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Image analysis of solid propellant combustion holograms using an imageaction software package.

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NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

IMAGE ANALYSIS OF SOLID PROPELLANT
COMBUSTION HOLOGRAMS USING AN
IMAGEACTION SOFTWARE PACKAGE

by

David Norman Redman

June, 1986

Thesis Advisor: John P. Powers

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Image Analysis of Solid Propellant Combustion Holograms
Using an IMAGEACTION Software Package

by

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requirements for the degree of

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ABSTRACT

This thesis describes a method of computer-controlled
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discussed as are possible solutions to these limitations.

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LIST OF ABBREVIATIONS

AOI   Area of Interest

NPS   Naval Postgraduate School

AVG   Average

DIA   Diameter

QUAD   Quadrant

CAMCORDER   Camera Recorder

I.   INTRODUCTION

This thesis research was conducted as part of a continuing project at the Naval Postgraduate School (NPS), which is investigating the effects of the addition of solid particulates to solid rocket propellant to enhance the performance characteristics. In order to correctly assess the effects of the particles, an accurate measurement of the sizes and quantities of the burning solid particles must be made with relation to their axial position within the port of the propellant grain.

Previous research has attempted this data collection through a number of different methods. [Ref. 1] This thesis concerns itself only with the use of holograms of the burning propellant in a cross flow section of the combustion chamber. The methods of obtaining these holograms at the NPS are discussed in detail in References 1 and 2.

Once the holograms are obtained, the problem is to analyze the data they contain. Considerable effort has been taken in this area to utilize a Quantimet 720 image processing system and a PDP-11/04 computer to conduct automated data retrieval on the reconstructed holograms. This research has been the subject of two previous theses [Ref. 1 and 3] which describe the process. This method of image reconstruction and data formation has experienced

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several major difficulties.

The Quantimet 720 has been the largest obstacle to this method. It has demonstrated very low reliability, with the system constantly unusable due to intermittent faults. Data outputs have varied significantly between sequential runs on the same hologram images when the system has operated.

In addition the Quantimet 720 requires that a clear distinction exist between the grey levels of the background and the object features in the input image. The system is unable to carry out any image processing to separate these two levels itself. The holograms used inherently contain light speckle which varies over the complete range of grey levels in the hologram. The Quantimet has been unable to distinguish between this speckle and the real features. The result is that the background and the features have overlapped and true feature counts have not been able to be obtained. [Ref. 1 and 4]

The Quantimet results required initiation of research into alternate methods of data retrieval for the holographic images. In particular, digital processing was felt to be required to separate the image features from the background of the hologram before sizing and counting the features. A set of ImageAction software was purchased to see if this was feasible. As this software runs on an IBM/AT computer augmented with a TV image acquisition and display plug-in board, the concept of carrying out the complete image

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enhancement and feature collection on that system appeared logical. In this manner the unreliability of the Quantimet system could be completely overcome.

Hence, rather than continuing with the previous work with the Quantimet 720, this thesis deals with a new approach to the problem. The initial requirement was to evaluate the ImageAction software to determine if it was able to reduce the background sufficiently to permit data extraction from the holograms. With this capability in hand, the next step was to write a software algorithm which was able to retrieve all the required feature data from the enhanced image.

This thesis is divided into four further chapters. Chapter II describes the ImageAction software, its capabilities and the routines of main applicability to this problem. A discussion of the format that the software uses to store images is also carried out, as it presented an obstacle to the further processing of the enhanced image. Chapter III contains a description of the program which was written to perform the feature data extraction on the enhanced image. Chapter IV describes the results obtained by using the completed IBM/AT processing method to extract data from a standard calibration reticle. Chapter V contains the concluding remarks.

II. HOLOGRAM IMAGE PROCESSING

The ImageAction software acquired for this project required both hardware and software to be installed on the IBM/AT. The hardware consisted of a PC Vision Frame Grabber board which plugs into the IBM/AT computer. This board takes an analog input video signal and digitizes it, assigning each pixel an integer value. This digital data is then stored in the frame memory on the board and is available for processing or transfer via the computer bus. The stored image can also be viewed, as the display logic on the board transforms the digital pixels back into analog form before sending it to a video monitor. The PC Vision board and the ImageAction software were both made by Imaging Technology Incorporated to carry out digital image processing.

The software package consists of a comprehensive, menu-driven set of routines which can carry out image processing, image graphics and limited image analysis. Once installed and loaded, ImageAction appears on both the computer screen and on the image display monitor. The monitor screen is used to display the image being processed and also the current software menu in use. The computer screen shows the software status, current prompts for both keyboard and mouse entries, and a help block if required.

From the main menu one can access via the mouse, all of the submenus to carry out the required processing. Figure 2.1 shows a complete breakdown of the ImageAction menus. [Ref. 5]
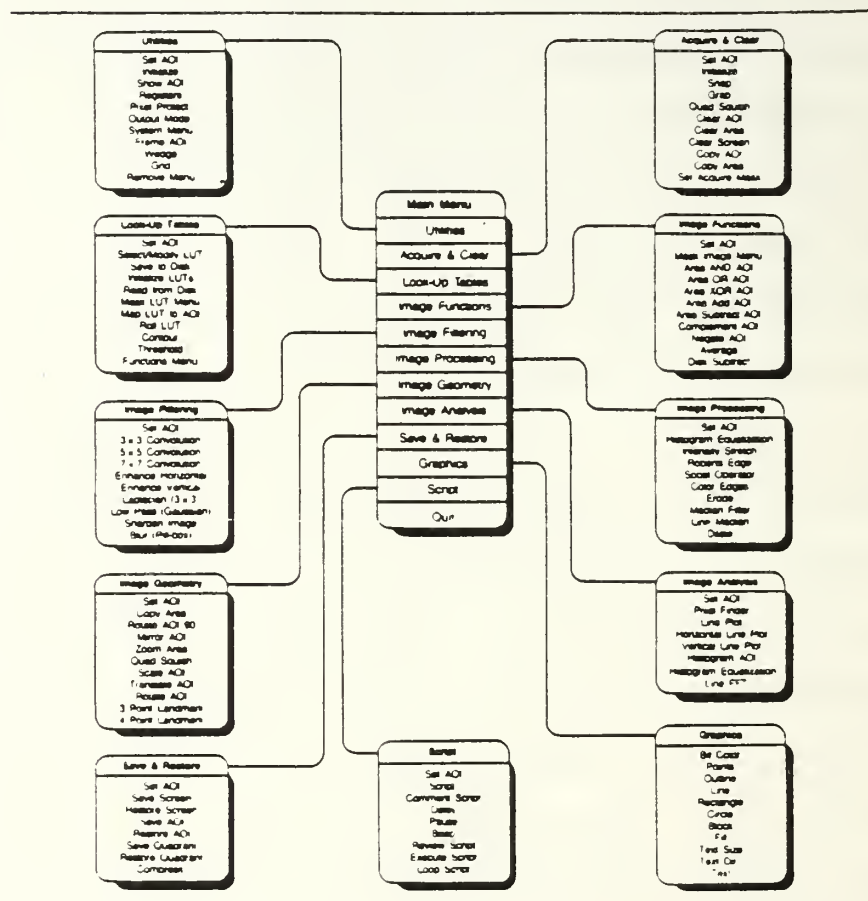
Figure 2.1   The ImageAction Menus
[Ref. 5, Figure 1-2]

The ImageAction software permits the processing of the entire monitor screen or it allows the subdivision of the screen into four quadrants. It is also possible to designate any rectangular portion of the screen as an Area of Interest

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(AOI), and to move this area into any quadrant for easier processing. Another very useful algorithm permits the entire screen to be compressed into one quadrant of the screen. This process is called a Quad Squish.

The ability to perform this function is important as it allows a full screen image to be processed and later have the data extracted in one fourth of the time. However, it must be noted that in order to do this, the algorithm only copies the even-numbered pixels on the even numbered lines. This implies that some of the smaller image features may be lost and that the resolution of larger objects may be affected.

Once an image is processed, graphics can be added to further enhance the image or to record specific information on it. The graphics capabilities include titling and script text as well as the drawing of limited geometric shapes.

With this general overview of the ImageAction software it is now possible to discuss its detailed application to the problem of hologram image processing.

A. ACQUIRING THE HOLOGRAM IMAGE

The ImageAction software requires a stored video image input. This means that the hologram must be reconstructed and then viewed by a video camera system, whose output either is fed directly as an RS170 standard video signal to

the PC Vision board or is stored on a video media so that it can later be played back into the PC Vision board.

Figure 2.2 shows the hologram reconstruction technique. A more detailed discussion on the actual mechanics of the process is available in Reference 1. Initially a VHS Camcorder was interfaced with the microscope. Later the VHS camera was replaced by a number of Newvicon cameras with increased light sensitivity. A discussion of the cameras used is included as Appendix A.
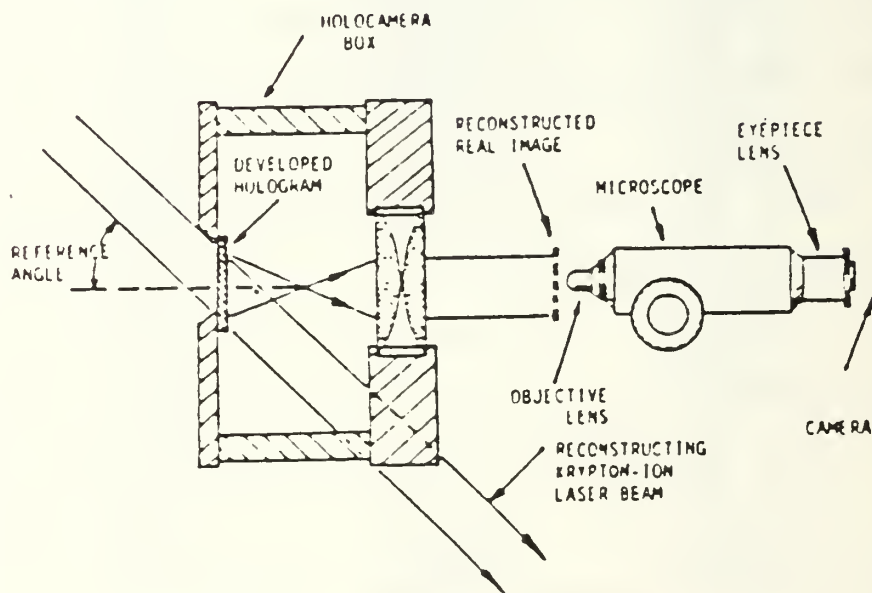
Figure 2.2 Hologram Reconstruction
[Ref. 1, Figure 1.1]

The microscope can be set for a variety of magnifications by rotating a front turret ring to align the desired set of optics. Images can be acquired using microscope objectives with magnifications of one, two, four

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or ten. As higher levels of magnification are used, the depth of field becomes smaller and so the focusing of the image becomes more difficult. Also as the magnification is increased, the field of view becomes narrower and so less light is available. Hence, more sensitive cameras are required.

In addition to the hardware shown in Figure 2.2 for the reconstruction and viewing of the hologram images, it is possible to place a spinning mylar disk at the location of the reconstructed real image. This disk serves to reduce the speckle in the reconstructed image but it also reduces the amount of light which enters the optics. This loss of intensity was originally a problem that was later overcome by using a more sensitive camera.

The video output of the cameras could be directly input into the PC Vision board as previously stated. However, due to the separate physical location of the reconstruction laser, the images were stored on a standard Beta video recorder and played back into the board.

Once the image is stored on video tape, there are three methods for entering it into the board. The first two, Snap and Grab, are similar in that they take one frame of the recorded image and display it for processing. The Grab technique is preferable as it permits the played-back image to be viewed until the desired frame is shown and then, by use of the mouse, that frame is "grabbed".

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The third method of acquiring an image in the computer is called Average. This technique takes a specified number of frames from the video input and averages their intensities, producing a final, single time averaged result. As the speckle background varies with time, this technique of acquiring the image was of some interest and was investigated in detail.

With the hologram image now in the computer, the next step was to attempt to enhance the image by reducing the background. The goal was to completely remove the speckle background from the image while not losing any of the real feature data.

B. IMAGE ENHANCEMENT

The PC Vision board assigns a grey value between zero (which is black) and two hundred and fifty-five (which is white) to each pixel of the image. In an ideal image, the particles to be analyzed would be of one grey level, preferably dark, and the background would be of a separate grey level, usually lighter. Figure 2.3 shows a histogram of the grey levels of an ideal image. The grey scale is the horizontal axis and runs from zero on the left to two hundred an fifty-five on the right. The vertical axis is a measure of the number of pixels of each grey value present in the image.

In practice, the background of an image is never all of one grey level and neither are the pixels of the particles. Even in a very clear white light reconstruction of an image, there are some bands of grey levels which exist for both.

Figure 2.3   Histogram of an Ideal Image

Figure 2.4 shows a histogram of a clear white light reconstructed image which has both particles and background present. (No speckle is present in the background.) The particle grey levels are to the left and are clearly separate from the band of background pixels to the right. Thus, if a threshold level was set between the two bands, all of the particle pixels could be set to one value, while the background pixels could be set to another. The ideal case could then be realized and the image could be analyzed.

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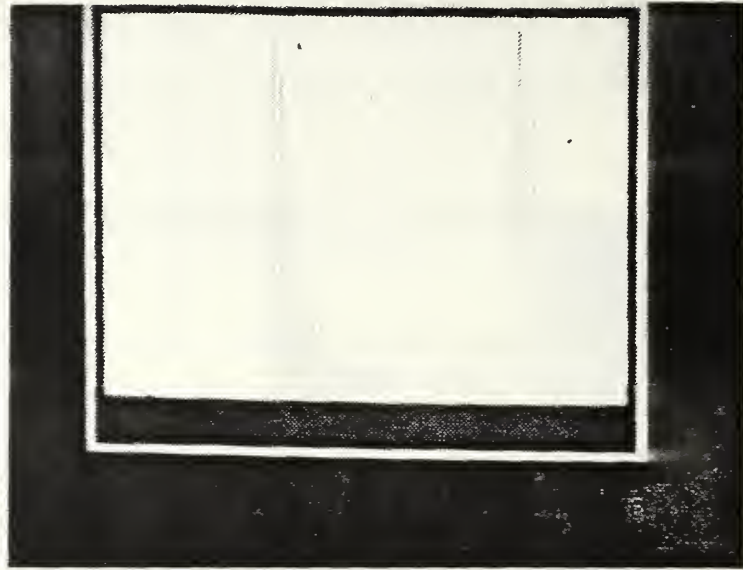
Figure 2.4   Histogram of a White Light Image

The hologram image background, however, is varied in intensity. It is generally more intense (lighter) than the desired particle features, but the speckle has salt and pepper intensities that can range over all of the grey levels present in the image. Hence dark speckle can appear on what should be a white background giving the appearance of more particles and lighter speckle can appear in the particle images causing them to appear to have holes.

Figure 2.5 shows a histogram of a hologram image which has particles present. The effect of the speckle is that there is no clear band of grey values for either the particles or the background. This makes the assignment of a threshold value impractical as the speckle exists

throughout. Hence the image cannot be converted back into the ideal case and the sizing analysis of the image cannot be done.
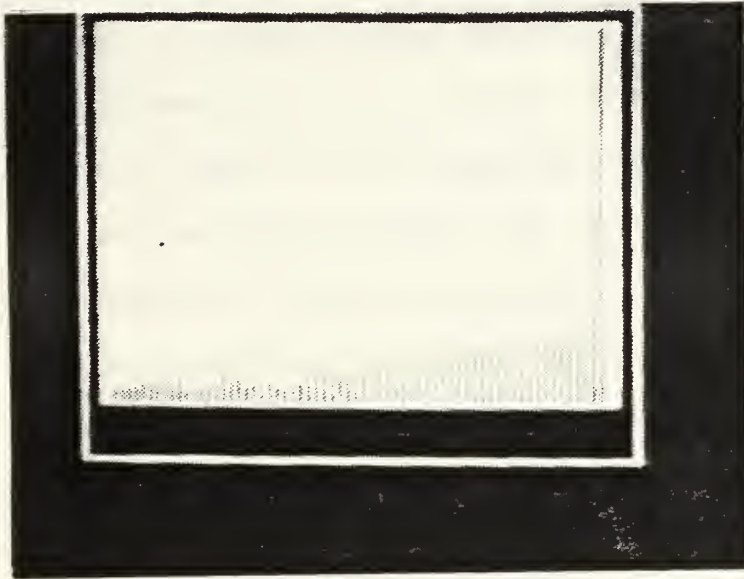
Figure 2.5 Histogram of a Hologram Image

What is therefore required is a system to process out the speckle in the image in order to establish a clearer separation between the grey levels of the particles and those of the background. The Quantimet system has no image processing capability and so cannot remove this speckle. This inability has greatly limited its use in this research. [Ref. 1]

1. Filtering

The ImageAction software has many methods of filtering and image processing. Of interest to the hologram

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image problem are the algorithms for convolution. These routines compare each pixel to the surrounding pixels and change the center pixel's value based on a weighted kernel. In this manner very small unwanted speckle can be convolved or filtered out of the background. It must be noted however that this also tends to blur or smear the actual particle shapes resulting in some loss of edge resolution.

Two of the ImageAction routines are particularly useful for reducing the presence of speckle. These are the Lowpass routine and the Blur routine. The kernel designs for these two algorithms are shown in Figure 2.6. It can be seen that the Lowpass routine involves a three-by-three convolution, while the Blur involves a five-by-five convolution.

```
                                  1   1   1   1   1
      1   2   1                   1   2   2   2   1
      2   4   2                   1   2   1   2   1
      1   2   1                   1   2   2   2   1
                                  1   1   1   1   1

    Lowpass Kernel                    Blur Kernel
```
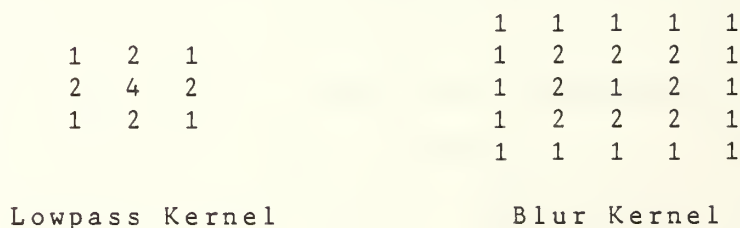
Figure 2.6   Convolution Kernel Values
[Ref. 5]

If the speckle is spatially very small, the Lowpass routine can increase (i.e., brighten) the speckle grey level without blurring the edges of the particle features significantly. However, if the speckle is larger (as is the case in the higher microscope magnifications), the Blur

routine must be used to completely remove the speckle. This operation results in significant smearing of the particle shapes.

While neither of these routines provides a wide separation of features and background to locate a threshold, use of these routines with a calibrated particle array can effectively remove all of the speckle and provide a useful threshold value as described in Section 4.B.

The ImageAction software also permits user-designed convolution kernels and several other weightings have been tried. It has been found that the results of the Blur and the Lowpass algorithms are sufficient for the problem to this date.

2.   Thresholding

Once the background speckle has been sufficiently removed by filtering, the entire image can be thresholded to completely remove all of the background. It is only required that the filtered background be increased to just one integer grey level more than the grey level of the brightest particle image. (Further separation causes a further increase in resolution.) Hence while some speckle may be still very apparent to the eye in the filtered image, it will be totally removed by thresholding.

The thresholding algorithm assigns a lower and an upper threshold value. All pixels which fall inclusively between these two values are give a value of zero and

therefore become black. All grey values outside of the range are given a pixel value of two hundred and fifty-five and are therefore made white.

With the image in this form it is now possible to extract the feature data information of the particles without any interference from the background. ImageAction has no sizing capability to carry out this extraction, unlike the Quantimet. Also the ImageAction software does not permit another program to be run concurrently. This implies that the processed image must be saved as a data file, so that another program can access it to carry out the feature data extraction.

C. SAVING THE ENHANCED IMAGE

The ImageAction software permits the processed images to be saved to disk. The image is stored in a string file that has a sixty-four byte header, followed by up to thirty-two bytes of comment and then the image. Assuming that the image has been compressed into one quadrant by the Quad Squish routine to speed up the processing, the image is 65,536 bytes long.

It must be noted that this image file is a string file that can be over 65,600 bytes long. Fortran does not easily read string sequences and the length of this string prohibits the use of any standard word processor to reformat it.

In order to make the stored image file easily readable by a Fortran program, a short Basic program was written to convert the file into a column file with a fixed I4 format. The details of this program are included in Appendix B.

D. AUTOMATIC PROCESSING

The ImageAction software also permits repetitive image processing techniques to be programmed to run automatically. This facility is done by the Script menu functions. Once the script function has been initialized with a file name, all subsequent steps are recorded until the script function is turned off. Then, by simply entering the subroutine's name while in the correct script sub-menu, the recorded steps will proceed automatically. This allows the hologram images to be rapidly processed and stored with operator interaction only when required.

With the image processed and stored in a Fortran readable format, it now is possible to proceed to extract the particle feature data from the image.

III. PARTICLE DATA COMPILATION

It is important to recall that the intention of this research was to produce a system which is capable of measuring the quantity and size of solid particulates in the combustion chamber of a rocket motor. These particulates are expected to range in size from 1 micron to 200 microns in diameter. [Ref. 2] They are also expected to be nearly spherical in shape.

The system must therefore be capable of counting the number of particles present in a given area of the combustion chamber. Further, it must be able to size them in terms of area or diameter. It must be able to distinguish which particles are round, since this capability can be used to exclude particles which are of irregular shape (such as fuel binder and chaff), and also to remove multiple overlapping particles which would upward prejudice the size data. With these requirements as the basis, a Fortran program was written to carry out the data extraction from the processed image.

A. THE PROGRAM FORMAT

The program was written in Fortran for several reasons. First, this language could easily accommodate all of the required functions and routines. Second, if this program was

to be used in conjunction with the Quantimet 720, the Quantimet 720 also uses Fortran as its programming language.

Third, the ImageAction software has been introduced as a stand-alone driver package called ITEX/PC. In this form, each of the functions in the menu-driven format can be called separately as subroutines. This driver package is available in the Fortran, Pascal and C languages. Hence, these subroutines could be easily imbedded into the data extraction program to create a single, complete algorithm for both the image enhancement and data tabulation, when the driver package was purchased. (This work is part of a follow-on thesis effort)

The program was written in a sectioned form, with each major step being written as a stand-alone routine. In this format it was felt that if any of the ImageAction driver routines were able to carry out one of the functions in a more economical manner, then it could be easily inserted. Also, this permitted each of the steps to be tested for correctness and for economy of time. This becomes important when processing up to 65,600 pixels of information.

The program was written to analyze a stored and reformed image file of one quadrant in size. This implies that the image to be processed must either have been only one quadrant large to begin with, or the full image must be Quad Squished prior to storing. Additionally, the image must have been stored with no comment included. If a comment is

included, the program will read the comment as part of the image and all of the data will be incorrect.

It was recognized early in the image processing portion of the thesis that each image was different in terms of background intensity, particle distribution and usable image area. This was in some cases due to the cameras used, but was also a function of the smoke in the background and the alignment of the recording and reconstruction lasers. Hence, it was realized that the data extraction algorithm would have to be able to accommodate these variations. The program was therefore written in a fully interactive format, with the user being prompted for all required input parameters or being given the option of using some predefined values.

Also included in the program is a predefined test image which can be used at any time to ensure that the algorithm is working correctly. This is particularly useful when changes are made to the routine. The test image and the correct outputs are shown in the comment statements of the program prior to each sub-function.

A complete copy of the program is available from the Thesis Advisor. Due to its length, it is not included here.

B. PROGRAM BREAKDOWN

As stated, the program is broken into sections. Each section will be briefly described, with the program limitations outlined.

1.   Image Input

    The first action required is to input the image to be processed. The user is offered the choice of using the test image or a data file image. If the data file image is selected, the user is then prompted to define the actual area of the input image which is to be processed.

    The variable frame is defined in terms of the X and Y coordinates of the upper left and lower right corners of the desired area. If the entire image is to be processed then the user selects 0,0 and 256,256 for the two corners of the variable frame.

    The data file is then read in. The program automatically strips off the first 64 data entries as these are the ImageAction header bytes. It then stores the image into a 256 by 256 array. It must be restated that the image must have been stored without a comment block, for if it has a comment, that comment will immediately follow the ImageAction header. Thus, the comment will be read in as part of the image and the image array will be destroyed.

    If the variable frame area is less than the full frame, the image is read into the top left corner of the array. All subsequent processing will only be done on the used area of the array.

    The user is then given the option of viewing the image to ensure that it has been read in correctly. The image is shown on the computer screen, with each pixel being

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the three digit integer value of its grey scale level. Only the top left corner of a large image can be viewed, however, this is normally enough to see if the image appears to be correct. If the image appears incorrect the user can start the routine over again.

2. Image Thresholding

The image is now thresholded. The user can define the upper and lower bounds of the threshold region. The initial values are usually determined by interactive thresholding while in ImageAction (before storing the filtered image). The array is reduced to zeros for all pixels outside of the threshold region and to ones for pixels inside the region. Once again the user is given the option to view the thresholded result. If the result is not as desired, the user can start over. It should be noted that the thresholding permanently alters the pixel array and so if the thresholding is not correct the image must be re-entered. (The program automatically reprompts the user for this requirement.)

3. Feature Identification and Labeling

The thresholded image is now converted to a feature-labeled image. The program does this by working through the image a row at a time. Starting in the upper left corner, each new pixel in turn is evaluated. If it is a zero it is skipped. If it is a one, the pixel to its left is evaluated. If the left pixel is non-zero then the new

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pixel is given the same value as its left partner. If the left pixel is zero then the pixel immediately above the new pixel is tested with similar results. Should both the pixel to the left and the pixel above be zero, then the feature count register is advanced one and the new pixel is assigned that number. This sequence is continued until all of the rows have been labelled in this manner.

Once all of the rows are done then the program goes through each row again, checking each pixel with the one above it. If the current pixel is zero it is skipped. If the pixel above it is zero, or of the same value, it is left with its current value. If the pixel above has a different value then all of the pixels with the value of the current pixel are changed to the same value as the pixel above. In this manner features which have a hole in them, or a section which is partially detached, are sure to be assigned the same feature number.

Once this row-to-row check is done, then all of the features are renumbered from one to the total number. The final result is that the array now contains a fully feature-labelled image, which can be processed for specific feature data. The user is once again given the option of viewing this image before continuing, and the total number of features is displayed.

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4.   Feature Statistics

The feature labeled image is now used to find the specific feature data which is required for the hologram image analysis. This includes each feature's X chord (or the horizontal diameter), the Y chord (or the vertical diameter), and the feature's total area. Each of these measurements is done as a pixel count.

The X chord is found by counting all of the continuous pixels of the same feature value in each row. Should a feature have a break in it, additional sums for the same feature are maintained for the row until the end of the row is reached. The largest sum is then used as that row's chord length for that feature. Then that row's chord values are compared to previous row's chord values for that feature number. The largest X chord length is kept, and the program continues to the next row.

The feature areas are computed at the same time as the X chord lengths by simply summing the total number of pixels encountered in each row for each feature number.

The Y chord lengths are computed in the same manner as the X chord lengths with the exception that the values are calculated column by column instead of row by row.

These measurements are all that is required to assess the hologram image for its particle content, as the other factors, such as circularity, can be found from them. Although all of these measurements are in terms of pixels,

it would be easy to convert them to actual size measurements if a known reference pixel size was available for the magnification of use in the image.

5. Feature Data Display

In order to carry out analysis of the feature data, it must be displayed in some usable form. The program was written to offer the data in two formats, depending on its intended use. The user is prompted for the desired form of output. After each display of the feature data, as either a table or a histogram, the user is given the opportunity to select additional data outputs, either in the alternate form or in a modified version of the current form.

a. Histogram Output

If the histogram form is selected, the user is advised of the total number of features and the maximum X chord length of all of the features. Prompts are then issued to define the lower X chord limit of the histogram, the upper X chord limit of the histogram and the number of bins that the histogram is to be broken into.

Next the user is asked if non-round features are to be excluded. If they are, a test flag is set and the program proceeds to form a histogram file.

The feature data is then sorted into the bins with each feature being counted into the bin of the correct chord size. Each feature is tested for roundness, if the test flag is set, by finding the magnitude of its X chord

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less its Y chord. If this magnitude is greater than two then the feature is excluded as non-round. The value of two was found by experimentally checking a number of hologram images and finding that over 95 % of the features met this criteria. In fact, 85 % had a magnitude less than two.

The bin values are then converted into percentage values by dividing each by the total number of features. The final result is then displayed as a data file and the user is advised of the total number of features and the number of features which were excluded due to non-roundness.

The user is then asked if a hard copy is requested. If one is, a copy of this histogram data is then copied to disk, where it can be later printed out or up-loaded to the NPS mainframe computer where it can be converted to graphical form by a plotting routine.

b. Tabular Output

If the tabular output is selected, then the feature data is printed out by feature number, displaying the area, the X chord length and the Y chord length. The user is again asked if a hard copy is required and, if so, a copy of the table is written to disk.

C. PROGRAM LIMITATIONS

The program was written for use on the IBM/AT and because of this, suffers from two main limitations. First,

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the memory space available on the IBM/AT and the program sizes are such that images with a maximum of only two hundred and fifty (250) particle features can be processed. The program will run with images that have more than this number, however, the feature specific data is lost.

The second major limitation is the time that it takes to run this program for large image sizes. If a full quadrant is to be analyzed, the program takes approximately two and one-half hours to run from start to finish. This is due to the number of operations and the speed of the IBM/AT.

Both of these problems could be overcome by running the program on the NPS mainframe computer. However this would require that the stored image be uploaded to the main computer and this in itself requires considerable time as it is a file of over 65,600 bytes. A further difficulty would be encountered if ImageAction drivers were to be included in the program, as the hardware and software for their use does not exist on the mainframe computer.

It is felt that a better alternative is to fully investigate the use of the ITEX/PC driver subroutines on the IBM/AT. It is possible that with their use the program may be substantially increased in speed. It is also thought that additional memory will be freed as the pixel array may not be required, since the PC Vision board can be used to store the image during processing.

D. SUMMARY

The feature data extraction program has been used on many processed images and has been found to operate well, given its two limitations. The use of the ITEX/PC driver subroutines may greatly enhance its performance. If additional measurements or calculations are required, they can be easily added into the routine due to its sectional format.

The program was used to produce the preliminary results which follow in Chapter IV.

IV. PRELIMINARY RESULTS

This chapter contains the results obtained by using the ImageAction software and the Fortran data retrieval program as outlined in the earlier chapters of this thesis. The test images for all of the results in this chapter were produced from a calibrated standard reticle.
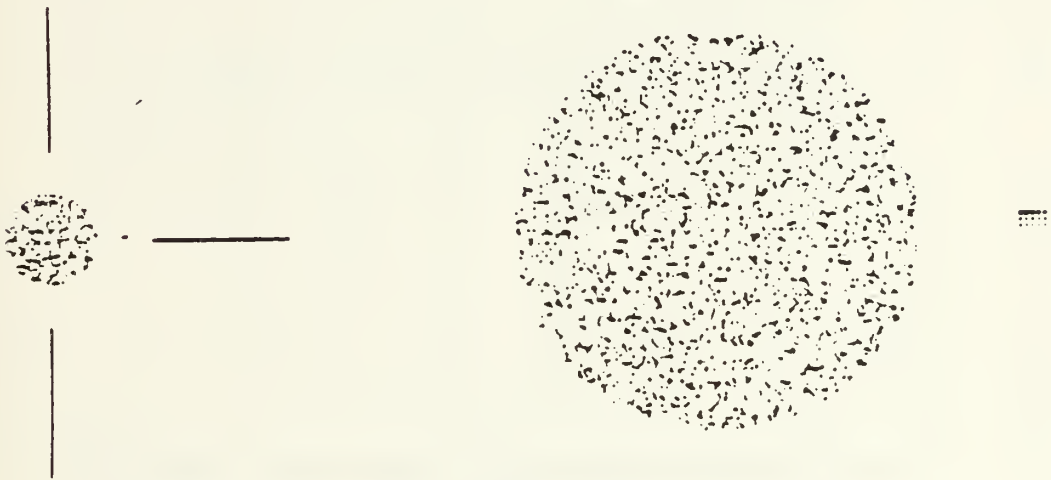
Magnified 1.5X   Magnified 8X

Figure 4.1   Calibration Standard Reticle
[Ref. 6, Figure 1]

The reticle consists of two sections as seen in Figure 4.1.   The circular portion of the reticle consists of approximately 10,000 opaque circular features of twenty-three (23) sizes ranging from five (5) to ninety-three (93) microns.   These features are randomly photo-etched into the eight (8) millimeter circular area.   The array to the right

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of the eight millimeter circular test pattern contains the twenty-three standard sizes of features arranged in rows of five features as shown in Figure 4.2 .

The calibrated array was used to investigate the effects of the image processing on the size of the processed particles. The manufacturer's data for the particle size distribution of the circular reticle portion of the standard calibrated image was used to evaluate the results obtained from the IBM/AT system.

9	7	5		
27	24	21	17	12
43	40	37	34	31
61	56	52	50	47
93	87	81	74	67

Figure 4.2   Calibration Array Sizes (Microns)
[Ref. 6]

This calibrated standard reticle was available in two forms. It was purchased etched onto a glass plate which could be used to carry out white light analysis of the system. It was later recorded onto a laser hologram in the same manner that the holograms were produced of the combustion products in the rocket motor. It should be noted that this test reticle hologram was recorded without the smoke present that occurs in the combustion holograms. Thus,

a discussion of the effects of smoke on hologram analysis can not be carried out.

A. THE EFFECTS OF IMAGE AVERAGING

The speckle properties exhibited by laser reconstructed hologram images have been previously discussed. As this speckle pattern is a random property, which can be considered time-varying due to vibrations and the laser coherence, it was felt that a large portion of this speckle could be removed by time-averaging the reconstructed image.

In chapter two, two alternative methods for time averaging of the reconstructed image were presented. These two methods included the use of the Average routine of the ImageAction software, or the inclusion of a spinning mylar disk in front of the microscope optics. The relative merits of each of these techniques was investigated and the results follow.

1. ImageAction Averaging

The ImageAction Average routine takes successive image frames and averages their grey levels. In this manner the random time-varying features in an image will be washed out, while the fixed features will not. Using this routine, image lengths of one, two, five, ten, fifteen and twenty frames were averaged. The resulting images were then filtered and thresholded to see the effects.
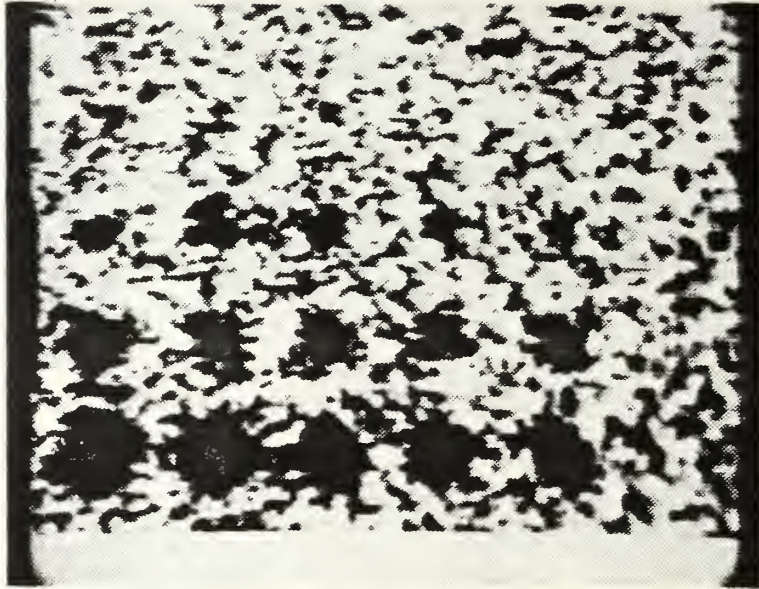
Figure 4.3   An Unaveraged Hologram Image
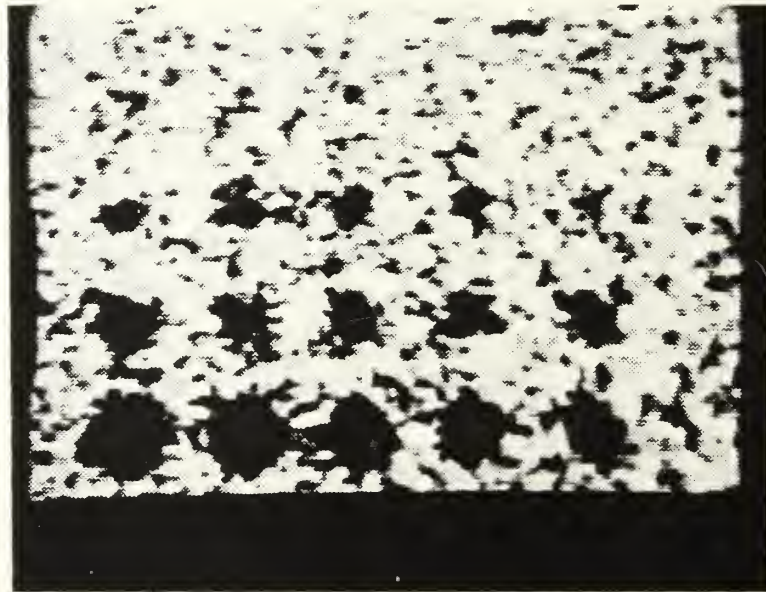
Figure 4.4   Twenty Frame ImageAction Average Hologram Image

The results were as expected. The averaging greatly reduced the speckle, even to the unaided eye prior to filtering and thresholding. An example of an unaveraged hologram image is shown in Figure 4.3 . An example of a twenty frame averaged hologram image is shown in Figure 4.4.

It should be noted that both of these images have not been filtered or thresholded. A comparison of the two figures shows that the time averaging has removed or reduced the lighter speckle out of the solid features. It has also reduced the amount of darker speckle from the lighter background.

It was also found, as expected, that by averaging a greater number of frames that the speckle was more reduced. This reduction occurred up until ten frames were averaged. The results for averaging fifteen frames and twenty frames were found to be the same for that of averaging ten frames. Thus, it was found that an application of the Average routine on ten frames was optimum.

2. Mylar Averaging

When the spinning mylar disk was inserted into the reconstruction equipment several interesting results were noted. First, the amount of light incident on the camera was greatly reduced and a much more sensitive camera was required. However, this proved not to be a problem as cameras were available which could easily make up for this loss (as discussed in Appendix A).

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It was also observed that the speckle was greatly reduced. This is due to the fact that the mylar disk is rotated at a rate greater than the 1/30 second integration time of the video camera. The mylar disk, therefore, changes the phase of the incident laser light over time, and thus changes the speckle pattern seen by the camera. Hence, the speckle values become washed out while the constant particle images do not.

Once again this was evident even to the unaided eye. However, when the image was filtered and thresholded in the same manner as the image using the Average routine, it was found that the two final images were identical. Hence the spinning mylar disk carried out the same function as the Average routine applied over ten frames or more.

The image produced by the spinning mylar disk was available immediately from the reconstruction apparatus. While the time-averaged ImageAction image required a time-consuming averaging process. Therefore, the spinning mylar disk was felt to be the better solution to achieve a time-averaged image.

3.   Mylar Plus ImageAction Averaging

In interest of completeness, an ImageAction Average image was made from one, two, five and ten frames of a mylar reconstructed image. Even after filtering and thresholding no improvement of the speckle reduction was found, even over the ten frame averaged image. Thus, the

averaged image produced by the spinning mylar was found to be optimal in both speckle reduction and in processing time.

B. THE EFFECTS OF IMAGE PROCESSING

The hologram images, even after time averaging, still exhibited a substantial speckle content. An example of this can be seen in Figure 4.4 and Figure 4.5 . Figure 4.5 shows the same time-averaged image as in Figure 4.4, only now thresholding has been done to highlight the speckle that remains in the picture that may be undetected by the eye.

Figure 4.5 Time-Averaged Hologram Image after Thresholding

Therefore the image must be further processed in order to remove this speckle prior to the feature data being extracted. Otherwise, this speckle will be counted as

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features.   It is this remaining speckle that was the partial cause of the Quantimet system's inability to correctly perform feature extraction on the reconstructed image. [Ref. 1]

The two further processing operations which are required are filtering and thresholding.   These two operations were described in Chapter Two.   The effects and limitations of these functions will now be covered.

1.   Filtering   .

The two predefined ImageAction types of convolution are Blur and Lowpass as described in Chapter two.   If the size of the remaining speckle after time averaging is large, then the Blur function must be used.   By "large", it is meant that the speckle appears to be of the same size as the smallest of the known feature sizes.   In cases where the speckle is not large, the Lowpass function is preferable as it causes less smearing of the edges of the feature particles.   In general, it was found that the Lowpass function could be used for microscope magnifications of times two and less.

When the correct filtering routine was applied, all of the remaining background speckle could be completely suppressed. However, it should be restated that the smaller particle features are also being suppressed by this filtering as are the edges of the larger features. Also, if two particle features are close together, their edges may be

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blurred together to form one solid particle. This last problem is particularly evident at lower magnifications.

2. Thresholding

With the speckle suppressed by the filtering it is now possible to produce a thresholded image that contains only known particle features and no background. An example of this is shown in Figure 4.6 .

Figure 4.6 Averaged, Filtered and Thresholded Image

3. Processing Limitations

Several things can be quickly noted from Figure 4.6. It can be seen that this image does not show the entire calibrated image as is shown in Figure 4.2 . The particles of diameters 5, 7, 9, 12, 17, and 21 have been

lost. However the background which is evident in Figure 4.4 and Figure 4.5 has been completely suppressed.

It was also evident that the size of the particles which were present in the image, could be varied in size by adjusting the level of the threshold. The image shown in Figure 4.6 shows the calibrated features at the largest threshold value before background speckle begins to appear. However the meaning of the pixel size of these features is clearly dependent on this threshold level. In a mixed target such as a combustion hologram, the question arises as to where to set the threshold level, as it will be hard to tell what is speckle and what are small particles.

The most obvious solution to this problem is to include the calibrated reticle on the back of the combustion chamber so that it becomes part of each hologram image. The threshold level for the hologram can be determined from this image and then applied to all subsequent images from that hologram. This solution is dependent, however, on a constant background average grey level, which may not be the case in a smoke-filled combustion chamber. Other techniques should be investigated to remove the smoke or other spatial variations of transmissivity if they become a problem. Some alternate techniques include bleaching the hologram [Ref. 4] or background grey-scale averaging techniques. [Ref. 7] This determination of the threshold setting, however, is clearly a limitation on the system.

Finally, it is necessary to consider why the six smallest particle features were missing in the processed hologram image of Figure 4.6. Looking at the images before thresholding (Figures 4.4 and 4.5) it can be seen that these six features do not readily appear in either of these two Figures. It may be possible that these small particle images were unresolved in the holographic recording of the calibrated reticle and they were not removed by the filtering and thresholding.

Figure 4.7 shows a white light image of the calibrated array before it was recorded on a hologram. (It is felt that the physical damage to this array that removed some of the deposition occurred after the hologram was made.) The smallest particle features can been seen in this Figure (at the arrows). Figure 4.8 shows this same image after it has been filtered and thresholded. The three smallest features of Figure 4.7 have been removed by the processing operation.

Hence, several reasons for the loss of the six smallest features in the hologram reconstruction are possible. First, some of the features may not have been resolved in the recording of the hologram of the calibration array. This could be due to a variety of reasons. It may be that the holographic process is unable to resolve particles of this size, however, this is not felt to be true in this case.

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Figure 4.7   White Light Calibration Array Image
Showing the Three Smallest Features   (Arrows)
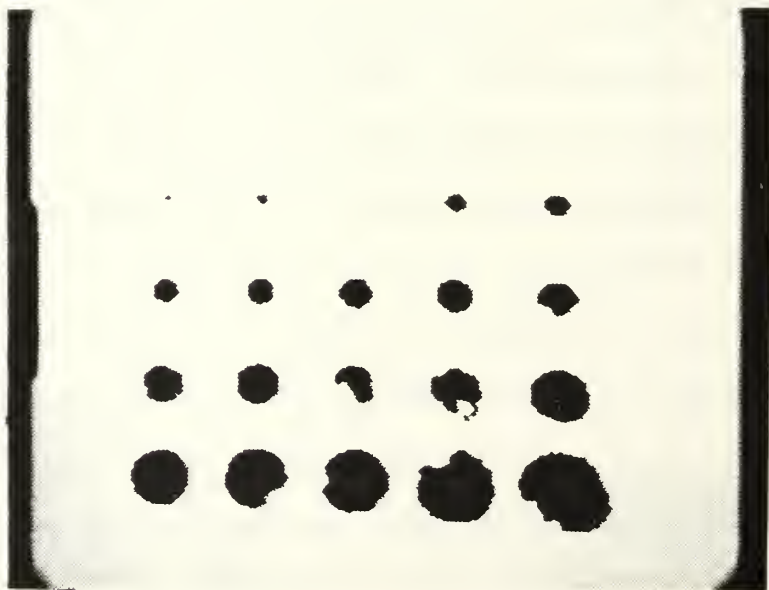
Figure 4.8   Filtered and Thresholded Calibration Array
Showing the Three Smallest Features Removed

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Alternatively, the hologram reconstruction process may cause particles of these sizes to be unresolved. This could be due to many reasons such as the intensity of the reconstruction laser, incorrect focusing of the optics, incorrect alignment of the optics, insensitivity of the recording cameras, etc. All of these areas need further investigation.

In the white light reconstruction, only the top three particles became unresolved after the filtering and thresholding (Figures 4.7 and 4.8). However, the next three sizes of particles were still clearly visible, so filtering should not affect these particle images. Therefore, in the hologram case the remainder of the particles should have survived the processing, however, an additional three particle images were lost due to unexplained causes.

Thus, it appears that the small array particles became unresolved due to a combination of the above causes. Regardless of the causes, the reduced resolution of the processed hologram image is a limitation on the system. If this limitation cannot be overcome, then the effect of the the inability of the system to reconstruct and process particles of these smaller sizes must be assessed with respect to the goals of this data retrieval system.

C. VERIFICATION OF THE IBM/AT SYSTEM

Taking the limitations of the system into account, the entire IBM/AT hologram data retrieval system was tested on

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two calibrated test images. The two images used were a
2X magnification of the white light reconstructed
calibration reticle, and a 2X magnification of the laser
reconstructed hologram of the calibration reticle.
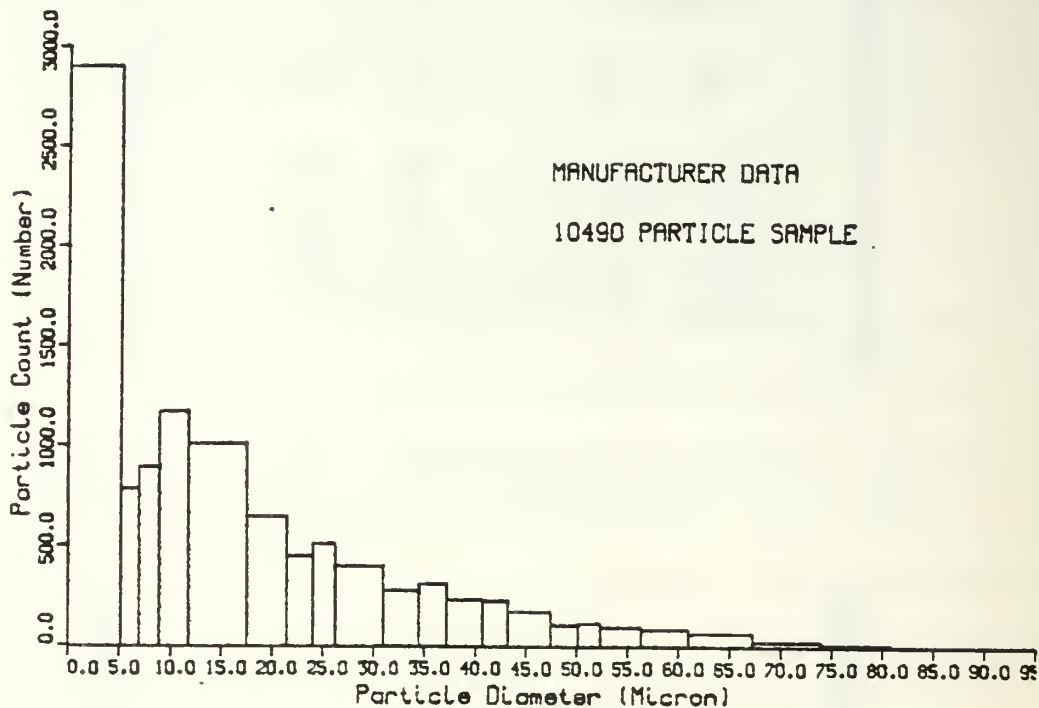
Figure 4.9   Manufacturer's Size Distribution
[Ref. 6]

The manufacturer's particle size distribution for the
calibration reticle is shown in Figure 4.9 . Each of the
particle sizes is plotted as a bar to show its relative
density. In order for this data to be compared to the two
reconstructed image results, it is required that the
diameter sizes be converted from lengths in microns, to
lengths in pixels. The details of this conversion as well as

the truncation of the manufacturer's data to exclude the unresolvable smaller particles are contained in Appendix C.

. 1.   White Light Calibration Reticle Results

The manufacturer's particle size distributions have been replotted for the white light reconstruction case. The resulting histogram is shown in Figure 4.10. As previously stated, details on how this modified plot was made are available in Appendix C. It is assumed that this data does not include any overlapping particles.
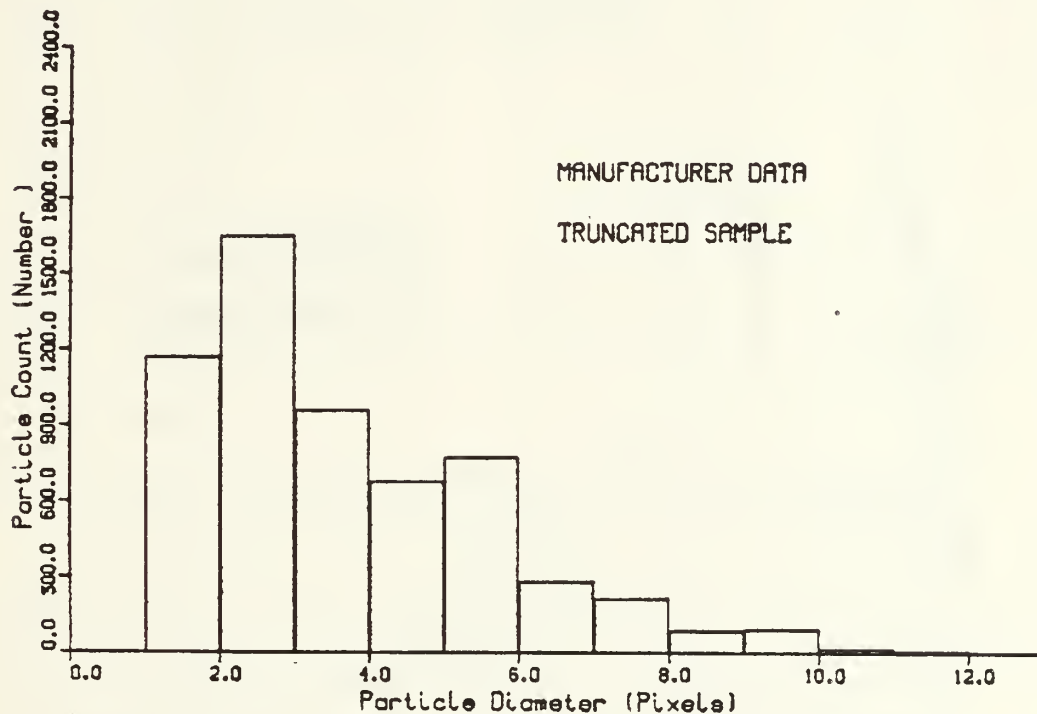
Figure 4.10 Manufacturer's Size Distribution
White Light Reconstruction 2X Magnification

The white light reconstructed image was taken using the spinning mylar disk as the time averaging device. It was then lowpass filtered, and the resulting image was

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thresholded to the level required to just remove the background speckle from the calibration array. The image was then stored in accordance with the procedures outlined in Chapter 2 and Appendix B.

The Fortran program of Chapter 3 was then run to extract the particle data. The tabular output and the histogram data output are included as Appendix D.

The plotted histogram of the results is shown in Figure 4.11 . It can be seen that the plot compares well with that of the manufacturer's data in Figure 4.10 .
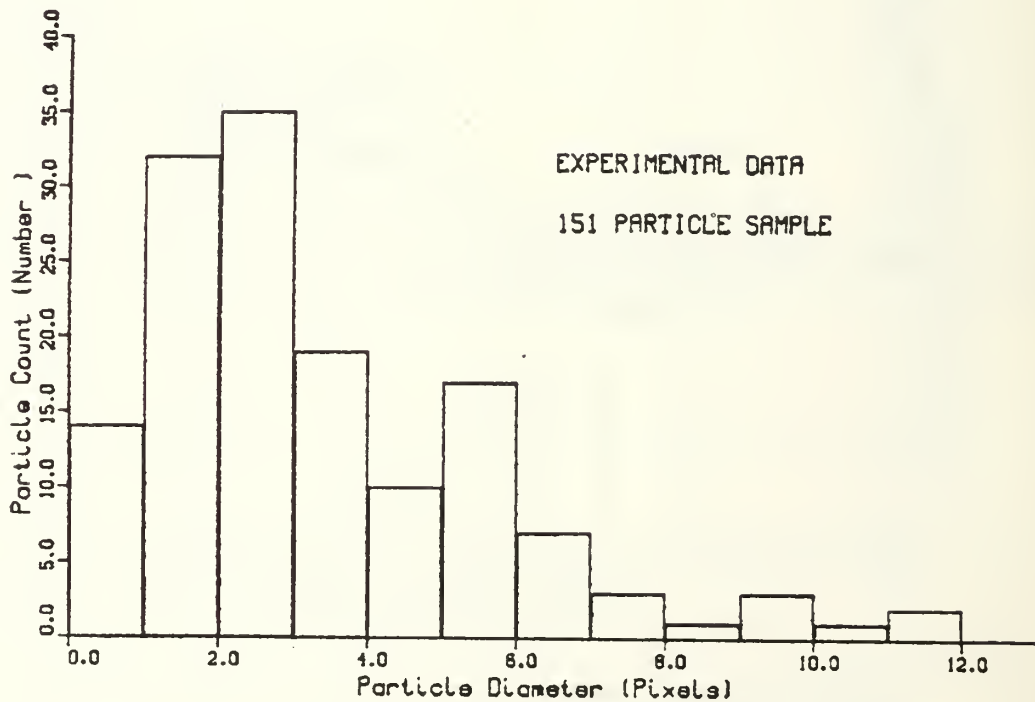
Figure 4.11   White Light Experimental Size Distribution

The general shape of the distribution of the manufacturer's histogram and the experimental data histogram

are the same. However, the experimental data indicates that more of the smaller particles have survived the processing than predicted. This could be due to a variation in the level of the background intensities between the area of the array and the area of the reticle pattern. This would result in the threshold level being set too low and some of the speckle features may have been included.

Also a very small number of particles appear to be larger than expected. This is probably due to overlapping particles which passed the roundness test. However, the number of particles in this group is small enough that they can be neglected.

Thus, it appears that for the white light reconstruction case, this method of processing and data recovery works very well with the exception of the smallest particle images.

2.   Laser Hologram Calibration Reticle Results

The manufacturer's particle size distributions have been replotted for the laser hologram reconstruction case as described in Appendix C. Since the unresolved particles are larger for this case, the curve is different from the white light case. The resulting histogram is shown in Figure 4.12.

The laser hologram reconstructed image of the calibrated reticle was taken using the spinning mylar disk as the time averaging device. It was then processed and thresholded in the same manner as the hologram calibrated

array. The thresholded image was then stored and the data file converted in the same manner as the white light image.

The Fortran program was run to extract the particle data. The tabular output and the histogram data output are included as Appendix E . It can be seen that there were more particles present in the hologram image than the white light image. The plotted histogram is shown in Figure 4.13. .
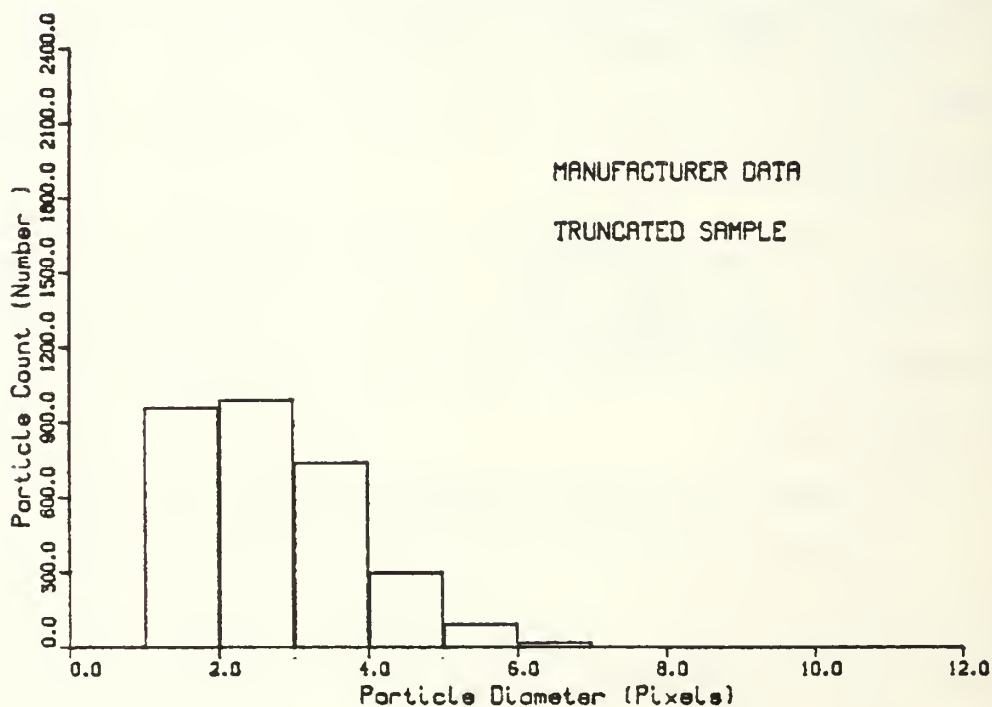
Figure 4.12 Manufacturer's Size Distribution
Laser Hologram Reconstruction 2X Magnification

Again it can be seen that the plot compares well with that of the converted and truncated manufacturer's data in its general size distribution. However, a larger number

of small particles are present in the experimental curve. As the width of the one pixel diameter range is now 13.1 microns instead of 7.3 microns, it is felt that these particles are still speckle which has survived the processing.

It can also be seen that a few larger particles are also once again present and it is still felt that these are due to overlapping particles.
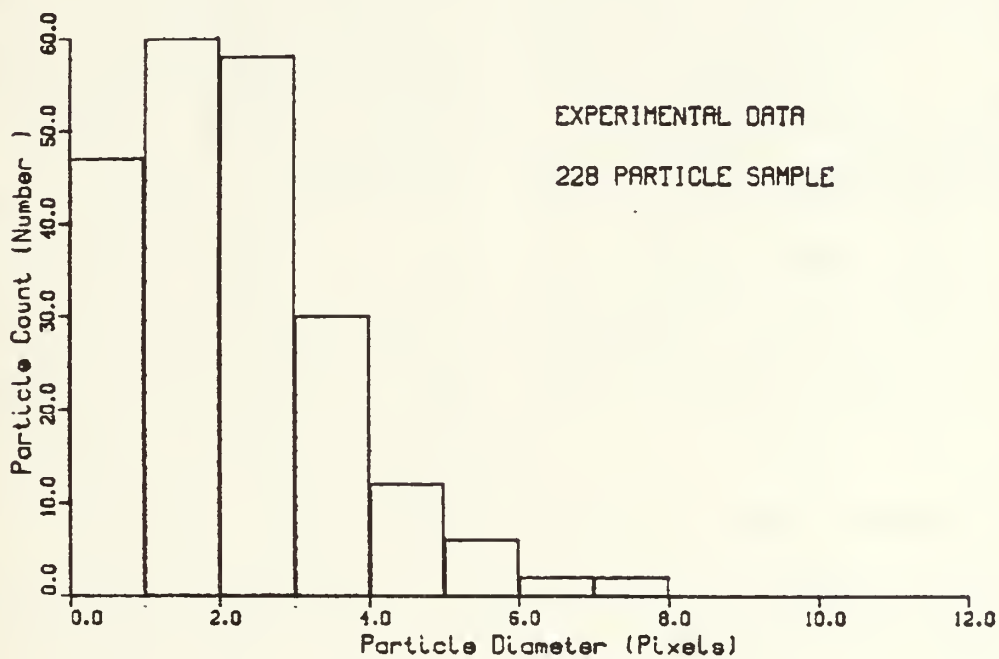
Figure 4.13 Hologram Experimental Size Distribution

D. SUMMARY

The results shown in this chapter have been obtained by using the IBM/AT system. They have shown that the system can produce usable data results from hologram images, with

some stated limitations. The loss of small particle images when using holograms requires further research to determine which particles are lost at each step of the process. In this manner corrective action can be attempted to overcome all or some of the losses. The effect of those lost particle sizes which cannot be recovered will have to be determined.

The effects of uneven background illumination caused by the presence of smoke in the rocket chamber also remains to be investigated. It is clear that if this smoke is present, then it will have to be removed by some process. If it is small enough it may well be removed by the filtering and thresholding. This remains to be seen.

V. <u>CONCLUSIONS</u>

The IBM/AT system for the processing of laser reconstructed hologram images has been discussed and the preliminary results from this system have been analyzed in Chapter IV. The combination of the ImageAction hardware and software with the Fortran data extraction program has produced results which compare favorably with those expected from calibrated sources. Therefore, it is felt that the IBM/AT system should undergo further research.

The system has three main limitations on its use which need further study before it can be considered truly effective. The most important of these limitations is the loss of the small particle features from the hologram images. The actual cause of the loss of all of these particles is not fully evident.

From the comparison of the white light reconstruction example and the laser hologram reconstruction of the same calibrated array it can be seen that the filtering and processing of the image may cause the particles of less than nine (9) microns to be lost. Further work may show that different convolution kernels may be able to retain even these small features. However, the comparison of these two images also shows that an additional three particles (with

sizes up to twenty-one (21) microns) have been lost in the hologram image.

The fact that these particles do not even appear to the eye in the unprocessed averaged image, suggests that they may be lost prior to the processing. Further investigation is required to determine if they are lost in the hologram recording, in the hologram reconstruction, in the image recording or in the image processing.

The IBM/AT system can be used to test other techniques to improve the first three of the potential loss areas. It may be found that the hologram photographic images do not have these size particles in them. However, once the best results have been achieved, the final minimum size of particle that can survive the entire process will have to be assessed against the aim of this system.

Assuming that the first limitation of the system is felt to be acceptable or can be improved upon, the second main area of concern is the length of time that it takes to completely analyze an image. At present, once the image is stored in video form, it can take up to three hours to process one full quadrant of an image. This includes the time to process the image, save it to a data file, convert the data file, run the data extraction program and then plot the resulting data into graphical form. This amount of time can definitely be reduced.

The subroutines that make up the ImageAction software are now available as independent drivers in the ITEX/PC software set. It is felt that the use of these routines should be fully investigated to try to speed up the entire IBM/AT system. If these routines can be called directly from the Fortran data extraction program, it is felt that much more than half of the time currently required can be eliminated.

Finally, the third main limitation of this system is the small area that can be analyzed at one time. This is due to the lack of memory space on the IBM/AT, as images of only 250 features can be processed. Once again it is felt that this problem can be largely overcome by using the ImageAction subroutines in the ITEX/PC software directly from the Fortran program. In this manner the monitor can be used as the pixel array memory and therefore the 256 by 256 array in the IBM/AT will not be required. This should free up more than enough memory to process an image with as many features as are present in a 1X magnification image.

In summary, this thesis has presented an alternate method of performing analysis on hologram images. The IBM/AT computer is the basis for a digital system that can carry out image processing as well as data extraction. The ImageAction software routines used are discussed. The Fortran program written to carry out the data extraction has been explained. In the preliminary results the system

demonstrated that it has the ability to perform the required
functions with some specific limitations. The causes for
these limitations are described and possible solutions have
been offered.

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APPENDIX A

LOW LIGHT CAMERAS

The hologram reconstruction process required that the image be viewed through a microscope and then be captured as a video image. A video camera was therefore required. As it was required that the image be stored on tape and brought to a separate location for processing, it was felt that the optimum camera would be a standard video camera/recorder (CamCorder). Thus the first camera used was a VHS Movie Camera. Detailed specifications on this camera are in Figure A.1 .

The VHS Movie Camera provided several advantages. A separate recording machine was not required and the camera had a built-in background sensing circuit, which automatically adjusted the aperture for varying illumination conditions.

It, however, also presented several disadvantages. First, the main lens was not removable. This caused problems in that the camera optics did not mate well with the microscope camera port. The result was that not all of the camera viewing area was illuminated and a black area around the outer perimeter of the image was formed. As well, due to the number of lenses in series, a darker spot was observed in the center of the image.

FEATURES /CAMERA	Panasonic VHS Movie Camera	Panasonic WV-1410	Panasonic WV-1460
LENS	6:1 Power Zoom, F1.4 (9-54mm), Not Removable	None, Standard Fitting	None, Standard Fitting
PICK-UP TUBE	NEWVICON	VIDICON	NEWVICON
HORIZONTAL RESOLUTION	525 LINES	600 LINES	600 LINES
MINIMUM ILLUMINATION	10 Lux	.5 Lux	.05 Lux

Figure A.1   Camera Standard Features

The major disadvantage of the VHS Movie Camera was discovered when it was used to view the laser-reconstructed holograms. While the camera had worked well for the white light reconstructed images, it was quickly discovered that the camera did not have the light level sensitivity required to record the hologram reconstructions.

The VHS Movie Camera was only able to be used to record images at magnifications of 1X, and then only if the spinning mylar disk was removed. It was therefore decided that a camera with a lower light sensitivity was required.

The next camera to be used was the Panasonic WV 1410. This camera is for low light level security surveillance. It did not have an internal recording system, and so an

external BETA recorder was used. The WV 1410 did not come with a lens, but it had a standard fitting that matched the camera adapter of the microscope. Thus, once installed, it produced images without either the outer dark halo or the inner central darker spot.

While the WV 1410 did not have an automatic aperture system, the image could be viewed directly by use of a monitor and the light level of the image was adjusted by varying the power of the reconstruction laser. At the lower magnifications of 1X and 2X this camera could be over-illuminated if the mylar disk was removed. However, it was found that at higher magnifications, and at lower magnifications with the spinning mylar disk, that the camera produced images that were too dark to process.

Hence the WV 1460 camera was tried. This camera had all of the advantages of the WV 1410 camera, and had sufficient sensitivity to be overilluminated at up to 10X magnification with the spinning mylar disk in place. By adjusting the laser power it could record images over the complete range of magnifications, with or without the mylar disk.

Thus, the WV 1460 was felt to be the optimum camera for this system and was used to record all of the hologram images used in this thesis. The white light images used in the thesis were taken with the Panasonic VHS Movie camera.

APPENDIX B

CONVERSION OF THE STORED IMAGE FILE

The ImageAction software permits an image that has been processed to be stored for later use. The program takes the image and stores it as a string file which contains an ImageAction header, a variable length comment block and an image block. In the image block each pixel is stored as an ASCII character with a decimal value from 0 to 255 in accordance with its grey level.

The Fortran data extraction program is designed to take this file and read the image portion into a two dimensional array, which it can then process. The Fortran program is limited, due to the 512K memory capacity of the IBM/AT and the array is therefore specified to be 256 by 256. This corresponds to one quadrant of the ImageAction screen, and the software permits a single quadrant to be stored.

Difficulty was experienced, however, when the data file was attempted to be read. Fortran does not permit easy access to string files and, in particular, excessively long string files. If the image is stored without a comment, the stored image file is 65,600 characters long. It is clear, therefore, that the data file had to be processed before it could be read into the Fortran program.

Conventional word processors also cannot handle string files of the length of this data file. In addition, the ImageAction header contains some undefined ASCII characters and so it was unreadable to them. Using the M/DOS Debug routine it was found that the header was 64 characters long. While the Debug routine could have been used to convert the image data file, this would have been a long manual operation, and so this was felt to be unacceptable.

The final desired form of the image data file was to have it as a fixed format column of data which could then easily be read by the Fortran program. Hence, it was decided that a program would have to be written in some other programming language which could convert the file. The resulting program was written in Basic and is shown in Figure B.1 .

The program takes the ImageAction stored file, named DATA.IMG, and reads a string of data from it. It should be noted that the longest string in Basic is 255 characters. Each ASCII character is then taken one at a time and converted to its decimal integer equivalent. The integer is then formatted into I4 format by adding the correct number of preceding zeros, and then it is stored back into the output file DATA. The program continues until it has done all 65,600 characters.

The program experiences difficulty if it encounters a character at the end of one of the input strings which is an

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ASCII control character. The ASCII control characters have integer pixel grey values in the image that range from zero (0) to twenty six (26). These characters force the program to abort as they will not permit the string section to be closed. This problem can be easily overcome by preprocessing the stored image to remove these control characters.

```
10    DIM LIST1(255)            ;VARIABLE DIMENSION
20    OPEN"O",1,"A:DATA"        ;OUTPUT FILE
30    OPEN"I",2,"A:DATA.IMG"    ;INPUT FILE
40    FOR J = 1 TO 257
50    LIST1$ = INPUT$(255,#2)   ;GET STRING OF DATA
60    FOR I = 1 TO 255
70    X$ = MID$(LIST1$,I,1)     ;SELECT ONE CHARACTER
80    P = ASC(X$)               ;GET INTEGER VALUE
90    IF P < 10 GOTO 130
100   IF P < 100 GOTO 160
110   PRINT#1,P                 ;STORE VALUE OF P
120   GOTO 190
130   Y$ = SPACE$(2)            ;ADD FORMAT SPACES
140   PRINT#1,Y$;P              ;STORE VALUE OF P
150   GOTO 190
160   Y$ = SPACE$(1)            ;ADD FORMAT SPACE
170   PRINT#1,Y$;P              ;STORE VALUE OF P
180   GOTO 190
190   NEXT I                    ;DO EACH CHARACTER
200   NEXT J                    ;DO NEXT STRING
210   CLOSE 1                   ;CLOSE OUTPUT FILE
220   CLOSE 2                   ;CLOSE INPUT FILE
```

Figure B.1 ImageAction Data File Conversion Program

Therefore, the steps required to store and convert the image data file are shown in Figure B.2 . These steps are carried out after the image has been processed and the desired results have been achieved. The image must be contained in only one quadrant. Should a full screen image be desired for data extraction, the ImageAction Quad Squish

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routine must be used used to compress the image before these steps are taken.

```
STEP 1          HIGH CLIP 225
STEP 2          MAP LUT TO AOI
STEP 3          ADD LUT 30
STEP 4          MAP LUT TO AOI
STEP 5          SAVE AOI AS A:DATA.IMG
STEP 6          RUN PROGRAM TR1.BAS
STEP 7          RUN FORTRAN PROGRAM
```

Figure B.2   Image File Storing and Conversion Steps

The ImageAction High Clip routine takes all of the image pixels above the stated value and makes them into the stated value. The memory values, however, are not changed until a Map Lut to AOI operation is done. The top 30 values must be removed before the entire image is increased by 30 because the ImageAction software works as a roll-around LUT system (i.e., when you add one to 255 it becomes 0).

This file conversion process has a large disadvantage in that it takes fifteen minutes to run the Basic conversion program. It then takes a further eighteen minutes to read the converted file into the Fortran data extraction program. It is felt that use of the ImageAction Driver routines as a part of the Fortran program could possibly eliminate the need for many of these steps. This alternative requires further research.

APPENDIX C

CONVERSION OF THE MANUFACTURER'S DATA
OF THE CALIBRATION RETICLE

The calibration reticle was produced by Laser Electro-Optics Ltd. The reticle portion of the image consists of an average of 10,490.7 dots which have been etched onto a glass backing. For use in testing the hologram imaging equipment, a hologram of the calibrated array and reticle was also made. The hologram was made in the same manner as the holograms from the combustion chamber.

The calibrated reticle consists of twenty-three (23) different sized circular particles which are deposited with known densities onto the glass in an eight (8.) millimeter circle. Beside the reticle is an array which contains each of the twenty-three (23) sized particles in rows of five.

Figure C.1 gives a complete breakdown of the sizes of the particles and the number of each of them present in the reticle. This data was used to plot the histogram shown in Figure 4.9 of the preliminary results.

The sizes of the particles for the calibrated array and reticle are measured in microns. However the sizes of the particles measured by the IBM/AT system are naturally measured by a number of pixels. A method of converting the micron diameters to pixels is required.

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PARTICLE NO.	DIAMETER (Microns)	NUMBER PRESENT (Avg)
1	5.14	2904.7
2	6.87	783.7
3	8.89	892.9
4	11.73	1168.6
5	17.47	1007.7
6	21.46	642.9
7	24.00	447.2
8	26.15	510.3
9	30.90	397.6
10	34.40	278.0
11	37.12	313.1
12	40.68	232.9
13	43.19	225.7
14	47.40	172.7
15	50.13	106.7
16	52.31	114.3
17	56.34	98.3
18	60.98	85.4
19	67.21	64.6
20	73.94	25.7
21	80.77	12.4
22	87.25	4.2
23	92.88	1.0
	TOTAL	10490.7

Figure C.1   Calibrated Reticle Data
[Ref. 6]

The size of a reconstructed particle image is a function of the magnification of the reconstructing optics, the type of monitor used, the type of filtering algorithm and the level of the image threshold. (This is assuming that the background intensity is constant throughout the image. Therefore, any comparison of sizes between images must be done under these conditions and limitations.)

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Clearly a white light reconstructed image and a hologram image will differ in several, if not all, of these aspects and, therefore, each must be considered separately. The white light reconstruction will be considered first.

In this case, an image of the calibrated array was taken at a 2X magnification and processed. The method of filtering and the level of thresholding was recorded so that it could be reproduced for the reticle image later. A photograph of the white light array is shown in Figure 4.8. The image was then stored and the Fortran program was run to extract the feature data. The tabular output has been reorganized for comparison and is shown in Figure C.2.

Using the X width data from Figure C.2 for all of the particles which were present and which were obviously not malformed, an average length per pixel was calculated. The diameter in microns for each of the particles was taken from the manufacturer's data in Figure C.1. The diameter per pixel is shown in Figure C.2 for each feature, as is the average. (It should be noted that the data for particle 4 was not used in forming the average length per pixel as the data had too large a variance to be considered.)

This average diameter per pixel value was then used as the conversion factor to convert the manufacturer's particle distributions to pixel diameters instead of micron diameters. This method is felt to be a relatively accurate conversion.

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PARTICLE NO.	AREA (PIXELS)	X WIDTH (PIXELS)	Y WIDTH (PIXELS)	DIA/PIXEL	REMARKS
1					MISSING
2					MISSING
3					MISSING
4	1	1	1	11.73	NOTE (2)
5	3	2	2	8.74	
6					MISSING
7	9	3	4	8.00	
8	13	4	5	6.66	
9	15	4	5	7.73	
10	17	5	5	6.88	
11	25	5	6	7.43	
12	28	5	7	8.14	
13	26	6	6	7.20	
14	35	7	8	6.77	
15	43	7	8	7.16	
16	25	6	7		NOTE (1)
17	44	8	8	7.04	
18	73	9	10	6.78	
19	74	9	11	7.47	
20	82	10	12	7.39	
21	100	10	12		NOTE (1)
22	125	12	14	7.27	
23	154	14	15	6.64	

AVERAGE   =   7.33 MICRONS/PIXEL

NOTE (1)   Particles were not used as their diameters
           appeared questionable in Figure 4.8 due to damage.

NOTE (2)   Particle not included in total average as it
           has too large a variance.

Figure C.2   Calibrated Array Feature Data
White Light Reconstruction

Using the conversion factor calculated as shown, a table for the white light reconstruction was made. The Table shows the width range in pixels verses the width range in microns and the total number of particles which fall into that size range. The number of particles in each range was found by summing the appropriate totals from the manufacturer's data in Figure C.1. The results are shown in the first three columns of Table C.1.

TABLE C.1   CONVERTED MANUFACTURER'S DATA
WHITE LIGHT RECONSTRUCTION

DIAMETER (PIXELS)	DIAMETER (MICRONS)	TOTAL NO. OF PARTICLES	TRUNCATED NO. OF PARTICLES
0 - 1	0.0 - 7.3	3688.4	0.0
1 - 2	7.3 - 14.7	2061.5	1168.6
2 - 3	14.7 - 22.0	1650.6	1650.6
3 - 4	22.0 - 29.3	957.5	957.5
4 - 5	29.3 - 36.7	675.6	675.6
5 - 6	36.7 - 44.0	771.7	771.7
6 - 7	44.0 - 51.3	279.4	279.4
7 - 8	51.3 - 58.7	212.6	212.6
8 - 9	58.7 - 66.0	85.4	85.4
9 - 10	66.0 - 74.0	90.3	90.3
10 - 11	74.0 - 81.3	12.4	12.4
11 - 12	81.3 - 88.6	4.2	4.2
12 - 13	88.6 - 95.9	1.0	1.0

A histogram of the total manufacturer's size distribution based on pixel diameters has been plotted and is shown in Figure C.3.

The large distribution of particles in the zero to one pixel area of the histogram is only true, however, if all of

the particles which are on the reticle can be viewed. This is not the case for the IBM/AT system. The smaller particles are not reconstructed and so they should not be included in the histogram.
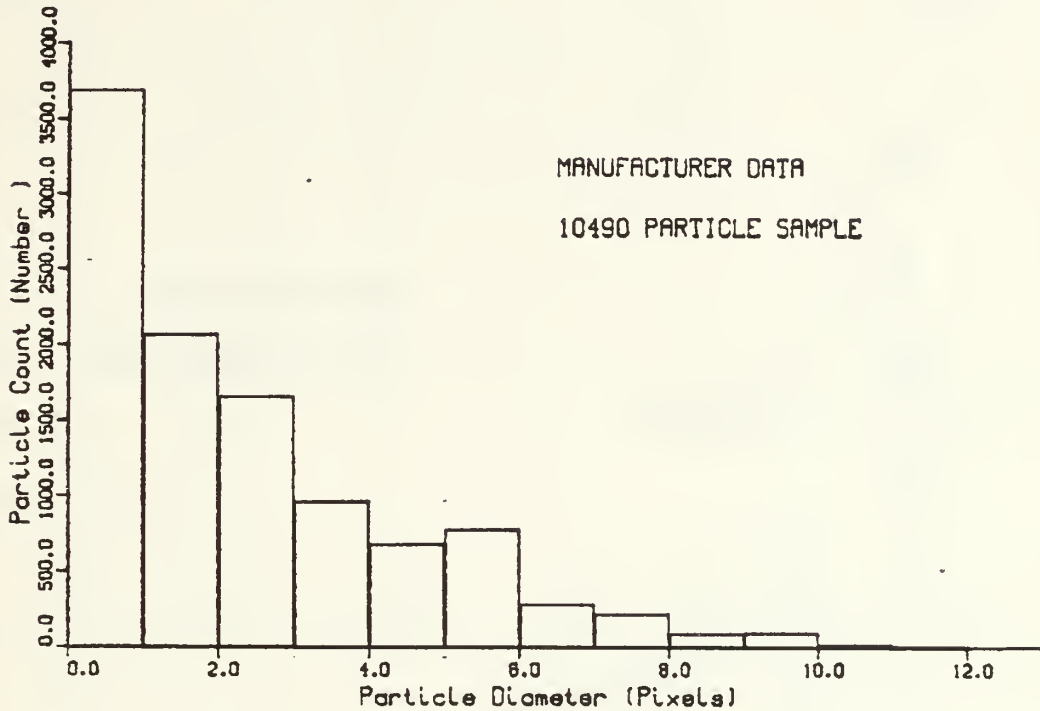
Figure C.3   Full Manufacturer's Size Distribution
White Light Reconstruction

Thus, a modified case is needed. Referring back to the particle image data in Figure C.2, it is seen that all particles smaller than 11.73 microns could not be reconstructed in the white light case. Figure 4.9 of the manufacturer's data has been replotted in Figure C.4 to show this threshold somewhere between diameters of 8.89 microns and 11.73 microns. As the particles on the array have

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discrete sizes, the exact location of this threshold line is
not known; however, it is known that it lies between these
two values. The particles which fall below this threshold
line must be truncated from the manufacturer's data in order
to accurately predict what can be expected from the IBM/AT
system.
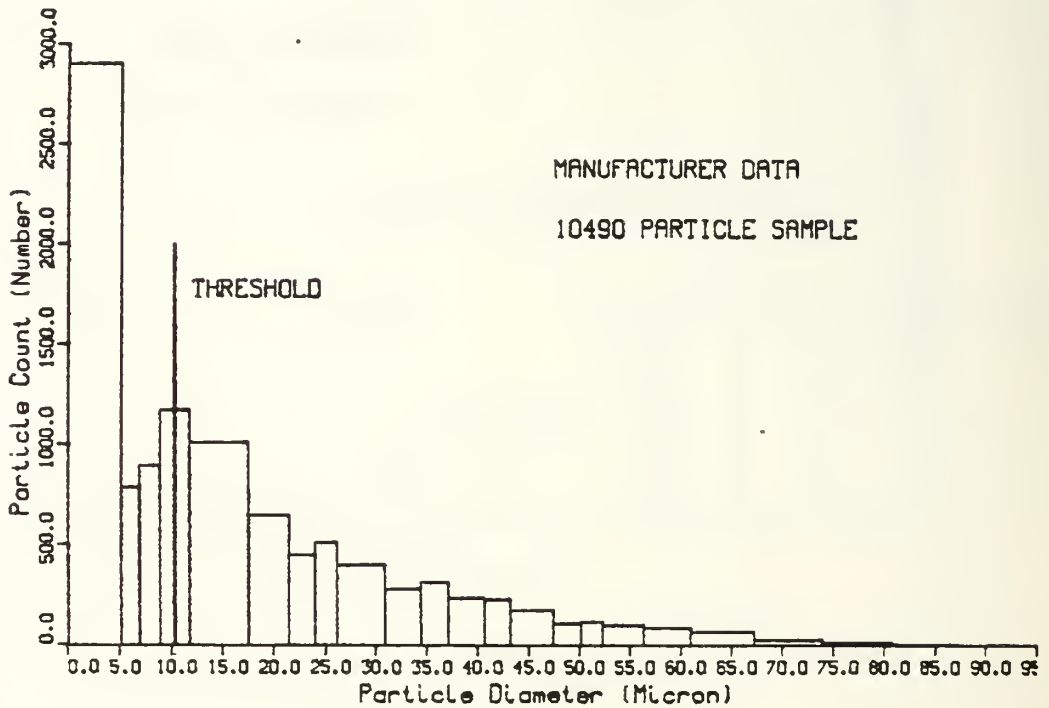
Figure C.4 Manufacturer's Data Showing
White Light Size Threshold

Truncating the manufacturer's data at this diameter
threshold, the numbers shown in the final column of Table
C.1 are found. It can be seen that all of the one pixel size
particles are excluded, as are some of the two pixel size

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particles. This truncated manufacturer's data has been plotted and is shown as Figure 4.10.

The analysis and conversion of the manufacturer's data for the hologram reconstruction will now follow the same steps as those taken in the white light reconstruction.

Again in this case, an image of the calibrated array was taken at a 2X magnification and processed. The method of filtering and the level of thresholding was recorded so that it could be reproduced for the reticle image later. A photograph of the hologram array is shown in Figure 4.6. The image was then stored and the Fortran program was run to extract the feature data. The tabular output is shown in Figure C.5.

Using the X width data as shown in Figure C.5, for all of the particles which were present and which were obviously not malformed, an average diameter per pixel was calculated. The diameters in microns for each of the particles was taken from the manufacturer's data in Figure C.1. The value for each feature is shown in Figure C.5, as is the total average. (It should be noted that the data for particle 7 was not used in forming the average length per pixel as the data had too large a variance to be considered.)

This average diameter per pixel value was then again used as the conversion factor to convert the manufacturer's particle distributions to pixel diameters instead of micron diameters.

PARTICLE NO.	AREA (PIXELS)	X WIDTH (PIXELS)	Y WIDTH (PIXELS)	DIA/PIXEL	REMARKS
1					MISSING
2					MISSING
3					MISSING
4					MISSING
5					MISSING
6					MISSING
7	1	1	1	24.00	NOTE (1)
8	2	2	1	13.33	
9	3	2	2	15.45	
10	4	2	2	17.20	
11	6	2	3	18.56	
12	8	3	4	13.56	
13	10	3	3	14.40	
14	17	4	5	11.85	
15	19	4	5	12.53	
16	14	4	5	13.08	
17	25	5	6	11.27	
18	21	5	6	12.20	
19	24	6	6	11.20	
20	42	7	9	10.56	
21	40	7	8	11.54	
22	51	8	8	10.90	
23	48	8	8	11.61	

AVERAGE = 13.08 MICRONS/PIXEL

NOTE (1)   Particle not included in total average
             as it has too to large a variance

Figure C.5 Calibrated Array Feature Data
Hologram Reconstruction

Using the conversion factor calculated as shown, a table

for the hologram reconstruction was made. The table shows

the width range in pixels verses the width range in microns

and the total number of particles which fall into that size

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TABLE C.2   CONVERTED MANUFACTURER'S DATA
HOLOGRAM RECONSTRUCTION

DIAMETER (PIXELS)	DIAMETER (MICRONS)	TOTAL NO. OF PARTICLES	TRUNCATED NO. OF PARTICLES
0 - 1	0.0 - 13.1	5749.9	0.0
1 - 2	13.1 - 26.2	2608.1	957.5
2 - 3	26.2 - 39.2	988.7	988.7
3 - 4	39.2 - 52.3	738.0	738.0
4 - 5	52.3 - 65.4	298.0	298.0
5 - 6	65.4 - 78.5	90.3	90.3
6 - 7	78.5 - 91.5	16.6	16.6
7 - 8	91.5 - 104.	1.0	1.0
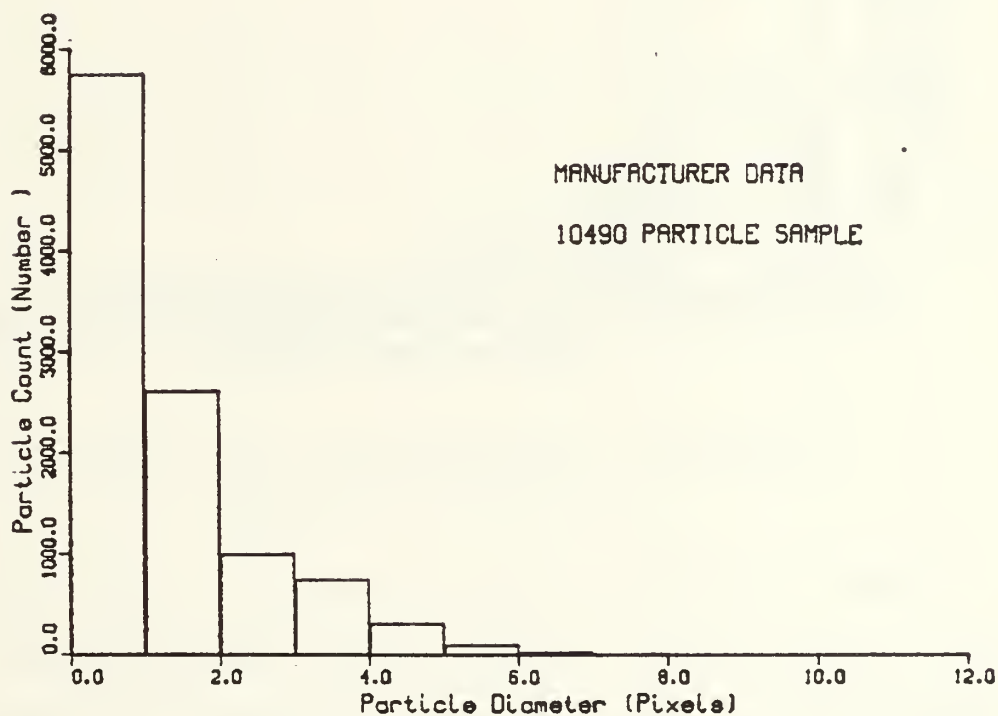
Figure C.6   Full Manufacturer's Size Distribution
Hologram Reconstruction

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range. The results are shown in the first three columns of Table C.2.

A histogram of the total manufacturer's size distribution based on pixel diameters has been plotted and is shown in Figure C.6.
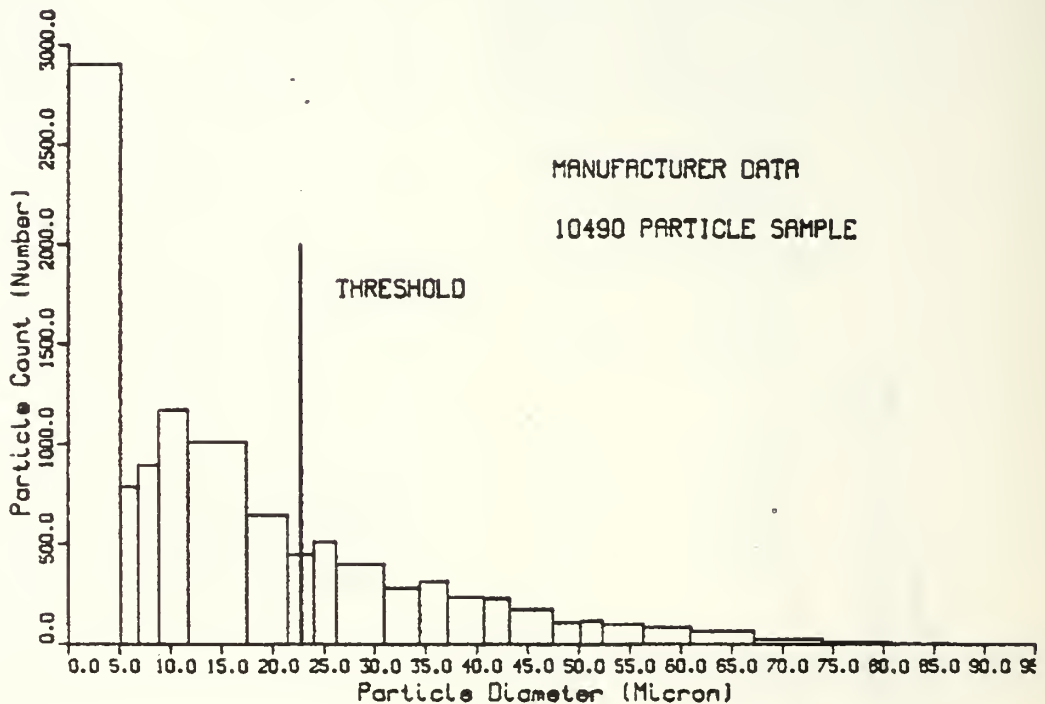
Figure C.7 Manufacturer's Data Showing
Hologram Size Threshold

Again a modified case is needed to remove all of the smallest particles which were not reconstructed in the hologram case. Referring back to the particle image data in Figure C.5, it is seen that all particles smaller than 24.00 microns could not be reconstructed. Figure 4.9 of the manufacturer's data has been replotted in Figure C.7 to show

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this   threshold   size line somewhere between particles   of
diameters of 21.46 microns and 24.00 microns.   The particles
which fall below this threshold line must be truncated from
the manufacturer's data in order to accurately predict what
can be expected from the IBM/AT system.

Truncating   the   manufacturer's   data at   this   diameter
threshold,   the   numbers shown in the fourth column of Table
C.2 are found. It can be seen that all of the one pixel size
particles are again excluded,   as are some of the two pixel
size particles.   This truncated manufacturer's data has been
plotted and is shown as Figure 4.12.

APPENDIX D

CALIBRATED RETICLE EXPERIMENTAL DATA
WHITE LIGHT RECONSTRUCTION

The calibrated test reticle was reconstructed using white light. It was then filtered, processed and thresholded in the same manner as was the white light illuminated calibration test array, shown in Figure 4.7. The Fortran particle data extraction program was then run on the converted data file. The histogram data table from the program is shown in Table D.1 and the tabular output is shown in Table D.2 .

TABLE D.1 HISTOGRAM FEATURE DATA OUTPUT

TOTAL NUMBER OF FEATURES = 151

TOTAL NON-ROUND FEATURES =   7

BIN SIZE (PIXELS)		NUMBER OF FEATURES	FEATURE DENSITY
FROM GREATER THAN	TO LESS THAN		
0.0	1.0	14	0.09
1.0	2.0	32	0.21
2.0	3.0	35	0.23
3.0	4.0	19	0.13
4.0	5.0	10	0.07
5.0	6.0	17	0.11
6.0	7.0	7	0.05
7.0	8.0	3	0.02
8.0	9.0	1	0.01
9.0	10.0	3	0.02
10.0	11.0	1	0.01
11.0	12.0	2	0.01

TABLE D.2 TABULAR FEATURE DATA OUTPUT

FEATURE NO.	AREA	X WIDTH	Y WIDTH	REMARKS
1	8	3	3	
2	21	4	6	
3	4	2	2	
4	8	3	3	
5	14	4	4	
6	72	10	10	
7	19	6	5	
8	12	4	4	
9	10	3	4	
10	2	1	2	
11	6	3	3	
12	7	2	4	
13	36	6	7	
14	4	2	2	
15	44	6	8	
16	10	3	4	
17	88	12	10	
18	24	6	6	
19	15	4	5	
20	28	6	6	
21	4	2	2	
22	58	7	10	NOT ROUND
23	4	2	2	
24	7	3	3	
25	18	4	5	
26	8	3	3	
27	2	2	1	
28	12	4	4	
29	35	6	7	
30	4	2	2	
31	6	2	3	
32	5	3	3	
33	3	2	2	
34	8	3	3	
35	1	1	1	
36	6	2	3	
37	10	3	4	
38	6	2	3	
39	34	6	7	
40	12	3	4	
41	7	3	3	
42	7	3	4	
43	6	3	3	
44	4	2	2	

FEATURE NO.	AREA	X WIDTH	Y WIDTH	REMARKS
45	8	2	5	NOT ROUND
46	19	4	6	
47	29	6	6	
48	29	5	7	
49	7	3	3	
50	7	3	3	
51	1	1	1	
52	32	8	6	
53	30	7	6	
54	4	2	2	
55	26	5	6	
56	6	2	3	
57	21	5	5	
58	64	11	7	NOT ROUND
59	8	3	4	
60	21	5	5	
61	4	2	2	
62	23	5	5	
63	74	9	10	
64	4	2	3	
65	2	1	2	
66	29	6	7	
67	14	4	5	
68	16	4	5	
69	7	3	3	
70	17	4	5	
71	9	3	4	
72	14	4	4	
73	34	6	7	
74	4	2	2	
75	4	2	2	
76	1	1	1	
77	34	7	7	
78	14	4	5	
79	4	2	2	
80	1	1	1	
81	2	2	1	
82	22	5	6	
83	63	11	9	
84	33	6	7	
85	12	3	4	
86	11	3	4	
87	5	3	3	
88	35	6	7	
89	6	2	3	
90	2	1	2	
91	35	6	7	

FEATURE NO.	AREA	X WIDTH	Y WIDTH	REMARKS
92	116	12	14	
93	19	4	6	
94	3	2	2	
95	11	3	5	
96	18	5	5	
97	2	2	1	
98	7	3	3	
99	7	3	3	
100	2	1	2	
101	17	4	5	
102	3	2	2	
103	10	4	3	
104	6	2	3	
105	51	7	9	
106	56	8	8	
107	5	3	2	
108	33	6	7	
109	17	4	5	
110	34	6	7	
111	6	2	3	
112	1	1	1	
113	48	7	8	
114	20	4	6	
115	7	3	3	
116	7	3	3	
117	95	10	12	
118	58	10	7	NOT ROUND
119	9	3	4	
120	1	1	1	
121	2	1	2	
122	10	3	4	
123	8	3	3	
124	8	3	3	
125	37	6	7	
126	1	1	1	
127	19	5	5	
128	46	7	8	
129	12	3	4	
130	19	5	5	
131	4	2	2	
132	2	2	1	
133	11	3	5	
134	54	8	9	
135	33	6	7	
136	4	2	2	
137	114	8	18	NOT ROUND
138	39	7	7	

FEATURE NO.	AREA	X WIDTH	Y WIDTH	REMARKS
139	7	3	3	
140	2	1	2	
141	6	2	3	
142	48	7	9	
143	124	15	11	NOT ROUND
144	19	4	6	
145	26	5	6	
146	64	10	8	
147	4	2	2	
148	10	4	3	
149	8	5	2	NOT ROUND
150	1	1	1	
151	2	2	1	

Note (1)   The data from these tables is shown in graphical

form in Figure 4.11 .

APPENDIX E

CALIBRATED RETICLE EXPERIMENTAL DATA
LASER HOLOGRAM RECONSTRUCTION

The calibrated test reticle was reconstructed using the laser hologram. It was then filtered, processed and thresholded in the same manner as was the laser reconstructed calibration hologram test array, shown in Figure 4.6 . The Fortran particle data extraction program was then run on the converted data file. The histogram data table from the program is shown in Table E.1 and the tabular output is shown in Table E.2 .

TABLE E.1 HISTOGRAM FEATURE DATA OUTPUT

TOTAL NUMBER OF FEATURES = 228

TOTAL NON-ROUND FEATURES = 11

BIN SIZE (PIXELS)		NUMBER OF FEATURES	FEATURE DENSITY
FROM GREATER THAN	TO LESS THAN		
0.0	1.0	47	0.21
1.0	2.0	60	0.26
2.0	3.0	58	0.25
3.0	4.0	30	0.13
4.0	5.0	12	0.05
5.0	6.0	6	0.03
6.0	7.0	2	0.01
7.0	8.0	2	0.01
8.0	9.0	0	0.00
9.0	10.0	0	0.00
10.0	11.0	0	0.00
11.0	12.0	0	0.00

TABLE E.2   TABULAR FEATURE DATA OUTPUT

FEATURE NO.	AREA	X WIDTH	Y WIDTH	REMARKS
1	21	4	7	NOT ROUND
2	4	2	2	
3	1	1	1	
4	7	3	3	
5	27	6	8	
6	20	5	5	
7	6	2	3	
8	11	4	4	
9	4	2	2	
10	1	1	1	
11	9	3	3	
12	3	2	2	
13	1	1	1	
14	1	1	1	
15	11	4	3	
16	8	3	4	
17	4	2	2	
18	8	3	4	
19	6	2	3	
20	7	3	3	
21	1	1	1	
22	13	2	8	NOT ROUND
23	15	6	3	NOT ROUND
24	1	1	1	
25	24	5	7	
26	1	1	1	
27	7	3	3	
28	4	2	2	
29	16	5	4	
30	2	2	1	
31	15	4	5	
32	7	3	3	
33	28	4	6	
34	9	4	3	
35	2	1	2	
36	5	2	3	
37	3	2	2	
38	3	1	3	
39	15	4	4	
40	4	2	3	
41	6	2	4	
42	1	1	1	
43	1	1	1	
44	3	2	2	

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FEATURE NO.	AREA	X WIDTH	Y WIDTH	REMARKS
45	2	1	2	
46	13	4	5	
47	4	1	4	NOT ROUND
48	2	1	2	
49	9	4	3	
50	3	2	2	
51	18	4	6	
52	1	1	1	
53	13	4	4	
54	13	5	4	
55	1	1	1	
56	4	2	2	
57	1	1	1	
58	6	3	3	
59	12	5	3	
60	9	3	4	
61	8	3	3	
62	11	3	4	
63	9	4	3	
64	14	3	5	
65	4	2	2	
66	2	2	1	
67	6	2	3	
68	25	7	5	
69	2	1	2	
70	1	1	1	
71	9	4	3	
72	1	1	1	
73	4	2	3	
74	3	2	2	
75	46	10	6	NOT ROUND
76	32	6	7	
77	19	5	5	
78	6	3	3	
79	6	3	2	
80	15	4	5	
81	15	4	5	
82	8	4	3	
83	7	4	3	
84	2	2	1	
85	7	3	3	
86	2	1	2	
87	3	1	3	
88	7	3	3	
89	1	1	1	
90	4	2	2	
91	10	3	4	

FEATURE NO.	AREA	X WIDTH	Y WIDTH	REMARKS
92	24	7	4	NOT ROUND
93	3	2	2	
94	1	1	1	
95	9	3	3	
96	3	2	2	
97	4	2	2	
98	27	6	6	
99	11	3	4	
100	7	3	3	
101	8	4	3	
102	5	2	3	
103	5	2	3	
104	4	2	2	
105	1	1	1	
106	3	2	2	
107	88	8	9	
108	3	2	2	
109	15	4	5	
110	19	5	5	
111	3	2	2	
112	8	3	4	
113	3	2	2	
114	8	3	3	
115	1	1	1	
116	4	2	3	
117	9	3	4	
118	5	2	3	
119	19	4	7	NOT ROUND
120	19	3	6	NOT ROUND
121	11	3	4	
122	7	3	3	
123	11	4	4	
124	15	4	4	
125	6	2	3	
126	1	1	1	
127	3	2	2	
128	7	3	3	
129	8	4	3	
130	7	3	3	
131	26	6	6	
132	7	3	3	
133	5	3	2	
134	2	2	1	
135	1	1	1	
136	9	3	4	
137	9	3	4	
138	2	1	2	

FEATURE NO.	AREA	X WIDTH	Y WIDTH	REMARKS
139	4	3	2	
140	1	1	1	
141	2	1	2	
142	14	3	5	
143	1	1	1	
144	9	4	3	
145	6	3	2	
146	4	3	2	
147	6	3	3	
148	23	5	6	
149	1	1	1	
150	22	5	5	
151	24	6	6	
152	3	2	2	
153	4	2	2	
154	7	3	3	
155	8	3	3	
156	25	4	8	NOT ROUND
157	17	4	7	NOT ROUND
158	2	1	2	
159	1	1	1	
160	1	1	1	
161	7	2	4	
162	9	4	3	
163	10	3	4	
164	5	3	2	
165	4	2	2	
166	3	2	2	
167	4	2	2	
168	3	2	2	
169	4	2	2	
170	4	2	2	
171	1	1	1	
172	6	2	4	
173	4	2	2	
174	8	3	4	
175	5	3	2	
176	1	1	1	
177	9	3	4	
178	2	2	1	
179	4	2	2	
180	24	7	5	
181	3	2	2	
182	14	4	5	
183	8	3	3	
184	8	3	3	
185	37	8	6	

FEATURE NO.	AREA	X WIDTH	Y WIDTH	REMARKS
186	2	1	2	
187	7	3	3	
188	5	3	2	
189	8	3	3	
190	17	4	5	
191	9	3	4	
192	11	3	5	
193	18	5	5	
194	4	2	2	
195	3	2	2	
196	10	3	4	
197	10	3	4	
198	10	3	4	
199	21	4	6	
200	28	10	3	NOT ROUND
201	7	2	4	
202	9	3	4	
203	11	4	4	
204	1	1	1	
205	13	5	4	
206	4	2	2	
207	1	1	1	
208	10	3	4	
209	1	1	1	
210	2	1	2	
211	12	4	4	
212	1	1	1	
213	14	4	4	
214	5	2	3	
215	2	1	2	
216	6	3	3	
217	4	2	2	
218	17	4	6	
219	4	3	2	
220	1	1	1	
221	5	2	3	
222	1	1	1	
223	3	2	2	
224	4	2	2	
225	23	6	4	
226	17	5	4	
227	6	3	3	
228	1	1	1	

Note (1)   The data from these tables is shown in graphical form in Figure 4.13 .

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