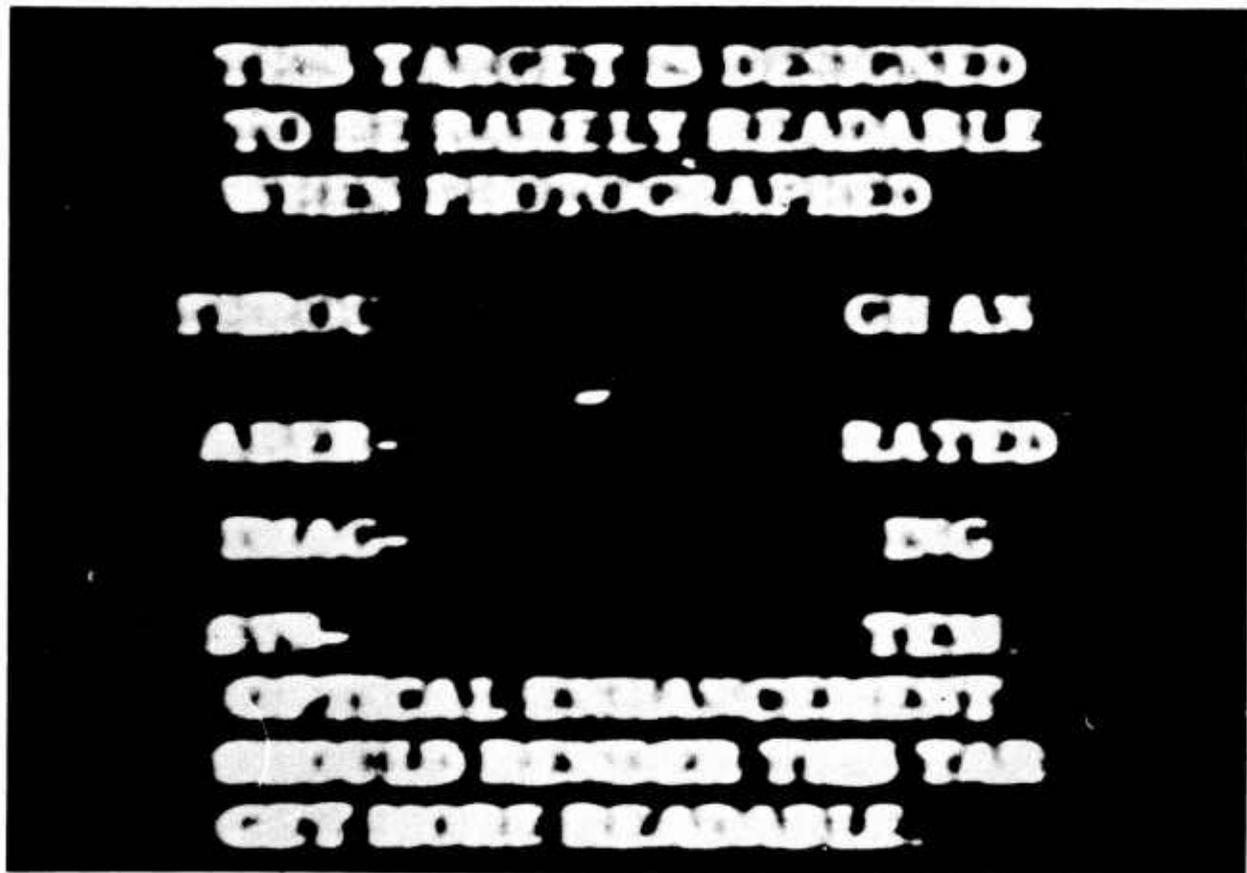


FIGURE 13 (a) Printed target degraded by moderate heat-generated turbulence; (b) restoration by coherent analog filtering.

preliminary thinking along this line is recorded by T. S. Huang and H. L. Kasnitz in Appendix 28.

Analog Processing by Corrective Convolution

PRINCIPLE

So far we have discussed digital computer processing in both the spatial frequency domain and the spatial domain, and optical analog processing in the spatial frequency domain by coherent reimaging. Optical analog processing in the spatial domain can also be done by convolving the blurred image with a corrective function using incoherent image formation. The fundamental problem here lies in the fact that negative intensities or transmissions are not achievable in incoherent imaging, yet the corrective convolving function must have negative lobes if any improvement is to be realized.

What one must do to overcome this difficulty is to form two images, one convolved with the positive portion of the corrective function, and the other convolved with what will be in effect the negative portion of the corrective function, although the latter must of course be a positive function during the formation of its image. The difference between these two images in register will be the corrected image.

A relatively simple way of achieving this result involves a modest modification of a scanning system wherein the transparency is scanned simultaneously with two noninteracting beams where, instead of the usual approximation to a point source for the scanning function, each beam has the appropriate shape to produce the corrective function. For example, if two apertures are made optically coincident by means of a beam splitter, and if they are illuminated with polarized light so that each is polarized at right angles to the other, then they can be imaged onto the transparency to be scanned, and the transmitted light can be separated by means of polarizers in front of two photocells. The outputs from the photocells are then fed into a differential amplifier which accomplishes the differencing, and the output of the amplifier is used to drive the playback system. The corrective function of course would be designed to correct for the normal scan and playback degradation as well as for the degradation which occurred in the formation of the transparency.

This method of corrective convolution by incoherent imaging is at present being pursued at the Optical Sciences Center of the University of Arizona. It has only recently been proposed and the construction of the apparatus is under way. No results are yet available.

ADVANTAGES

The principal advantages of this method in contrast with other methods are as follows. In contrast with digital methods, this method is inexpensive (no computer required) and the processing time is zero (assuming that the digital methods also require scanning and playback). In contrast with coherent reimaging techniques, this method operates by incoherent image formation, and is thus free of disturbance from the phase structure in the film and support and from parasitic interference effects which plague coherent image formation. Also the filtering masks are somewhat easier to make because they are pure transmission filters and need no phase masking. In contrast with electronic analog processing, which is similar except that the image is processed during its existence as a time-dependent electronic signal, the optical method provides the proper two-dimensional correction, whereas the electronic analog process is essentially one dimensional, and it is extremely difficult to provide proper correction in the direction perpendicular to the scan direction.

LIMITATIONS

In principle, this method is no more restricted in its ability to restore a linear isoplanatically formed image than any other method. It does, however, suffer from a number of practical limitations. First, for its operation to be correct, it must operate on a linear positive transparency, and the range of linearity considerably restricts the dynamic range over which the image can be allowed to vary without significant impairment of the correction. Then there are questions as to the accuracy with which the masks can be made to provide the proper corrective function and the flexibility with which they can be changed. Also, because the scanning element is no longer a point source but a complicated extended distribution, conventional use of a flying-spot scanner tube is out of the question, and either a complicated scan function on the tube or replacement with an optomechanical mechanism is called for. In either case, maximum scan rates will be considerably lower than is the case for the usual scan system.

IV WAVEFRONT- RECONSTRUCTION IMAGING OF COHERENTLY ILLUMINATED OBJECTS

In a conventional imaging system, a combination of lenses and/or mirrors is used to form an image and cast it onto an energy-sensitive surface, where the image is recorded. We consider here an alternative possibility, namely that of recording the energy distribution that is directly incident on the collecting aperture of the system; under certain conditions, which will be discussed here, an appropriate operation on the recorded energy distribution will yield a pair of images of the original object. This alternative image-forming technique, which is based on the principles of "wavefront-reconstruction imaging" or "holography,"^{10, 11} will be seen to be potentially immune to many of the atmospheric effects that degrade the quality of directly formed images. As in the case of processed conventional images, the ultimate resolving power of the imaging system is the diffraction limit of the collecting aperture. However, for the imaging technique discussed here, this limit can be approached with the use of only one simple postdetection processing operation, namely a Fourier transformation.

¹⁰D. Gabor, *Nature* 161, 777 (1948); *Proc. Roy. Soc. (London)* A197, 454 (1949); *Proc. Phys. Soc.* B64, 449 (1951).

¹¹E. N. Leith and J. Upatnieks, *J. Opt. Soc. Am.* 52, 1123 (1962); *J. Opt. Soc. Am.* 53, 1377 (1963); *J. Opt. Soc. Am.* 54, 1295 (1964).

FUNDAMENTALS OF THE PROCESS

Wavefront-Reconstruction Imaging in the Absence of a Random Medium

Referring to the geometry of Figure 14(a), suppose that a point-source object is placed at distance R from a collecting aperture of diameter D . In addition, let a mutually coherent "reference" point source be placed at distance δ from, and approximately coplanar with, the object. In the absence of a random medium, the pattern of interference between the object and reference waves across the collecting aperture consists of a series of uniform, equally spaced, sinusoidal fringes of intensity. Let this interference pattern be recorded on film, and let a positive or negative transparency be produced. If care is taken to assure that the amplitude transmittance of the transparency is linearly proportional to intensity incident during exposure, then that transparency has the properties of a sinusoidal amplitude grating. Referring to Figure 14(b), if the transparency is placed in a collimated coherent beam and followed by a converging lens, then in the back focal plane of that lens will appear three bright points of light, namely the three diffraction orders generated by the grating-transparency. The zero-order component, appearing on the lens axis, is not of interest, for it is present even

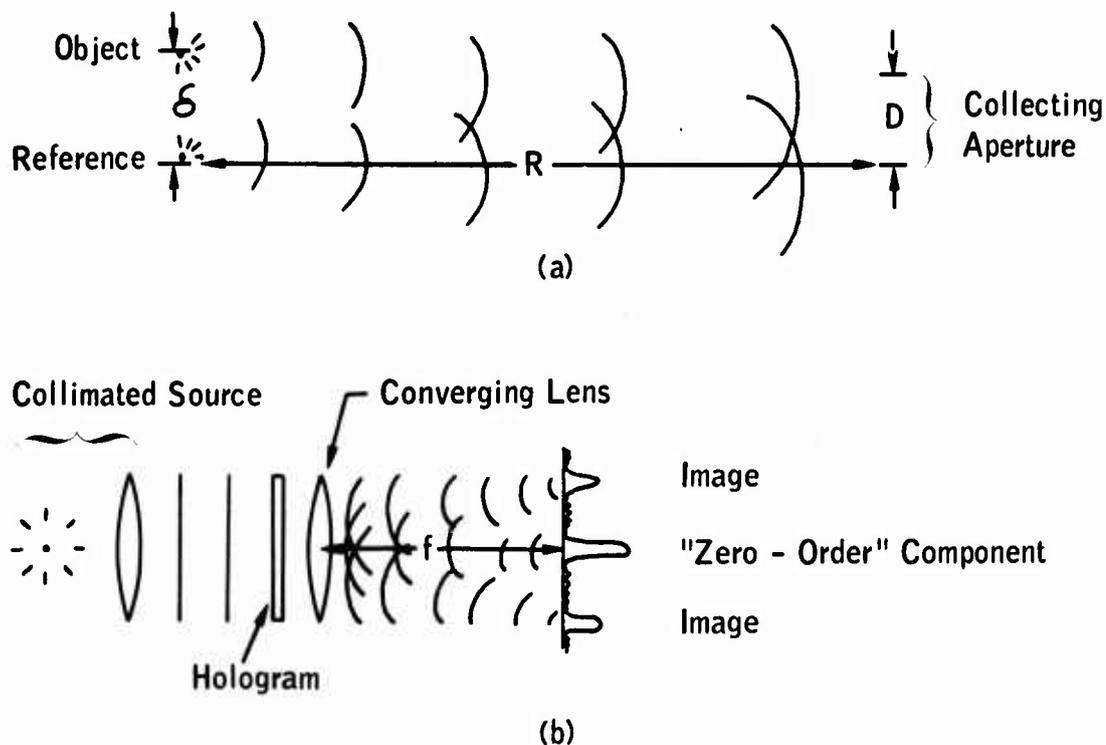


FIGURE 14 (a) Recording the hologram; (b) reconstruction of the twin images.

when the object point source is absent. The two first-order components, deflected to opposite sides of the lens axis, are direct results of the presence of the object, and may be regarded as images of it. Thus a pair of twin images of the object have been reconstructed from the recorded interference pattern.

When a more complicated object, consisting of a multitude of point sources, is present, each object point interferes with the reference to produce a sinusoidal fringe pattern with a period determined by the spacing of that object point from the reference. Thus a sinusoidal grating is produced by each object point, and a pair of twin images of each such point is produced at precisely the proper location in the image plane, yielding a pair of twin images of the entire object.

In this explanation of the image-forming process, we have neglected the intensity variations generated by the interference of each object point source with each other object point source. These object-object interference effects may be neglected when either of the following two conditions is satisfied: (1) The maximum width of the object is less than the minimum spacing between the reference and object; or (2) the total energy density incident from the object at any point on the collecting aperture is less than the energy density incident from the reference. The latter condition will be satisfied in most of the problems of interest here.

Wavefront-Reconstruction Imaging in the Presence of a Random Medium - Heuristic Treatment¹²

Suppose that a stationary phase-perturbing screen is introduced at distance p from the collecting aperture, as shown in Figure 15, and consider the effects of that screen on the interference pattern across the aperture. Again assuming a point-source object for simplicity, two spherical waves are incident on the screen, diverging from two spatially separated points. Immediately behind the screen appear two expanding wavefronts that have been randomly warped by passage through the screen. If at any given point on the collecting aperture the rays incident from both sources have undergone nearly identical phase shifts, then to a first approximation the pattern of interference is unaffected by the presence of the screen. However, such a situation will occur only with certain restrictions upon the distance from the screen to the collecting aperture and on the coherence width of the wavefronts emerging from the random screen. These restrictions will be perfectly satisfied if the random screen is situated immediately against the collecting aperture, in which case the two rays striking any point on the

¹²J. W. Goodman et al., Appl. Phys. Letters 8, 311 (1966).

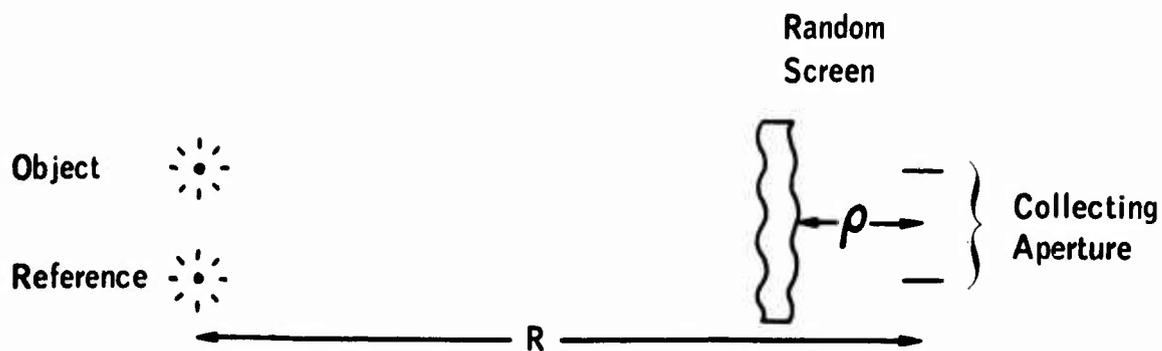


FIGURE 15 Introduction of the random screen.

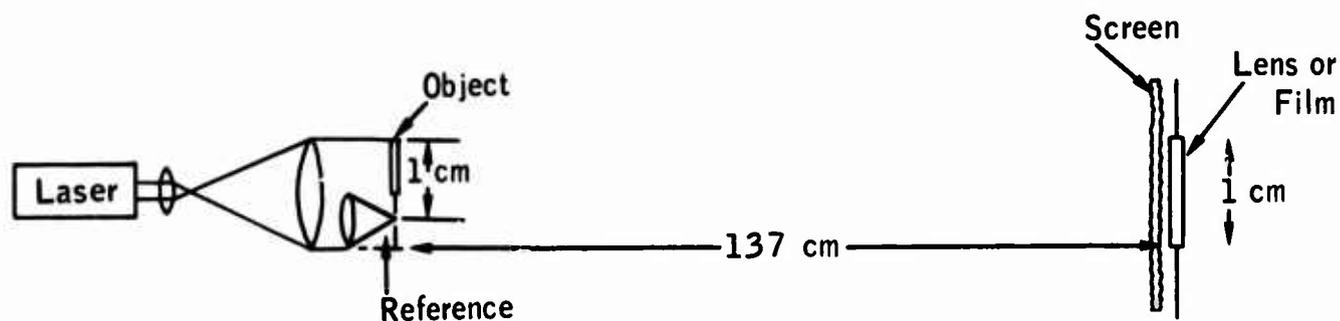


FIGURE 16 Geometry of the experiment.

aperture have undergone exactly the same phase delays. Thus phase perturbations close to the collecting aperture have relatively little effect on the quality of the reconstructed images. Note that it is precisely these same perturbations that degrade the quality of a conventionally formed image most severely!

Experimental Results

A number of experimental results are available that confirm the basic predictions of the heuristic treatment. Figure 16 illustrates the experimental arrangement that has been used. A helium - neon cw laser emitting coherent 6328 Å light illuminates an object that consists of transparent letters "STANFORD" on an opaque background. In addition, a portion of the laser light is focused to a bright point in the plane of the transparency to serve as a reference. The distance between the top of the letters and the reference point is about 1 cm. At a distance of 137 cm from the transparency is a collecting aperture of 1 cm diameter, in which is placed either a positive lens for the case of conventional imaging or a piece of photographic film for the case of wavefront-reconstruction imaging. The



FIGURE 17 Conventionally formed image - no random screen.

diffraction limit of such an aperture will yield about twenty resolution cells from top to bottom of each object letter.

Figure 17 shows a conventionally formed image of the object and reference, obtained in the absence of a random medium. Note that the slight granularity of the letters confirms that the resolution limit of the system is being approached. Next, a random medium, consisting of the shower glass shown in Figure 18, is inserted immediately in front of the collecting aperture, yielding the conventionally formed image shown in Figure 19. Note that the resolution capability of the system has been completely destroyed.

The random medium is now removed, and the lens is replaced by a piece of Kodak 649F film. The collecting aperture remains unchanged at 1 cm diameter. The pattern of interference incident on the aperture in the absence of the random medium is recorded and the resulting transparency is placed in the optical system of Figure 14(b). Figure 20 shows the distribution of light intensity across the back focal plane of the reconstructing lens, showing the pair of twin images, each of quality comparable with that produced by the unperturbed conventional system. The random medium is now reinserted in its original position immediately in front of the collecting aperture. The reconstructed image obtained in such a case is shown in Figure 21. The image appears to consist of a diffraction-limited version of the object superimposed on a blurred background.



FIGURE 18 The random screen.

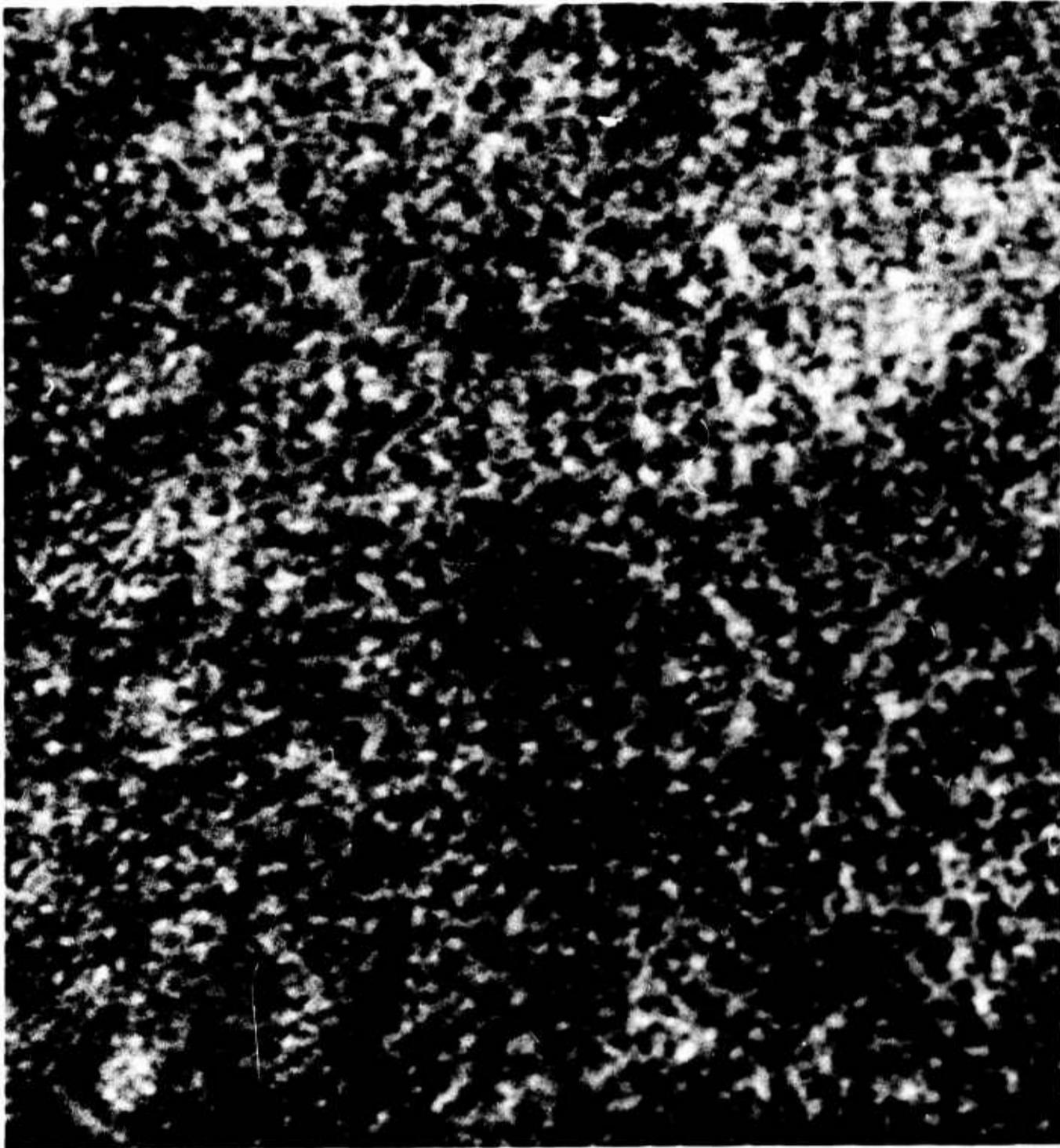


FIGURE 19 Conventionally formed image -- random screen present.



FIGURE 20 Wavefront-reconstruction image – no random screen.

The origin of the blurred background is the random amplitude variations of the waves incident on the recording aperture after passage through the perturbing medium. While phase variations of the two wavefronts will cancel, the amplitude variations will not, thus leading to a random amplitude modulation of the recorded interference pattern. Additional effects of this unwanted amplitude modulation are discussed on page 59.

A limited number of other experiments have been performed, including successful imaging through a beaker bottom (both stationary and moving) and through turbulent hot water. The blurred background of the images in Figure 21 was found to disappear when the medium was time-varying over the exposure duration.

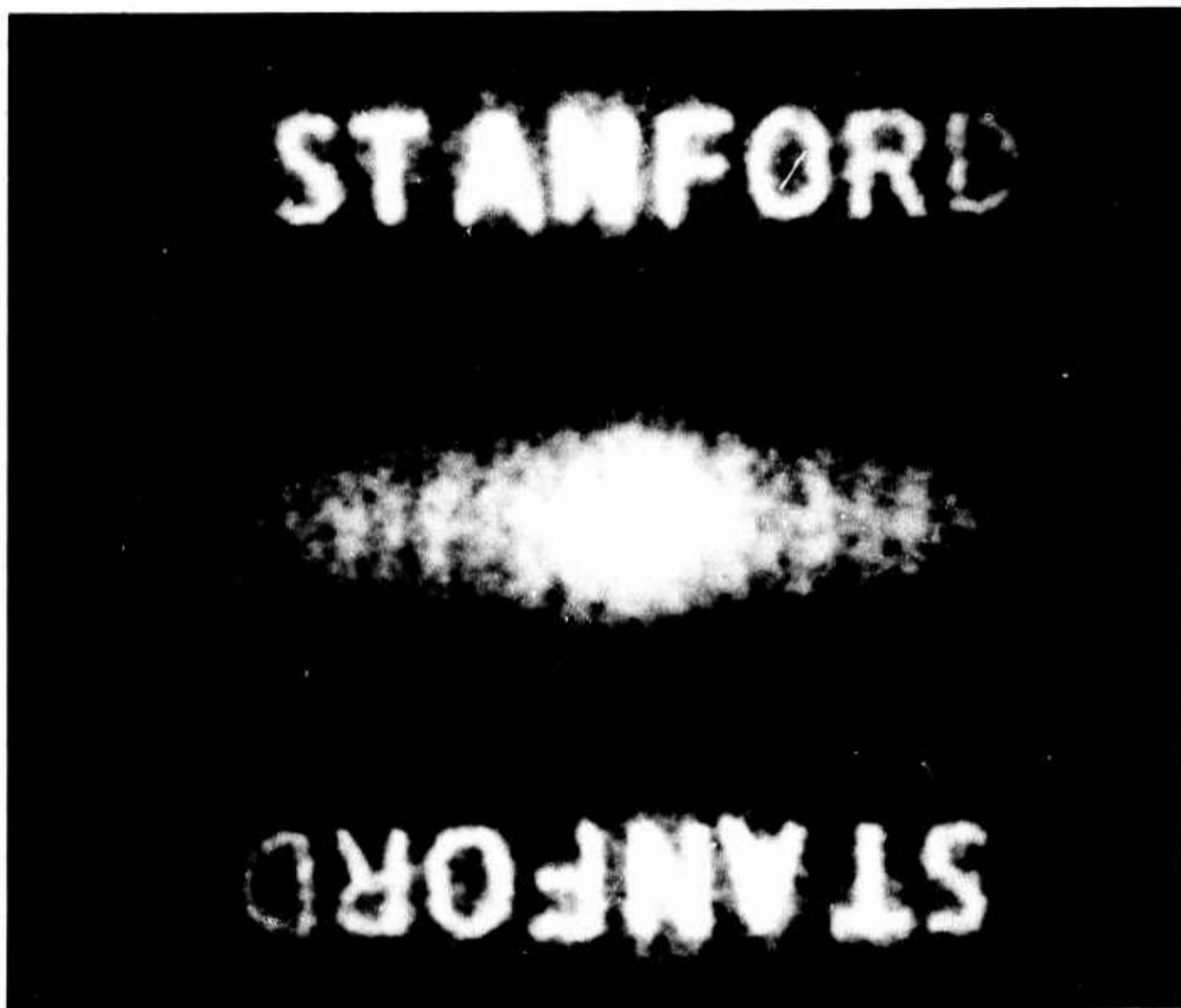


FIGURE 21 Wavefront-reconstruction image – random screen present.

The Isoplanatic Condition and the Fresnel-Zone Condition

A more rigorous formulation of the problem of wavefront-reconstruction imaging through random media can be constructed from the Kirchhoff diffraction integral as a starting point. Such a development is carried out in the first part of Appendix 29. The results of that analysis show that two conditions are required for the formation of an undistorted interference pattern in the presence of a thin random screen:

- (1) The "isoplanatic" condition

$$\delta \ll (R/\rho)\Delta ,$$

where δ is the maximum object-reference separation, Δ is the correlation width of the wavefront emerging from the random screen, with R and ρ defined in Figure 15; and

- (2) The "Fresnel-zone" condition

$$\sqrt{\lambda \rho [1 - (\rho/R)]} \ll \Delta .$$

The isoplanatic condition is, of course, simply a restriction on the angular subtense of the object and reference. The Fresnel-zone condition is, in effect, the requirement that the random screen be so close to the aperture that diffraction effects are negligible.

While both conditions are required for the formation of an undistorted interference pattern, it is important to consider the effects of violating the Fresnel-zone condition, for indeed diffraction effects can be quite significant for layers of the turbulence located near the tropopause. The results of violating this condition are therefore investigated in the second part of Appendix 29, where it is shown that the sole consequence of diffraction effects is the introduction of a random intensity modulation across the interference pattern. The analysis assumes, of course, that the isoplanatic condition remains satisfied. The reader may also consult Appendix 30 for a discussion of diffraction effects for a specific type of nonrandom perturbing screen.

Finally, it should be pointed out that, while the analysis has assumed a thin random screen, the results can readily be extended to a thick medium, composed perhaps of a multitude of layers. Effectively, the wavefront-reconstruction

system removes the image degradation introduced by those layers of turbulence for which conditions (1) and (2) are satisfied. The result is an image that is comparable in quality to that produced by a conventional imaging system operating through only those layers of turbulence for which conditions (1) and (2) are not satisfied.

Effects of Random Intensity Variations

As discussed above, when diffraction effects are not negligible, the interference pattern is perturbed by a random intensity modulation. The effects of this random modulation are extremely important, for it introduces a random noise in the reconstructed image, thus providing a fundamental limit to the quality of the image data. A detailed analysis is carried out in the second part of Appendix 29, where it is shown that two major sources of noise arise: (1) light is deflected out of the strong zero-order component and may tend to obscure parts of the object that lie close to the reference; and (2) a portion of the light in the images themselves is spread out, yielding a diffraction-limited image superimposed on a blurred background.

The signal-to-noise (S/N) ratios associated with these effects are also investigated in the second part of Appendix 29. The image degradation caused by the light deflected out of the zero-order component is found to depend critically on the relative strength of the reference and object. This effect places an upper limit on how much stronger than the object the reference should be. The effects of the light deflected out of the images themselves are more difficult to predict, for the resulting image quality appears to depend on the structure of the image itself. We must, for the present, simply refer to experimental results, such as those shown in Figure 21, to verify that usable S/N ratios can be achieved in practice. This particular aspect of image degradation requires further investigation before any more complete conclusions can be reached. In particular, the crucial question of what S/N ratios can be achieved in the real atmosphere must be answered.

Effects of Time Variations of the Random Medium

We consider next the effects of time variations of the random medium on the quality of the reconstructed images. Suppose that the Fresnel-zone requirement (2) and the isoplanatic requirement (1) are satisfied. The changing phase perturbations of the random medium result in changing phase distributions of the object

and reference waves at the collecting aperture. However, under the two conditions cited above, the temporal phase variations of the reference and object at any point on the recording plane are identical, yielding an interference pattern that is unaffected by the changes of the medium.

When the Fresnel-zone inequality approaches equality, the effects of random intensity variations must also be considered. In such a case the time variations of the random medium will actually improve the quality of the reconstructed images. As the medium changes during the recording interval, the "hot spots" of intensity move across the collecting aperture, yielding a time-integrated intensity distribution that is more uniform than the instantaneous intensity distribution. More precisely, if $a^2(t)$ is the time-varying intensity incident at a specified point on the detector, the mean value of

$$\int_0^T a^2 dt$$

increases with exposure time T , while the standard deviation increases as $\sqrt{T\tau}$, where τ is the correlation time of $a^2(t)$. Thus the S/N ratio is increased by a factor T/τ when the medium changes with time. The general prediction of an improvement of S/N ratio with changing media has been verified experimentally although no quantitative measurements have been made.

APPLICATION TO THE PROBLEM OF IMAGING SPACE OBJECTS

Obtaining the Reference

Perhaps the most fundamental question to be answered in applying wavefront-reconstruction techniques to the problem of imaging space objects is that of how to obtain a reference. For the case of a cooperative target, the answer is straightforward. A cube-corner retroreflector, or an array of such retroreflectors, can be attached to one end of the target or extended out from the target on some appendage. The radar cross section of the cooperative reflector must be sufficiently great to assure that the reference energy will drive all the detector elements into a useful range of operation, i. e., produce an output that is at least comparable with the rms detector noise. In addition, the angular divergence of the reflector should be sufficiently large to avoid angle-aberration problems. An array of small diffraction-limited cube-corners would therefore seem desirable.

For the case of an uncooperative target, the reference problem is a more severe one. The possibility of supplying the reference from a high-flying airplane or balloon is considered in Appendix 31, where it is determined that this approach is not feasible at present due to the extreme positioning accuracy required of the reference vehicle to assure that its reflector lies within an isoplanatic patch. In addition, extreme requirements are placed on the coherence length of the optical source by such an approach (see Energy and Coherence Requirements, page 68).

A more attractive possibility is that of using a strong specular glint off the target itself as a reference. Such specular glints are commonly observed when space targets are viewed in sunlight, and in fact are a major problem in obtaining good images in the conventional manner, due to the limited dynamic range of available detectors. It seems probable that such glints will also be observed when the target is coherently illuminated, and the possibility of using these specular reflections as references should be given serious consideration.



FIGURE 22 Conventional image of a .45 caliber bullet.



FIGURE 23 Wavefront-reconstruction image of the bullet shown in Figure 22, without a separate reference.

The feasibility of the above ideas has been tested in a laboratory experiment. A .45 caliber bullet was illuminated by cw 6328 Å laser light; a conventional image of the bullet is shown in Figure 22. Note in particular that the rounded nose of the bullet is providing a relatively strong specular reflection, while the rear of the bullet is less strongly reflecting. Next let the camera lens be removed and replaced by a piece of photographic film of equal aperture size. If the pattern of interference generated by the bullet alone is recorded, the reconstructed image of Figure 23 can be obtained in the usual fashion. Again it should be emphasized that no reference was supplied in this case other than the specular reflection from the nose of the bullet. The twin images generated by the wavefront-reconstruction

process are readily identified in the picture. The resolution retained in the images is excellent, although there is considerable image noise. This noise could be substantially reduced if more care were taken in the two photographic steps of the process.

It is clear that the ability to obtain good wavefront-reconstruction images of objects by use of a specular reflection as a reference is very heavily dependent on two requirements. First, the specularly reflecting area must be located near the edge of the object in order that the twin images do not overlap. Second, there must be a single strong specular reflection.* Multiple specular reflections of roughly equal intensity will produce a number of overlapping images, thus hindering the problem of object identification. Note that both these requirements imply that several holograms must be recorded before a favorable orientation and geometry are obtained by chance. However, the target can be illuminated many times during a single pass, so the probability of obtaining a good image on each pass may be high. Experiment will, of course, be the true test of this conjecture.

There are two other questions concerning the reference that must also be answered, namely, the effects of the finite size of the specularly reflecting area and the effects of motion of the reference and object. These questions are considered in the two sections immediately following.

Effects of Finite Reference Size

When specular reflections from the object are used as a reference, the effects of finite reference area on the resolution in the reconstructed image must be considered. As a first fundamental point, if the size of the specularly reflecting area is smaller than the size of a diffraction-limited resolution cell on the object, then there exists an equivalent point-source reference that will produce the same field distribution observed across the collecting aperture of the receiving system. Thus when the specularly reflecting area is not resolvable by the diffraction-limited collecting aperture, the finite size of the reference will not degrade the resolution in the reconstructed image.

If the size of the specularly reflecting area exceeds the size of a diffraction-limited resolution cell, then degradation of resolution will result. To estimate the seriousness of this degradation, we may use the following argument. Let the distributed reference be envisioned as consisting of a multitude of point sources closely packed. Each point reference generates a pair of twin images in the

* Techniques do exist by means of which the effects of multiple reflections can be removed. Such techniques are reported by R. F. vanLigten in Appendix 32.

reconstruction process. However, each point on the reference is in a slightly different geometrical relationship with the rest of the object, and hence the various reconstructed images will be slightly displaced with respect to each other. In effect, the resulting image is a convolution of the specularly reflecting area with the remainder of the object, yielding an image resolution cell that is about as wide as the sum of the widths of (1) the reference area, and (2) the diffraction-limited resolution cell on the object. The existence of this convolution relation should not be too surprising, for the reference and object field incident on the collecting aperture are multiplied together for the interference pattern and Fourier transformed in the reconstruction system. Thus by the convolution theorem, we would expect to find the reconstructed image to consist of a convolution of the specularly reflecting area with a diffraction-limited image of the object.

Effects of Target Motion

The applicability of wavefront-reconstruction techniques to the problem of imaging space objects depends very critically on the effects of target motion during the exposure period. Assuming that the reference is rigidly attached to the space vehicle (e. g., a specularly reflecting surface or a cube-corner), two types of motion are of primary concern: (1) linear translation of the vehicle, and (2) rotation of the vehicle. The effects of these two types of motion are investigated in the third part of Appendix 29. Angular rotation is found to place far more severe restrictions on exposure duration than does linear translation. To obtain high-quality pictures of rotating satellites, it would appear imperative that short-pulse (e. g., 20-nsec) Q-switched lasers be used as the optical source. Even when such a source is used, there can occur some extreme geometries for which large rapidly tumbling satellites will not be imaged over their full extent. However, such unfavorable conditions would not occur very frequently in practice.

Collecting Optics

The incident interference pattern must ultimately be captured by an optical system and measured. Detector surface areas are generally not large enough to allow collection of reasonable amounts of energy without the use of additional optics. Thus the primary purpose of a predetection optical system is to match the small physical size of the detector to the larger physical size of an energy-collecting aperture. A discussion of the requirements that the optical system must satisfy in order to produce high-fidelity final images is given in Appendix 33 by R. F. vanLigten.

Detector Requirements

A number of different photosensitive devices might be considered for detection of the incident interference pattern. These possibilities include image orthicons, vidicons, photographic plates and films, and photodetector arrays. The important parameters that influence the choice of a detector are: (1) the number of available resolution elements on the detector surface; (2) the "threshold energy" (i. e., the incident energy required to produce an observable effect) of a single resolution element; (3) the quantum efficiency of a single element; (4) the statistical distribution of resolution-element sensitivities; and (5) the spatial distortion inherent in the detector. The first two factors are particularly important in determining the amount of reference energy required to drive the detector to a satisfactory "bias" level. The third and fourth factors influence the S/N ratio that can be achieved in the reconstructed image when sufficient reference energy is present (see page 65). The last factor influences the fidelity and resolution of the final image.

It is important to emphasize that high resolution is generally not a necessary attribute of the detector in the applications of concern here. To record the pattern of interference generated between the light arriving from the reference and the light arriving from the object point most widely separated from the reference, the detector should have at least twice as many linear resolution elements as the number of fringes captured by the optical system. The relationship between the number of fringes, n , per unit length and the angle ϕ between reference and object points is, for small fields of view,

$$n = \phi/\lambda.$$

At a wavelength of 0.7μ , a target-reference separation angle of 20 sec of arc gives 140 fringe periods per meter. Assuming a 48-in. collecting aperture, a detector with 340×340 resolution elements would suffice. Such a requirement is within the capability of most television camera tubes. If sufficient reference energy is available at the detector, then a higher-resolution detector can be used. However, if, as in the uncooperative satellite case, reference energy is at a premium, the minimum required number of resolution elements should be used.

To provide some comparison of the various possible detectors, consider the "sensitivity thresholds" of the various candidates. Photographic film is limited by grain sensitivity and gross fog. The random variations of sensitivity from grain to grain are particularly severe when the minimum number of resolution elements must be used due to limited reference energy. Vidicons, image orthicons, and other photoelectric detectors are limited by the quantum efficiency of the

photosurface, plus detector dark current and electron beam noise. As an estimate of detector quality, the energy per resolution element required to produce an additional response equal to gross fog, beam noise, or dark current can be specified. The approximate figures (in joules per resolution element) for several typical detectors are indicated in the following table. Approximate resolution capabilities are also shown.

<u>Detector</u>	<u>Energy Threshold/ Res. Element</u>	<u>No. of Res. Elements</u>
Photomultiplier array (RCA 7265)	10^{-18}	Limited only by number of detectors used
Image orthicon (RCA 7198)	10^{-16}	10^5 resolution elements per detector
Spectroscopic plate or film (Kodak IV-N)	10^{-15}	4×10^6 resolution elements per cm^2
Vidicon (RCA 8521)	10^{-14}	5×10^5 resolution elements per detector

From the threshold energy standpoint, the photomultiplier array is most desirable (and also the most expensive when 10^5 detector elements are required). The image orthicon provides a less expensive alternative with a sensitivity that is adequate in many cases. The possible use of image intensifiers (the sensitivity of which is comparable with that of the image orthicon) should also be given serious consideration.

The question of dynamic range requirements for the wavefront-reconstruction system should be given further attention. It can definitely be said that the dynamic range requirements are less severe than for the detection of a conventionally formed image of a typical satellite. When the dynamic range of the detector is exceeded, the primary effect is the generation of multiple images. If the reference is actually a part of the object, these multiple images will overlap, thus reducing the image fidelity. However, the dynamic range of the interferogram will generally be substantially smaller than the dynamic range of the corresponding image.

Signal-to-Noise Ratio in the Reconstructed Image

The wavefront-reconstruction system may be regarded as the spatial analog of an optical heterodyne detection system. As such, it is possible to demonstrate that, for an array of detectors of uniform sensitivity, the signal-to-noise (S/N) ratio*

*By signal-to-noise ratio, we mean here the ratio of the image intensity generated by the object to the standard deviation of the noise intensity at that same point.

at a given point in the reconstructed image is

$$S/N = \frac{\eta N_p}{1 + (E_N/E_R)} \quad (11)$$

where η is the quantum efficiency of the photodetector, N_p is the average number of photons incident on the entire collecting aperture from the one object resolution cell corresponding to the image point in question, E_N is the average noise energy (due to background and internal noise*) incident during the exposure interval, while E_R is the reference energy incident during that interval. Note that, for practical reasons, the detector may have to be shuttered "on" for a time duration longer than the reference pulse duration. In such a case, the noise energy E_N is that incident during the longer period, while the reference energy E_R is that incident during the duration of the received pulse.

Background light can have two effects on the quality of the reconstructed image. First, it can reduce the S/N ratio as indicated in Eq. (11). Second, a small portion of the background can interfere with the reference to produce an image of the background source that may be superimposed on the desired image. The discussion of the temporal filtering properties of holograms in the third part of Appendix 29 implies that only that portion of the background energy that lies within a bandwidth $1/2T$ cps about the reference (where T is the duration of the reference) will contribute to the reconstructed image of the incoherent background. Thus for a 20-nsec pulse, the background sources are suppressed in the reconstructed image as if they had been passed through an optical filter of bandwidth 50 mc (0.001 Å)!

The important sources of background include the sun ($1.8 \times 10^{-1} \text{ W cm}^{-2} \text{ sr}^{-1} \text{ Å}^{-1}$), the daytime atmosphere (1.2×10^{-7}), the moon (1.3×10^{-7}), starlight and clouds. An interference filter of 10 Å bandwidth can be used before detection. The receiver field of view can be limited to the angular extent of the transmitted beam (10^{-8} sr). For the strongest sources, the anticipated background power at an entrance aperture of 1 sq m is:

Sun	$1.8 \times 10^{-4} \text{ W}$
Daytime Atmosphere	$1.2 \times 10^{-10} \text{ W}$
Moon	$1.3 \times 10^{-10} \text{ W}$

* Internal detector noise is referred back to an equivalent noise energy incident on the receiving aperture.

If the detector exposure time can be held to 1 msec and the number of detector resolution elements is 340×340 (allowing a 20-sec-of-arc field of view) the number of joules of background energy received per resolution element is:

Sun	1.6×10^{-12}
Daytime Atmosphere	1.0×10^{-18}
Moon	1.1×10^{-18}

Thus, with the exception of the direct sun, the background noise contribution is less than the internal noise of an image orthicon (cf. Detector Requirements, page 65). In addition, the image of the background, having been effectively filtered by a 0.001 \AA filter, will be entirely negligible as compared with the quantum noise of Eq. (11), even for the case of the direct sun.

For calculation of the anticipated S/N ratios that can be achieved with a specific laser, for the cases of both cooperative and uncooperative targets, see Energy and Coherence Requirements, page 68.

Analog versus Digital Processing

In the discussion of the first part of this chapter, an optical system that can produce a real image of the object from the recorded hologram was described. The basic operation performed by the system is precisely a Fourier transformation. The image intensity is thus found as the squared modulus of the Fourier transform of the recorded interference pattern.

Since the process of Fourier transformation can be performed either digitally or by the analog techniques illustrated in the first part of this chapter, serious consideration should be given to the advantages of each possibility. Analog techniques certainly have an advantage of simplicity when the interference pattern is recorded on photographic film in the initial detection process. However, when more sensitive electronic detectors are used, several advantages of digital techniques become clear. First, nonuniformity of detector sensitivity can, to a large extent, be programmed out of the system, at least to the extent that those nonuniformities are constant in time. A similar correction for spatial distortions introduced by the detector can be performed. Equally important, if there exists a strong uniform intensity on which weak fringes are superimposed, this strong background can be programmed out of the system. A similar operation with the analog system could not be performed so readily; while a large portion of the resulting zero-order spot in the reconstructed image could be blocked with a stop,

there may remain residual diffraction rings that extend out to the first-order image. Lastly, digital processing provides a greater potential accuracy in the reconstructed image data.

To illustrate the feasibility of digital techniques in the present processing problem, an IBM 360 could be provided with adequate storage, and a 512 x 512 array of outputs could be Fourier transformed in about 5 min, assuming that the Cooley-Tukey algorithm is used. In conclusion, then, the use of digital techniques to process the interferograms appears quite feasible and offers a number of significant advantages in the present application.

Energy and Coherence Requirements

To obtain successful wavefront-reconstruction images of space targets, certain rather specific requirements must be satisfied by the optical source of illumination. First, we should note that the process of hologram formation is fundamentally an interference phenomenon. To obtain interference fringes of the highest possible visibility, thus assuring the largest possible S/N ratio in the reconstructed image, the coherence length of the transmitted radiation should be as long as possible. Thus if we wish to image a target of depth d meters (along the line of sight), the bandwidth of the transmitted radiation should not exceed c/d cps, where c is the velocity of light. Equivalently, the coherence length of the source should be no shorter than the maximum depth of interest.

To image successfully the largest space objects of interest in their most unfavorable orientations, a coherence length of at least 30 m would be required. However, such unfavorable orientations occur rather infrequently, and a coherence length of 3 or 4 m should yield rather good results for most cases of interest. Note that a 20-nsec pulse occupies only about 6 m in space, and therefore a Q-switched ruby source with a coherence length of 1/2 the fundamental limit would probably be quite adequate.

The power requirements to obtain adequate illumination of space vehicles should also be considered in some detail. The energy density e (in joules/meter²) produced at a collecting aperture located at distance R from the illuminated target is

$$e = \frac{E_T \sigma t^2}{4\pi R^4 (\Delta\theta)^2} \quad (12)$$

where E_T is the total energy transmitted directly toward an object in a beam of angular width $\Delta\theta$, σ is the effective optical cross section of the object, and t is

the transmission factor for the path both from the transmitter to the object and from the object to the receiver. For purposes of later calculation, the cross section of a diffraction-limited cube-corner of side b is given by

$$\sigma = \frac{4\pi b^4}{3\lambda^2} , \quad (13)$$

while the cross section of a diffusely reflecting surface, illuminated normally and observed normally, is

$$\sigma = 4A\rho , \quad (14)$$

where A is the projected area of the target (assumed smaller than the area of the incident beam) and ρ is the surface reflectivity.

To illustrate the energy requirements, consider the following hypothetical experiment that could be performed with a cooperative satellite. Let the reference be supplied by an array of 200 1-cm cube-corners (an array of small retroreflectors is preferred to a single large retroreflector to avoid angle-aberration effects). Using Eq. (13), the optical cross section of the reference array is about $2 \times 10^7 \text{ m}^2$. We assume a 2-J Q-switched laser with a beam divergence of 10^{-4} rad. The target range is taken to be 200 km, and the atmospheric transmittance t^2 is assumed to be 0.5. Under such conditions, the energy density \mathcal{E}_R incident on the collecting optics is found to be

$$\mathcal{E}_R = 10^{-7} \text{ J/m}^2.$$

As discussed above under Detector Requirements, an image orthicon with 340×340 detector elements can be used with a 1 sq m collecting aperture to cover a 20-sec-of-arc field of view. Thus the reference energy must be divided between 115,600 detector elements, yielding a reference energy per detector element of about

$$E_R = 10^{-12} \text{ J}.$$

As pointed out in the discussion of detectors, the average noise energy per resolution cell is about 10^{-16} J for the image orthicon. Thus the reference exceeds the noise level by four orders of magnitude.

Once adequate reference energy has been assured, the energy received from a typical resolution cell on the target itself must be calculated. We suppose that the resolution cell consists of a 10 cm by 10 cm patch on the target, and that the

incident illumination is diffusely reflected from that patch. Assuming a reflectivity $\rho = 0.5$, the cross section of the resolution cell becomes $\sigma = 2 \times 10^{-2} \text{ m}^2$, yielding a total energy collected from that cell of

$$E_o = 2 \times 10^{-16} \text{ J}$$

or about 660 photons. For a detector quantum efficiency of 4 percent (S-20 photo-surface at 6943 Å), we find, using Eq. (11), that the S/N ratio in the reconstructed image is

$$S/N \cong \eta N_p \cong 26.$$

Thus a relatively noise-free image could be obtained with these parameters.

Consider next the more difficult case of an uncooperative target. We suppose that a reference is supplied by a specular reflection off the vehicle. Current estimates are that the specular reflections exceed the diffuse reflections by about five orders of magnitude in intensity. Thus knowing the cross section of a diffusely reflecting area, we can estimate that of a specularly reflecting area. Using the previously calculated $\sigma = 2 \times 10^{-2} \text{ m}^2$ for the diffuse patch, we then estimate $\sigma \cong 2 \times 10^3 \text{ m}^2$ for the specular reflection. The reference energy per detector element becomes, in this case,

$$E_R = 2 \times 10^{-16} \text{ J/res. element.}$$

Again using Eq. (11), we find

$$S/N \cong \frac{26}{3/2} = 17.$$

Thus in spite of the fact that the reference is 10^4 times weaker in the uncooperative case, the S/N ratio does not drop drastically.

In conclusion, then, a Q-switched ruby source with 2-J output in a 20-nsec pulse should yield reasonably good pictures if its coherence length is 2 or 3 m. A more conservative design might employ a laser with a 20-J output, again in a 20-nsec pulse with a few meters coherence length.

Availability of Laser Sources

We have just stated the following requirements for active imaging of space objects.

Pulse Length	20 nsec
Pulse Energy	2 to 20 J
Pulse Coherence	Half pulse length

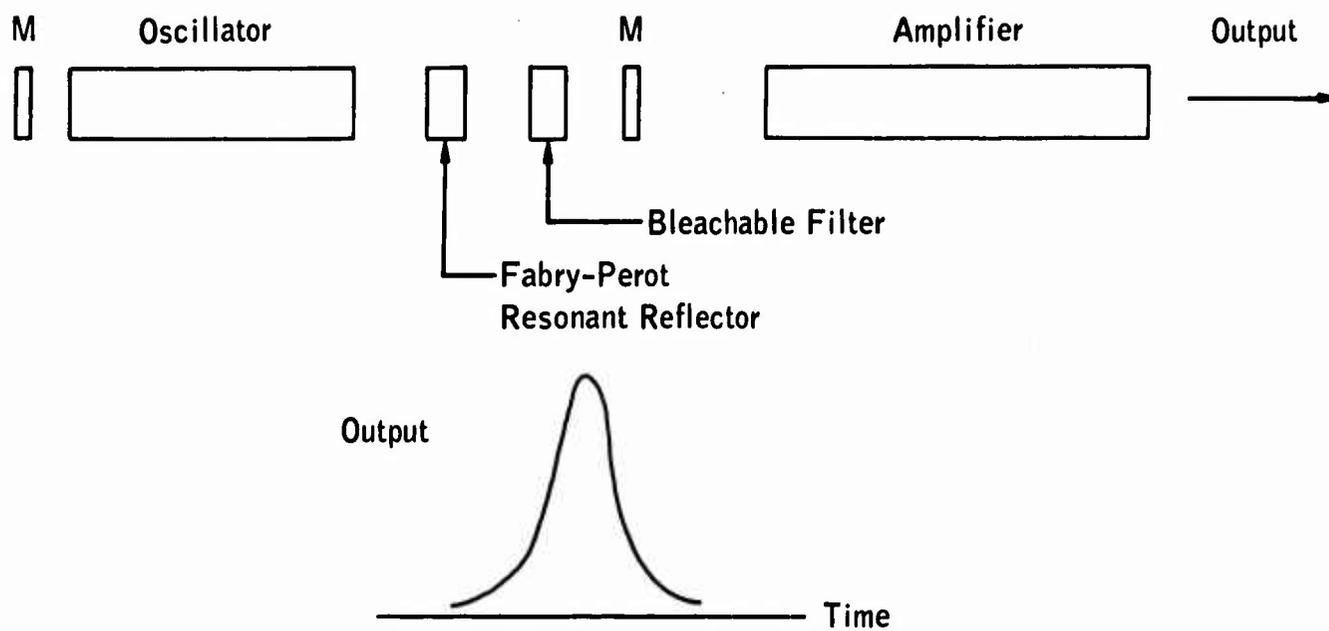


FIGURE 24 Laser oscillator amplifier combination for the production of short coherent pulses.

Both ruby and glass lasers seem to be reasonable candidates to meet these requirements. We consider only ruby because of the greatly reduced film sensitivity at the wavelength of Nd glass (1.06μ).

The required performance can be obtained by the method described by Hercher.¹³ His arrangement is illustrated in Figure 24. The oscillator is designed to satisfy the coherence and pulse length requirements. It is followed by an untuned single-pass amplifier to bring the output energy up to the required value. The bleachable filter acts as a Q-switch which keeps the spectral width of each mode within the required limits, while the Fabry-Perot resonant reflector suppresses axial modes other than the one of interest. In a 3 in. x 1 cm diameter rod, output energies of tenths of a joule are readily achievable. The output has a spectral width no larger than approximately 100 Mcps, corresponding to the pulse length when the pulse shape is taken into account. The output of the amplifier should have the same temporal coherence properties as its input, but it might be well to verify this point.*

Synchronization with an untuned amplifier should present no difficulty. Both the oscillator and the amplifier would be pumped with essentially simultaneous 10^{-3} sec pumping pulses. With the oscillator turns on, the amplifier will be sufficient to provide the required gain.

Some typical characteristics of the amplifier for a conservative design are given below for 1-cm-diameter amplifier rods.

¹³M. Hercher, App. Phys. Letters 7, 39 (1965).

*The variation of dielectric properties of the amplifier as a function of the inversion is the point at issue here.

	<u>Required Length</u>	<u>Pump Energy</u>
2-J output	3 in.	1000 J
20-J output	20 in.	6000 J

At the 20-J output level in a 1-cm rod corresponding to 10^9 W/cm² output, we are approaching the damage level for ruby.

The one difficulty with this whole approach, however, is that ideally one would like to have the returns from both the reference and object points to be relatively constant over the pulse length so that the reference signal will be large over most of the pulse length. The laser described here, and in fact Q-spoiled lasers generally, emit approximately Gaussian-shaped pulses. The rise time of a conventional Q-switched pulse is determined largely by the loop gain, while the decay is determined by the passive resonator Q. In order to flatten the pulse and make it more rectangular, some sort of controlled saturable gain mechanism would have to be introduced. One could imagine, for example, a Kerr cell in the system with a properly shaped gain controlling signal applied to it. The Kerr cell should not be located inside the cavity, since one may then encounter substantial broadening effects due to stimulated Raman and Brillouin scattering. Outside the cavity we will lose perhaps half the oscillator output, but this could be made up with more amplification. Apparently not much work has been done on pulse shaping for these very short pulses.

In summary, it seems to be a pretty straightforward matter with careful design to achieve pulses having the required energy output and coherence properties. The pulse shapes, however, are somewhat less than ideal and some effort might profitably be directed at improving them.

OTHER PROPOSED ACTIVE SCHEMES

In the course of this study, a few other schemes were suggested for using a laser to obtain image information about a satellite. Because these proposals were somewhat tangential to the main subject of image restoration, or because they were preliminary and unevaluated, they have been included in the present report only as appendixes.

In Appendix 34, R. O. Harger discusses a method for generating contours of constant depth, or range, on the reconstructed image using two holograms. This method has been demonstrated experimentally in the laboratory. There is some question whether the depth resolution (approximately 1 m) is good enough to be interesting for satellite images.

R. E. Hufnagel describes a Doppler scheme for obtaining a one-dimensional image of a satellite, in Appendix 35. It depends on the fact that if the satellite has any relative rotation with respect to an observer who continuously faces it, reflections from points at different distances from the axis of rotation will show different Doppler shifts. This permits reconstruction of the satellite's reflectivity in the direction normal to the axis of rotation; imaging in the direction parallel to the axis would have to be done by conventional means. The Perkin-Elmer Corporation has made an extensive paper study of this proposal, but no experiments have yet been done.

In Appendix 36, S. A. Collins suggests that a large telescope might be used, not as a receiver, but as a high-grade transmitter to focus a laser beam on a satellite, the beam being scanned across the satellite by means of auxiliary optics, and the reflected light being collected in a "photon bucket." The anticipated advantage would be improved S/N ratio. At the present writing, this scheme has not been studied in detail.

V PREDETECTION PROCESSING SYSTEMS

Although most of the attention of the Summer Study was directed toward what might be called "postdetection image processing" (given an image, what can we do to make its information content more intelligible?), two systems were described which in some sense use electronic means to improve the quality of an image before it is recorded. These might be called "predetection image processors." While of course neither system provides a complete answer to the problem of degraded imagery, both systems contain working hardware, and the results of laboratory tests have been sufficiently impressive to merit a description of each system in this report.

The first system, invented by R. L. Gregory of Cambridge University, involves a technique for selecting automatically, and in real time, those instants when the major features of an image are in their statistically correct positions (as determined from a previously taken long-exposure negative) and maximally sharp. It then builds up a single picture from a series of very short exposures taken at such instants of best seeing. The original purpose was to get improved lunar and planetary pictures, where the object to be photographed is available for periods of the order of an hour. Some thought has been given during the course of the study to the problem of photographing fast-moving satellites. The Gregory system is described in the following section, with some additional notes in Appendix 37.

The other scheme discussed here (see page 85) is the electronic image motion stabilization system developed by Itek Corporation. In this scheme, optical feedback is used to keep the image of a small object, or the centroid of a larger image, fixed on the retina of an electron image tube, in spite of actual motion of the object, the propagating medium, or the image tube mount. A prototype system has been built and extensively tested; frequency response is good up to 2,000 cps. It appears reasonable that the system would work satisfactorily on a large telescope.

AN AUTOMATIC REAL-TIME SAMPLING TECHNIQUE FOR MINIMIZING IMAGE DISTURBANCE

This method¹⁴ for reducing the deleterious effects of atmospheric disturbance upon telescopic images is not based upon any specific mathematical model of the physics of the atmosphere, or its changing transfer function; neither is it a technique for improving pictures already obtained. What it does attempt to do is to select automatically, and in real time, those moments when the major features of the image are in their statistically correct positions and maximally sharp. Having first established the statistical properties of the object — e. g., a planet or highly magnified part of the moon — it builds up a single picture through a series of short exposures occurring at those moments when the image satisfies a statistically correct "master." The final picture will contain more information than the original "master," since the sampling process serves to reject disturbances by selecting those moments — down to a few microseconds — when the image is at its best, over a period of minutes or several hours in duration. The final picture is thus built up of perhaps thousands of very brief exposures, which are photographically integrated to give a single picture. This should be largely free of disturbance, since displaced images are rejected by mismatch with the statistical "master." An essential feature is that the "master" gives a priori information. This is built up by the instrument itself and is not fed in by any preconceptions of the operator, who does not need to know anything of the nature of the object being photographed.

The evidence for claiming that this is a practical and useful method is primarily experimental and is not based upon a detailed mathematical analysis. It has been found to work well in the laboratory, with simulated disturbance, and

¹⁴R. L. Gregory, *Nature* 203, 274 (1964). This work has been supported financially by the Paul Fund of the Royal Society. Mr. Stephen Salter built the final version of the present apparatus.

it is about to be tested on an 8-in. telescope at the University of Cambridge with a fully engineered version of the apparatus. It is hoped to test the method on a larger telescope after these initial trials. This report will be limited to discussing its basic design features and the results of laboratory tests with controlled simulated disturbance.

Evidence that Selective Sampling in Real Time Should Be Useful

1. It is well known that planetary astronomers get better than average pictures by visually sampling those moments when the "seeing" appears best, using an electrical shutter operated with a Morse key. We will refer to this as "key sampling."

2. It is generally believed that more can be seen visually through a telescope than from photographs taken through the same instrument under similar "seeing" conditions. This is evidently due to real-time sampling by the eye and brain of the observer — which is not possible once the photograph is taken, since all the (integrated) disturbance is present simultaneously on the photograph. (A further benefit may be conferred by the eye's ability to follow, or track, selected features in motion, but this we will not attempt to simulate electronically.)

3. The best planetary photographs so far obtained are composites of several selected pictures. The selection is done after the photographs are taken and not in real time. This is an essential difference from the real-time key sampling method (mentioned in 1 above) and we will argue that it is essentially less efficient than sampling in real time.

All these methods can give some improvement. They thus serve as hints as to what might be accomplished by a really efficient automatic device working in real time. To this end, it is worth looking at the practical difficulties of the above methods (especially methods 1 and 2); for if we find that, though they are inefficient, they yet confer some benefit, then we may be encouraged to proceed with an automatic device designed to overcome their specific limitations.

Practical Limitations of above Methods

1. Key-sampling depends upon the human observer making many rapid decisions over a duration of minutes or hours. Now human observers are poor at this task for two reasons: (a) eye - hand reaction time and (b) loss of vigilance. This becomes serious after about 20 min, as found in radar operators engaged in somewhat similar tasks, when efficiency falls off dramatically. Eye - hand

response time to rather indefinite signals, such as slow changes in the clarity of an image, may be expected to be greater than 0.2 sec. We thus have the situation of real-time sampling with an "on" delay of at least 0.2 sec and an "off" delay of 0.2 sec. Given the observed rate of change of the turbulence, it is indeed surprising that such delayed sampling confers any benefit. Surely it could be improved by reducing the delay, by automatic means, to the millisecond or microsecond regions.

A further limitation of the human observer is his inability to maintain a constant criterion for sampling. An automatic system, providing specific and unchanging criteria, should be considerably better.

2. The way in which the eye and brain sample moments of best seeing is no doubt complicated, and is but incompletely understood. It is not clear how far this is pure time-sampling (analogous to a simple on-off shutter), and how far the perceptual system makes use of prior information — correct or incorrect — upon which to base perceptions of fleeting or changing objects. Considered as pure time-sampling, the visual system is limited by its sensitivity and integration time, though not, as in the key-sampling case, by reaction time; for it does not in the least matter if perceptions are delayed, provided they are accurately reported or recorded at some later time. The sensitivity of the eye is highly dependent upon its state of light-adaption. After a period of 1 hr in complete darkness, flashes of 200 quanta of green light falling upon the cornea can be detected (corresponding to about 10 quanta absorbed by the "rod" receptor cells); but under conditions of high ambient light, such as when observing the moon, sensitivity is reduced by several orders. The total range of sensitivity is about 100,000:1. Also, the eye will not integrate successive exposures having intervals greater than its essential integration time of around 0.2 sec, whereas a photographic plate can be used to integrate with long time intervals between each exposure. Time sampling of short exposures over long intervals can therefore be far more efficient for photographic plates than for the unaided eye.

3. The building up of composite pictures from a number of selected "best" pictures is essentially different, for the selection of the pictures used to build up the final composite is not done in real time. Thus, although the human observer is used for making the selections (perhaps aided by objective references, such as gratitudes, for determining the positions of each feature), he has unlimited time available for his decisions of which pictures to include. He is thus in a far better position than the key-sampler, working in real time, who is handicapped by his eye - hand reaction time. But there are still limitations. A serious difficulty is that each picture must be sufficiently well exposed to convey enough information for a decision to be taken on its quality. Now this is serious, for it sets a lower

limit to the exposure time — the time sample — of each of the pictures used to build up the composite. In practice, this means that for the moon, each constituent sample-time must be perhaps 0.01 sec. An automatic system working in real time need not be limited in this way. It need not rely upon an exposed photograph for its sampling decisions, as we will show later, and it can operate with sampling times in the millisecond, or even microsecond, range.

Further disadvantages of composite photography are the large number of photographs required for each composite and the labor required to produce it. If the exposure time were reduced, there would be a penalty in the increased number of separate pictures which would need to be taken, processed, and selected, if the improvement by sampling is to be maximal. In fact, for more or less complete information retrieval with individual exposure times in the millisecond range, one would have to contemplate several thousand processed photographs for each final composite. A system which made its decisions nonphotographically could avoid this costly and time-consuming process.

The technique to be described provides a single picture which is built up from millisecond or microsecond samples, in real time, and so the final picture is available immediately, without the delay, the cost, or the tedium of selecting the best few of many thousands of photographs, which have then to be compiled to give a composite. This is done, using defined objective criteria, upon a single photographic plate, which is immediately available for study.

General Description of Proposed Technique

The technique involves three stages. Stage 1 requires the building up of a statistically correct master negative of the major features of the object. This gives a priori information for later automatic selection in real time. Stage 2 involves a decision system, such as an electronic gate level, which may be adjusted to determine the acceptable goodness of fit with the master negative. Stage 3 is some kind of high-speed shutter, which is actuated by the "reject/accept" signal, allowing light from the telescope to reach the camera giving the final picture when disturbance is minimal. We will now describe the general principles of the equipment for accomplishing these operations.

STAGE 1

The statistical master is essentially a picture, taken through the fluctuations, with considerable exposure time. Since the disturbance is in general Gaussian, this gives density gradients of the outlines of the larger features. (Small features may

be entirely lost through smearing.) A point object, such as a star, or a barely resolved satellite, will be represented by a peak of high density surrounded by a gradient of lessening density. The region of maximum density will represent the mean position of the point object in the field of view of the instrument, which will of course be continually tracking the object throughout. We thus obtain the statistical master by direct photography, using an exposure time which is long in comparison with the bandwidth of the disturbances, so that it truly reflects the statistical nature of the disturbance.

This photographic plate is removed from the telescope and processed as a transparent negative of the (fluctuating) image. It is then replaced in precisely the same position in the telescope's optical system. The image falls upon this master negative. We now find the key feature of the scheme: whenever the image most nearly corresponds to the master negative, it is most nearly cancelled by the negative. Thus, if we allow the light passing through the negative to fall upon a sensitive photomultiplier, we find that its output is minimum when the image is statistically correct. We thus have a signal — minimum output from the photomultiplier — which indicates minimum disturbance of the image by the atmosphere, or tracking error of the telescope. In fact, we have a U-shaped voltage output, whose minimum indicates "minimum disturbance," with a sharply rising voltage for mismatch, in two dimensions of error. This minimum is unique, and therefore unambiguous, except in the special case of objects consisting of exactly repeated patterns, when we will get the same minimum should the image be displaced by multiple cycles. (This will occur only with objects such as equally spaced lines or squares, and can be ignored in the present context.) Apart from this case, the "accept" signal is unambiguous. Of course, a reject signal (rise in photomultiplier output) may represent any kind of disturbance, but for our purpose, we do not need to know what kind of disturbance has taken place. It is only the reject signal which is unambiguous, but it is only this which matters to us here.

Experiment shows that we have an extremely sensitive technique for detecting the presence of disturbance, in real time. It will detect not only lateral translational shifts of the image as a whole (as for small aperture telescopes viewing through atmospheric disturbance), but also lateral shifts of any part or parts of the image (corresponding to several disturbance "cells," found with large aperture instruments). It will detect local size changes of the image (which are frequently found in practice), or rotational shifts (which seem infrequent). Further, it will detect at least some kinds of static degeneration, though further experiment is required to determine its precise properties in this connection.

We have, then, a technique for detecting, objectively, disturbance of images in real time. From now on, the design problems are straightforward, involving conventional techniques.

STAGE 2

Having detected disturbances and obtained a unique "accept" signal, we pass this to a simple analog computer which receives the fluctuating mismatch signals. The operator decides how long he wishes to continue the sampling to build up his picture. He sets this duration (which could be, say, a minute, or several hours) into the computer which accepts the fluctuating signals. It then sets the gating level so that there will (probably) be just sufficient total exposure from the summed sample exposures to expose the plate for the final picture. The computer employs operational amplifiers with adjustable "droop rates" for this.

STAGE 3

This stage is a high-speed on-off optical shutter which allows a camera to "see" the fluctuating image only when it conforms to the statistical master. This involves a beam splitter (since the image must also simultaneously be available to the processed master negative) and a high-speed mechanical or electronic shutter. So far we have only used electromagnetically operated shutters, which give minimum exposures rather less than 1 msec, but ideally we would probably use some kind of image converter, or intensifier, with a short time-constant phosphor allowing exposures to be made down to a few microseconds. The shorter the minimum possible exposure, the greater chance we have of catching the image when it closely matches the master within the limited time available for the total sampling. It is therefore important to use the highest convenient shutter speed.

Further Considerations

If the object has some features which are slowly changing – such as shadows on the moon – the object itself will gradually fail to match the master, and so we cannot expect reliable "accept" signals for the photography. Given the system as described above, it would be necessary to raise the acceptance gate level, but this would allow samples otherwise different from the object – giving a poor final result. This situation might be dealt with by allowing the master to change slowly, either by using a sequence of photographs, or by some kind of phosphor with a suitable time constant. This might be convenient in any case, for it would avoid our having to remove the master for processing.

Can this kind of system be used for photographing satellites? Here we have no experimental data for guidance. If the satellite is stable (not spinning), then the limitation is the total observing time allowed by its rapid transit across the sky. But since it will present a slightly different view to the observer as it

transits, the useful viewing time is likely to be limited to perhaps a minute. This means that the master would almost certainly have to be made at an earlier transit.

A rapidly spinning satellite is even more difficult. Here one might try either rotating the master (either physically, or optically as with a Dove prism), or one might try adding a cyclical reject signal, allowing the system to work only when the satellite presents a chosen orientation to the observing telescope.

Will It Work?

We have built a system of this kind, and found that it works well with simulated disturbance — either simple lateral shifts produced by an oscillating Plexiglas plate placed before the optical system, or random ripples produced on a water surface through which a test object is viewed. There seems no limit to the improvement obtainable — provided there are some matching moments. If these occur with the atmosphere, we can be sure it will work for objects such as the moon or planets. Artificial satellites, especially when spinning, are more difficult and only a real trial will give the answer.

A major uncertainty at the present writing is how well the performance of the system with a small telescope (say 8 in.) can be extrapolated to a large telescope (say 48 in.). A naive argument assuming a number of uncorrelated blobs across the aperture would indicate that the probability of having all parts of the image simultaneously "right" decreases very rapidly with increasing aperture area (although of course the required exposure time is less for a larger aperture too). Again only a real experiment will give a convincing answer.

Examples of Results

Figure 25 shows a rough moon model, photographed through lateral disturbance produced by an oscillating Plexiglas plate placed between the model and the optical system.

Figure 26 shows this same model, taken through the same disturbance but with the sampling shutter operating. The reject/accept ratio sampling is set for 6:1. This gives considerable improvement, as may be noted especially in the small features, which are joined by smearing by the disturbance, but appear separated when the sampling shutter is operating. A reject/accept ratio of around 100:1 gives virtually perfect pictures.

These pictures were made with the original crude apparatus, to test the feasibility of the scheme, using camera optics and no telescope.



FIGURE 25 Rough moon model with sampling shutter inoperative.



FIGURE 26 Same model as shown in Figure 25, but with sampling shutter operating.

ELECTRONIC IMAGE MOTION STABILIZATION

Introduction

Image motion caused by air turbulence is a significant factor in the quality of photographs obtained from telescopes of moderate aperture and often a dominant factor in the case of photographs from small apertures. The ability to stabilize this motion throughout the exposure period would give the system designer an additional and important parameter to work with during system design optimization.

For example, where he may now select a fast and relatively grainy emulsion so as to permit short exposures, with image stabilization he might select a fine-grain emulsion for use with longer exposures. This will produce a better signal-to-noise (S/N) ratio in the final picture. Such photographs have clearly more potential for subsequent restoration of additional image losses. Moreover, such photographs are superior for human viewing. Experiments have been carried out in which image scale and object resolution (as tested by a low-contrast three-bar target) have been maintained constant on films of different granularity. Dramatic differences in quality are observed.

In the telescopic observation of extended astronomical objects like the moon, it is common to observe different parts of the surface moving simultaneously in different directions. For objects of smaller angular size such as satellites, there is a higher probability of coherent motion since the light bundles from all object points traverse essentially the same sample of the turbulent atmosphere. Thus the ability to stabilize an image moving as a whole is particularly applicable.

The Electronic Image Motion Stabilization System (EIMS) was designed to solve this and other image motion problems. The system has been implemented in both inertial motion sensing open-loop and optical tracking closed-loop feedback systems and applied to a number of specific problems. The following description applies to an existing closed-loop system prototype which is suitable for satellite photography.

The system is based on the fact that while under some conditions (motion, size, and brightness, for example) there might not be enough exposure to enable conventional photography of the object, there may nevertheless be enough information to determine the position (and motion) of the image. The position of an extended image can be established with an accuracy determined by the summation of the S/N ratios of all the individual elements.

If the instantaneous position of the image is known, it can be deflected in such a way that it always falls on the same place on the film. In essence, the effect of the angular motion of the object with respect to the camera can be

reduced or completely eliminated, thus allowing the exposure time, Δt , to be increased without loss of resolution due to smear. This gain in exposure time can be used to obtain pictures where pictures might not otherwise be possible because of low light level or to improve the S/N ratio so as to get more useful pictures.

Optical Feedback EIMS System

The EIMS closed-loop system presently in use is built around a specially constructed electron image tube around which two deflection coils generate electromagnetic fields to deflect the electron stream. This permits a controlled displacement in x and y of the image on the phosphor output screen. With the deflection circuits inactive, motion of the telescope image on the photocathode input of the image tube is duplicated in the output. The motion of the output is sensed by four photocells whose outputs are fed to operational amplifiers which in turn drive the deflection amplifiers to compensate the motion. The device will lock to an object whose image centroid lies in the region covered by the photocells and hold it indefinitely.

Figure 27 shows a schematic of the system. Figures 28 and 29 show the original prototype. This prototype is currently being used to drive a servo-controlled mount for a 16-in. aperture experimental telescope in which the error signals provide mechanical tracking for low-frequency image motions and electronic stabilization to reduce the higher frequencies to zero.

In experiments covering a period of over a year, the system has proved capable of locking successfully to a wide range of scenes. The system has been used quite successfully in tracking and stabilizing the motion of low-flying aircraft against a bright sky background, a condition substantially less favorable than expected for the satellite application.

System Bandwidth

Although the bandwidth of the feedback can be increased up to the megacycle region, higher light levels will be required due to the increase in noise. The prototype being tested was designed to be limited by the frequency response of the P-11 phosphor screen.

The following experiment was devised to determine the system bandwidth. The system gain was adjusted for optimum tracking of the 4-mm light spot. The feedback loop was opened and an ac signal, e_i , was applied to the deflection

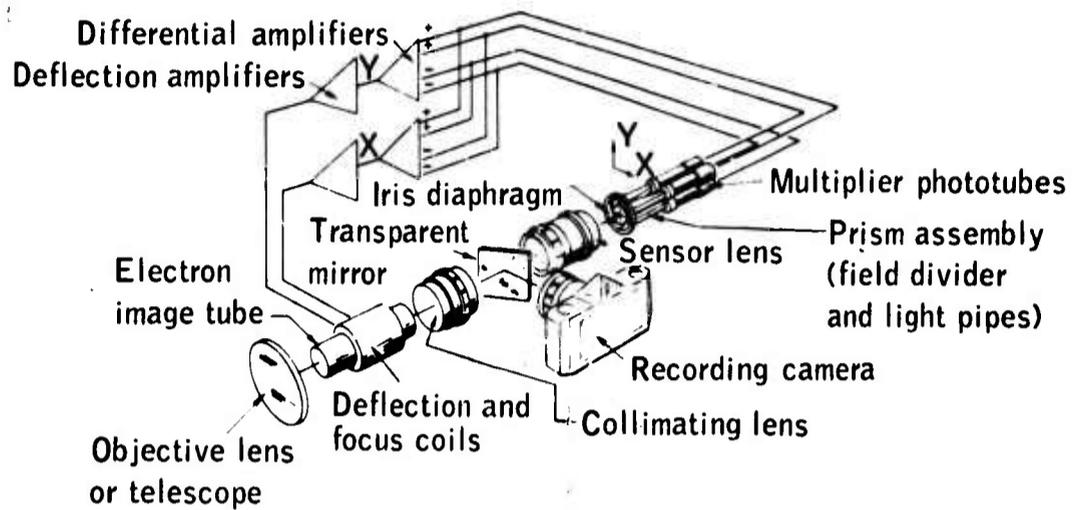


FIGURE 27 Schematic of optical feedback image motion stabilization system.

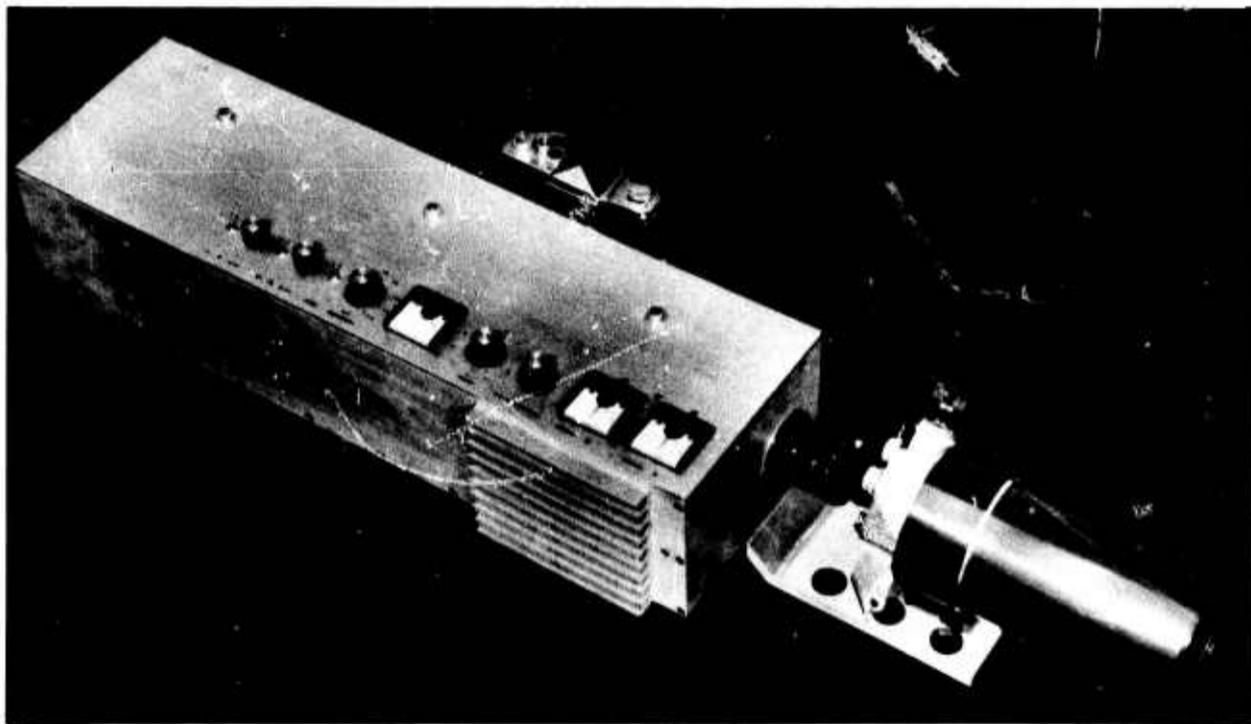


FIGURE 28 Experimental optical feedback EIMS system with 35-mm recording camera and 1,600-mm-focal-length, $f/18$ Questar telescope.

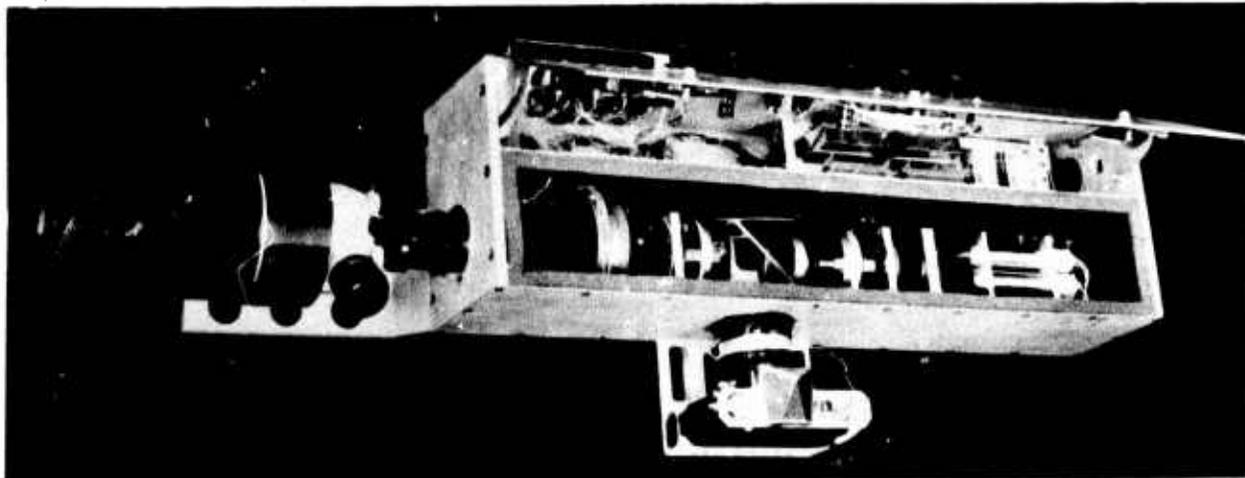


FIGURE 29 Feedback system with cover raised, showing layout of optics and electronic components.

amplifier (Figure 30). The sensor output, e_o , was measured at different input frequencies. The open-loop system function

$$G(s) = e_o/e_i$$

is plotted in Figure 31. The closed-loop response, $G(s)/[1+G(s)]$, plotted in Figure 31, represents the effective stabilization versus frequency. The error function, $1/[1+G(s)]$, also plotted in Figure 31, is the ratio of input to output motion, ignoring noise and geometrical distortions.

Clearly, the system is capable of accurately tracking motion with a spectrum up to 2,000 cps. This capability has also been demonstrated in field tests.

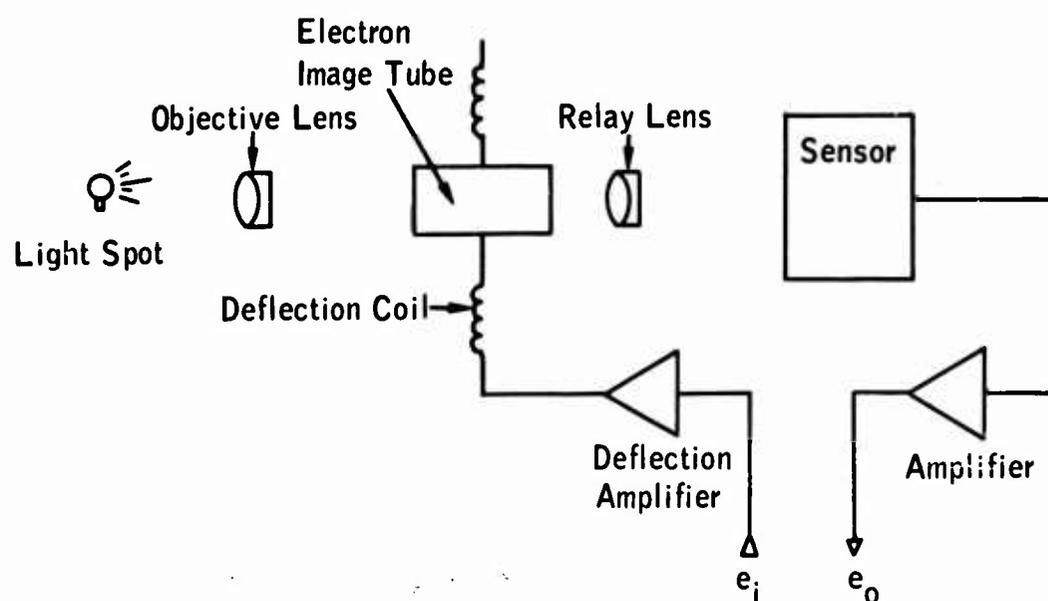


FIGURE 30 Diagram of feedback system with loop opened.

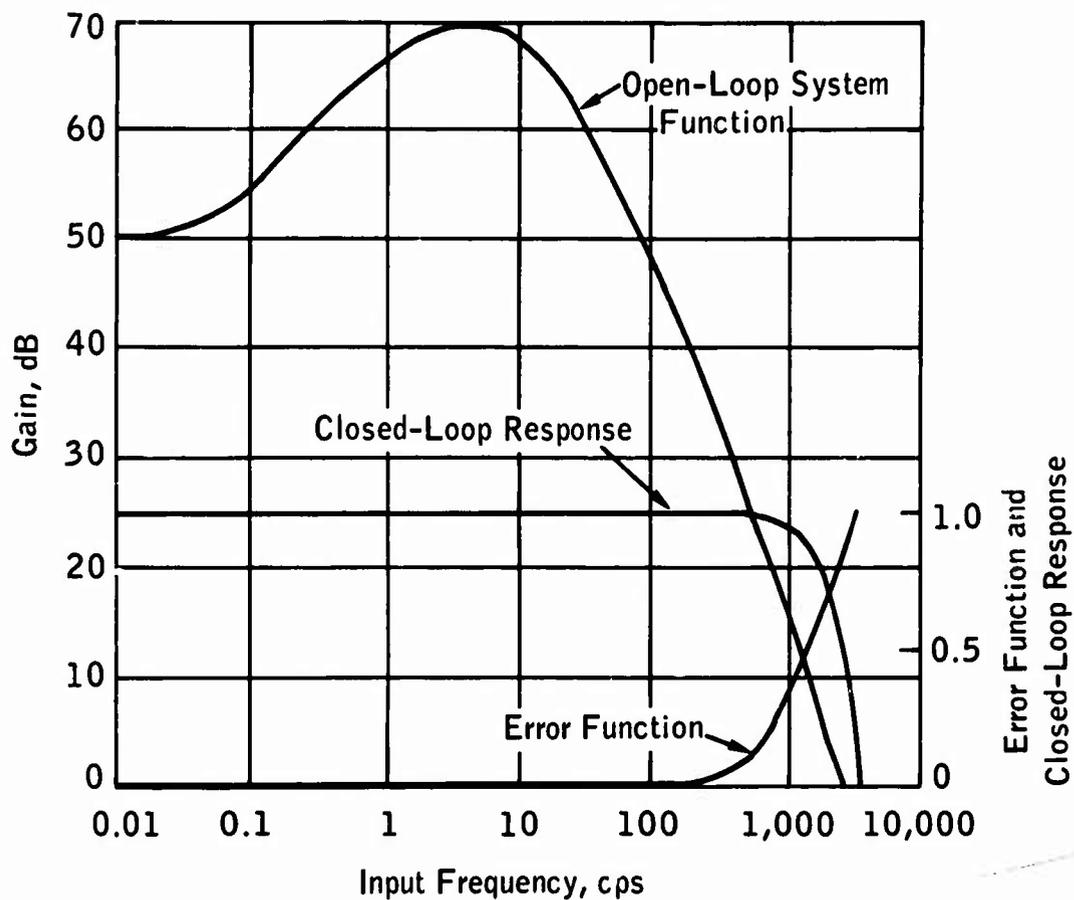


FIGURE 31 Open-loop system function, closed-loop response, and error function of EIMS system.

Calibration of Photocathode Illuminance

Targets were obtained by illuminating transparent test targets and masking them to the desired size. Absolute calibration was established by an SEI spot photometer. The light was adjusted by neutral density filters in steps of 10, using crossed polarizers for interpolated values. Table 1 gives the target brightness used and the photocathode illuminance governed by the T/22 lens. Expected absolute accuracy is within a factor of 2. The color temperature was 2,870° K.

TABLE 1 Stabilized Resolution as a Function of Photocathode Illumination

Light Meter Scale	Photocathode Illuminance (ft-c)	Stabilized Resolution line pairs/mm
12	1.6×10^{-1} *	16
11	8×10^{-2}	14
10	4×10^{-2}	13
9	2×10^{-2}	14
8	1×10^{-2}	11
7	5×10^{-3}	11
6	2.5×10^{-3}	11
5	1.3×10^{-3}	10
4	6×10^{-4}	10
3	3×10^{-4}	9
2	1.5×10^{-4}	8
1	7.5×10^{-5}	5**
0	3.7×10^{-5}	5**
-1	1.8×10^{-5}	5**
-2	9×10^{-6}	3**
-3	4.5×10^{-6}	1**

* Corresponds to an object plane highlight luminance of 13,000 ft-c imaged on the photocathode by a T/22 lens.

** Calculated from amplitude of noise in deflection current.

Stabilization as a Function of Motion Amplitude

Among experiments which have been carried out to determine the performance of the prototype, the following is representative. A high-contrast 4.6-mm-diameter target, consisting of dark bars on a bright background, was vibrated with random motion, with a Gaussian amplitude distribution and a bandwidth of about 100 cps, by a loudspeaker driven by band-limited random noise. The target was photographed at 1-sec exposure with the recording camera set at $f/16$ both unstabilized (Figure 32) and stabilized (Figure 33). This procedure was repeated at increasing motion amplitude, and the results are given in Table 2.

TABLE 2 Comparison of Unstabilized and Stabilized Resolution for Several Motion Amplitudes

rms Motion Amplitude (mm)	Unstabilized Resolution (line pairs per mm)	Stabilized Resolution (line pairs per mm)	Dynamic Improvement $\left(\frac{\text{Stabilized Resolution}}{\text{Unstabilized Resolution}} \right)$
0	18	--	NA
0	--	18	NA
1.92×10^{-1}	2	16	8
3.83×10^{-1}	1	16	16
7.7×10^{-1}	5×10^{-1}	16	32
1.53	2.5×10^{-1}	16	64
3.05	1.25×10^{-1} *	16	128
6.2	6.2×10^{-2}	13	210

*Calculated.

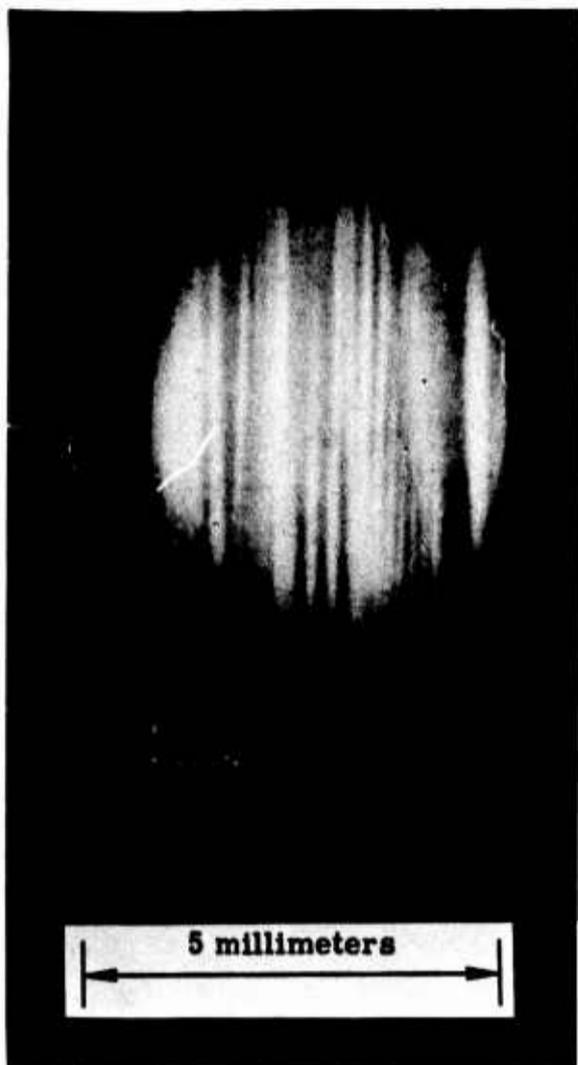


FIGURE 32 Unstabilized-motion
1.53-mm rms, photocathode illumination 1.6×10^{-1} ft-c, resolution 2.5×10^{-1} line pairs per mm, exposure time 1 sec.

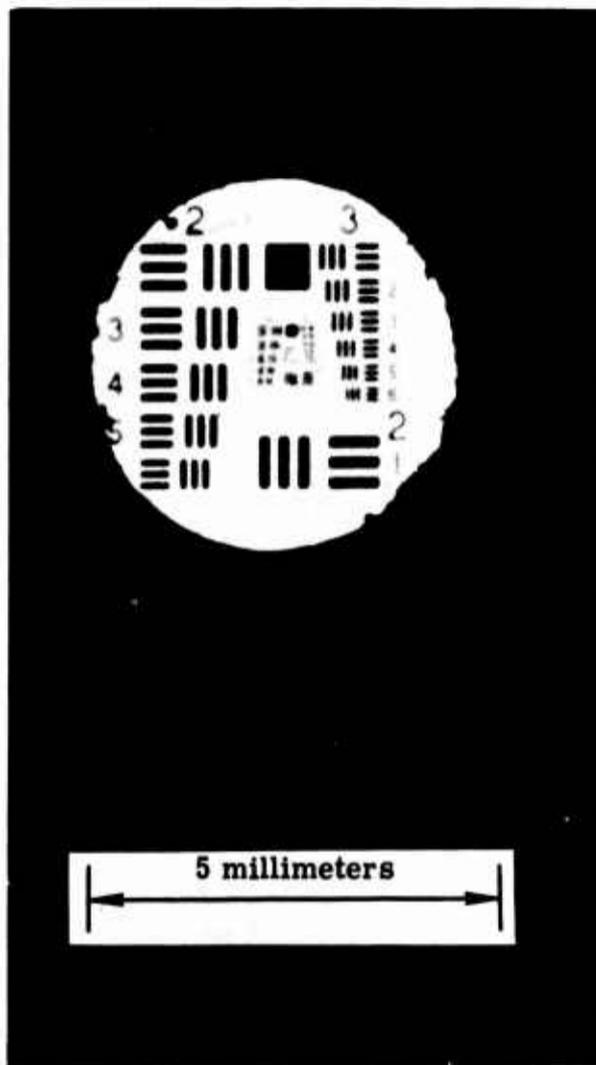


FIGURE 33 Stabilized-motion
1.53-mm rms, photocathode illumination 1.6×10^{-1} ft-c, resolution 16 line pairs per mm, exposure time 1 sec.

Applicability to Large Telescopes

The Cloudcroft telescope operating at $f/16$ has a focal length of approximately 770 in. and a field of about 6 mm in diameter at 1.5 min of arc. Across such a diameter the tube is capable of recording 60 line pairs per mm and this is a good match to an $f/16$ diffraction-limited optical system, which when combined with film can be expected to have a high-frequency cutoff of about 50 line pairs/mm. The EIMS system prototype has been operated extensively with a lens aperture at $T/22$ on objects illuminated in sunlight and with images of about this size. Thus it appears reasonable to extrapolate the satisfactory test performance to the large telescope case. This also suggests that the system could be applied to a practical test at minimal development cost. The approach is considerably easier to

implement than other devices for obtaining stabilization, such as the open-loop system of DeWitt et al. (Sky and Telescope, November 1957), or the 2-cps-bandwidth mechanical system of Leighton (Scientific American, June 1956).

SUPPLEMENTARY

INFORMATION

NOTICE OF CHANGES IN CLASSIFICATION,
DISTRIBUTION AND AVAILABILITY

69-18 15 SEPTEMBER 1969

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