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Title: PARTICLE DISTRIBTUION MEASURMENTS USING IN LINE FRAUNHOFER HOLOGRAPHY

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Particle Distribution Measurements Using in-line Fraunhofer Holography

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ABSTRACT

In-line Fraunhofer holography has been developed and implemented at Los Alamos National Laboratory to measure particle distributions of fast moving particles. Holography is a unique diagnostic that gives unambiguous information on the size and shapes of particle distributions over a three dimensional volume. Currently, the capability of measuring particles two microns in size which travel many mm/μsec has been demonstrated in hydrodynamic experiments at the Pegasus Pulsed Power Facility. Normally, for setting up an in-line holography experiment for measuring particles a few microns in size, the holographic film would be placed less than one centimeter from the particles. However, due to the high energy associated with the dynamic experiment, an optical relay system is used to relay the interference pattern 35 cm so thAT glass hologram will survive. After the hologram has been made the data must be extracted. This is accomplished by using a laser to reconstruct the data in space. This three dimensional image is then digitized via a CCD camera and a three axis actuator system. After the data has been digitized it is then analyzed with intelligent image processing algorithms. Details will be described below.

1. IN-LINE HOLOGRAPHY

Holography offers many advantages over other imaging techniques. Unlike microscopy which has a very limited depth of field holography can record over a large depth of field many orders of magnitudes larger. Holography is fundamentally a three dimensional imaging technique. In addition, when a hologram is used to reconstruct the data, an actual three dimensional image of the data is recreated so information about the particle size and shape can be extracted directly from the hologram. This is an advantage over the light scattering methods which rely on models in order to extract information about the particle size.

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In-line Fraunhofer holography has been developed and implemented at Los Alamos National Laboratory to measure particle distributions of fast moving particles. Holography is a unique diagnostic that gives unambiguous information on the size and shapes of particle distributions over a three dimensional volume. Currently, the capability of measuring particles two microns in size which travel many mm/μsec has been demonstrated in hydrodynamic experiments at the Pegasus Pulsed Power Facility. Normally, for setting up an in-line holography experiment for measuring particles a few microns in size, the holographic film would be placed less than one centimeter from the particles. However, due to the high energy associated with the dynamic experiment, an optical relay system is used to relay the interference pattern 35 cm so that the glass hologram will survive. After the hologram has been made the data must be extracted. This is accomplished by using a laser to reconstruct the data in space. This three dimensional image is then digitized via a CCD camera and a three axis actuator system. After the data has been digitized it is then analyzed with intelligent image processing algorithms. Details will be described below.

Keywords: Holography, in-line Fraunhofer holography, Pegasus, ejecta

1. IN-LINE HOLOGRAPHY

Holography offers many advantages over other imaging techniques. Unlike microscopy which has a very limited depth of field, holography can record over a large depth of field many orders of magnitudes larger. Holography is fundamentally a three dimensional imaging technique. In addition, when a hologram is used to reconstruct the data, an actual three dimensional image of the data is recreated so information about the particle size and shape can be extracted directly from the hologram. This is an advantage over light scattering methods which rely on models in order to extract information about the particle size.

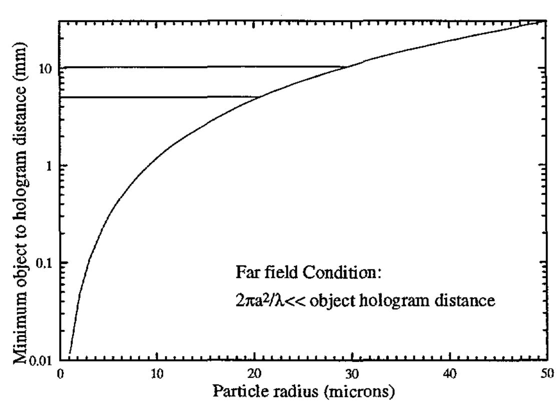

Figure 1: Plot showing minimum particle to hologram distance (z) for a given particle radius.

Many articles have been written describing holography for use in measuring small objects in a volume. For example, Ref. 1, 2 and references included therein provide a fairly complete description of these techniques. For the current discussion, the in-line Fraunhofer holography technique is used to make particle size measurements. An advantage of this technique is the simplicity of the geometrical configuration. For instance, in traditional holography a laser beam is split and later recombined with the scattered beam to form the hologram. In-line Fraunhofer holography requires only a single beam. As the single laser beam passes through the region where the particles reside, part of the beam is scattered and part is unscattered. These two beams interfere at the film plane to form the hologram. In order to record high quality data using this technique certain conditions must be met. First, the experiment should be designed so that at least 80% of the beam[3] passes through the region of interest unchanged. This will assure that enough reference beam is available so that a good interference pattern is formed which is the information required to reconstruct the particles. A second requirement is that the far field condition must be met. This condition states that the minimum particle to hologram distance (z) must meet the following criteria:

$$z >> \frac{2\pi a^2}{\lambda} \qquad 1.)$$

where a is the radius of the particle, and λ is the wavelength of the laser light. Fig. 1 shows a plot of this equation. For example, if a particle 3 microns in radius is to be measured, one far field corresponds to 100 microns. Therefore, the hologram should not be any closer than 100 microns. Thus, for small particles the far field condition is not difficult to achieve.

Of particular concern is the irradiance distribution at the plane of the hologram. This is the distribution that arises from the presense of particles scattering light and the resulting supperpostion of the scattered and unscattered light. If an opaque sphere is illuminated with laser light the irradiance distribution is given by[4]:

$$I(r) = \left(\frac{B}{m}\right)\left\{1 - \frac{kma^2}{|z|}\sin\left(\frac{kr^2}{2m|z|}\right)\left[\frac{2J_1\left(kar/_z\right)}{kar'/_z}\right] + \left(\frac{kma^2}{2|z|}\right)^2\left[\frac{2J_1\left(kar/_z\right)}{kar'/_z}\right]^2\right\} \qquad 2.)$$

where r is the radius of a given point in the plane of the hologram, a is the radius of the particle scattering the light, k = $2\pi/\lambda$, m is the magnification, and z is the particle to hologram distance. The equation contains three terms. The first term is just a constant and the second term describes the interference between the reference beam and the scattered light. The last term is the irradiance distribution as given by Fraunhofer diffraction for a circular aperture. This last term is plotted at the top of Fig. 2, and the interference term is plotted at the bottom for a=1.0 micron, λ = 0.530 micron, and z=2 mm. Notice that the ratio for the two curves close to the origin is about 650 which indicates the Fraunhofer term is negligible. Therefore, the second term is the only important term and should be faithfully recorded. This term is composed of a high frequency sine function which depends only on the hologram to particle distance, and a low frequency

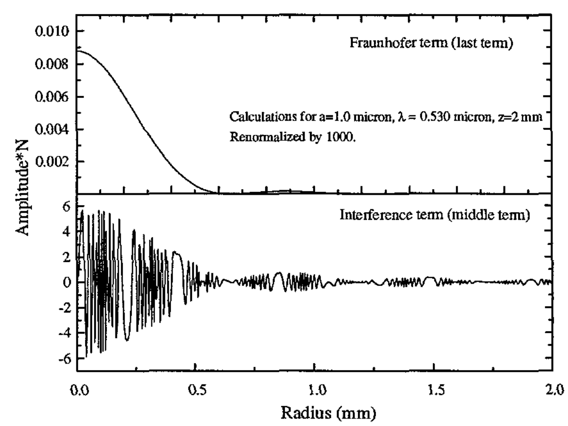

Figure 2: Comparison between the last two terms in Eq. 1. Terms have been multiplied by N=1000.

Bessel function. The Bessel function contains all the information about the particle size. Fig. 3 plots Eq. 2 for four values of z which range from 2 to 8 mm for a fixed particle radius of 1 micron. Both the low frequency and high frequency component are easily seen. It is importance is to record at least the first lobe of the Bessel function. The ability to record the first lobe of the Bessel function depends of the solid angle accepted by the hologram. The solid angle is given by: $d\Omega(a,z) = {dA}/{z^2}$ where dA = πr^2 is the area of a circle in the plane of the hologram where r is the radius given by the zero of the first lobe. For example, for z equal to 8mm, fig. 3 the hologram should have a radius of about 3 mm if enough information is to recorded to reconstruct a particle with a radius of 1 micron. For the current dynamic applications placing a hologram 8 mm from the particles is not possible because the film would not survive the experiment. Therefore an optical relay system is used to move the interference pattern 35 cm. This is illustrated in Fig. 4. In the figure the incoming beam scatters and forms a virtual interference pattern. The virtual interference pattern is 2 mm from the front end of the volume being interrogated, and 8 mm from the back end of the volume. This virtual interference plane is located at the conjugate of the lens and is relayed roughly 35 cm to where the hologram is placed. The top three calculations shown if fig. 3 correspond to the irradiance distribution that would be observed at this virtual position. Clearly more information is recorded for particles closer to this plane. By using the optical transfer system the recording of the intereference pattern is limited by the solid angle and resolution of the lens system. The bottom of Fig. 3 shows what part of the irradiance distribution is being passed by the optical transfer system which is located about 40 mm from the particles. Even though the optics is much further away than the virtual interference plane, the area of the collecting optics (radius=18 mm) is large enough so that the first lobe of the Bessel function is passed for a 1 micron radius particle. The optics has a limited resolution of 400lp/mm which is much less than the resolution of the holographic filem which has a resolution of 5000lp/mm. This reduced resolution blurs the high frequency component which presumably reduces the ability to locate the axial position of the particle.

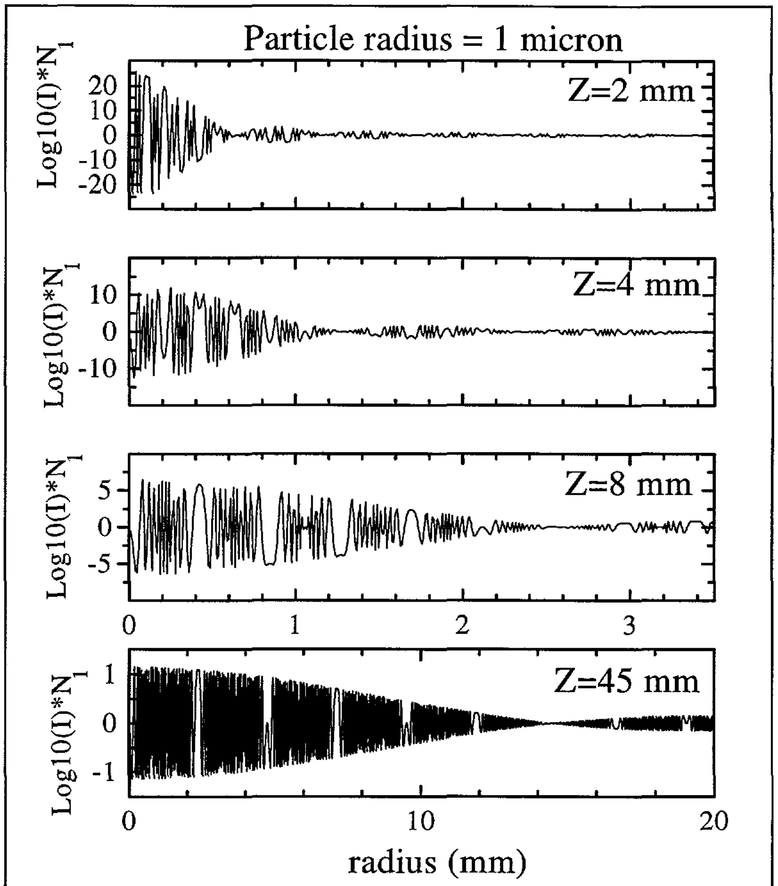

Figure 3: Eq. 2 is plotted for four different values of z ranging from 2 mm to 45 mm. The distributions have been normalized by N_1 = 1E3. The x axis is the radius of a circular intensity distribution in the plane of the hologram.

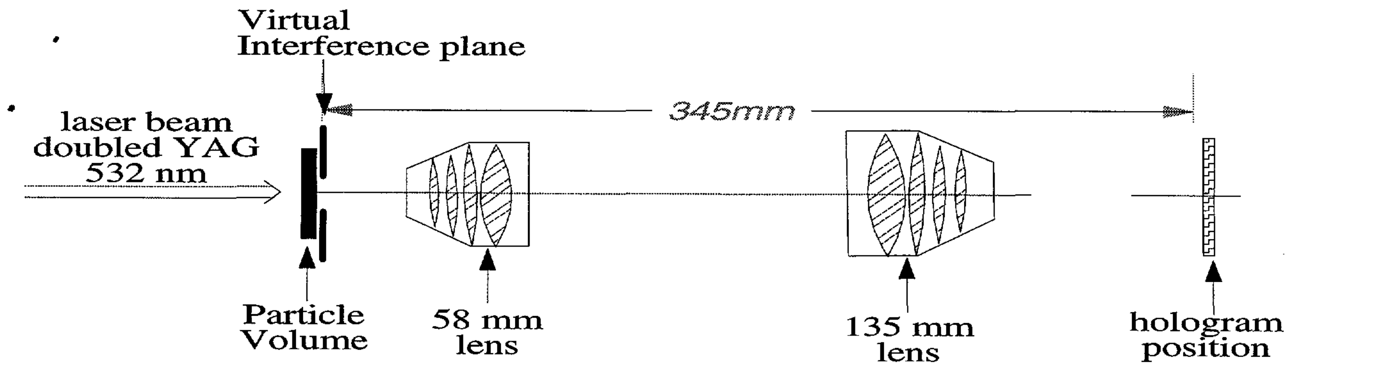

Figure 4: Optical relay system used to transfer the interference pattern 35 cm to the hologram. For the experiments, a mirror is placed between the two lens. The particle volume extends 6 mm in depth and covers an area with a diameter of 12 mm.

2. DYNAMIC EXPERIMENTS

The holography system discussed here has been developed for hydrodynamic experiments at the Pegasus Pulsed Power Facility at Los Alamos National Laboratory. Fig. 5 shows a part of the Pegasus Facility. Not shown in the figure are the capacitor banks which dump 5 mega-amps of current through the power flow channel shown in the figure. At the end of the power flow channel is the target assembly where the physics experiments take place. A blow-up of this region is shown in Fig. 6. In this region a cylinder with dimensions 2.0 cm high and 5.0 cm in diameter accept the high current. As the current flows through the cylinder the **J**x**B** force implodes the cylinder radially inward. The imploding cylinder then impacts a target cylinder. The resulting collision sets up a shock wave in the target which propagates through the cylinder and at the inner target surface debris is ejected with a wide range of velocities. It is this debri that is measured using holography. Fig. 6 also shows a third cylinder called a collimator. The collimator is used to mask the ejecta so that the density of particles entering into the inner cylinder can be controlled. The ejecta that passes through the mask enters into the collimator region which is where the holography experiment is performed. Fig. 6 shows the optical

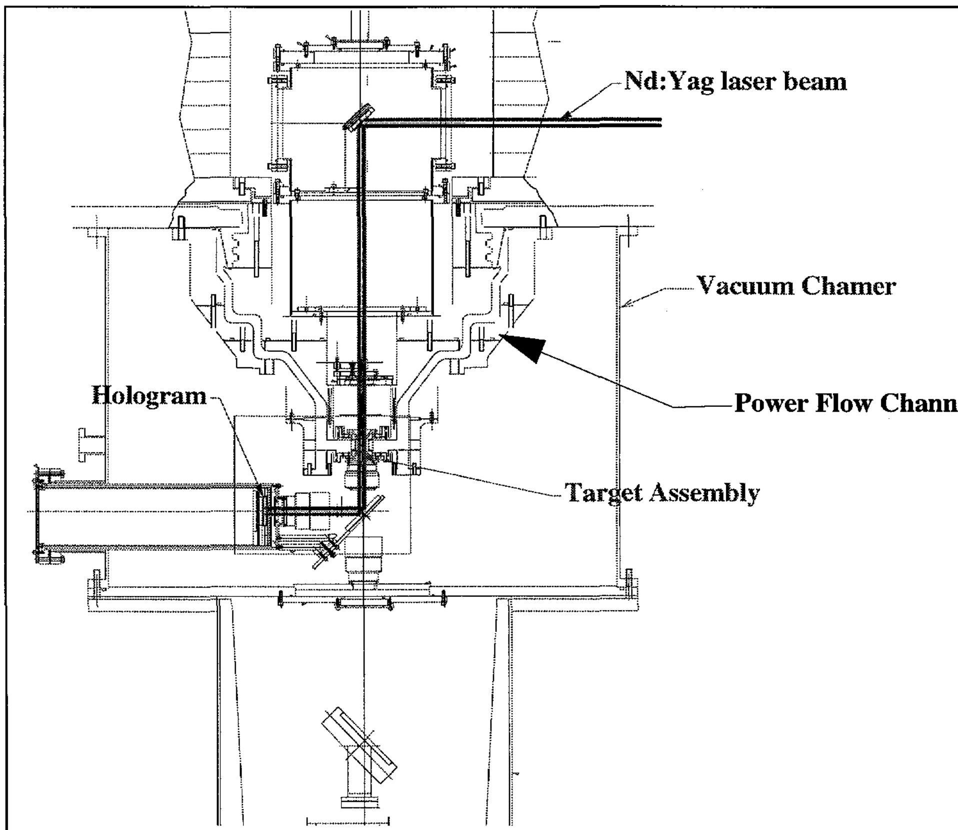

Figure 5: Pegasus machine with holography system shown. Target assembly is shown near the center where the laser beam passes through. Fourier lens system is used to relay image as shown.

transfer system which is used to relay the virtual interference pattern to the hologram. For making holograms of small particles traveling many mm/µsec it is necessary to use a pulsed laser with a sufficiently small pulse width to reduce blurring. For these experiments a frequency-doubled Nd:Yag laser is used which delivers a 60mJ 100 ps pulse at 532 nm. With the given pulse length the blur due to the particle velocity ranges from 0.350 µm - 0.750 µm for particles traveling between 3.5 mm/µsec and 7.0 mm/µsec respectively.

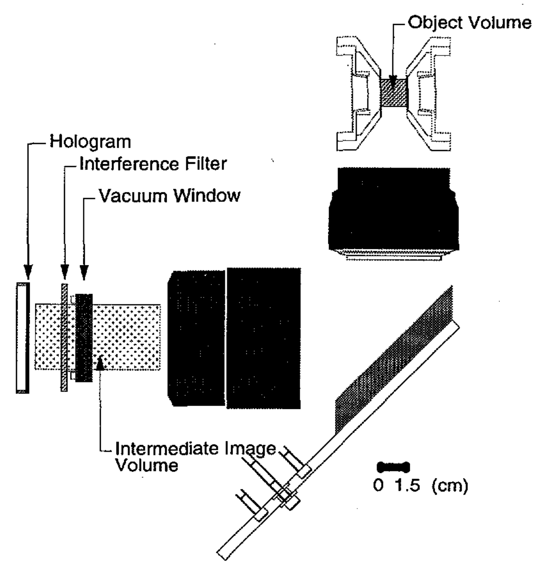

Figure 6: Blow up target assembly and associated holography optical relay system. The object volume is relayed to the intermediate image volume with a magnification of 2.6 in the x-y plane and 6.8 along the z axis.

3. HOLOGRAM DATA RECONSTRUCTION SYSTEM

In this section the data reconstruction and analysis will be described. As mentioned earlier the data that is recorded occupies approximately 1 cm^3. The analysis procedure follows two major steps. The first step is to reconstruct the data and acquire the data via camera and store to disk. The second step is to take the digital data and analyze the images extracting the particle size and location. Fig. 7 shows a schematic of how the data is reconstructed during the first step. The figure shows a laser beam coming in from the left side. The laser is spatially filtered and expanded so as cover the entire hologram. The CCD TV camera, laser, and all optics are fixed with only the hologram moving in three dimensions. As the laser beam passes through the hologram a three dimensional image is formed in space in front of the

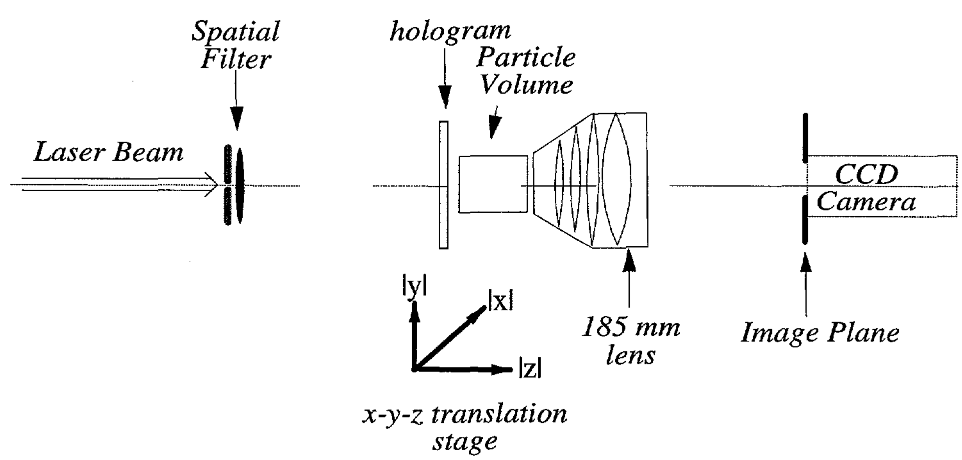

Figure 7: Illustration of reconstruction system. Laser beam is used to reconstruct image shown. Hologram moves on a three dimensional stage and the camera digitized images.

hologram. A corresponding virtual image is formed in front of the hologram. A magnifying lens placed before the CCD TV camera collects a well defined portion of the real image and relays a small portion of the image to the camera which is grabbed and stored to disk. By moving the hologram, different portions of the real image of the hologram can be examined. Using a computer to control the movement in a methodical manner, a digital three-dimensional representation of the holographic data is built.

Fig. 8 introduces a number of data concepts associated with this digital three-dimensional data set. The basic building block is the image data shown at the upper left in Fig. 8. Collectively, the image data acquired along the z-axis can be "stacked" atop each other and are called stack data as shown in the upper right of Fig. 8. When the last image data has been acquired for a stack, the computer shifts the hologram along the horizontal. A shift to the right is indicated in the volume data shown in Fig. 8. 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 overlaps with the previous stack (nominally 10% overlap). Correlation within this overlap region is used to register the data sets. Again, the hologram is shifted along the x-axis and a new stack is acquired. The process is repeated until the programmed number of stack data has been acquired in the z direction. At this point, the hologram is shifted vertically (nominally 90% of the image height) rather than horizontally. The middle part of Fig. 8 illustrates this as a downward shift in the volume data. The stack data acquired constitutes a row of stack 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 all the data frames have been acquired. In this manner, the complete volume of data is acquired. For a complete scan, the total number of image data sets acquired is expected to exceed several thousand.

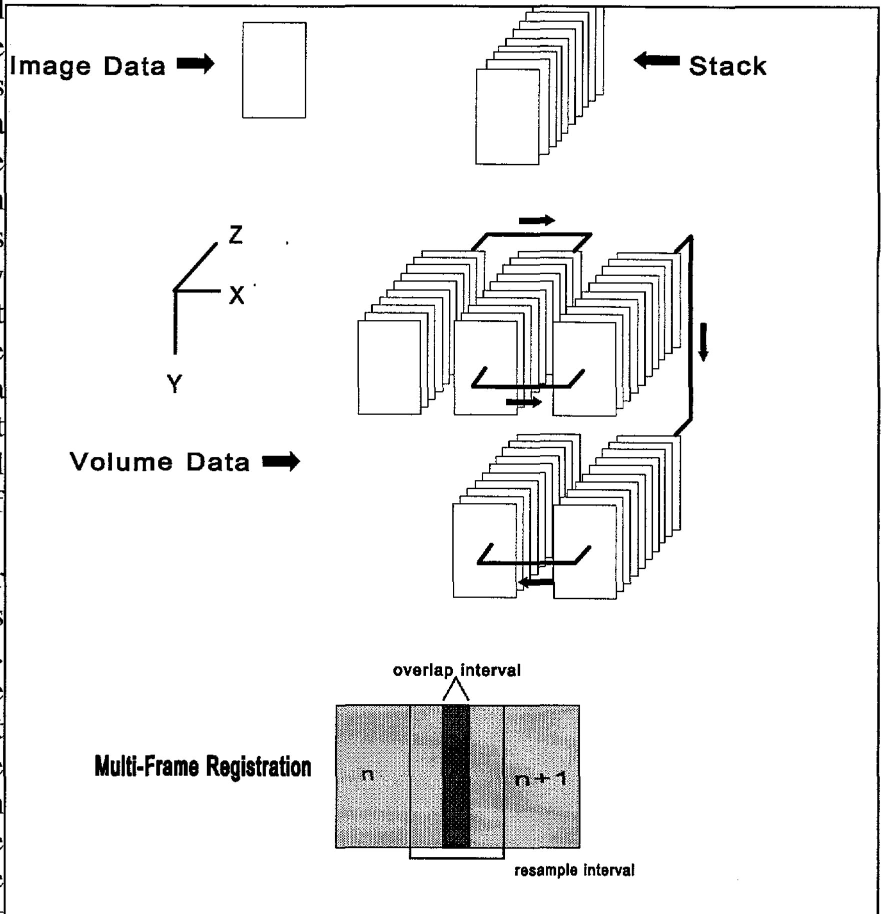

Figure 8: Three data processing steps illustrated.

3.0 Data Processing Procedure

Data processing proceeds at a different level for each concept just described. At the image level processing, the data are segmented (i.e., particle data identified). The image segmentation step develops a background noise model. Dynamic classification thresholds are then derived from the noise model.

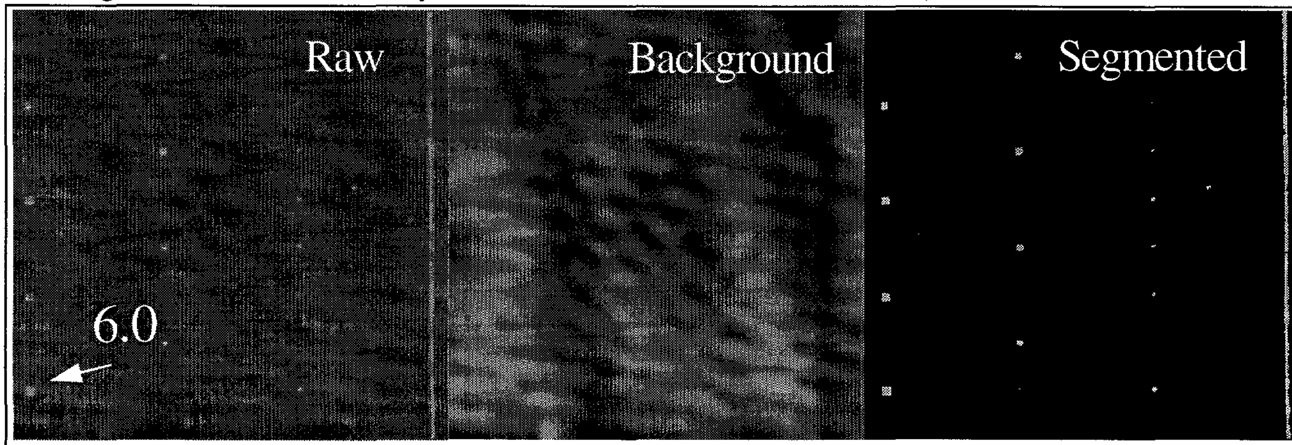

Figure 9: Raw image data is shown at the left. Image is of opaque squares ranging from a micron up to 6 microns in size. The middle figure is the modeled background of the raw data image. The image on the right is the segmented image showing just the particles that have been extracted from the background.

Data exceeding the local thresholds are segmented as particle data. These steps are illustrated in Fig. 9. In the figure a raw data image is shown to the right. The raw data shows square patterns ranging from 2.5 to 6 microns in size. The raw data also shows a background noise that varies across the image. This background is modeled and is shown in the middle figure. The final step is segmentation of the data and that is shown at the far left of Fig. 9. After the segmented images have been acquired the images are processed. The segmented image data are stacked atop one-another. Particles (i.e., contiguous data points in three dimensions) are then extracted. After extraction, the particle data are analyzed. During analysis, particle features are calculated and compared with discriminates and thresholds set by the user. Particles that pass the discriminant test are accepted, while those that fail are rejected. Collective volume processing begins after all stack data have been processed. The overall task of collective volume processing is to count the number of particles. However, a number of problems must be addressed first. The first problem concerns registration between the different stacks of data (i.e., determining the true overlap between data sets). Next, with the true overlap derived, corrections for the multiply-counted particles in the overlap regions are made. Finally, a data file is created which includes the three dimensional coordinates of the particle, its cross sectional area in the focus plane, and the extend of the particle along the beam axis.

5. CONCLUSIONS

At Los Alamos a program has begun to develop in-line holography for making dynamic particle distribution measurements. Because of the nature of the experiments a specialized optical transfer systems is used to relay an interference pattern far enough away from the experiment that a glass hologram will survive the experiment. These types of measurements also require a short pulsed high power laser system so as to reduce blurring of the particles as the exposure takes place. A complete data reconstruction system has been developed for reconstructing the data from the hologram and digitizing the data for analysis. A data analysis capability has been briefly described in which many gegabytes of image data are analyzed in which particle size and position are extracted. This capability is being applied to many dynamic experiments currently being carried out at the Pegasus pulsed power facility.

5. ACKNOWLEDGMENTS

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4 : See Eq. 4.18 in Ref. 2.