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PHOTOGRAPHIC IMAGE ENHANCEMENT

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Abstract

Deblurring capabilities would significantly improve the scientific return from Space Shuttle Crew acquired images of the Earth and the safety of Space Shuttle missions. This summer, deblurring techniques were developed and demonstrated on two digitized images that had been blurred in different ways. The first was blurred by a gaussian blurring function analogous to that caused by atmospheric turbulence while the second was blurred by improper focussing. It was demonstrated in both cases that the nature of the blurring i.e. gaussian and Airy, and the appropriate parameters could be obtained from the Fourier transformation of their images. The difficulties posed by the presence of noise necessitated special consideration. It was demonstrated that a modified Wiener frequency filter judiciously constructed to avoid over emphasis of frequency regions dominated by noise resulted in substantially improved images. Even though the deblurred images were similar to the original unblurred images, their Fourier transformed images were similar not as similar, indicating that more refined techniques applied to the Fourier image could result in further improved images. Several important areas of future research were identified. Two areas of particular promise are the extraction of blurring information directly from the spatial images and improved noise abatement from investigations of select spatial regions and the elimination of spike noise.

Introduction

The Space Shuttle Earth Observation Office serves as the repository of over 100,000 photographs form the Manned Space Flight Program. Photographs are taken to monitor both the lift-off and the landing of the Space Shuttle, and to document environmental, geological, meteorological and oceanographic phenomena observed from orbit. Inadvertently a number of these are blurred by improper focussing, relative camera-object motion, atmospheric distortions i.e. shock waves or thermal gradients, etc. Atmospheric distortions are particularly annoying since they restrict NASA's ability to monitor the effects of lift-off on the shuttle and the decent of the orbiter's wheels during landing. To gain access to important engineering and scientific information contained in blurred photographs, it is necessary to apply image processing techniques. The more sophisticated of these involve digitization of the raw image and subsequent computer processing of the degitized images or their Fourier transforms.

The research accomplished as a Summer Faculty Fellow involved the development and implementation of a deblurring procedure to handle a) the digital gaussian blurring which is analogous to that caused by atmospheric turbulence and b) blurring due to improper focussing e.g. actual focal lengths differing from expected values due to thermal effects, etc. Although there is no apparent indication of the source of blurring in the spatial images, there are definite indications of the source of blurring in the Fourier (transformed) images. Thus to improve a spatial image one first diagnoses the Fourier images for signs of the source of blurring and then used that information to construct a frequency "filter" that reduces the effects of blurring in the Fourier image which in turn would produce a sharper spatial image. However, the presence of unknown noise in the original images and increased by the digitalization process, necessitates special consideration. In particular, even though blurring reduces the high frequency components compared to the lower frequency ones, simple enhancement of the higher frequency amplitudes will not necessarily improve the image, since it could increase the overall noise to signal ratio by introducing high frequency amplitudes that are noise dominated. The trick is to judiciously emphasize only those frequency regions where the signal to noise ratio is acceptable. There are many excellent text dealing with digital processing (1,2,3) and discrete Fourier transforms(4,5) that provide the background for the work described in this report.

II Theory and Approach

II.1 Blurring as a Convolution Process: the Point Spread Function

In general a blurred image is the result of light that would have arrived at a particular point being spread over a number of points. If the distribution is the same for all points in the image and if the light is incoherent then in the absence of noise the final intensity at a point (pixel) m,n would be given by

$$\sum_{m', n'} \mathrm{P.S.F.}_{m-m', n-n'} \, f^{s}_{m', n'}$$

where P.S.F. is the point spread function, i.e. the image of an ideal point source in the object plane, $f^{s}_{m,n}$ is the sharp image that would have formed in the absence of blurring and noise.

For the images of interest the digitization process yields an image made up of NxN pixels (N=512). Due to the blurring bringing light rays into the image region that would have otherwise not nave entered it, the summation in this expression should include m''s and n''s outside the range of 0 to N-1. Nevertheless, the sum is usually assumed to be limited to this range to avoid having to deal with an "underdetermined problem" (6).

Noise is always present in the image. It can be the result of electronic cross-talk, round-off errors in the digitization process, random, inhomogeneous chemical processes in the original film, etc. Noise can be divided into two contributions: one independent and the other dependent on the signal, i.e. f^{s}(7). In the latter case it could be incorporated into the point spread function. Since we have little knowledge of the nature of the noise, except that it is usually dominant at high frequencies, we will describe it by an unknown function $n_{m,n}$ and write the expression for the blurred image as

$$f^{b}_{m, n} = \sum_{m', n'} \mathrm{P.S.F.}_{m-m', n-n'} \, f^{s}_{m', n'} + n_{m, n} \qquad (1)$$

The next step is to invert the sum in equation 1 and solve for f^{s}. Since the summation is usually referred to as convolution, the inverse process is referred to as deconvolution. The basic technique is to expand all functions in terms of a complete set of basis functions which will turn the summation into a simple product of the expansion coefficients.

II,2 Fourier Transformations

For simplicity we use the traditional discrete Fourier expansion

$$f_{m,n} \quad = \quad \sum_{k,l} F_{k.l} \exp 2\pi i(\, km + ln)/N \qquad (2a)$$

where there are N values of k and l.
The inverse Fourier transformation is then given by

$$F_{k,l} \quad = (1/N^2) \sum_{k,l} f_{m,n} \exp - 2\pi i(km + ln)/N \qquad (2b)$$

In the following we will use lower case letters , e.g. f, for the spatial images and upper case letters, e.g. F, for the Fourier transformed image. The Fourier transform of the point function,P.S.F., is called the modulation transfer function,M.T.F..

In terms of the Fourier transformed variables equation 1 takes the form

$$F^b{}_{k,l} \quad = \quad F\,^s{}_{k,l} \cdot \text{M.T.F.}_{k,l} + N_{k,l} \qquad (3a)$$

Deleting the common subscripts and solving this equation for the Fourier transform of the sharp image function yields

$$F^s \quad = \quad F^b/\text{M.T.F.} \quad - \quad N/\text{M.T.F.} \qquad (3b)$$

II.3 Noise Considerations

If the modulation transfer function and the noise, N, were both known then equation 3b could be used to find F^s and a subsequent inverse Fourier transformation would yield a sharp image. For the sake of discussion let us assume that we have a reasonably good understanding of the blurring process and have a good approximation to P.S.F. and thus to M.T.F. Most likely the blurring extends over a few spatial pixels and M.T.F. will be small at high frequencies, i.e. large values of k and l. Blurring due to improper focussing, relative motion, atmospheric turbulence are in general of this type. The first two sources of blurring have M.T.F.'s that vanish on contours in the k,l space. Where ever M.T.F. is small the contribution from noise, N/M.T.F., in equation 3b can be significant. Consequently, approximating F^s by F^b/M.T.F.can result in large noise contributions. The normal procedure to avoid this problem is to multiply F^b by a "filter" function which uses information about the noise to approximate 1/M.T.F. where noise is unimportant and avoids contributions from regions where noise dominates. The Wiener filter is the most common filter discussed in the literature (2,3,4,6):

$$W^{-1} = \text{M.T.F.} \cdot (1 + |N/F^{s} \cdot \text{M.T.F.}|^{2})$$

As it stands this expression requires knowledge of the amplitude of the function to be calculated and the unknown noise contribution. A simple way to suppress noise is to replace N/F^{s} with a constant (3) or a constant times a gaussian, e.g. $C \exp c(k^{2}+l^{2})$. In the former case the constant could be chosen to be the value of M.T.F. at frequency in the range where the maximum value of W is desired. A gaussian would do a better job of modelling N/Fs than a constant but it involves finding appropriate values for two instead of one parameter.

Another approach is to notice that when M.T.F. vanishes F^{b} is equal to N. Consequently, if $F^{b}{}_{o}$ is the value of F^{b} where M.T.F. = 0, then $(F^{b} - F^{b}{}_{o})$/M.T.F. would avoid the introduction of excessive noise, since $- F^{b}{}_{o}$ removed the noise.

III Applications : A Tale of Two Images

In this section we discuss two applications of the deblurring techniques described in the previous section. The first application involves an image blurred digitally by convolution with a gaussian spread function. This is the digital analogy of atmospheric turbulence for long exposure times(1,8). The second involves an image blurred by defocussing the lens of the digitizer and thus is an example of blurring due to improper focussing.

III.1 Enhancement of an Image Blurred by Gaussian Convolution

Figure 1a shows the original image and figure 1b shows the image blurred by convolution with a point spread function which is gaussian within a 5 by 5 square of pixels. Figure 1c shows an enhanced image obtained by applying a filter to the Fourier transform of the blurred image. It should not be considered an ultimate product but simply a demonstration of the results that could be obtained without expenditure of the time needed to fine tune the enhancement process. Figures 2a,b and c show the Fourier transformed images corresponding to those shown in figure 1. Clearly the Fourier image (figure 2c) reconstructed from the Fourier transform of the blurred image (figure 2b) is an improvement but still differs considerably from the Fourier transformation of the sharp image (figure 2a) especially in the intermediate to high frequency region. Figure 3 shows the inverse of the deblurring filter used to obtain figure 2c from figure 2b.

There were three important aspects in constructing the deblurring filter:

1. Only in a 5 by 5 spatial pixel region was the P.S.F. non-zero.
2. Inside that region the P.S.F. could be described by a single coefficient in the exponent of the gaussian.
3. The filter would have to deviate sufficiently form 1/M.T.F. in the high frequency region where 1/M.T.F. would be large and noise could be expected to dominate.

The Fourier images shown in figures 2a and 2b were used to obtain the coefficient for the "gaussian" M.T.F. This was done by taking the Fourier transform of their ratios which in the absence of noise would be the P.S.F. Although the resulting function did not vanish outside the 5 by 5 pixel region, presumably due to noise, there was sufficient accuracy within that region to determine the coefficient within a 5% variance.

Knowing that in the continuous case the Fourier transform of a gaussian is again a gaussian, a preliminary filter was constructed using a gaussian M.T.F. The resulting image was unrecognizable, presumably due to high frequency noise. Next a one constant Wiener-like filter (see section II.3) which emphasized the medium to low frequencies ($N/\sqrt{6}$) was used. This gave a reasonable but rather grainy image. The final result shown in figures 1c and 2c was obtained by replacing the gaussian M.T.F. in the Wiener-like filter by the M.T.F. resulting from a P.S.F. having only a gaussian distribution within a 5 by 5 pixel region. The squareness of this pixel region gave extra emphasis to the high frequency components near the axes and consequently removed most of the graininess. Further refinements could be expected from a more judicious choice of the constant in the filter or optimization of a two constant filter (see section II.3).

III.2 Enhancement of an Image Blurred by Improper Focussing

Figures 4a, b and c show the original, blurred and the first order restored image and figures 5a, b and c show their respective Fourier transforms. The first two images were made using the video digitization system. Though it is no evident from the figures as shown, the top 1/16 of both images is missing as a result of the digitization process. Such spatial-domain truncation causes over shooting or ringing in subsequent filtered image (p. 26 ref. 1). A crude attempt was made to fill in these region, which replaced a few strong $l \approx 0$ constant frequency by the scratchy like region of with N/16 centered on the l axis as shown in figure 5b. It is thought that remnants of this spatial domain truncation are the cause of the ringing seen in figure 4c.

Knowing that the blurring process is due to defocussing one can expect to see the zero contours of the appropriate M.T.F. in the Fourier transform of the blurred image. If the P.S.F. is a uniform disk, the the M.T.F. is the discrete equivalent of the Airy function. A subroutine was then written to generate Airy-like M.T.F.'s for a uniform solid disk of variable radius surrounded by an annulus whose value decreases from that of the disk to zero at a variable outer radius. The halo visible where F^b drops down to the background noise, was used to estimate the radius of the disk. Then using this estimate, Airy-like M.T.F.'s were generated. A disk with a diameter of about five pixels and a fuzzy annulus of two pixels width was selected. Comparing it to the F^b shown in figure 5b, it was seen that the first zero contour was in the halo region and that the second zero contour just enclosed the region where F^b was still significant. Thus the Fourier transform of an image blurred by improper focussing contained sufficient information to identify by visual inspection an appropriate M.T.F. However, there were other M.T.F.'s resulting from varying the disk radius and the annulus width that had similar zero contours. The one chosen gave slightly better results although the fuzzy annulus had little of no effect on the ringing. Having an appropriate M.T.F. , a Wiener-like filter was chosen that gave maximum emphasis in a frequency circle of radius 80 pixels. Clearly the resulting. Fourier image represents an improvement but is not identical to that of the unblurred image. Perhaps the most improvements in the deblurred image are to the letters on the wings of the orbiter and the upper regions of the solid fuel rockets.

IV Future Research

The research described herein revealed several interesting avenues of future work. Two prominent areas of importance in designing the deblurring filters are the identification of the appropriate M.T.F. from Fourier transforms of the blurred images and noise abatement. The latter area of work may lead to preprocessing the blurred images, e.g. with windowing functions. Another important investment of research time is that of progressing systematically through a series of blurred images. These images should be classified as much as possible beforehand into groups having similar blurring processes. It is clear that any strategies developed in working with a few images need to be tested and refined by considering other images. In this section each of these areas of work will be reviewed.

V.1 Construction of M.T.F.'s from Images

Each blurring process can be expected to have its own point spread function (P.S.F.) and an associated modulation transfer function (M.T.F.). A priori knowledge of the blurring process is helpful, but not essential. For example, the circular halo observed in the second but not the first image considered in section III is characteristic of improper focussing. The lack of a halo would suggest another type of blurring, e.g. gaussian. Relative motion would have a line segment for a P.S.F. For the simplest case, that of a straight line segment, i.e. constant velocity, the resulting M.T.F. would have rectangular symmetry. A combination of improper focussing and relative motion has a M.T.F. that is the product of the individual M.T.F.'s for each process. Blurring due to atmospheric turbulence under certain conditions would be gaussian and would not result in a halo pattern. In many cases, the only means of identifying the M.T.F. and the parameters needed to describe it will be from the Fourier image. Visual inspection of a Fourier image for the halo pattern probably is the fastest means of identifying the source of blurring. Having appropriate M.T.F. parameters, e.g. the exponent coefficient of a gaussian or the diameter of the disk in the case of improper focussing. How much of this work could be accomplished by a computer remains to be seen.

In principle, it is possible to extract P.S.F. parameters directly from features of the spatial image. In particular, if the image pixels associated with a single point of the sharp image can be identified then one has the P.S.F. In theory such information is also contained in the profiles of edges and lines in the blurred image. The change of pixel values perpendicular to an edge can be shown to be proportional to the pixel values of the P.S.F. measured along the diameter in the same directions.

IV.2 Noise Abatement

The two examples considered in section III have clearly shown that identification of the M.T.F. is only the first step. Care must be taken to avoid emphasis of noise. The approach used there of a one or two parameter Wiener-like suppression of high frequency contributions was a rather crude method of noise abatement. It would be better if the source or the nature of the noise could be identified and removed by a separate frequency filter. For example, in working with the first image, it was found that setting all amplitudes inside circular arcs of radius N/4 around the four corners of the Fourier image had no visual effect on the unblurred image. In the case of spike noise, where individual pixels are radically different in value from the surrounding pixels, a subroutine could search and remove such "sparkle". Sparkle is most prominent near the corners of the Fourier image where little if any signal is present. It is in contrast to the more cloud-like structure typical of the low frequency region where signal dominates. It should be possible to obtain information on noise by studying select portions of the spatial image, e.g. if a region is known to be uniform in intensity, then any ripple in its Fourier transform may be assumed to be noise. Identifying regions or individual pixels of the Fourier image as noise dominated and their removal would greatly reduce the importance of the choice of parameters in the deblurring filter.

IV.3 Image Truncation and Windowing

In dealing with the image blurred by improper focussing, ringing supposedly due to spatial truncation was observed. In this particular case, the upper sixteenth of the image was not present due to the digitalization process. Because of the cut-off of the camera, it is barely noticeable in figures 2a, b or c. However, an attempt to fill in the missing area removed strong vertical lines near l=0 and created the scratchy band about 32 pixels wide, i.e. N/16. This is an indication of the importance of spatial truncation on the Fourier image. It would be worthwhile to see what effect the edges of an image have on its Fourier image. There are many different types of window functions(1) that remove the effects of the edges and could help us to see which Fourier features are important and which are spurious.

V Summary and Conclusion

The two examples discussed in section II, demonstrated the significant improvement that can be accomplished in enhancing blurred images. Information needed to construct the frequency filters which manipulate the Fourier images can be extracted from the Fourier as well as the spatial image. For the two examples considered, the nature of the blurring mechanism was evident from the presence or absence of halos in their Fourier transforms. It was also found that once the type of blurring was recognized if was easier to use the Fourier images to fix the appropriate parameters. Supposedly methods could be developed to extract the needed information from features of the spatial images that might complement the work with Fourier images. Similarly, noise reduction could proceed from identification of spike noise etc. in the Fourier image or from studying select regions of the spatial image.

In conclusion, it has been demonstrated that blurred images can be enhanced using information extracted from the images themselves. However, there is plenty of research and art work to be done before JSC has a cookbook for deblurring images.

VI References

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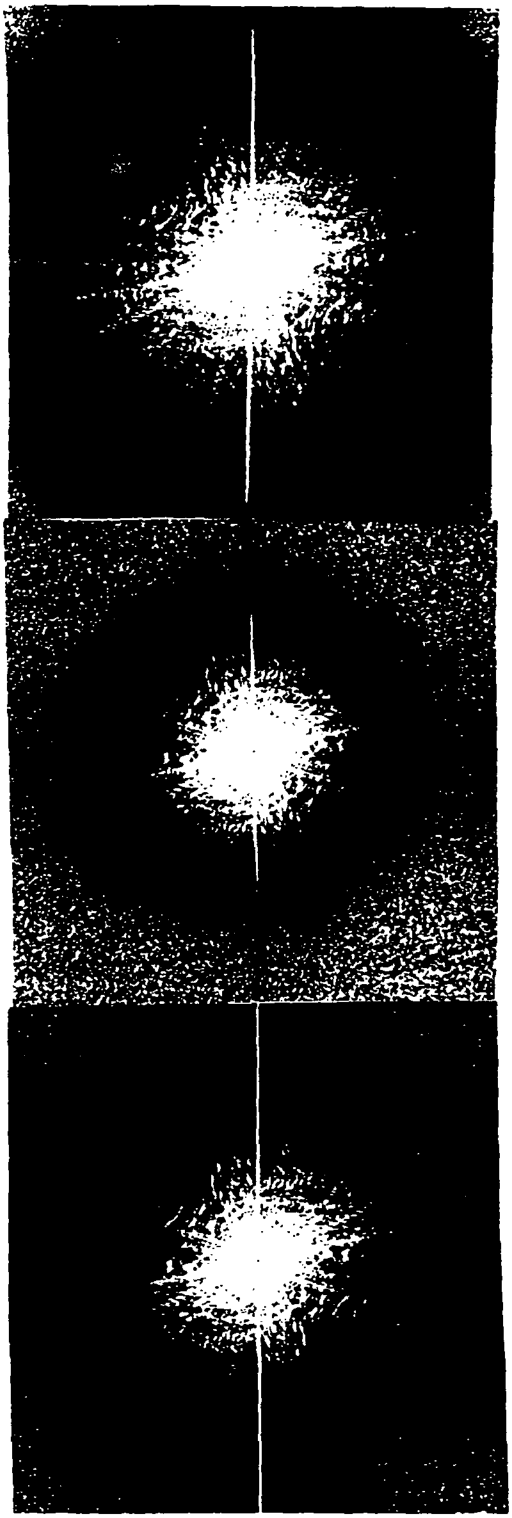
Figures 1a, 1b and 1c



Figures 2a, 2b and 2c

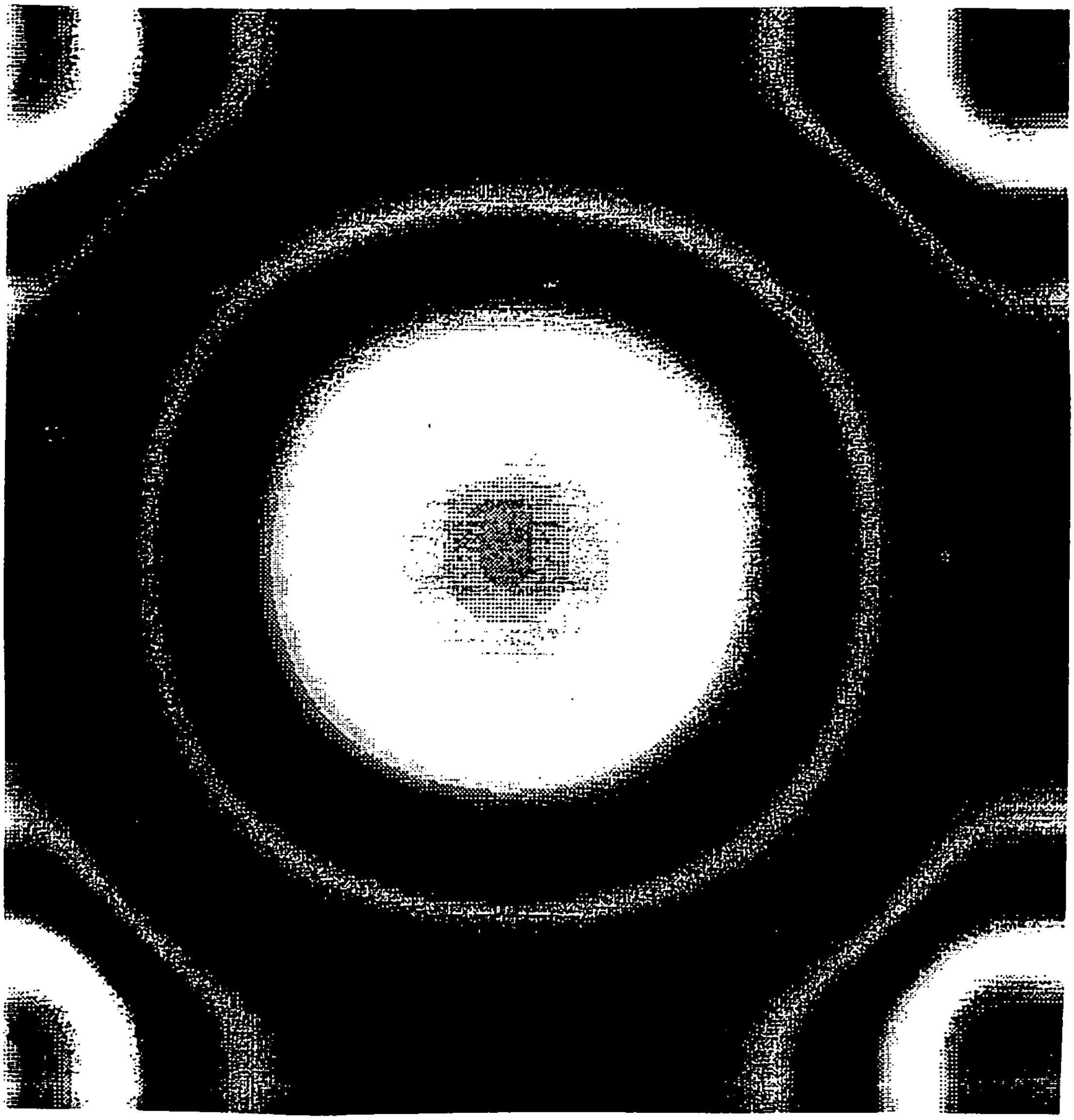


Figure 3

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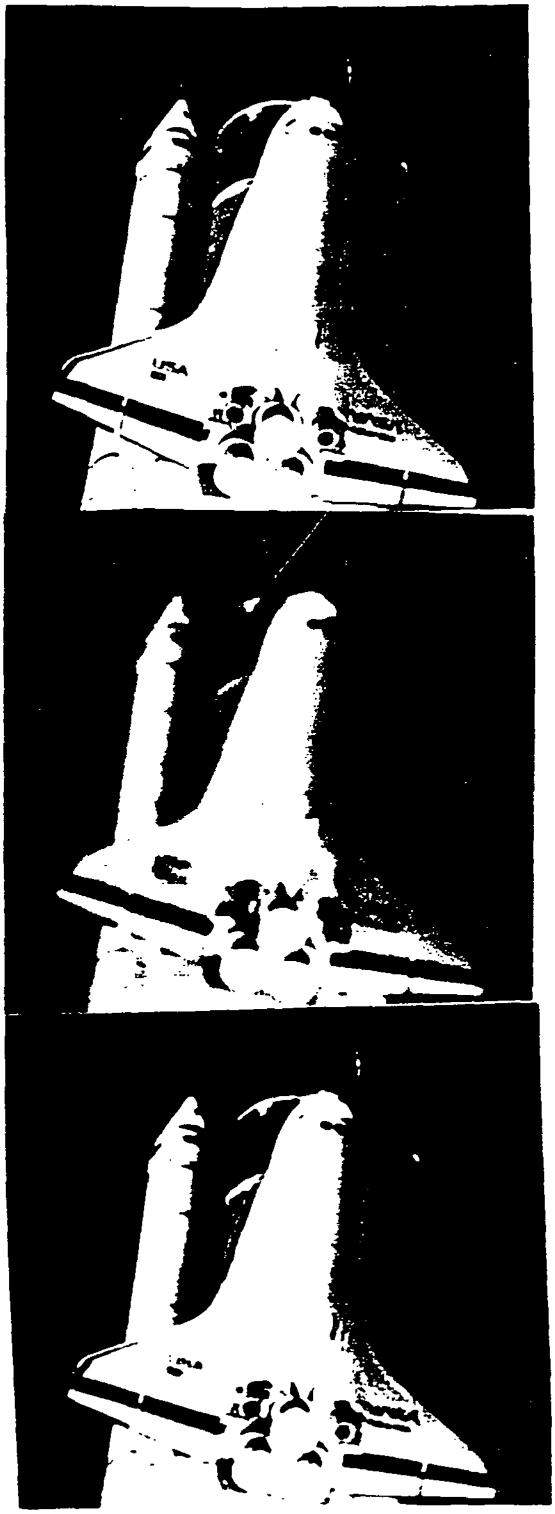
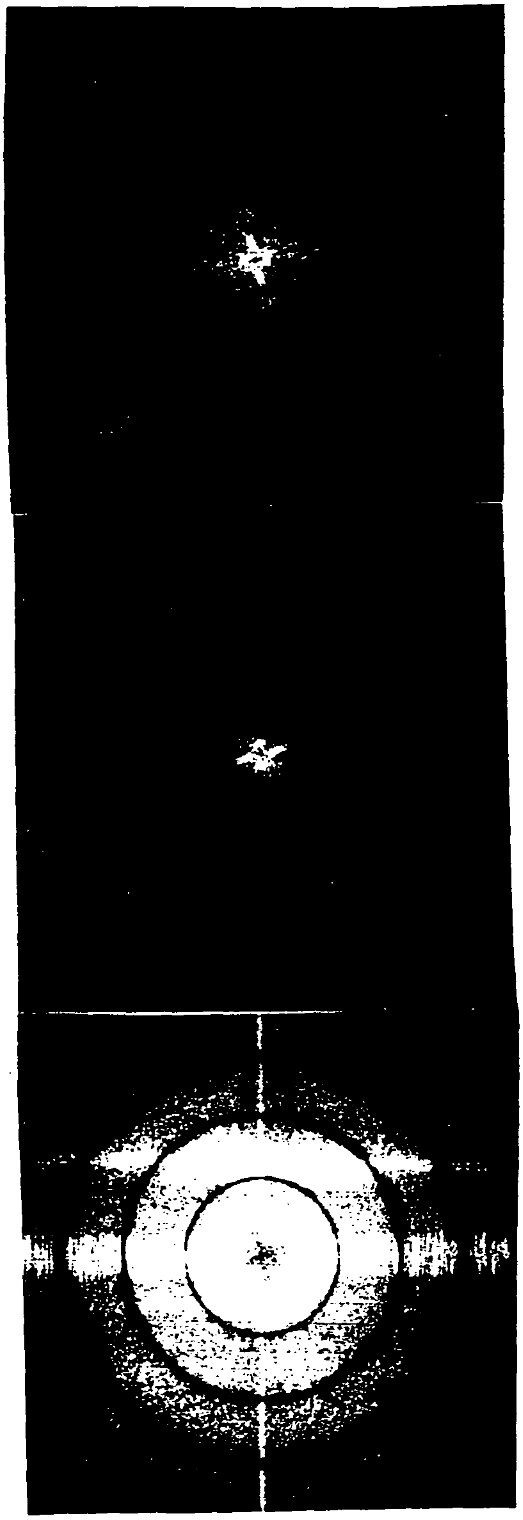


Figures 4a, 4b and 4c



Figures 5a, 5b and 5c