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Deriving Particle Distributions from In-Line Fraunhofer Holographic Data

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Abstract

Holographic data are acquired during hydrodynamic experiments at the Pegasus Pulsed Power Facility at the Los Alamos National Laboratory. These experiments produce a fine spray of fast-moving particles. Snapshots of the spray are captured using in-line Fraunhofer holographic techniques. Roughly one cubic centimeter is recorded by the hologram. Minimum detectable particle size in the data extends down to 2 microns. In a holography reconstruction system, a laser illuminates the hologram as it rests in a three-axis actuator, recreating the snapshot of the experiment. A computer guides the actuators through an orderly sequence programmed by the user. At selected intervals, slices of this volume are captured and digitized with a CCD camera. Intermittent on-line processing of the image data and computer control of the camera functions optimizes statistics of the acquired image data for off-line processing. Tens of thousands of individual data frames (30 to 40 gigabytes of data) are required to recreate a digital representation of the snapshot. Throughput of the reduction system is 550 megabytes per hour (MB/hr). Objects and associated features from the data are subsequently extracted during off-line processing. Discrimination and correlation tests reject noise, eliminate mulitple-counting of particles, and build an error model to estimate performance. Objects surviving these tests are classified as particles. The particle distributions are derived from the data base formed by these particles, their locations and features. Throughput of the off-line processing exceeds 500 MB/hr. This paper describes the reduction system, outlines the off-line processing procedure, summarizes the discrimination and correlation tests, and reports numerical results for a sample data set.

1.0 Introduction

This paper describes the processing and analysis of in-line Fraunhofer holographic data at the Los Alamos Operations (LAO) of Bechtel Nevada. These data are acquired during hydrodynamic experiments[1] at the Pegasus Pulsed Power Facility at the Los Alamos National Laboratory (LANL) in Los Alamos, New Mexico. In the experiments, the positions of numerous high-speed, small particles are captured on holographic film. After the data has been recorded, it is optically reconstructed, digitized, and analyzed. First, the hologram is reconstructed on the Holographic Reduction Bench located in the LAO Secure Computing Laboratory (SCL). During the reconstruction, thousands of images of the reconstructed hologram are acquired in a sytemmatic, computer controlled scan. When properly correlated, these image data recreate a portion of the experiment. Next, during processing of the data, tests to reduce the data are run. These tests discriminate against noise, correlate particles, and extract the particle information (size and location) for the volume represented by the thousands of images.

Section 2 summarizes the data reconstruction (or reduction) procedure. Section 3 documents how the reduced data are processed, and Section 4 presents sample results illustrating the complete run-stream. Finally, Section 5 is a summary of this paper.

Examples in the literature describing holographic analysis of small particles may be found in References 2 and 3. The interest in this effort has been in developing and implementing an automatic analysis system to process gigabyte amounts of image data to extract and characterize particles extending down to 2 microns.

2.0 Holographic Reduction Bench

Figure 1 sketches the layout of the Holographic Reduction Bench components. Major components include: laser, laser power supply, ND wheel, collimating lens, stages and controller, relay lens, camera, and PC control system. Safety features to prevent casual access during laser operations include door interlock and warning panel.

The laser (at the far left) illuminates the hologram at a wavelength of 532 μm. Beam intensity and spot size are controlled by the ND wheel and collimating lens, respectively. Coherent scattered light from the hologram reconstructs a three-dimensional volume of data. The relay lens images a slice of this data to the camera. On commands issued by the PC control system, the camera captures this slice as a digital image. The image data are then displayed and written to a removable hard disk for storage. In the experiment space, each slice corresponds to a slab that is roughly 400 microns wide, 300 microns high, and 10 microns thick.

Between frames, the PC control system guides the stages through an ordered set of positions, forming different, but related and overlapping, slices. Figure 2 introduces a number of data concepts related to this ordered set of positions. The coordinate system at the top defines the reference for the motions. First, there is the image data (upper right) which is the thin slab of data just described. In general, the stages move the hologram along the z-axis between frames. Collectively, the data slabs acquired along the z-axis (i.e., beam axis) can be "stacked" atop each other and are called a data stack, or stack data. Three hundred images or more may be included in a single stack with spacing normally being 10 microns.

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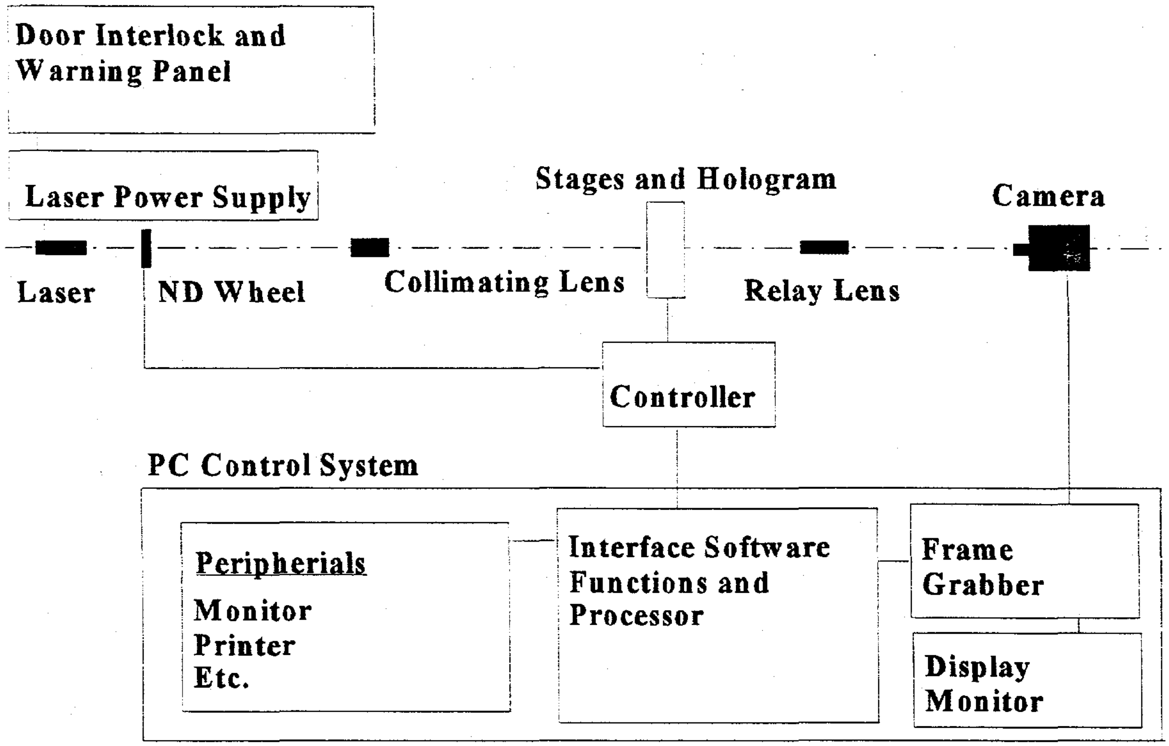

Figure 1. Sketch of Holographic Reconstruction Bench

When the last image data frame has been acquired for a stack, the computer shifts the hologram along the horizontal (x-axis). A shift to the right is indicated in the volume data shown in Figure 2. Following this shift, the hologram is again stepped along the z-axis, but in a direction opposite the previous. A new stack equal in the number of frames to the previous stack is acquired. This new stack represents another small box of volume data that probably overlaps with the previous stack (nominally 10-25% overlap), which is used to register the data sets.

Again the hologram is shifted along the x-axis and a new stack is acquired, creating a row of stack data. The process is repeated until the row is completed. At this point, the hologram is shifted vertically (y-axis; nominally 75-90% of the image height) rather than horizontally. Figure 2 illustrates this as a downward shift in the volume data. This process is repeated, but with the horizontal shifts between stacks now running in the opposite direction. A new row of stack data is acquired. At the end of this row, the hologram is again shifted vertically and the process is repeated until the desired volume is scanned. In this manner, a volume of data is acquired.

In summary, thousands of digital image data sets are acquired in a single scan with the Holographic Reduction Bench. These data sets are ordered so that hundreds can be stacked to form a stack of data. These stack data overlap with adjacent stack data. A digital representation of the volume is formed by the collection of all stack data. Throughput of the reduction system is 550 megabytes per hour. The next step, processing the data, is described in Section 3.

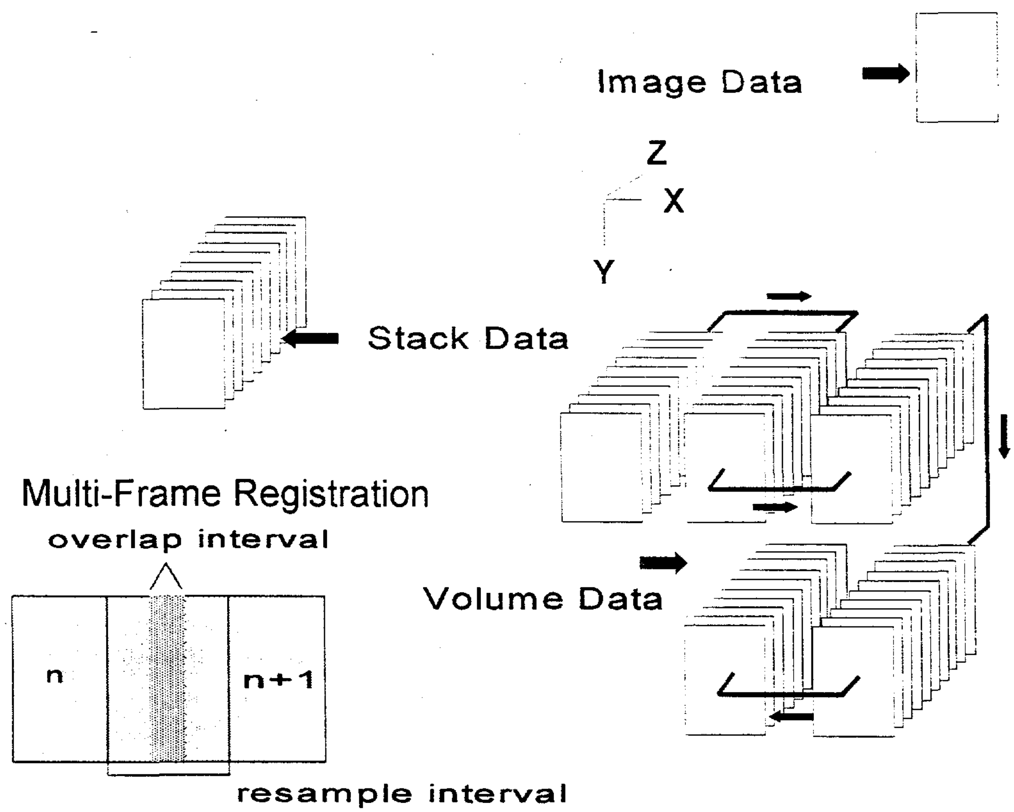

Figure 2. Sketch Illustating Data Concepts

3.0 Data Processing

The data processing procedure includes segmenting images, extracting particle location and size, and correlating the particle data from the volume in a timely manner. Segmentation proceeds at the image data level while extraction and correlation proceed at the stack and volume levels, respectively. The processing at each level is outlined below.

3.1 Image Level - Segmentation

At the image level, each pixel is evaluated to determine if the data are particle data. In the present circumstance, the particle data ride atop a complex background formed by the local behavior of the background within the hologram and a fixed noise pattern attributable to the optics of the reconstruction bench. The philosophy of the processing is to segment data that are distinctly different from the combination of the trends in the background in the holographic data and the fixed pattern noise. Success depends on how well the processing models the background.

To start, the processing separates the fixed noise pattern into reflection noise and common background noise generated within the CCD camera faceplate. A sample of the fixed noise pattern encountered in this work is shown in Figure 3. This image was generated by averaging a large number of data sets. Through a process of elimination, the striations running diagonally from the lower-left to the upper-right are identified as reflections at the faceplate of the CCD camera. The source of the broad rings is interference between optical windows and lens surfaces and is fixed for each image. The common background noise is obtained as an area average (nominally 15 microns by 15 microns), while the reflection noise is calculated as the difference between the fixed pattern noise and common background noise. The broad background noise is assumed to create a multiplicative error in the data, and the reflections are considered to be additive.

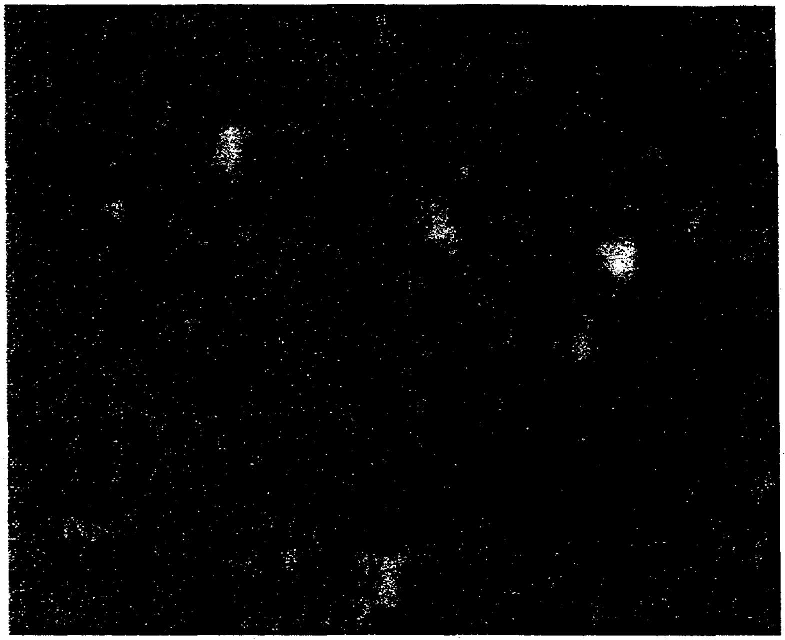

Figure 3. Fixed Pattern Noise

In the first correction, each data set is divided by the common background noise. As this may "over correct" the data, a weighted average of the original data set and the corrected data is used. To identify structure (i.e., wires, cross hairs, or any strong abnormality in the background), the processing fits a two-dimensional trend in the data (linear in x and y) to the weighted average. Deviations (and their statistics) in the trend are computed. Large, positive deviations (defined in terms of the statistics of the deviations) are identified as structure. A mask is generated from this structure data. The first order estimate of the local background is then constructed using the weighted average data. At points identified as structure, the weighted average data are replaced with the trend data.

Next, a second order estimate of the background is computed as the area average (nominally 15 microns by 15 microns) of the first order estimate. Adding the reflections completes the third and final estimate of the background. This estimate of the noise background includes the local trends in the holographi data, corrections for strong structure, reflections from the faceplate, and common backgr nd noise. Although not perfect, this estimate is sufficient and permits processing of thousands of frames to continue at an acceptable pace.

Subtracting the final background from the flattened data set yields the signal excess. Particle data will have positive values for the signal excess. Values less than zero for the signal excess are set to zero. Statistics of the signal excess are then computed.

Because of the averaging process and nature of the background, there is a tendency for the signal excess to be greater when the background is high. In a simple effort to model this relationship, the signal excess is fit to the background using a linear least squares fit. Only positive signal excess values greater than three counts are used in the fitting procedure. Mask (or structure) data are excluded from the fitting procedure. Statistics are then computed for the errors in this fit.

Positive errors in the fit that greatly exceed reasonable statistics are classified as particle data. The large, positive deviations in the two-dimensional trend (i.e., mask data) are classified as possible particle data. Contiguous particle and/or possible particle data points are then segmented from the image. If a set of segmented data points contains at least five particle data points, the entire set is judged to be particle data. If the segmented set has less than five particle points, the entire set of segmented points is considered to be clutter and is rejected.

The steps are summarized below.

> Generate fixed pattern noise, G
> Separate G into reflections R and common background noise C
> For each data set I:
>> Obtain weighted average data set as $W = (1-\omega)I + \omega I/C$, $(\omega = 0.10 \text{ to } 0.90)$
>> Generate two-dimensional trend, T and deviations from trend, D
>> Compute statistics (average and root-mean-square) of D, μ_D and σ_D
>> Generate Mask, $M = 0$ if $D < \Lambda\, \sigma_D$, and $M = 1$ otherwise, $(\Lambda > 5)$
>> Generate first order background, $B^{(1)} = (1-M)W + MT$
>> Generate second order background, $B^{(2)}$ = area average of $B^{(1)}$
>> Generate third order background, $B^{(3)} = B^{(2)} + R$
>> Compute signal excess, $S = F - B^{(3)}$
>> Fit signal excess to third order background, $S = A_0 + g\,B^{(3)}$ for $S > 3$
>> Compute statistics of S, μ_S and σ_S
>> Identify as particle data when $S - A_0 - g\,B^{(3)} > \Gamma\sigma_S$, $(\Gamma > 3)$
>> Identify Mask as possible particle data
>> For each set of contiguous particle and/or possible particle data
>>> Accept as particle if contains at least 5 particle data points
>>> Reject as clutter if contains less than 5 particle data points

After clutter rejection, the data are loaded for stack level processing, which is described next.

3.2 Stack Level - Extraction

As each image is segmented, the segmented data are stacked atop each other, building a three-dimensional representation of the segmented data within the stack. When the data for the stack has been segmented, stack level processing, or extraction, begins.

In this stack level processing, associated particle data points between successive images are extracted. The conditions for association are that each associated data point must be near another data point of the associated set. In the same image, "near" means being within a number, N, of pixels from another member of the association. Between adjacent images, "near" means being within N pixels of the mirror imaged data point (point directly below or above). This is basically the three-dimensional version of contigious particles during segmentation.

As a set of associated data points are extracted, the set is characterized. Characterization includes location of center-of-mass, number of planes, area (obtained as average of area in the three center planes), z-extent (extent along z-axis), x-extent (extent along z-axis), and y-extent (extent along z-axis). The set is then subjected to a series of discrimination tests. These tests require that the set extend over a minimum number of planes, that the set exceed a minimum area, that the z-extent exceed a limit defined by its area, that the z-extent not exceed another limit also defined by its area, and that the x-extent and y-extent not exceed certain limits used to define structure (i.e., wires). If the set passes these discrimination tests, the set is classified as a particle. Otherwise, the set is rejected as clutter. If classified as a particle, the particle and its characteristics are tabulated.

3.3 Volume Level - Correlation

Volume level processing begins after all data stacks have been processed. At volume level processing, the particle data in the overlap region between the different stacks are registered. Using an initial estimate, the registration provides the best global estimate for the overlap between adjacent stacks. This best global estimate is based on maximizing the matching of particle location and size.

The registration process also estimates alignment errors. The alignment errors are assumed to be in the orientation of the camera and are corrected with simple image rotation.

Registration identifies multiply-counted particles in the overlap region and tags particles that fail to match. Failures to match are interpreted as noise or errors. An error rate is estimated based on these failures.

Accepted particles, their sizes, and locations are tabulated as the particle distribution functions. This final particle count includes correction for the multiply-counted particles and match failures.

3.4 Processing Summary

This section has summarized the data processing function. In this summary, the processing was separated into three distinct phases, namely, segmentation, extraction, and correlation. The segmentation phase processes each digital image separately and determines which pixels are possibly particle data. This determination is based on a comparison of the data to an estimate of the background that is derived through a lengthy procedure. Each set of contigious particle data are then classified as particle data or rejected as clutter.

The particle data for an entire stack are processed during the extraction phase. In this phase, particle data from one image are associated with particle data from neighboring images. Each set of associated particle data are extracted as one entity and characteristics are computed for the associated set. These characteristics are then subjected to a number of discrimination tests. If these characteristics pass all the tests, the data are accepted; if not, the data are rejected.

After extraction is completed for all stacks, processing continues with correlation of particles through the volume. In this phase, the particle data in the overlap regions between the adjacent stacks are correlated. This correlation step also computes an image rotation correction, identifies multiply-counted particles, and builds an error rate. Tabulation of the final set of particles produces the desired distribution functions.

Throughput of the analysis just described is 350 megabytes per hour. Plans to remove the CCD camera faceplate are expected to eliminate the fixed pattern noise. Without the need to deal with the fixed pattern noise, the throughput will increase to 500 megabytes per hour.

4.0 Sample

A sample target and hologram were produced to calibrate the algorithms and to illustrate the processing. The target consisted of two glass plates separated by a narrow void (100 or so microns). A large number of three-micron-sized particles were mixed into solution and poured into this void. After the solution had set, a hologram was made of the target. In the geometry of the Holographic Reduction Bench, this formed a layer 100 microns thick along the z-axis. A representative scan area was identified. This scan consisted of 148 frames per stack by four frames per row by four frames per column. In this scan volume, the three-micron-sized particles were confined to the center ten frames in each stack. The scan was executed on the Holographic Reduction Bench. A mosaic formed from the middle frame of each stack is presented in Figure 4.

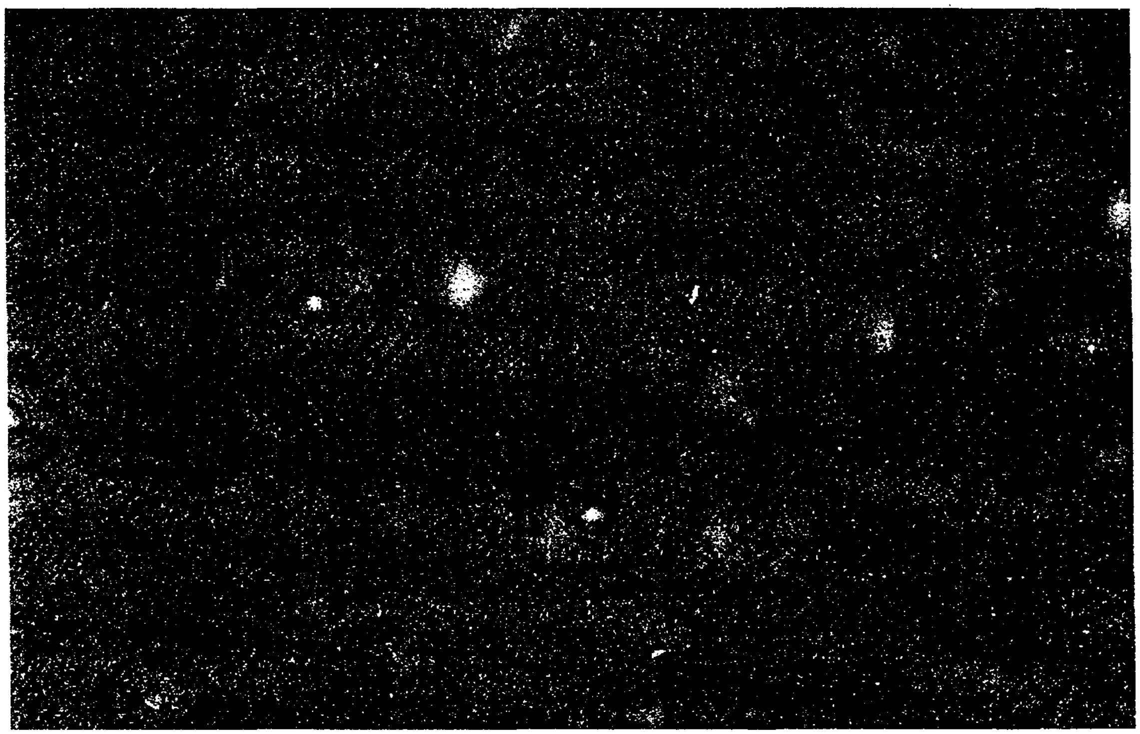

Figure 4. Mosaic of 4 x 4 Sample Scan

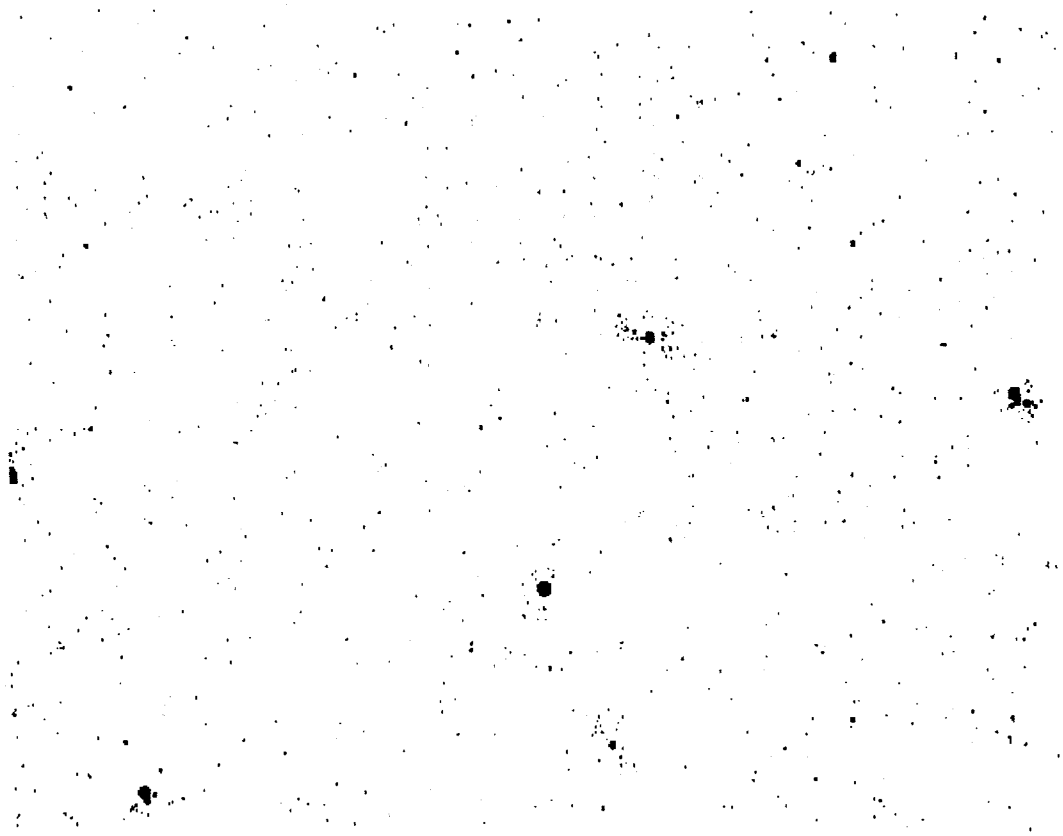

Figure 5. Sample Presentation of Particle Distribution Function

This mosaic is corrected for the expected overlap (25%), but not for the true overlap nor for image rotation. Dimensions are roughly 1.6 mm by 1.2 mm. The seven or so very large particles are air bubbles and/or dust. The air bubbles are confined to the same volume as the three-micron-sized particles. The dust particles may lie on any of the four glass faces (two each per plate). The two inner faces define the boundary of the narrow layer.

The data were processed in the procedure described with $\omega = 0.35$, $\Lambda = 8$, and $\Gamma = 5.5$ for the same background as shown in Figure 3. During the extraction phase, only adjacent pixels (N = 1) were considered to be associated. Best estimate for the overlap deduced from the registration was 25.5% and 25.5% in the horizontal and vertical, respectively. A 0° was calculated with an error of ±1.2°. The unmatched failures produced an error rate of 8.8%.

To display the resultant distribution function, the particle data are presented as circular, black particles on a white background, as shown in Figure 5. The perspective is along the z-axis (z coordinant information is lost in the display). Particle size is indicated by the circular area. The large dots are obviously the air bubbles and/or dust particles. The large particle near the center left is missing. This particle lies in the overlap region between two stacks. The differences in the z position along the z-axis was different enough so that the particle was not matched. This can be a problem when the particles are large enough that they extend through the top or bottom of the data. In such cases, the proper center of mass is not calculated.

The density of the smaller particles is high near these large particles. A more detailed examination of the actual distribution functions shows that the small particles near the large particles lie inside the glass used to form the target. This is unrealistic. In actuality, the images of the larger particles fragmented as they moved out of focus during the scan. This fragmentation can confound the processing.

To reduce the effects of fragmentation, the data were reprocessed. This time, during the extraction phase, data association was relaxed to include data within N = 5 pixels. In addition, the discrimination test was set to reject particles larger than 10 microns. The goal was to extract as much of the data associated with the air bubbles and/or dust particles and reject them based on size. The result of this processing is shown in Figure 6. The new discrimination eliminates the large particles and most of their related satellite particles.

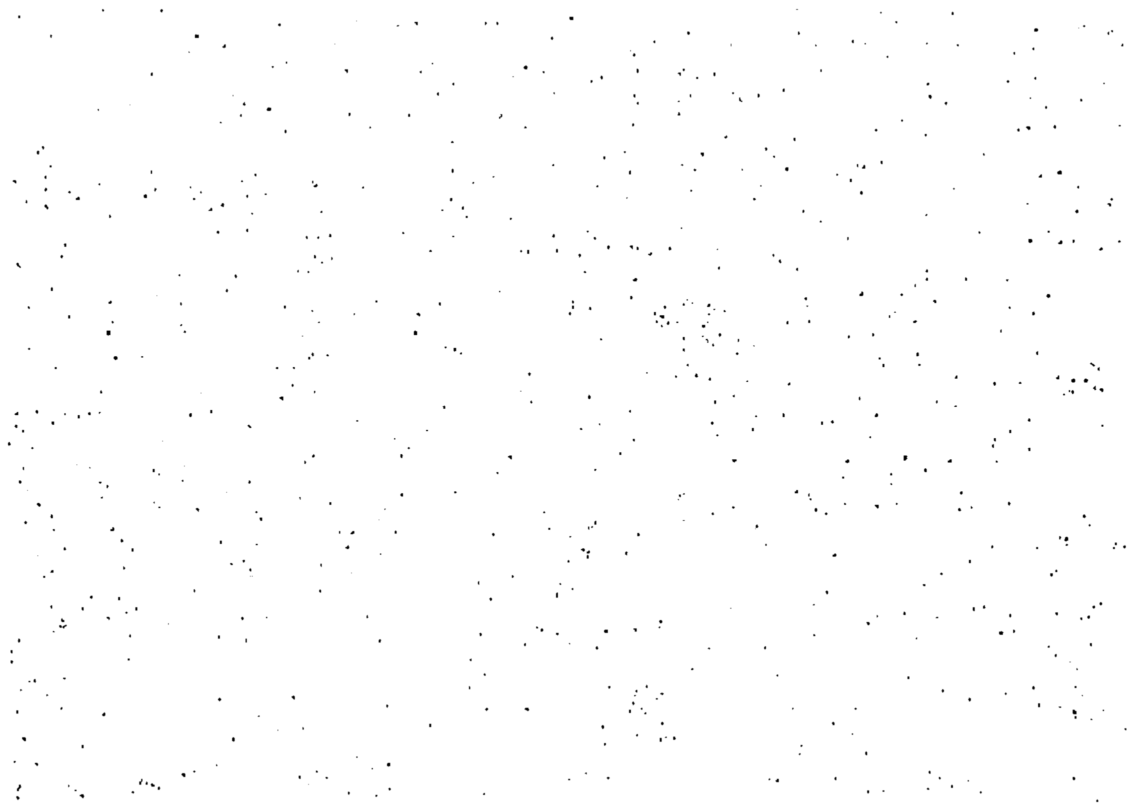

Figure 6. Display of Particle Distribution Functions with Discrimination Against Large Particles

The average size for the accepted particles is around 4.5 square microns, or 2.5 square microns smaller than what would be expected of a three-micron-sized particle (assuming a sphere and three- micron diameter). Detectable area is $A = \pi D^2 / 4$ for a spherical particle with diameter D. Edge detection is difficult for these small particles. If errors in the edge detection produce an error dD in defining the diameter, the error in the area is $dA = \pi D \, dD. / 2$. Where dA = 2.5 square microns and D = 3 microns, an error of dD. = 0.53 microns (or roughly 1 wavelength) is deduced in defining the size of the particles. This is no surprise.